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Study of Arc-Discharge Plasma Actuators for the Control of Shock-Wave Boundary-Layer Interaction



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This dissertation is submitted for the degree of
Doctor of Philosophy

May 2023

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This dissertation contains fewer than 36,000 words, including appendices, bibliography, footnotes, tables and equations and has fewer than 130 figures.

Xiuxiu Chen

May 2023

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Abstract

The shock wave boundary layer interaction (SWBLI) occurs in transonic, supersonic and hypersonic applications, for example, the transonic aerofoil, and supersonic inlet. In the occurrence of SWBLI, the incoming boundary layer is subject to an intense adverse pressure gradient caused by the shock wave, leading to a separation. Apart from boundary layer separation, other adverse effects include enhanced turbulence and additional unsteady load to the structure. All those adverse effects will degrade the aerodynamic efficiency and lead to potential structural failure. Flow control is thus needed to address the SWBLI. Recently, the arc-discharge plasma actuator has emerged as a new type of active control device to enhance the SWBLI flow control.

This thesis explores the fundamental characteristic and flow control mechanism of arc-discharge plasma actuators, focusing on the localised arc filament plasma actuator (LAFPA) and the plasma synthetic jet actuator (PSJA). Theoretical, experimental investigations and numerical simulations were conducted to illustrate the performance of these actuators within a wide range of setups and operation conditions, including the operation frequency (0.5-2 kHz), the cavity volume (128-512 mm³) and the discharge energy (2.8-11.3 mJ). The traditional Z-type Schlieren technology was applied to visualise flow structures and capture detailed propagating information of gas dynamic interfaces after the arc discharge (e.g. thermal plasma kernel, shock waves, jet flow). Numerical simulation through ANSYS Fluent was also applied in support of the experimental data and compared with a developed 1D code. Direct numerical simulations (DNS) of the shock wave boundary layer interaction (SWBLI) control through LAFPA were well analysed through collaboration. The effect of PSJAs on the transonic shock wave boundary layer control was conducted by the Unsteady Reynolds-averaged Navier-stokes equations (URANS).

Several findings have been derived from the investigation at hand. Firstly, the fundamental flow characteristics of LAFPA employing flush electrodes and electrodes located outside the wall have been effectively captured. Schlieren imaging enabled confirmation of the plasma kernel's shape, blast wave propagation, and thermal fluctuation. Secondly, using five PSJA models, simulations in a quiescent environment are conducted, facilitating detailed analyses of the instantaneous evolution of velocity, pressure, and temperature. By developing a one-

dimensional code, orifice velocities could be predicted for different input energy levels and cavity volumes, with outcomes consistent with 3D simulations. Additionally, DNS results demonstrated the control mechanism of LAFPA to SWBLI, whereby the high-frequency operation of LAFPA resulted in the emission of precursor shock waves (PSWs) that merged with the separation shock by coalescing into an oblique shock. Lastly, URANS results revealed that the arc-forced micro jets effectively controlled the central separation area of the transonic SWBLI.

Publications

- 1 Chen, X., Sun, Z. (2022). Plasma kernel model and energy transformation characteristic of plasma synthetic jet actuator. *Physics of Fluids*, 34(12), 126104.

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Nomenclature

Roman Symbols

$\dot{q}$	Heat loading
A_o	Orifice area
B	Energy parameter for plasma kernel
c_0	Speed of sound at standard environment
C_f	Friction coefficient
c_p	Constant pressure heat capacity
c_v	Constant volume heat capacity
c_{p0}	Specific heat capacity
D_c	Cavity diameter
E_c	Cavity internal energy
E_d	Discharge energy
E_k	Kinetic energy
E_p	Potential energy
f	Operating frequency of actuators
H_c	Cavity height
I	Actuator currents
L_c	Cavity length

l_d	Distance between two electrodes
l_w	Electrodes' lengths outside the wall
M_g	Molar gas constant of a gas
m_k	Mass of plasma kernel
Ma	Mach number
p_0	Ambient pressure, $p_0 = 101325$ Pa
q	Time-dependent power density
R	Specific gas constant
r_c	Inner length scale of the plasma kernel
r_k	Radius of plasma kernel
Re	Reynolds number
S_c	Source term
St	Strouhal number
T_0	Ambient temperature, $T_0 = 300$ K
t_c	Inner time scale of the plasma kernel
T_k	Temperature of plasma kernel
t_k	Characteristic time of plasma kernel
u	Characteristic velocity
U_{ref}	Streamwise reference velocity
V_c	Cavity volume
V_d	Energy deposition volume
V_k	Volume of plasma kernel
V_p	Peak velocity
W_c	Cavity width

Greek Symbols

δ	Domain of the heated area
ε	Non-dimensional deposition energy
η	breakdown efficiency
η_k	Kinetic energy efficiency
η_p	Potential energy efficiency
η_T	Heating energy efficiency
γ	Heat capacity ratio, $\gamma = 1.4$
λ_k	Non-dimensional radius after plasma kernel breakdown
v	Non-dimensional cavity volume
ρ_0	Air density under standard environment
ρ_k	plasma kernel density
τ_k	Non-dimensional time after plasma kernel breakdown

Acronyms / Abbreviations

AC	Alternating Current
CVP	Counter-rotating Vortex Pair
DBD	Dielectric barrier discharge
DC	Direct Current
DNS	Direct Numerical Simulation
IGBT	Insulated Gate Bipolar Transistor
K-H	Kelvin–Helmholtz
LAFFA	Local arc filament plasma actuator
LES	Large Eddy Simulation
MVG	Micro-ramp vortex generator

ns-DBD Nanosecond Dielectric barrier discharge

PCC Phantom Camera Control

PSJA Plasma synthetic jet actuator

PSWs Precursor Shock Waves

PT Pulse Transformer

RANS Reynolds-Averaged Navier-Stokes equations

SA Spalart-Allmaras

SST Shear Stress Transport

SWBLI Shock-wave boundary-layer interaction

URANS Unsteady Reynolds-Averaged Navier-Stokes equations

ZNMF Zero-net-mass-flux

Chapter 1

Introduction

1.1 Background

In the occurrence of SWBLI, the incoming boundary layer is subject to an intense adverse pressure gradient caused by the shock wave, leading to a boundary layer separation, enhanced turbulence and additional unsteady load to the structure. One example of SWBLI in the aerospace industry is the phenomenon of shock-induced separation in supersonic and hypersonic flows. In this case, the interaction between a shock wave and the boundary layer of an aircraft's wing can cause the boundary layer to separate from the wing, leading to a loss of lift and increased drag. This can significantly impact the aircraft's efficiency and safety. Another example of SWBLI in the automotive industry is the phenomenon of shock wave-induced flow instability in high-speed combustion engines. In this case, the interaction between a shock wave and the boundary layer of the engine's combustion chamber can cause instabilities in the fuel-air mixture, leading to incomplete combustion and reduced engine performance. This can decrease fuel efficiency, increase emissions, and potential engine damage. In the energy production industry, SWBLI can also be a concern in various applications, such as in gas turbine engines and wind turbines. In these systems, SWBLI can cause performance degradation and potential damage to the turbine blades, leading to decreased efficiency and increased maintenance costs [4].

Therefore, flow control techniques, which aim to alleviate these adverse effects, play an essential role in many SWBLI flow areas and various flow fields. A single flow control device or an array of flow control devices can affect a large downstream area and have the requisite control authority to manipulate high-momentum flow. To address SWBLI in real industrial fields, researchers and engineers use various techniques, such as numerical simulations, wind tunnel experiments, and advanced flow control methods [1, 6, 13, 63]. These methods aim to understand the complex physics of SWBLI better and to develop effective strategies for

mitigating its negative effects on engineering systems [16, 112]. The motivation for this work is to understand, characterize, and develop plasma actuators capable of alleviating adverse SWBLI flow conditions.

As a new type of active flow control device, Arc-discharge plasma actuators are devices that use plasma generated by electrical discharges to manipulate the flow of fluids. These actuators have gained significant attention in recent years due to their potential to improve the efficiency and performance of various engineering systems, such as aircraft, turbines, and combustion engines. The basic principle of an arc-discharge plasma actuator involves applying a high voltage to two electrodes, which are separated by a small gap filled with a neutral gas. The voltage ionizes the gas, creating a plasma channel that can interact with the surrounding fluid. The plasma channel can induce changes in the flow field by generating an electric field or inducing a momentum transfer through a phenomenon known as the plasma-induced force [77]. The performance of arc-discharge plasma actuators is highly dependent on several parameters, including the applied voltage, the frequency of the electrical pulses, and the geometry of the electrodes. Additionally, the properties of the plasma, such as its temperature, density, and composition, can also affect the performance of the actuator. Research into arc-discharge plasma actuators has shown promising results in various applications, including boundary layer control, flow separation control, and noise reduction. However, further studies are necessary to understand the complex physics behind these devices fully and to optimize their design for practical use in engineering systems.

Although the application of arc-discharge plasma actuators has become a research hot spot in recent decades, the flow control mechanism for different plasma actuators still remains unclear. This work aims to analyse the characteristics of various actuators and understand their capability of releasing adverse flow conditions. Theoretical, Experimental and numerical methods have been used to analyse the flow characteristic generated by arc-discharge actuators. The effect on the shock wave boundary layer interaction, which is the key point of the flow control, has been investigated. The exact mechanisms by which the flow control techniques interact with the shock wave and the boundary layer interaction (SWBLI) are also discussed in details. This will provide a better understanding of flow control physics of SWBLI, enable the development of optimized flow control techniques for practical applications, and facilitate the investigation of flow control performance in more complex and realistic flow configurations.

Before we further introduce the flow control of the SWBLI, the scheme of boundary layer transition and the flow separation is first illustrated.

1.1.1 Boundary layer transition

Boundary layer transition is the process describing the transformation of a boundary layer from laminar to turbulent [89, 88]. Boundary layer transition is caused by the growth of particular instabilities in the flow near the surface [103]. The instabilities can exist due to surface roughness, surface features, or the natural growth of the boundary layer. Figure 1.1 is a sketch describing the series of instabilities that transform laminar flow to fully turbulent flow from Schlichting et al. [89]. The differences between laminar and turbulent boundary layer flow make each type useful or undesirable. For example, the skin friction drag associated with laminar flow is lower than with turbulent flow. However, laminar flow is more susceptible to flow separation than turbulent flow because it can be influenced more easily by an adverse pressure gradient or surface features. Therefore, inducing or delaying boundary layer transition is the potential goal of flow control.

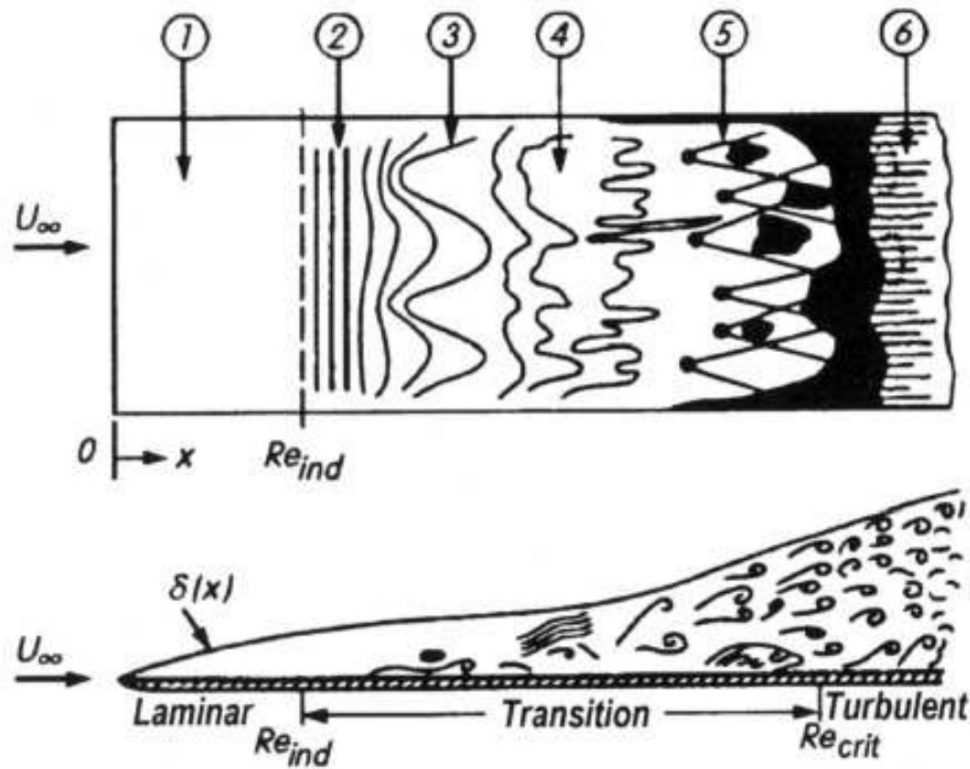


Fig. 1.1 Sketch of flow over a flat plate through the transition from a laminar to the turbulent boundary layer. The regions of flow from 1-6 are (1) stable laminar flow, (2) unstable Tollmien-Schlichting waves, (3) three-dimensional waves and vortex formation, (4) vortex decay, (5) formation of turbulent spots, and (6) fully turbulent flow, respectively. Reprint from Ref.[89].

There are several techniques that can be used to control or delay boundary layer transition. One technique is to use passive control devices, such as roughness elements or trip strips, to promote the onset of turbulence at an earlier location than naturally occurring [84], which can help to reduce the size of the turbulent boundary layer and decrease the drag on the surface. Another technique is active flow control, which involves using external energy sources to influence the boundary layer transition. For example, air jets can be injected into the boundary layer to disrupt the growth of instability waves and delay the transition to turbulence. The active flow control technique has the advantage of being adjustable and adaptable to changing flow conditions [70]. In addition to these techniques, researchers are also exploring the use of novel materials and surface coatings to modify the behaviour of the boundary layer [31, 34]. For example, surfaces that are coated with a layer of microfibers can create a turbulent boundary layer at lower Reynolds numbers than a smooth surface, which can reduce drag and improve aerodynamic performance [46].

For the boundary layer instabilities, many studies of boundary layer transition reveal a unique difference between boundary layer development over two-dimensional, flat surfaces and three-dimensional, curved surfaces. The surface curvature allows centrifugal forces to create vortical motion within the boundary layer, introducing so-called Taylor-Gortler instabilities [83]. These instabilities are considered primary and include secondary instabilities, each occurring at separate frequencies. When applying flow control techniques, all modes of instability can prompt transition. Therefore, the ideal flow control technique would prevent one type of instability without perturbing a different kind of instability. The instability responsible for the transition is also a function of velocity. For example, for Mach less than approximately four, the Tollmein-Schlichting instability growth rate dominates transition. However, for Mach more fantastic than four, the instability growth rate of higher frequency Mack modes dominates transition [97]. Such dependence on velocity requires an actuator capable of tuning the actuation frequency to the immediate flow conditions. For these circumstances, active flow control can be highly adjustable and adaptable to change flow conditions. This means that the control mechanism can be changed to achieve the desired effect, and can also respond to changes in the flow, such as variations in the velocity or turbulence intensity.

Plasma actuation is easy to produce controllable broadband aerodynamic actuation, which has potential in the field of boundary layer transition control. Figure 1.2 shows the plasma actuation for the boundary layer transition. When the laminar flow comes across the actuation position, the electrical energy will energize the boundary layer and transfer it into highly turbulent flow [120]. There are several applications of plasma flow control actuators for boundary layer transition. Streamwise and spanwise arrays of flush, plasma-generating

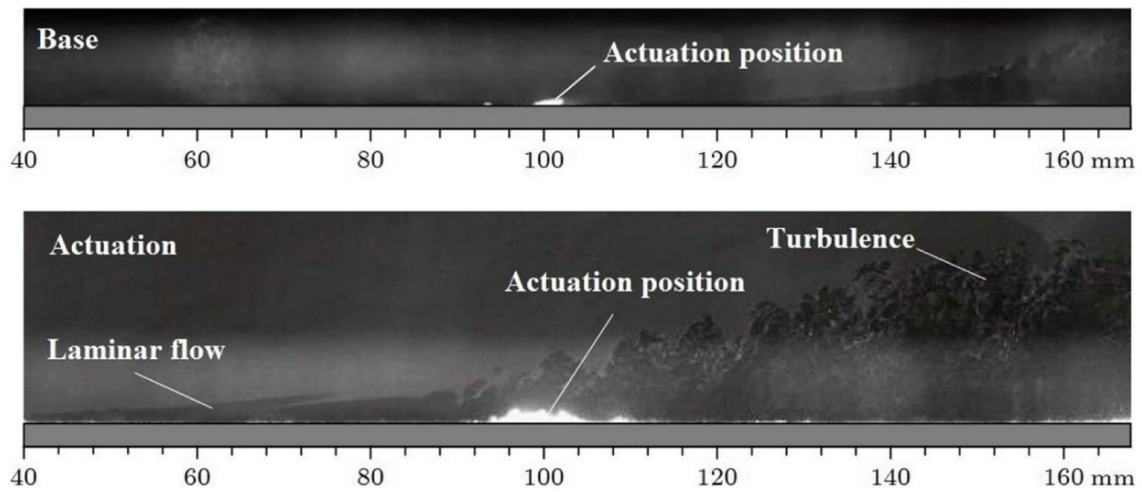


Fig. 1.2 Verification of the boundary layer transition control effect of high-energy surface arc discharge at Mach 3 [120].

surface electrodes have been studied in laminar, transitional, and fully turbulent boundary layer flow [74]. Velocity distributions in the low-speed wind tunnel have been acquired for planar panels covered by a uniform, glow-discharge surface plasma in atmospheric pressure air. It is shown that plasma between symmetric streamwise electrode strips caused significant increases in panel drag, while asymmetric spanwise electrode configurations produced a significant thrust. It also shows that the primary cause of the phenomena is a combination of mass transport and vortical structures. Furthermore, this is induced by piezoelectric solid electrohydrodynamic (EHD) body forces on the flow. Yates et al. [121] conducted a test of a plasma-based active flow-control system to accelerate and delay cross-flow induced boundary-layer transition on a cone at an angle of attack at $Ma = 6$ under quiet-flow conditions. The flow controllers were assessed by their impact on the transition location and wave number of the largest-amplitude hot streaks. The transition location was accelerated by critical forcing (actuator wave number equals wave number of naturally largest-amplitude waves) and delayed by sub-critical forcing (actuator wave number larger than natural waves). The disturbance wave number input of the plasma actuators was observed downstream on the model for many of the plasma-on runs, demonstrating that the plasma actuators introduced discrete forcing into the flow. Yang et al. [120] have reviewed the research progress of hypersonic boundary layer transition control experiments. As a new type of active flow control method, plasma has certain advantages, with the potential to control a variety of unstable modes and the ability to obtain effects of promoting transition and delaying transition control.

1.1.2 Flow Separation

Flow separation is a typical flow phenomenon of concern which adversely affects fluidic component performance. Flow separation occurs when an adverse pressure gradient exists along a surface and causes the flow to lose momentum in the boundary layer and eventually reverse direction. The adverse pressure gradient can exist for a variety of reasons, including a surface contour away from the free stream, a normal shock on a transonic airfoil or a shock wave boundary layer interaction between a reflected oblique shock and a boundary layer. Flow separation can occur in a variety of situations, such as around the leading edge of an airfoil, at the junction of two surfaces, or behind a bluff body in a fluid stream. The extent and severity of flow separation depend on factors such as the Reynolds number of the flow, the surface geometry, and the angle of attack or incidence of the fluid stream. When flow separation occurs, the flow becomes unsteady and turbulent, with fluctuations in velocity, pressure, and vorticity. The resulting eddies can lead to increased drag on the surface, reduced lift, and reduced efficiency of the system. In extreme cases, flow separation can lead to the complete stall of the system, where there is no lift generated at all. Flow separation is generally associated with increased drag or a loss of lift in all flows or a reattachment zone that can lead to increased heat transfer to the surface in supersonic and hypersonic flows. One of the most important objectives of flow control is to delay the boundary layer separation, whose possible favourable practical consequences may be, for instance, the improvement of the pressure recovery of diffusers, the reduction of the drag of bluff bodies or the increase of the maximum lift of airfoils [63].

Many researchers have developed and tested methods of flow separation control in a variety of applications. Chang et al. [12] presents an extensive review of flow separation techniques. The use of moving boundaries, which utilize the no-slip condition at the surface in order to energize the fluid close to the wall, has been explored in the past. The momentum of the boundary layer may also be enhanced by means of the injection of a fluid into the near-wall vicinity. Flow separation is a complex and highly nonlinear phenomenon, and its prediction and control are important areas of research in fluid dynamics. Numerical simulations and experimental studies are used to investigate the conditions and mechanisms that lead to flow separation, as well as to develop techniques to control or mitigate its effects. Examples of these techniques include the use of flow control devices, such as vortex generators or boundary layer suction, or modifications to the surface geometry to reduce adverse pressure gradients and promote smoother flow.

1.1.3 Non-dimensional factors

Several key non-dimensional factors need to be clarified before further introducing the control of shock-wave boundary-layer interactions. The first one is the Reynolds number, Re , defined as the ratio of inertial forces to viscous forces within a fluid that is subjected to relative internal movement due to different fluid velocities.

$$Re = \frac{uL}{\nu} \quad (1.1)$$

where u is the characteristic velocity, which is normally chosen as the incoming flow velocity in the investigation of the boundary layer, and L is the characteristic length depending on the issue of investigation. ν is the kinematic viscosity of the fluid, normally air.

The second non-dimensional factor is the Strouhal number, St , which usually describes oscillating flow mechanisms. The Strouhal number is often given as

$$St = \frac{fL}{u} \quad (1.2)$$

where f is the frequency of vortex shedding, L is the characteristic length and u is the flow velocity.

Mach number Ma is a normal factor to describe the velocity in the order of speed of sound and can be given as

$$Ma = \frac{u}{c} = \frac{u}{\sqrt{\gamma M_g T}} \quad (1.3)$$

where c is the speed of sound. γ is the adiabatic index (or 'heat capacity ratio'), normally chosen as 1.4. M_g is the molar gas constant of a certain gas, defined as molar gas constant M divided by the molar mass of the gas. T is the local temperature.

1.2 Shock Wave Boundary Layer Interaction (SWBLI)

Shock wave–boundary-layer interaction (SWBLI) is a fundamental phenomenon in gas dynamics that has been observed in many practical situations, ranging from transonic aircraft wings to hypersonic vehicles and engines [4, 48, 64]. Clemens et al. [15] illustrated three conventional canonical interactions (shown in Figure 1.3), the compression ramp, reflected shock, and blunt-fin interactions, and reviewed the low-frequency unsteady driven mechanism of SWBLI in detail. Interactions were categorized as strong interactions and weak interactions based on the size of separation bubbles, mainly affected by downstream instability or fluctuations in the upstream boundary layer, respectively. The flow field structure of SWBLI

has prominent unsteady characteristics. Regardless of the configuration, many experimental and numerical studies have shown the coexistence of two distinct characteristic frequencies: shock motions involve low frequencies. At the same time, the mixing layer downstream of the separation exhibits unsteadiness whose frequencies are higher than those observed in the shock motions but are still below the energetic scales of incoming turbulence. Inside the re-circulation bubble, both motions are at play. Turbulent boundary layer fluctuations are referred to as high-frequency unsteadiness [86]. Significant low-frequency components are much lower than the pulsation frequency of the turbulence-related system in the boundary layer [23, 94].

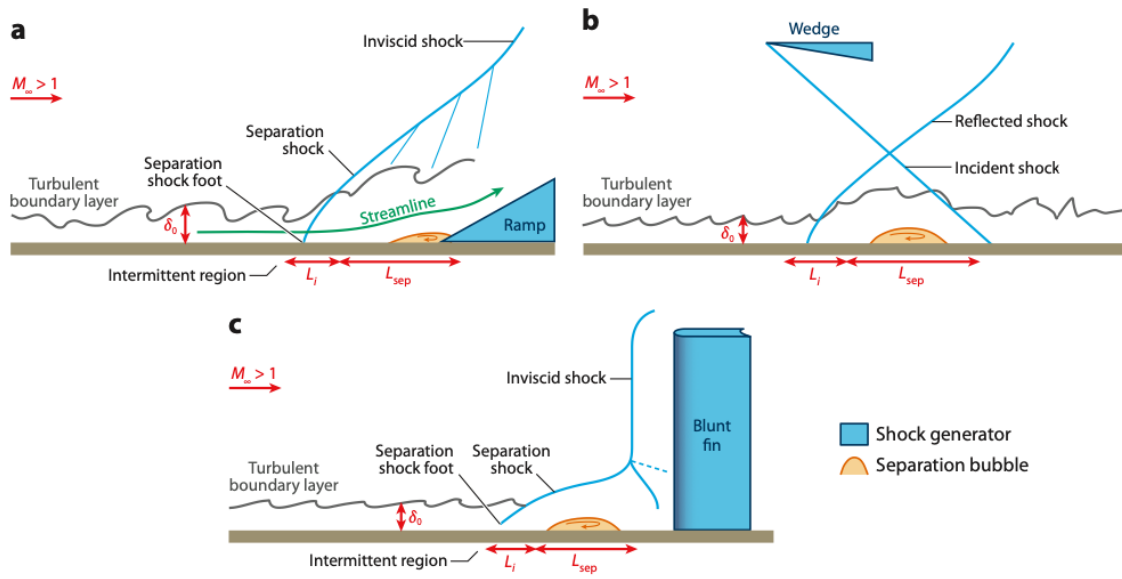


Fig. 1.3 Schematic diagrams of three canonical SWBLI: (a) Compression ramp; (b) reflected shock, and (c) blunt fin [15].

The flow separation induced by SWBLI degrades the aerodynamic efficiency and gives rise to potential structural failure. In an external flow, such as transonic wings, SWBLI will lead to a significant increase in aerodynamic drag and generate additional unstable torque, which brings a severe threat to the safety of the aircraft. In an internal flow, such as a supersonic air intake, the SWBLI phenomenon will increase the wall pressure load, seriously reduce the aerodynamic efficiency of the engine, and hinder the performance improvement of the aircraft. The development of high-speed aircraft and combined power requires the development of advanced SWBLI control technology [8]. Flow control is a meaningful way to reduce the adverse effect of SWBLI. Applying a flow control excitation upstream of the SWBLI interference area is able to promote the transition of the boundary layer or

increase the turbulence of the incoming flow. The effect of suppressing flow separation can be achieved, and in some cases, the intensity of the shock wave can even be weakened.

1.2.1 Transonic SWBLI Flow Control

This section describes the investigation of the characteristics of transonic SWBLI flow control. The critical difference between transonic interactions and other SWBLIs is the presence of subsonic flow behind the shock wave. Steady subsonic flow does not support waves, and any changes in flow conditions are gradual in comparison to supersonic flow [4]. This imposes constraints on the shock structure in the interaction region because the downstream flow conditions can feed-forward and affect the strength, shape, and location of the shock wave causing the interaction. The flow surrounding a transonic SWBLI must satisfy the supersonic as well as subsonic constraints imposed by the governing equations. The interaction also is sensitive to downstream disturbances propagating upstream in the subsonic regions. In contrast, supersonic interactions are “shielded” from such events by the supersonic outer flow [4].

The most common example of a transonic SWBLI is found on transonic-aircraft wings where the wing shock interacts with the wing-boundary layer (shown in Figure 1.4). The presence of shock waves on a transonic airfoil causes reductions in total pressure that are directly linked to the generation of drag. As a result, a contribution to the wake-pressure profile of a transonic airfoil is from the viscous drag on the airfoil and the pressure losses caused by the shock. A closely related example is the interaction inside transonic turbine- and compressor-blade cascades, where local regions of supersonic flow are terminated by shock waves that interact with the blade-boundary layers. However, transonic SWBLIs also can be found in the engine intakes of supersonic aircraft, in which the oncoming super-sonic flow is compressed and decelerated to subsonic velocities. Transonic SWBLIs also is encountered in industrial flows such as inside ducts and diffusers. The schlieren picture in Figure 1.5 shows a transonic interaction with shock-induced flow separation taking place in a channel [4]. In addition to the near-normal shock, the main flow field features are the oblique shock induced by separation, the shear layer issuing from the separation point, and the development of turbulent eddies that survive into the far-downstream part of the interaction. The sketch of this flow shows that this structure, typical of shock-induced separation in transonic flow, is termed a lambda shock pattern. The shape of the downstream part of the isobaric-separated region is more conjectural because the reattachment process depends on the coupling with an outer flow, which is primarily subsonic.

To prevent transonic SWBLI inconveniences, several flow control techniques have been studied: bleeding, blowing, and adaptive geometries like two-dimensional (2D) and three-

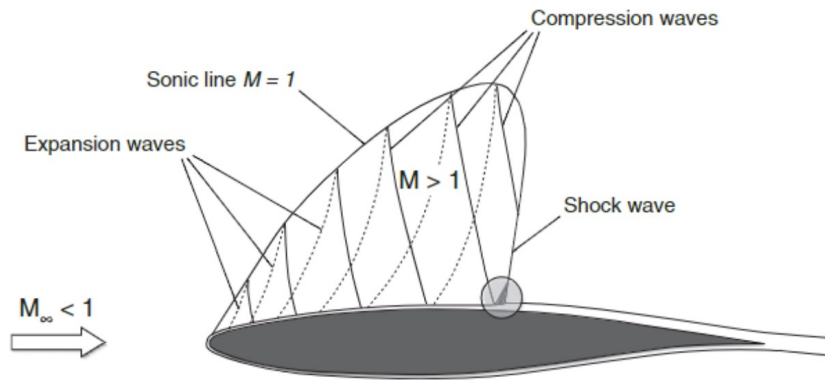


Fig. 1.4 Sketch of SWBLI on transonic wing [4].

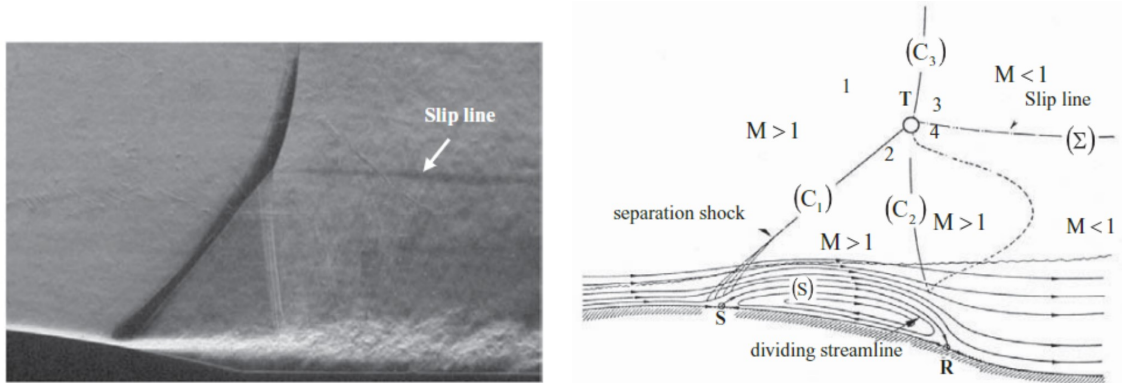


Fig. 1.5 Schlieren visualisation of a flow separation induced by normal shock interaction and a Sketch of the flow [4].

dimensional (3D) bumps, diverters, vortex centringors (VGs) [4]. Figure 1.6 compares three different flow control techniques, including active control by suction slot, passive propose surface control and contoured wall or bump [96] with a reference case without any control. By removing the low-energy part of the boundary layer in the reference case, the upstream propagation mechanism is inhibited and the thickening of the boundary layer is reduced significantly in Figure 1.6(c). The flow behaviour for transonic flows then tends towards the perfect-fluid solution with a near-normal shock extending down close to the surface. Thus, any action that energises the boundary layer also tends to strengthen the shock because any spreading caused by the interaction is reduced. In the latter case, Figure 1.6(b) and (d), the entropy production through the shock is increased; thus, the wave drag is higher. Conversely, because the downstream boundary-layer profile is fuller, the momentum loss in the boundary layer is reduced. This is a critical problem in flow control for SWBLI, because certain wave drag reductions can combine with another viscous drag increase, or the reduction of viscous

drag may cause a wave drag increase. So it is difficult to evaluate each flow control technique, and the performance always depends on the real application flow situations. The flow control achievement should be evaluated carefully from a whole system point of view.

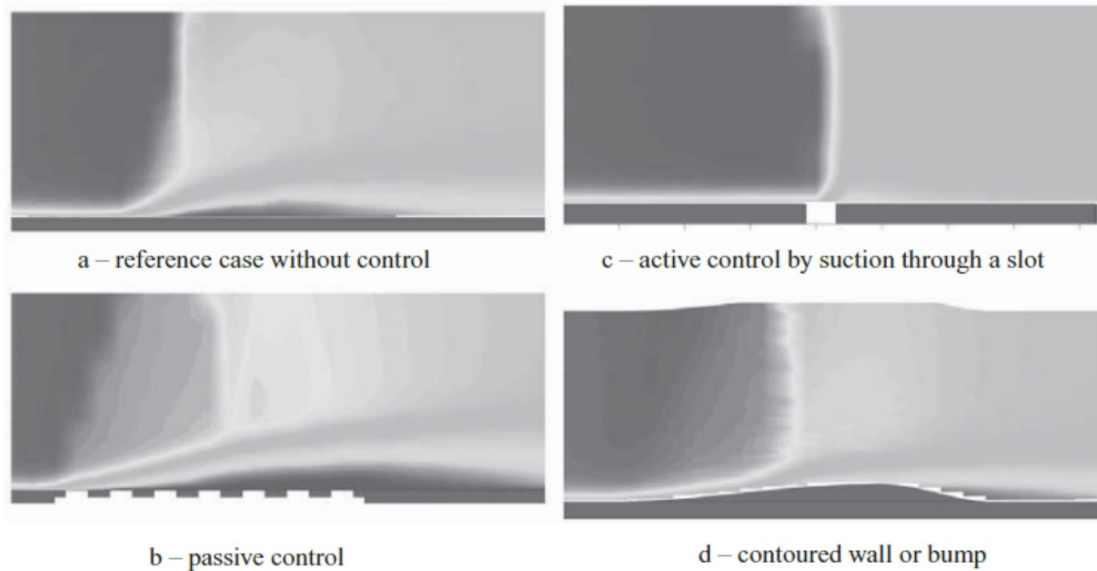


Fig. 1.6 Schlieren images of passive and active SWBLI flow control in a transonic flow [96]

The micro ramp is another attempt to control the SWBLI through passive devices. Babin-sky et al. [4] produced a steady near-normal shock wave in a $Ma = 1.4$ inflow experimentally using a dual-channel working section. Micro vortex generators were added to determine their potential for removing flow separation. Although micro ramp was found to reduce the extent of separation, flow asymmetry in three-dimensional can be significantly increased in some configurations. Roy et al. [76] conducted a computational investigation to evaluate the effectiveness of a porous medium as a passive control mechanism that can be used to reduce drag in a normal-shock-wave/boundary-layer interaction at transonic speeds. The reduction in overall drag is accomplished through recirculation within the porous medium, which mainly weakens the shock structure and reduces the wave drag. The numerical Schlieren images of pre-shock and post-shock conditions are shown in Figure 1.7. The pressure recovery varies sharply with the pre-shock length, or alternatively, the starting location of the porous cavity. In contrast, the extension of the porous cavity after the shock does not have a significant impact on pressure recovery.

In principle, shock control techniques aim at the reduction of drag and suppression of flow breakdown or buffet. Despite extensive research into the transonic flow and boundary layer flow control, there remains a significant research gap in understanding the interactions between shock waves and boundary layer flow control. One area of particular interest is the

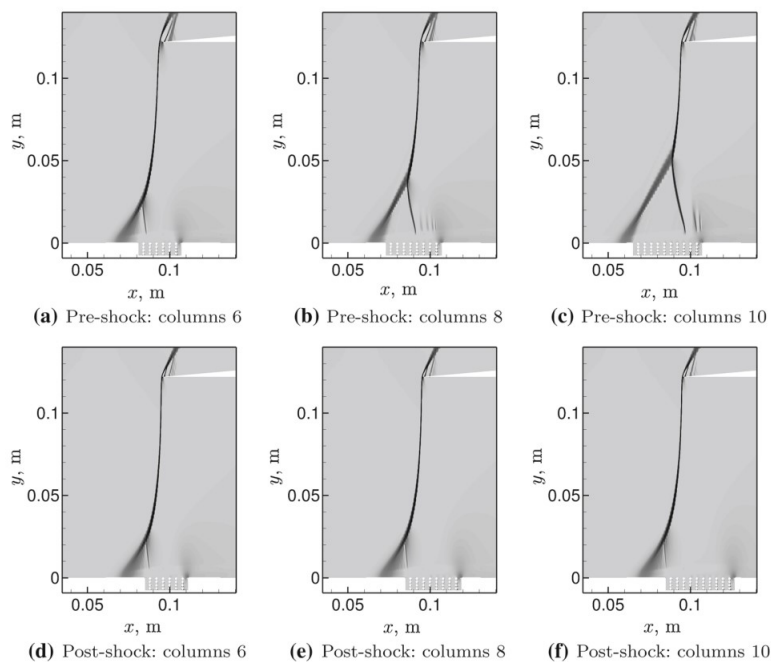


Fig. 1.7 Numerical Schlieren visualisation with variation in the length of the porous region, not centred at the tip of shock-holding plate [76]. The number of columns represents different levels of the porous medium.

use of active flow control techniques, such as plasma actuators, to manipulate the boundary layer flow in order to reduce the impact of shock waves. However, there is still much to be learned about the effectiveness of these techniques, as well as the most efficient and effective ways to implement them.

To guide the design of airfoils, transonic shock buffet phenomena have been extensively investigated by both wind tunnel tests and numerical simulations. Because of the reasonable computational cost, the unsteady RANS (URANS) simulation is often used to investigate the large-scale flow structures induced by the shock-wave oscillation in the buffet phenomena and to predict the buffet onset. Thierry et al. [104] investigated the influences of the turbulence model on the buffet prediction. Their results indicated that the prediction accuracy of the buffet onset largely depends on the turbulence model. Crouch et al. [19] conducted the URANS computation of an airfoil at various angles of attack and performed a global stability analysis to detect the buffet onset. Based on the global stability analysis, they proposed a method of predicting the buffet onset in which the instability growth rate exceeds 0. The prediction results showed a good agreement with the experiment. Although previous studies revealed some insights, some researchers reported that the prediction accuracy largely depends on the RANS turbulence model and suggested that appropriate numerical methods

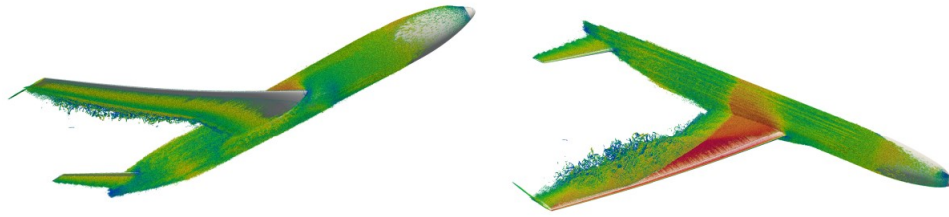


Fig. 1.8 Iso-surfaces of Q-criterion colored by velocity [101].

both in spatial and temporal discretisations are necessary to eliminate the numerical diffusivity as much as possible.

Thomas et al. [105] investigated the sensitivity of turbulence models, numerical fluxes, and limitations for the shock oscillation behaviour. The shock oscillation behaviour is found to be very sensitive to the employed numerical methods. Apart from URANS, large eddy simulation (LES) is an attractive choice to study the detailed physics of the complicated shock buffet phenomena. Tamaki et al. [101] demonstrated the capability of the wall-modelled large-eddy simulation (WMLES) for predicting buffet phenomena over a 3D aircraft configuration. A sample of conducting WMLES around complex 3D geometries is shown in Figure 1.8. However, the conventional wall-resolved LES requires resolving both the inner- and outer-boundary layer, which is difficult to be applied due to the huge calculation cost.

1.2.2 Supersonic SWBLI Flow Control

The difference between transonic SWBLI and supersonic SWBLI lies in the speed of the flow relative to the speed of sound. In transonic SWBLI, the flow speed is close to the speed of sound, which is typically between Mach 0.8 and Mach 1.2. In supersonic SWBLI, the flow speed is greater than the speed of sound, typically Mach 1.2 or higher. Transonic SWBLI is characterized by the presence of both subsonic and supersonic regions in the flow field. The interaction of the shock wave with the boundary layer can lead to a range of flow phenomena, such as shock-boundary layer interactions, shock-induced separation, and shock-induced transition. These phenomena can have a significant impact on the performance and stability of aircraft at transonic speeds. Supersonic SWBLI, on the other hand, is characterized by the presence of a strong shock wave that interacts with the boundary layer of the flow. The interaction can lead to a highly turbulent and unsteady flow field, which can cause significant aerodynamic heating, pressure fluctuations, and drag. These effects can have a major impact on the design and performance of hypersonic vehicles, such as scramjets and spaceplanes.

There are several typical supersonic SWBLI investigation models in this field, including shock or ramp-induced SWBLI. Figure 1.9 shows the global organization of the incident shock wave boundary layer interaction obtained by spark Schlieren visualization [26]. The strong pressure gradient leads to the separated boundary layer. In this case, the incident shock is reflected near the Mach line as an expansion wave, whereas the leading reflected shock originates upstream of the recirculating zone. The compression waves located in the relaxation zone needed to turn back the flow parallel to the wall after its passage through the expansion fan are barely visible in this visualization. Concerning the boundary-layer behaviour, there are no fundamental differences among the separations induced by an incident shock, a ramp, and a normal shock. In all instances, the boundary layer responds in the same way to a given pressure rise regardless of the cause. This behaviour is illustrated by the laminar-flow calculations for an identical upstream Mach number shown in Figure 1.10. The wall-pressure distribution for a separated ramp flow is nearly coincident with that produced by a shock reflection if both are subjected to the same overall pressure rise [90].

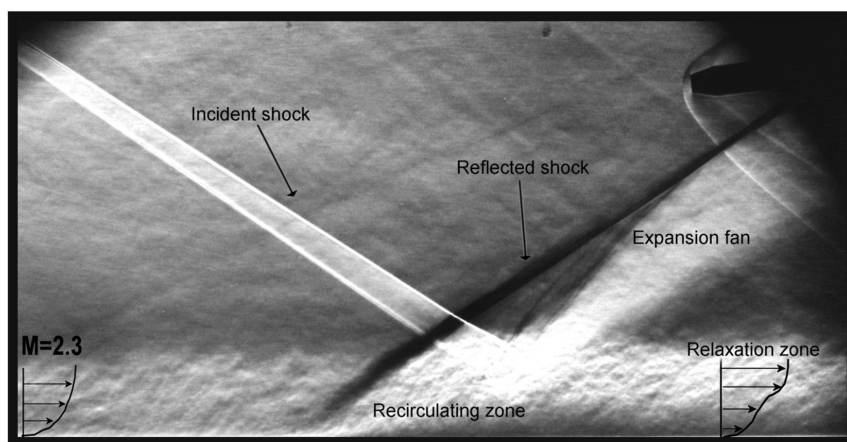


Fig. 1.9 Spark schlieren visualization of the interaction, flow deviation of 8° [26].

Numerous experimental investigations have been conducted in the field of shock wave/boundary layer interactions (SWBLIs). Wang et al. [111] examined the behaviour of unsteady SWBLI structures induced by self-excited and forced oscillations. Their study revealed a hysteretic effect and phase lag between the shock wave position and pressure distribution. Schlieren and PIV images of an oblique shock wave oscillation frequency were presented in Figure 1.11. Grossman et al. [42] explored the impact of the sidewall gap on oblique shock wave/boundary-layer interaction in three gas cases. The high-speed Schlieren technique was utilized to examine SWBLI flow organisation and unsteadiness. Sun et al. [100] evaluated the effects of ramp angle and Reynolds number on the compression ramp SWBLI experimentally in a Mach 2.0 flow.

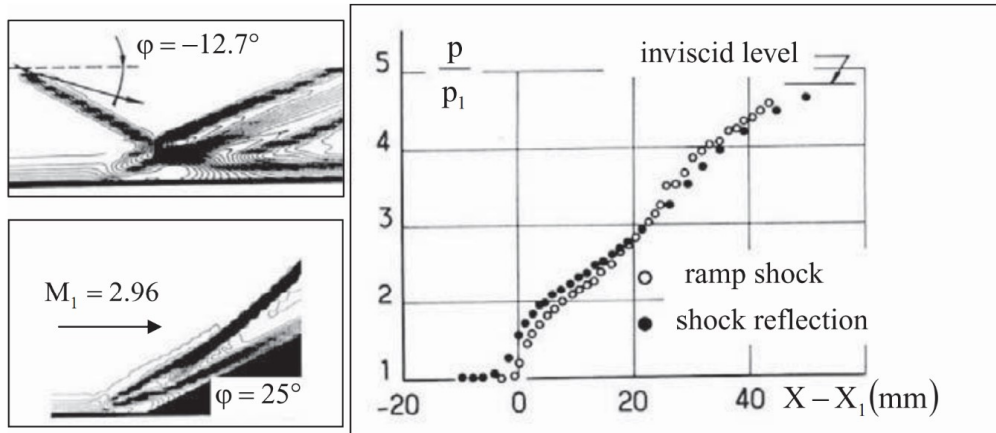


Fig. 1.10 Shock- and ramp-induced separation of a turbulent boundary layer [90].

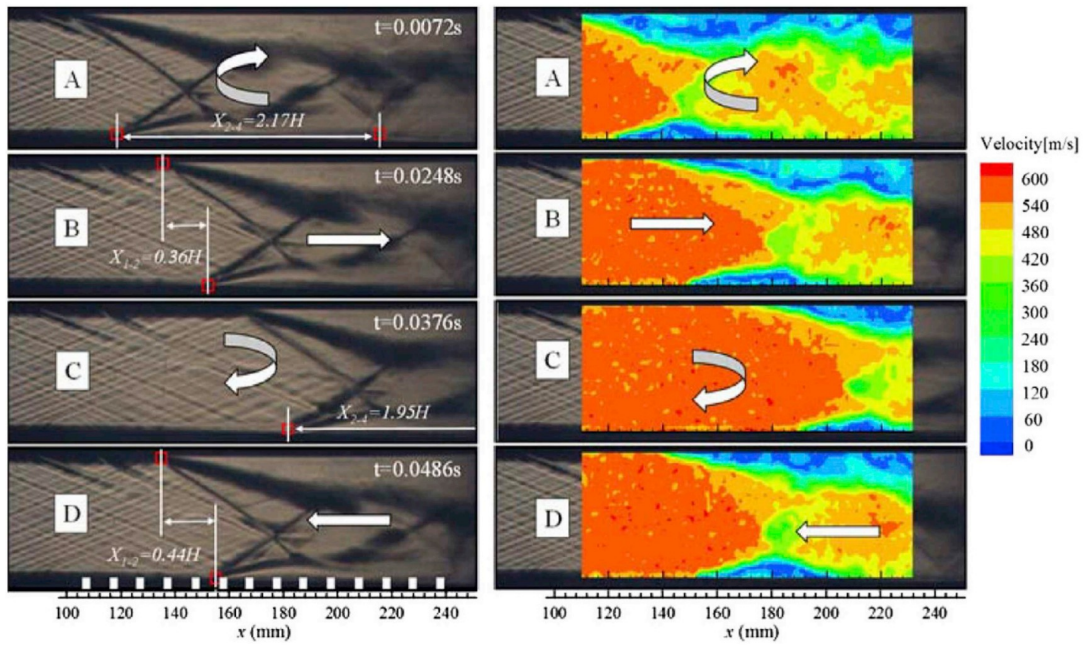


Fig. 1.11 Schlieren and PIV images for an oblique shock wave oscillation frequency [111].

Although experimentally investigating supersonic shock wave boundary layers has advanced significantly over the years [4], there are still several shortcomings limiting the accuracy and reliability of modelling SWBLI. Measuring the properties of supersonic shock waves in boundary layers requires high-resolution sensors and intrusive instruments. The finite spatial and temporal resolution of sensors can lead to uncertainties and errors in the measurements. The presence of sensors and other intrusive instruments in the test section of the wind tunnel can interfere with the flow and alter the behaviour of the shock wave, limiting the accuracy of experimental results.

The limitations of experimental techniques have led to several recent studies that have employed direct numerical simulation (DNS) for supersonic SWBLI investigation with great success. Adams et al. [1] first begin research on the compression ramp shock wave boundary layer interference via DNS. A novel hybrid shock-capturing scheme is used to discretise the compressible Navier-Stokes equations with the accuracy required by DNS for transitional and turbulent flow. Wu et al. [115] also conduct a study on the low-frequency instability of shock waves by DNS. Results in Figure 1.12 show that the size (including the length and height) of the separation bubble changes significantly with a low frequency that is comparable to that of the low-frequency shock motion.

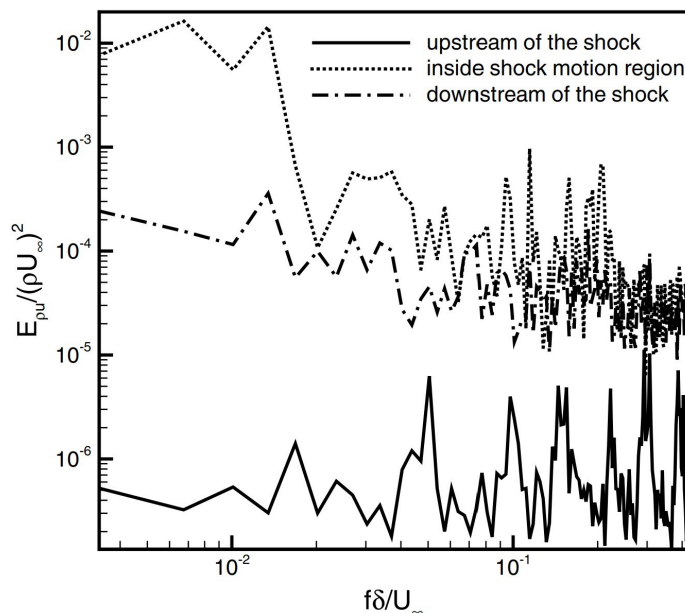


Fig. 1.12 Spectra of mass-flux signals at different streamwise locations from DNS results [115].

Tong et al. [107] conducted a study using Direct Numerical Simulation (DNS) to investigate the interaction between incident shock wave and supersonic turbulent boundary

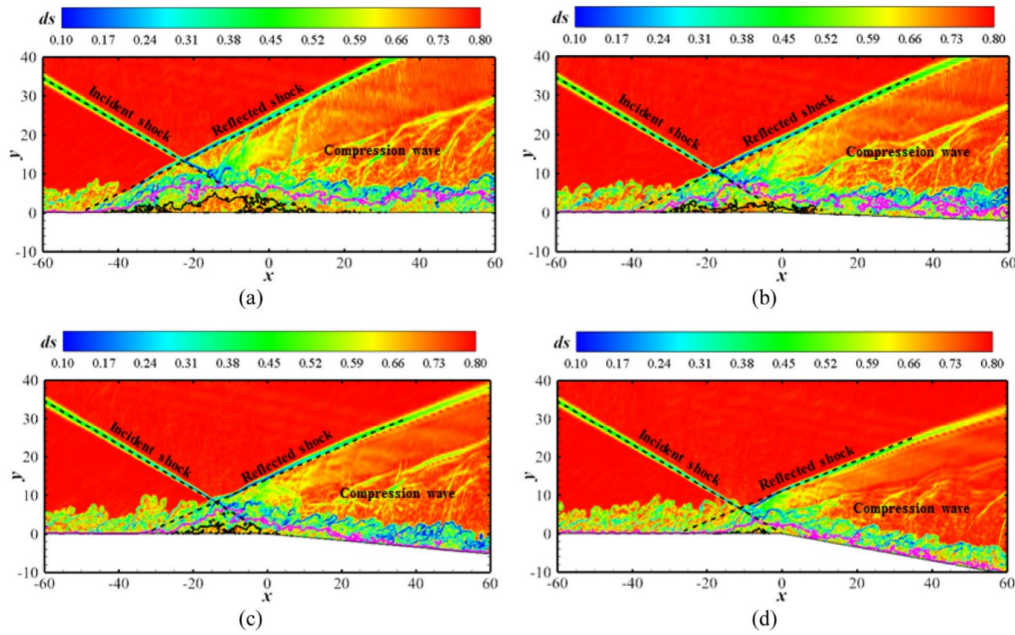


Fig. 1.13 Instantaneous density gradient fields in the $x - y$ plane for different expansion corner degrees. Black and pink lines correspond to the iso-line ($u = 0$) and sonic line, respectively [107].

layer near an expansion corner at a Mach number of 2.9. The findings indicate that the expansion corner has a significant impact on the flow field. Specifically, it reduces the extent of the separation bubble and suppresses three-dimensionality at the reattachment point, as shown in Figure 1.13. This is attributed to the pressure gradient induced by the expansion corner, which reduces the strength of compression waves. Furthermore, the study reveals a substantial reduction in the size of the separation bubble, which causes the reflected shock to move closer to the expansion corner. This observation suggests a decrease in the interaction length as the expansion effect becomes stronger. Overall, the above investigations provide valuable insights into the issues related to shock wave/boundary layer interactions and offer guidance for future research.

Controlling the flow of supersonic shock waves in boundary layers is an important research topic in aerospace engineering and related fields. Various flow control strategies have been proposed and studied to improve the performance and efficiency of high-speed aircraft and spacecraft. Here are two strategies of passive and active flow control techniques for supersonic SWBLI. Sun et al. [98] conducted A direct numerical simulation study on the hypersonic shock-wave boundary-layer interaction controlled by a micro ramp vortex generator (MVG). The effects of the MVG on the shock wave/boundary layer interaction are investigated. The results show that the heat flux and friction after the interaction have

been reduced apparently by the MVG. Such reduction is mainly caused by the flow pattern near the reattachment and the alteration of the vortical structures after the interaction. When the MVG is mounted, the streamlines at the reattachment will be deflected by the saddle point existing in the topology, and the high-speed fluids will not impinge upon the wall directly. The abrupt increases in the heat flux and friction are greatly depressed. Kinefuch et al. [54] numerically explores the flow physics associated with nanosecond pulsed plasma actuators that are designed to control shock-wave induced boundary-layer separation in a Mach 2.8 supersonic flow. They applied an LES and an energy deposition model for the plasma actuation. The dielectric barrier discharge produced plasma is approximated as a high-temperature region. The calculation successfully demonstrates a definite difference between the parallel and canted electrodes. The canted electrode leads to a reduction of the interaction strength, with a corresponding thinning of the boundary layer due to the momentum transfer.

In conclusion, The shock wave boundary layer interaction (SWBLI) is a critical phenomenon that occurs in high-speed flow, particularly in transonic and supersonic regimes. SWBLI can lead to significant increases in drag, which can negatively impact the performance and efficiency of aircraft and other high-speed vehicles. Therefore, controlling SWBLI is of great importance in aerospace engineering. One way to control SWBLI is through boundary layer flow control techniques. By manipulating the boundary layer flow, it is possible to reduce the impact of the shock wave on the surface of the aircraft or vehicle. This can lead to a significant reduction in drag, which can improve the vehicle's fuel efficiency, range, and speed. SWBLI flow control is particularly important for military aircraft, where high-speed manoeuvrability is critical. By reducing the impact of SWBLI, it is possible to improve the aircraft's performance and manoeuvrability, making it more effective in combat situations. Additionally, SWBLI flow control can also be beneficial for commercial aircraft, where reducing drag can lead to lower fuel costs and increased profitability. Research in SWBLI flow control is ongoing, and new techniques are constantly being developed to improve the effectiveness of flow control methods. The development of more accurate computational models has also allowed for more efficient testing and optimization of these methods. Overall, SWBLI flow control is an important area of research in aerospace engineering, with significant potential to improve the performance and efficiency of high-speed vehicles.

1.3 Plasma Flow Control Actuators

As it has been discussed above, active flow control and passive flow control are two different approaches used to manipulate the flow over an object, intending to enhance its aerodynamic

performance. Passive flow control methods such as vortex generators can effectively suppress the flow separation caused by SWBLI. Still, the fixed installation position and geometric profile make it difficult to achieve an optimized effect under general working conditions, and additional resistance will be generated. In recent years, many SWBLI active flow control studies have been conducted internationally. As one popular choice of flow control, plasma flow control has technical advantages such as fast response (order of μs), wide frequency bandwidths (1 Hz~100 kHz), and higher intensities. In the case of shock wave boundary layer interaction (SWBLI) flow control, active flow control can provide several advantages over passive flow control. Passive flow control relies on static devices such as vortex generators, turbulence generators or roughness elements to create turbulence and, thus, delay the onset of flow separation. However, these devices are fixed and their effectiveness depends on the flow conditions, which can limit their performance over a wide range of operating conditions.

In contrast, active flow control involves using actuators, such as jets or plasma actuators, to manipulate the flow through dynamic control of the boundary layer. This approach provides several advantages over passive flow control, such as: 1). Enhanced control: Active flow control enables precise manipulation of the flow field, allowing for optimal control of the flow separation and boundary layer transition. 2). Wide operating range: Active flow control devices can be designed to operate over a wider range of flow conditions than passive devices, providing greater flexibility in controlling the aerodynamic performance of the object. 3). Improved efficiency: Active flow control can be used to reduce drag and increase lift, leading to the improved overall efficiency of the object. 4). Reduced weight and complexity: Active flow control devices can be designed to be lightweight and compact, reducing the overall weight and complexity of the object. In conclusion, active flow control provides several advantages over passive flow control in SWBLI flow control. However, its successful implementation requires careful design and optimization of the active control devices to achieve optimal performance under a wide range of operating conditions.

Active flow control is a control method to change the characteristics of the flow field by applying external energy to the flow field through actuators [11, 43, 66, 113]. It can use excitation actively, and the driving process of the actuator is controllable, which can effectively solve off-design problems of passive flow control technology. Based on the type of actuator, Cattafesta et al. [11] divided active flow control methods into four main categories: fluidic, moving object/surface, plasma actuator and others, shown in Figure 1.14. The most common type of the first category is jets, including zero-mass jets and active synthetic jets. The second actuators usually use moving parts or deformable surfaces to cause local flow field changes. Russell et al. [77] reviewed a group of flow control methods that employ Joule heating to do so and can collectively be called energy deposition flow control methods. It

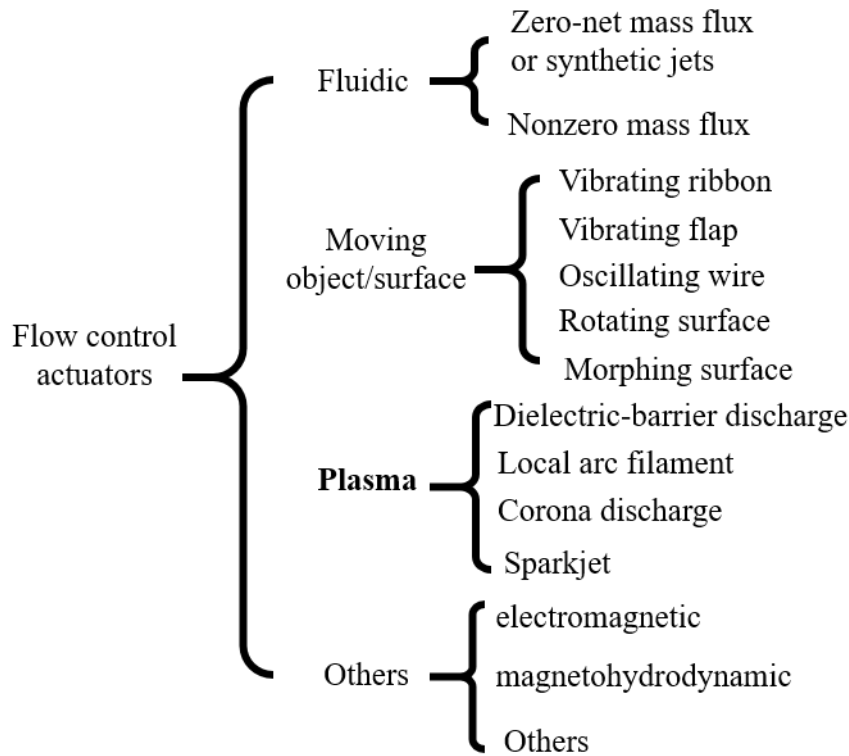


Fig. 1.14 Type classification of flow control actuators [11].

introduces the energy deposition flow control methods discussed are surface plasma actuators, laser energy deposition and microwave-generated plasma. These types of actuation methods are of particular interest for applications to high-speed flows.

This work focuses on the third type of flow control actuators in Figure 1.14, which is Plasma actuators. It has gained popularity recently because of its solid-state and fast response [29, 49, 77, 82]. The control mechanism of plasma actuators has a variety of physical phenomena, including thermal effect, impact effect, physical property change, and frequency coupling [11], which are significant developing directions in the flow control field. There are three popular variants of plasma actuators, dielectric barrier discharge (DBD) plasma actuator, local arc filament plasma actuator (LAFPA) and Sparkjet. The plasma actuator using a spark jet has been developed into Plasma synthetic jet actuator (PSJA). Despite some differences in their operating principles, these plasma actuators share some similarities. Firstly, they all rely on the generation of a plasma arc discharge in order to manipulate the flow of air or other fluids. The plasma discharge can ionize the surrounding air molecules, creating charged particles and an electric field that can be used to control the flow of air. Secondly, all three types of plasma actuators are non-intrusive, meaning that they do not physically interact with the flow of the fluid. This is advantageous because

it means that they do not cause significant disturbances to the flow or add additional drag. Finally, all three types of plasma actuators are used to manipulate the flow in a controlled manner, with the aim of reducing drag, increasing lift, or improving the overall efficiency of an aerodynamic system. However, there are also some differences between these plasma actuators. For example, DBD plasma actuators typically use a high voltage to generate a plasma discharge across a dielectric material, while LAFPA and PSJA use a combination of electrodes and magnetic fields to create a plasma synthetic jet that interacts with the flow. The following sections will discuss the physics and application of DBD plasma actuator, LAFPA and PSJA in detail.

1.3.1 Dielectric Barrier Discharge (DBD) Plasma Actuator

Dielectric Barrier Discharge (DBD) plasma actuators are high-voltage devices that generate plasma to produce localized vortices in the fluid flow. This technology was first investigated by Yung et al. [110] and has been widely studied in recent years for its potential applications in flow control and aerodynamics [17, 74], with numerous experiments and numerical simulations exploring its mechanism and effects on the flow. The basic geometry of a simple DBD is shown in Figure 1.15. The mechanism of a DBD plasma actuator involves three main stages: electrification, plasma Expansion and interaction with the fluid. The dielectric barrier prevents direct current conduction but allows the high-frequency AC voltage to pass through, ionizing the gas in the gap between the electrodes and creating a plasma discharge. When a high-voltage AC electrical field is applied across the electrodes, the electric field strength exceeds the dielectric strength of the gas, ionizing it and creating a plasma discharge. The plasma discharge generates charged particles and free radicals, which can produce various effects, such as generating lift, drag or vortex forces on an object. As the aerospace industry deals with much higher freestream velocities, research is required for these actuators to become more capable and suited for application in the aerospace industry.

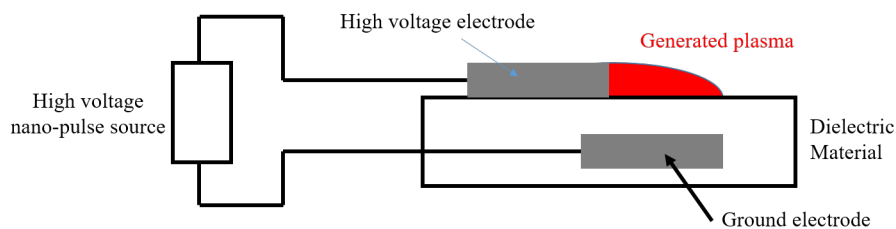


Fig. 1.15 A conventional dielectric barrier discharge (DBD) plasma actuator.

The fundamental flow features induced by the dielectric barrier discharge (DBD) plasma actuator are examined using experimental techniques. Specifically, Ukai utilized schlieren

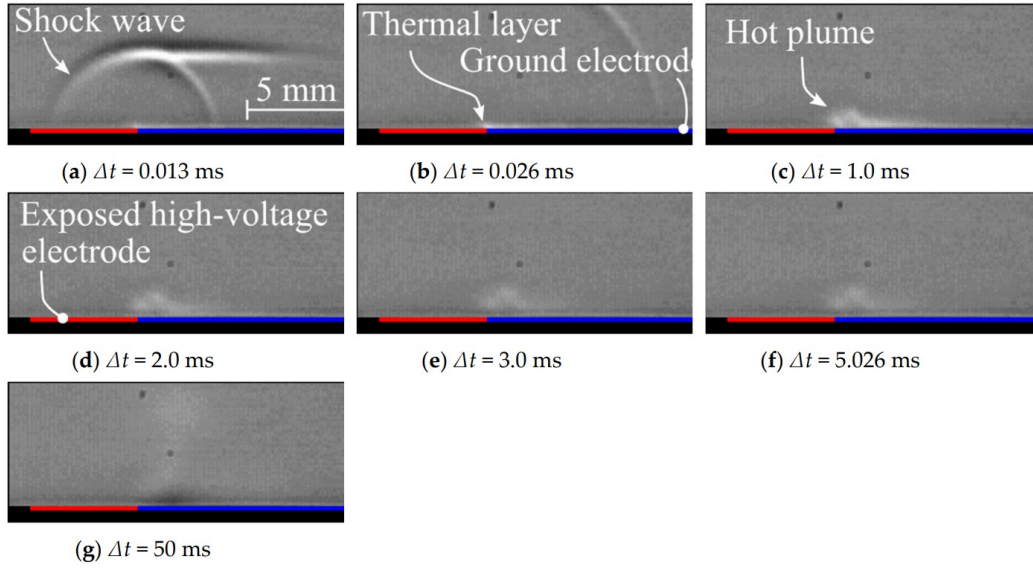


Fig. 1.16 The thermal perturbation and the shock waves in the no-burst plasma discharge case [108].

imaging to investigate the thermal fluctuation induced by a nanosecond-DBD plasma actuator [108]. Results show that upon discharge, a hot plume develops within milliseconds, distinct from the propagation of shock waves that occurs in microseconds. Notably, the region of highest temperature is observed at the edge of the exposed high-voltage electrode where relatively strong brightness is present, as illustrated in Figure 1.16. Moreover, Liu et al. conducted a comprehensive study to examine the thermal characteristics of DBD plasma actuation over an airfoil/wing surface, evaluating its anti-/de-icing performance for aircraft in-flight icing mitigation [62]. On the other hand, Xue et al. [118] investigated the formation and motion of vortices generated by DBD plasma actuation under periodic burst-mode actuation. As evidenced by Figure 1.17, schlieren visualization effectively captures the position and region of vortices in comparison to Particle Image Velocimetry (PIV) measurement. Self-similar patterns of the vortex flow field are discerned for a brief period following vortex formation within each burst cycle.

Due to the use of high-speed aerodynamics, particularly for SWBLI control and drag reduction, investigations on ns-DBDs, have attracted the interest of various researchers in recent years. Roupassov et al. [75] examined the use of ns-DBD actuators to control subsonic flow separation, using both experimental and computational methods. Fig. 1.18 taken from Roupassov et al. [75] shows the improved aerofoil performance through the application of an ns-DBD plasma actuator. When the actuators were conducted, the lift force was enlarged (with an optimal frequency range of approximately 100 kHz). This was due to the flow

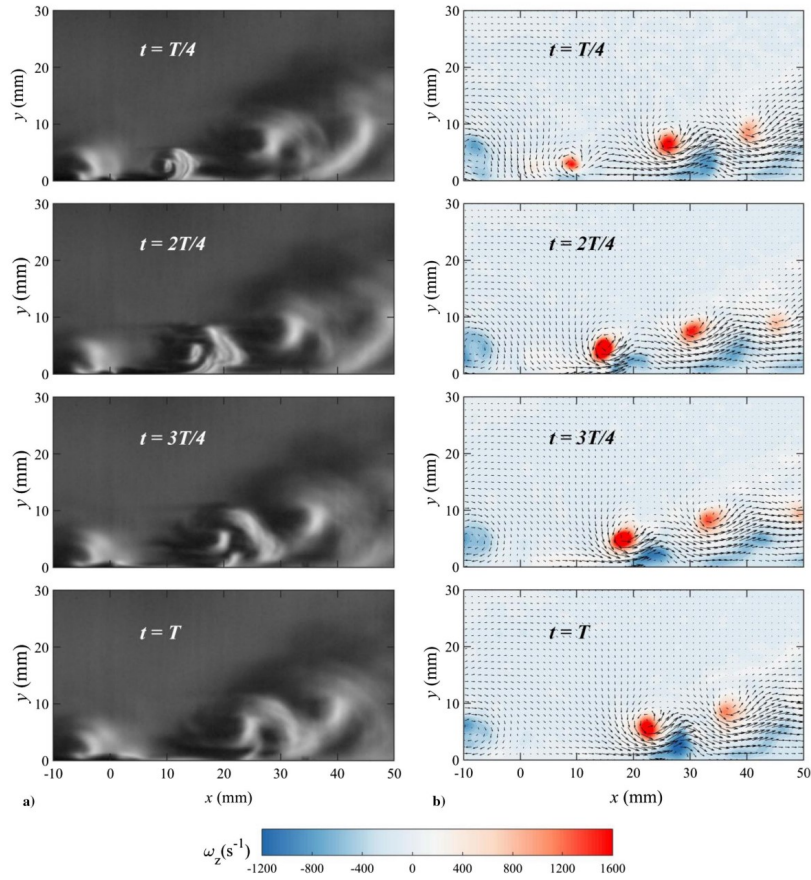


Fig. 1.17 Vortex evolution induced by DBD operation for $f = 50\text{Hz}$ and $\tau = 0.5$: a) schlieren visualization and b) PIV measurement [118].

re-attachment. Without the actuators, the flow is separated. The slight increase in drag force was the consequence of the turbulization of the boundary layer [75].

Nishihara et al. [69] demonstrated that ns-DBD actuators could be used to alter the location of a shock generated by a wedge, and evaluated the effectiveness of the nanosecond pulse DBD plasma actuators in influencing the behaviour of oblique shocks and shock/boundary layer interactions based on numerical simulation and experiments. The results indicated that plasma actuators could be used to control and manipulate the behaviour of oblique shocks and the shock/boundary layer interactions. Esfahani et al. experimentally investigated the DBD excitation of flow instability over a VR-7 airfoil at a post-stall angle. A single ns-DBD plasma actuator was mounted near the leading edge of the airfoil. Results show that excitation of plasma actuator at low Strouhal numbers induced organized, large-scale, coherent structures in the shear layer over the separated region. In contrast, excitation at higher Strouhal numbers resulted in smaller, less-coherent structures in the shear layer that quickly developed over the airfoil and disintegrated [30].

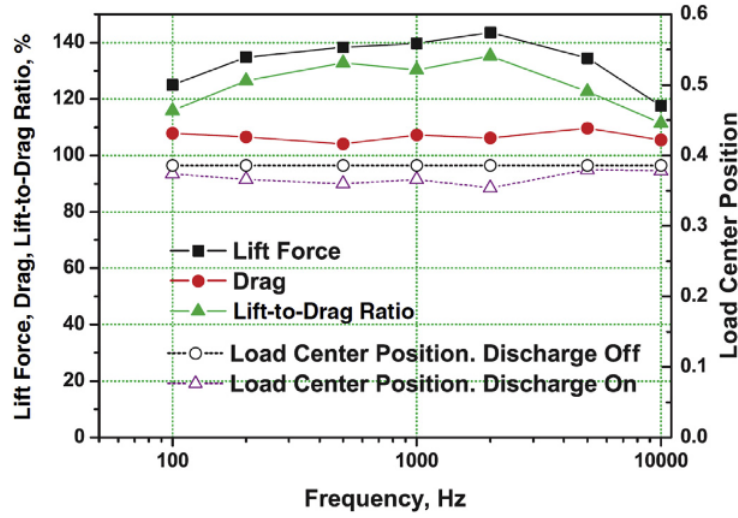


Fig. 1.18 Lift-to-drag ratio under different frequencies [75].

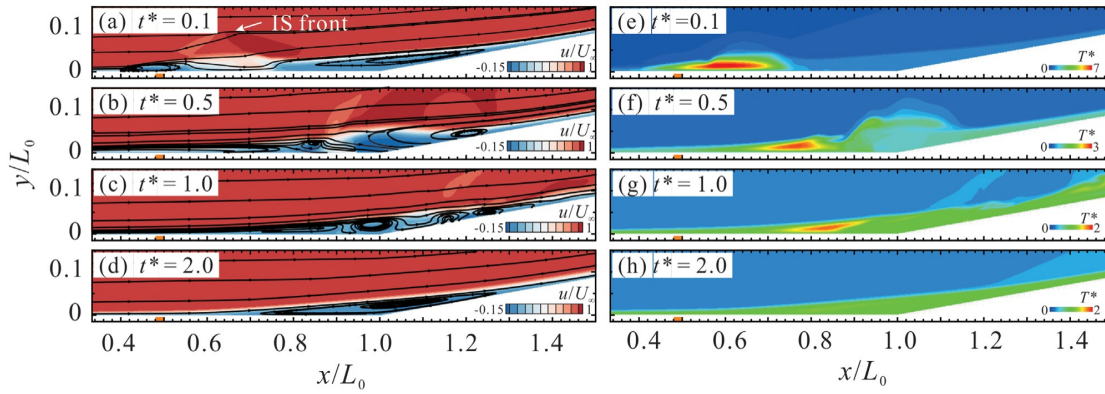


Fig. 1.19 Contours of instantaneous normalized streamwise velocity u/U_1 (left column) with streamlines superimposed and non-dimensional temperature T^* (right column) [14].

Chen et al. [14] evaluated the control performance of a pulsed nanosecond dielectric barrier discharge (ns-DBD) plasma actuator with varied pulse voltages and locations on a supersonic compression corner using experiments and numerical simulations. Figure 1.19 shows how velocity and temperature develop when DBD is installed close to the separation region where the suppression of the separation region is more effective. The induced vortices form the initial separation bubble near the original separation point of the boundary layer in Figure 1.19(a) and (e). Then, the original shear layer is destroyed, and the original induced separation bubble is elongated and flattened, leading to a shorter length of the bubble compared with the steady state.

Despite extensive research introduced above, there are still unexplored areas that hold potential for valuable insights. While DBD plasma actuators have several advantages,

including low power consumption, lack of moving parts, and capability to operate in a wide range of conditions, they also have some shortcomings, such as limited efficiency. DBD plasma actuators are not very efficient in converting electrical power into fluid motion, which can limit their practical applications. Also, DBD plasma actuators typically induce a tangential force on the fluid, which can limit their ability to control the flow direction. Overall, those two disadvantages need to be considered when evaluating their suitability for specific applications.

1.3.2 Localized Arc Filament Plasma Actuator (LAFPA)

LAFPA is a recently developed category of arc discharge plasma actuators, typically comprised of two tungsten electrodes located at a few millimetres (1~10 mm) apart on the surface of the plate, a gas supply, and a power source. When a high-voltage electrical discharge is applied to the electrode, it ionizes the surrounding gas, creating a plasma channel. This plasma channel can be used to create a flow disturbance or modify the flow field in a controlled manner, making the LAFPA a useful tool for various applications such as flow control, turbulence mitigation, and aerodynamic testing. The localized aspect of the LAFPA refers to the fact that the plasma channel is confined to a small region near the electrode, allowing for precise control of the flow disturbance. A typical Schematic of LAFPA can be seen in Fig. 1.20, including the plate and electrodes flush with the plate surface and separated at a 2 mm distance. Figure 1.21 shows the flow field evolution of LAFPA after the arc discharge on the surface. In the beginning, a spherical front blast shock wave can be observed above the plasma arc column induced by the immediate electrical energy deposition, and the shape of the arc heated region is relatively regular compared to the following snapshots. Later, the arc-heated region becomes chaotic and starts to diffuse around [35].

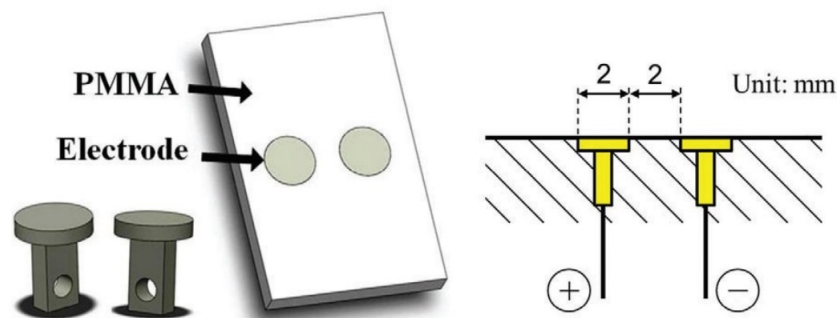


Fig. 1.20 Schematic of the localized arc filament plasma actuator [35].

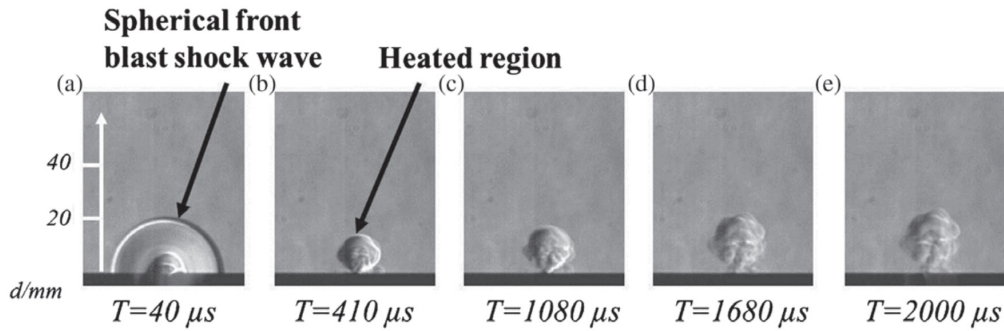


Fig. 1.21 Flow field evolution of LAFPA [35].

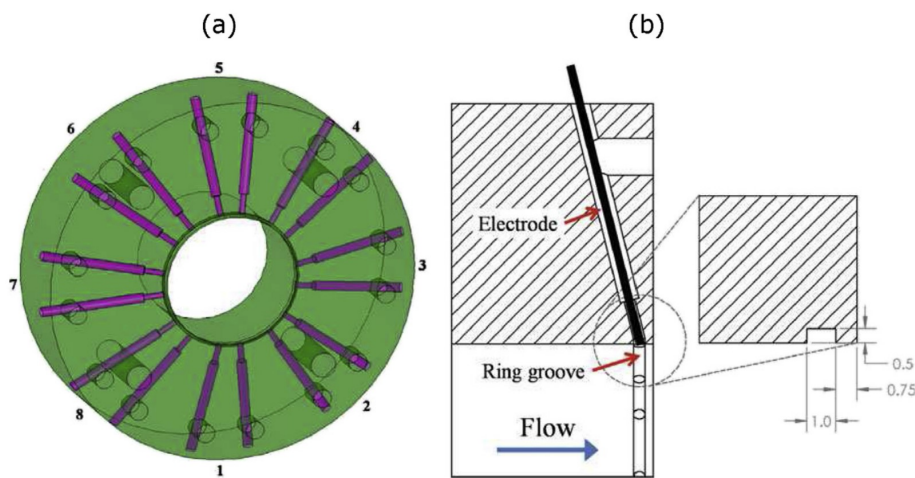


Fig. 1.22 Schematic of LAFPA's applied to a nozzle showing (a) entire nozzle section illustrating groove housing for actuator (b) cross-section of the nozzle to illustrate features [44].

LAFPA was originally developed at Ohio State University by Samimy et al. [78], and was used to control the flow by rapid heating of the fluid due to the pulsed electrical discharges in Samimy's work. The rapid heating caused the creation of pressure waves that originated from the thermal heating of the air during the breakdown and affected the flow dynamics. At this stage, the resistance across the air gap between electrodes (as depicted below) was significantly higher compared to after breakdown, leading to a greater release of heat in accordance with Joule's first law, as it was proportional to the resistance. The design of the actuator was a conventional design that consisted of a pair of electrodes, separated by an air gap, typically made of tungsten to mitigate erosion from high temperatures, that extended from the surface into the flow field. The schematic of an array of LAFPAs is shown in Figure 1.22. These electrodes were connected to a high-voltage and high-frequency power supply.

Samimy et al. [78] also showed that the plasma would be stretched and blown off during each discharge without shielding from the flow. To prevent the distortion of the plasma, a 1 mm groove was cut deeply to house the actuators shown in Figure 1.22. The comparison of voltage before and after cutting the groove showed that the groove stabilised the voltage and prevented the plasma from being blown off when the AC voltage was at a minimum. Samimy et al. [78] also compared the power consumption at different frequencies with and without the groove to house the actuator electrodes. As expected, the ring groove resulted in a significant reduction in power consumption at lower frequencies. However, at higher frequencies, above 30 kHz, the power consumption for both cases converged to the same order as that of the no-flow case because the time between AC current peaks was not long enough to 'blow off' the plasma away from the electrodes.

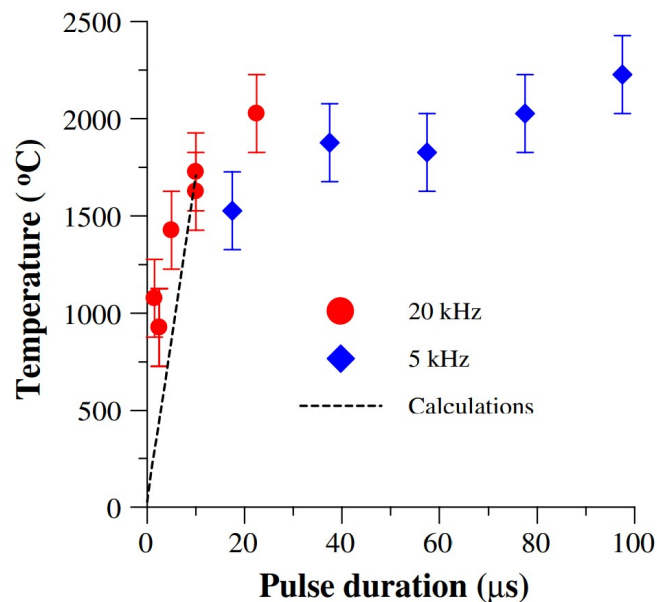


Fig. 1.23 Effect of supply voltage pulse duration on the temperature of plasma discharge from LAFPA actuator [109].

A later study by Utkin et al. [109] focused more on the effect of the supply voltage, including frequency and pulse duration, on the actuator performance via experiments. The plasma temperature was measured by measuring emission spectra of partially rotationally resolved nitrogen. This is a valid measure of actuator performance since the primary medium for flow control by these actuators originates from rapid heating of the flow. It was observed that an increase in the supply frequency led to a corresponding increase in the temperature, shown in Figure 1.23. This conclusion could firstly be validated by the emission spectrum where a high-intensity peak could be found at the wavelength corresponding to Tungsten

electrodes at high frequency. This indicated a stronger electrode erosion at the higher frequency as a result of higher temperatures. The effect of pulse duration on the temperature also showed that a higher frequency corresponded to a higher temperature due to the reduced time for cooling between two adjacent discharge processes at higher frequencies. The linear correlation between the pulse duration and the temperature with a sharp slope at a higher frequency showed that cooling from convection by the flow was not significant at each duration [109].

Two aspects of the LAFPA's technical usage, high-speed jets and SWBLI flow control, have been investigated by various researches [2, 25, 53, 78, 80, 122]. Samimy et al. [79], which investigated LAFPA's for high-speed jet control, suggested that the actuators could exert control over the flow in one of two ways: streamwise vorticity generation or forcing the jet at an instability frequency, shown in Figure 1.24. Streamwise vorticity generation was able to control the mixing process and noise characteristics of high-speed jets [122]. However, the utilization of tabs on the nozzle surface in these methods resulted in obstructions, leading to diminished thrust and sub-optimal performance under off-design conditions. The actuation of the jet at a frequency coinciding with one of the jet's instabilities has been implemented at elevated subsonic speeds [53]. However, the supersonic jet control requires high amplitude and high-frequency excitation, and therefore, the above control method has not been successfully applied in supersonic conditions.

Another topic for the application of LAFPA is the control of SWBLI, which was first considered by Caraballo et al. [9] and focused on the manipulation of SWBLI. The mechanism for control consists of two aspects. The first is the generation of streamwise vorticity in a similar manner to that of micro ramps. The second is the manipulation of the unsteadiness apparent in SWBLI using the broad frequency range capability of LAFPA's. It showed that the upstream leg of a λ -shape shock wave oscillated at $St = 0.03$ while the downstream leg oscillated at $St = 0.5$, and confirmed that the unsteadiness of the upstream leg of the λ -shock that was controlled by the LAFPA's. Fig. 1.25 presented the increased velocity in the boundary layer when plasma actuators were operated in these two Strouhal numbers compared with the baseline. They also observed that the separation and reattachment of the boundary layer are closely related to the spatial and temporal organisation of the vortices, which play a crucial role in the transfer of energy and momentum in SWBLI.

However, Webb et al. [114] extended the investigation on the previous work by Caraballo et al. [9] on the using LAFPA's to realise SWBLI control, and concluded non-negligible disagreements compared with previous studies [9, 27]. Webb et al. [114] found that LAFPA shifted the SWBLI region upstream, which was contradicted by the conclusion of Caraballo et al. [9] who suggested that actuation by LAFPA's increased the boundary layer velocity.

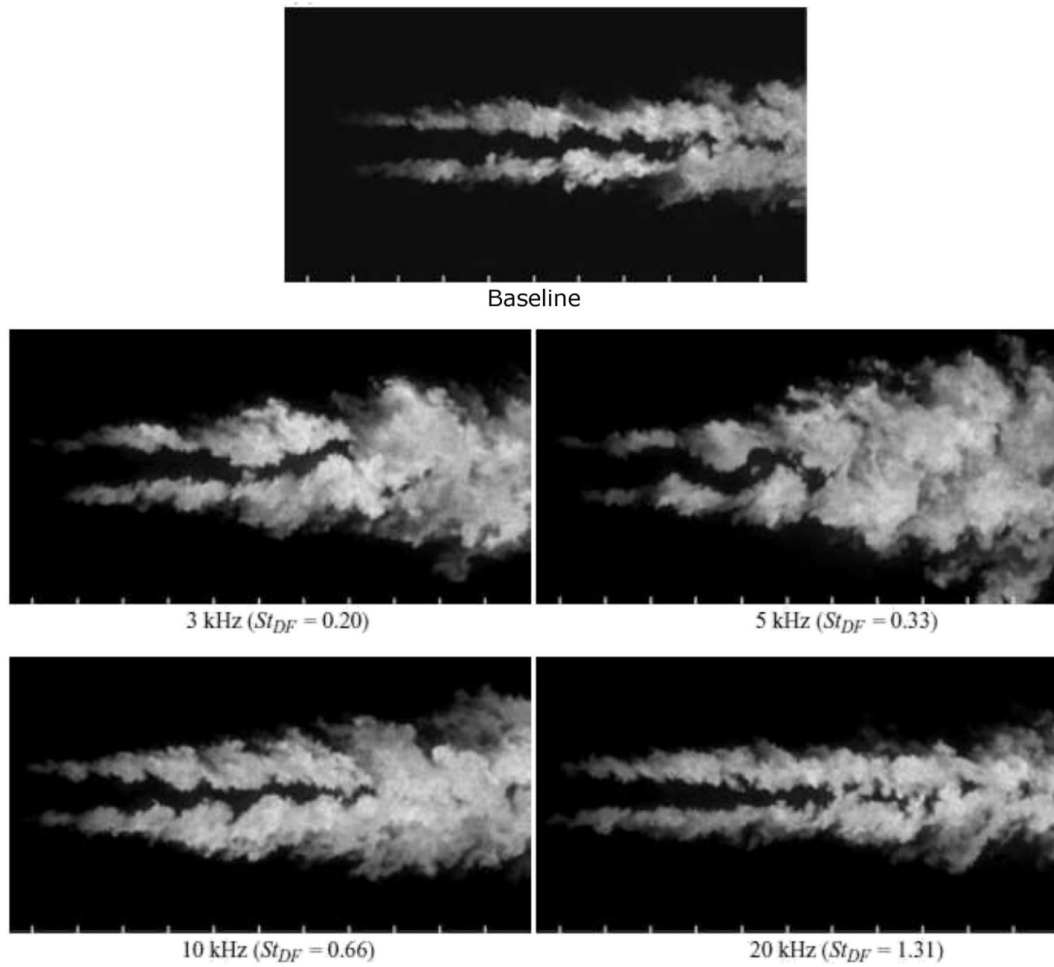


Fig. 1.24 Instantaneous images of laser light sheet scattered by mixing layer of a high-speed jet forced by LAFPA's at different forcing frequencies [79].

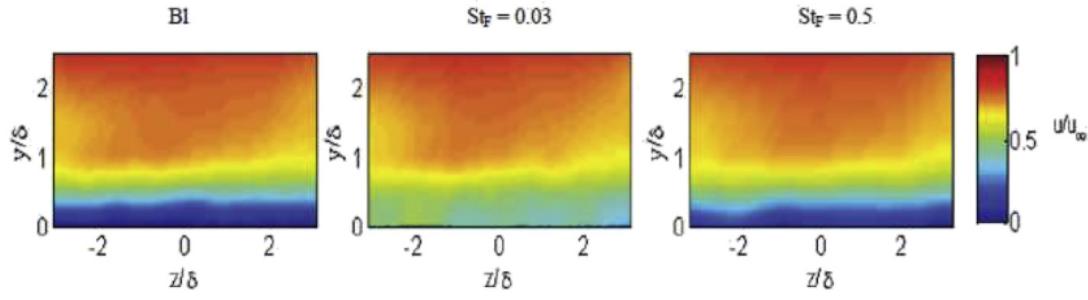


Fig. 1.25 Streamwise velocity distributions in the boundary layer for different LAFPA forcing frequencies with the actuators located upstream of the SWBLI (z/δ represents the location of the actuators) [9].

Another disagreement between them was the mechanism of control itself. Caraballo et al. suggested that the excitation of the SWBLI unsteadiness was the main mechanism, while Webb et al. suggested that simply the heating of the boundary layer was the control mechanism. Firstly, there was no significant "peak-effectiveness" frequency observed within the range $f_F \leq 1.5$, suggesting that forcing the SWBLI at its natural frequency was not a key factor of SWBLI control. Secondly, the actuator location upstream of the SWBLI had a little significant effect on its performance. When attempting to excite an instability or natural frequency, the region of excitation is an important factor in its effectiveness. Overall, Webb et al. [114] suggested that heating the boundary layer was the mechanism for control, which was consistent with results from Dupont et al. [27] that heating the boundary layer upstream of a shock wave will result in its upstream movement. In general, based on these two studies, it is clear that LAFPA's can have a noticeable effect on SWBLI, while more research is necessary to better understand the mechanism of the control.

Tang et al. [102] conducted a LAFPA flow control using five actuators connected in series with adjustable frequency to control the shock wave/boundary layer interaction at compression ramp in a $Ma = 2.0$ flow, shown in Figure 1.26. The results show that the separated wave foot gradually presents bifurcation and partial disappearance with the increasing pulse number of the LAFPA, indicating the decline in the shock intensity. Figure 1.27 compares Schlieren images in the interaction region under different control frequencies. The increase in frequency enlarges the affected region and further weakens the downstream shock under 10 kHz and 20 kHz, while no noticeable change can be observed under the case of 5 kHz actuation. Tian et al. [106] also investigated the flow control mechanism of the plasma actuator array for ramp-induced SWBLI under low and high frequencies. Flow visualisation realized by high-frame Schlieren techniques indicates a significant change in the separation shock in experiments due to thermal injection. More importantly, because

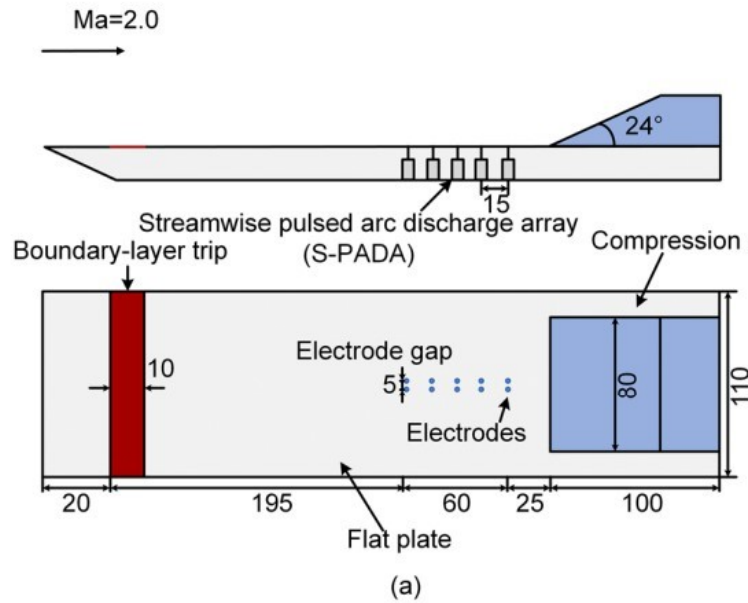


Fig. 1.26 The compression ramp model with LAFPA [102].

the high-frequency actuation mode operates at relatively low energy, it can provide quasi-continuous perturbations, providing stable control for separation shock weakening. The RMS of the Schlieren intensity field (I_{rms}) in the case of 10 kHz shows a similar distribution as Figure 1.27 measured by Tang et al. [102], which indicated a thickened shock and an enlarged interaction region at the ramp. However, the key factor which dominates the flow control effect of LAFPA still requires further investigation.

The above discussion has reviewed two general topics of LAFPA's usage. Except these, LAFPAs have also been used to control various flows by excitation of natural instabilities [81], and also applied for subsonic and supersonic heated and unheated jet control for noise reduction and mixing enhancement [61, 119]. Samimy et al. [81] explored the use of free shear-layer instabilities as a means of controlling high-speed flows, focused on the excitation of these instabilities through various techniques and examined the resulting changes in flow behaviour and aerodynamic performance. In conclusion, the Localized Arc Filament Plasma Actuator (LAFPA) have emerged as a promising technology for controlling the flow patterns in supersonic wind tunnels. By generating plasma arcs at the surface of a model, LAFPA can create a controlled disturbance that modifies the boundary layer and affects the flow separation. The use of LAFPA has been shown to be effective in mitigating the effects of SWBLI, which is a major challenge in supersonic wind tunnel testing. The localized and controlled nature of the plasma arcs generated by LAFPA makes it a suitable tool for investigating and mitigating the effects of SWBLI. With the continued advancement of

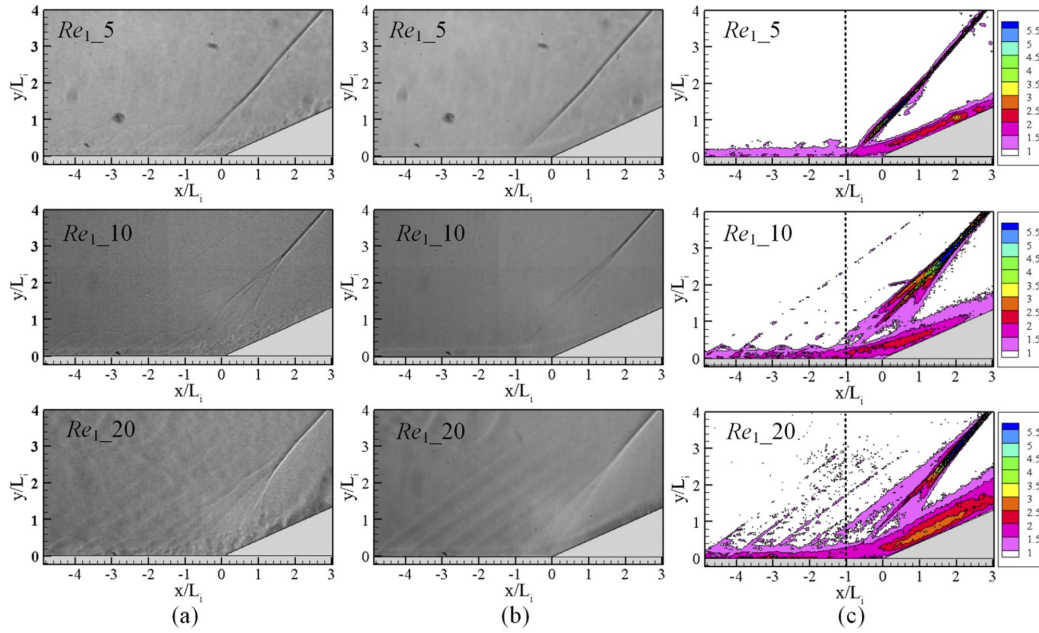


Fig. 1.27 The SWBLI controlled by the LAFPA under three different frequencies, namely, Re_{1_5} (5 kHz), Re_{1_10} (10 kHz), and Re_{1_20} (20 kHz): (a) the instantaneous of the schlieren intensity field; (b) the mean of the schlieren intensity field (I_{mean}); and (c) the normalized rms of the schlieren intensity field (I_{rms}) [102].

LAFPA technology, it is expected to play an increasingly important role in the design and testing of supersonic vehicles.

1.3.3 Plasma Synthetic Jet actuator (PSJA)

Plasma synthetic jet actuator consists of a tiny cavity, usually $20 \sim 2000 \text{ mm}^3$ in volume, with embedded electrodes and has an orifice, usually $1 \sim 2 \text{ mm}$ in diameter, through which air can pass freely. In the last two decades, plasma synthetic jet actuators have drawn significant attention from the active flow control community. Due to their ability to produce high velocity ($>300 \text{ m/s}$) pulsed jets at high frequency ($>5 \text{ kHz}$), thus promise to be applied in high-Reynolds number practical flows (e.g., aircraft wings, inlets, helicopter blades).

The SparkJet actuator, an early version of PSJA and developed the first experimental and modelling of the actuator, was originally developed by the John Hopkins University Applied Physics Lab in 2003 [43]. The device comprised three electrodes, including an anode, a sharp cathode and a grid, all embedded in a ceramic body. A weak cathode-to-grid discharge triggered the device, while the immediate release occurred between the cathode and anode, shown in Figure 1.28. An updated version of these devices was then presented by Cybyk et al. [20, 21], with the grid electrode removed and the electrical discharge directly generated

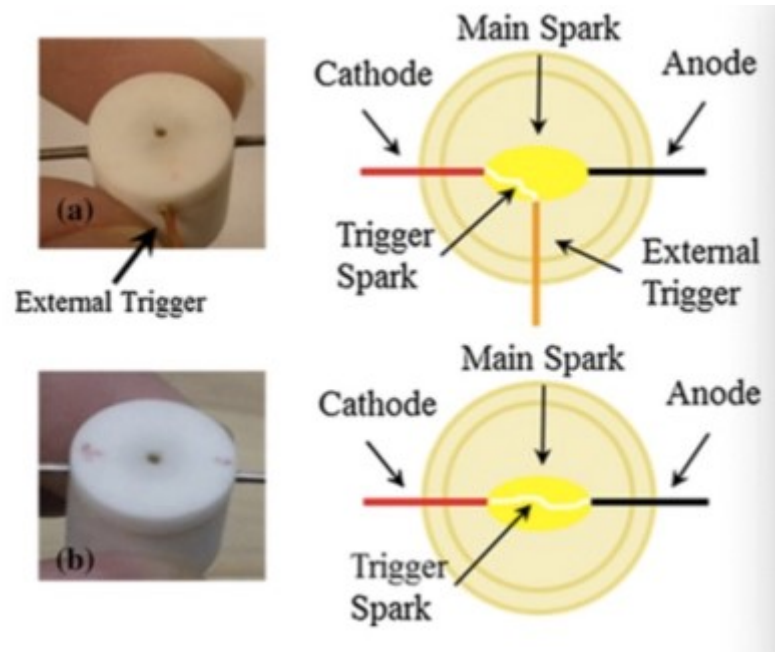


Fig. 1.28 Schematics and photographs showing SparkJet trigger mechanisms a external trigger (3-electrodes), b pseudo-series trigger (2-electrodes) [43].

between the anode and cathode. These adjustments enabled a more straightforward structure, higher robustness, and greater flexibility in testing. Nevertheless, as another consequence of removing the external trigger, the discharge energy in Cybyk's setup becomes dependent on the breakdown voltage of the air gap [20], inconveniencing the tuning of the issued jet intensity.

The whole operation of the PSJA can be described as three stages, shown in Figure 1.29. Stage 1 is characterized by a brief arc discharge within the cavity to produce a hot plasma kernel. Stage 2 involves pressuring the high-pressure and temperature air through the tiny orifice, generating a high-momentum jet to interact with the external flow. Stage 3 involves a cooling/refresh phase before the beginning of the next arc discharge (Stage 1). The physics and other details about each stage will be described in the following sections.

1) PSJA Stage 1 - Arc Discharge

Stage 1 uses a brief, high-voltage arc discharge process sustained by increasing the voltage across the anode and cathode until reaching the breakdown voltage between electrode tips. After the arc breakdowns, the rest of Stage 1 involves the conversion of electrical energy into Joule heat, which generates a plasma kernel, and blast wave and leads to a rising cavity temperature and pressure. Stage 1 ends when the arc discharge

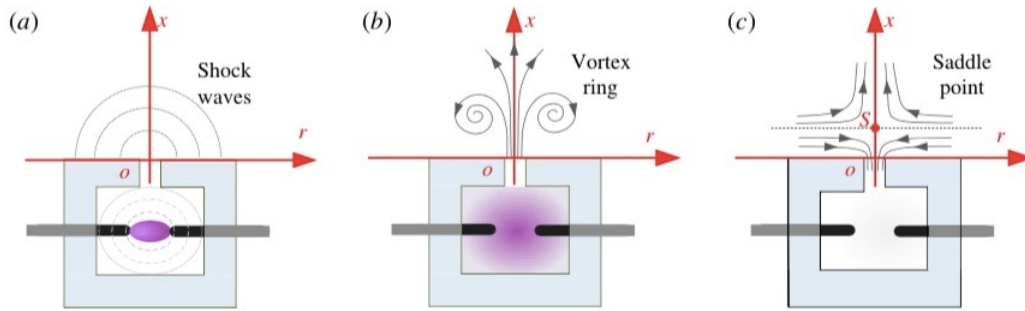


Fig. 1.29 Conceptual formation and evolution of a PSJA: (a) energy deposition; (b) jet stage and (c) refresh stage [128].

is completed and the temperature and pressure of the air in the cavity have reached their maximum values.

2) PSJA Stage 2 - Jet Flow

Stage 2 is the PSJA jet formation, which is an unsteady process initiated by the sudden pressure drop across the orifice after stage 1. As the cavity air is forced through the orifice, the cavity pressure decreases due to the decrease of the cavity density. The duration of Stage 2 is primarily controlled by the cavity volume, orifice area, and heat transfer. The jet flow can also be affected by the contour of the orifice throat. At the very end of Stage 2, the momentum of the flow passing through the orifice further decreases the cavity pressure below ambient pressure extending Stage 2 until the adverse pressure gradient decreases the jet momentum to zero.

3) PSJA Stage 3 - Refresh

Finally, once the jet momentum is zero, the decreased pressure in the cavity forces the flow to reverse and increase the pressure and density of the cavity air. Further reduction in cavity temperature occurs due to free air convection to the cooling cavity walls and electrodes. Stage 3 typically lasts long enough to raise concerns about PSJA frequency limitation. For example, if the time from Stage 1 to the end of Stage 3 exceeds 1 ms and an actuation frequency of 1 kHz is desired, the arc discharge will occur when the cavity density is lower, and the temperature is higher than the first actuation event. The lack of cavity density and mass leads to a lower momentum output during Stage 2 and a decreased ability to affect the external flow.

Emerick et al. [28] conducted an initial SparkJet analysis with a limited collection of Schlieren images of a SparkJet issuing into quiescent flow. It has enabled the acquisition

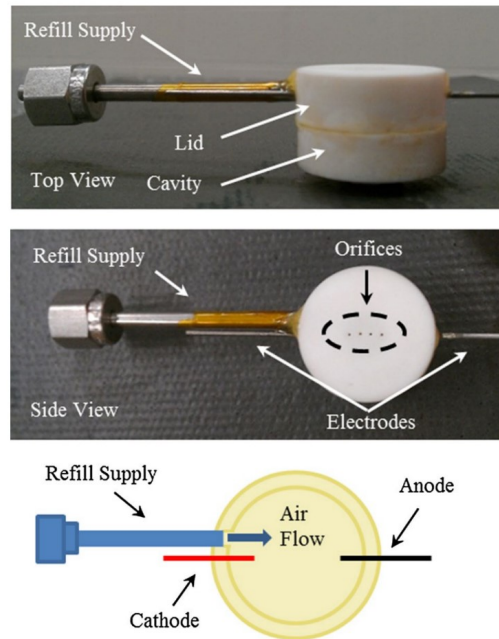


Fig. 1.30 Photographs and schematic of SparkJet actuator with cavity refill supply [28].

of early jet development micro-Schlieren imagery, using the micro-Schlieren technique to visualize the flow field and quantify the velocity of distinct flow features. Experimental cavity pressure and arc power measurements are conducted to estimate efficiency. A nonzero net mass flux (ZNMF) version of the actuator incorporates an active refill supply pressure port as seen in Figure 1.30. This version utilizes compressed air and a one-way poppet check valve to supply air to the cavity of the actuator. The refill supply air potentially reduces the refill time of the actuator and may aid in high-frequency testing. Figure 1.31 shows micro-Schlieren images of the PSJA flow for a single PSJA and an array of 4 PSJAs after Stage 1 was initiated, respectively. These images show evidence of the PSJA formation as a blast wave (called a precursor shock by other researchers) that appears only $8 \mu\text{s}$ after Stage 1 initiates. The blast wave is immediately followed by the jet front, which develops into a fully turbulent jet.

The performance of the plasma synthetic jet actuator is affected by various parameters, including input electrical energy, actuation frequency, electrode spacing, cavity volume, orifice area, etc. ONERA conducted a series of experimental and numerical investigations on the effect of different characteristics of PSJA, including the orifice diameter, lid material, and operation frequency on the pressure rises in the cavity [10, 45, 87]. Results show that factors that lead to a decreasing pressure rise in the chamber consist of at least three sources, decreasing orifice diameter, decreasing lid thermal conductivity and increasing actuation

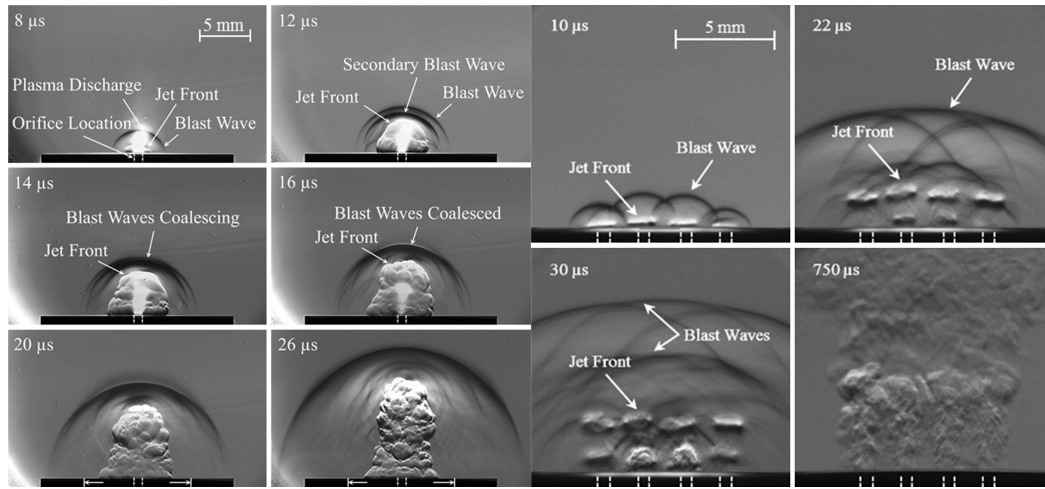


Fig. 1.31 Micro-schlieren images at two-time delays after Stage 1 initiation showing the a) blast wave and b) turbulent jet formation in the early portion of Stage 2 [28].

frequencies. These results suggest that maintaining a prescribed pressure rise in the cavity at high actuation frequencies requires increased thermal heat transfer through the actuator materials.

Many organisations focus on developing a simplified theoretical model to understand the working process and the further modification direction of plasma actuators [72, 132, 124]. Zong et al. [126–130] has conducted a series of experimental studies on the characterisation and application of the PSJA. Zong et al. [132] built a novel analytic model of a plasma synthetic jet actuator (PSJA), considering both the heat transfer effect and the inertia of the throat gas. The frequency characteristics of a PSJA with 87 mm^3 volume and different orifice diameters are investigated based on the analytic model combined with experiments. The whole cycle characteristics and the repetitive working process of PSJA can be predicted with this model. Popkin et al. [72] provides a method for modelling the complex, multi-physics, multi-dimensional processes associated with a SparkJet actuator by using a one-dimensional analytical model derived from the Euler and thermodynamic equations under varying assumptions. This model is compared to CFD simulations and experimental data (1 mm orifice diameter, 84.8 mm^3 cavity volume and 0.5 J energy input) to verify and/or modify the model where simplifying assumptions poorly represent the actual actuator. The model was exercised to explore high-frequency actuation and methods of improving actuator performance.

A well-developed code is still needed to develop a more realistic comparison with experiment data, especially for large cavity cases. Because of these codes' simplicity (volume average), the peak pressure and temperature rise after the arc discharge in real

physics would be neglected. It can be valid for small cavity actuators whose non-dimensional cavity volume (cavity volume normalized by arc discharge volume) is small. But with the development of different PSJA applications, large cavity cases also draw much attention. The large cavity actuator calculation performance may induce significant variations where the volume averaged value is lower than the local value in the cavity.

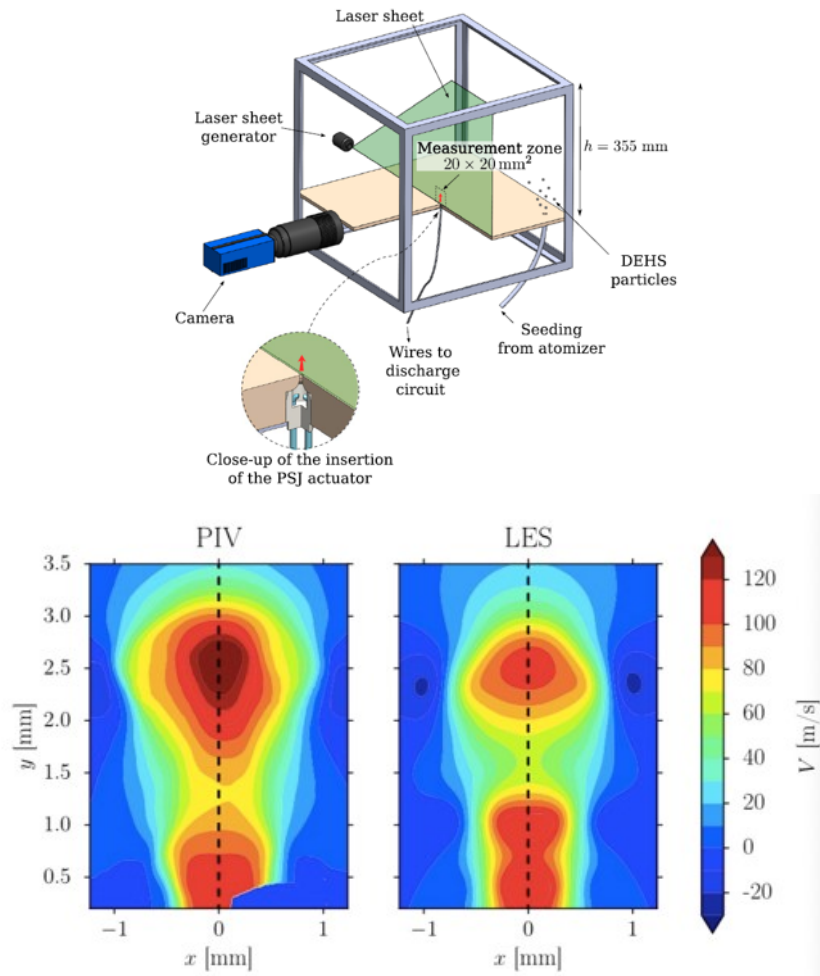


Fig. 1.32 PIV experiment set up and the comparison of the PIV and LES jet velocity [57].

In the numerical investigation part, ONERA conducted a two-dimensional, axisymmetric, URANS simulation of the PSJA interacting with a quiescent flow and a cross-flow assuming a prescribed energy input using their in-house CFD code called CEDRE CFD [56]. An original approach was developed based on a specific energy deposition model that permits a description of the ejection phase of a PSJA actuator developed at ONERA [24]. Based on this approach, a numerical model was calibrated and validated, allowing the simulation of detailed jet evolution in different cases. The comparison between numerical results and

experiments indicates that the jet topology is well reproduced since the position of some identifiable structures, such as the first vortex ring and the end of its tail, is in very good agreement. They also conducted the PIV experiment and LES comparison about the PSJA flow characteristic[57]. The experiment set-up and the PIV and LES velocity counter are shown in Figure 1.32. Experimental and numerical findings are considered to conclude in a quantitative manner on the dominant sources of uncertainty for such experiments and on the errors induced by particle dynamics that should be expected.

PSJA is also used as an effective active actuator for SWBLI flow control. Narayanaswamy et al. [67, 68] conducts studies on PSJA controlling SWBLI and finds that when PSJA was applied to the upstream SWBLI compression slope, the separation region would show a noticeable expansion trend. Further analysis showed that the motion frequency of the separation shock tended to the excitation frequency of PSJA, and the large-scale low-frequency instability was effectively suppressed. Based on these results, the high momentum of jet flow plays an essential role in the flow control mechanism. It has a potential performance in SWBLI frequency control because of its changeable frequency ability, which pursuits a high flow control application. Greene et al. [41] investigates the use of pulsed plasma jets (spark jets) to reduce the separation induced by shock wave-boundary layer interaction generated by a 20° compression ramp in a Mach 3 flow. Results show that plasma jets with a specific pitch angle ($\alpha = 20^\circ$ shown in Figure 1.33) from the wall and a certain pulsed ($St = 0.018$) can reduce the distance between the separation line and the compression ramp corner by up to 40 % and increase the integrated momentum in the downstream reattached boundary layer, with a concomitant increase in the shape factor. The control effect of separation line displacement is shown in Figure 1.34.

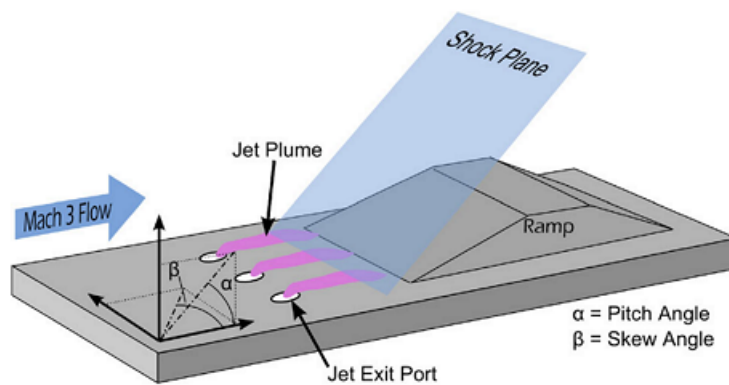


Fig. 1.33 Schematic of locations of jets and compression ramp [41].

The blast waves, which are also generated by arc discharge, significantly affect flow structures in PSJA. Emerick et al. [28] installed a Sparkjet array, which is an active flow

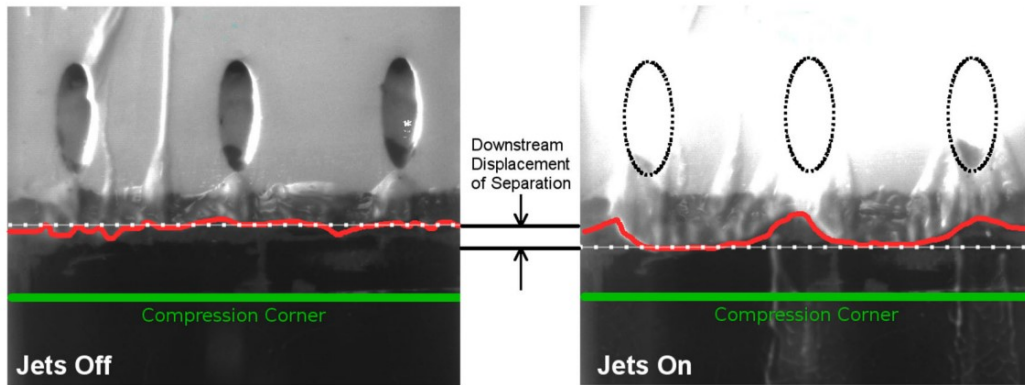


Fig. 1.34 Downstream displacement of separation line with jet off and jet on [41].

control device for high-speed flight control with no mechanical/moving parts and zero net mass flux, in a wind tunnel to observe the fluid mechanism of blast wave formation (visualized by high-resolution shadowgraphy). The blast waves are created by the actuator within a very short delay after the initial discharge (~ 20 ms) and are found to have a more substantial, or at least a comparable effect on the flow field relative to the jets produced by the SparkJet actuator. The interaction between blast waves and the tunnel boundary layer can also be observed during these short time delays. Chedevergne et al. [13] investigated the response of a high Re isothermal jet to a PSJA at $Ma = 0.6$ via PIV measurement and numerical simulation. Large-scale coherent structures are found downstream of the PSJA and are driven by the major perturbations, which are *pressure waves* generated by the arc discharge in the cavity of the PSJA, while the pulsed microjet by PSJA appeared to be of secondary importance. The coherent perturbation may be formed by the amplification of instabilities of the jet mixing layer and can be modelled as the impulse response of a high- Re subsonic jet. Sun conducted the PSJA flow control in hypersonic flow.

PSJA can be used in various other industrial applications. Gao et al. [37] proposed a novel deicing method based on a plasma synthetic jet actuator because of the merits of simple structure and no need for deflection of the aircraft skin. PSJA has a fast response ($80 \mu s$) and the ability to exert a strong impact (chamber dynamic pressure reaches 4486 kPa) on the ice. Overall, the PSJA can have a broader scope of use and optimization direction, while the deep fluid mechanism is still worthy of being further investigated.

1.4 Dissertation Objectives and Structure

Despite the significant progress in arc-discharge plasma actuator research in recent years, there still exist some research gaps that need to be addressed. One of the major gaps in

current arc-discharge plasma actuator research is the lack of understanding of the complex plasma physics that governs the interaction between the plasma and the surrounding fluid. While many studies have investigated the effects of various actuator parameters, such as the applied voltage and frequency, on the actuator's performance, there is still limited understanding of the fundamental plasma physics underlying these effects. For instance, the exact mechanisms by which the plasma interacts with the surrounding fluid, such as the formation and dynamics of plasma vortices and shock waves, are not yet fully understood. Fewer studies are focusing on the fundamental operating principles of the LAFPA. Since LAFPA and PSJA have the same arc-discharge process and nearly the same flow features (the plasma kernel, jet flow and blast waves), this work is going to investigate their flow features in a quiescent atmosphere. Another important research gap is that arc-discharge plasma actuator research for the SWBLI flow control mechanism is not fully investigated. The main flow control mechanism of LAFPA that has been proposed is streamwise vorticity instability and heating effect. For PSJA, high-momentum jet flow plays a dominant effect for supersonic flow control applications [38, 117]. However, high-momentum jets, blast waves and thermal perturbations generated by these plasma actuators can have relatively equivalent effects under different application conditions. Addressing these research gaps in arc-discharge plasma actuator research will require a combination of experimental, theoretical, and computational approaches. This will provide a better understanding of the underlying physics, and enable the development of optimized designs for practical applications to achieve enhanced flow control performance.

There are two main aims of this dissertation. The primary goal of this dissertation is to understand the fundamental flow mechanism of arc-discharge plasma actuators supported by experimental measurement and CFD modelling. Moreover, applying these actuators in transonic and supersonic SWBLI flow control and understanding the flow control mechanism is the second aim. This gives rise to the following objectives:

- 1) Experimentally examine the flow characteristics of LAFPA;
- 2) Build up a theoretical model for PSJA and examine the flow characteristic of PSJA through theoretical, experimental and numerical methodology;
- 3) Explain the flow control mechanism of LAFPA for supersonic SWBLI;
- 4) Apply PSJA for transonic SWBLI and evaluate the flow control effect.

This dissertation consists of 6 chapters based on these objectives. They focus on the aerodynamic characteristics of arc-discharge plasma actuators and flow control mechanisms for SWBLI.

Chapter 1 introduces the background and literature review of shock wave boundary layer interaction flow control and arc-discharge plasma actuators. A comprehensive review of the research on SWBLI flow control is carried out from the experimental and numerical points of view. The fundamental definition and various applications of different arc discharge plasma actuators and their application were discussed.

Chapter 2 demonstrates a Z-type high-speed Schlieren experimental set-up and designs on LAFPA testing. The experiments were conducted to capture the plasma kernel, the blast waves and the thermal fluctuation flow phenomenon of this type of plasma actuator. A conceptual model for the flow characteristic was given with full details and analysis.

Chapter 3 conducts a theoretical, experimental and numerical investigation to clarify the plasma kernel model and energy transformation characteristics of plasma synthetic jet actuator(PSJA). Plasma kernel and blast wave theory were used to describe the formation and evolution of the arc-discharge energy deposition process and build a plasma kernel model. Five plasma synthetic jet actuators with different cavity volumes and different discharge energy were modelled numerically to investigate the energy transformation characteristic of PSJA. The experiment data was used to validate the numerical results. An optimised 1-D modelling for arc-discharge plasma actuators and compares it with 3D simulations focusing on the flow mechanism of PSJA.

Chapter 4 presents a detailed analysis of DNS results of SWBLI controlled by LAFPA, including pressure, friction coefficient and velocity profile. The time-averaged separation bubble changed from the original uniform region spanwise to the larger triangle body in the flow direction. Furthermore, the precursor shocks emitted during the LAFPA operation coalesced into an oblique shock and merged with the separation shock, suggesting that the control was realised through re-organising the shock wave system.

Chapter 5 demonstrates a detailed analysis of URANS results of SWBLI controlled by arc-forced micro-jet flow, which can significantly reduce the centre separation zone caused by SWBLI. The control of the separation zone is mainly achieved by the streamwise rotating vortex pair generated by the micro jets. With pulsed arc-discharge jet flows, the velocity profile in the separation zone fluctuates on time and has the same responding frequency as the actuator.

Chapter 6 presents a summary of conclusions and plans for future studies on both active flow control methodology and SWBLI investigation.

Chapter 2

Flow Features and Fluctuation Characteristics Study of LAFPA

The objective of this chapter is to present a comprehensive analysis of the LAFPA operation phenomenon in the atmosphere, while simultaneously elucidating the fundamental flow characteristics through Schlieren experiments. These flow features encompass the plasma kernel and blast waves that occur after arc discharge, as well as the wide-ranging thermal fluctuations that arise in the atmospheric environment. The experimental methodology of the arc-discharge plasma actuators and imaging techniques are initially delineated, followed by the introduction of the power equipment and the design of the LAFPA. Ultimately, the Schlieren images are exhibited and meticulously scrutinised.

The acquisition of high-speed Schlieren experimental measurements is primarily intended to investigate the physics of plasma arc discharge for LAFPA. In order to comprehend the effects on the performance of the arc-discharge plasma actuator, including power frequency and electrode gap, the design parameters for LAFPA were varied. Through this variation, the actuator's operation and efficiency can be captured in its interaction with the surrounding atmospheric flow.

The research on LAFPA characteristics is still in its nascent stages and has several limitations. One of the primary limitations is the lack of extensive experimental data and a comprehensive understanding of the fundamental physics involved in LAFPA operation. Prior to the present study, experimental results of a single LAFPA operation in the atmosphere were limited, which is imperative for understanding its working principle. As a result, efforts were directed towards measuring the flow field of LAFPA operation. The heated volume characteristic generated by LAFPA operation is worthy of investigation, as thermal fluctuation is believed to exert a dominant influence on boundary layer transition.

2.1 Experimental Methodology

2.1.1 Schlieren techniques

Schlieren technology has been developed by Tepler's application of the knife-edge method to the field of compressible flow field display [55, 95]. When a knife edge is used, the system is generally referred to as a schlieren system, which measures the first derivative of gas density in the direction of the knife edge. If a knife edge is not used, the system is generally referred to as a shadowgraph system, which measures the second derivative of density. Its working principle is to use the phenomenon of irregular deflection of light passing through a compressible flow field. Schlieren techniques can visually display the structure of various interference areas without disturbing the measured flow field, intuitively reflect the change of the flow field characteristic structure before and after plasma flow control, and can reflect the boundary surface to a certain extent. Schlieren techniques have investigated various gas-dynamic issues, especially in high-frequency circumstances. Schlieren is an optical technique that relies upon lenses, mirrors, and cameras to image refractive disturbances in transparent media. In the experiment, a knife edge was used to cut off part of the light source image. When the flow field was not disturbed, the light intensity of the light source image at any point on the photographic plate was constant. When the light passed through the compressible flow field and was deflected, the disturbed light source image would have a displacement in the vertical direction of the knife-edge. The light intensity of each part of the light source image on the photographic plate would change, and the characteristic structure of the compressible flow field would also occur [67].

High-speed Schlieren techniques offer numerous benefits for experimental investigations in fluid mechanics and related fields. On the one hand, high-speed Schlieren techniques enable the visualisation of otherwise invisible flow fields and fluid phenomena, including shock waves, boundary layers, and turbulence. On the other hand, high-speed Schlieren techniques offer a very high temporal resolution, allowing researchers to capture and study transient flow phenomena that occur in a matter of microseconds, such as plasma actuator operations [7].

Figure 2.1 depicts the schematic of a Z-type high-speed Schlieren setup employed for plasma actuator investigation. A continuous LED lamp served as the light source, producing a bright output. A spherical-convex lens was used to collimate the light, which was then directed towards the first mirror. The collimation of light was further enhanced by a pair of concave mirrors, each measuring 8 inches in diameter and having a focal length of 6 feet. The light beam was reflected through the test section and projected onto the second mirror, which reflected the beam once again. A sharp knife edge was inserted at the focus to block

a portion of the light, allowing the remaining light to be brought to focus by the lens. The resulting light beam was captured by a high-speed camera. By capturing the amplitude of each ray in the beam, the instrument generated a pure phase disturbances as a grey-scale amplitude image in the camera. The z-type Schlieren configuration folded the optical path, introducing off-axis aberrations that are typically manageable.

The equipment used in this study is described in detail as follows. A Phantom M310 high-speed camera was utilized to record frames at a frequency range of 14~62 kHz, which allowed for a temporal separation of $16 \sim 71 \mu\text{s}$ between two consecutive images. To reduce the temporal integration within each exposure, the camera's exposure time was set to the minimum allowable value of $1 \mu\text{s}$. The spatial resolution of the Schlieren image was calibrated to be 0.216 mm/pixel. The arc discharge was manually initiated by triggering an oscilloscope that generated a 5 V waveform signal with a pulse width of $10 \mu\text{s}$. The synchronisation between the Schlieren imaging system and the discharge was accomplished by using the oscilloscope to trigger the camera simultaneously. The Phantom Camera Control (PCC) software was used to collect and process camera data on a computer.

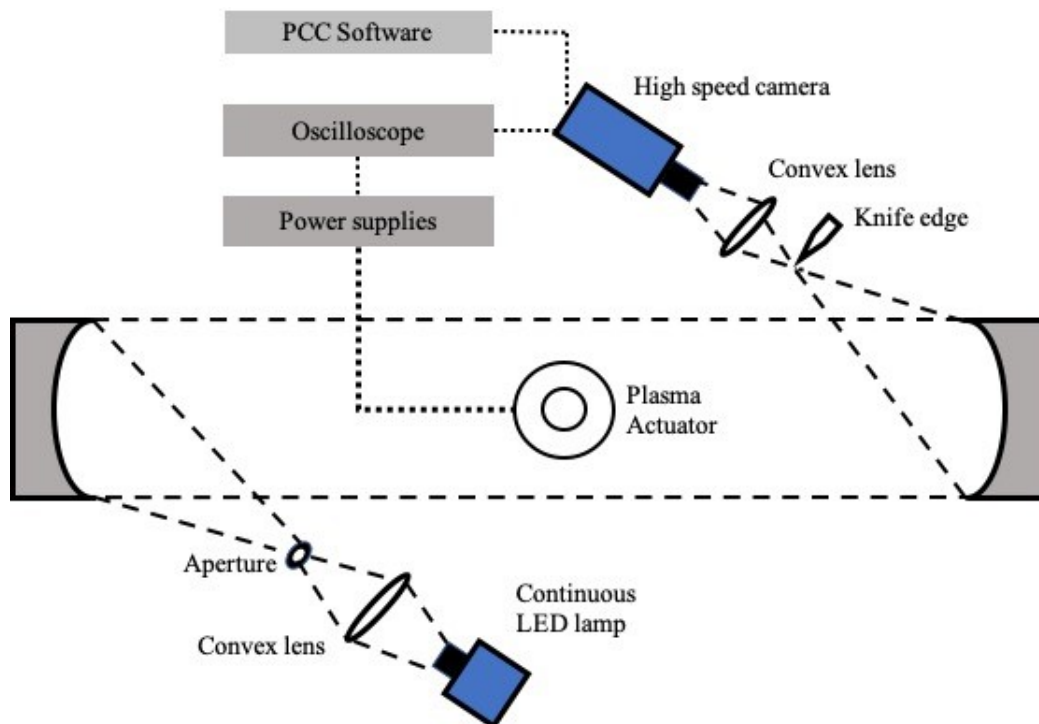


Fig. 2.1 Schematic illustration of a Z-type high-speed Schlieren setup for plasma actuator investigation.

2.1.2 LAFPA Design

The power equipment utilized in this study was a high-voltage microsecond pulse generator, which was used for initiating the arc discharge. A photograph of the high voltage microsecond pulse generator used in the laboratory is shown in Figure 2.2. The diagram of the inner power supply circuit is shown in Figure 2.3. It consisted of a front-stage DC charging part, a low-voltage pulse forming part, a pulse transformer, and other components. The working principle of the system can be briefly explained as follows. Initially, a relatively stable DC voltage was obtained on the voltage stabilising capacitor C_0 through full-bridge rectification via the variable AC voltage in the input range of 0~250 V through the auto-voltage regulator. Then, the primary storage capacitor C_2 was charged through the charging inductor L and diode, D_1 . When the semiconductor switch IGBT (Insulated Gate Bipolar Transistor) was turned on, the primary energy storage capacitor C_2 discharged through the IGBT-pulse transformer PT primary circuit, resulting in a low-voltage pulse on the pulse transformer PT primary inductance. The pulse transformer increased the low-voltage pulse and generated a microsecond-level high-voltage pulse on the secondary side. The output was a 0~20 kV high-voltage pulse with a rise time of 2 μ s, as illustrated in Figure 2.4. The calculation of arc power was unfeasible due to the unavailability of current and voltage probes; however, an estimate of 2.8 mJ discharge energy was performed later through comparison to simulation work in Chapter 3. The repetition frequency of the pulse generator system ranged from 0 to 10 kHz, which limited the research range of this study.



Fig. 2.2 High voltage microsecond pulse generator in the lab.

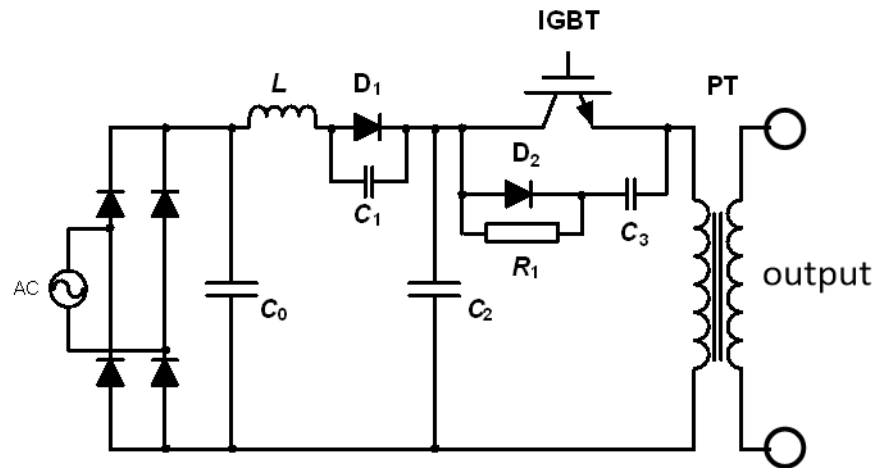


Fig. 2.3 Schematic diagram of the inner power supply circuit for high voltage microsecond pulse generator.

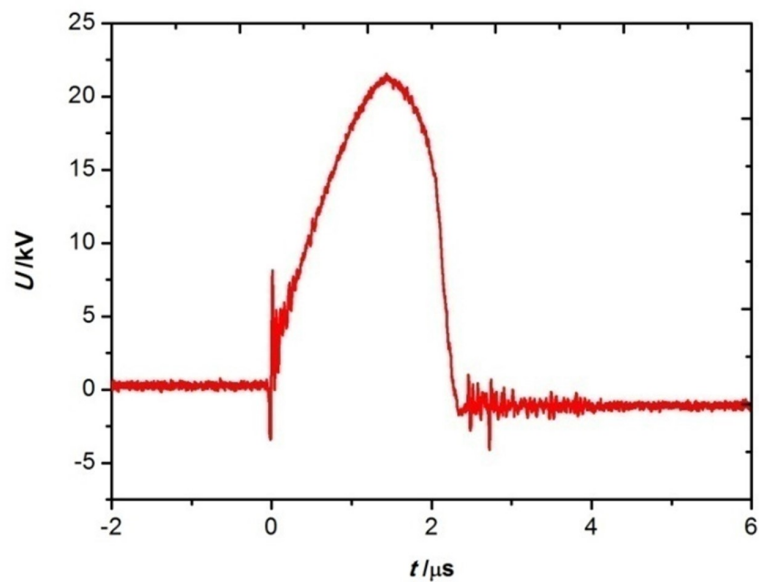


Fig. 2.4 Microsecond pulse generator voltage profile.

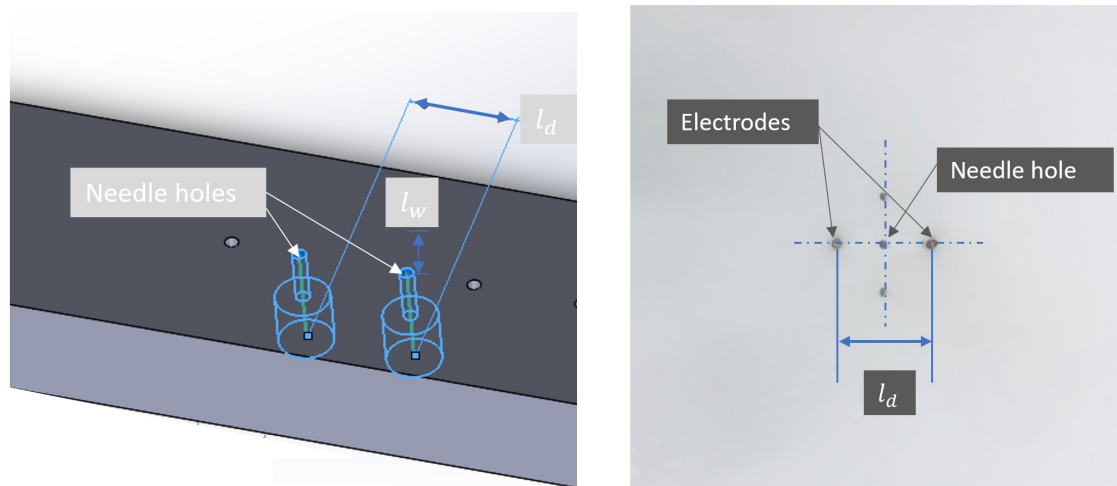


Fig. 2.5 Setup of Localized arc filament plasma actuator(LAFPA). Left: plastic plate with embedded LAFPA. Electrodes distance $l_d = 5$ mm and electrode length outside the wall $l_w = 0$ mm ; Right: ceramic plate with LAFPA. Electrode distance $l_d = 5$ mm/ 10 mm and electrode length outside the wall $l_w = 1$ mm/ 3mm.

The design of LAFPA incorporates a plate housing, tungsten anode, and cathode. The electrodes used are tungsten needles with a diameter of 1 mm and are typically situated within the needle holes with the tips flush to the plate surface, or alternatively, set within a groove with a depth of several millimetres ($1 \sim 5$ mm) to avoid blow-off during flow control [78]. To better understand the flow phenomenon between two electrodes, two operating conditions are tested: one with the electrodes flush to the surface and the other with electrodes inserted into the flow, with a length of l_w . The LAFPA device is operated with two different materials for the plate: an acrylic sheet with a thickness of 10mm and a ceramic plate with the same thickness. The flush LAFPA is operated with the acrylic sheet, which allows for visibility through the electrodes, while the outside surface LAFPA is operated with the ceramic plate. These design and operational aspects are depicted in Figure 2.5.

The present experimental study explores the effects of different triggering frequencies (0.5 kHz, 1 kHz, and 2 kHz) and different electrode positions on LAFPA. Table 3.1 presents the relevant information for the different cases examined, including four flush LAFPA cases (Case 1, Case 2, Case 3, and Case 4) and two cases (Case 5 and Case 6) where the electrodes are positioned slightly outside the wall surface. The latter cases were designed to investigate the formation and evolution of the plasma kernel in the atmosphere and to facilitate comparison with the flush LAFPA cases. It is worth noting that the high-speed camera frame rate differs for each case, which results in varying time durations between two continuous schlieren images.

Table 2.1 Parameters of arc-discharge plasma actuators

LAFPA	l_d , mm	l_w , mm	Actuation Frequency, kHz	Frame rate, kHz
Case 1	5	0	1	62
Case 2	5	0	0.5	40
Case 3	5	0	1	40
Case 4	5	0	2	40
Case 5	5	1	1	14
Case 6	10	3	1	14

2.2 Results and Discussion

2.2.1 Flow Visualisation of LAFPA Operating at Atmosphere

The phenomenon known as arc discharge refers to the electrical breakdown of a gas, resulting in a prolonged electrical discharge. This discharge, when occurring in gases near atmospheric pressure, is typically characterised by high current densities, high temperatures, and visible light emission. In this section, we examine the formation and evolution of the thermal core region after surface arcing associated with LAFPA operation, analysing the temporal evolution of arc-discharge flow features through a series of images obtained by progressively varying the time delay. Figure 2.6 illustrates the early-stage ($0 \sim 80 \mu s$) flow field for LAFPA operating in atmospheric conditions, with the darker grey region at the bottom of the image representing the basement of the acrylic plate with the electrodes settled in it shown as the black lines in the middle. The electrode distance of 5 mm is marked by the white lines (in Figure 2.6) at the top left position as the length scale, and a time signal is provided at the top right position. T0 is the first image taken at the arc discharge. Although both the micro-second power machine and camera were triggered by the pulse generator, the capture time differed slightly (less than $1 \mu s$) from the arc discharge. Blast waves and plasma kernel features were also marked on the images. The white arrow is set vertically to the plate with an end at the middle of the blast wave propagation semi-arc line. The plasma kernel is the central bubble set between the electrodes near the surface. Analysis of the images reveals that the plasma kernel and the blast wave were generated by the sudden electrical energy deposition at T0. The blast wave propagation velocity was estimated by tracking the position of the leading edge of the blast wave in the vertical direction from T0 to $T0 + 32 \mu s$, yielding a velocity of approximately 375 m/s, which is close to the speed of sound, c . Additionally, the plasma kernel was observed to expand over time due to thermal convection and blast

wave drag, with the shape of the plasma kernel changing from a uniform cylinder to a bulging bubble with a cusp in the middle position. From $T_0 + 48 \mu s$ to $T_0 + 80 \mu s$, the formation of the plasma kernel in the atmosphere environment could be seen more clearly. The shape further developed into a peach shape with a separated expansion bubble, marked at $T_0 + 64 \mu s$. This process was mainly generated by normal thermal convection. The phenomenon after arc discharge of LAFPA shows that the electrical energy of LAFPA was mainly converted into shock waves and local thermal energy propagation.

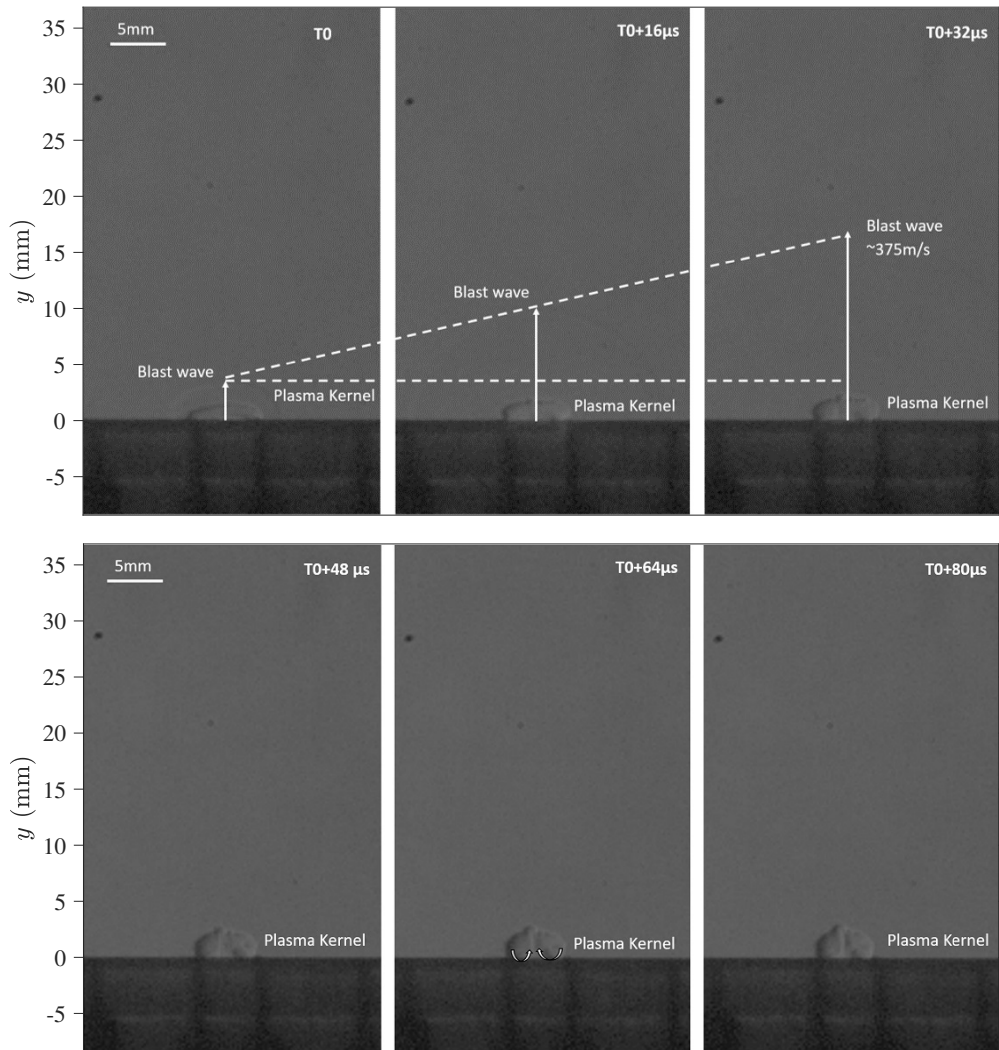


Fig. 2.6 Early stage ($0 \sim 80 \mu s$) of first pulse instantaneous Schlieren images of flow features with LAFPA of 5mm electrode distance at atmospheric condition.

Figure 2.7 further shows the thermal effect of LAFPA on the surrounding flow near the surface from $T_0 + 160 \mu s$ to $T_0 + 1000 \mu s$. A hot plume grew after the deformation of the plasma kernel. As soon as the plasma was discharged, a thermal layer called plasma kernel

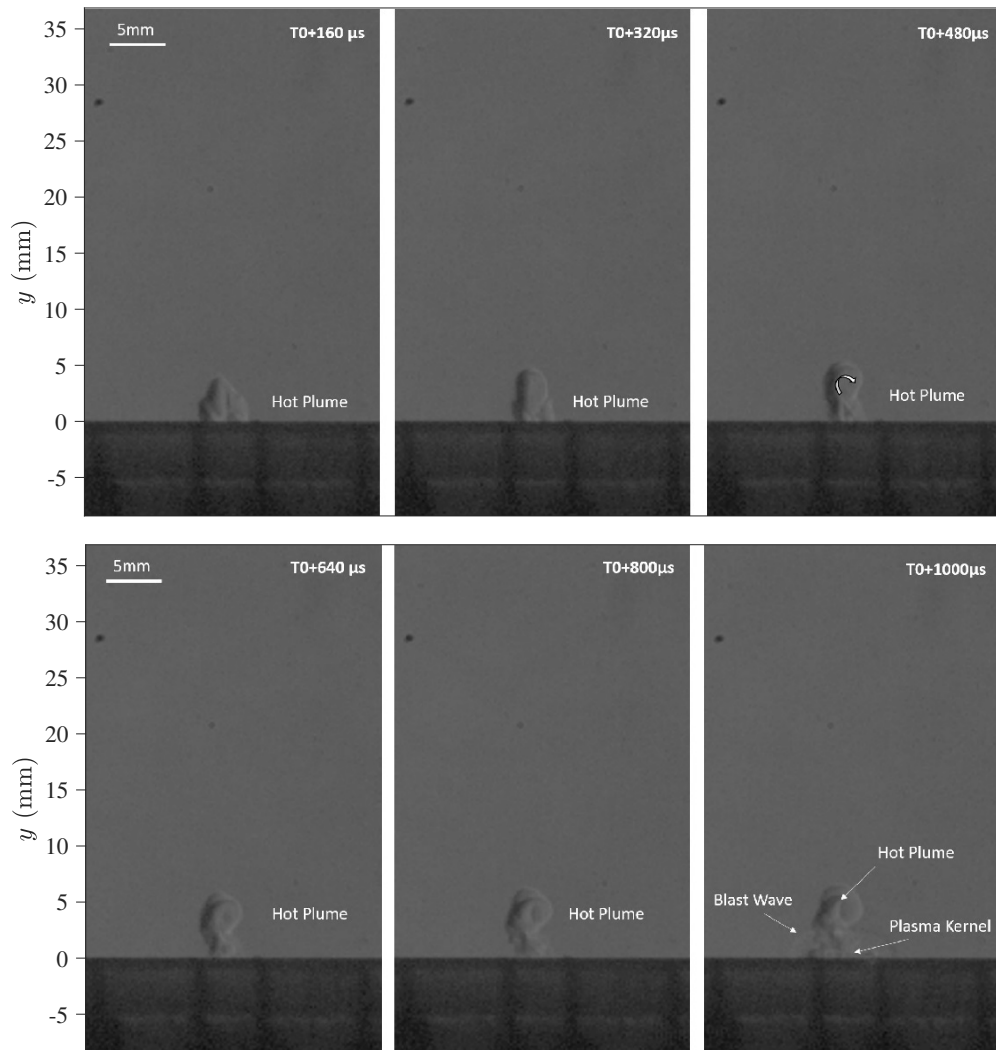


Fig. 2.7 Late stage (160 ~ 1000 μ s) of first pulse instantaneous Schlieren images of thermal fluctuation with LAFPA of 5 mm electrode distance at atmospheric condition.

formed above the actuator (Figure 2.6). The highest temperature occurred at the surface of electrodes. The high temperature induced a hot plume after 160 μ s time elapsed; the hot plume grew and was visible because the hot plume moved due to natural convection while the temperature gradient in the edge of the hot plume was significantly high. The grown hot plume was then diffused into the surrounding air. Except for the volume expanded in the vertical direction, the hot plume and the thermal pattern also developed significantly. During $T_0 + 160 \mu\text{s} \sim T_0 + 480 \mu\text{s}$, the hot plume started to rise, and the connection between the hot plume and electrodes aggregated to the centre. At 480 μ s, there formed a clear circulation region above two electrodes where there was a shrinking throat formed by the previous two reducing bubbles in Figure 2.6. As the hot plume kept rising, the size of the hot plume

increased very slowly, but the throat region was getting blurred, corresponding to a lower pressure gradient. At the elapsed time of $T_0 + 1$ ms when the plasma was discharged the second time, there generated the second plasma kernel and blast wave. The original thermal pattern was destroyed and combined with the second shock wave effect.

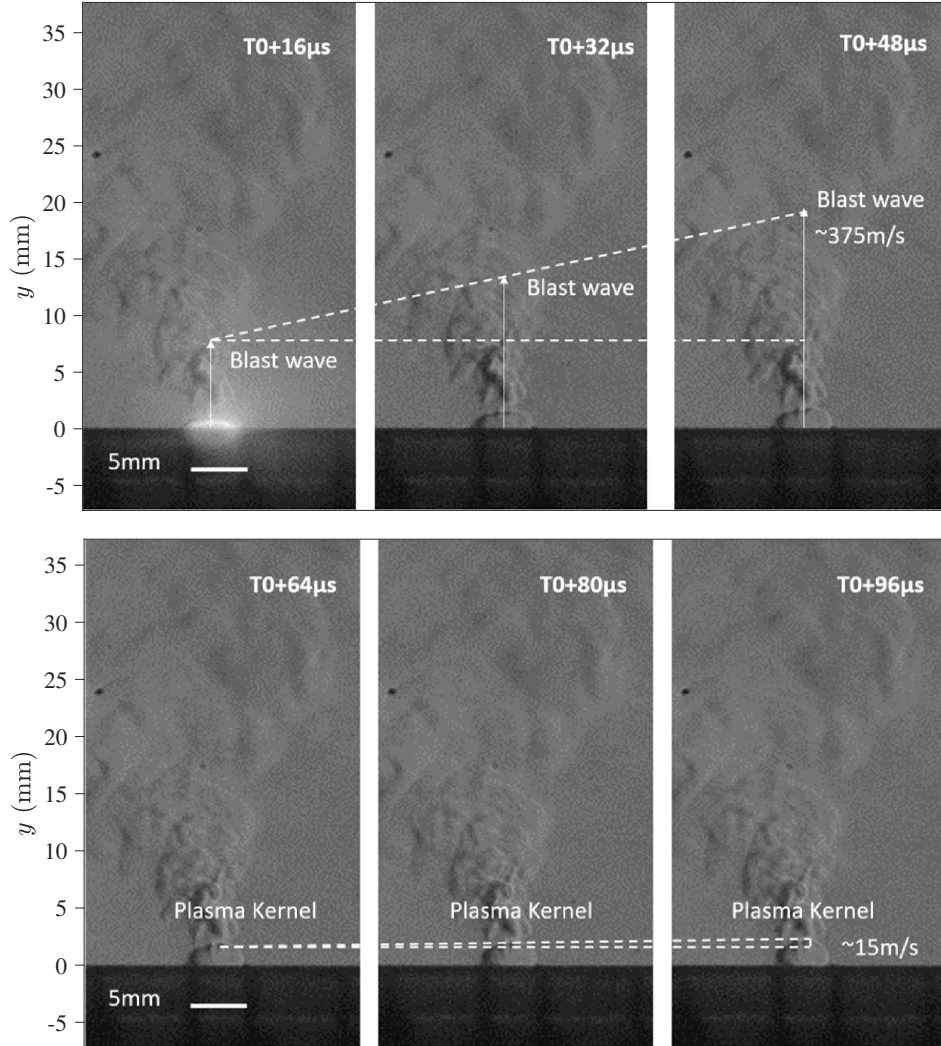


Fig. 2.8 Multi pulse stage instantaneous Schlieren images of flow fluctuation with LAFPA of 5 mm electrode distance at atmospheric condition.

After hundreds of arc discharge pulse generations, Figure 2.8 shows fully-developed flow fields for LAFPA with a 5 mm electrode distance operating at atmospheric conditions. The statistically-affected region, the hot plume, occupied almost the entire camera field of view with a shape of an expanding inverted triangle. This was because the amount of energy deposited into the air increased and was not fully decayed within an order of microseconds, which resulted in the growth of a large fluctuation hot plume.

At $T_0 + 16 \mu\text{s}$, the arc-discharge light and the blast wave generated by the sudden electrical energy deposition were still visible. The blast wave propagation velocity was estimated versus the time after discharge also to be 375 m/s, indicating the overall temperature change in the free domain was not significant, and also, the energy release of each pulse did not vary much under 1 kHz operating frequency. The plasma kernel also expanded with time as the first pulse phenomenon. The plasma kernel propagation velocity was estimated versus the time after discharge to be 15 m/s, a relatively low momentum level. The thermal pattern above the plasma kernel had a typical structure, the hot plume generated from the last arc discharge. The flow field on the top domain of the image was much more complicated, generated from the interaction of a series of hot plumes with the surrounding fresh air. The fluctuation domain was slightly blown to the left side of the image because of the wind effect when the camera was not covered by glass for a clear image. Overall, the operation of the actuators at $f = 1 \text{ kHz}$ generated hot gas region, which kept interacting with the main flow and diffusion energy upward.

Schlieren image can quantify the induced velocity field as a velocimetry technique [2, 93], for example, based on the image intensity integral function and its relationship with the gas density [18]. Due to the development of high-speed cameras and computers with high data processing capacity, there has been a growing increase in the development of Schlieren image velocimetry techniques. Conventional PIV software programs are the most commonly used for Schlieren image velocimetry for their long-time improvement and ability to measure the many parameters of interest in fluid mechanics. Fu et al. [33] initially implemented a commercial Particle Image Velocimetry (PIV) software to analyze Schlieren images captured by a high-speed camera. To establish a connection between the motion observed in the image pattern and the flow movement, an indispensable step was to interpret the flow field based on the visual appearance of the flow field. Traditionally, a fluid can be viewed as a continuous medium comprised of an infinite number of constituent elements. For image data processing, researchers propose that the fluid elements be defined as spatial volumes whose projection on the image corresponds to a single image pixel. This approach has yielded valuable velocity data from Schlieren images, and has expanded the potential applications of Schlieren systems. This method offers advantages in analyzing transient flow fields where PIV systems are not suitable, such as in situations involving gas explosions, buoyant flow, or dense smoke, where it is difficult or impossible to introduce particles.

In this dissertation, the explosions and arc discharge near the surface make the PIV technique hard to be applied. The PIV software, Dynamic Studio, was used to analyse Schlieren images, which can obtain the velocity field of LAFPA near electrodes. Figure 2.9 shows the velocity distribution of LAFPA at the beginning of pulse duration from $T_0 + 32 \mu\text{s}$

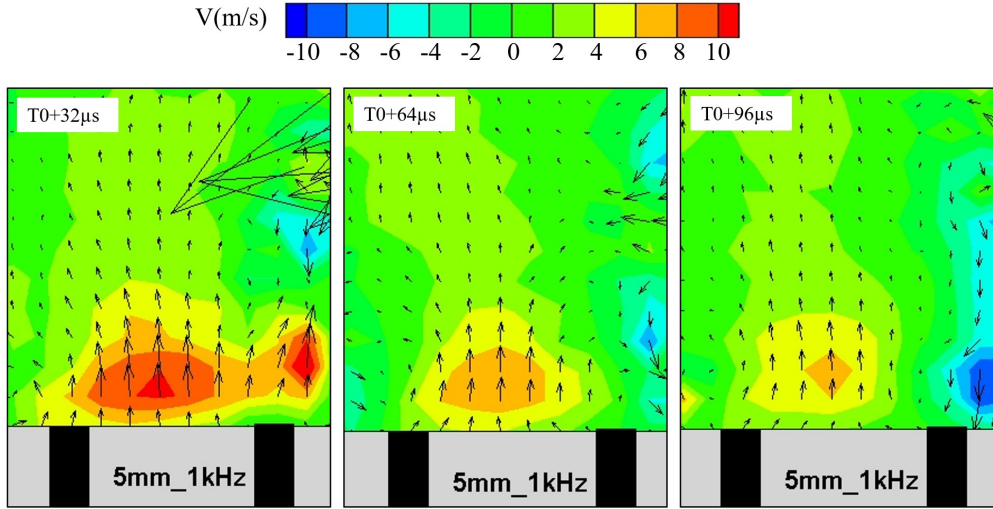


Fig. 2.9 Flow velocity of LAFPA near the surface extracted from Sequence of Schlieren images using PIV data processing (DynamicStudio). window size= 12×12 with 75% overlap.

to $T_0 + 96 \mu\text{s}$. Considering the typical structures near the surface, which consists of various high-pressure gradient layers, the velocity field near the surface can be calculated more accurately compared with conventional PIV using particle seeding. At $T_0 + 32 \mu\text{s}$, the near-surface plasma kernel flow forms a high-velocity region as the red region in the first image of Figure 2.9, induced by arc discharge near the surface. The peak velocity is around 10 m/s. A pair of vortices can be found on both sides of the red bubble in the first images and will further induce reverse flow in the following two images. Then the bubble keeps flowing upwards but with a reduction of the velocity of 8 m/s because of fluid viscous diversion. The two counter-rotating vorticities at the electrode side, which are generated by nature convection, keep expanding into larger regions and cause stronger reverse flow. At $T_0 + 96 \mu\text{s}$, the bubble has left the surface with a central velocity of 4 m/s. On the other hand, there are still limitations to deriving velocity distributions from Schlieren images. In the top right side of the first image in Figure 2.9, there are several irregular velocity vectors detected from regions with low-pressure gradients and low velocity. Because of low-pressure gradients, Schlieren signals are relatively small, leading to a large signal-to-noise ratio and a higher probability of fake results. Because this series of Schlieren images are blurred in a large area, only the typical structure of plasma kernel evolution near the surface can be well illustrated through this technique. However, We can still confirm that the LAFPA-induced flow has a much lower momentum effect compared to the jet flow induced by PSJA, which is discussed in Section 3.4.3.

2.2.2 Flow Fluctuation Characteristic of LAFPA

The investigation of the oscillation characteristic of LAFPA is of significant interest, as it can dominate the flow unsteady term. The interaction between the plasma discharge and the surrounding fluid generates turbulence, leading to fluctuations in the flow field. The frequency range of the arc discharge power supply determines the upper limit of the LAFPA's operating frequency. In this particular study, an arc discharge is supplied by a power machine in the frequency range of 0~3 kHz. The utilisation of a high-speed camera permits the acquisition of a large ensemble of images within a brief period of actuator operation. Notably, Figure 2.10 displays three instantaneous Schlieren images of flow field fluctuation at various operating frequencies. The 500 Hz case exhibits a smaller interaction region and a smaller gas density gradient when compared to the 1 kHz and 2 kHz cases. Furthermore, the thermal pattern fluctuation of the 1 kHz case contrasts significantly with that of the 2 kHz case. The flow region at 2 kHz displays a broader plume shape, while the 1 kHz affected region has a slender shape and coherence hot plume features near the arc discharge surface.

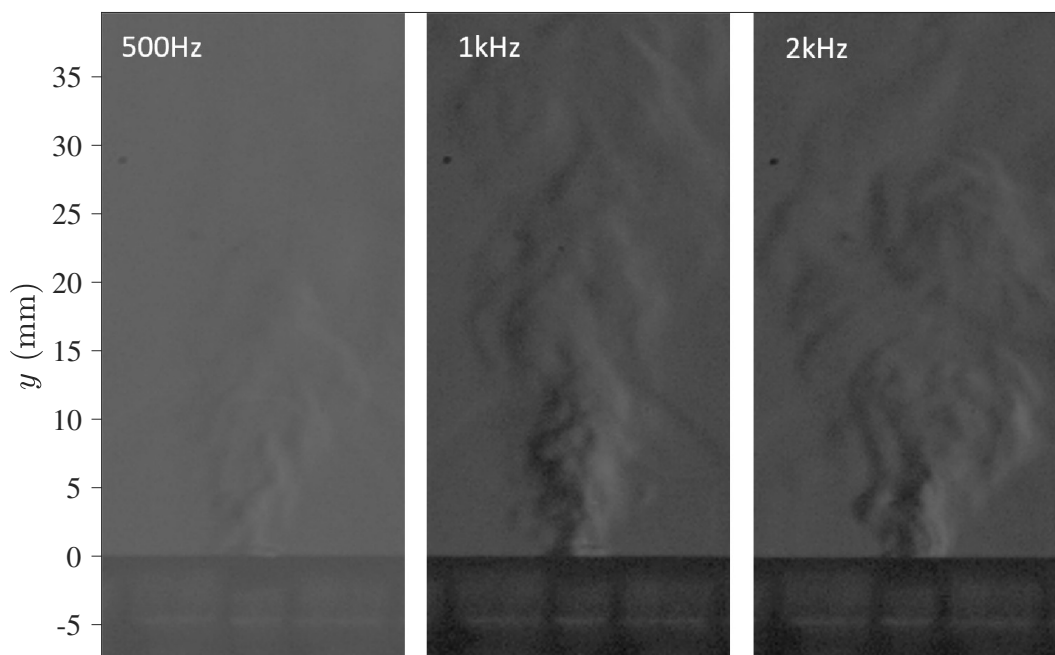


Fig. 2.10 Samples of instantaneous Schlieren images of thermal fluctuation with LAFPA operating at different frequencies.

Apart from qualitative observation of the Schlieren snapshots, the RMS Schlieren intensity field was used as a semi-quantitative way to reveal the flow field fluctuations. The convergence of the RMS of the schlieren images intensity was found to be slow, requiring large amounts of images [100]. The statistics of the recorded schlieren intensity fields (namely, the root-

mean-square of intensity I_{rms}) are also going to be examined in this study. The data ensemble for each LAFPA operation in the current study comprised 9,000 images, which was deemed sufficient to ensure statistical convergence.

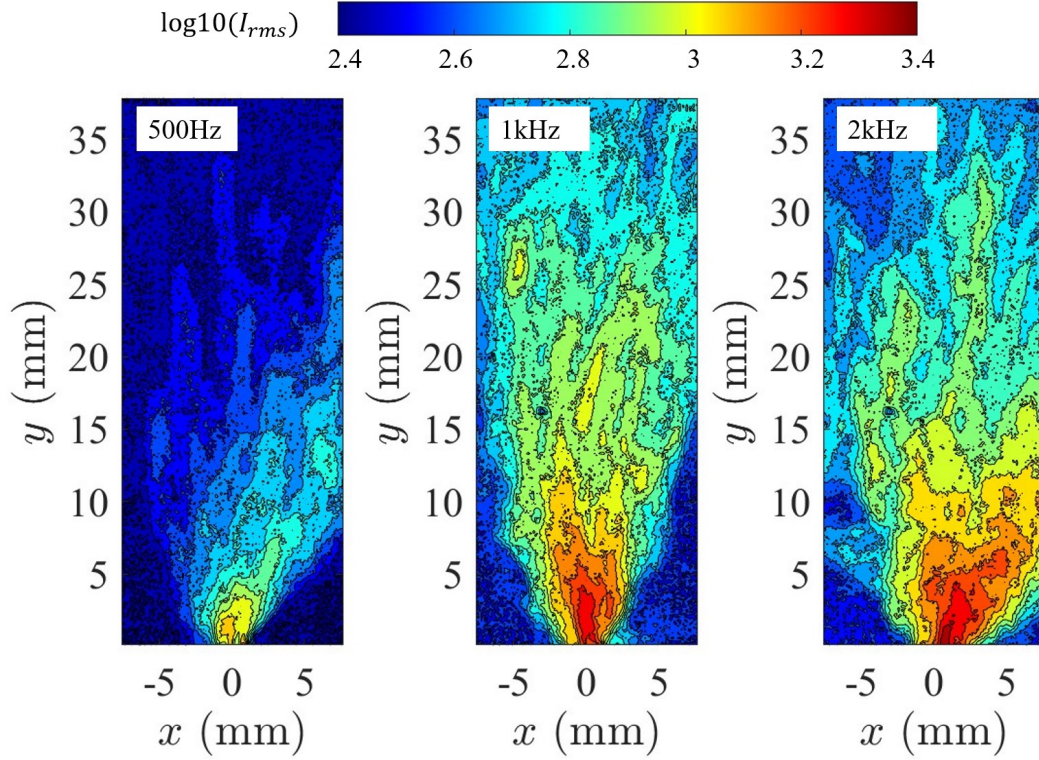


Fig. 2.11 RMS of Schlieren images' pixels intensity under LAFPA operating at 0.5 kHz, 1 kHz and 2 kHz.

Figure 2.11 depicts the I_{rms} of Schlieren intensity for LAFPA operating at different frequencies (0.5 kHz, 1 kHz, and 2 kHz). The red domain represents a high-intensity fluctuation, revealing a clearly visualised turbulent region resulting from the arc discharge of LAFPA. When assessing the frequency effect, it was observed that an increase in frequency led to a rise in the high I_{rms} value region, indicating that higher operating frequencies generated larger flow interaction regions in the atmosphere situation. As shown in the figure, when the LAFPA operate at a low frequency of 0.5 kHz, the yellow bubble near the bottom is quite small. Because the flow domain did not cover with glasses, which means this is an open-area test. So there exists a little bit of natural blow air, which makes the vertical developing flow be blown over to the right side along the y direction. The 1 kHz case shows a dramatic difference. The red I_{rms} domain becomes more significant and the overall fluctuation area occupies the total image. The bottom high fluctuation zone is more focused within the electrode distance of 5 mm. When the frequency surpassed 1 kHz, the interference area

increased without a significant height increment in the vertical direction, but rather thickened horizontally to a certain extent. This is interesting to show that for LAFPA, higher operation frequency can contribute more local thermal effect rather than the vertical momentum effect. Or the low momentum effect is too weak to sustain a vertical flow for too long, so the more continuous pulses would not change the interaction height further downstream after 1 kHz. Overall, it confirms that the thermal fluctuation effect of LAFPA plays a dominant role in an atmosphere test situation.

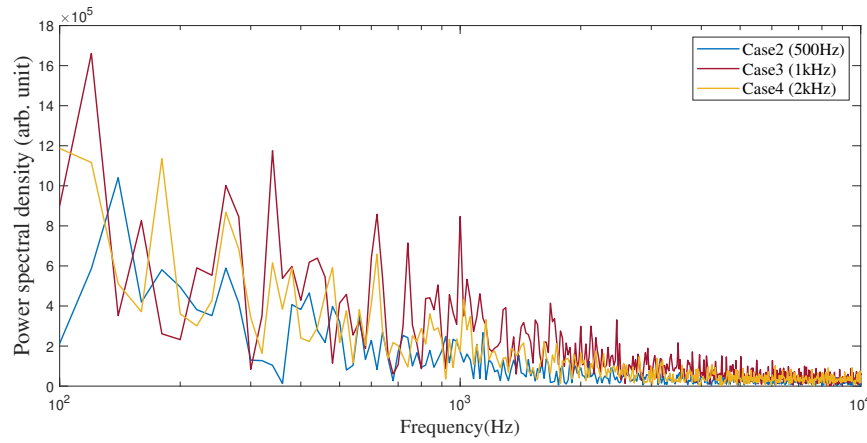


Fig. 2.12 Power spectral density distributions at the coordinate $(x, y) = (0, 5)$ under different operation frequencies.

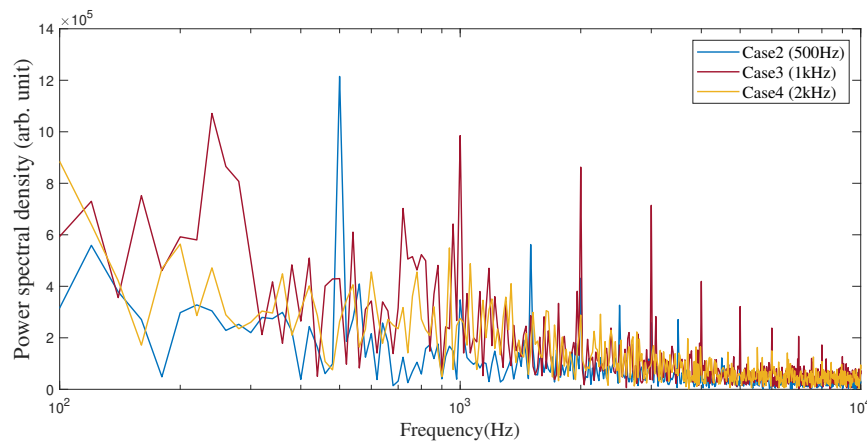


Fig. 2.13 Power spectral density distributions at the coordinate $(x, y) = (0, 1)$ under different operation frequencies.

The thermal fluctuation has mainly one dominant frequency: the pulse frequency. As shown in Figure 2.11, the dominant fluctuation exists on the actuator surface and at the upper domain of the exposed electrode. Power spectral density analysis is a technique used in signal

processing to analyze the frequency content of a time-series signal. It is a measure of how the power of a signal is distributed over different frequencies. Thus, we present the results of the Schlieren intensity frequency analysis at the coordinate $(x, y) = (0, 5)$ and $(x, y) = (0, 1)$ in Figure 2.12 and Figure 2.13. In the position of $(0, 5)$, the high magnitude of the power spectral density appears around 0.1 to 1 kHz, but no characteristic frequency for the three cases stands out significantly. However, at the near-surface position of $(x, y) = (0, 1)$, Case 2 had the typical frequency of 0.5 kHz, which was the same as the pulse frequency, and Case 3 also showed the peak frequency at 1 kHz with specific peaks at a high-frequency region. On the other hand, specific peaks in Case 4, whose pulse frequency was 2 kHz, did not appear. This may be caused by the quality of the image near the surface, and further investigation is needed to discover. The comparison of these two position results shows that the characteristic fluctuation domain mainly happened near the surface within the area of the electrode gap.

2.2.3 Flow Visualisation of LAFPA with Electrodes Outside

Figure 2.14 shows the instantaneous Schlieren images of LAFPA with electrodes 1 mm outside the surface (Case 5). The image reveals the presence of a ceramic plate at the bottom, which is black, and electrodes as two black spots located near the plate surface. The flow visualisation captured key features such as the plasma kernel, blast wave, and hot plume. The plasma kernel, initially in the shape of a cylinder, was bent by the shock wave drag and thermal convection, ultimately forming an arc shape. During the late stage of the first pulse, from $T_0 + 429 \mu s$ to $T_0 + 643 \mu s$, the size of the hot plume was relatively small and slender, and it did not flow upward but instead deformation between the electrodes. It is postulated that the vertical momentum effect of LAFPA with electrodes outside is lower than that of surface LAFPA. This is due to the fact that the surface LAFPA pushes the air upwards, while the electrodes outside the surface push the air between them slightly downwards, resulting in a noticeable effect when the electrodes are positioned at a greater distance from the surface.

In order to investigate the flow phenomenon between the electrodes, the present study explores Case 6 with a 10 mm electrode gap and 3 mm height from the surface. As illustrated in Figure 2.15, the flow features at the first pulse time duration of Case 6 are compared. It is observed that a distinct arc discharge plasma kernel with a diameter of 1 mm is formed, exhibiting a bend, due to the drag from the shock wave propagation. Subsequently, the transformation of the plasma kernel occurs at a slower rate, primarily attributed to natural thermal convection with less momentum effect than surface LAFPA. The plasma kernel eventually diffuses or spreads out between the two electrodes over time. Such a behaviour can be ascribed to the continuous motion of ions and electrons in the plasma, which collides with neutral particles in the gas, thereby transferring energy and momentum. As a result,

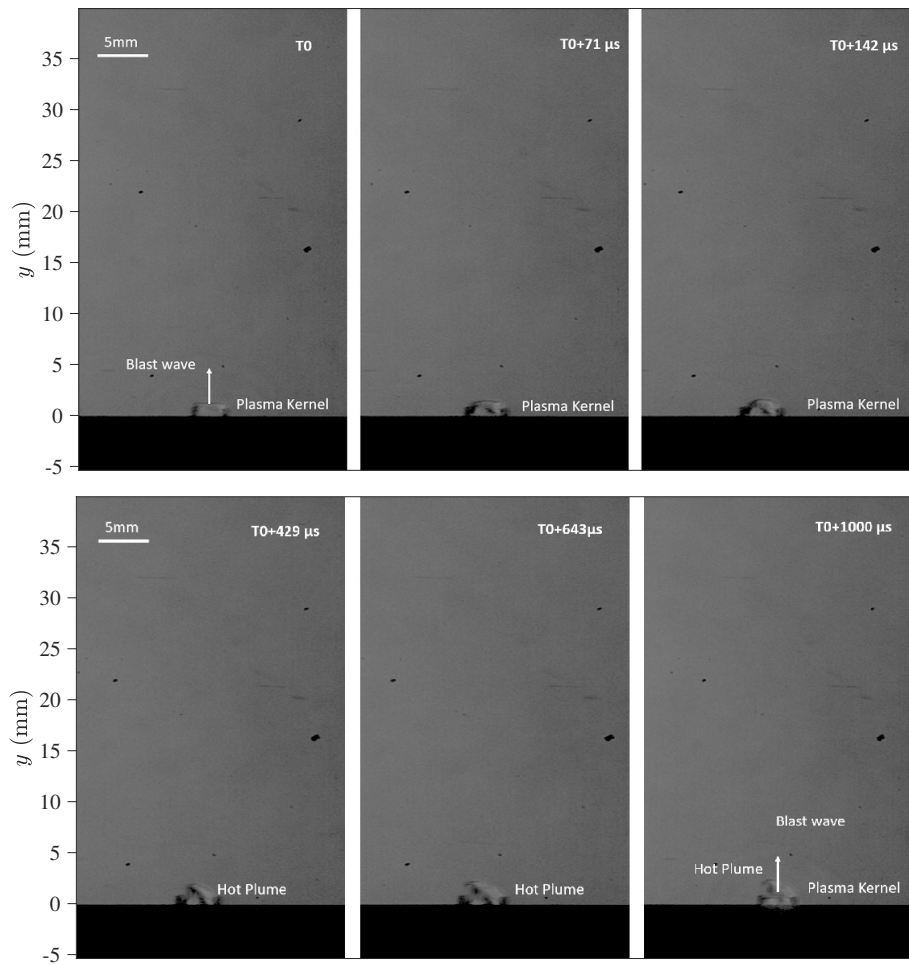


Fig. 2.14 First pulse instantaneous Schlieren image of the flow features generation and development of LAFPA with electrodes outside the surface with 1 mm (Case 5).

the plasma becomes less dense, leading to a reduction in its conductivity. After $429 \mu\text{s}$, a sizable hot plume was observed at the centre of the electrodes. Upon arc discharge between the two electrodes, the surrounding gas undergoes heating and cooling, giving rise to thermal diffusion. The high temperature generated in the plasma kernel and electrodes results in the thermal expansion of the gas, which in turn induces a pressure gradient facilitating thermal diffusion. It is noteworthy that the shape of the hot plume differs significantly from that of the hot mushroom plume depicted in Fig. 2.7. This observation implies that LAFPA with electrodes located outside the surface of the flow exhibits reduced impact on vertical direction diffusion but exerts a more pronounced local effect in the space between the electrodes.

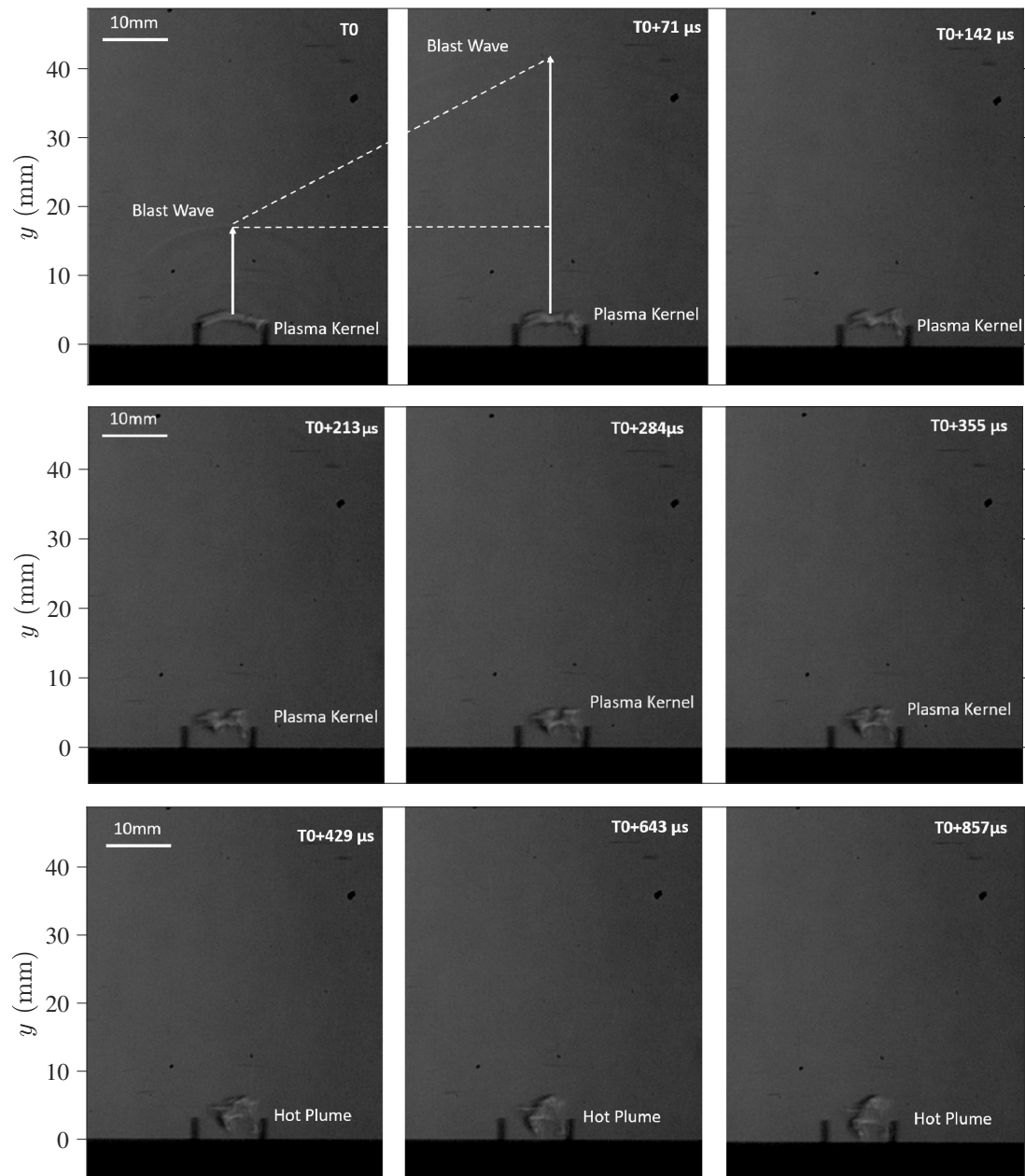


Fig. 2.15 First pulse instantaneous Schlieren image of the flow features generation and development of LAFPA with electrodes outside the surface with 3 mm (Case 6).

Figure 2.16 presents multiple visualisations of the arc discharge flow. The second arc discharge occurred between the tops of the electrodes, while the fourth and fourteenth pulsed arc discharge events were located at different regions. The fourth discharge took place in the bottom region between the two electrodes, whereas the fourteenth was initiated at a cross-section within the electrodes, owing to the temperature and density distribution in that area. The properties of the gas in which the arc discharge occurs can impact the ionisation degree and diffusion of the plasma kernel. Diverse gases exhibit dissimilar ionisation potentials and reaction rates, leading to varied plasma kernel properties and behaviours. Moreover, the direction of the plasma kernel induces distinct blast wave propagation directions, resulting in more complex force effects on the plasma kernel expansion. The influence on arc discharge between different pulses can depend on several factors, such as the duration, intensity, and frequency of the pulses, as well as the properties of the gas and electrodes. This phenomenon warrants further investigation.

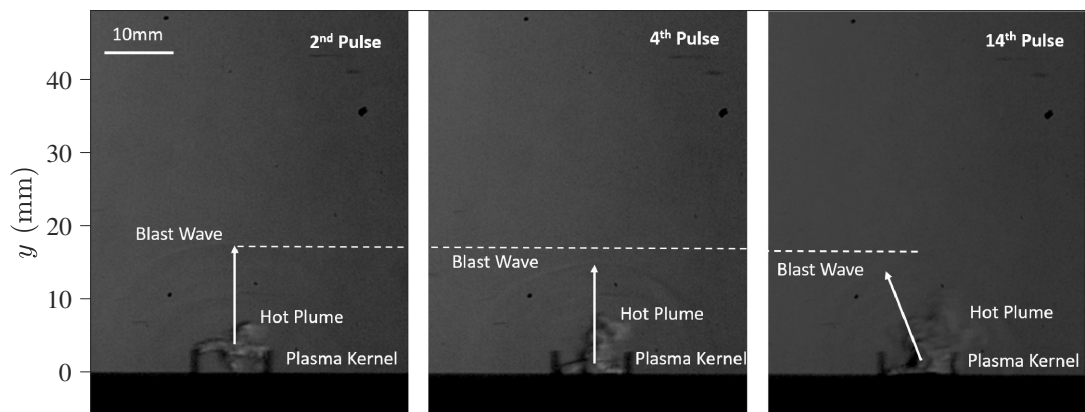


Fig. 2.16 Multi-pulse instantaneous Schlieren images of the flow features generation and development of LAFPA with electrodes outside the surface (Case 6) between three pulses (2nd, 4th, 14th).

2.2.4 Conceptual Model of LAFPA Flow Features

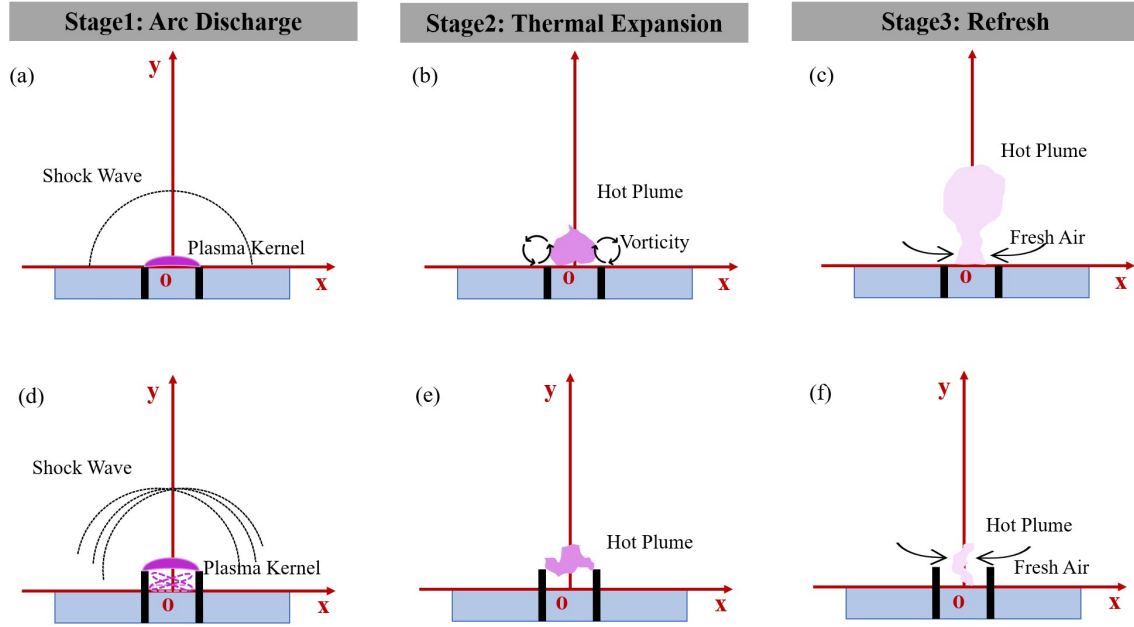


Fig. 2.17 Conceptual model of LAFPA flow features: (a)~(c) surface LAFPA; (d)~(f) LAFPA with electrodes outside the surface.

The flow evolution process of a surface LAFPA and a LAFPA with electrodes outside the surface is summarised in Figure 2.17, including three stages. Stage 1 is arc discharge, which is the electrical energy deposition process and generates a hot plasma kernel and shock waves near the surface. Stage 2 is thermal expansion, the jet, which should be called low momentum flow caused by the local high temperature and pressure air, will have less effect on the main flow boundary condition. In stage 3, the surrounding air recovers to the initial condition with a very short delay, leading to good operation at a very high frequency. Figure 2.17 (a)~(c) show the flow feature conceptual model for surface LAFPA. During the energy deposition stage, a solid pulsed arc is initiated by external electrical energy, rapidly heating and pressuring the gas between electrodes. The flow pattern of stage two is a central bubble of a hot plume with convection-induced vorticities near the surface. The peach-like hot plume is developing upwards. Then, ambient cold gas is ingested into the gap of electrodes, mixing with the residual high-temperature low-density gas. Figure 2.17 (d)~(f) shows the flow feature conceptual model for LAFPA with electrodes outside the surface. During the arc-discharge stage, a plasma kernel is formed between two electrode tips outside the surface, which occasionally occurs in a different direction and causes variation in the propagation direction of the blast waves. In the thermal expansion stage, the hot plume formed by the

plasma kernel is smaller and more localised compared to the hot surface plume in surface LAFPA due to the transformation process. The refresh stage involves an even smaller size of the hot plume, indicating that the thermal diffusion of LAFPA with electrodes outside the surface is highly localised. This is in contrast to surface LAFPA, which develops upwards due to the momentum effect. LAFPA with electrodes outside the surface exhibits a more localised thermal diffusion process during the arc-discharge and thermal expansion stages, resulting in a smaller and more concentrated hot plume during the refresh stage compared to surface LAFPA.

2.3 Conclusions

In this chapter, a Z-type high-speed Schlieren technique was employed to investigate the flow phenomena of various LAFPAs. The experimental setup and design of diverse LAFPAs were elaborated on in detail. The flow physics of LAFPA was explored by employing different actuator pulse frequencies and LAFPAs featuring electrodes outside the surface. The primary conclusions are summarised as follows.

The present study initially provides an overall flow visualisation of LAFPA. The results reveal the formation and evolution of a plasma kernel, blast waves, and thermal hot plume. Three prominent features are well illustrated by instantaneous schlieren images in single pulse cycles and multi pulses. After the arc discharge of LAFPA, a distinct hot plasma kernel and shock waves are observed. The primary shock wave velocity for LAFPA was measured at 375 m/s, whereas the thermal expansion zone diffused upward at a rate of 10 m/s due to natural convection. But this velocity will decay quickly after 64 μ s, which confirms that the LAFPA-induced flow has a much lower momentum effect compared to the jet flow induced by PSJA. Thermal expansion plays a dominant role in electrical energy transformation.

Then, regarding the fluctuation characteristic, the dominant frequency of LAFPA is the operation pulse frequency. Only the area near the surface can well represent the typical fluctuation. The actuator operating at a low frequency (500 Hz) will generate a relatively small total interaction area, while a higher operating frequency (1 kHz) increases the overall interaction area. However, keep increasing the frequency to 2 kHz will not enlarge the interaction area more significantly. It can only wider the region. This is interesting to show that for LAFPA, higher operation frequency can contribute more local thermal effect rather than the vertical momentum effect.

Lastly, a comparison of the flow characteristics between surface LAFPA and LAFPA with electrodes outside the surface is presented. While the formation and evolution of the plasma kernel blast wave and hot plume process are similar for both types of LAFPA, the patterns of

the hot plume and overall air interaction differ significantly. The surface LAFPA exhibits a larger impact on the vertical direction, indicating a stronger momentum effect than LAFPA with electrodes outside the surface. Furthermore, the transformation of the hot plume due to thermal conduction primarily occurs in the electrode region, resulting in a much smaller overall interaction for this type of LAFPA. A conceptual flow feature model is presented for both types of LAFPAs.

Chapter 3

Energy Transformation Characteristics Study of PSJA

This chapter conducted a theoretical, experimental and numerical investigation to clarify the plasma kernel model and energy transformation characteristics of plasma synthetic jet actuator (PSJA). Plasma kernel and blast wave theory were used to describe the formation and evolution of the arc-discharge energy deposition process and build a plasma kernel model. Schlieren experiments visualized the formation and evolution of the synthetic jet flow and used it as a validation of the numerical simulation. Five plasma synthetic jet actuators with different cavity volumes (128-512 mm³) and different discharge energy (2.8-11.3 mJ) were modelled numerically to investigate the energy transformation characteristic of PSJA.

There are many parameters determining the performance of the Plasma synthetic jet actuator, such as the input energy, the actuation frequency, the cavity volume, the electrode spacing, the size of the orifice, etc. Therefore, clarifying the working process and working principle can be beneficial to the design and performance optimization of arc-discharge plasma actuators. The motivation for this work is to fully estimate the flow characteristic and energy transformation of PSJA under medium cavity volume; Assessing different output energy terms of plasma actuators is the first step before applying these actuators to flow control applications. Moreover, a comparative study comparing 3D CFD simulation and the 1D code is presented in this chapter to gain confidence in the developed 1D model for PSJA design. Many organisations focus on developing a simplified theoretical model to understand the working process and provide further modification direction of plasma actuators.

3.1 Theoretical Model

3.1.1 Plasma Kernel

Based on previous Schlieren images of LAFPA in Chapter 2, after arc discharge, there will be a hot area between the electrodes, which is the high-temperature plasma kernel. Since the formation happens within a short time (less than $1 \mu\text{s}$), we assume that the plasma kernel is a cylindrical hot source generated after the arc discharge, despite complicated reactions during the air breakdown process. Figure 3.1 shows the formation and expansion of plasma kernel in the initial microseconds. l_d is the distance between electrodes. $t = t_k$ and $r = r_k$, are the plasma kernel formation time and radius.

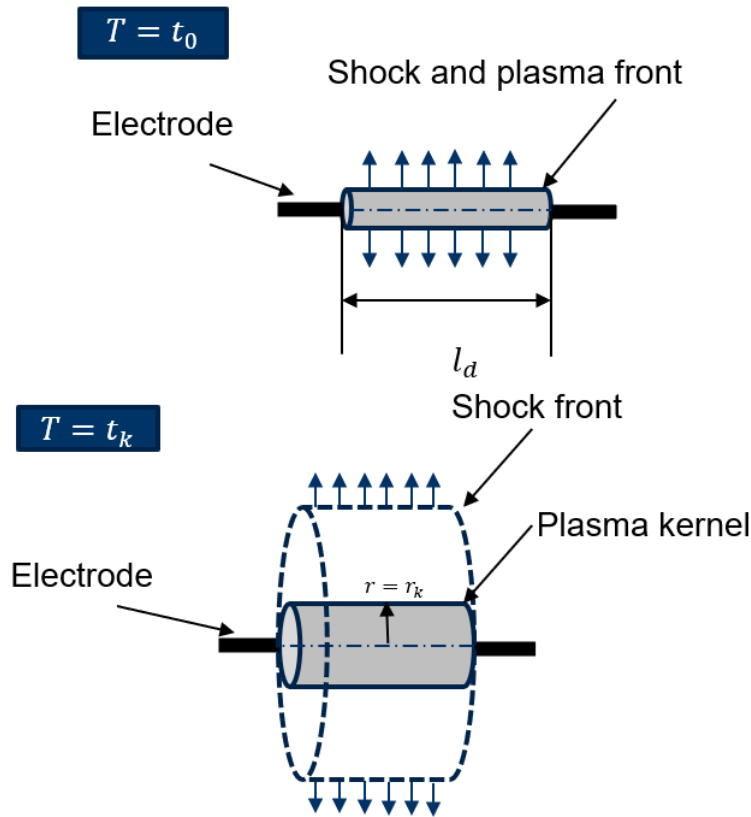


Fig. 3.1 Formation and expansion of plasma kernel. At $T = t_0$, the arc discharge just happened between the electrode distance l_d ; At $t = t_k$, the shock wave expanded and the plasma kernel formed with radius $r = r_k$.

At $T = t_0$, just after the arc discharge, there is a thin cylindrical source, with the front of the blast wave and plasma generated at its boundary. Based on theoretical assumptions (cylinder symmetry, instant deposition of the breakdown energy, neglecting diffusive processes), the rate of plasma expansion by a blast wave is governed by the amount of breakdown energy

per unit length E_d/l_d , the ambient pressure and density p_0 , ρ_0 and the heat capacity ratio $\gamma_0 = c_{p0}/c_{v0}$ [60, 71, 123]. Since the problem has no explicit characteristic time and length scales, it is governed by its inner length scale

$$r_c \sim \sqrt{E_d/(l_d p_0)} \quad (3.1)$$

and inner time scale

$$t_c \sim r_c/c_0 \quad (3.2)$$

with the speed of sound c_0 at ambient

$$c_0 = \sqrt{\gamma_0 p_0/\rho_0} \quad (3.3)$$

The shock disturbance is assumed to be similar at all times, changing only its linear dimensions with increasing time. It is also assumed that the gases are perfect, with constant specific heat ratios. Energy losses from ionization and radiation are neglected. Under these assumptions, the distance of the shock front from its initial position is related to the time by the expression. So the system characteristic radius scale r_c and time scale r_c are defined as

$$r_c = \sqrt{E_d/(l_d B \gamma_0 p_0)} \quad (3.4)$$

$$t_c = r_c/c_0 \quad (3.5)$$

The energy parameter B results from the theory of strong blast waves and is dependent on the symmetry of the problem. B is a numerical constant depending upon the geometry of the shock wave and the specific heat ratio γ_0 . In our case, the geometry is cylindrical blast wave expansion and for air the $\gamma_0 = 1.4$, Jones et al. [51] finds $B = 3.94$. By fixing the plasma kernel boundary at $\rho/\rho_0 = 0.9$ and invoking the density profiles given in Ref.[71], the proper non-dimensional boundary and time elapsed after breakdown for our definition of the hot plasma kernel can be defined as

$$\lambda_k = \frac{r_k}{r_c} = 0.5 \quad (3.6)$$

$$\tau_k = \frac{t_k}{t_c} = 0.57 \quad (3.7)$$

This study supplements the theoretical calculation values for the plasma kernel and blast wave. The core region of the arc discharge has high-temperature gas clusters and shock waves, which can be used to determine the parameter for actuator design and its material selection. Therefore, it can provide a reference value for industrial applications. When

the plasma kernel radius r_k is determined, the plasma kernel volume V_k is fixed. So the temperature rise in this domain can be calculated from thermal equations. The plasma kernel temperature T_k is defined as the average temperature in the plasma kernel domain.

$$V_k = (r_k)^2 \pi l_d \quad (3.8)$$

Then the energy balance for the fixed-volume open system is given by

$$m_k c_p T_k = m_0 c_p T_0 + E_d \eta \quad (3.9)$$

$$\rho_k V_k c_p T_k = \rho_0 V_k c_p T_0 + E_d \eta \quad (3.10)$$

where η is the breakdown efficiency after energy deposition, which is a consequence of the separation of the blast wave from the hot plasma kernel. Here need to clarify that this efficiency is not the percentage of electrical energy transferred to thermal energy, which is called discharge efficiency, nearly 0.3 in the literature [39]. Because in the model, the deposition energy E_d value is directly given. ρ_k is the plasma kernel density. T_0 is the initial cavity temperature, equal to the ambient temperature. c_p is specific heat for constant pressure, depending on the pressure and temperature calculated by D' Angule et al. [22]. So, the generic thermodynamic equation used to determine T_k is given by

$$T_k = \left(\frac{E_d \eta}{V_k \rho_k} + \frac{c_p T_0 \rho_0}{\rho_k} \right) / c_p \quad (3.11)$$

Jones et al.[50] have suggested an empirical relationship between shock over-pressure and radius, for cylindrical shock waves, of the form

$$\left(\frac{2(\gamma+1)}{\gamma} \frac{\delta p}{p_0} \right) = \left(\alpha \left((1 + \beta \lambda^2)^{\frac{3}{8}} - 1 \right) \right)^{-1} \quad (3.12)$$

where α and β are given by

$$\alpha = (3/8)^{\frac{3}{5}} c^{\frac{8}{5}} \quad (3.13)$$

$$\beta = (3/8)^{\frac{8}{5}} c^{\frac{-8}{5}} \quad (3.14)$$

The adjustable parameter c thus determines the point of the intersection of the strong shock and weak shock asymptotes to Eq. (3.12). Jones et al. [50] assumed that $c = 1$. The peak pressure P_k of blast wave due to a line source energy input can be

$$P_k = p_0 + \delta p \quad (3.15)$$

3.1.2 Energy Transformation

The process of energy transfer after an arc discharge is complicated and has attracted much more attention. At first, electric energy is gradually converted isotropically to the energy of motion. However, as shock waves form, kinetic energy is converted irreversibly back to thermal energy generating plasma kernel, at a rate which increases rapidly as shock strength decreases. Figure 3.2 shows how the energy converts after the arc discharge. The total input electric energy is E_d , and after an extremely short time, there will be a plasma kernel between electrodes. A small proportion of the energy will be released into the environment, including the heat transfer to the iron electrons Q_{ht} , and the radiation heat loss Q_{rad} . A large amount of energy will transfer to the flow within the blue dash line, which is $(h + u^2/2) * m$. The energy balance equation is shown in Eq. (3.16).

$$E_d = (h + u^2/2) * m + Q_{ht} + Q_{rad} \quad (3.16)$$

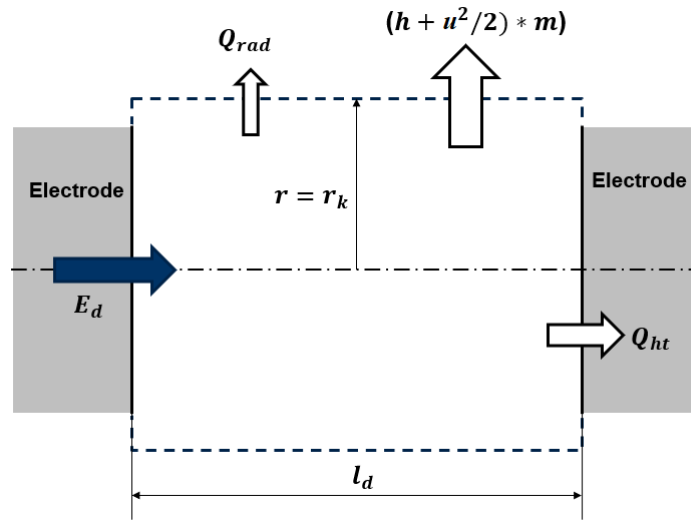


Fig. 3.2 Energy transformation between two electrodes after arc discharge (Discharge energy E_d , heat transfer to electrodes Q_{ht} , radiation loss to the environment Q_{rad} and flow energy $(h + u^2/2) * m$).

In the theoretical model, Q_{ht} and Q_{rad} are neglected considering the low energy deposition level in this study. We assume that the discharge energy has totally been converted into the flow. The rest of the thermal energy will be converted into the internal energy and kinetic energy of the flowing mass. This is the complete energy transformation just after arc discharge. Then, for LAFPA, the shock wave front will transport quickly far away from the main plasma kernel domain. Although the shock strength partially converts back to thermal

energy, there still has shock wave energy loss to the far away domain in a short time, which in some conditions can reach 10% of input energy [99].

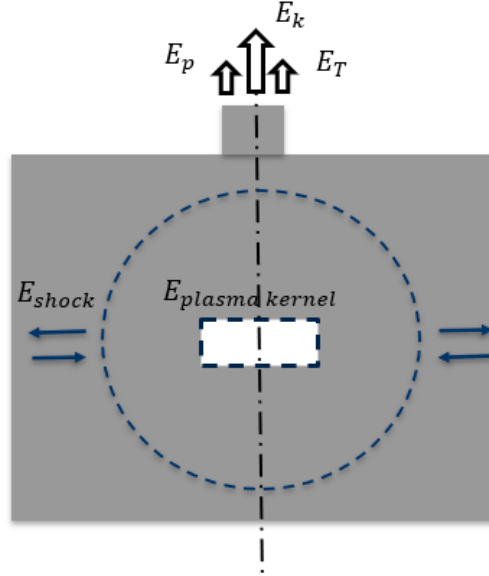


Fig. 3.3 Simplified energy transformation of a PSJA. (thermal plasma kernel energy $E_{plasma\ kernel}$ and shock potential energy E_{shock} , the orifice output energy term : kinetic energy E_k , potential energy E_p and thermal energy E_T).

However, for PSJA, much more thermal energy and shock wave energy convert to kinetic energy to generate high-momentum jets. The energy transformation term of PSJA is shown in Figure 3.3. In the energy deposition stage, the arc heating region only occupies a small region of the whole cavity. Most of the cavity is pressurised through the propagation and the reflection of arc-induced shock waves, which is an entropy-increases. The smaller the heating volume to cavity volume ratio, the larger the dissipated mechanical energy. Finally, the pulsed thrust drops as the cavity length rises [131]. The thermodynamic cycle efficiency is positively correlated with the non-dimensional energy deposition. The primary energy transfer efficiency is shown below. Usually, the electrical discharge energy E_d can be resolved by integrating the signal of voltage times current, which is shown in Eq. (3.17). But the experiment does not test the high voltage and current during arc discharge. So the deposition energy E_d value is directly given based on the simulation validation. Various energy terms need to be clarified for further discussion.

Electrical Discharge Energy:

$$E_d = \int V(t) \cdot I(t) dt \quad (3.17)$$

Cavity Internal Energy:

$$E_c = c_v \cdot m_c \cdot T_0 \quad (3.18)$$

Non-dimensional Deposition Energy

$$\varepsilon = E_d/E_c \quad (3.19)$$

Non-dimensional Cavity Volume

$$v = V_c/V_d \quad (3.20)$$

Kinetic Energy:

$$E_k = \int 0.5 \cdot m \cdot v^2 \cdot dt = \int 0.5 \cdot \rho \cdot u \cdot A \cdot u^2 \cdot dt \quad (3.21)$$

Potential Energy:

$$E_p = \int P \cdot v \cdot A \cdot dt = \int P \cdot u \cdot A \cdot dt \quad (3.22)$$

Heating Energy:

$$E_T = \int c_v \cdot m \cdot T \cdot dt = \int c_v \cdot \rho \cdot u \cdot A \cdot T \cdot dt \quad (3.23)$$

Kinetic Energy Efficiency:

$$\eta_k = E_k/E_d \quad (3.24)$$

Potential Energy Efficiency:

$$\eta_p = E_p/E_d \quad (3.25)$$

Heating Energy Efficiency:

$$\eta_T = E_T/E_d \quad (3.26)$$

3.1.3 PSJA 1D governing equations

During the last two decades, different modelling approaches have been developed to simplify the calculation of PSJA operating performance [73, 132]. Initial PSJA analysis debuted with a simplified, first-order, one-dimensional analytical model. The governing equations used to model the PSJA cycle involve basic thermodynamics and fluid dynamics are shown below.

Stage 1 -initial condition

To initiate Stage 1 of the cycle, an instantaneous energy input, E_d , of an assumed value from the arc discharge energy is used to determine the temperature rise in the cavity from T_1 , the temperature before the arc discharge, to T_2 , the temperature after the arc discharge. The generic thermodynamic equation used to determine a temperature rise due to energy input is given by

$$\Delta T = T_2 - T_1 = \frac{E_d}{mc_v} \quad (3.27)$$

Since the internal energy in the cavity can be defined as

$$E_c = mc_v T_1 \quad (3.28)$$

The arc discharge temperature in the cavity will rise to

$$T_2 = T_1 \left(1 + \frac{E_d}{E_c} \right) \quad (3.29)$$

Then T_2 is used to calculate the peak temperature at the beginning of Stage 2. Using the ideal gas law and under the assumption that no mass has exited the cavity during this instantaneous energy deposition, the peak pressure, P_2 , is determined by

$$P_2 = \rho R T_2 = \rho R \left(1 + \frac{E_d}{E_c} \right) \quad (3.30)$$

The above calculation results are used as the initial conditions of the 1D code as in most of the literature.

Stage 2

The next assumption to simplify equations is that the density, pressure, and temperature inside the cavity are uniform and that only significant velocity values are uniform in the orifice volume only. Governing equations are presented here.

Mass conservation:

$$\frac{d\rho}{dt} = -\frac{\rho A_o U}{V} \quad (3.31)$$

Momentum conservation:

$$\frac{dU}{dt} = \frac{1}{\rho} \left(\frac{(P - P_e)A_o - \rho U^2 A_o}{V_o} - U \frac{d\rho}{dt} \right) \quad (3.32)$$

Energy conservation:

$$\frac{dP}{dt} = \left(\frac{R}{c_v V} \right) \left(\dot{q} \rho V - (P - P_e) U A_o - \rho \left(c_v T + \frac{1}{2} U^2 \right) - V_o \left(\rho U \frac{dU}{dt} + (1/2) U^2 \frac{d\rho}{dt} \right) \right) \quad (3.33)$$

Constitutive relations:(thermal and caloric equations of state)

$$p = \rho R T, \gamma = 1.4 \quad (3.34)$$

During Stage 2, the pressure ratio between the cavity and outside leads to the need for a choked and unchoked flow condition. The isotropic pressure ratio equation is set at $Ma = 1$.

$$\frac{P}{P_\infty} = \left(1 + \frac{\gamma-1}{2} Ma^2 \right)^{\frac{\gamma}{\gamma-1}} = 1.893 \quad (3.35)$$

Therefore, Stage 2 is segmented into a choked flow condition followed by an unchoked flow condition that depends on the pressure ratio between the cavity pressure and the external pressure.

The shock wave reflection in the PSJA cavity has been observed from Schlieren experiments and previous literature[73], which brings about high-frequency vibrations of the jet parameters at the exit of the orifice. In this study, an empirical formula of the changing cavity pressure was added on the basis of the basic 1D code to reflect this pressurization characteristic.

$$P_0 = p_2 + iP_k/15 \quad (3.36)$$

where $i = 1 \sim 5$.

Stage 3

The derivation and equations described for Stage 2 are identical to those used to simulate Stage 3, except where equations describe the flow passing through the orifice. Therefore, the surface integral in original conservation equations involves ambient conditions rather than cavity conditions.

Mass conservation:

$$\frac{d\rho}{dt} = -\frac{\rho_\infty A_0 U}{V} \quad (3.37)$$

Momentum conservation:

$$\frac{dU}{dt} = \frac{1}{\rho_{\infty}} \left(\frac{(P - P_{\infty})A_0 - \rho_{\infty}U^2A_0}{V_0} - U \frac{d\rho}{dt} \right) \quad (3.38)$$

Energy conservation

$$\frac{dP}{dt} = \left(\frac{R}{c_v V} \right) \left(\dot{q}\rho V - (P - P_{\infty})UA_0 - \rho_{\infty}(c_v T_{\infty} + \frac{1}{2}U^2) - V_0 \left(\rho_{\infty}U \frac{dU}{dt} + (1/2)U^2 \frac{d\rho}{dt} \right) \right) \quad (3.39)$$

The system of equations described in previous contents was solved using the initial value problem solver in MATLAB called *ode45*. The MATLAB code used to run the simulations is presented in the Appendix. The *ode45* solver is based on the explicit Runge-Kutta numerical approximation method designed to solve a set of ordinary differential equations as a function of time.

3.2 Schlieren Experiment

The PSJA design used to support this dissertation included the use of a cavity housing, tungsten anode and cathode, as shown in Figure 3.4.

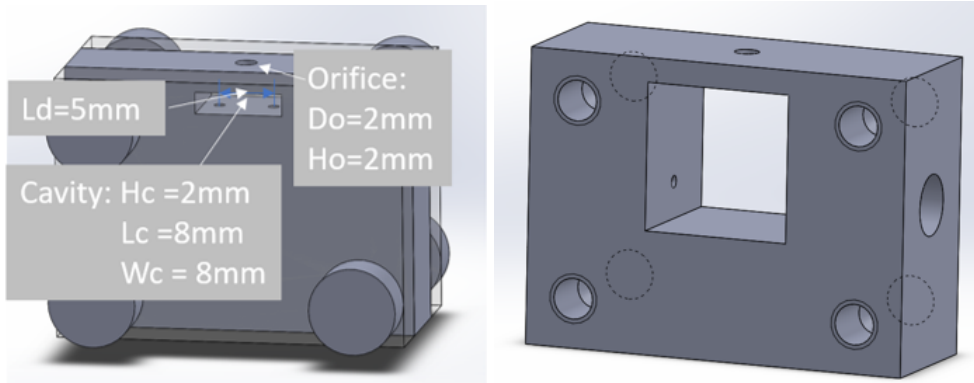


Fig. 3.4 3D Models of the base component of the plasma synthetic jet actuator with tiny cavity volume (left) and big volume (right).

The electrodes were constituted of two 1 mm diameter tungsten needles separated by a distance of 5 mm. Actuation was achieved through a high-voltage pulse generator detailed in Chapter 2. The cavity within the shell possessed dimensions of 8 mm in length, 8 mm in width, and 2 mm in height, with an orifice of 2 mm in diameter and 2 mm in height. To enable observation of the flow phenomenon within the cavity, plexiglass was selected for

the front and rear baffles. In order to enhance the clarity of the internal flow pattern, a larger cavity with dimensions of 12 mm in length, 8 mm in width, and 12 mm in height was also employed. However, owing to the low output energy of the power equipment utilized during the experiment, the pressure and temperature increase were insufficient to sustain a strong jet flow. Consequently, the Schlieren image failed to capture a clear jet flow, and the larger cavity was not used for comparison of PSJA performance. Rather, it was employed solely to capture the evolution of the plasma kernel within the cavity, reflecting the limitations of the current experimental setup. Accordingly, numerical simulation is required to investigate the energy transformation characteristics of the PSJA in greater detail.

Previous studies have suggested that there was an upper limit on the operating frequency for PSJA because of thermal effects in the cavity. It is because, after several working cycles, the PSJA became too hot to inhale fresh cold gas from the mainstream, resulting in a choked condition. [72]. Typically, PSJAs have been shown to operate efficiently at repetition rates of up to several kilohertz. However, the upper-frequency limitation can vary depending on the specific design parameters and operating conditions of the PSJA. Therefore, it is necessary to carefully consider the design and operational parameters of the PSJA to determine its optimal operating frequency range. In this experiment, the PSJA was triggered at a 1 kHz frequency, considering the power equipment limitation and the cavity size.

3.3 Numerical Method

3.3.1 Configurations and Grids

The computational model for the atmospheric environment with PSJA active controllers is illustrated in Figure 3.5. Essentially, the cavity for PSJA is a cuboid with an orifice of $D_o = 2$ mm and $H_o = 2$ mm which is orthogonal to the $x - z$ plane. The outflow domain is 30 mm in x, y directions and 60 mm in z directions. The width (W_c) and lengths (L_c) of the cavity are 8 mm and 8 mm, and the height changes from 2 mm to 8 mm, generating cavity volume changing from 128 mm³ to 512 mm³. The red cylindrical region in the figure shows the energy deposition domain, which is the gap (5 mm) between the electrodes. The diameter of the energy deposition region is 1.0 mm, which is the same as the electrode diameter. The energy source term of plasma energy deposition is applied in this area. The investigated non-dimensional deposition energy, ε , and non-dimensional deposition volume, v , varied in 0.06~0.12 and 33~130, respectively. Other parameters of different cases are shown in Table 3.1, including the volume, the cavity height and the cavity internal energy.

Table 3.1 Parameters of arc-discharge plasma actuators computational models

PSJA	H_c , mm	W_c , mm	V_c , mm ³	E_d , mJ	E_c , mJ	ϵ	ν
Case1	2	8	128	2.8	47	0.06	33
Case2	4	8	256	5.7	94	0.06	65
Case3	8	8	512	11.3	189	0.06	130
Case4	4	8	256	2.8	94	0.03	65
Case5	4	8	256	11.3	94	0.12	65

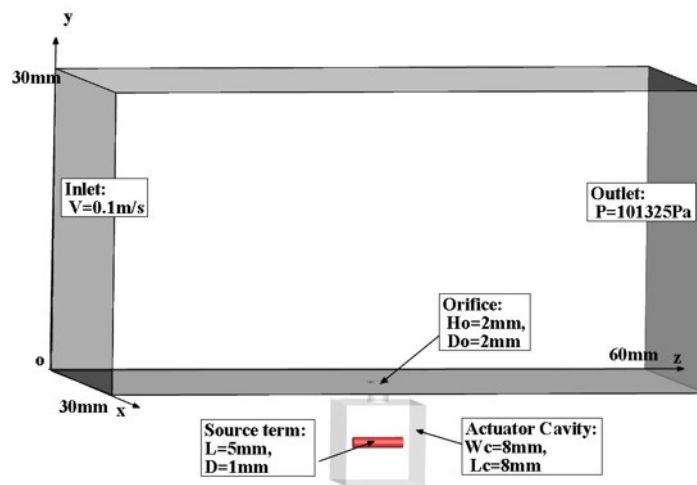


Fig. 3.5 Configurations of numerical models for PSJA with a cavity volume of 512 mm³ and large open domain of 30 mm in x , y direction and 60mm in z direction. The red domain is where the energy source term was added.

The structured grid for the numerical calculation was generated by the software ICEM CFD. Figure 3.6 shows an overall view of the mesh and some details for special places. The main body of the out domain was discretized by H-type grids, and regions marked in Figure 3.6 were discretized by O-type grids to improve the grid quality. The red mesh of the plasma region was generated separately to load energy source terms during the simulation. To resolve the wall effect, the distance of the first off-wall mesh layer was set to 1 μ m, which ensures y^+ is less than 1 to meet the requirement of the turbulence model. The total number of the grid was 2.5 million nodes.

3.3.2 Numerical Method and Boundary Conditions

In this study, the commercial CFD solver ANSYS Fluent was used to solve unsteady Navier-Stokes equations. The compressible coupled density-based solver was adopted for the

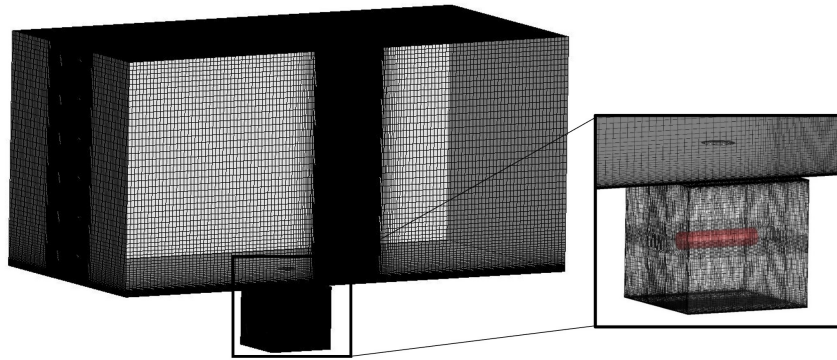


Fig. 3.6 Computational mesh for plasma synthetic jet actuators. Red cylinder: plasma region.

numerical simulations. The ideal gas model was used to model gas properties, and the Sutherland equation was adopted to simulate the kinematic viscosity of air which is sensitive to temperature. The second-order upwind discretization schemes were used to compute the convective fluxes. The least squares cell-based method was adopted to compute the viscous terms. To simulate the turbulence effect, the SST $k-\omega$ turbulence model with enhanced wall function treatment was adopted [3, 125]. The SST $k-\omega$ turbulence model is a combination of the 1988 Wilcox $k-\omega$ model in the near wall region and the standard $k-\epsilon$ model in the detached regions [65]. It is used owing to its accurate prediction of jet flows [47].

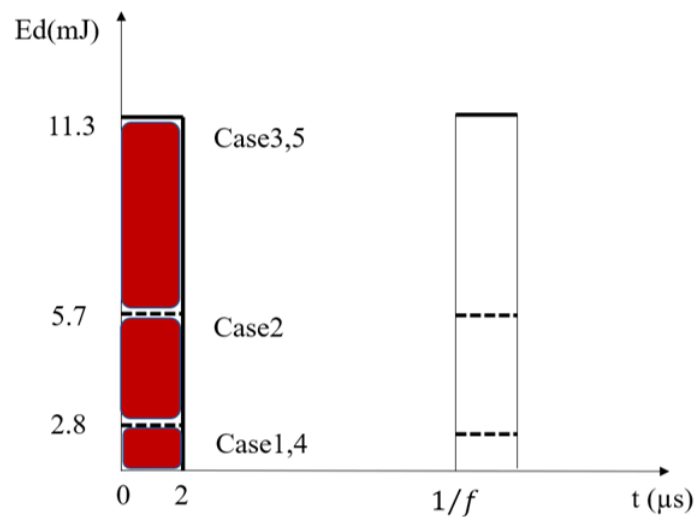


Fig. 3.7 Energy source term added in one pulse duration.

Boundary conditions were chosen to match the atmospheric conditions of Schlieren experiments of PSJA; both upper and lower walls were set as adiabatic walls. The inlet was set as velocity 0.1 m/s and the outlet set was as a 1 atm pressure-outlet condition, which

formed the atmospheric out domain and was beneficial for the simulation convergence. The initial conditions are $P = 101325$ Pa, and $T = 300$ K. Both the left and right side edges were set as adiabatic walls. Fixed walls, including the cavities with their channels, were set as a no-slip, adiabatic condition with $T = 300$ K. The deposition energy (E_d) was added to red mesh regions periodically within certain times. The time step size was 10 ns for the calculation, and convergence criteria were 10^{-6} for mass, velocity, energy and turbulence.

The challenging point of the arc-discharge simulation is the energy deposition method. Essentially, measured data of voltage and/or electric current are needed to determine factors of the electric circuit element. Determining an accurate source term is beyond the scope of the current study. Therefore, a simplified energy deposition method was chosen, which was constant widespread energy source terms in a short time duration ($2 \mu\text{s}$) shown in Figure 3.7. In the study, a single operation of a PSJA was investigated. Thus, the operational frequency was assumed to be 1 kHz, so that individual pulsing does not affect each other in plasma generation. There was a report that a 5 kHz pulsing frequency was achieved for stable repetitive actuation [67]. Thus, the 1 kHz assumption for pulsing frequency was appropriate for the independent operation of a PSJA. Limited by computational costs, the total simulation was 1 ms, which covered a fully operating and developing time of one pulse. Sutherland's law was used for viscosity and thermal conductivity, which could correspond well with real gas properties under 5000 K [40].

3.4 Results and Discussion

3.4.1 Formation and Evolution of Plasma Kernel

The plasma kernel evolution of PSJA in the cavity is different from the plasma kernel evolution of LAFPA in the open flow discussed in Chapter 2. The plasma kernel evolution of PSJA in the cavity exhibited unique characteristics.

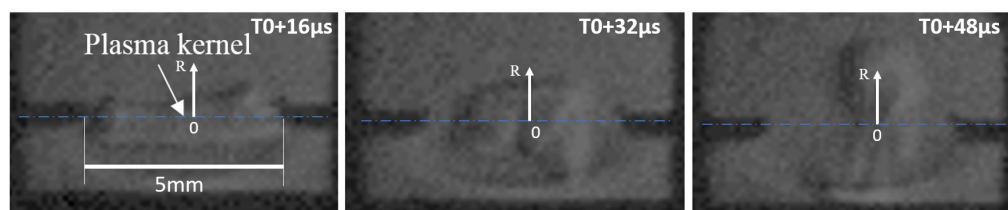


Fig. 3.8 Schlieren images of plasma kernel generation and development within the big cavity ($V = 1200 \text{ mm}^3$).

Experimental Schlieren images in Figure 3.8 are captured during experiments introduced in Chapter 2. It illustrates the formation and evolution of the PSJA plasma kernel in a large cavity. The length scale of 5 mm is the distance between two electrodes. The axis of symmetry is the blue dashed line, and the radius direction of the plasma kernel is also marked as the R direction. Initially, a bone-like heating area, double the size of the electrode diameter on both sides, was formed after arc discharge at $T_0 + 16 \mu\text{s}$. The ionic wind effect near the electrodes played a significant role in shaping the plasma kernel, whereas a cylindrical shape between the electrodes was assumed in the theoretical model. The hot core region expanded due to the lower air density in the cavity compared to atmospheric conditions. Subsequently, at $32 \mu\text{s}$, the plasma kernel shape ceased to expand radially but continued to expand towards the centre to form a mushroom shape. The significant deformation of the plasma kernel was due to the shock wave pressure rise and thermal diffusion in the cavity. The pressure wave reflected in the cavity squeezed the plasma kernel towards the centre and pushed it out. So far, because of the simplified assumption, the theoretical model can not reasonably predict the shape evolution of the plasma kernel in reality. We can have a comparison between the theoretical model and 3D simulation.

Table 3.2 Theoretical calculation of plasma kernel formation.

Plasma Kernel	Symbols	Case1	Case2	Case3
Non-dimensional discharge energy	ϵ	0.06	0.06	0.06
Discharge energy	E_d , mJ	2.8	5.7	11.3
Characteristic length scale	r_c , mm	1	1.4	2
Characteristic time scale	t_c , μs	2.9	4.2	5.9
Radius of Plasma Kernel	r_k , mm	0.5	0.7	1
Time of Plasma Kernel	t_k , μs	1.7	2.4	3.4

Based on the plasma kernel theory, the plasma kernel radius and the time for the plasma kernel formation can be calculated using Eq. (3.4) when the input energy is given. For our cases, the parameters of the plasma kernel are listed in Table 3.2 under different levels of the discharge energy. The time of the leading edge expanding to the radius of the plasma kernel was derived in three cases shown in the last row of the table. It is clear that with increasing discharge energy, the radius and time of the plasma kernel would also increase. Since these results were established on simplified assumptions, including an instant line source energy deposition and spatial axial symmetry, theoretical results may differ from reality and result from simulation work. Figure 3.9 shows the comparison of temperature distribution after an arc discharge at the axis of symmetry at a different radius between the plasma kernel model

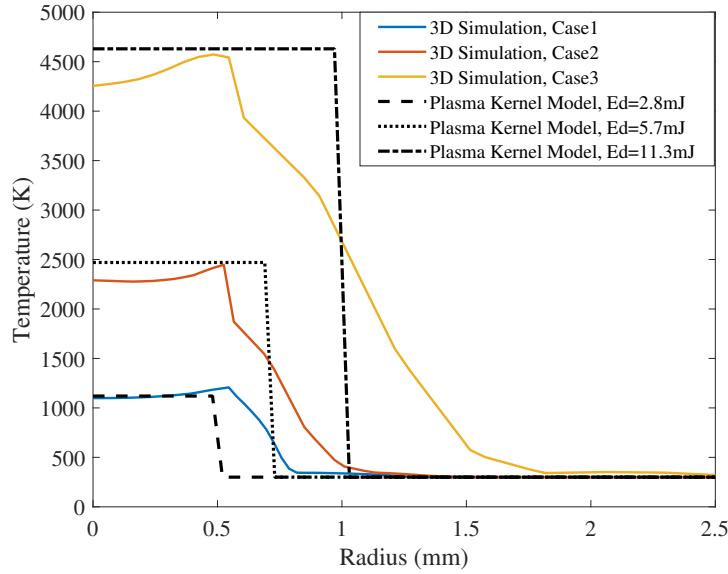


Fig. 3.9 Radial temperature distribution under different deposition energy when plasma kernel formed at $t = t_k$.

and 3D simulations. The agreement of the plasma kernel expansion radius was found to be reasonably good. Because the energy deposition radius of the cylinder in the 3D simulation is already 0.5mm, the expansion radius of the 3D plasma kernel will be slightly larger than the real results. The mean kernel temperature predicted was approximately 1100 K, 2500 K and 4600 K in three cases, respectively. Here, the ρ_k was chosen from the deposition volume average density of simulation results, which is hard to get from the density profile in the previous work [71]. The comparison with the theoretical model suggested that about 10% of the breakdown, energy was lost simply by the pressure wave separating from the hot plasma kernel. In Case 1, the simulated temperature (blue curve) was almost consistent with the modelled temperature in the centre, while the other two circumstances corresponded to an overestimated temperature. This is because case 1 has a short plasma kernel formation time, which is $1.7 \mu s$, while the 3D energy deposition duration is $2 \mu s$. So the case 1 temperature distribution within the 0.5 mm radius area did not have time to expand. On the other hand, the temperature gradient (slope of curves) in all three cases appeared to be at the same level. For 3D simulations, after $2 \mu s$ constant energy deposition, the hot domain would interact with the surrounding cold air, which generated the thermal diffusion slope.

Figure 3.10 shows how the plasma kernel developed after formation from $t = 10 \mu s$ to $t = 100 \mu s$ for Case 1, case 2 and Case 3. Three subplots in the first row just after the energy deposition at $t = 10 \mu s$ and the second and the third row correspond to the following time at $t = 50 \mu s$ and $t = 100 \mu s$. In the initial stage at $t = 10 \mu s$, the plasma kernel remained in a

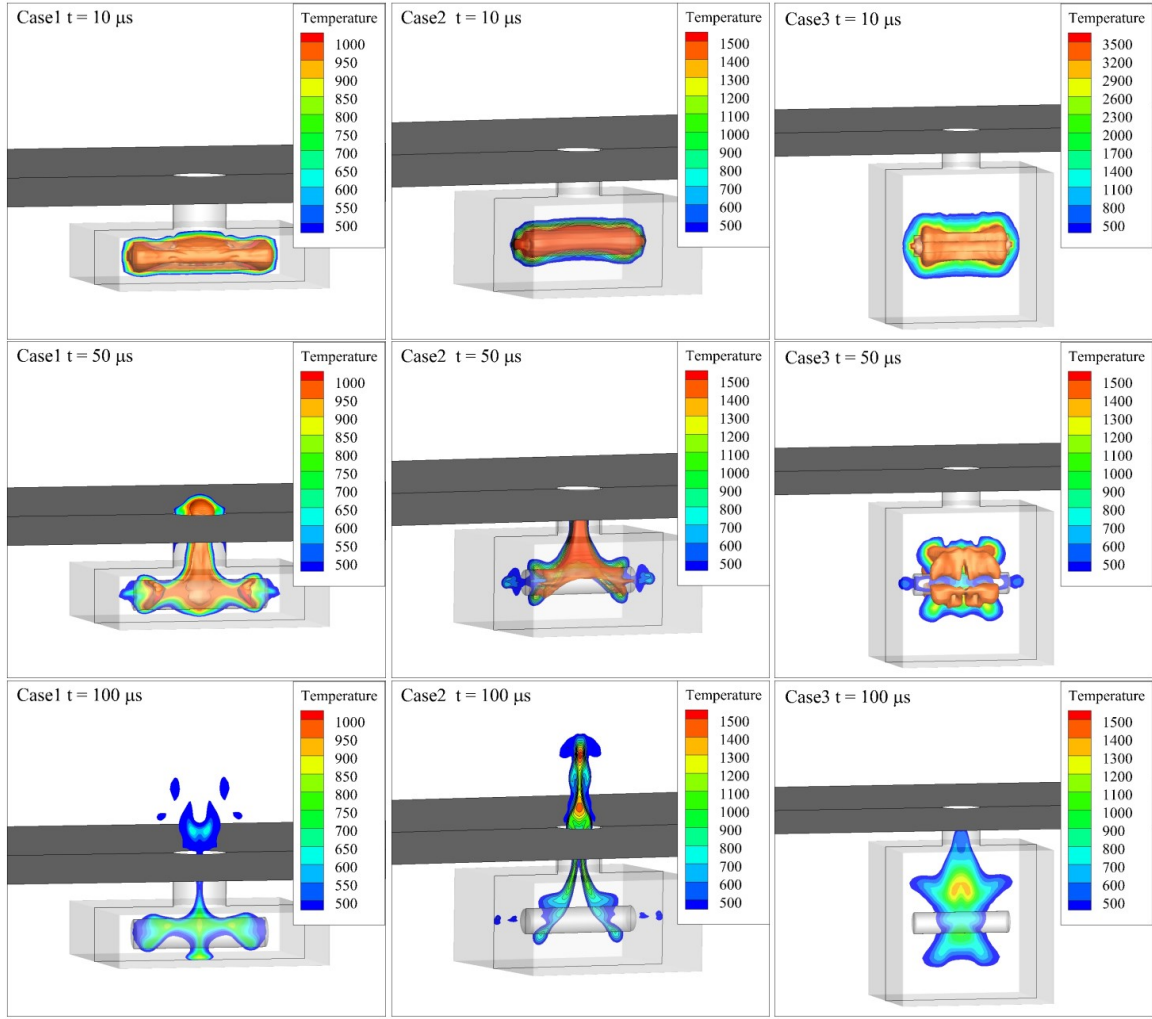


Fig. 3.10 Formation and evolution of Plasma Kernel in the cavity for Case 1 (left column), Case 2 (middle column) and Case 3 (right column) from $t = 10 \mu s$ to $t = 100 \mu s$.

cylinder expansion, and the expansion volume increased with the deposition energy. In the second row of Case 1 and Case 2, because of the smaller cavity volume, the hot plasma kernel was pushed out by the jet flow through the orifice. In contrast, in Case 3, the kernel still is compressed in the centre domain by the pressure reflection in the large cavity. At $t = 100 \mu s$, the core of the hot region is still significant for Case 2, which has a medium volume size and energy deposition value. At the same time, the jet outside of the orifice dissipated very fast for Case 1 and thermal diffusion in the cavity for Case 3. The reason for such difference should result from the cavity's different heat capacities, which depend on its volume and the deposition energy level. First, for a small cavity PSJA, the high pressure and temperature rise are nearly the same, and the cavity gas will be pushed out quickly. But for large cavity PSJA, the high-pressure blast wave will first generate jet flow near the orifice, and the hot plasma

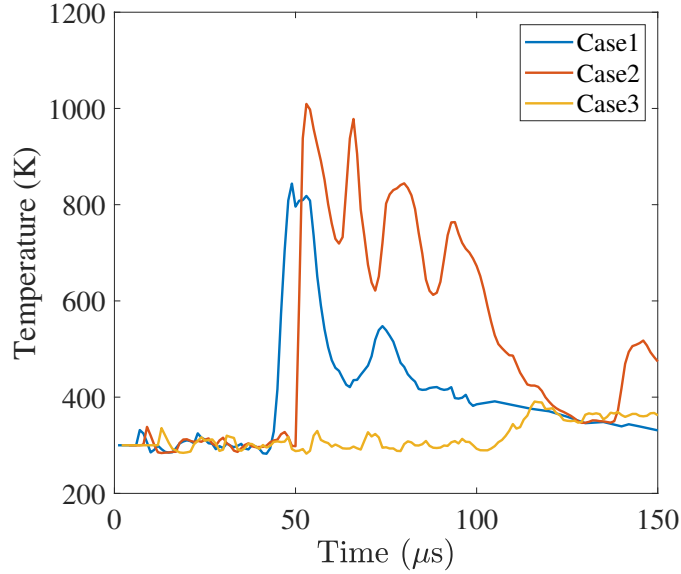


Fig. 3.11 Temperature profiles at the exit of orifice in Case 1-3.

kernel will keep a thermal expansion stage in the cavity and will be pushed out much later. In Case 3, the cavity volume was large enough to dissipate most heat generated from the plasma kernel. Mass convection transports only a tiny portion of the heat out of the orifice. Consequently, to form a hot jet by a plasma kernel in the form of PSJA, there should be an optimal cavity volume; a large volume would lead to heat being consumed by dissipation inside the cavity.

Figure 3.11 shows the temperature evolution at the orifice exit. It corresponds very well with the 3D evolution images in Figure 3.10. The high-temperature signal at the orifice was got at nearly $t = 50 \mu\text{s}$ for Case 1 and Case 2, while Case 3 shows a slight temperature rise after $t = 100 \mu\text{s}$. Although three cases have the same non-dimensional deposition energy first, the overall output heating energy will vary. For the PSJA application, a detailed thermal analysis is needed to evaluate the actuator's performance fully.

3.4.2 Reflection and Propagation of Blast Waves

Figure 3.12 compares the pressure distribution, especially the pressure peaks, with modelled results. In the radial direction, pressures in Case 2 and Case 3 reached their maximum values roughly at the same radius position as the model. Pressure peaks of all three cases were higher than modelled results, but the ratio of overestimated pressures appeared to be higher in Case 2 and Case 3. This is because the model was built for the arc discharge in an open-air domain, while the 3D simulation arc discharge occurred in a tiny cavity. The pressure rise

would be larger because of the cavity effect. In Case 1, the pressure at the centre remained at a similar level between $r = 0 \sim 0.8$ mm before reaching its peak because of a short time delay of $2 \mu\text{s}$ and constant energy deposition in 3D simulation within $2 \mu\text{s}$. Moreover, the peak pressure radius predicted in Case 1 is less than the plasma kernel model, which is opposite to Case 2 and Case 3. This is because the kernel model characteristic time of Case 1 is $2.9 \mu\text{s}$, which is quite near the 3D simulation constant energy deposition time $2 \mu\text{s}$, while Case 2 and Case 3 have a longer characteristic time. The energy deposition time of Case 1 generates a lagged response of pressure propagation at the very beginning.

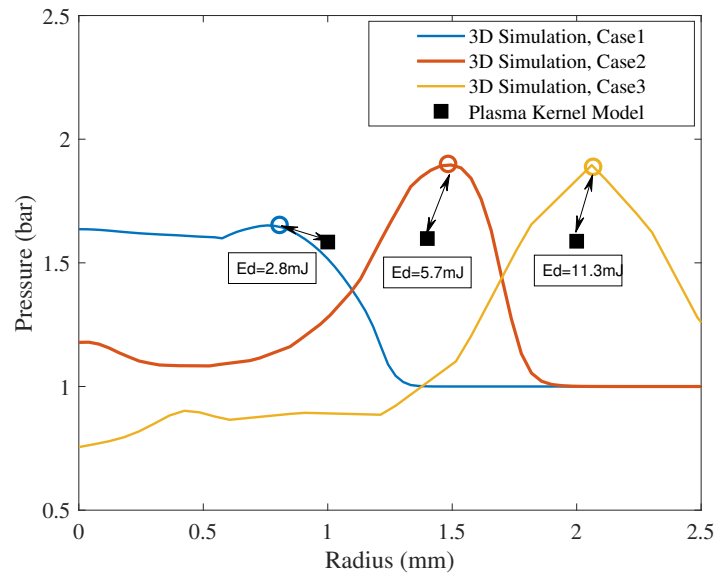


Fig. 3.12 Radial pressure distribution under different deposition energy when plasma kernel formed at $t = t_k$ compared with 1D modelled results (black square).

Figure 3.13 shows the pressure evolution at the orifice exit, and Figure 3.14 illustrates the fast Fourier transformation of the pressure signal. It indicates an oscillatory behaviour of the pressure at the orifice, which corresponds well with the series of blast waves in numerical Schlieren images above. The first blast wave peak pressure was 1.42 bar, 1.51 bar and 1.48 bar for Case 1, Case 2 and Case 3, respectively. With the cavity height increasing, the orifice exit to the discharge centre length is increasingly generating a time delay between Case 2, and Case 3 with Case 1. Pressure wave ejection results from the complex behaviour of pressure waves and their reflections inside the cavity. These interactions increased the overall driving pressure of a plasma synthetic jet actuator, thus affecting the performance. Consequently, we investigated the behaviour of the pressure wave inside the cavity by searching for correlations between causes since these would be critical factors in increasing the actuator's performance. FFT results show various peaks spaced approximately 10 kHz apart, corresponding to several

characteristic peak frequencies. In particular, the peak near 45 kHz is offered in all three cases. Also, different particular peak frequencies around 100 kHz are shown up for each case.

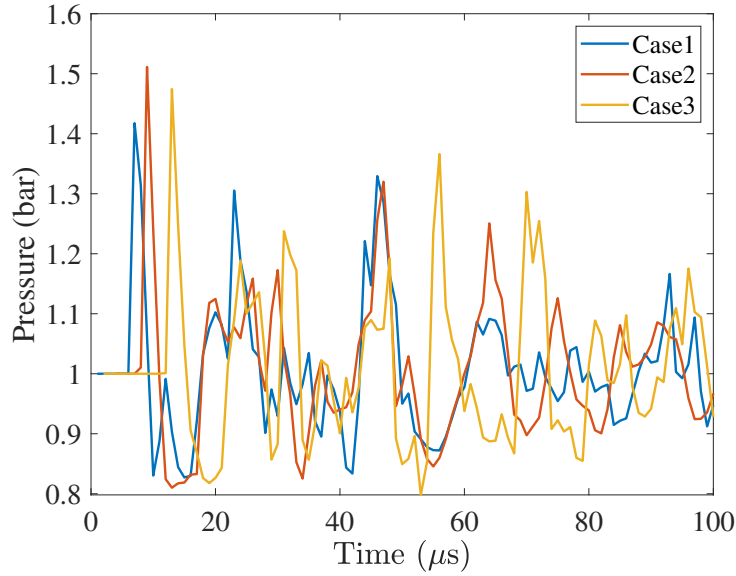


Fig. 3.13 Pressure signal at the exit of orifice and Fast Fourier transform of pressure signal in Case 1-3.

In order to provide a clear evolution of blast wave manipulation, the instantaneous flow field of the computation domain is presented in Figure 3.15. from $t = 10 \mu s$ to $t = 50 \mu s$ for Case 1, Case 2 and Case 3. In the initial stage at $t = 10 \mu s$, the blast wave has propagated out of the orifice for Case 1 and Case 2, while for the big cavity Case 3, the initial blast wave just reached the cavity wall in the y -direction and reflected back in the z -direction. At $t = 30 \mu s$, because of the smaller cavity height for Case 1, the propagation of the reflected blast wave is faster than in Case 2 and Case 3. The reflection in the cavity can still be captured clearly in Case 3, while Case 1 and Case 2 shows a merged effect of both direction reflection. At $t = 50 \mu s$, a series of blast waves propagated away from the actuator after the energy was discharged due to the reflection of the initial blast wave in the cavity. In Case 2, the y -direction reflection of the blast wave is well captured. The reflection of the blast waves in the cavity continuously occurred in the cavity and supported the initial stage of jet flow.

Based on the analysis above, it can be reasonably speculated that the base frequencies mean that this frequency component was from extremely complicated interactions between several pressure waves propagating inside the cavity, which mainly depended on the structure of the cavity. The characteristic frequency equation is shown in Eq. (3.40), Eq. (3.41) and the schematic diagram is shown in Figure 3.16. f_1 and f_2 is the base frequency, W_c and

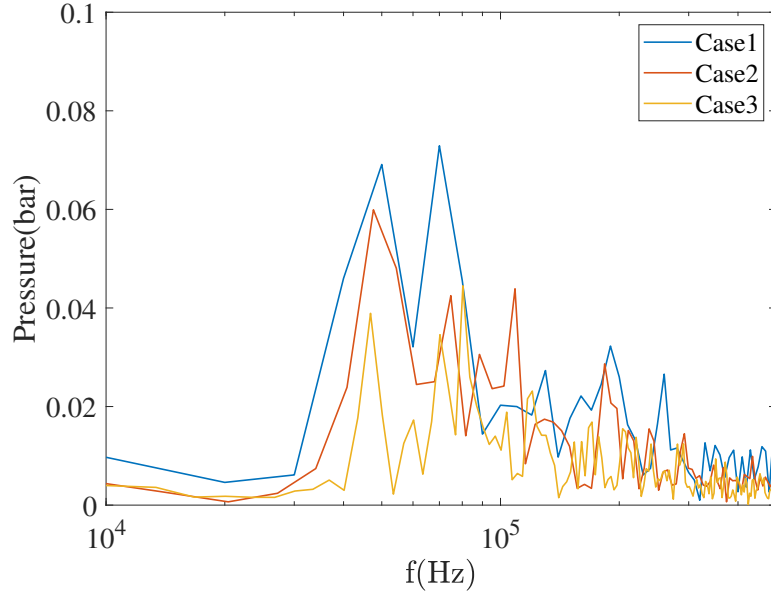


Fig. 3.14 Fast Fourier transform of pressure signal in Case 1-3.

H_c are the width and height of the cavity, and constant a is the propagation velocity of the reflected waves. In general, the propagation velocity is equal to the sound speed. Table 3.3 shows the results of the simulation FFT results and empirical equation calculation. The characteristic frequency f_1 corresponds well to the 3D numerical pressure signal. Meanwhile, f_2 falls in the typical peak frequency in Figure 3.14. The propagation speed depended on the fluid characteristics, especially affected by the temperature. So the 3D simulation results will slightly differ from the calculation. Besides, there are some other frequencies of the frequency spectrum in Figure 3.14 to which the equation is not applicable. The reason could be that the typical geometry also includes the cavity corner. So the interaction between different direction reflections of blast waves may contribute to the phenomenon.

$$f_1 = a/W_c \quad (3.40)$$

$$f_2 = a/H_c \quad (3.41)$$

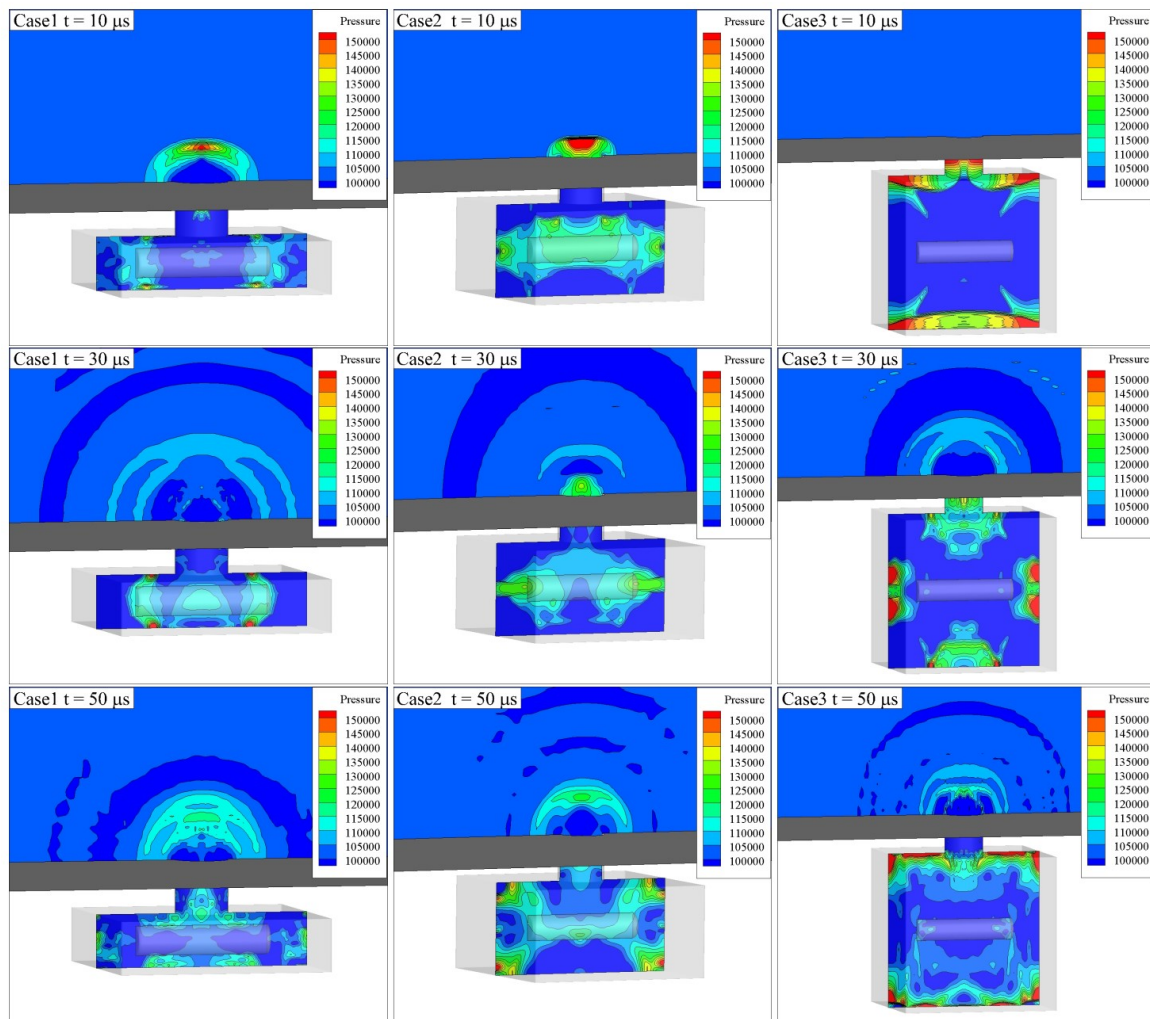


Fig. 3.15 Reflection and propagation of blast waves in the cavity for Case 1 (left column), Case 2 (middle column) and Case 3 (right column) from $t = 10 \mu s$ to $t = 50 \mu s$.

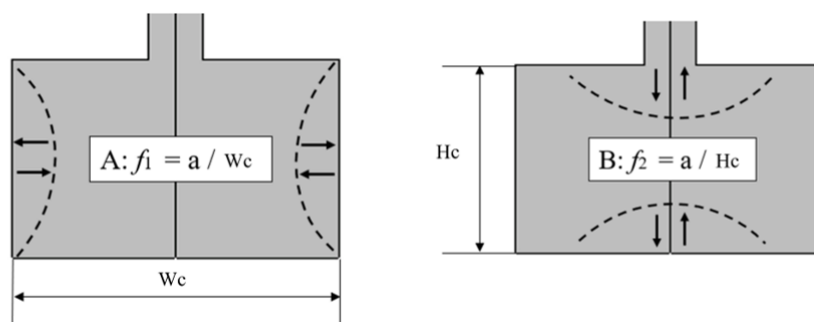


Fig. 3.16 Conception model of reflection of blast waves in the cavity. Left: the form of reflected blast wave under base frequency f_1 ; Right: the form of reflected blast wave under based frequency f_2 .

Table 3.3 Theoretical calculation of two base frequencies of blast waves in Case 1-3.

Frequency(kHz)	Source	Case 1	Case 2	Case 3
f_1	Simulated	45	45	45
	Eq. (3.40)	43	43	43
f_2	Simulated	70	100	80
	Eq. (3.41)	171	86	43

3.4.3 Jet Evolution of PSJA

The jet flow produced by the PSJA is further studied. Figure 3.17 and Figure 3.18 show the instantaneous and averaged Schlieren images of PSJA jet evolution with the electrodes in a small cavity (128 mm^3). The instantaneous images chosen in the figures are representative of the whole set of 75 images for each instance. In the experiments, initial conditions in the cavity could have slight interaction with each arc discharge, revealed by the iso-contour of pressure gradient in Schlieren images. For example, the instantaneous images (on the left of each row, smaller than the mean images in Figure 3.17 and Figure 3.18) clearly showed jets which were influenced by these initial conditions. The size and shape of the jets were slightly different in different discharge cycles of the same phase. At $t = 4071 \text{ } \mu\text{s}$, the initial jet body was wider than other moments in the same phase. However, in the mean image (on the left), the effect of the initial conditions was reduced. At $71 \text{ } \mu\text{s}$, the air in the cavity was squeezed out through the orifice, forming a hemispherical jet of high momentum. The width of the initial jet was twice the diameter of the orifice, and the height reached 3 mm in the y direction.

At $t = 142 \text{ } \mu\text{s}$, a further developed mushroom-like jet formed, and the jet front developed further upwards to 6 mm, propagating at a velocity of nearly 45 m/s. A powerful and robust jet body was generated. In instantaneous images, the topology of this part transited independently and differed from the initial part. At $t = 4142 \text{ } \mu\text{s}$, the propagating vortex ring structure was well captured. For the mean image, the overall outline was consistent, but the detailed structure was blurred. Only the position of the jet front going forward could be clearly confirmed. Usually, the jet not only carried high momentum but also carried a larger amount of thermal energy from the cavity. It is speculated that the unheated initial flows were pushed outside by the instantaneous pressure rise, and subsequently, the arc-heated jet was compelled from the inner cavity. But Schlieren experiment can not tell the jet temperature, and it is difficult to tell whether the hot plasma kernel was pushed out or not. According to the temperature cloud in Figure 3.10, the hot plasma kernel was pushed out at $50 \text{ } \mu\text{s}$ for case 1, which is the same geometry design as the Schlieren experiment. This can confirm that for small cavity cases, the pressure rise and heat expansion in the cavity works on the jet formation through the orifice nearly at the same time.

Figure 3.18 displays the outcomes obtained at a considerably later time delay of $213 \text{ } \mu\text{s}$ and $284 \text{ } \mu\text{s}$, respectively. Despite the lapse in time, the jet generated by the electrical discharge and initial heat generation within the cavity persisted. Prior analytical and experimental investigations have suggested that the pressure within the actuator cavity attains atmospheric pressure, and the temperature declines to the atmospheric level after $100 \text{ } \mu\text{s}$. As a consequence, the base of the jet appeared fragile and tenuous in the later time delay instance

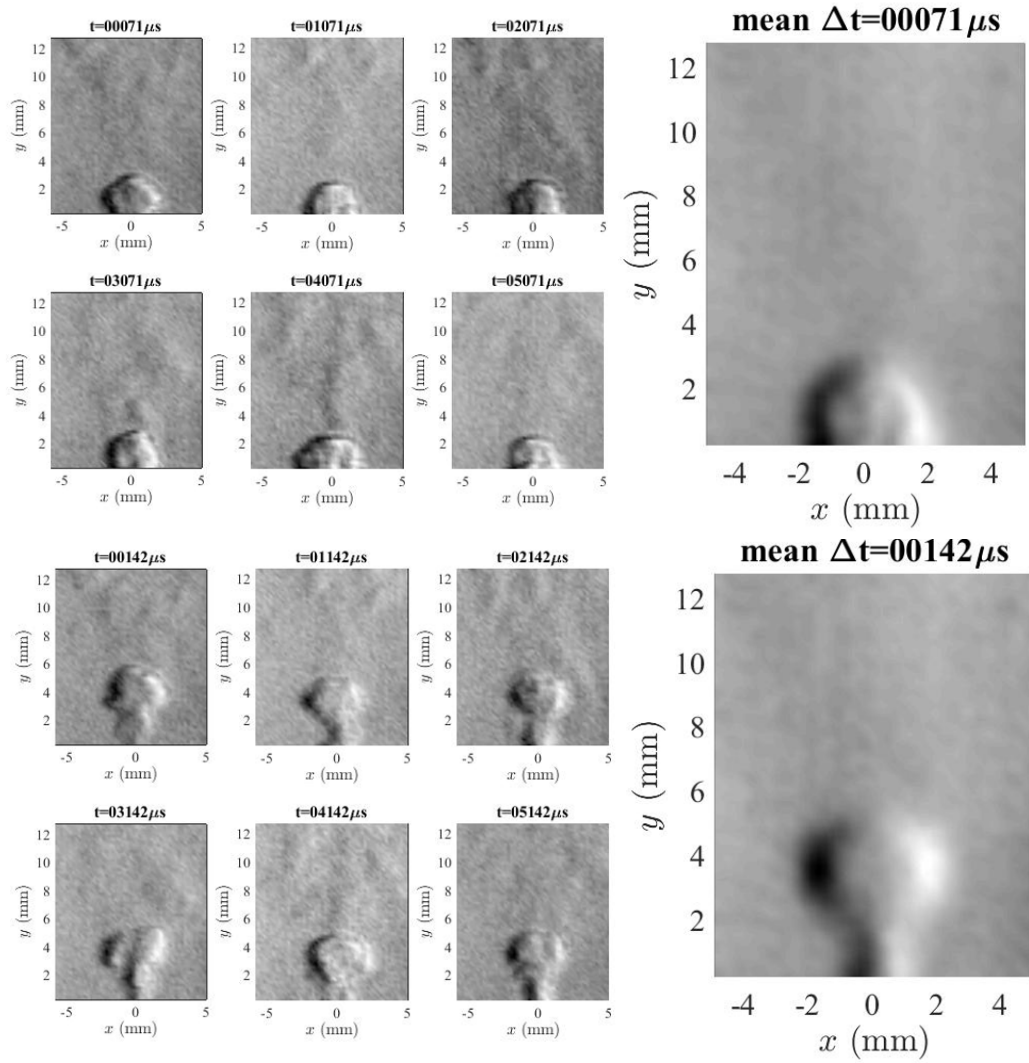


Fig. 3.17 Instantaneous Schlieren images of exhaust from a 2 mm orifice PSJA at standard conditions (mean $dt = 71 \mu s$ and mean $dt = 142 \mu s$).

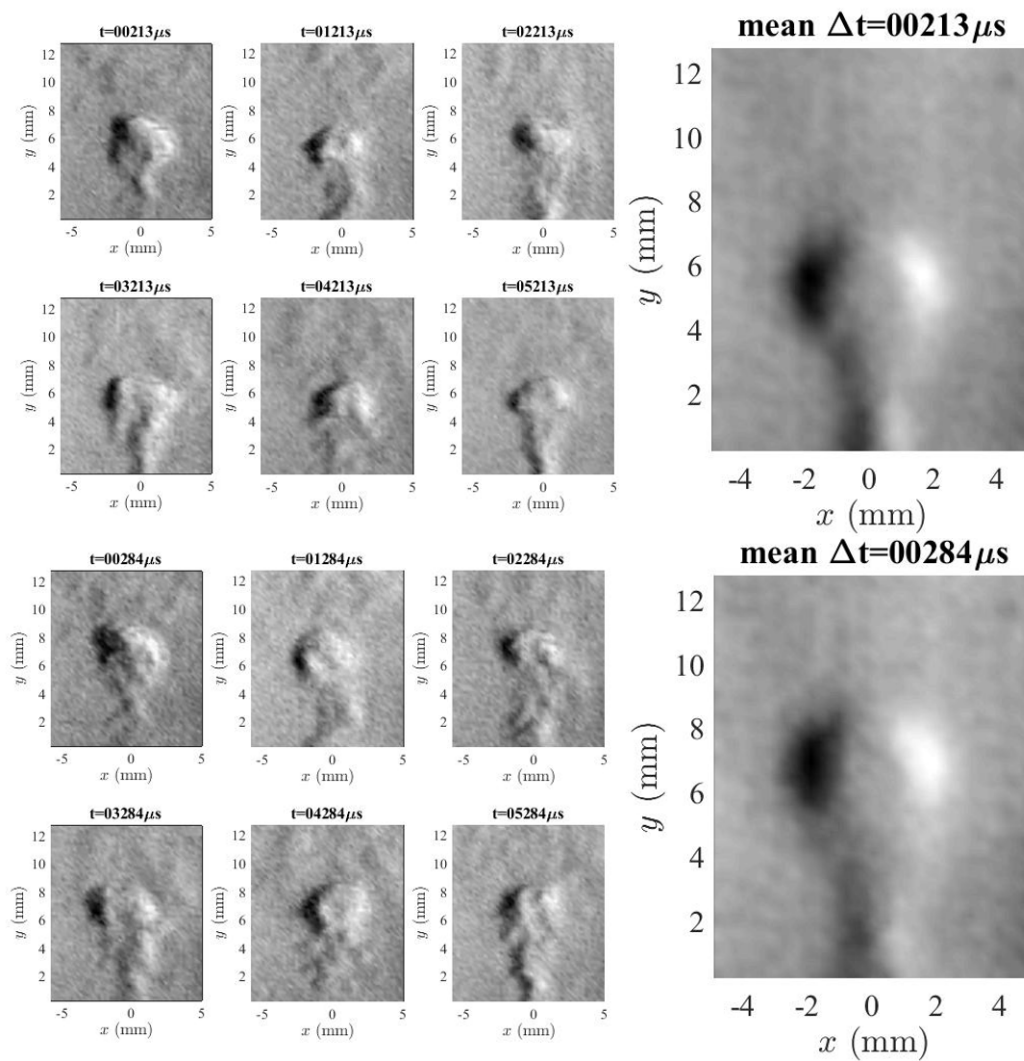


Fig. 3.18 Instantaneous Schlieren images of exhaust from a 2 mm orifice PSJA at standard conditions (mean $dt = 213 \mu s$ and mean $dt = 284 \mu s$).

images, signifying the majority of the air within the cavity was expelled, and the actuator entered stage 3 of a refresh. Notably, the jet front expanded to 9 mm in the y direction.

A comprehensive quantitative analysis was conducted to examine the impact of cavity geometry and deposition energy on jet velocity. The accuracy of the simulation results was verified through a comparative assessment of experimental Schlieren images and numerical Schlieren images, which were employed to track the time evolution of the jet-front position, as depicted in Figure 3.19. The main structure of the induced jet was well recovered, as well as the jet front evolution. The density gradient was vertical for both types of results. In the Schlieren mean images (on the top row), the effect of the initial conditions was reduced. In this study, computational results simulated an arc discharge starting from conditions at rest. Consequently, numerical Schlieren pictures are not strictly consistent with either an instantaneous experimental image or a mean image, but with an intermediate situation that could be considered closer to mean images. Indeed, due to the fine resolution of the mesh, the range of the density gradient was much larger in the Schlieren experiments. Iso-contours of pressure gradients are plotted on a sufficiently large range to display most of the density gradient levels. Numerical results show much clear jet formation and evolution patterns visualizing the vortex rings. The jet front position can be abstracted from the images and compared below.

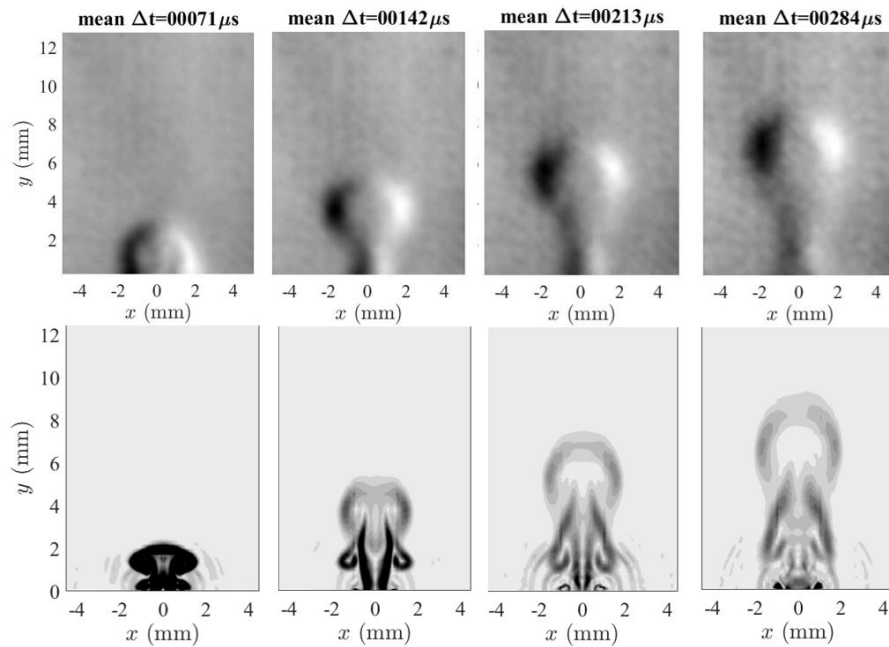


Fig. 3.19 Comparison of numerical simulation and Schlieren experiment photography of the jet propagation. Top row: averaged Schlieren image; bottom row: Simulation results.

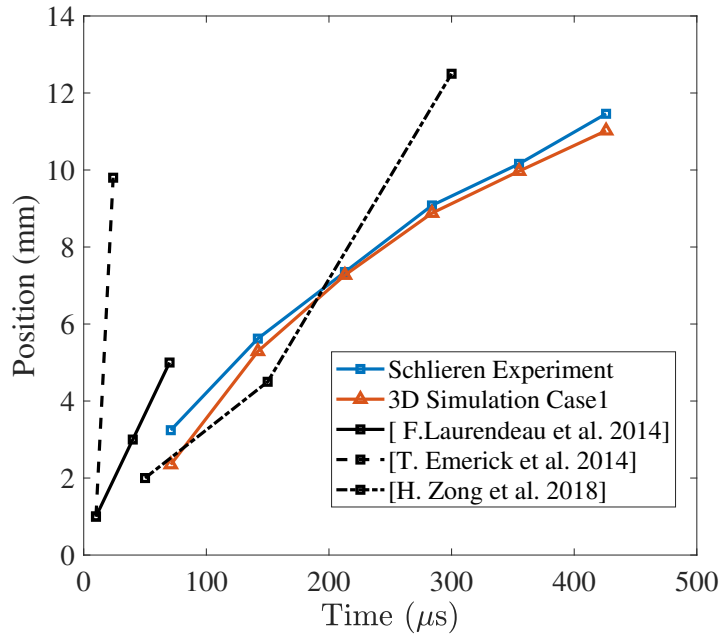


Fig. 3.20 Jet front evolution of Schlieren results and simulation results of Case 1 compared with reference data [28, 56, 128].

Figure 3.20 illustrates a comparison between the jet front positions obtained from the computations and experimental observations. The initial point derived from experiments differed significantly from the computational results. One plausible explanation for this disparity is that the identification of the jet front in the experimental images was challenging, particularly at the initial stages of jet formation. This may be the constant energy deposition within $2 \mu s$ used in 3D simulation, causing the delay of the jet front at the very beginning. As we have seen, the pressure rises in the cavity dominate the early stage of jet flow. So, in reality, it is a little bit quicker response to the pressure rise. Nonetheless, the subsequent points were in close correspondence, with the curve slope gradually decreasing over time. Three different cases from the literature are extracted and compared in the figure [28, 56, 128]. They covered a wide range of volume size ($50 \sim 1700 \text{ mm}^3$) and deposition energy, which is shown in Table 3.4. For a tiny cavity and high deposition energy, the slope of the jet front curve was extremely high at the beginning, while the large cavity case had a much smaller jet propagation rate at first. However, the slope increased after $200 \mu s$ for Zong's case, which was the largest cavity case.

The jet front position delay phenomenon for the large cavity case was also captured in our study, shown in Figure 3.21. The slope of the position of the leading edges decreases as the jet evolves. From Case 1 to Case 3, the propagation speed of the leading edge increased

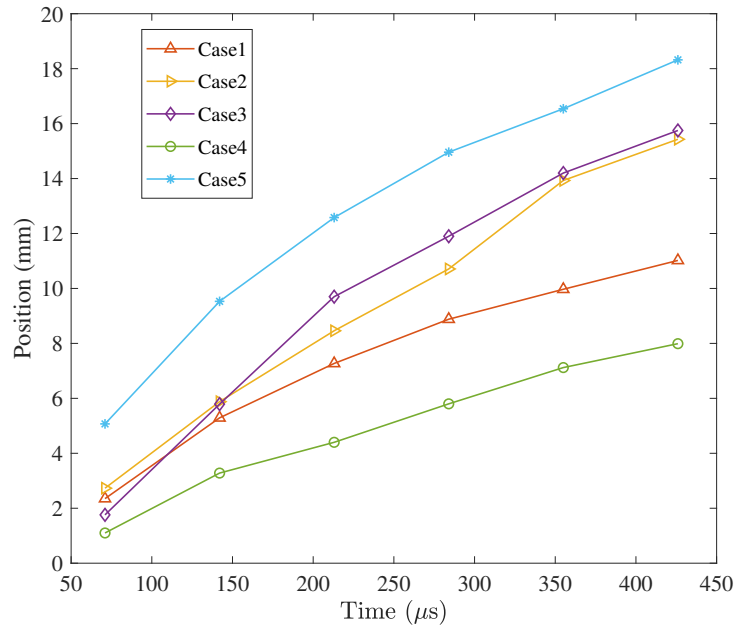


Fig. 3.21 Jet front propagation from simulation results for 5 cases in Table 3.1.

as the volume increased at the first 200 μs , and then, the slope tended to be similar except for Case 2. The larger cavity had a delayed jet reaction but had more mass to support the jet evolution. In Case 2, Case 4 and Case 5, where the volume of the cavity was the same, the location of the leading edge increased as the deposition energy increased. For a tiny cavity and high deposition energy, the propagation speed of the jet front holds relatively steady in the whole jet phase. However, the large cavity case (Case 3) had a smaller jet front position at first but increased time. This is because the larger cavity had a delayed blast wave propagation at the beginning, but later with the blast wave reflection in the cavity, much potential energy was transferred back to thermal energy to sustain the jet flow at the late stage. At the same time, the large cavity actuator had more mass to support the jet evolution.

The temporal evolution of the orifice area-averaged exit velocity of 3D simulation is shown in Figure 3.22 and Figure 3.23 for Case 1 to Case 5. Overall, qualitative trends between different curves were similar. Multiple jets and refresh stages were observed within one cycle. During the primary jet stage, the exit velocity initially showed a sharp increase and, afterwards a slow nonlinear fluctuation drop, which was generated by the pressure wave fluctuation in the cavity. The peak values of the exit velocity were 80 m/s, 150 m/s and 100 m/s for Case 1, Case 2 and Case 3, respectively. It is clear that the jet intensity of Case 3 was extremely higher than other cases and had a longer jet duration. PSJA with a much smaller volume would generate a high-intensity jet and a short jet duration because of the smaller

cavity mass. For Case 2, Case 4 and Case 5, the jet duration time was nearly the same, which was $150\ \mu\text{s}$, and therefore, we can deduce that the jet duration time highly depended on the non-dimensional cavity volume. This means the jet duration time is mainly dependent on the cavity volume. Moreover, the peak jet velocity increased with the enhancement of non-dimensional deposition energy significantly.

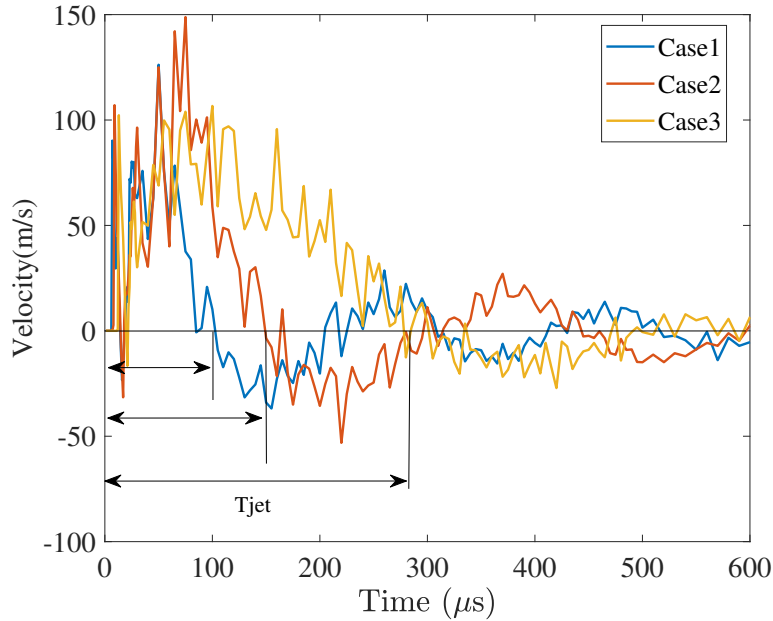


Fig. 3.22 The time evolution of the jet exit velocity for different cavity volume.

Table 3.4 shows detailed parameters of plasma synthetic jet from different resources [28, 56, 128], including the volume, the non-dimensional deposition energy, the non-dimensional deposition volume, the peak velocity and the jet duration. It is interesting to notice that the peak velocity was not always increasing with the increase of non-dimensional energy deposition when the volume of the PSJA was extremely small ($66\ \text{mm}^3$) or large ($1696\ \text{mm}^3$). This may be explained by the energy transformation process in jet duration. Normally, the reflection of high-pressure blast waves and the diffusion of hot plasma kernel both contribute to the ejection of the cavity mass through the tiny orifice. The dominant factor for different cases may differ, such as for small cavities. The pressure effect will be significant because of the short jet duration, while the heating effect may take charge of the motivation for jet formation for large volume cases.

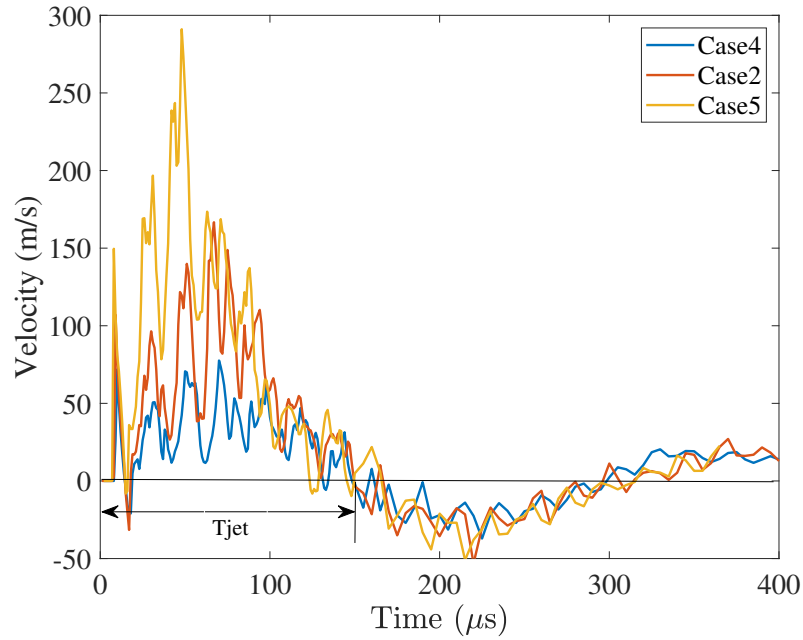


Fig. 3.23 The time evolution of the jet exit velocity for different energy deposition.

Table 3.4 Parameters of energy transformation for PSJA

PSJA	Volume, mm ³	ε	ν	V_p , m/s	T_{jet} , μs
Case 1	128	0.06	33	80	105
Case 2	256	0.06	65	150	150
Case 3	512	0.06	130	100	300
Case 4	256	0.03	65	78	150
Case 5	256	0.12	65	291	150
F. Laurendeau et.al [56]	66	0.13	0.014	170	-
T. Emerick et.al [28]	356	-	-	310	550
Zong et.al [128]	1696	0.28	0.002	116	545

3.4.4 Efficiency Transformation of PSJA

The variation of η_k , η_p and η_T with non-dimensional cavity volume ν and energy deposition ε is shown in Table 3.5. The output heating energy includes the internal energy of the cavity, so the efficiency is beyond 100%. There is no trend of this energy term with ν or ε . But within our research range, Case 2 has the largest heating energy efficiency.

Table 3.5 Energy efficiency of arc-discharge plasma actuators.

Case number	η_k , %	η_p , %	η_T , %	ε	ν
Case 1	1.3	53.4	143.6	0.06	33
Case 2	1.8	48.5	161.6	0.06	65
Case 3	1.3	41.7	105.1	0.06	130
Case 4	0.6	50.0	132.1	0.03	65
Case 5	2.6	36.3	123.9	0.12	65

The variation of η_k and η_p with non-dimensional cavity volume is shown in Figure 3.24. Results show that the proportion of potential energy decreases linearly with non-dimensional cavity volume, while kinetic energy efficiency shows no significant tendency. This is because as the volume increases, the reflection path of the shock wave in the cavity increases, resulting in more energy dissipation. Thus, the pressure wave energy at the outlet is weakened. This can also be confirmed with Figure 3.13. Although the deposition energy increased from 2.8 mJ to 11.3 mJ, the pressure at the exit of the orifice shows no significant increase because of the cavity increase. The proportion of Kinetic energy is below 2%; the potential energy occupies 40 %-55 % of the total deposition energy. Mechanical energy transformation is a combination of kinetic energy and potential energy. So the overall mechanical energy efficiency of the plasma synthetic jet actuator is at a level of 50%.

The variation of η_k and η_p with non-dimensional energy deposition ε is shown in Figure 3.25. Results show that the proportion of kinetic energy increases with non-dimensional deposition energy, while potential energy shows an inverse tendency. For Case4, Case2 and Case5, the peak velocity at the orifice exit dramatically increased with non-dimensional deposition energy increasing in Figure 3.23. The more electronic energy was deposited, the higher the jet flow velocity would be. However, the proportion of deposition energy transferred into the potential energy gradually drops since the magnitude of the potential energy did not increase much as the deposition energy increased. Reasonable guessing is that the potential energy's magnitude depends on the cavity's volume and the initial condition but is not sensitive to the deposition energy. This phenomenon requires further investigation.

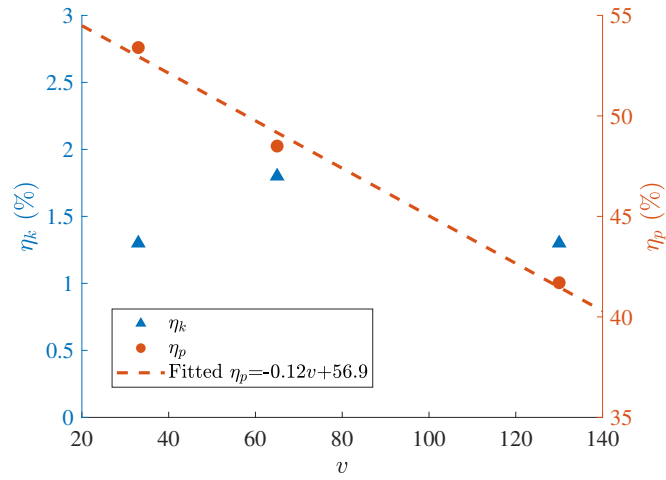


Fig. 3.24 Variation of kinetic energy efficiency η_k (blue triangle) and potential energy efficiency η_p (red circle) with non-dimensional cavity volume. Red dash line: linear fitting of potential energy efficiency, $\eta_p(\%) = -0.12v + 56.9$.

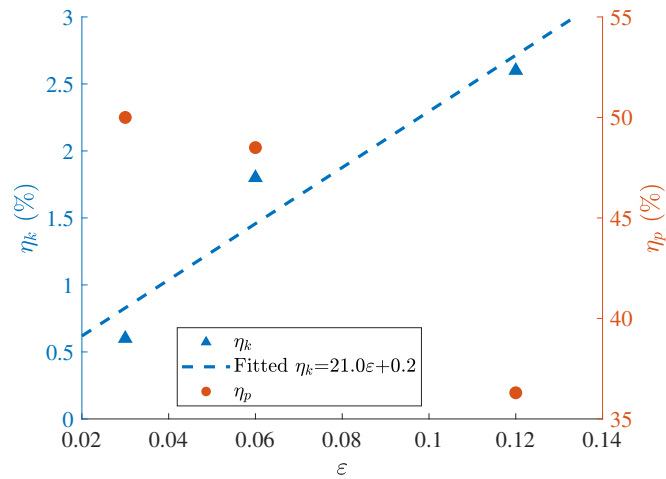


Fig. 3.25 Variation of kinetic energy efficiency η_k (blue triangle) and potential energy efficiency η_p (red circle) with non-dimensional deposition energy. Blue dash line: linear fitting of kinetic energy efficiency, $\eta_k(\%) = 21\epsilon + 0.2$.

3.4.5 Developed 1D Code and 3D Simulation Comparison

To support the modelling assumptions related to viscosity, choked jet flow, one-dimensional pressure, temperature, density and velocity, the 1D model and CFD results are compared in Figure 3.26 and Figure 3.27. Figure 3.26 shows that the overall comparison between the velocity curves is quite good for previews 1D code [72] for Case 1 and Case 4, which is the small cavity and low energy deposition cases. For 3D simulations, fluctuations of the velocity value at the orifice were generated by the reflection behaviour of the pressure waves in the cavity. While 1D mean velocity at the orifice shows smooth curves changing with time and agrees well with the 3D simulation mean value at each stage for the PSJA working process. This comparison does not necessarily prove the assumptions but certainly supports them. With this level of support in the initial 1D development, the consistency between the velocity curves is much better, not only the mean peak value and the decreasing phase curves.

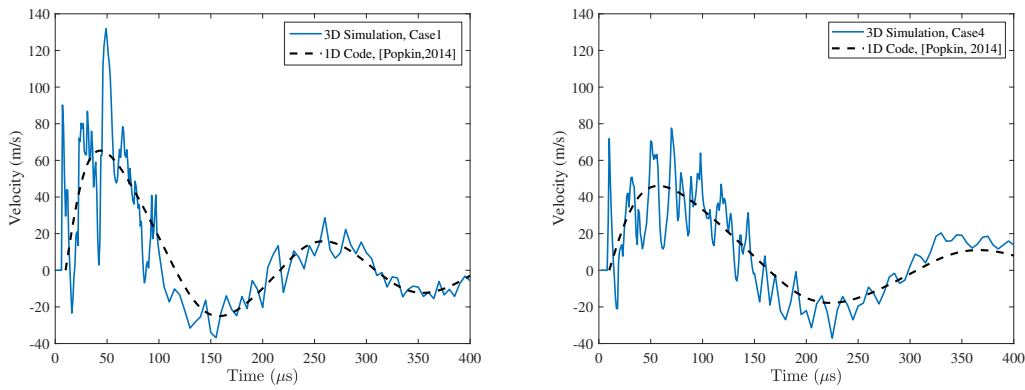


Fig. 3.26 Comparison of the orifice velocity versus time-based on CFD simulations and 1D code. Blue solid line: 3D simulation results; black dash line: 1D code results from Popkin et al. [72]. Left: Case 1; Right: Case 4.

While small cavity and low energy deposition cases are consistent with the basic code [72], Case 2 and Case 5 cannot agree well with the basic code. Figure 3.27 shows that overall variations between velocity curves in the 1D basic code and developed code and CFD results for Case 2 and Case 5. The largest disparity occurred at the decreasing stage of the PSJA cycle and was likely due to the highly unsteady flow present in the cavity and orifice as the jet formation began. Also, the peak value of velocity V_p and jet duration time T_{jet} did not consistently do well with the simulation results. However, for the 1D developed code in Figure 3.27(right), two modelling results were quite consistent with the 3D simulation at each stage, and both the jet duration time and peak values were well captured. This means the developed code complied with the pressure fluctuation equations can better resolve the characteristic of the PSJA, especially for large cavities and higher energy deposition cases.

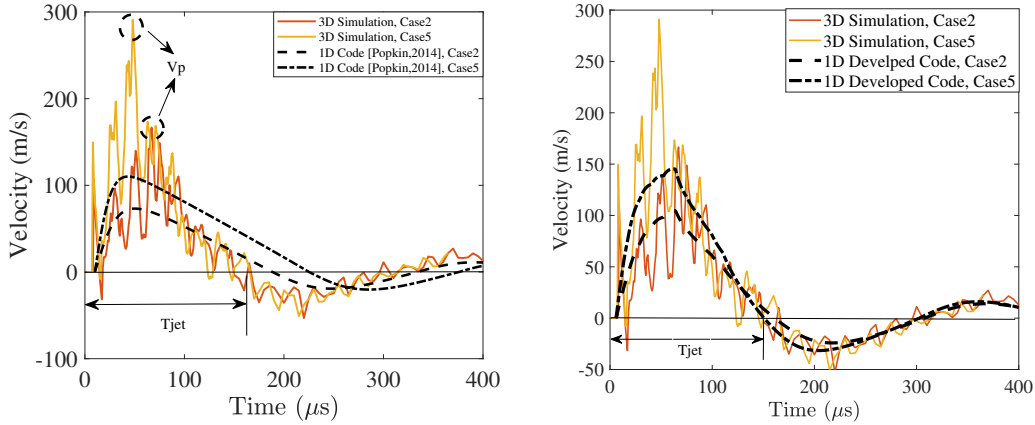


Fig. 3.27 Comparison of the orifice velocity versus time-based on CFD simulations and 1D code. Left: Comparing 3D simulation with 1D code from Popkin et al. [72]; Right : Comparing 3D simulation with 1D code developed code in this dissertation.

3.5 Conclusion

In this chapter, the plasma kernel model and the energy transformation characteristic were applied to describe the formation and evolution of the arc-discharge energy deposition process. The Schlieren experiment was used to capture the plasma kernel and jet flow phenomena. Five plasma synthetic jet actuators were modelled numerically to investigate the proportions of the output kinetic energy, potential energy and heating energy under different input non-dimensional deposition energy and volume levels. The main remarks of this chapter are as follows.

Given specific deposition energy, the theoretical plasma kernel radius and the evolution time could be predicted theoretically, and the peak pressure and temperature rise in the cavity can also be calculated. Considering the thermal energy efficiency, we were able to match the plasma kernel temperature and size quite well with localized constant energy deposition 3D simulation results. For different PSJAs, these simulations also allowed a better understanding of how the convective phenomenon strongly influenced the hot plasma kernel expansion in the cavity. This reinforces the importance of the localized deposition simulations performed with the simplified geometry, especially for large cavity actuators. Moreover, the thermal wall fluxes play a limited role in the energy balance of the cavity in the case of a single pulse since the high-temperature kernel only occupies a narrow domain in the cavity and would be pushed out within the jet duration. The propagation and reflection of blast waves generated by the arc discharge in the actuator cavity were also clarified, contributing to the formation and evolution of the high-momentum jet flow.

For a tiny cavity and high deposition energy, the propagation speed of the jet front holds relatively steady in the whole jet phase. However, the large cavity case had a slower jet propagation rate at first but increased later within time. This is because the larger cavity had a delayed blast wave propagation at the beginning but later with the blast wave reflection in the cavity, much potential energy was transferred back to thermal energy to sustain the jet flow at the late stage. At the same time, the large cavity actuator had more mass to support the jet evolution. For constant cavity volume, the location of the leading edge of the jet increased in a logarithmic form as a function of the deposition energy.

Then, the mechanical energy transfer efficiency is discussed. The proportion of kinetic energy increased linearly with non-dimensional deposition energy ϵ , while the proportion of potential energy decreased linearly with non-dimensional cavity volume as its magnitude held steady. This is because as the volume increased, the reflection path of the shock wave in the cavity increased, resulting in more energy dissipation. The 1D code with a developed pressure fluctuation equation is built in good agreement with 3D simulations. This work improves the original code by introducing the line source shock theory and the empirical formula of cavity pressure change. The improved calculation results are in better agreement with the 3D simulation results, reflecting the respiration-like properties of PSJA.

Overall, This work enhanced the understanding of flow physics after arc discharge for plasma synthetic jet actuators. In particular, it provides a new point of view towards the contribution of the blast wave and the hot plasma kernel that sustains the jet flow, and the energy transformation characteristic.

Chapter 4

Application of a LAFPA for the Control of Supersonic SWBLI

One advantage of LAFPA for SWBLI flow control is its ability to produce a highly localized plasma discharge. This allows for precise control of the plasma-induced flow disturbances and their effects on the boundary layer properties, such as momentum, turbulence, and heat transfer. By selectively modifying the boundary layer properties in specific regions of the flow, such as near the shock wave, LAFPA can enhance the aerodynamic performance of the system, reduce drag, and delay flow separation. Another advantage of LAFPA for SWBLI flow control is its flexibility in terms of electrode configuration and placement. LAFPA can be designed and optimized for various electrode geometries and configurations, such as linear, arc-shaped, or segmented electrodes. This allows for tailored and efficient flow control effects for different flow conditions, geometries, and applications. Lastly, LAFPA can operate at a much higher frequency range with intense electrical energy deposition to the flow field, while PSJA can not operate at a much higher frequency because of the cavity refresh time.

An application of high-frequency LAFPA for supersonic SWBLI flow control was conducted by DNS method in the Air Force Engineering University, Xi'an China [92]. The DNS data was collected from them and analysed in detail in this Chapter to investigate the LAFPA flow control mechanism further. As has been discussed in the literature review part, many papers focus on the thermal or momentum exchange effect of LAFPA in the boundary layer for supersonic flow control. However, the blast waves effect of this kind of plasma actuator on the mainstream shock wave system is lacking in the investigation. This chapter improved the understanding of the flow control mechanism of LAFPA for supersonic SWBLI.

4.1 Numerical Method

4.1.1 Configurations and Grids

The ramp-induced supersonic SWBLI model is shown in Figure 4.1. The incoming stream is $Ma = 2.9$ and compression is 24° slope angle. The dashed area is the computational domain of numerical simulation with a spanwise length of 16mm and the coordinate axis origin is set at the compression slope. In this study, the localized arc discharge plasma actuator is simplified as a heat source model and substituted into the simulation model setting as shown in Figure 4.2. The energy deposition domain is a cuboid, 5 mm in length, 5 mm in width and 2 mm in height off the wall. It can present a LAFPA with a 5 mm electronic distance in a spanwise direction.

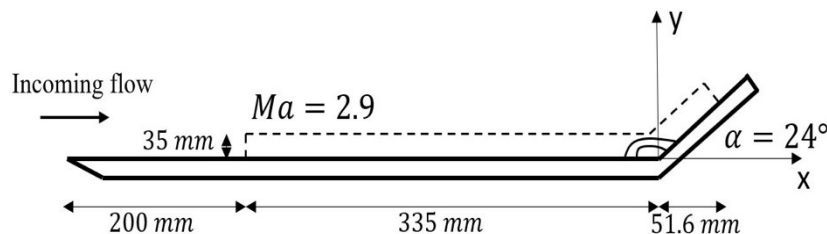


Fig. 4.1 Schematic diagram of simulation Settings for the model.

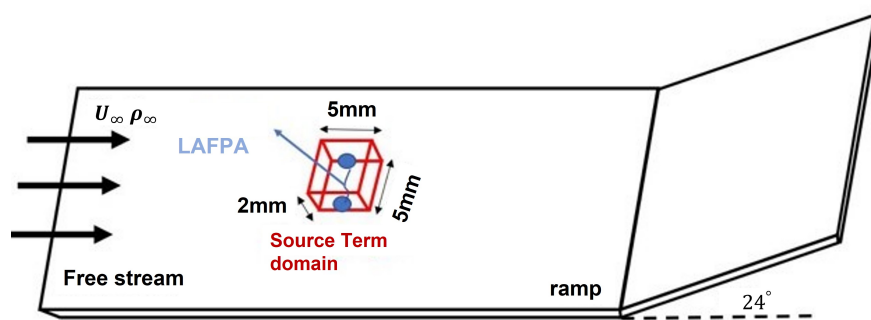


Fig. 4.2 Phenomenological model of plasma excitation by pulsed arc discharge.

Figure 4.3 shows the computational domain grid, and it is divided into 2160, 160 and 140 in three dimensions, generating a total number of 48 million nodes. The near-wall grid is 0.001 mm, which is fine enough to capture a detailed vortex near the wall. To avoid the reflection of the numerical disturbance, a buffer region with progressively coarsening meshes is assumed near the far field and outlet boundary.

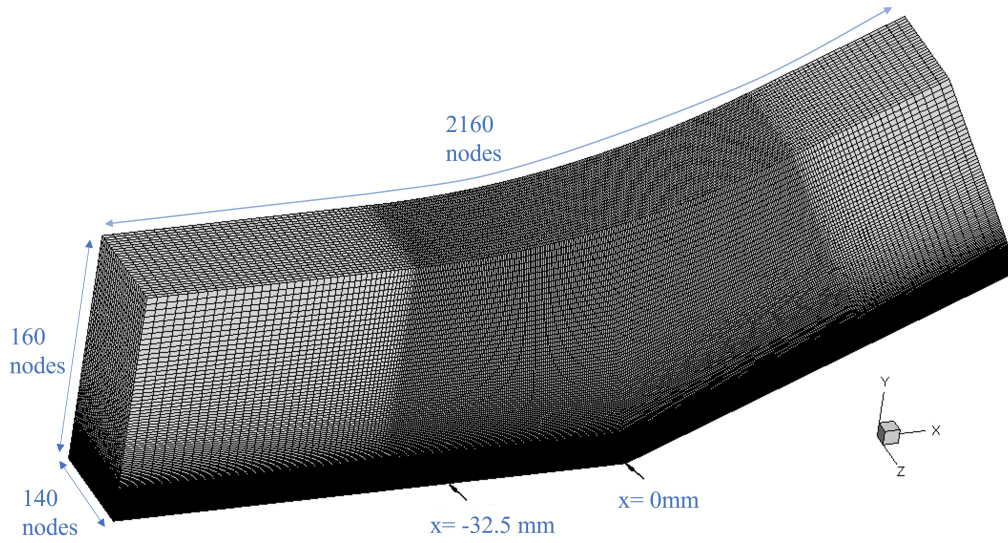


Fig. 4.3 Mesh for the LAFPA domain.

4.1.2 Governing Equations

The governing equations are the non-dimensionalized conservative form of the continuity, momentum, and energy equations in the curvilinear coordinate, which is shown in Eq. (4.1):

$$\frac{\partial(J^{-1}U)}{\partial t} + \frac{\partial(\hat{E} - \hat{E}_V)}{\partial \xi} + \frac{\partial(\hat{F} - \hat{F}_V)}{\partial \eta} + \frac{\partial(\hat{G} - \hat{G}_V)}{\partial \zeta} = S_C \quad (4.1)$$

In Eq. (4.1), J represents the Jacobian transformation coefficient in the numerical simulation, where the physical coordinate system is transformed into the computational coordinate system by the Jacobian coefficient. U is the conserved variable, E , F and G represent non-viscous fluxes; E_V , F_V and G_V represent viscous fluxes; t is time, ξ , η and ζ are the normal curvilinear coordinate, and S_C is the energy source term.

The single-pulse energy deposition was added uniformly in the form of power density into a hyperthermic region. The source term S_C is the time-dependent power density q , and it was added to the spatial domain of the heated area δ , shown in Eq. (4.2). The single-pulse source term energy in the study is 14 mJ. The energy deposition distribution frequency is 50 kHz, and the deposition time period is 2 μs .

$$S_C = q(t) \cdot \delta(x, y, z) \quad (4.2)$$

$$\delta(x, y, z) = 1(-35 < x < -30, 0 < y < 2, 5.5 < z < 10.5) \quad (4.3)$$

The non-dimensional scheme is based on the freestream quantities, and all length scales are normalized with 1 mm. Time scales are dimensionalized by $1/U_\infty$, energy by $\rho_\infty U_\infty^2$, and temperature by T_∞ . The Sutherland's law is taken in computing to calculate the viscosity, and the ideal gas are employed for the current simulation.

4.1.3 Numerical Method and Boundary Conditions

A OpenCFD software developed by Li et al. [58, 59] was used to conduct DNS. The program solves the N-S equations governing the flow through a high-precision differential method and has significant advantages in high-precision solutions and the capture of discontinuities. The inviscous terms are solved using the Steger-Warming splitting and the fourth-order bandwidth-optimized Weighted Essentially Non-Oscillatory scheme (WENO-SYMO) of Wu and Martin [115, 116]. For the discretization of viscous terms, the eighth-order central scheme is selected, and time advance is performed by means of the third-order TVD-type Runge-Kutta method. The simulation time step is 10 ns.

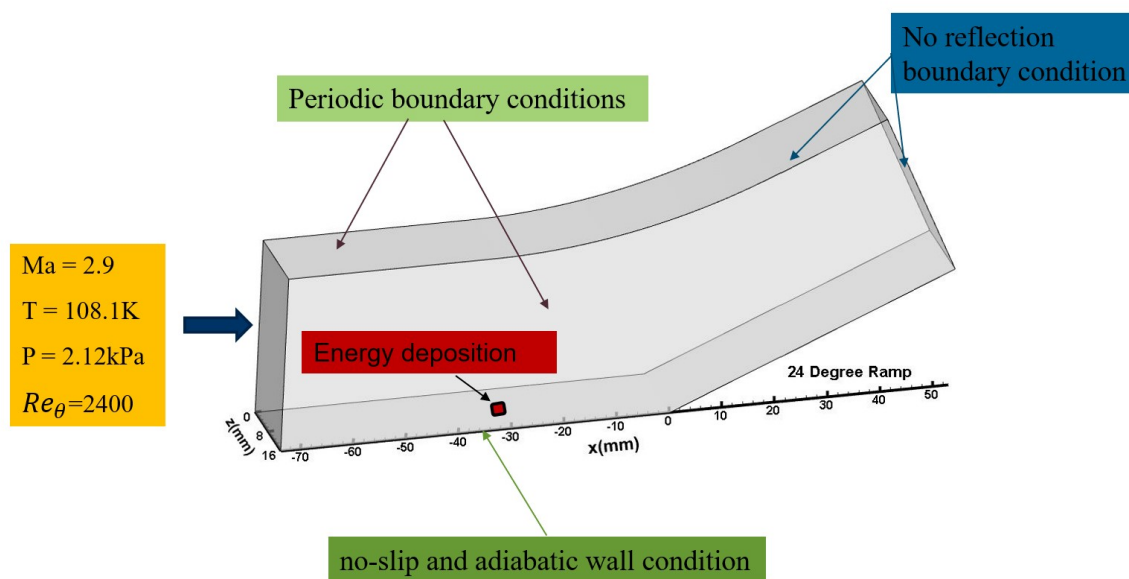


Fig. 4.4 DNS boundary condition set up.

The inlet condition is the direct numerical modulus of laminar flow in a two-dimensional plate example, with an incoming flow of 73 kPa, 293 K, the wall temperature is set to 307 K, which is consistent with Bookey's experiment [6]. The proposed stationary solution is located 200 mm downstream of the leading edge of the plate, where the flow is developed into a fully turbulent boundary layer condition from the leading edge. This information is

used as the inlet boundary condition for a three-dimensional DNS study. In addition, a no-slip and adiabatic wall condition is applied to the ramp surface. Periodic boundary conditions are used in the spanwise direction of the computational domain. The boundary condition set up is shown in Figure 4.4.

4.1.4 Validation

Table 4.1 compares parameters of simulation setup in this study and experimental setup from Bookey et al. [6]. Parameters of the flow field measured by the experiment, conditions of the incoming flow and the wall surface calculated in the simulation are completely following the experimental test data. By comparing the entrance parameters in the corner area ($x = -30$ mm), the friction coefficient C_f , and boundary layer thickness δ can be found in good agreement with experimental data, validating the accuracy of direct numerical simulation results with a maximum deviation of less than 3%.

Table 4.1 Flow field parameters at the corner ($x = -30$ mm).

Flow parameters	Bookey's experiment	Current simulation	Deviation(%)
Re_θ	2400	2344	-2.3
C_f	2.57×10^{-3}	2.57×10^{-3}	0
θ (mm)	0.43	0.42	-2.3
δ (mm)	6.7	6.5	-3.0

The law of the wall is a fundamental concept in fluid mechanics that describes the behavior of a turbulent boundary layer near a solid wall. Comparing the law of the wall for DNS and experimental data is important because it provides a means of validating the accuracy of DNS simulations. Figure 4.5 (up) shows the mean flow velocity profile at $x = -35$ mm upstream the law of the wall for DNS and experiment data. In the upstream non-interference area, the velocity profile of the boundary layer calculated in this study agrees well with the experimental results. However, there is a specific error in the near-wall area ($y < 2$ mm). Figure 4.5 (bottom) shows the comparison of the law of the wall for DNS and experiment data. For the experiment data, The curve shows a well-defined turbulent profile with small logarithmic and wake regions characteristic of a low Reynolds number turbulent boundary layer. The curves were scaled using the friction velocity derived using the Clauser method [6]. The deviation below the logarithmic law for $y^+ < 100$ is probably due to the probe interference effects [6]. For DNS data, it well presents the basic wall law and is consistent with the empirical equations. The magnitude of the discrepancy between

the experimental results and the simulation was limited to an acceptable level of 5%. Overall, the reliability of the direct numerical simulation program is very high.

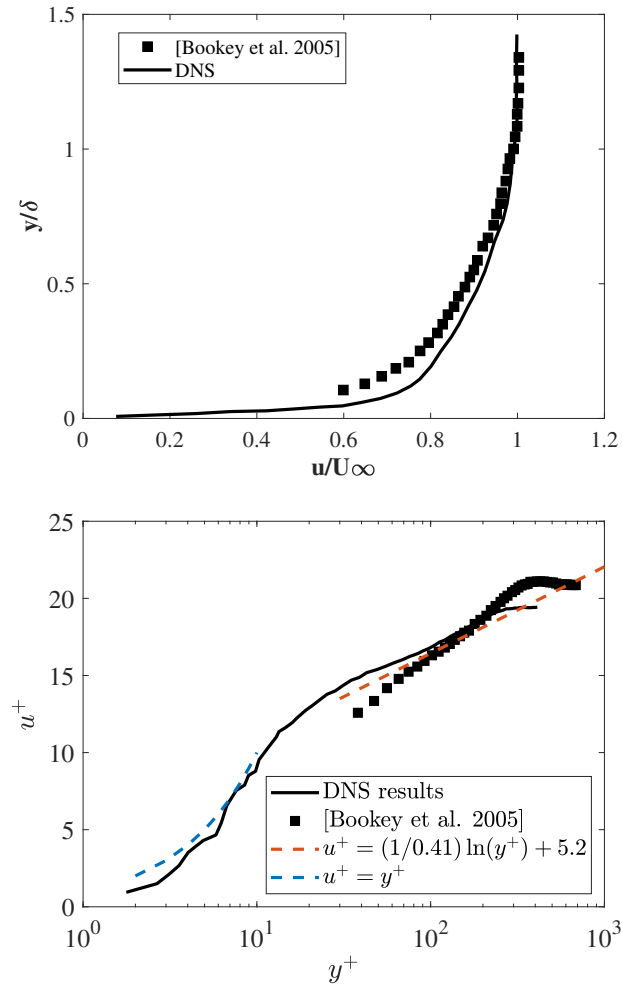


Fig. 4.5 Comparison of the velocity profile and the law of the wall from DNS and experimental data [6].up: Velocity profile of Mach 2.9 undisturbed boundary layer. bottom: Van Driest transformed velocity profile.

4.2 Results and Discussion

4.2.1 Comparison of Baseline and With control Cases

The baseline and with-control time-average results are compared to evaluate the overall flow control effect of LAFPA for supersonic SWBLI. Figure 4.6 is the cloud diagram of the distribution of time-averaged wall friction coefficient in the baseline model and the control model. The blue region represents the negative value of the friction coefficient, which means there flow separation happens. For the without-control model, the separation zone ranged from $x = -13$ mm to $x = 6$ mm, and the distribution of the friction coefficient was roughly uniform along the spanwise direction. Two peaks of friction coefficient were also captured after the corner on the ramp, which indicated the reattachment flow has two pairs of flow convergence and divergence lines. The convergence position was approximately at $z = 7$ mm and $z = 14$ mm, and the position of the divergence lines was nearly at $z = 12$ mm and $z = 16$ mm. This phenomenon has also been captured in previous experiments and has been explained by the counter-rotating stream-wise vortices [32]. These so-called Görtler vortices arise from the instability of a boundary layer with sufficiently concave streamwise curvature [91].

For the with-control model, the cloud diagram changed dramatically. At the plasma actuator position ($x = -35$ mm), there turned up the two contrary value areas. It can be explained by the continuous energy deposition of LAFPA at this position, which forced the nearby upstream flow to return and enhanced the downstream flow. At the downstream of the actuator, the spanwise uniformity of the separation zone was destroyed. The value of the friction coefficient on both spanwise sides increased without separation, while the area of the negative value in the central part extended from $x = -22$ mm to $x = 10$ mm. The separation zone presents a triangle shape after the corner line. At the same time, there only had one convergence line after the separation, which meant the G_T number was reduced after the corner. It is worth guessing that because of the LAFPA control, the turbulent boundary layer was enhanced, and the displacement thickness became larger. Both sides around the actuator flow were accelerated because of the local back by the continuous energy deposition.

The distribution of the wall friction coefficient averaging along the spanwise direction is given in Figure 4.7. For the baseline model, upstream of the separation zone, the value keeps constant at 0.0025. When the front part of the mainstream shock wave intruded into the boundary layer and the adverse pressure gradient forced the flow separate, the surface friction coefficient dropped to -0.001 and fluctuated between -0.001 to 0 from -18 mm to 5 mm in the x direction. Then, after the corner flow reattachment onto the ramp, forcing C_f to recover a positive value and keep climbing up to 0.004. For the control model, It can

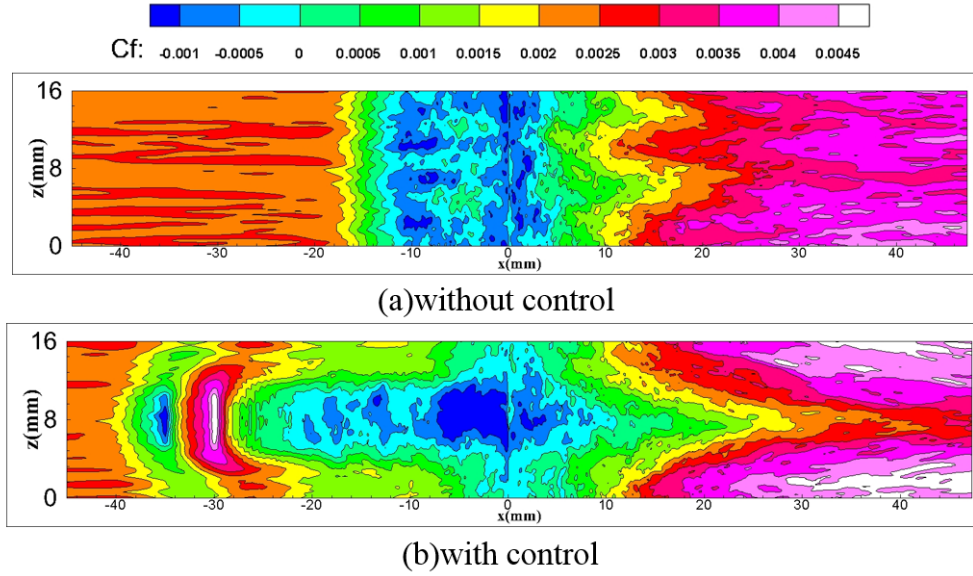


Fig. 4.6 Coefficient of friction near the wall of time-averaged results.

be clearly observed that in the area where the plasma actuator is applied, the wall friction coefficient presents a wave shape of the right side ascending to 0 and the left side descending to about 0.004. Compared with the baseline model, the friction coefficient on the wall surface starts to decline in advance after control is applied. The average length of the separation zone decreases along the flow direction, changing from 23 mm to 10 mm. From Figure 4.6, we can see that while negative friction coefficient at central plane extent, positive friction coefficient enhanced at both side planes, which contributes to the average shortened separation region at Figure 4.7. After the corner, the two models have the same trend to recover the C_f , but the control model value is slightly lower than the baseline model and climbs up to a higher constant value of 0.0042.

Figure 4.8 shows the time-averaged wall pressure distribution averaging along the span-wise direction. For the case without control, the pressure increased dramatically upstream of the corner ($x = 0$ mm), and the adverse pressure gradient was generated, which will cause flow separation near the corner because of the supersonic separation. For the with control case, the pressure line has a peak at -32.5 mm, where the plasma actuator takes place. After the peak, the pressure line recovered to a height of 1.4 and kept increasing. At $x = -5$ mm, both cases came to the same point. However, the increasing rate of the pressure after $x = -5.0$ mm has been reduced slightly, compared to the baseline model, which means the wave drag on the wall has reduced.

Table 4.2 gives a quantitative comparison of the flow control effect, including the wall surface friction coefficient and wall pressure. The total area of the negative region decreased

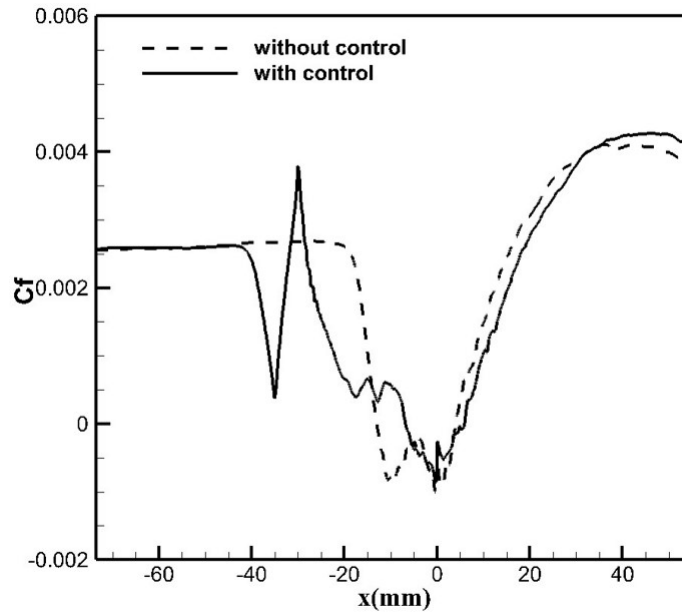


Fig. 4.7 Span wise averaged friction coefficient distribution on the wall of time-averaged results.

slightly by 2.4%, which means the plasma actuator parameter used in this article cannot decline the separation area on the wall efficiently. But the area average friction coefficients on the wall reduced significantly by 9.1 %, which means the total friction drag is decreased. Besides, the wall non-dimensional pressure decreased by 6.3%, which also means the wave drag of the SWBLI to the wall is reduced. In conclusion, the LAFPA in this study can contribute to the positive flow control effect for supersonic SWBLI.

Table 4.2 Mean flow control effect of LAFPA for supersonic SWBLI.

	Negative C_f area ⁽¹⁾ (mm ²)	Area-average C_f	Wall pressure P/P_∞
Without control	255	0.0022	4.04
With control	249	0.0020	3.79
Changed by	-2.4%	-9.1%	-6.3%

⁽¹⁾ The area integration of the local friction coefficient C_f in the reverse region where there is a negative C_f , used to derive the area average of C_f .

4.2.2 LAFPA Effects on Flow Field of SWBLI

The flow control mechanism is further investigated in this section. From the top view and the analysis of the surface friction coefficient in Fig. 4.6, it is clear that the uniformity of

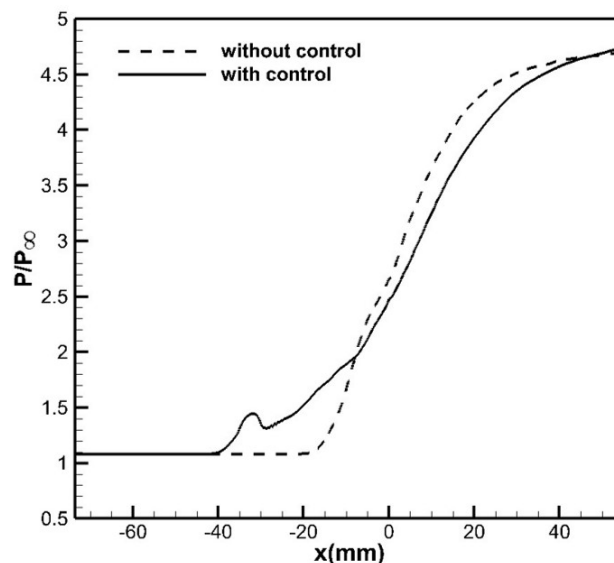


Fig. 4.8 Spanwise-averaged pressure distribution on the wall of time-averaged results.

the reverse-flow region along the spanwise of the baseline model is destroyed by the plasma actuator control effect. The comparison of the boundary layer velocity profiles between different spanwise locations can further reveal the destruction of this uniformity. Figure 4.9 compares the streamwise plane velocity counters between baseline (up row) and with control (bottom row) results. For the baseline model, the negative U value region at the corner position ($x=0$ mm) in the baseline model is nearly identical for both the center plane ($Z=8$ mm) and the side plane ($Z=15$ mm), consistent with the uniform C_f distribution on the wall. However, a different distribution is observed with the control model. At the center plane, the flow affected by the LAFPA induced an upstream expansion separation region up to $x = -25$ mm, while the negative blue region disappeared on the side plane. These findings reveal changes in the 3D separation bubble, which will be discussed in later paragraphs.

Figure 4.10 presents the evolution of the boundary layer velocity, comparing u velocity profiles at four streamwise positions ($x = -32.5, -23.4, -11.8$ and 0.0 mm) and at three spanwise locations ($z = 8$ and 15 mm). For the baseline where the control is not activated, the boundary layer height increases slightly and shapes of velocity profiles are nearly the same before reaching the corner at $x = 0$ as the flow goes downstream. At the corner ($x=0$ mm), the negative u velocity appears from 0 mm to 1.5 mm in the y direction, corresponding to the separation bubble. The boundary layer thickness reaches the highest position of 8 mm and the velocity profiles show a constant slope that leads to constant shear stress among the whole boundary layer. The velocity profile changed dramatically along the stream-wise position when the LAFPA operation. The baseline boundary layer shape is destroyed and replaced by a twisted curve profile shape. At $x = -11.8$ mm on the central plane, the height of

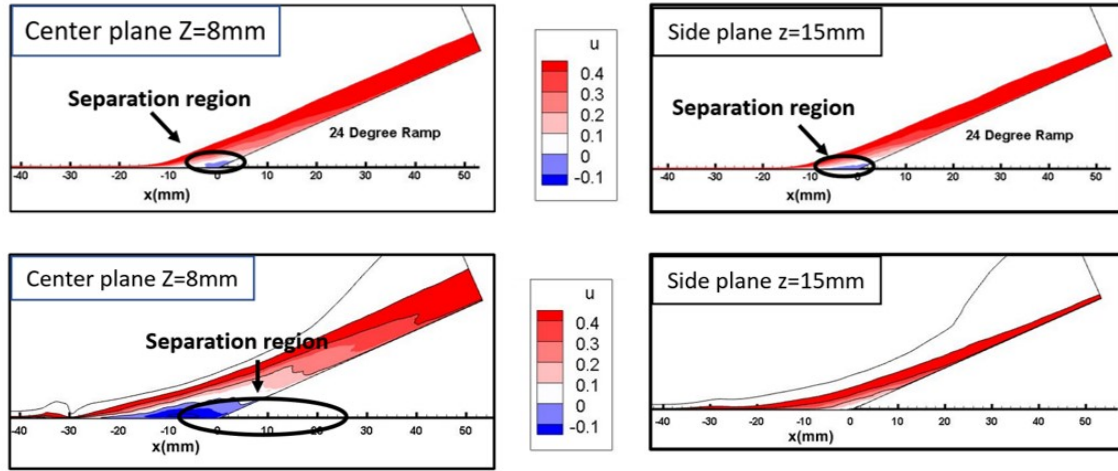


Fig. 4.9 Mean flow stream-wise velocity contour at plane $z = 8$ mm and $z = 15$ mm. up row without control, bottom row with control.

the negative velocity region enlarges to 2 mm, and it can be speculated that the separation beginning position goes even upstream. At the corner, the negative value u/U_{ref} increases from -0.1 m/s to -0.2 m/s, and the height of the negative velocity region enlarges to 4 mm. Moreover, the boundary layer thickness reaches 15 mm, almost two times to thickness in the baseline model. That means along the streamwise direction LAFPA results in increasing the turbulence in the boundary layer, leading to the enhancement of the shear layer thickness. At the same time, the separation area is also enlarged, which can be found in the negative u profile area. At the side plane ($z = 15$ mm), although the boundary layer thickness also increases slightly in the flow direction, the negative value at $x=0$ mm decreases from -0.05 m/s to 0, which means at both sides the anti-separation ability is enhanced and the reversed flow region shrinks.

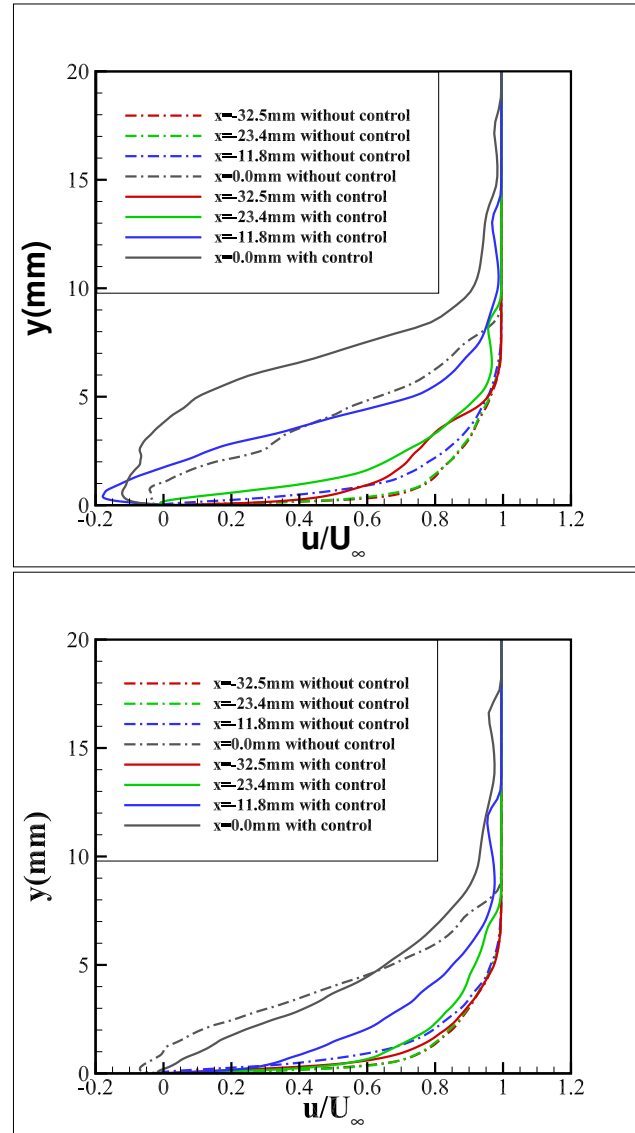


Fig. 4.10 The stream-wise velocity component at $z = 8$ mm (up), 15 mm (bottom). Profiles are shown for a varying stream-wise distance from the plasma actuator position ($x = -32.5$ mm). Dashed line: without control; solid line: with control.

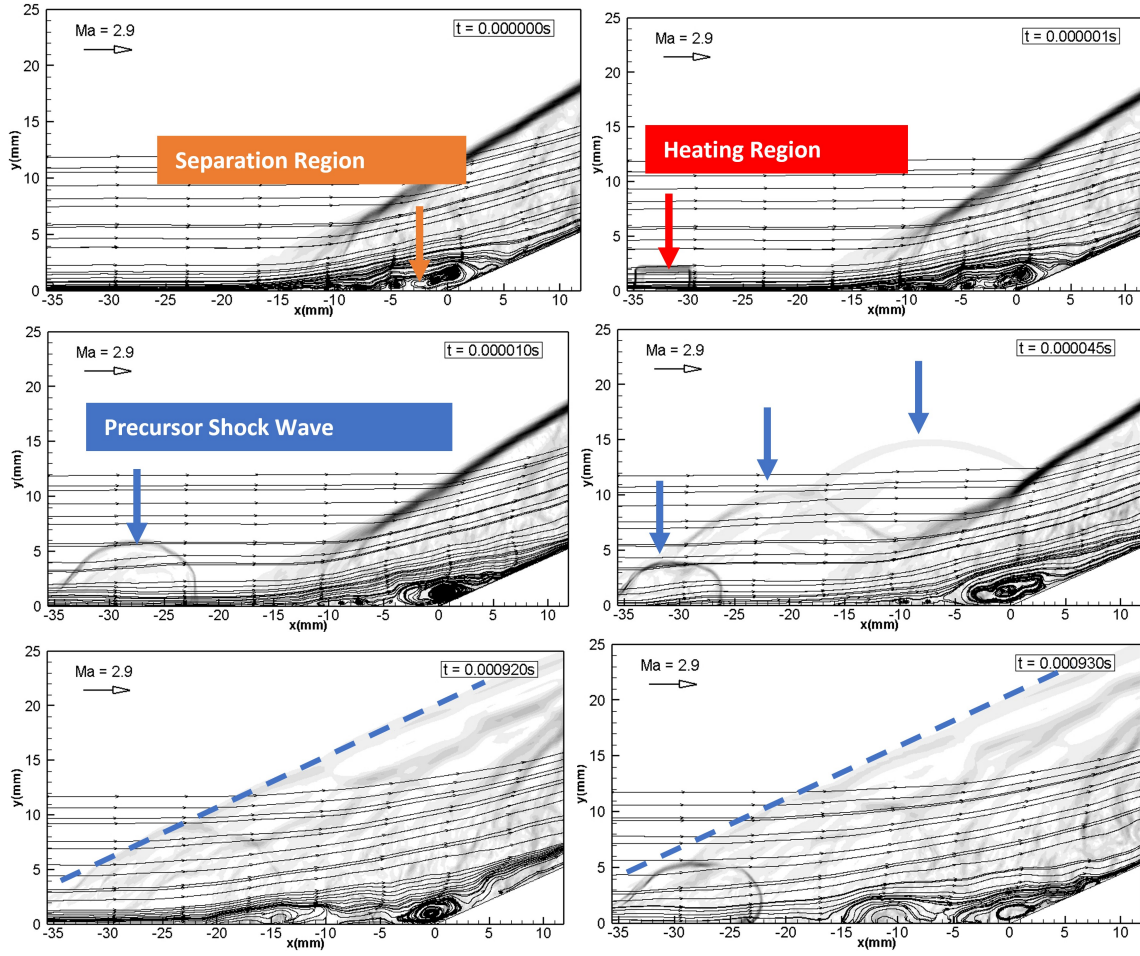


Fig. 4.11 Streamlines in (x, y) -planes showing the interaction between plasma actuator and SWBLI. Pressure gradient contours show the shock location.

In order to provide a clear evolution of shock wave manipulation, instantaneous numerical Schlieren (density-gradient magnitude) of the DNS are presented in Figure 4.11. It plots two series of consecutive times with a time interval of about $5 \mu\text{s}$. The first series is from $0 \mu\text{s}$ to $45 \mu\text{s}$ representing the start period of the LAFPA operation, and the second is from $920 \mu\text{s}$ to $930 \mu\text{s}$, which is the later multi-pulses stage of the calculation. Contours of the numerical schlieren are plotted as the background to show the shock wave and the precursor shock waves (PSWs). Streamlines are also added to show the flow separation. It clearly shows the PSWs of LAFPA generating and interacting with the mainstream shock wave within time. At $t = 0 \mu\text{s}$, when the PSWs have not been generated, the flow structure has not been affected yet. The prominent features are the mainstream shock wave and the separated region presented by the return streamline. It is clear that the foot portion of the mainstream shock wave inserts into the boundary layer at 6 mm height. The separation lengths are nearly

15 mm from -10 mm to 5 mm in the streamwise direction. From frames 1 μs to 20 μs , the first PSW occurred at 1 μs shaped as a square volume, since the energy deposited at the same volume. Then the precursor shock wave fully developed into a semi-minorant, passively carried by the mainstream toward the SWBLI region. At this stage, the precursor shock wave does not interact with the SWBLI, and the mainstream shock wave has not been disturbed. At the same time, the separation region varies with time. From 10 μs to 45 μs , the second and third PSWs turned up and the first one continued to expand and climbed to the foot part of the mainstream shock wave. At the height of $y = 6$ mm, the first PSW interacts with the separation shock wave and the latter begins to oscillate and bifurcate. After the continuing effect of PSWs, the original shock wave was disturbed, replaced by a series of weakened shock waves. The insert height changed from 6 mm to 11 mm in the y direction. At this stage, the separation bulb climbed into the ramp, and it seems that it is pushed by the power of the series PSWs in the plasma arcing process.

After sufficient PSWs took place with high frequency, from 920 μs to 940 μs , it is clear to see that the mainstream shock wave has been disturbed totally under 25 mm height and replaced by a series of weakened shock wave networks. It is encouraging to detect that PSWs emitted when the LAFPA operation re-organizes the mainstream shock wave system. As time passes away, the separation area in the spanwise central suction also changes shape and becomes larger in the streamwise direction, increasing by 5 mm from -10 mm to -15 mm. Moreover, the original separation bubble seems to collapse into two bubbles under the PSWs' interaction. Compared to Gan's experiment results [36], DNS also shows a strong first pulse which shortens the separation shock wave, but because of the high frequency (50 kHz), the foot part of the mainstream shock wave does not have time to recover which is totally different from the experiment. It is reasonable to say high-frequency fluid characteristics play an important role in the LAFPA flow control process.

Figure 4.12 illustrate the 3D flow domain using numerical schlieren slices and velocity distribution near the wall. From the spanwise and streamwise slices, the formation of three PSWs systems is built within the main flow field. At the same time, the intensity of turbulence flow underneath the shock wave became significant. In the spanwise direction, the withes of the PSW shape are also expanded within the distance increase from the LAFPA energy deposition at $x = -32.5$ mm. At $x = -20$ mm, the bottom edge has reached the side edge of the spanwise direction. Because of the pressure gradient under the shock wave, the negative velocity domain expanded in a streamwise direction but shrank in the spanwise direction. As the series PSWs propagate through the main fluid, it causes the fluid ahead of it to slow down and compress, while the fluid behind it experiences a sudden expansion. This creates a region of high-pressure, high-temperature fluid behind the shock wave, which can have

significant effects on the behaviour of the flow. The adverse pressure gradient underneath the shock system causes the expansion of the separation domain.

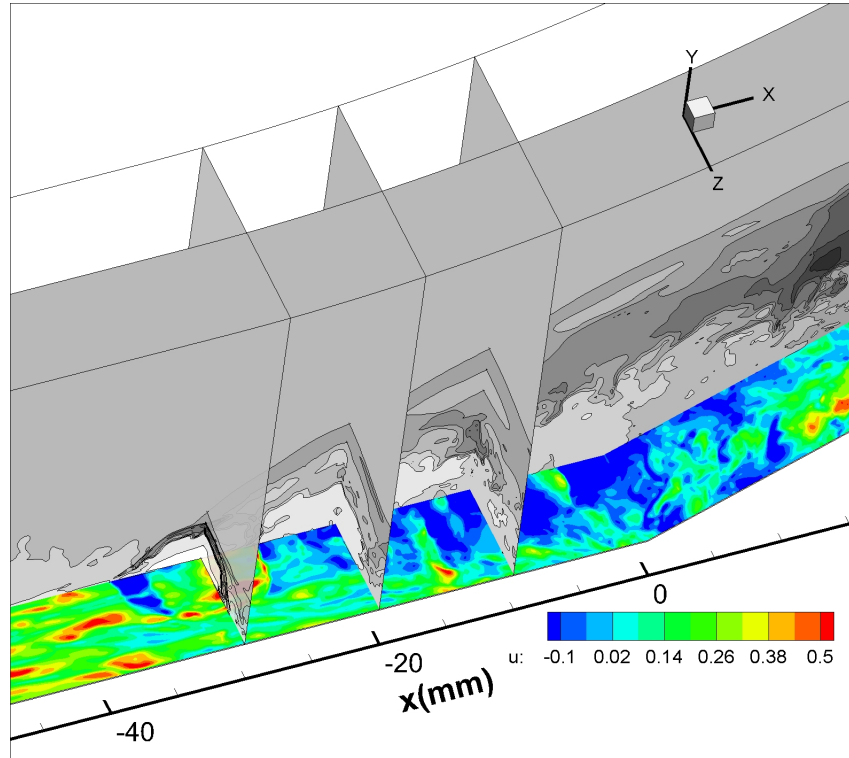


Fig. 4.12 Slices of numerical schlieren (on $x = -30$ mm, -20 mm, -10 mm and $z = 8$ mm plane) and velocity distribution near the wall.

In a turbulent boundary layer, the flow is characterized by the presence of coherent vortices that are responsible for many of the observed turbulent structures. These vortices are large-scale eddies that are organized in a relatively consistent pattern, and can persist for long periods of time. Streamwise vortices are elongated structures that are aligned with the mean flow direction, while spanwise vortices are structures that are oriented perpendicular to the mean flow direction. Streamwise vortices are typically associated with low-speed streaks in the boundary layer, and are responsible for the generation of turbulent fluctuations that are perpendicular to the mean flow direction. Spanwise vortices, on the other hand, are associated with the generation of streamwise turbulent fluctuations, and are responsible for the formation of hairpin vortices and other complex structures in the boundary layer. The organization of these coherent vortices is critical to the behaviour of the turbulent boundary layer, as they can interact with each other to produce complex structures and dynamics. The length scales of these vortices can range from the order of the boundary layer thickness to several times the boundary layer thickness, and they can persist for time scales on the order of

the turbulent eddy turnover time. Overall, the coherent vortices in a turbulent boundary layer are a fundamental aspect of the dynamics of the flow, and their interactions are responsible for many of the observed characteristics of the turbulent flow, including the generation of turbulent fluctuations, the development of the boundary layer, and the transport of momentum and energy.

Figure 4.13 plots the isosurface of the discriminant of the velocity gradient tensor, which is a quantity used to identify vortices structures in incompressible flows [5]. Upstream of the shock wave boundary layer interaction, coherent structures are observed. Near the corner where the interaction takes place, the structures are more disordered and of smaller size. There are two possible reasons accounting for the change of the structure extent. First, the structures can be chopped by the strong shock and become smaller. Second, fluids are compressed through the shock, and the vortical structures are also compressed and become smaller. When the energy deposition happened at $t = 1722 \mu s$, the square structure was induced by the intense energy release. After several microseconds, this square shape because of the deposition cubic volume became more round and the right side moved further downstream, while the left side expands a little bit upstream. This is because of the strong PSW. On the one hand, it expands itself. On the other hand, it is dragged by the main flow downstream. When a hemispherical shock wave propagates near the surface, it can induce changes in the boundary layer coherent vortices. Initially, the boundary layer flow exhibits large-scale, elongated streamwise vortices, which are oriented in the direction of the mean flow. As the hemispherical shock wave propagates near the surface, it interacts with these vortices, causing them to be stretched and distorted in the spanwise direction. This is due to the fact that the shock wave induces a strong spanwise pressure gradient, which can alter the shape and orientation of the vortices.

The shock wave can also lead to the formation of additional vortices in downstream and upstream, which are smaller in scale and more tightly wound than the initial vortices. These newly formed vortices are oriented in the spanwise direction and are generated by the baroclinic torque resulting from the interaction between the shock wave and the mean flow. This is shown at $t = 1724 \mu s$. The precise characteristics of the new vortices depend on the strength and speed of the shock wave. The propagation of the LAFPA-induced hemispherical shock wave near the surface can induce complex changes in the boundary layer coherent vortices, including both stretching and distortion of the initial vortices, as well as the formation of new, spanwise-oriented vortices. These changes can have a significant impact on the transport and mixing of mass, momentum, and heat within the boundary layer, and can play an important role in a wide range of aerodynamic and fluid dynamic phenomena. After $10 \mu s$, at $t = 1732 \mu s$, the original intense square vortices domain became round shape

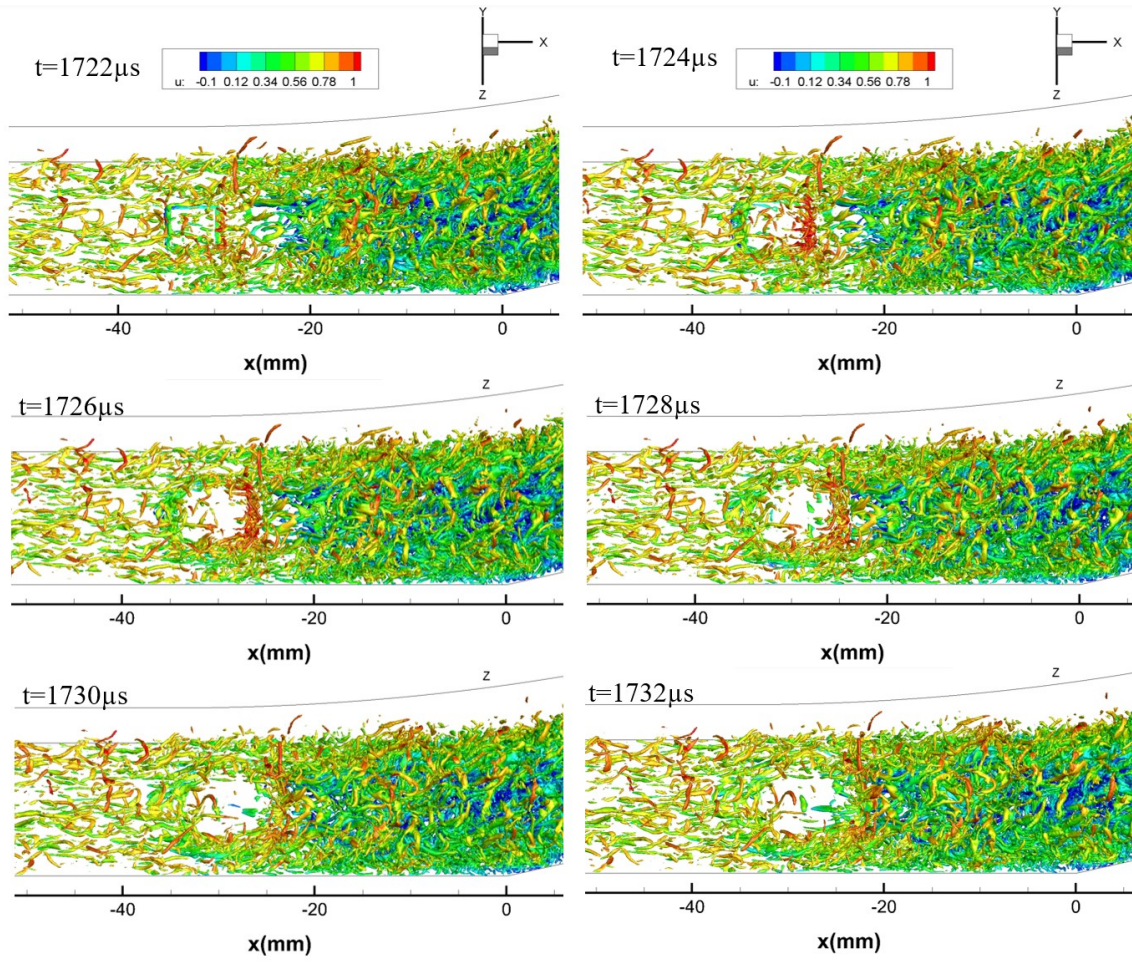


Fig. 4.13 Isosurface of the second invariant of velocity gradient Q at $10 \mu s$ time duration after energy deposition at $t = 1722 \mu s$.

and moves downstream. This is because the PSW strength decreases with the expansion and the pressure effect within the boundary layer also decreased. These vortices induced by the PSW interacted with the main flow coherent structures and slowly came together.

The primary observed effect of the LAFPA's forcing was to move the reflected shock upstream. This showed that the displacement was largest during the part of the forcing period that the LAFPA's were arcing. However, the LAFPA's are also heating the flow, and this behaviour and trend are also interesting to investigate. Figure 4.14 shows the non-dimensional temperature contour with white streamlines at different phase-locked times. At $t = 2 \mu s$, it is clear that after energy deposition, there will generate a significantly hot region, which is the yellow region near the surface. The light yellow domain is the temperature rise after the last pulse. The separation bubble has moved upstream to the bottom of the second light yellow domain. There are two main affected influence the stream. One is the temperature gradient and another is the adverse pressure gradient induced by the shock wave. So the pressure gradient will force flow to separate and reverse upstream, while the hot expansion will force flow expanded downstream. From the images, we can see the bubble shape changed from a cubic to a diagonal oval shape. It is also interesting to notice that When the temperature decreases over time, the size of the separation bubble becomes larger. It can be explained by the thermal and pressure effect interacting in this domain.

When a fluid flows over a surface, the boundary layer is the thin layer of fluid that is affected by surface friction. The behaviour of the boundary layer can be affected by a number of factors, including thermal gradients and pressure gradients. A positive thermal gradient refers to a situation where the temperature of the fluid increases as it moves along the surface. This can be caused by a variety of factors, such as heat transfer from the surface, or mixing with warmer fluid. An adverse pressure gradient, on the other hand, refers to a situation where the pressure of the fluid increases as it moves along the surface. This can cause flow separation. If both a positive thermal gradient and an adverse pressure gradient are present in the boundary layer, the two effects can interact with each other in complex ways. In this study, the positive thermal gradient tends to cause the fluid to expand near the surface and become less dense, which can result in a reduced pressure gradient. This can help to counteract the effects of the adverse pressure gradient and delay the transition of the boundary layer. However, the adverse pressure gradient is much stronger than the hot expansion will be put upwards and the separation can still exist underneath the thermal expansion.

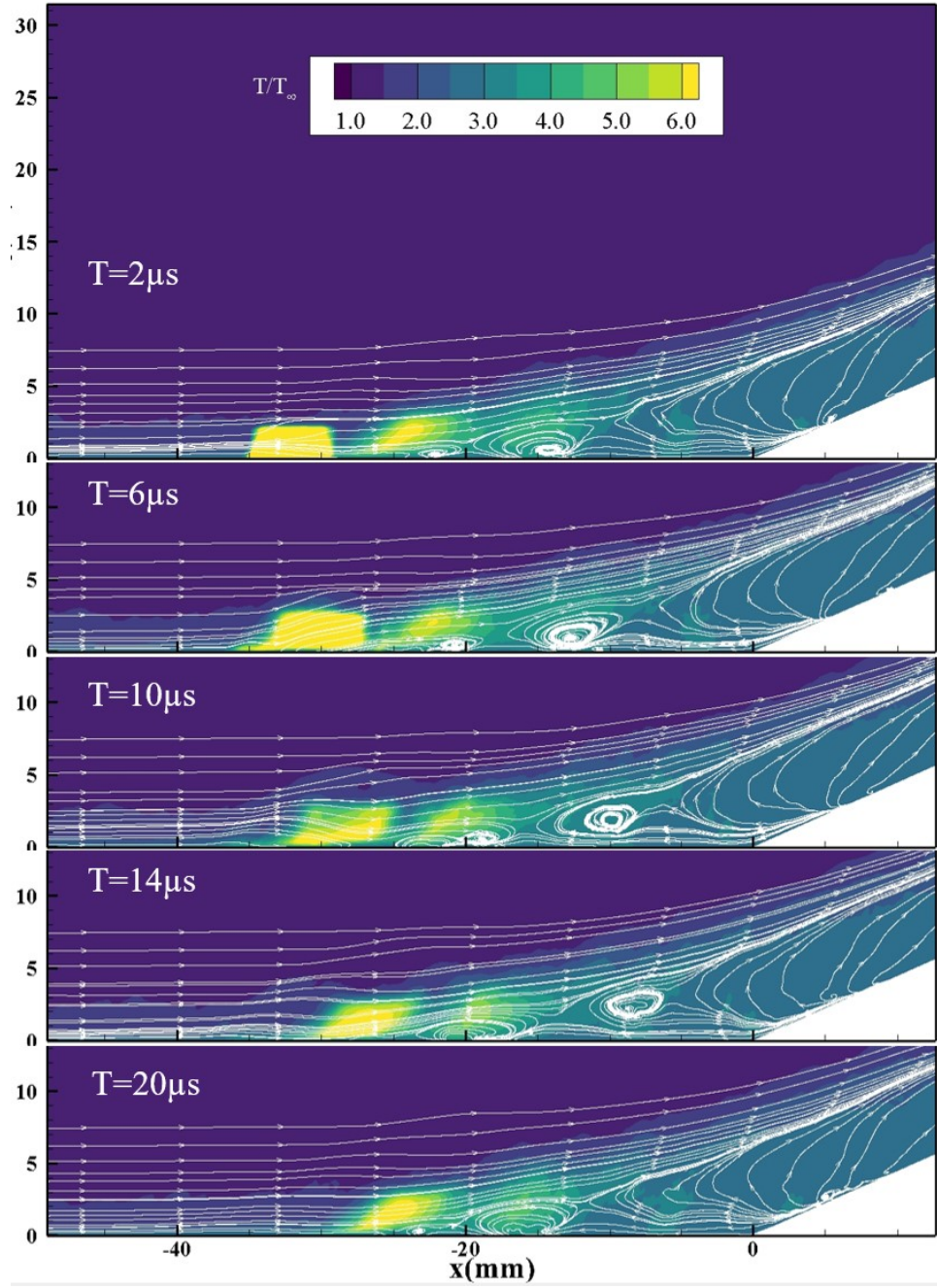
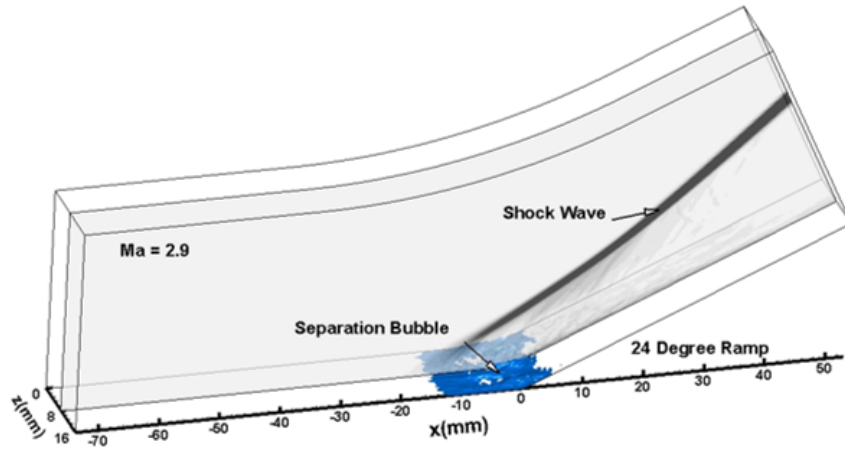
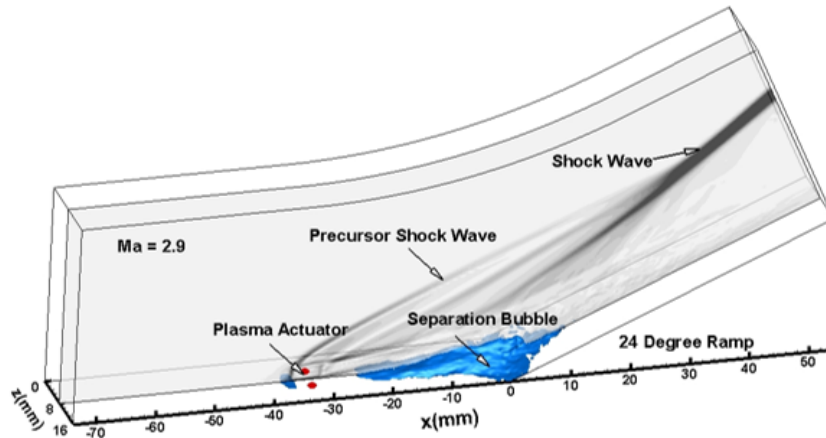


Fig. 4.14 Phase averaged temperature counter with white streamline as a time sequence.

4.2.3 Conception Model for LAFPA SWBLI flow control



(a) without control



(b) with control

Fig. 4.15 Time-averaged numerical Schlieren of the flow field. Blue surface: iso-surface of zero velocity, which encloses the reverse flow region. (a) Model without plasma control; (b) Model with plasma control.

Figure 4.15 shows the numerical Schlieren of the mean flow for baseline and with plasma control model in the centre streamwise plane, and the separation bubble is also visualized by the iso-contour surface defined as $u/U_\infty = 0$. The ramp deflection angle is large enough for the incoming boundary layer to separate. The separation region begins where the large shock wave pressure gradient inserts deeply into the incoming boundary layer. For the baseline model, the blue bubble covers -13 mm to 6 mm in the x direction. Compared with the baseline model, the flow field in the control model is sophisticated. The separation bubble

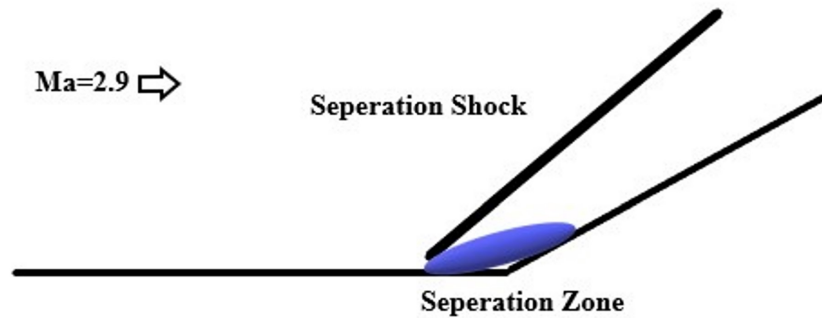


Fig. 4.16 Conception Model of supersonic SWBLI flow.

changes from the original small uniform region spanwise near the ramp corner to a larger triangle body along the streamwise direction. The front part of the darkest line has disappeared, replaced by a series of weakened lines, showing that PSWs play an important role in the shock wave and SWBLI system reorganization. On the other hand, the weakened shock enlarges the shock region in the x direction in the central part of the computational domain. That can explain why the central separation area enlarged since PSWs caused the adverse pressure gradient from the boundary layer and in advance compared to the mainstream shock waves. Besides, the side flow was accelerated to be strong enough to avoid separation.

At the same time, the thermal effect of LAFPA also contributes to the flow control mechanism. Both high temperature and high pressure induced by LAFPA work as a physical bump at the LAFPA position, which will cause the flow block of this region and further upwards the main shock wave foot and accelerate the side flow velocity. On the other hand, the positive thermal gradient tends to cause the fluid to expand near the surface and become less dense, which can result in a reduced pressure gradient within the separation domain. Because of the interaction of thermal gradient and pressure gradient in the boundary layer, the transition and turbulent level enhanced. Which can be recognised as a virtual ramp surface to the main flow.

Based on the previous analysis in this chapter, a conceptual model is established to reveal the primary mechanism of supersonic SWBLI flow control by a high-frequency operation LAFPA. The flow control conceptual models are illustrated in Figure 4.16 and Figure 4.17 to provide a more comprehensive understanding of the control outcome. Figure 4.16 shows the typical flow features in baseline SWBLI, including the separation wave and separation region in the front view, as well as the separation domain after the separation shock. Figure 4.17 displays the responses of these flow structures to a high-frequency plasma actuator (50 kHz, 14 mJ). As the plasma actuation is turned on, the size of the separation bubble in the streamwise

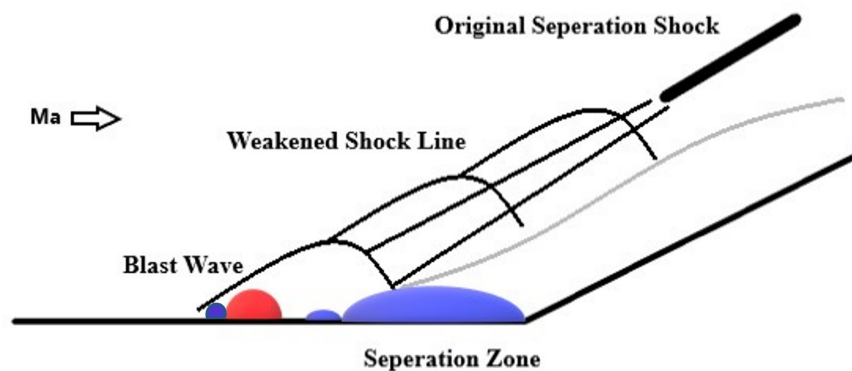


Fig. 4.17 Conception Model of LAFPA for supersonic SWBLI flow control. Red semi-sphere: blast wave of plasma-generated hot plume.

plane is extended in length and height, and the overall separation shock foot moves upstream to the position of LAFPA. Simultaneously, the intensity of the separation wave is greatly weakened by a series of weakened shock lines generated by the PSWs. Additionally, due to the thermal and blast wave block produced by the plasma actuator, the streamline separated at the actuator and side flow is accelerated, increasing the ability to resist flow separation at both sides. The flow after the actuator will introduce the separation domain because of the adverse pressure gradient. Finally, as shown in the view of Figure 4.15, the separation zone presents a cone shape, namely, the separated flow is intensified in the middle plane of the model and is suppressed on both sides of the model.

4.3 Conclusions

In this chapter, the DNS data was carefully analyzed to illustrate the flow control mechanism of LAFPA for supersonic SWBLI. Despite the wide proposed flow control mechanism of momentum and thermal effect on the boundary layer, the localized arc filament plasma actuator (LAFPA) exerts a unique control effect on the supersonic shock wave boundary layer interaction (SWBLI) by reorganizing the strong shock wave profiles into a series of weaker shocks. The intense high-frequency arc discharge energy was released into the flow, generating a series of precursor shock waves (PSWs), which plays a primary role in SWBLI flow control in our case.

The overall control effect was analyzed based on pressure, friction coefficient, and velocity profile data, and the mean control effect was obtained. As a result of the LAFPA, the time-averaged separation bubble changed from a small, uniform spanwise region to a larger, triangular body. This is because the flow block at the LAFPA position accelerated

the side flow, enhancing the ability to resist flow separation on both sides. The area average friction coefficients on the wall reduced by 9.1% significantly, which means the total friction drag is decreased. The wall non-dimensional pressure decreased by 6.3%, which also means the wave drag of the SWBLI to the wall is reduced. The LAFPA show an improvement in the aerodynamic efficiency of this supersonic SWBLI system.

The flow control mechanism of the LAFPA was also discussed in detail. It was found that precursor shocks were emitted during LAFPA operation, which coalesced into an oblique shock and merged with the separation shock, leading to the re-organization of the shock wave system. So that the separation bubble expanded upstream in the central domain. Because of the flow block at the LAFPA position, the incoming flow is separated and accelerated at both sides after passing the plasma actuation to avoid flow separation. Additionally, the intensity of turbulence flow underneath the shock wave became significant. The positive thermal gradient near the surface tends to cause the fluid to expand near the surface and become less dense. Finally, the conceptual model of LAFPA for SWBLI flow control was given.

Chapter 5

Application of an array of PSJAs for the Control of Transonic SWBLI

The PSJA can be used to manipulate the boundary layer near the surface of an object in high-speed flow. By controlling the timing and location of the plasma discharge, the PSJA can be used to generate small-scale vortices that can help to reduce boundary layer separation and improve flow attachment. This can lead to a reduction in drag and an improvement in aerodynamic performance. In the case of transonic SWBLI, the PSJA can be used to control the interaction between the shock wave and the boundary layer by generating vortices that help to reduce the size and strength of the shock wave. This can lead to a reduction in drag and an improvement in the efficiency of the flow. The PSJA is particularly useful in this context because it can be used in a non-intrusive manner, meaning that it does not require any physical modification of the object or the flow.

Steady micro jets are a flow control technique that can be used to mitigate transonic shock wave boundary layer interaction (SWBLI). The technique involves the injection of small jets of fluid into the boundary layer, which can modify the boundary layer behaviour and reduce the negative effects of SWBLI, such as increased drag and reduced aerodynamic efficiency. However, there are several shortcomings associated with the use of steady micro jets for SWBLI flow control. On the one hand, Steady micro jets can only provide a limited amount of flow control, and their effectiveness depends on the size and location of the jets. In some cases, the benefits of the jets may be outweighed by the added weight and complexity of the injection system. On the other hand, the use of steady micro jets can potentially cause boundary layer separation, especially at high angles of attack. This can lead to increased drag and reduced performance. This can make the technique less effective in certain flight regimes. Overall, while steady micro jets can provide some benefits for transonic SWBLI flow control, they may not be the most effective or practical solution for all applications.

This chapter employs the commercial computational fluid dynamics software Fluent to examine the flow control effects of an array of micro-jets and plasma synthetic jet actuators (PSJAs) on SWBLI in a transonic channel. The primary criterion for evaluating the effectiveness of the control techniques is the reduction of the size of the separation zones, including central and corner separations. Specifically, the mitigation of central separation is primarily achieved through the use of micro-jets. The effectiveness of steady micro-jets versus arc-pulsed unsteady micro-jets is meticulously compared in detail. In the end, the evolution of streamwise and spanwise vortices was illustrated and discussed.

5.1.1 Configurations and Grids

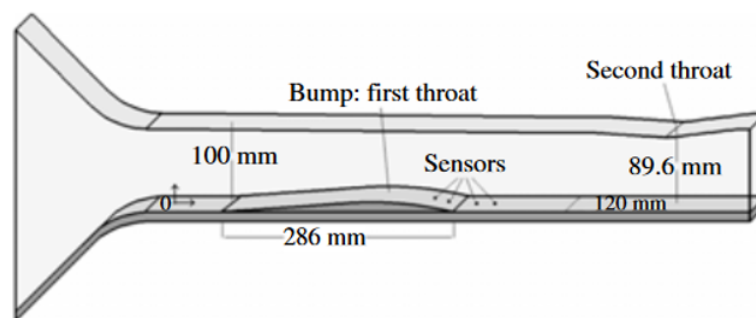


Fig. 5.1 Schematic diagram of transonic S8Ch wind tunnel [85, 86].

The baseline model of bump-induced transonic SWBLI is shown in Figure 5.1, which is the Déleré bump configuration of the S8Ch wind tunnel of the ONERA Meudon Center. Detailed Schlieren and PIV results are shown in the literature [85, 86]. In this chapter, numerical models are built according to this configuration, and baseline model results are compared with experimental data to validate the numerical methodology. The wind tunnel test section has a span-wise of 100×120 mm, and its lower wall is a profile of 286 mm designed to produce a uniform supersonic flow. The second throat of the adjustable cross section is placed at the outlet and caused by the choking effect of a shock wave whose position and intensity can be adjusted continuously. The ratio between the two sections is 1.12, and the shock occurs at Mach number $Ma = 1.4$ outside the interaction region.

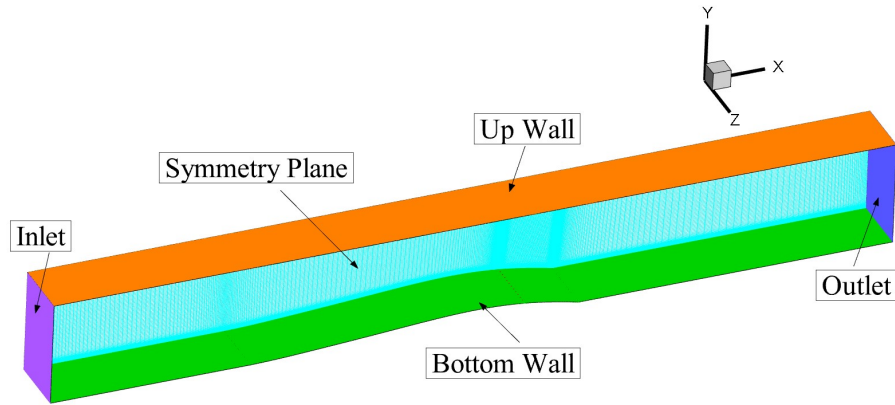


Fig. 5.2 Computational grid of baseline model corresponding to half of the transonic wind tunnel in Figure 5.1.

Half of the tunnel domain within a span-wise of 60 mm was built to save the computational resource. The computational mesh for the baseline model is a structural mesh generated by ICEM CFD, shown in Figure 5.2. It was divided into 360, 160 and 140 in x , y and z dimensions, respectively, generating total nodes of 8 million. The near wall grid was 0.001 mm and with an expansion ratio of 1.2 to fulfil the mesh requirement of y^+ .

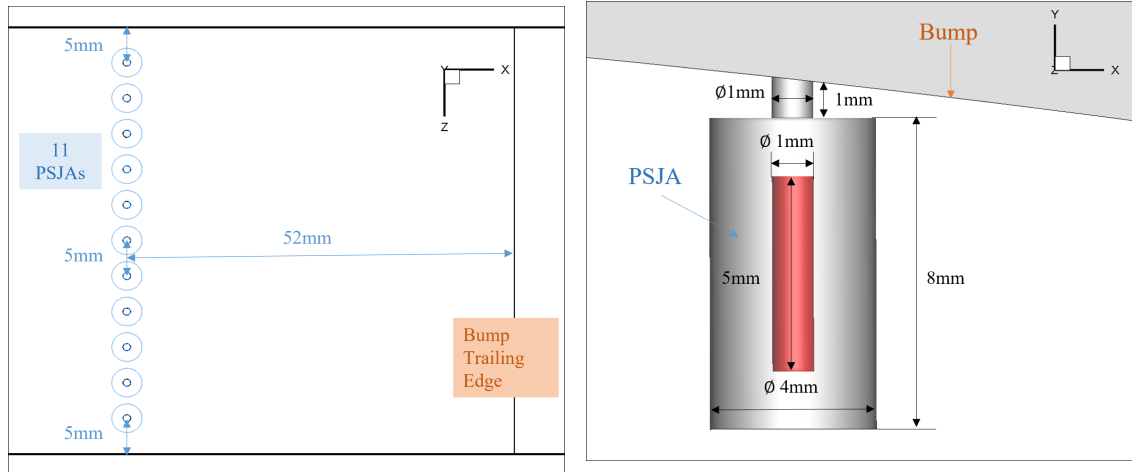


Fig. 5.3 Array PSJAs setup in with-control numerical models. Left: top view of 11 PSJA distribution; Right: enlarged size of single PSJA.

The structure of arrays of PSJAs was embedded into the tunnel, shown in Figure 5.3. There were 11 PSJAs located underneath the bump at $x = 300$ mm with a distance of 52 mm to the bump trailing edge, which is 20 mm (4δ) upstream to the shock foot position ($x = 320$ mm). Each PSJA was distributed at an equal distance of 5 mm from each other and to the symmetry and side wall. The structure and mesh of a PSJA are shown in Figure 5.4. It had

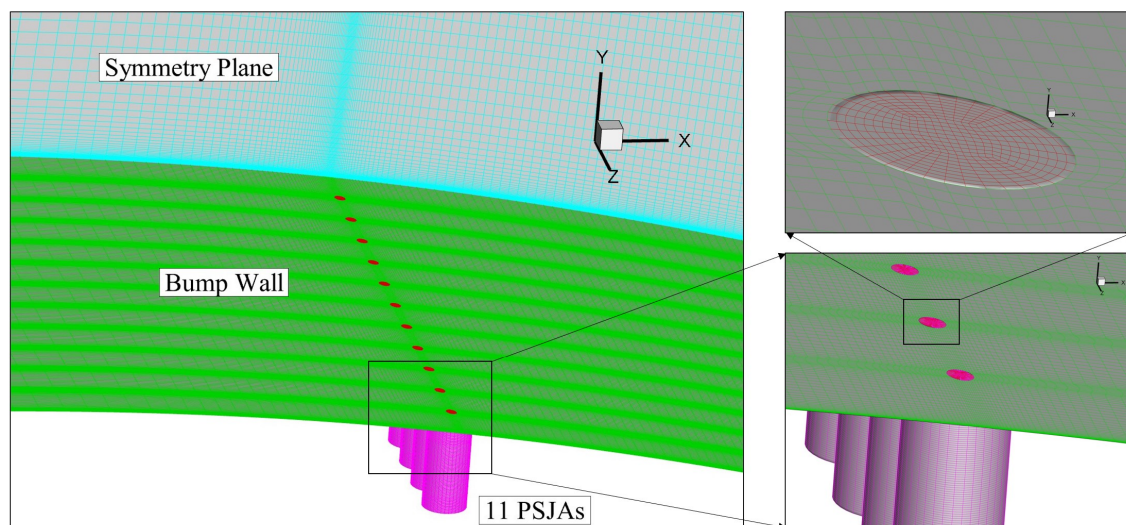


Fig. 5.4 Computational mesh of with control numerical models. Left: the overview of 11 PSJAs and the bump wall; bottom-right: enlarged figure of single PSJA; upper-right: enlarged figure of the mesh of the nozzle exit.

an orifice of 1 mm in diameter and 1 mm in height. The diameter (D_c) and height (H) of the cavity were 4 mm and 8 mm, which equated to a total cavity volume of 100 mm^3 . The red domain (Diameter 1 mm $\times$ Height 5 mm) was set at the plasma kernel, which was added with the energy deposition. The PSJA mesh is shown on the right with 0.1 million nodes.

5.1.2 Numerical Method

In this study, the commercial CFD solver ANSYS Fluent was used to solve Unsteady Navier-Stokes equations (URANS). The compressible coupled density-based solver was adopted for numerical simulations. The air ideal gas model was used to model gas properties, and the Sutherland equation was adopted to simulate the kinematic viscosity of air, which was sensitive to the temperature. The second-order upwind discretization schemes were chosen to compute convective fluxes. The least squares cell-based method was adopted to compute the viscous terms. To simulate the turbulence effect, different turbulence model was selected and compared in the next section of mesh independence and validation. The realize $k - \varepsilon$ turbulence model with standard wall function treatment was adopted based on its best consistency with baseline experiment. The boundary conditions have been chosen to match the experimental configuration described in Figure 5.1; both upper and lower walls are considered adiabatic walls, and the boundary layers start developing in the settling chamber. The inlet pressure of the tunnel is 101325 Pa, and the outlet pressure condition is adjusted to place the shock wave close to the position in the experimental configuration (approximately

$p = 62$ kPa at $x = 0.65$ m). For the PSJAs and wind tunnel connection, an interface is set. The orifice and the cavity are set as an adiabatic wall. The bottom of the PSJAs is set to be a pressure inlet of 101325 Pa, generating the steady micro jets without energy deposition in the red domain and arc-discharge pulsed micro jets with energy deposition.

The initial conditions were set as 101325 Pa for pressure and 300 K for temperature. The left side edge was set as a symmetry wall representing half of the wind tunnel. The fixed walls, including the cavities with their channels, were set as a no-slip, adiabatic condition with the temperature set to be 300 K. The deposition energy ($E_d = 5.7$ mJ) was added to red mesh regions constantly within certain times as Chapter 3. The time step size was 10 ns for the calculation, and the convergence criteria were $1e^{-6}$ for mass, velocity, energy and turbulence.

5.1.3 Mesh Independence and Validation

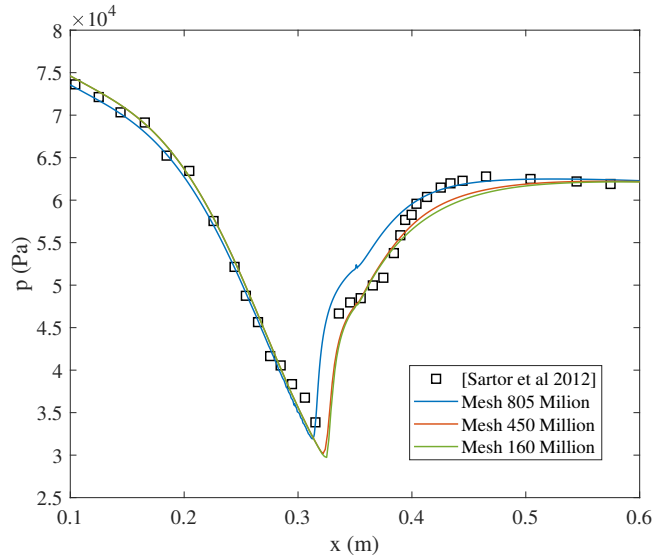


Fig. 5.5 Wall pressure comparison between the experimental results and the RANS solution.

The mesh independence is firstly validated by the wall pressure comparison between experimental results and RANS simulation results with different sizes of mesh, shown in Figure 5.5. The static pressure rises at $x = 320$ mm, corresponding to the shock foot. The re-circulation bubble is characterised by a small pressure plateau, and after the separated zone, the pressure reaches the value imposed at the downstream boundary. RANS computations under coarse, medium and fine mesh numbers are in fair agreement with the experimental investigation, while the fine mesh is able to capture the location of the pressure increase more

accurately compared with the medium and coarse. Also, considering the mesh connection with the PSJAs domain, the fine mesh will be used to simulate the baseline and with control models further.

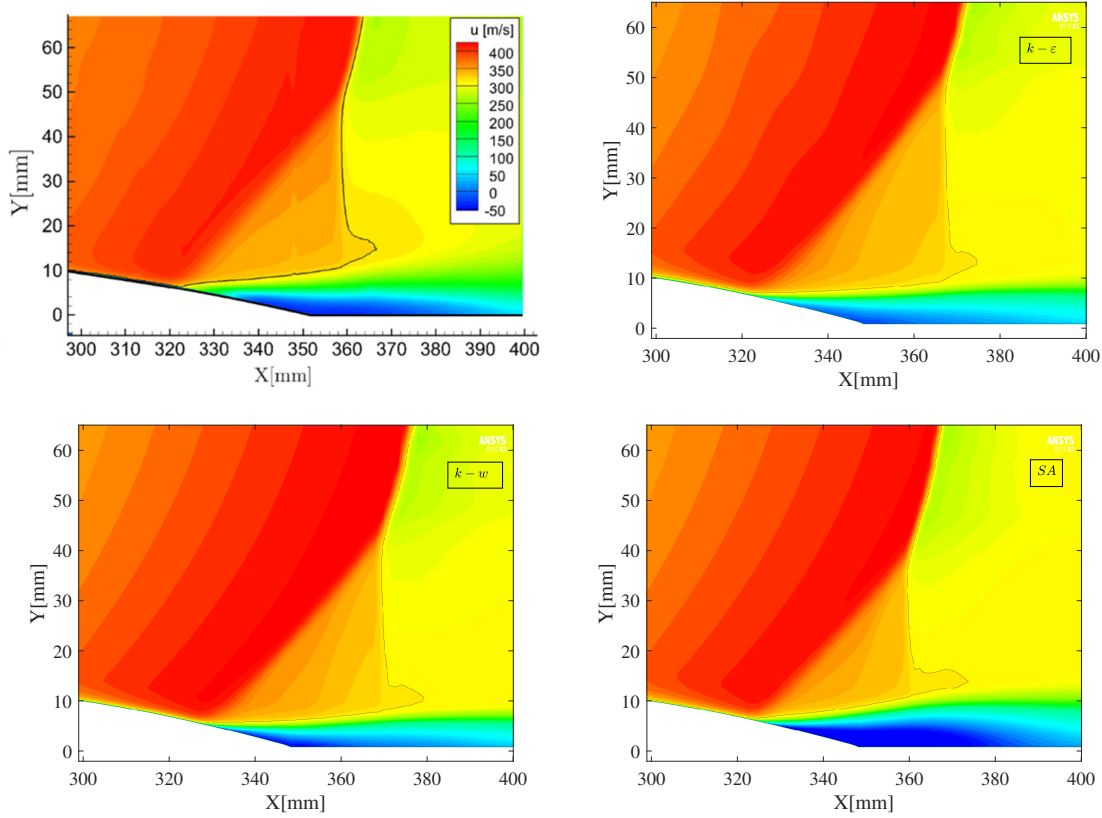


Fig. 5.6 Comparison of velocity fields between the experimental PIV measurements and the numerical results with different turbulence models. Top-left: Experimental results of baseline model [85]; top-right: numerical results based on $k - \varepsilon$ model; bottom-right: numerical results based on $k - \omega$ model; bottom-right: numerical results based on SA model.

Figure 5.6 shows a comparison between the experimental time-averaged PIV measurements obtained by Sartor et al. [85] and those of the RANS simulation using different turbulence models. The black line in four sub-figures is the iso-contour of $Ma = 1$ (shock position). The shock position in the result of $k - \varepsilon$ model is mostly consistent with the experimental result, while the other two models both lead to an extended tail in the foot of the shock position. On the other hand, the bottom part of the shock position (at $x = 320$ mm) in the experiment is slightly upward than the results from the $k - \varepsilon$ model and $k - \omega$ model but closer to the SA model. In the $k - \varepsilon$ model, the turbulence is assumed to be isotropic and homogeneous, and the model uses separate transport equations for the turbulent kinetic energy (k) and the rate of dissipation of turbulent kinetic energy (ε). The $k - \varepsilon$ model tends to

over-predict the turbulence levels in regions of high shear and strain, leading to a suppression of the boundary layer downstream of SWBLI. The Spalart-Allmaras (SA) model, on the other hand, uses a single transport equation for the turbulent viscosity, which is related to the turbulent kinetic energy and the specific dissipation rate. The SA model takes into account the anisotropy of the flow and the influence of the pressure gradient on the turbulence. But the SA model apparently overpredicts the thickness of the boundary layer downstream of the bump because it includes the effect of the turbulence damping function. Overall, the $k - \epsilon$ model is chosen as the turbulence model to solve the simulation.

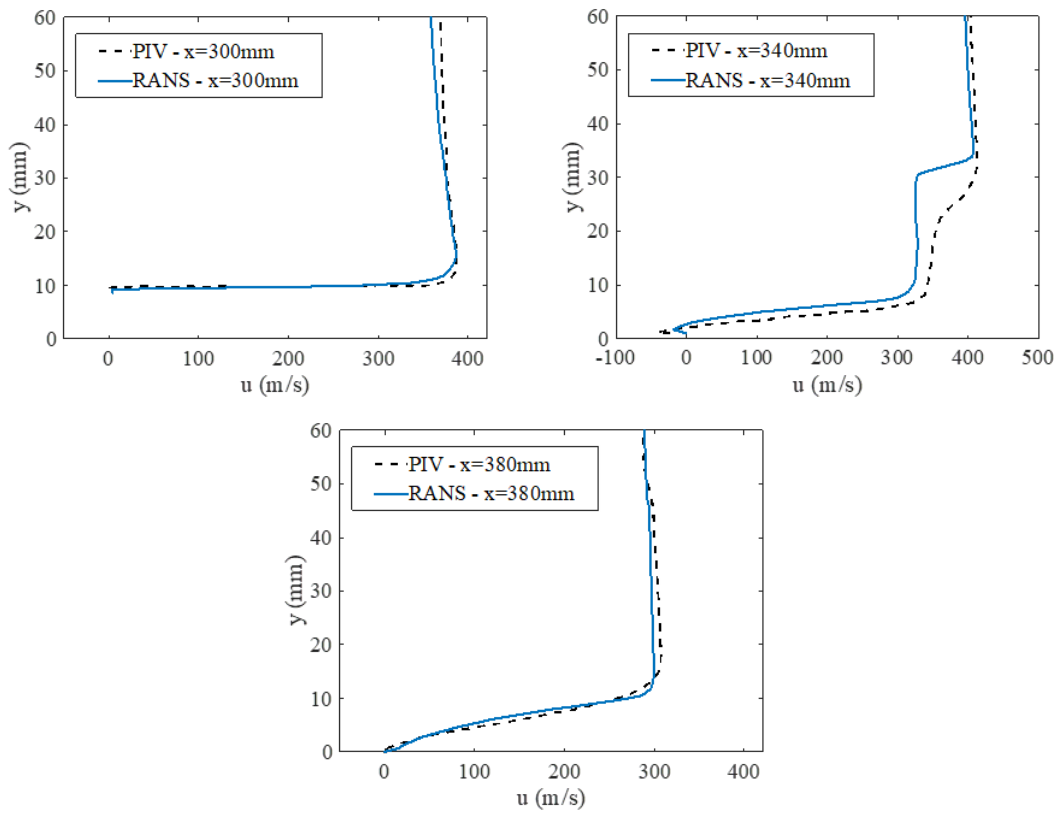


Fig. 5.7 Velocity profiles from the numerical simulation and the PIV measurements at different streamwise locations of x .

Figure 5.7 presents three velocity profiles, taken upstream of the shock wave ($x = 300$ mm), in the interaction region ($x = 340$ mm) and downstream of the separated zone ($x = 380$ mm). The PIV measurement and the RANS result are in fair agreement outside the separated region, with a slight velocity deficit in the numerical simulation. However, at $x = 340$ mm, PIV measurements indicate similar velocity profiles inside the re-circulation zone and in the supersonic region, but a different distribution across the shear layer. This discrepancy

can be attributed to the different λ shapes of the shock. The RANS results also show this phenomenon, but with a higher shear layer distance from the wall.

5.2 Results and Discussion

5.2.1 Evolution of Arc-Discharge Forced Micro Jets Flow

Considering the low-pressure wind tunnel situation, the essential plasma synthetic jet actuator can not be applied directly in this case, which lacks air supplied into the cavity and cannot establish the refreshing process. Therefore, the plasma actuator is developed with an atmosphere air supply at the bottom of the cavity, which can also provide air supplies as steady micro-jets when the arc discharge is off.

Plasma kernel

This section presents an analysis of the evolution of arc-discharge forced micro-jets flow, encompassing the plasma kernel and blast wave generation in the cavity of array plasma actuators and the micro-jets flow forced by the arc-discharge. The temperature contour at the spanwise plane of $x = 300$ mm within $30 \mu\text{s}$ is shown in Figure 5.8, depicting the evolution of the plasma kernel within the cavity. The red region indicates the deposition of energy within the initial $2 \mu\text{s}$. As expounded in Chapter 3, at $t = 2 \mu\text{s}$, the arc-discharge phenomenon has not yet interrupted the overall flow domain above the orifice. For each actuator cavity, there is a noteworthy temperature rise within the center of the cavity, up to 2500 K, due to the delayed response of the convection and conduction.

At $t = 10 \mu\text{s}$, the hot plasma kernel expands, with its top side being pushed near the orifice exit, featuring a sharp edge. The temperature of the plasma kernel decreases significantly to 450 K at $t = 20 \mu\text{s}$ due to the mixing of inlet fresh air from the bottom, which efficiently cools down the hot domain. Moreover, the plasma kernel transforms into a spindle shape, with a narrow top and an expanded bottom size, as generated by the pressure rise in the cavity. At $t = 30 \mu\text{s}$, the temperature distribution within the cavity becomes uniform at a low level of around 315 K. However, there is no significant temperature rise at the orifice exit, indicating that the hot plasma kernel has dissipated within the cavity, and only a small fraction of thermal energy has been pushed out.

Figure 5.9 presents the temperature distribution along line 1. The temperature distribution at the orifice exit of different actuators is generally similar. At $t = 10 \mu\text{s}$, the temperature rises from 270 K to 300 K and continues to increase to 310 K at $t = 40 \mu\text{s}$. The temperature then decreases to 295 K at $t = 50 \mu\text{s}$. The overall temperature rise is not significant in comparison

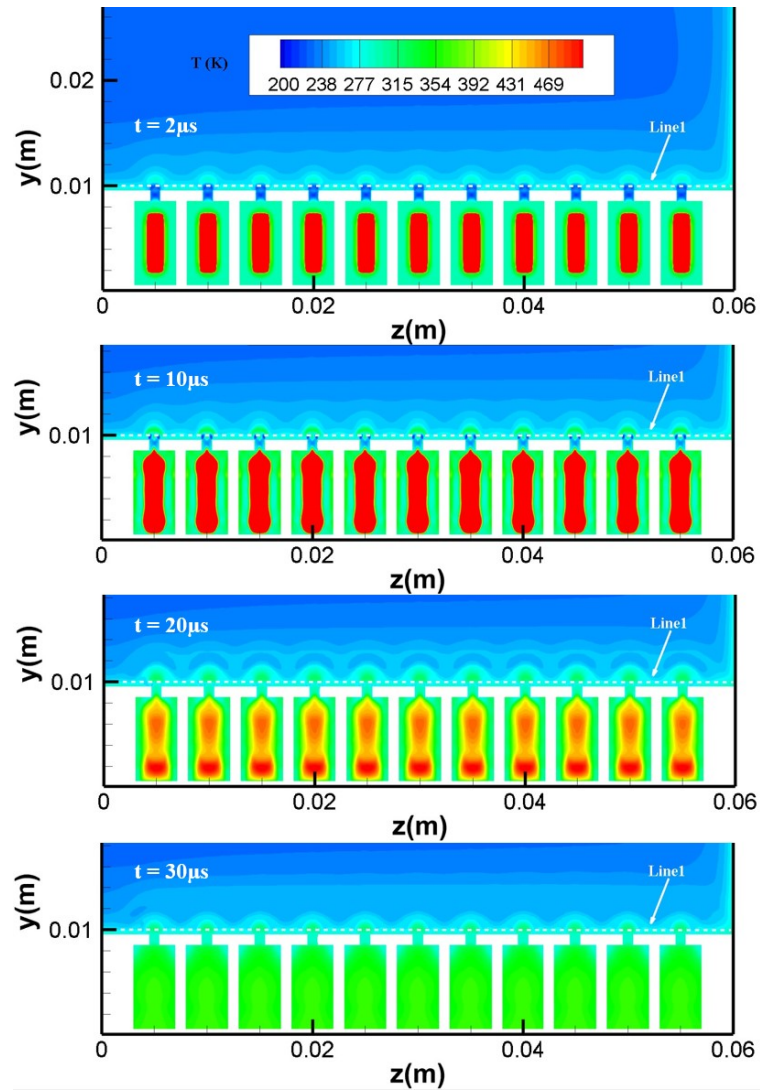


Fig. 5.8 Temperature contour at spanwise plane of $x = 300$ mm from $t = 2 \mu s$ to $t = 30 \mu s$.

with Figure 3.11 in Chapter 3. Therefore, the arc-discharge forced micro-jets flow, in this case, does not exhibit a substantial thermal effect.

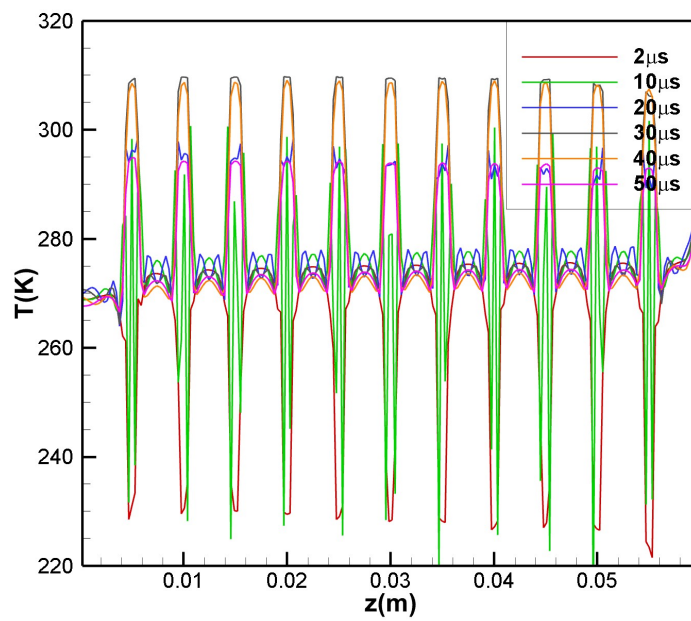


Fig. 5.9 Temperature distribution along line 1 in Figure 5.8, located above the exit of the jet orifice at $y = 10$ mm.

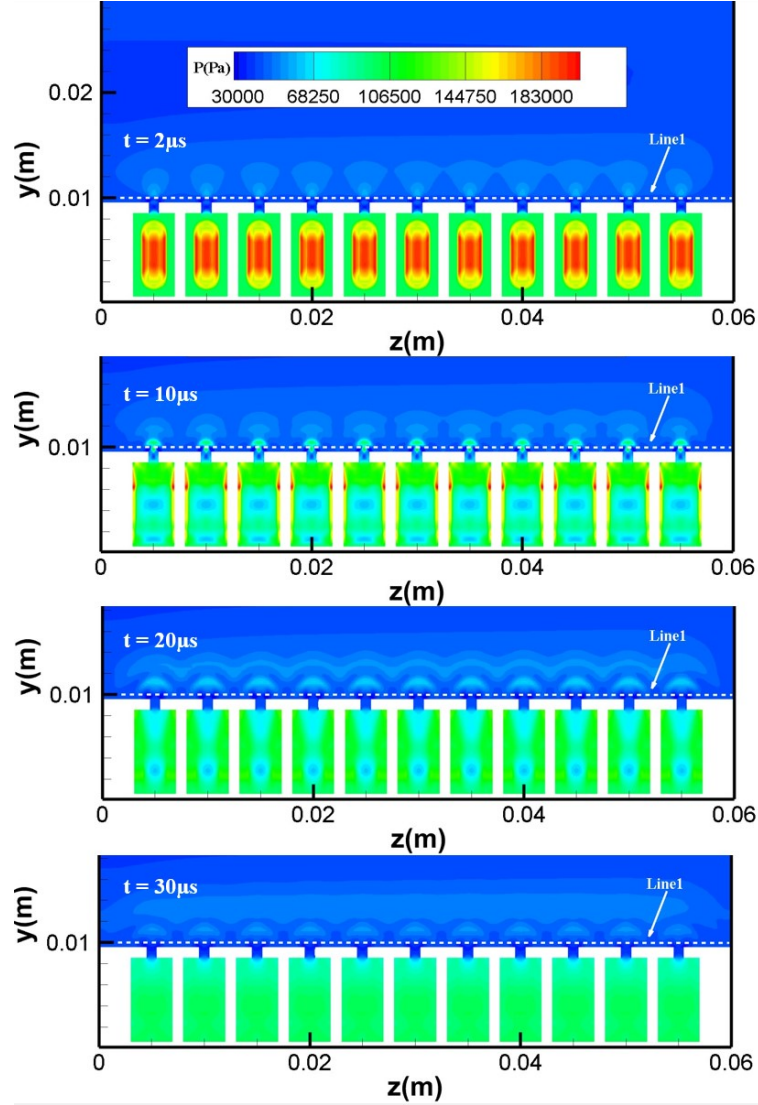
Blast wave

Fig. 5.10 Pressure contour at the spanwise plane of $x = 300$ mm from $t = 2 \mu\text{s}$ to $t = 30 \mu\text{s}$.

In Figure 5.10, the evolution of the blast wave via pressure distribution at the spanwise plane of $x = 300$ mm after a single arc discharge is presented. At $t = 2 \mu\text{s}$, the bubble-like blast wave induced by the energy deposition of arc discharge is visible within the cavity, with a high red value in the z direction and a comparatively lower yellow value in the y direction. The other domain of the cavity maintains atmospheric pressure. For steady micro-jets conditions, this generates a pressure differential between the cavity and the main outflow region, thereby sustaining the micro-jet flow. At $t = 10 \mu\text{s}$, in contrast to the thermal energy transportation demonstrated in Figure 5.8, the pressure response is much quicker

and significant. An evident pressure change is observed at the orifice exit right after the arc discharge. The compression waves downstream of the blast wave in the cavity create a fan-shaped contour at the exit. Additionally, the blast wave reflection within the cavity is captured in the z direction, with reflected pressure along the cavity's vertical and top walls. Due to the bottom boundary condition of the inlet flow, there is no reflection at the bottom. At $t = 20 \mu\text{s}$, a significant pressure wave is present above the orifice, propagating first to $y = 0.014 \text{ m}$, followed by a second pressure wave to $y = 0.012 \text{ m}$. Meanwhile, the pressure reflection within the cavity has dissipated, leaving only a weak pressure wave within the central part, primarily induced by the plasma kernel's thermal effect. This phenomenon can be attributed to the air supply from the bottom, which cannot sustain the pressure reflection within the cavity. At $t = 30 \mu\text{s}$, the overall cavity pressure has returned to atmospheric pressure, and only a faint pressure wave is observed outside of the orifice.

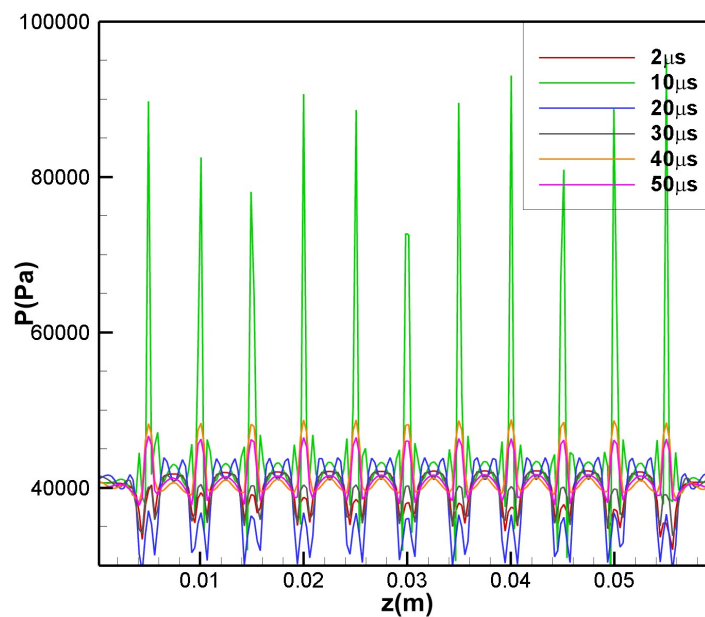


Fig. 5.11 Pressure distribution along line 1, from $t = 2 \mu\text{s}$ to $t = 50 \mu\text{s}$.

In Figure 5.11, a waveform of the first pressure rise peak value at the orifice exit of the plasma actuator array is presented along line 1. It is observed that the pressure wave propagation is influenced by the position of the actuators along the z direction. Notably, the first blast wave exhibits a slightly different propagation position at $t = 10 \mu\text{s}$ in Figure 5.10 leading to pressure value fluctuation in Figure 5.11 at $t = 10 \mu\text{s}$. However, the subsequent pressure rise diminishes significantly, indicating that the actuator's strong forced effect is only one pulse combined with a much weaker pressure fluctuation force. Therefore, to enhance the micro-jets' force effect, a more optimal design method for this type of plasma actuator

could be to close the bottom inlet flow during the high-pressure reflection duration, which is normally within $50 \mu\text{s}$ (see Figure 3.13 in Chapter 3).

Jet velocity profile

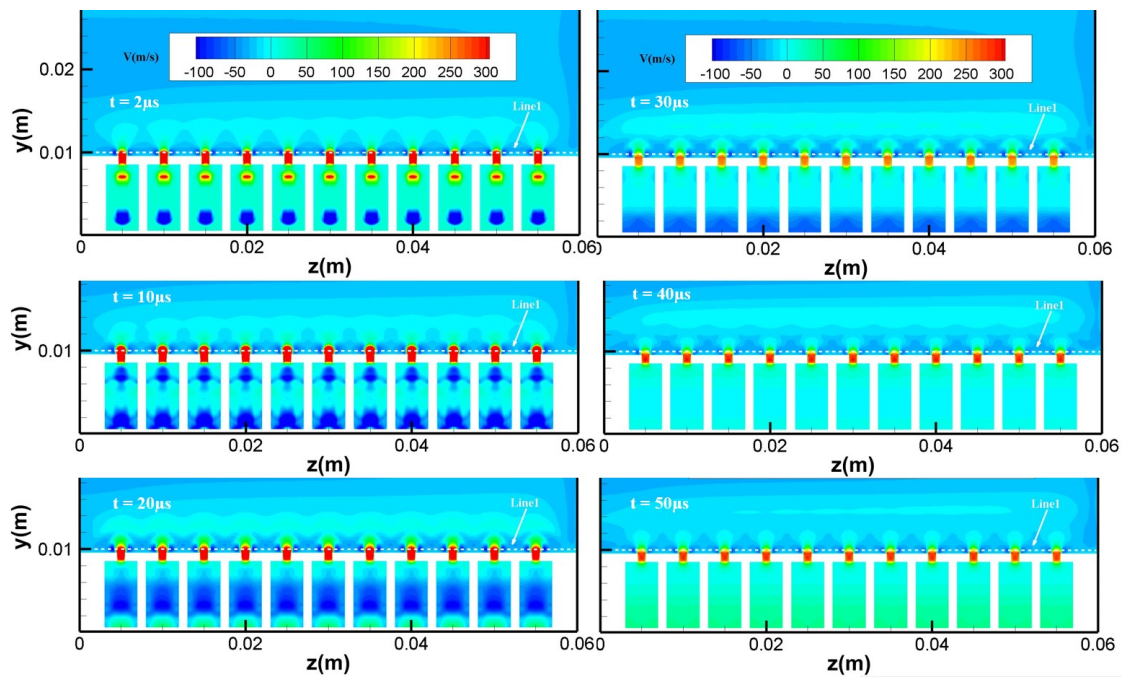


Fig. 5.12 Velocity contour at spanwise plane of $x = 300 \text{ mm}$ from $t = 2 \mu\text{s}$ to $t = 50 \mu\text{s}$.

Figure 5.12 shows the distribution of the y-direction velocity field at the central cross-section of the actuator ($x = 300 \text{ mm}$) after the first discharge. Without the arc discharge, the pressure ratio of the inlet and outlet of the jet cavity reached around 3, leading to a choked jet flow, shown as the red domain at the orifice. At $t = 2 \mu\text{s}$, when the energy loading was completed, a high-speed impact zone appeared upward and downward in the cavity due to the rapid release of energy. At $t = 10 \mu\text{s}$, because of the first blast wave force, the jet choke domain extended upwards across line 1. Also, the reflection of the blast wave can be revealed by the velocity contour at the bottom of cavities. Then, after the first blast wave passed, the pressure decreased in the cavity near the orifice region. So, the jet flow velocity showed a decrease, and the red choked domain at orifices also shrank and weakened over time until $t = 30 \mu\text{s}$. Then, because of the air supply from the bottom of the cavities, the pressure in cavities recovered, and the flow kept choking at orifices over time with an increasing velocity, shown in Figure 5.13(bottom).

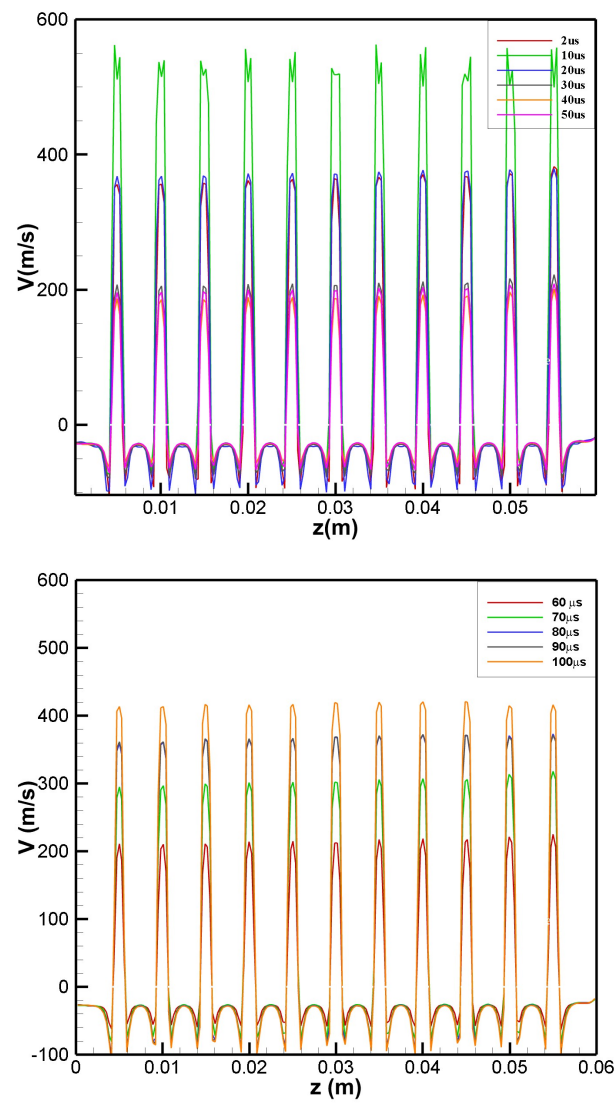


Fig. 5.13 Velocity distribution at line 1 from $t = 2 \mu s$ to $t = 100 \mu s$. Upper: velocity fast response during $2 \sim 50 \mu s$; bottom: velocity recovery $60 \sim 100 \mu s$.

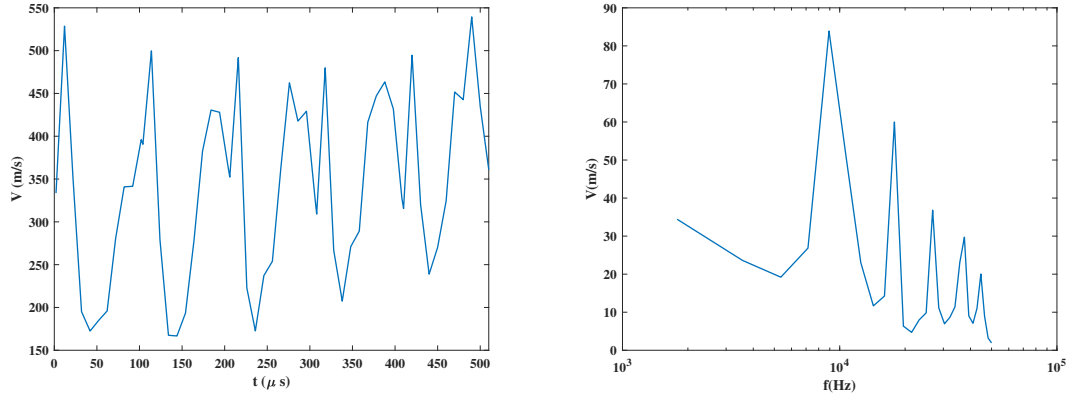


Fig. 5.14 Velocity at the exit of orifice $(x, y, z) = (0.3, 0.01, 0.03)$. Left: Jet velocity signal for five pulses duration; Right: Fast Fourier transform of the velocity signal.

Figure 5.13 presents an analysis of the temporal evolution of the velocity distribution along line 1, encompassing a time window ranging from 2~100 μ s. The results indicate that the velocity magnitude attained its peak value at the exit after 10 μ s, followed by a gradual decay towards the steady-state value, which was reached within the subsequent 10 μ s. Beyond this point, the velocity experienced minor fluctuations around the steady-state level, which was approximately 300 m/s. The analysis further reveals that the jet characteristics along line 1 remained unaltered for different actuator positions. The velocity variation at the exit of the orifice located at $(x, y, z) = (0.3, 0.01, 0.03)$ can be depicted as a function of time in Figure 5.14. The plot spans a duration of 500 μ s and corresponds to five arc discharge pulses of varying durations. A significant waveform is observed over the course of one pulse duration, which is 100 μ s. The evolution of the jet velocity exhibited a similar pattern as illustrated in Figure 5.14(Left). To further explore the frequency characteristics of the velocity signal, the fast Fourier transform was applied and presented in Figure 5.14(Right). The resultant spectrum indicates the presence of a characteristic frequency of 10 kHz, which corresponds to the operation frequency of the plasma actuator.

The effect of micro jet flow control on the boundary layer flow depends on the direction and intensity of the jet injection. In this case, the micro jets are directed perpendicular to the surface, and they can cause a boundary layer detachment from the surface, which can lead to increased turbulence and then sustain the adverse pressure gradient induced by the shock wave. As shown in Figure 5.15, the introduction of the jet at $x = 300$ mm modified the boundary layer of the incoming flow and formed a smaller recirculation zone downstream of the orifice. The high-speed jet causes significant changes to the boundary layer. Initially, at $t = 50$ μ s, the jet flow creates a turbulent mixing layer, which is the region where the high-speed jet mixes with the shear layer. As the mixing layer develops, from 50 μ s to 100

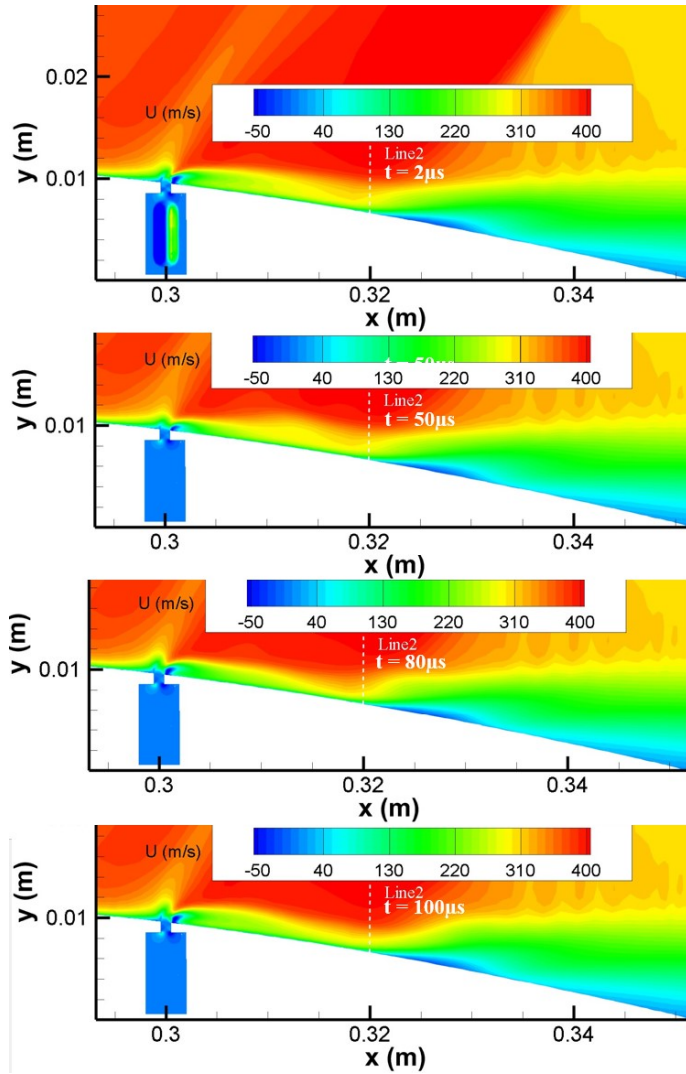


Fig. 5.15 Velocity distributions at the streamwise-section of $z = 0.01$ m, from $t = 2 \mu\text{s}$ to $t = 100 \mu\text{s}$.

μs , it causes changes to the boundary layer near the surface. The high-speed jet cause the boundary layer to become thinner and more turbulent, which can increase the rate of heat and mass transfer between the surface and the surrounding fluid. The increased turbulence can also sustain the great adverse pressure gradient at $x = 0.32$ m, where separation happens for the baseline model.

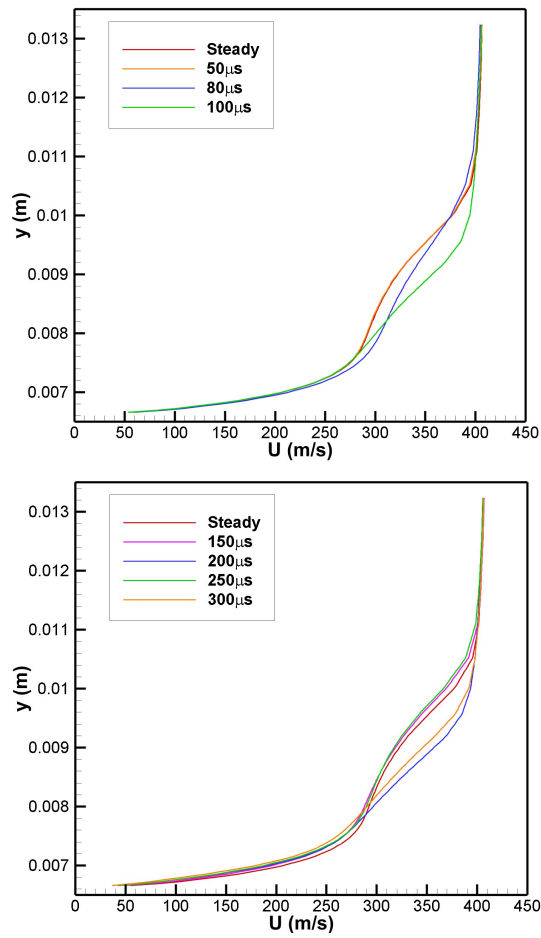


Fig. 5.16 Velocity distributions PSJA control at the downstream location of line 2 corresponding to different times. Up: 2~100 μ s, Bottom : 150~300 μ s.

Figure 5.16 depicts the velocity curve at line 2 in Figure 5.15 subsequent to the initiation of a hot jet by the plasma actuators, spanning from $50 \mu\text{s}$ to $100 \mu\text{s}$ and $150 \mu\text{s}$ to $300 \mu\text{s}$, and compared with the steady state information. The overlap between the steady state and $t = 50 \mu\text{s}$ shows that the downstream boundary layer at line 2 remained unaffected by the jet flow at the time $t = 50 \mu\text{s}$. However, by $t = 80 \mu\text{s}$, the boundary layer was propelled upwards, and the thickness and shape of the boundary layer underwent alterations. Following the generation of arc discharge force, an escalation in the velocity profile near the bottom wall within the $y < 0.011 \text{ m}$ range emerged in contrast to the steady state, as illustrated by the blue and green lines in Figure 5.16. Subsequently, the near-wall boundary layer velocity progressed further at $t = 100 \mu\text{s}$, gaining more strength than the steady state, once the plasma-generated jet had fully affected the downstream region. The following two pulses from $100 \mu\text{s}$ to $300 \mu\text{s}$ shows the same boundary layer evolution trend, which is at $200 \mu\text{s}$ and $300 \mu\text{s}$ the near-wall boundary layer velocity gaining more strength than the steady state.

5.2.2 Evolution of Vortex Pairs Induced by Arc-Discharge Micro-Jets

The generation and motion of the vortex structures are the mechanisms used for the steady and pulsed jets in supersonic cross flow to control the shock wave/boundary layer interaction. Therefore, the corresponding analysis of the vorticity $\vec{\omega}$ is the key point, defined as the curl of the flow velocity:

$$\vec{\omega} = \nabla \times \mathbf{u} \quad (5.1)$$

Figure 5.17 and Figure 5.18 present the x -component of the vorticity in two different downstream locations of the array in a time sequence. The counter-rotating vortex pairs (CVP) can be clearly seen in the frame. The counter-rotating vortex pair structure observed to dominate the jet cross-section was generated in the near field region of the jet. Such vortex pair can be considered to be associated with the evolution of vorticity in the jet's shear layer as well as pressure differences between the upstream and downstream regions of the jet [52]. In this study, CVPs generated by micro-jets separated by 5 mm developed downstream independently of each other. The vortex size in the central area was the same, while the size of the vortex near the wall was smaller. This is due to the strong adverse pressure gradient near the wall. The downstream vortex system periodically changed size with time, and the vorticity closer to the sidewall surface had larger variation amplitudes.

Figure 5.19 shows the 3D view of the evolution of the vorticities at $t = 40 \mu\text{s}$. The counter plane shows the streamwise vorticity. The surface streamlines on the wall are coloured white to reveal the motion of the vortices. The range of influence of the streamwise rotating vortex is more concentrated, and the core height of the main vortex pair is lower. As the distance

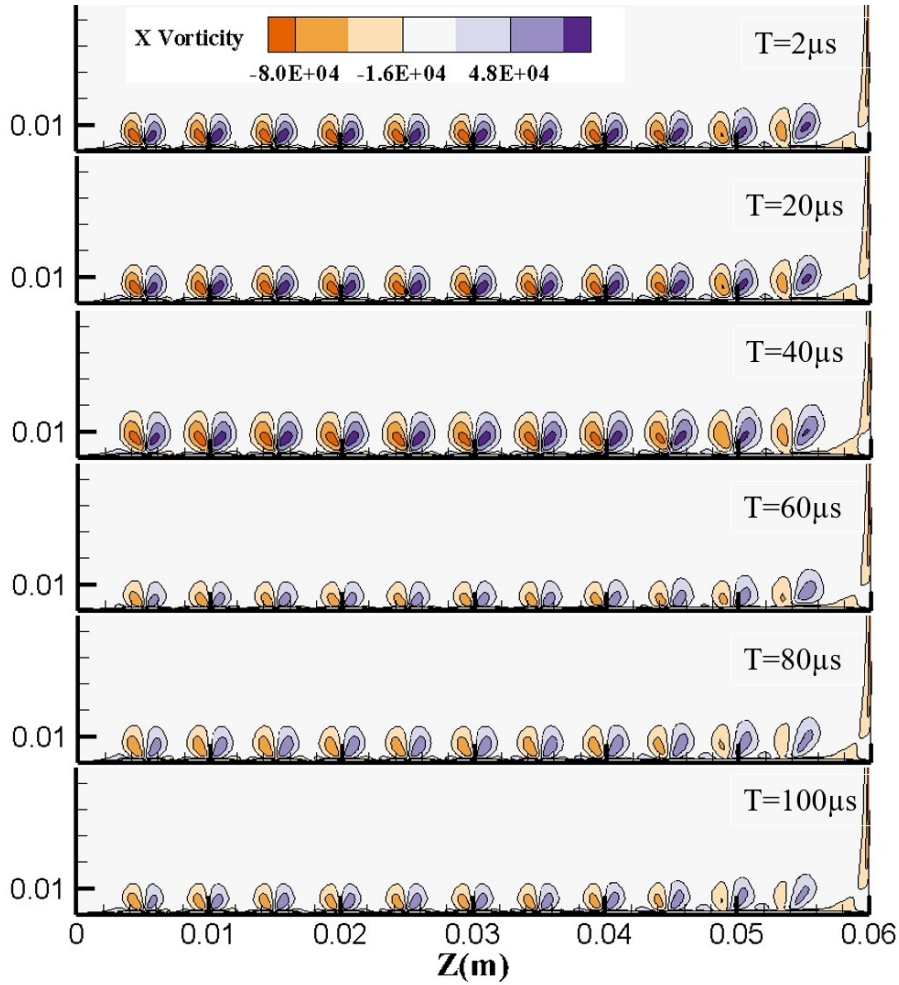


Fig. 5.17 Vortices (x -component) produced by Arc-Discharged Forced Micro Jets configuration on a transverse plane at $x = 310$ mm.

from the orifice increased, the streamwise rotating vortex intensity decreased monotonically. The intensity of the vortex also decreased along the streamwise direction. In the boundary layer, the intensity of CVPs typically decreases over time due to several factors. One factor is the effect of viscosity, which causes vortices to diffuse and lose intensity as they move through the boundary layer. This diffusion is caused by the transfer of momentum and energy between the vortex and the surrounding fluid, which causes the vortex to decay. Another factor is the effect of entrainment, which causes the vortices to draw in surrounding fluid as they move through the boundary layer. This entrainment causes the vortex core to broaden and become less intense over time, reducing its effectiveness in controlling the flow. As a result, the effectiveness of CVPs in controlling the flow may decrease over time, and the design and implementation of CVP-based flow control techniques must take these factors into account. In our case, the near side wall CVP became weak quickly with the increasing

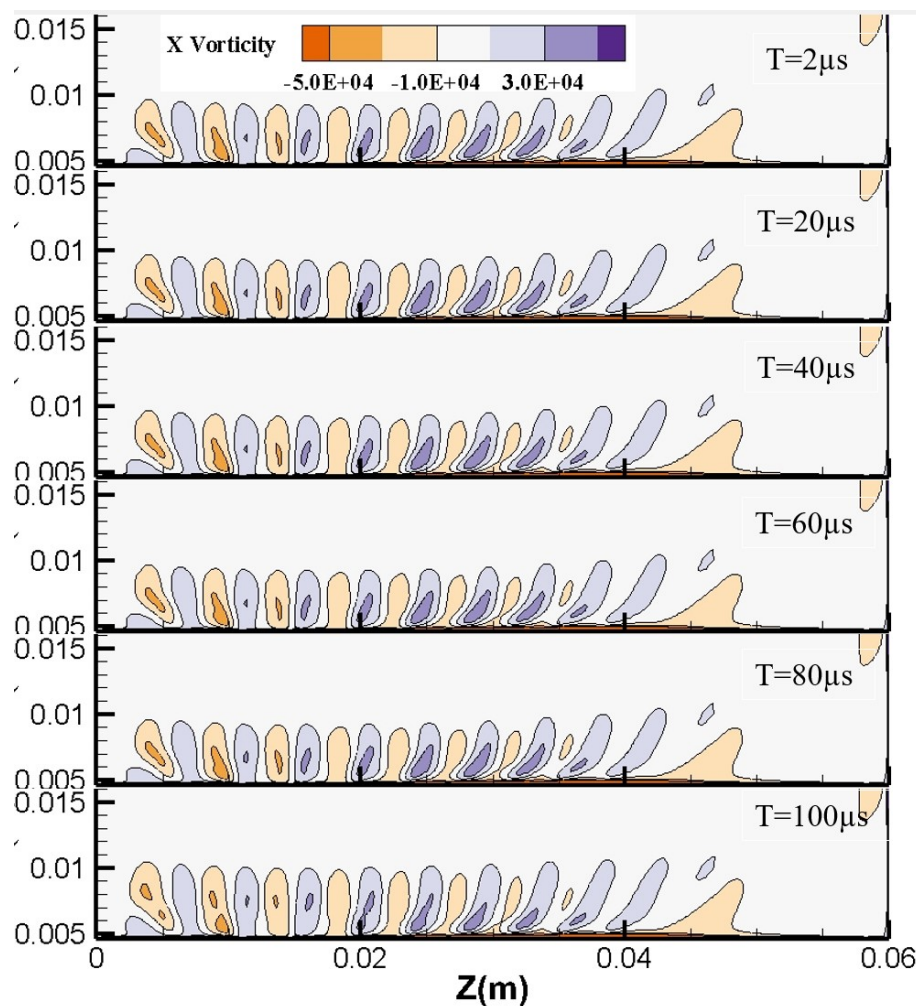


Fig. 5.18 Vortices (x -component) produced by Arc-Discharged Forced Micro Jets configuration on a transverse plane at $x = 330$ mm.

distance and nearly disappeared at plane $x = 330$ mm. Therefore, the separation bubble near the corner was hard to be destroyed by the evolution of these CVPs.

Figure 5.20 and Figure 5.21 shows the spanwise vorticity evolution at plane $z = 10$ mm and $z = 50$ mm. When the jet was vertical, large-scale vortex structures would appear in the downstream separation zone, which was still clearly visible on the two-dimensional plane. It made the separation zone split in the spanwise direction. The larger the vortex structure was, the more thorough the split was. When encountering the separation zone, the energy was, thus, not sufficiently large to tear it apart, shown in Figure 5.19. This mainly reflects the behaviour of the trailing counter-rotating vortex pair. The main counter-rotating vortex pair should have moved above the separation zone. As the jet was injected into the flow, it generated a Z vorticity that was oriented in the plane of the injection angle. The

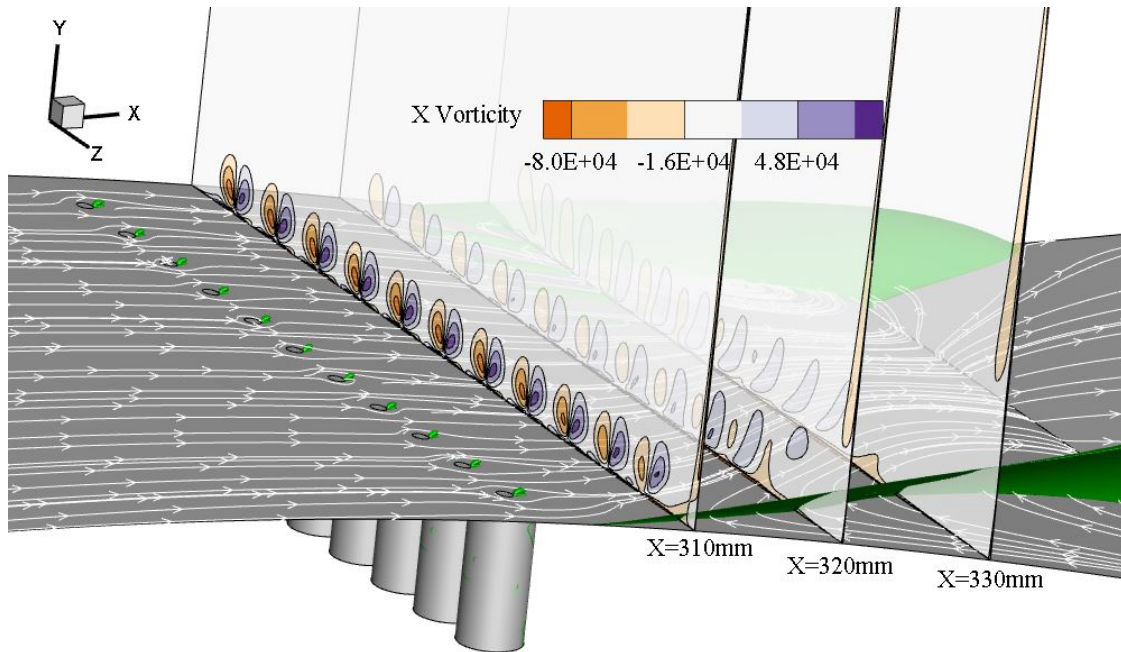


Fig. 5.19 The streamwise vorticity contours and the white surface streamtraces on slices $x = 310$ mm, $x = 320$ mm and $x = 330$ mm at $t = 40 \mu s$. Surface streamlines are coloured white. The iso-surface ($u = 0$ m/s) is coloured green.

vorticity grew and developed downstream as it interacted with the surrounding flow, leading to the formation of a series of counter-rotating vortices. As the Z vortices interacted with the boundary layer, they induced a mixture of fluid and reduced the size of the separation region. The vortices caused the flow to undergo a three-dimensional distortion, which induced a spanwise velocity component that interacted with the streamwise flow and the boundary layer. Overall, the interaction of the Z vortices with the separation region is a complex process that involves the exchange of momentum and energy between the vortices and the flow. The vortices can cause the separated flow to reattach to the surface, reducing the size of the separation region and improving the overall performance of the flow.

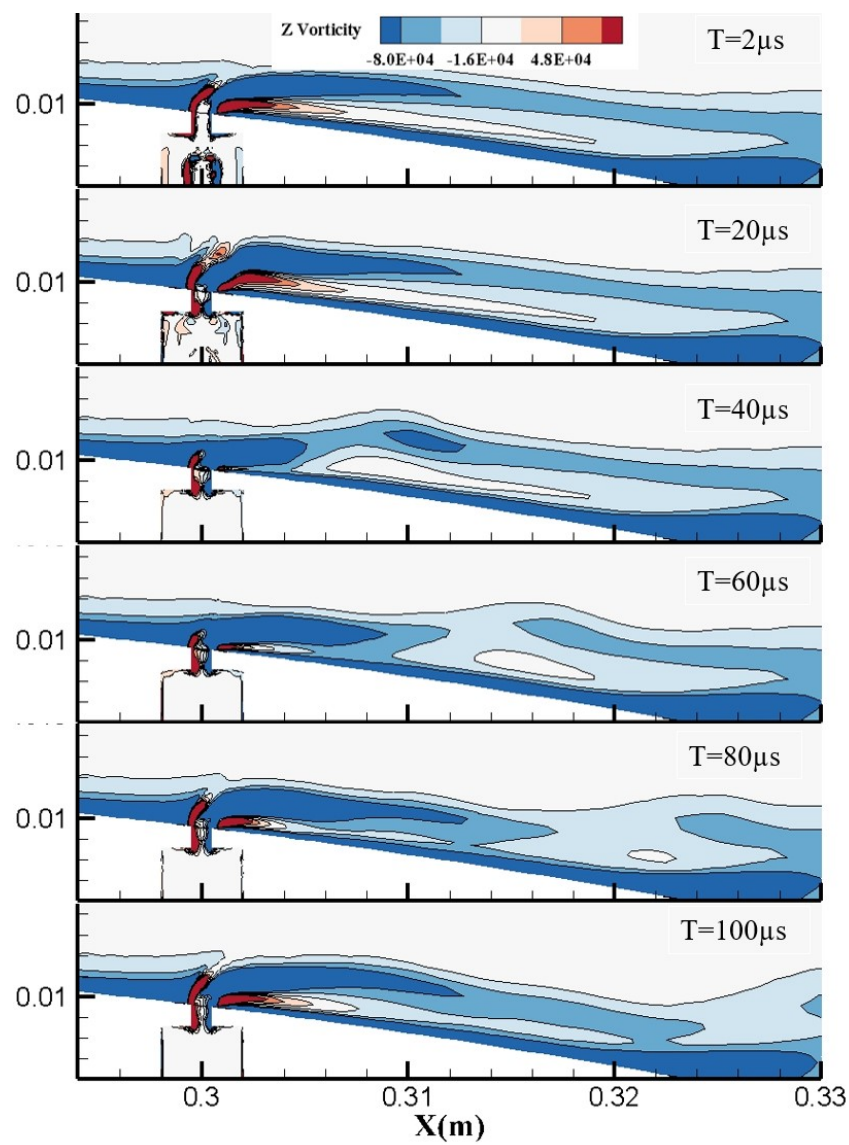


Fig. 5.20 Contours of spanwise vorticity (z -component) on time sequence at $z = 10$ mm.

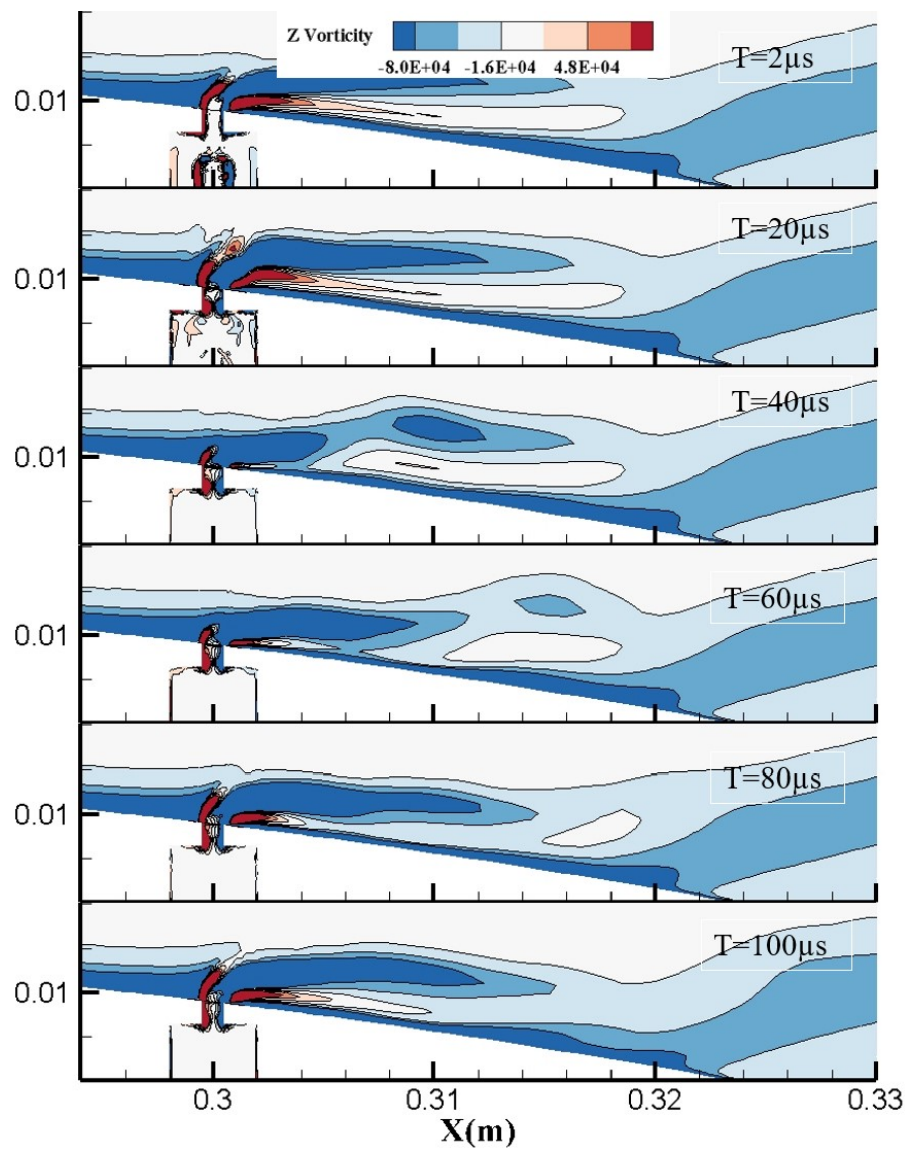


Fig. 5.21 Contours of spanwise vorticity (z-component) on time sequence at $z = 50$ mm.

5.2.3 Control Effect of Steady Micro Jets on the SWBLI

In this section, the control effect of steady micro-jets on the overall performance of the SWBLI is assessed. The goal of the micro-jets flow control is to reduce the separation zone of the transonic SWBLI. This should improve both the homogeneity and the total mechanical energy of the flow downstream of the SWBLI, where the losses of stagnation pressure due to the boundary layer and the corner flow separation are clearly visible.

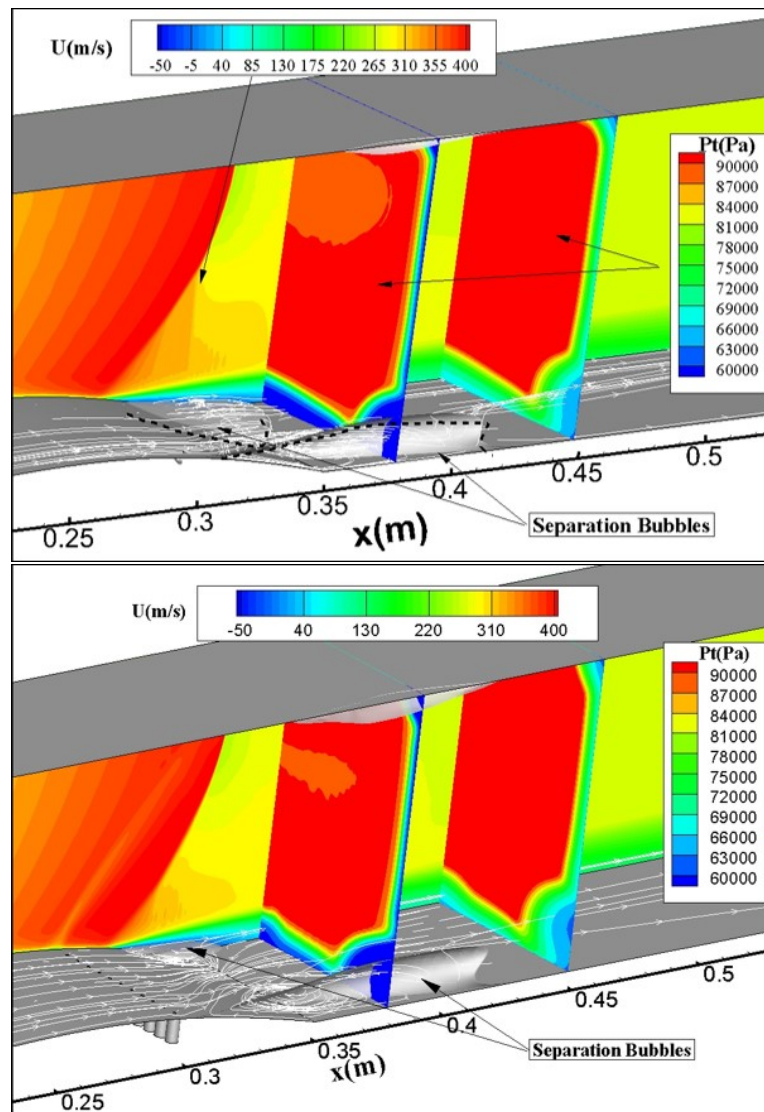


Fig. 5.22 Comparison between baseline (upper) case and with steady micro-jets control (bottom) case. including gray surface characterized as the iso-contour of velocity $u = 0$, white near wall streamline, symmetry plane U velocity counter and spanwise plane pressure counter at $x = 0.38$ m and $x = 0.45$ m.

Figure 5.22 presents the velocity distribution of the symmetry plane, the pressure distribution of the cross-section (at $x = 0.38$ m and $x = 0.45$ m), the size of the separation bubble, and the near wall streamlines for both the baseline and controlled conditions. The Reynolds-averaged Navier-Stokes (RANS) simulations capture the characteristic features of SWBLI, such as the λ -shaped shock wave, separation bubble formation, and downstream total pressure loss. The results indicate that the addition of micro-jets flow causes the breakdown of separation bubbles in the central zone and reduces the size of the separation zone. This effect is due to the momentum addition by the micro-jets, which has been discussed in the last section. The micro-jets generate a series of counter-rotating pairs of vortices that enhance the mixing of the boundary layer with the external flow. At the same time, the total pressure recovery in the centre bottom plane is increased at $x = 0.38$ m and $x = 0.45$ m, which means an aerodynamic efficiency increase of the wind tunnel inlet air. However, no substantial change is observed in the near-sidewall separation bubble, Which in some circumstances is enlarged. Because the total pressure counter at $x = 0.38$ m and $x = 0.45$ m plane's bottom corner side is decreased with a slightly larger corner bubble with a low value. Last but not least, at the symmetry plane, the jet flow also induced the compression wave from the jet outlet position of $x = 0.3$ m. The shock λ -shaped above the separation region is changed. The overall wave loss is decreased, generating a larger total pressure increase in the following spanwise plane middle region. In conclusion, the findings provide insights into the complex SWBLI phenomena and demonstrate the potential of micro-jet control in mitigating the adverse effects of SWBLI.

The distribution of the wall friction coefficient in the baseline model and the control model are compared in the cloud diagram in Figure 5.23. The white area in the diagram corresponds to negative friction coefficients, which indicate flow separation. In the baseline model, a large area is covered by the central and corner separation zones, and the friction coefficient distribution is roughly uniform along the spanwise direction. In contrast, the control model exhibits a strengthened effect of shear stress downstream on both sides of the jet, with a weaker effect closer to the sidewall surface. The central separation area is significantly reduced, indicating a notable weakening of the separation. However, the sidewall separation area slightly increases compared to the baseline model. Further analysis of the underlying mechanisms and optimization of the control strategies can lead to improved performance and efficiency in such applications. Table 5.1 shows the center separation and corner separation area for baseline and with micro-jets control. The center separation domain reduced by 82%, while the corner separation increased by 12%. So the total separation area decreased by 44 % for the micro-jet control model.

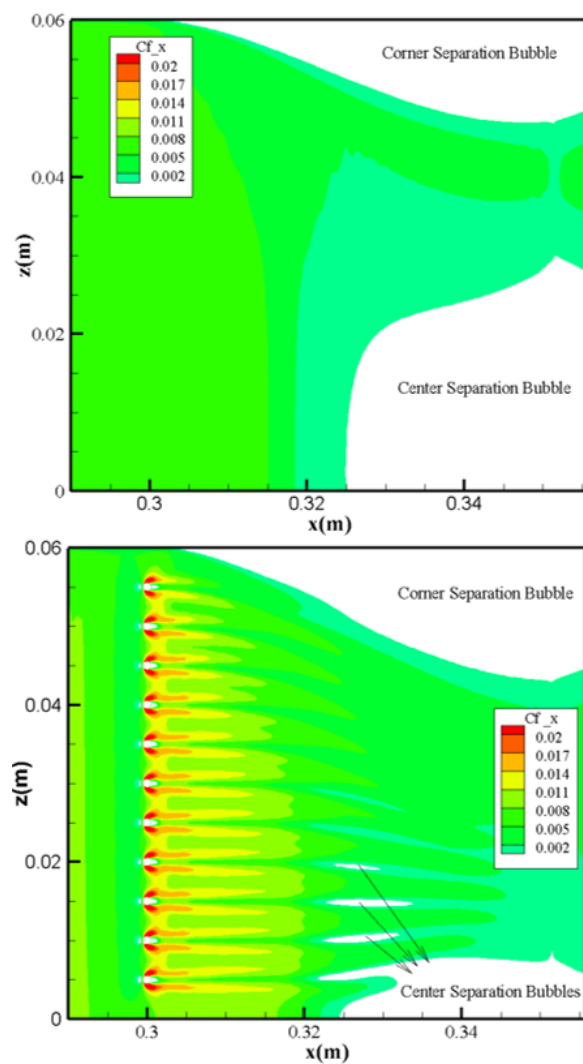


Fig. 5.23 Skin friction coefficient near the wall. Upper: baseline model; bottom: steady micro-jets model.

Table 5.1 Steady micro-jets flow control separation effect.

Area (mm ²)	Center Separation	Corner Separation	Total Separation
baseline	1128	779	1907
With control	199	876	1075
Changed by	-82%	+12%	-44%

5.2.4 Control Effect of Arc-Discharge Forced Micro Jets on the SWBLI

With the jet being activated, a discharge excitation of 10 kHz was added to form an arc-forced jet. This could change the stable inactive jet flow control to the active disturbance control, thereby improving the low-frequency instability characteristics of SWBLI flows. As the arc discharge is turned on at 10 kHz, the jet flow downstream will have the same fluctuation reaction. So the separation area at the centre and the corner also changed. Figure 5.24 shows the centre and corner separation area changes with time. The corner bubble fluctuated at a smaller amplitude compared to the centre separation, and the overall trend is horizontal. However, the centre separation area shows an increased fluctuation rate changed from 200 to 225 mm². This means although arc discharge forced jet flow does have the potential to interact with corner separation bubbles, the overall separation is still increased.

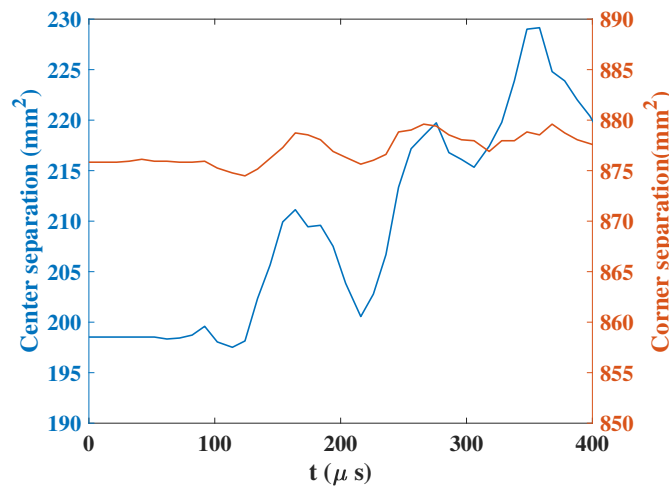


Fig. 5.24 Center and corner separation area change with time.

Table 5.2 gives a quantitative comparison of the separation region in both cases. The central area of the separation region decreased dramatically by -81%. But at the same time, the corner separation area on the wall increased by 12 %, resulting in a total separation area reduction of 43%, which is slightly smaller than the steady micro-jets flow control effect.

Table 5.2 Time-averaged arc-discharge forced micro-jets flow control separation effect.

Area (mm ²)	Center Separation	Corner Separation	Total Separation
Baseline	1128	779	1907
With control	209	877	1086
Changed by	-81%	+12%	-43%

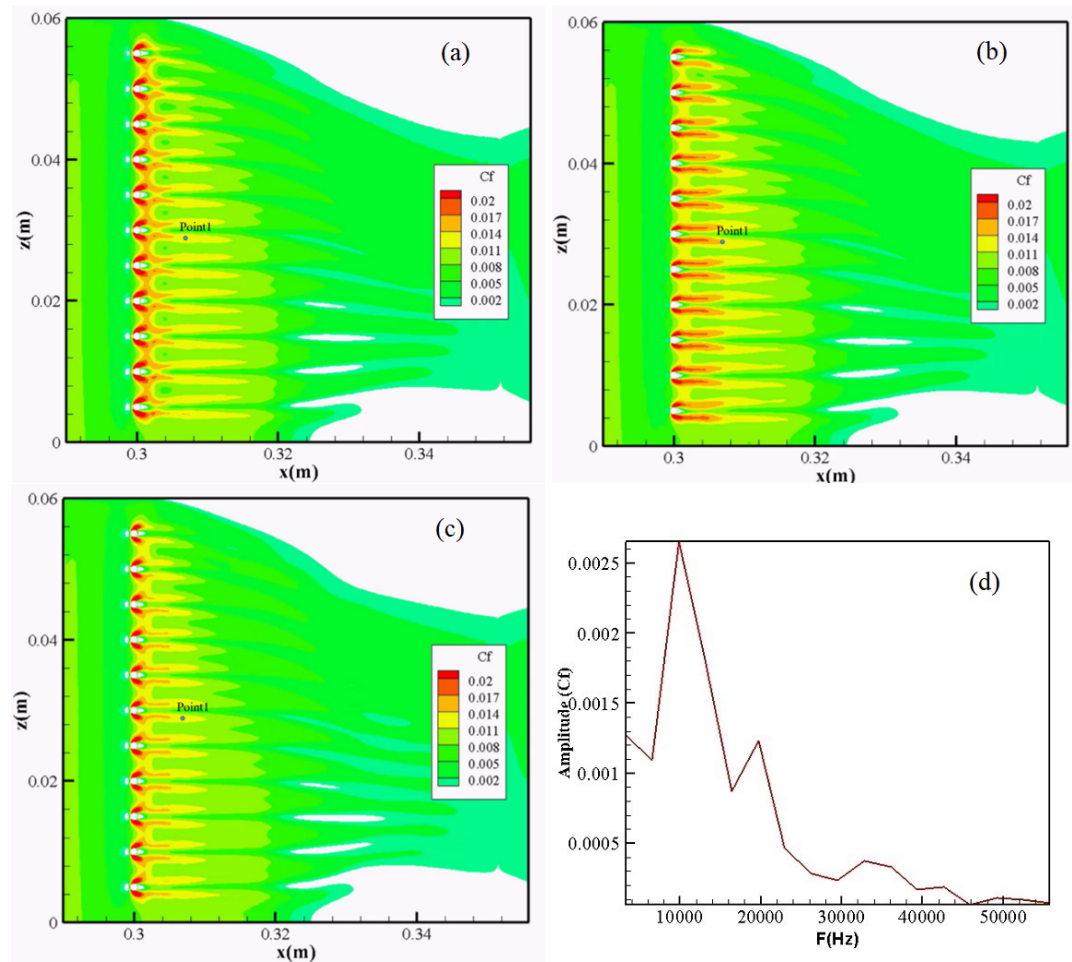


Fig. 5.25 Unsteady simulation results of coefficient of skin friction near the wall at different times and frequency characteristic at point1. (a): $t = 20 \mu s$; (b) $t = 50 \mu s$; (c) $t = 100 \mu s$; (d) FFT results

The distribution of the wall friction coefficient in the arc control model is presented in cloud diagrams in Figure 5.25. The white region represents the negative value of the friction coefficient, corresponding to where flow separation happened. At $t = 20 \mu s$, the electric energy in the cavity was transformed into jet flow mechanical energy, and a strong shock wave was generated through the orifice, which interfered with the original jet flow. Because of the block of the jet flow, the flow velocity increased on both sides of the orifice outlet. Over time, the perturbation developed downstream. At $t = 50 \mu s$, the friction coefficient of the jet on both sides downstream was enhanced. At the same time, the separation bubble on the wall was subjected to a specific impact. At the end of one discharge cycle ($t = 100 \mu s$), the size and range of the friction coefficient of the left and right jets shrank, and the wall separation area decreased significantly. The vibration spectrum of monitoring point 1 is

presented in Figure 5.25(d). The main frequency of the downstream vibration response is consistent with the discharge frequency (10 kHz). It shows that the disturbing jet had a more substantial interference effect on the SWBLI flow field.

5.3 Conclusions

In this chapter, various micro-jet flow control methods are presented for regulating the separation zone in supersonic shock wave boundary layer interaction (SWBLI). These methods comprise both passive and active control techniques for steady micro-jets and arc-forced micro-jets. To assess the efficacy of these methods, numerical simulations were conducted, and the results were compared. The baseline model was calculated using the commercial software Fluent, and the Reynolds-averaged Navier-Stokes (RANS) calculations were found to be in agreement with experimental observations. Subsequently, the basic model was modified by introducing an array of pulsed supersonic jet actuators (PSJAs) with an inlet air supply at the cavity bottom.

The steady micro-jets can significantly reduce the overall separation area of the transonic SWBLI by 44%, albeit with a weaker impact on the separation area near the sidewall. On the other hand, the unsteady micro-jets flow forced by the arc exhibits a considerable interference effect on the SWBLI flow field, primarily in the case of sidewall separation. Specifically, steady micro-jets do not alter the separation bubble at the sidewall, while unsteady jets can induce vibrations at the corner separation edge. The micro-jets generation of streamwise rotating vortex pairs plays a crucial role in mitigating the separation zone. Furthermore, the upwash and downwash motions induced by the central unsteady vortex pair and trailing vortex pair complete the momentum exchange with the boundary layer and contribute to the control of the separation zone.

In this case, the arc-forced micro-jets did not yield a superior flow control effect concerning the reduction of the separation bubble. However, it did generate downstream flow fluctuation frequencies consistent with the actuator pulse frequency. Furthermore, it effectively transported substantial momentum exchange to the boundary layer, leading to streamwise and spanwise separation line variation. Nonetheless, an optimised design is necessary to enhance the applicability of arc-discharge forced micro-jets for SWBLI flow control.

Chapter 6

Conclusions & Future works

This chapter of the dissertation provides a comprehensive summary of the diverse range of results and conclusions that have been presented throughout this work. The primary objective of this study is to develop a fundamental understanding of the working principles of arc discharge plasma actuators, with the intention of leveraging this knowledge to achieve flow control of shock-wave boundary-layer interactions. In this regard, two distinct types of actuators, namely localized arc discharge plasma actuators (LAFPA) and plasma synthetic jet actuators (PSJAs), were comprehensively investigated. The flow mechanism of the actuation was analyzed using a multifaceted approach involving theoretical analysis, Schlieren experiments, and numerical simulations. These techniques were employed to visualize and scrutinize the underlying flow phenomenon that occurs after the arc discharge of a single plasma actuator and assess the application for the SWBLI flow control. The main conclusions and future works are as follows.

6.1 Conclusions

- 1) For the flow characteristic of LAFPA, the high-speed Z-type Schlieren experiments captured the formation of a thermal plasma kernel, shock wave after an arc discharge and the thermal hot plume evolution in the atmosphere. The reaction zone developed upward mainly due to thermal diffusion, and the expansion speed of the thermal core zone was nearly 10 m/s at the very beginning. It could be estimated that the conversion of electrical energy to kinetic energy was limited, and most energy dissipated as thermal energy for the hot plume evolution. Moreover, the influence of different discharge frequencies (0.5 kHz, 1 kHz, 2 kHz) was experimentally studied. The range of the interference area gradually increased with the increase in frequency. But with a frequency higher than 1 kHz, the average height of the interference area did not

increase significantly; only the width was expanded. On the other hand, the fluctuation characteristic near the surface was consistent with the actuator operation frequency. Moreover, the flow phenomenon of LAFPA with electrodes outside the surface was also studied for comparison. Different flow evolution patterns have been well compared, and a conceptual model has been given for LAFPA with electrodes flush to the surface and electrodes outside the surface. The surface LAFPA had a large effect in the vertical direction, which indicated a larger momentum effect compared to LAFPA with electrodes outside the surface.

- 2) For PSJA, five numerical cases of PSJA with different cavity volumes and deposition energy were simulated. The effects of dimensionless cavity volume and energy on the energy transformation characteristics of PSJA have been compared and analysed. The evolution of the plasma kernel generated by the arc discharge within the cavity and outside the orifice was well captured. The propagation and reflection of blast waves generated by the arc discharge in the actuator cavity were clarified, and the reflection characteristic frequency was defined using geometry parameters. The plasma kernel and high-pressure waves both play dominant roles in sustaining the jet flow of PSJA. For different PSJAs, these simulations also allowed a better understanding of how the convective phenomena strongly influenced the hot plasma kernel expansion in the cavity. These studies reinforce the importance of the localised deposition simulations performed with the simplified geometry, especially for large cavity actuators. For a tiny cavity and high deposition energy, the propagation speed of the jet front held relatively steady in the whole jet phase. However, the large cavity case had a slower jet propagation rate at first but increased later within time. Then, the mechanical energy transfer efficiency was discussed. The proportion of kinetic energy increased linearly with non-dimensional deposition energy, while the proportion of potential energy decreased linearly with non-dimensional cavity volume as its magnitude held steady.
- 3) An improved 1D code has been established in this study, which can better reflect the velocity at the exit of the orifice for PSJA. Most of the 1D codes in the literature did not consider the pulsating effect of the continuous reflection of the shock train in the cavity, resulting in the deviation of the velocity peak and drop curves from the actual situation. This work has improved the original code by introducing the plasma kernel theory and the empirical formula of cavity pressure fluctuation. Calculations have proven that with specific deposition energy, theoretical plasma kernel formation radius and time could be estimated, and the peak temperature and pressure rise within the cavity could

be more realistic. The improved calculation results of the velocity evolution at the PSJA orifice exit are in better agreement with the 3D simulation results.

- 4) The DNS data analysis expands the flow control mechanism of LAFPA to supersonic SWBLI. First, the overall control effect was analyzed based on pressure, friction coefficient, and velocity profile data, and the mean control effect was obtained. The time-averaged separation bubble changed from a small, uniform spanwise region to a larger, triangular body. This is because the flow block at the LAFPA position accelerated the side flow, enhancing the ability to resist flow separation on both sides. The flow control mechanism of the LAFPA was also discussed in detail. It was found that precursor shock waves (PSWs) were emitted during LAFPA operation, which coalesced into an oblique shock and merged with the separation shock, leading to the re-organization of the shock wave system. The intensity of turbulence flow underneath the shock wave became significant. Additionally, the positive thermal gradient induced by LAFPA operation near the surface tended to cause the fluid to expand near the surface and become less dense, which could result in sustaining the adverse pressure gradient. Finally, the conceptual model of LAFPA for SWBLI flow control was given.
- 5) The steady micro-jets and arc-discharge forced micro-jets were conducted to reduce separation zones in a transonic shock-wave boundary layer interaction flow control. The steady microjet flow could effectively reduce the central separation area of the transonic SWBLI, but it had a weak effect on the separation area of the sidewall. The control of the separation zone is mainly achieved by the streamwise rotating vortex pair generated by the micro jets. For arc-discharge forced micro-jet flows, the velocity profile in the separation zone fluctuated and had the same responding frequency as the plasma actuator. There exhibited a significant interference effect on the SWBLI flow field, primarily in the case of sidewall separation. Overall, the arc-forced micro-jets did not show a superior flow control effect in terms of the reduction of the separation bubble. However, it effectively transported momentum exchange to the boundary layer further downstream.

6.2 Future Works

This section of the dissertation includes a clear statement of the task that remains.

- 1) The theoretical and numerical simulation investigation for LAFPA will be necessary. So far, the flow field evolution of LAFPA is well captured through the Schlieren

experiment. However, the numerical results for localized arc filament simulation need to be estimated and compared to experimental data. An accurate model for LAFPA, which can predict the thermal flow on the surface or between the electrodes perfectly, will contribute to further investigation in flow control.

- 2) For PSJA, shortcomings in the 1D model related to modelling the arc discharge and heat transfer are of immediate interest for future work. The development of fluctuation characteristics due to multiple discharges deserves further study to improve the applicability and accuracy of the PSJA design. The 1D code needs further correction due to thermal effects. Because multiple consecutive releases will further exacerbate the thermal effect, previous studies have fully demonstrated this. At the same time, due to the limited discharge frequency of PSJA, the change of pulse impact with the increase of frequency is also worthy of further study.
- 3) High-speed Schlieren or PIV experimental studies are needed to evaluate the control effect of interaction with an SWBLI flow field. For the LAFPA application case, the pulsed arc excitation has a thermal effect and can induce the momentum effect in the boundary layer. Quantitatively measuring the changes in the temperature, pressure, velocity, and other parameters is necessary through the experimental method. Moreover, temperature and pressure sensors can be installed to monitor the process and reveal the thermodynamic effects of the PSJA. Last but not least, multiple pulse simulations and experimental measurements are needed to evaluate the effect of the plasma kernel model when the initial situation varies.
- 4) For the array of PSJAs applications, only the URANS calculation is carried out in this study, which cannot fully reflect the turbulent effect of jet development in the boundary layer. Further DNS or LES calculations and experimental studies are required. More computational and experimental verification work would also be of interest. There have been decades of research in flow control, and new control actuators are constantly being produced, enriching the subject. Active control methods based on discharge control give more possibilities for flow control. Combining actuators with existing passive rules can also have an interesting control effect. These deserve further exploration.

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Appendix A

Code

This is the main function the one-dimensional analytical model, which utilizes one of MATLAB's built in ODE solvers (ode45) based on explicit Runge-Kutta. See MATLAB help on ode45 for more information. The ODE solver finds the time history of cavity pressure, density, and temperature; the velocity of the air moving through the orifice of a PSJA.

```
%*****
```

```
%clear
%clc
%close all
format compact
global Ao V Cv Patm vo R Tatm rhoatm Q hc
% Load SparkJet design parameters
[Ao, V, Cv, Patm, vo, R, Tatm, rhoatm, Q, hc]=parameters;
```

```
%Define Initial Conditions
rhoc0=rhoatm;%Initial cavity density
Vc0 = V;%Initial cavity volume
m0=rhoc0*Vc0; %Calculate mass inside cavity
Tc0=Tatm+Q/(m0*Cv); %Initial cavity Temperature
U0 = 1e-5;%Initial interface1 velocity
T=[]; %Initialize T vector
Y=[]; %Initialize Y vector
```

```

Pc00=rhoc0*R*Tc0; %Initial cavity Pressure
r=hc/2;
dt=r/340;
rc=sqrt(Q/(0.005*3.94*Patm*1.4));% characteristic radius
Pk=Patm*(0.56*((1+4.8*(r/rc)^2)^(3/8)-1))^(-1)*1.4/(2*(1.4+1));
% Peak Pressure

%INPUTS
% t - time (sec)
% y - 4x1 vector containing the values of density,
% velocity, pressure, Volume
% respectively, with respect to time.
%
%OUTPUTS
% dy - 4x1 vector containing the changes in density,
% velocity, pressure, Volume
% respectively, with respect to time.

freq=86000; %actuator characteristic frequency
events=5; % pressure rise times
for i = 1:events
%rhoc0=rhoatm;
Pc0=Pc00+(i)*Pk/35;
%Run ODE solver with (redefined) initial conditions
options = odeset('RelTol',1e-6, 'AbsTol',...
[1e-6 1e-6 1e-6 1e-6]);
[t,y]=ode45(@PSJA_thermal,[(i-1)*(1/freq+1e-9)+dt i*1/freq+dt],...
[rhoc0 U0 Pc0 Vc0],options);
%Build time and variable vectors
Y(length(Y)+1:length(Y)+length(t),1:4)=y;
T(length(T)+1:length(T)+length(t),1)=t;
rhoc0=y(end,1);
U0=y(end,2);
Pc0=y(end,3);
end

```

```

for i = events+1:events+events
%rhoc0=rhoatm;
Pc0=Pc00-(i-events)*Pk/15;
%Run ODE solver with (redefined) initial conditions
options = odeset('RelTol',1e-6, 'AbsTol',...
[1e-6 1e-6 1e-6 1e-6]);
[t,y]=ode45(@PSJA_thermal,[(i-1)*(1/freq+1e-9)+dt i*1/freq+dt],...
[rhoc0 U0 Pc0 Vc0],options);
%Build time and variable vectors
Y(length(Y)+1:length(Y)+length(t),1:4)=y;
T(length(T)+1:length(T)+length(t),1)=t;
rhoc0=y(end,1);
U0=y(end,2);
Pc0=y(end,3);
end

for i = events+events+1 : events+40
%Run ODE solver with (redefined) initial conditions
options = odeset('RelTol',1e-6, 'AbsTol',...
[1e-6 1e-6 1e-6 1e-6]);
[t,y]=ode45(@PSJA_thermal,[(i-1)*(1/freq+1e-9)+dt i*1/freq+dt],...
[rhoc0 U0 Pc0 Vc0],options);
%Build time and variable vectors
Y(length(Y)+1:length(Y)+length(t),1:4)=y;
T(length(T)+1:length(T)+length(t),1)=t;
rhoc0=y(end,1);
U0=y(end,2);
Pc0=y(end,3);
end

% Plot time history of density, orifice velocity, pressure (kPa)
%figure
plot(T*1e6,Y(:,2),'--m','LineWidth',3)
%hold on

```

```

figure
plot(T*1e6,Y(:,3)/1000,'--b','LineWidth',2)
%figure
%plot(T*1e6,Y(:,4)*1e9,'--r','LineWidth',3)
xlabel('Time (\mus)','FontSize',24)
ylabel('See Legend','FontSize',24)
%set(gca,'FontSize',24)
%legend('1-D Velocity (m/s)')
%'1-D Pressure (kPa)')
%'1-D Density (g/m^3)',
%, '1-D Volume(mm3)'

function dy = PSJA_thermal(t,y)
global Ao V Cv Patm vo R Tatm Rair rhoatm
dy=zeros(3,1); %Algebraic Equations
T = y(3)/(y(1)*R); %Ideal Gas Law
dy(4)=0; % volume

%Define pressure boundary condition at orifice between choked and
%unchoked flow
if y(3)>1.893*Patm
Pe=y(3)/1.893;
elseif y(3)<=1.893*Patm
Pe=Patm;
end

if y(2)>0 %Stage 2 Discharge
%Mass
dy(1) = -y(1)*y(2)*Ao/V;
%Momentum
dy(2) = 1/y(1)*(((y(3)-Pe)*Ao-y(1)*abs(y(2))*y(2)*Ao)/vo-...
y(2)*dy(1));
%Energy
dy(3) = (0-((y(3)-Pe)+y(1)*(Cv*T+(y(2)^2)/2))*...
y(2)*Ao-vo* (y(1)*y(2)*dy(2) + 0.5*y(2)^2*dy(1)) ) /(Cv*y(4)/R);

```

```

elseif y(2)<0 %Stage 3 Refresh
%Mass
dy(1) = -rhoatm*y(2)*Ao/V;
%Momentum
dy(2) = 1/rhoatm*(((y(3)-Patm)*Ao-rhoatm*abs(y(2))*y(2)*Ao)...
/vo-y(2)*dy(1));
%Energy
dy(3) = (0-((y(3)-Patm)+rhoatm*(Cv*Tatm+(y(2)^2)/2))*...
y(2)*Ao-vo*(rhoatm*y(2)*dy(2)+0.5*y(2)^2*dy(1)))/(Cv*y(4)/R);
end
end

function [Ao, V, Cv, Patm, vo, R, Tatm, rhoatm,Q, hc]=parameters
%*****
%This function defines the design parameters for the PSJA.
%
%INPUTS (NA)
%
%OUTPUTS
% Ao - Orifice Area (m^2)
% V - Cavity volume (m^3)
% Cv - Specific heat of air
% Patm - Atmospheric Pressure (Pa)
% vo - Orifice Volume (m^3)
% R - Specific gas constant for air (J/kg*K)
% Tatm - Atmospheric Temperature (K)
% RM - Thermal Resistance of Macor
% Re - Thermal Resistance of electrodes
% Rair - Thermal Resistance of air inside SparkJet
% cavity
% rhoatm - Atmospheric Density (kg/m^3)
% Q - Capacitor Energy (J)
%*****
R=287.05; %Specific gas constant for air in J/kg*K
Cp=1004; %Specific heat of air for constant pressure
Cv=Cp-R; %Specific heat of air for constant volume

```

```
Tatm=288; %External flow temperature
Patm=101325; %External flow pressure
rhoatm=Patm/(Tatm*R); %External flow density using ideal gas law
Q=11.3e-3; %Energy discharged by spark
ro=0.002/2; %Orifice radius (m)
Ao=pi*ro^2; %Orifice area
ho=0.002; %Orifice height
vo=Ao*ho; %Throat volume
hc=0.004; %Cavity height
dc=0.008; %Cavity Diameter
wc=0.008; %Cavity width
Acc=wc*dc; %Cavity cross-sectional area
V=Acc*hc; %Cavity volume
end
```