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REVIEW PAPER

Recent Developments on Synthetic Jets

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ABSTRACT

Synthetic jet is a form of pulsatile jet where the flow is synthesised from the ambient air and it does not need any external source as the flow is induced from the fluid existing around orifice/nozzle. This property makes synthetic jet unique compared to pulsatile and continuous jets. Recently, the synthetic jet is being widely used for flow control, mixing and heat transfer enhancement in aerospace applications. Focused on reviewing the recent developments on synthetic jet characterization and their applications resulting from the development of advanced diagnosing tools.

Keywords: Synthetic jet, vortex ring, flow control, jet mixing process, heat transfer enhancement, turbulence

NOMENCLATURE

Re	Reynolds number
St	Strouhal number
Nu	Nusselt number
S	Stokes number
M	Mach number
D	Diameter
D_o	Diameter of the orifice
L	Characteristic length, stroke length
h	Slot width
b	Cross stream location
x	Streamwise coordinate
y	Cross-stream coordinate
z	Normalised axial distance
f	Frequency
t	Time
v	Velocity of the jet
U	Fluid velocity
U_{cl}	Time-averaged centreline velocity
ν	Kinematic viscosity
ρ	Fluid density
δ	Boundary layer thickness

1. OVERVIEW

Synthetic jet (SJ) is conventionally formed by periodic expulsion and suction of fluid from an orifice (Fig. 1). The expulsion and suction at the orifice is caused by the back and forth movement of a diaphragm inside the cavity. In the expulsion phase, fluid in the cavity comes out from the orifice rolls up and forms a vortex ring[1] due to boundary separation (Time t_1 and t_2 in Fig. 1). The ambient fluid surrounding the orifice drawn back into the cavity while the vortex ring is moved away from the orifice due to its self-induced velocity during the suction phase at the design conditions (t_3 and t_4). However, the vortex ring formed during expulsion phase is drawn back into the orifice during the suction phase of the cycle and no effective jet flow is formed at the orifice downstream[2] at certain off-design conditions.

A continuous back and forth diaphragm movement create a time-averaged jet named SJ along the downstream direction which was observed long time ago[3]. The presence of vortical structures ranging from integral length scale to micro scale in the jet makes SJ highly effective for flow control, mixing and heat transfer compared to the continuous and pulsatile jet. In SJ, the individual vortex ring collapses into turbulent structures separately due to circumferential instability and do not get paired up or undergo leapfrogging which results in higher level of fluctuations compared to pulsatile jets where the vortices interaction causes the jet to be more uniform in the axial region. It can be used in components ranging from miniature electronic chips (cooling) to the larger aircraft wings (separation control) as the SJ flow is generated from the ambient fluid (no need of external storage).

The name SJ was given by Glezer[4] as it is synthesised from the working fluid surrounding in the system. It is also known as zero-net-mass flux (ZNMF) jet as there is no net-flux of fluid during the operation. However, it transfers linear momentum to the flow. The flow field of the SJ is divided into two distinct regions due to its highly transient characteristics. The first region is called a developing region and it is closed to the orifice where the periodic vortex rings and their interactions dominate the jet flow. Here, SJ evolution depends strongly on the formation and translation of the vortex rings in the presence of the time-periodic reversed flow[5]. The second region is a developed region, which is away from the orifice where the vortical structures resulting from the vortex

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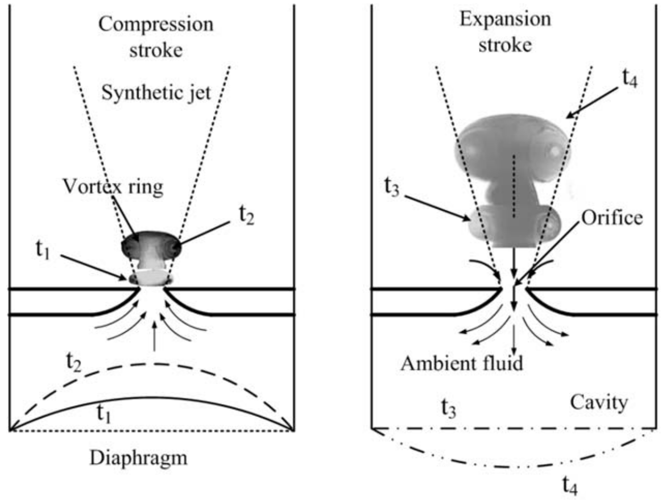


Figure 1. Synjet evolution during forward and backward motion of a diaphragm.

rings interaction break down into turbulence[6]. The far-field characteristics (centre-line velocity decay, stream wise and cross stream velocity distributions) of round SJ are closer to that of conventional turbulent round jets[7].

1.1 Generation Mechanism

Synthetic jet is produced using numerous methods such as piezoelectric (thunder actuators, bimorphs, plasma actuators), acoustics (loudspeakers), electromagnetic (solenoids) and mechanical driver (piston). Piston and loudspeaker can be used for generating the SJ where the response time and jet size are less critical. Piston-cylinder arrangement[8] was used for scaling the round SJ and acoustic actuator[9] was used for propelling the autonomous underwater vehicles. Solenoid actuator[10] was used for studying the enzyme activity. Piezoelectric composite diaphragms such as Bimorph and Thunder[11] actuators were used for studying the effect of dimensional cavity parameters on SJ peak velocities. Recently, piezoelectric composites are widely used as a diaphragm for flow control and miniature cooling applications as they are lightweight and capable of producing microscale displacements with the minimum amount of energy and have a rapid response time.

1.2 Governing Parameters

There are many parameters which govern the formation of SJ such as actuator operating parameters, actuator geometrical parameters, and the fluid parameters (Fig. 2). The number of dependent variables for a given SJ configurations and operating conditions can be limited using dimensional analysis. The combination of different non-dimensional parameters such as stroke ratio (*L/D*), Reynolds number ($\mathrm{Re} = UD/\upsilon$), Strouhal number ($St = fD/U$), and Stokes number ($S = \sqrt{2\pi f D^2/\upsilon}$) obtained from the above parameters are used for characterising the SJ depending on the dominant parameters. Where *D* is the diameter, *L* is stroke length, *U* is velocity, ν is Kinematic viscosity, and ρ is fluid density. If there is a significant change

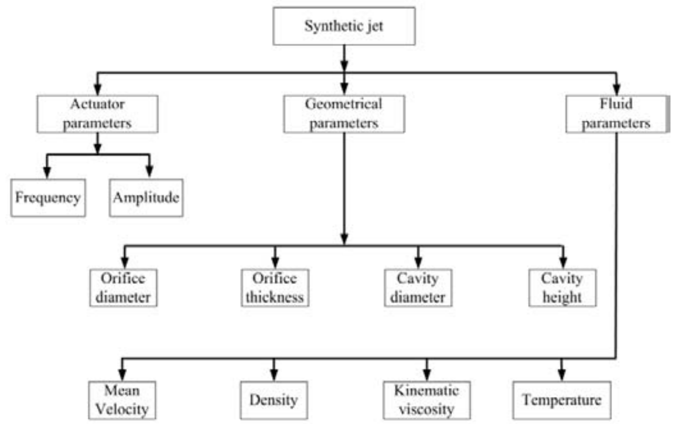


Figure 2. Parameters governing the synthetic jet.

in density ($\Delta\rho/\rho > 5\%$), the SJ evolution is also affected by the Mach number (M).

2. EVOLUTION OF SYNTHETIC JET

The train of vortex rings moved downstream does not undergo either pairing or sub-harmonic interactions during evolution[5]. Each vortex ring develops a spanwise instability, loses it coherence and ultimately undergoes a transition to turbulence[12]. It becomes similar to the mean jet flow and behaves like a 2-D jet in the far field. The spreading rate and the entrainment of SJ with ambient fluid depend on the geometry of the orifice. The SJ and continuous jet generated from a rectangular slot showed that the SJ behave as that of continuous jet and exhibit identical velocity profiles at the far field[13]. The SJ entrained more ambient fluid and highly influenced by vortex pairs in the near field which resulted in rapid growth of jet width and volume flux compared to the continuous jet (Fig.3).

A formation criterion[14] ($K < 1/St = \mathrm{Re}/S^2$) for SJ was established using either *St* or *Re* and *S* which is validated using particle image velocimetry (PIV), laser Doppler anemometry (LDV) and numerical simulation. Here, the constant K was approximately 1.0 and 0.16 for two-dimensional and axisymmetric SJ (Fig. 4). High-speed compressible SJ[16] was investigated for its possible use in supersonic flows by varying the orifice diameter, actuation frequency, and the compression ratio. An asymmetry was developed in the rise and fall times of the pressure curve due to compressibility effects. This caused a shift in the duty cycle of the system toward greater periods in suction phase. Near field velocity of the jet increased with increase in non-dimensional time during the blowing phase up to the maximum displacement (Fig. 5). The development of shock-cell structures within the jet and a maximum jet velocity upto 600 m/s were observed. The compressible SJ was dominated by a strong starting jet similar to the impulsive flow generated from shock tubes[17, 18] in contrast to the conventional SJ.

A simple static compressible model[19] showed that the magnitude of the peak jet velocity depends on four geometrical (diameter of cavity and orifice, cavity length, and orifice thickness) and two diaphragm (frequency and amplitude) operating parameters for the circular SJ. The actuators may operate in two distinct regimes (Helmholtz resonance and

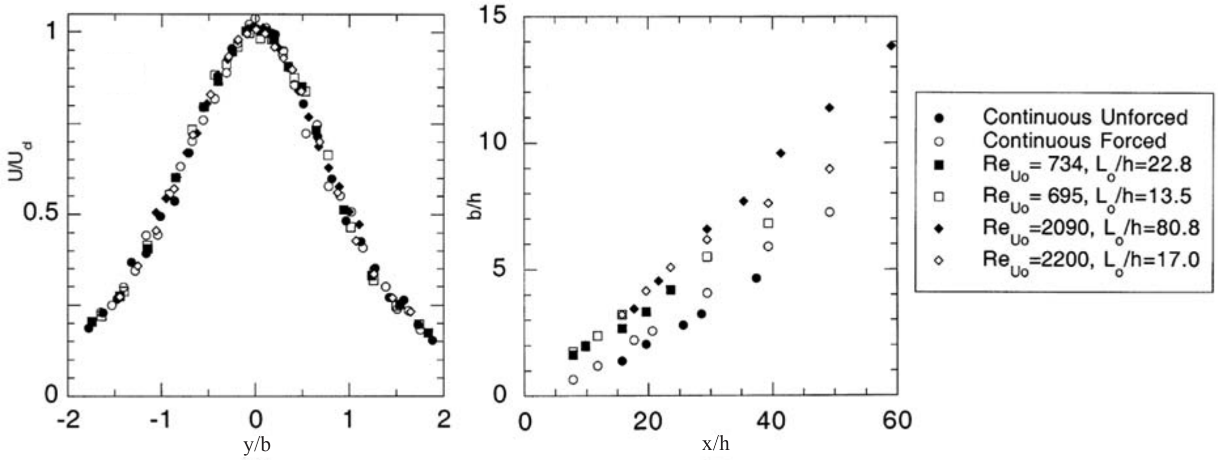


Figure 3. (a) Mean velocity (b) Jet width[13].

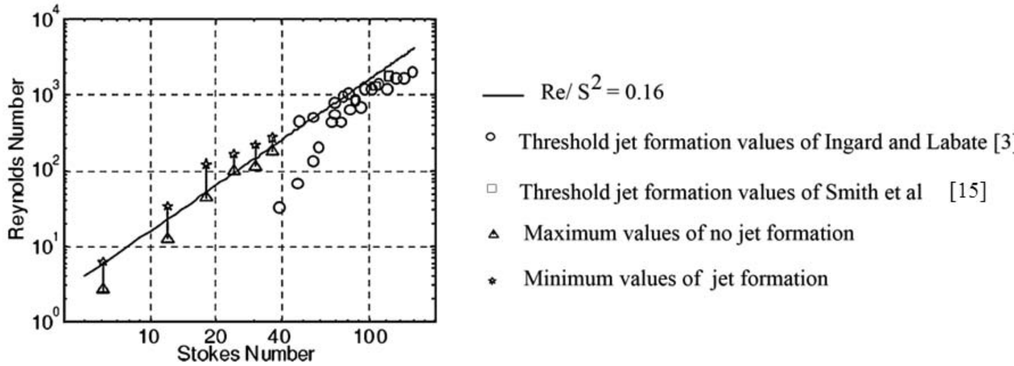


Figure 4. SJ formation criterion for axisymmetric case[14].

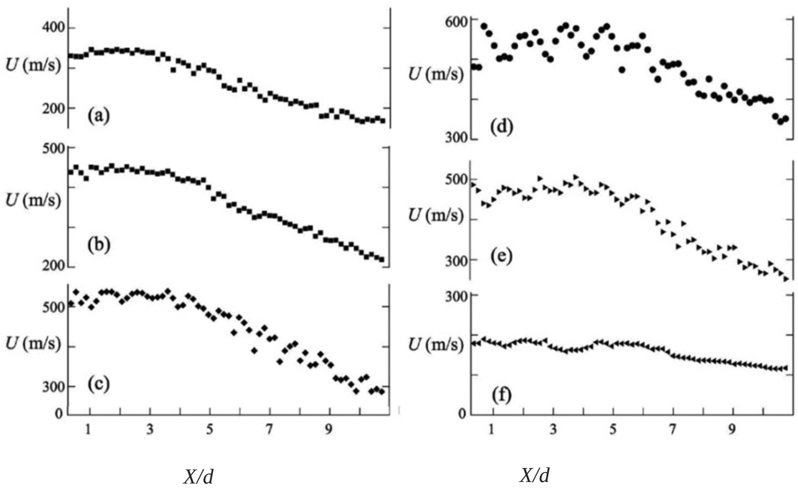


Figure 5. Centerline velocity[16] at t= (a) 0.30, (b) 0.34, (c) 0.38, (d) 0.42, (e) 0.46, and (f) 0.5.

viscous flow regimes) depending on the flow conditions inside the orifice duct. SJ emanating from single slot, single hole, three slots and three holes[20] showed that the jet coming out from the single-slot orifice had a stronger entrainment and more vigorous penetration compared to the single-hole orifice.

3. APPLICATIONS OF SYNTHETIC JET

Synthetic jet can transport the momentum, energy, and vorticity similar to the vortex ring[21] as it consists of a train of vortex rings. The ability to change the frequency, amplitude, size and the shape makes the SJ as an ideal choice for a diverse range of applications. Though the operation of synjet looks easy, it requires high level engineering to produce a device[22] that will last in industrial applications. SJ modules are widely researched to control flow separation over aircraft wing and aerodynamic noise. Applications of SJ are classified into three categories based on its primary role: (a) Flow control, (b) Jet mixing, and (c) Heat transfer enhancement.

3.1 Flow Control

In flow control, a slight change in flow induced by some mechanism produces a highly favourable condition such as an increase in lift, decrease in drag, enhancement in mixing and reduction in aerodynamic noise etc. SJ has the potential to alter the flow quite efficiently near the no-slip walls by energising the boundary layer. A wind tunnel study[23] on the pairing between the SJ and the cross flow showed a Coanda-like attachment of the separated shear layer on the airfoil top surface.

A specially designed periodic array of SJ actuators[24] placed in the near-wall region of a turbulent boundary layer showed that the streamwise velocity fluctuations were reduced by up to

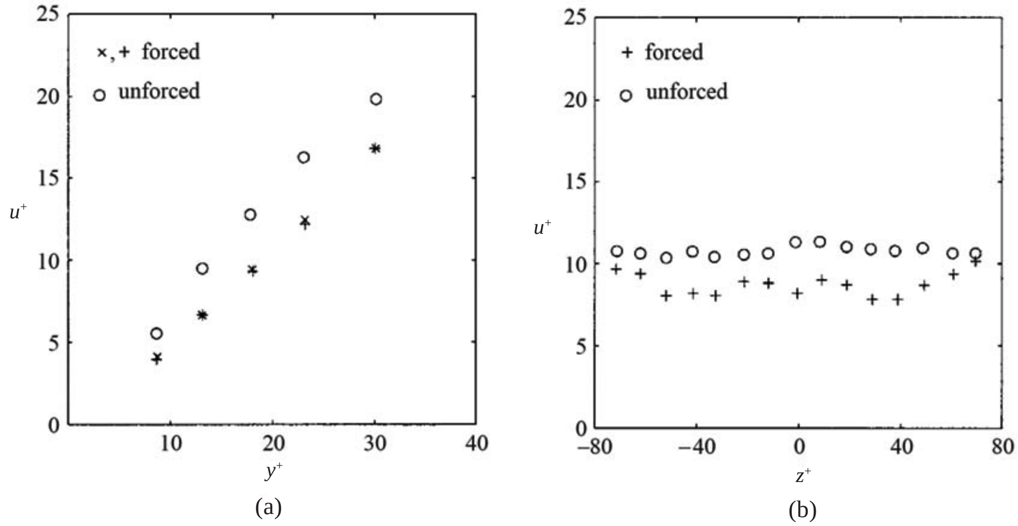


Figure 6. Mean velocity[24] (a) wall normal direction at x^+=10 (b) spanwise direction at y^+=15.

30 per cent and extended for several hundred non-dimensional viscous lengths in the streamwise direction (Fig. 6). The wall pressure fluctuations and the mean wall shear stress were also reduced by up to 15 per cent and 7 per cent respectively. The control of separated flows over aerodynamic surfaces using two strategies was reviewed by Glezer[25], *et al*. In the first approach, the actuation period scales and the time-periodic shedding of coherent vortices were part of the wake. In the second approach, the actuation had a characteristic wavelength smaller than the length scale in the flow. Therefore, global effects were decoupled from the actuation frequency.

Greenblatt[26] investigated the concept of near wake vortex management of a flapping semi-span model by means of boundary layer separation control using active and passive controls. The separation control applied near the flap edges had exerted significant control over either outboard or inboard edge vortices while producing relatively small lift and moment excursions. A study[27] on the suppression of post-stall separation over an unconventional 2-D airfoil using SJ actuators showed a complete suppression of separation over a significant range of angles of attack. The airfoil stalled at the angle of attack greater than 5° could continue to get attached to the surface up to 25° when SJ was employed. The SJ became highly effective as its frequencies exceed the characteristic shedding frequency of the airfoil.

Application of plasma actuator[28] in a flat plate boundary layer flow had shown an increase in peak jet velocity as the actuator pulsing frequencies were increased. The SJ placed in a laminar boundary layer[29] for Re varying from 16 to 658 showed three types of vortical structures namely hairpin vortices, stretched vortex rings and tilted/distorted vortex rings (Fig. 7). It was observed that the SJ induced hairpin vortices and the stretched vortex rings were responsible for delaying the separation. A plasma SJ[30] used in the supersonic flow revealed that the jet velocity increased with increase in discharge duration and temperature. A maximum jet velocity of 1450 m/s was obtained for 3000 K with 20 µs discharge time. The SJ actuator operating with a non-sinusoidal waveform[31] had shown a drag reduction by up to 29 per cent by delaying the flow separation around a circular cylinder.

Plasma SJ actuators were also used for relocating the separation shock[32] generated by a compression ramp. A study at M=3 revealed that the shock was displaced downstream by about 4 times the boundary layer thickness for a time period of about 5–10 µs when the plasma jets were pulsed at either 60 or 1 kHz (Fig. 8). The pulsed-plasma-jet array actuators might be an effective tool for shifting the dominant frequencies of oscillation of the separated flow which were expected to produce structural-panel resonance.

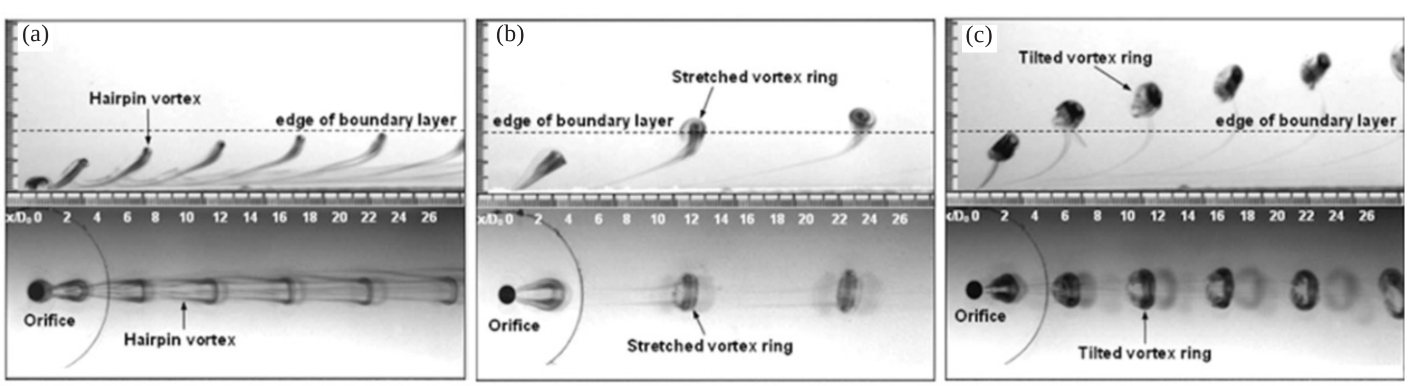
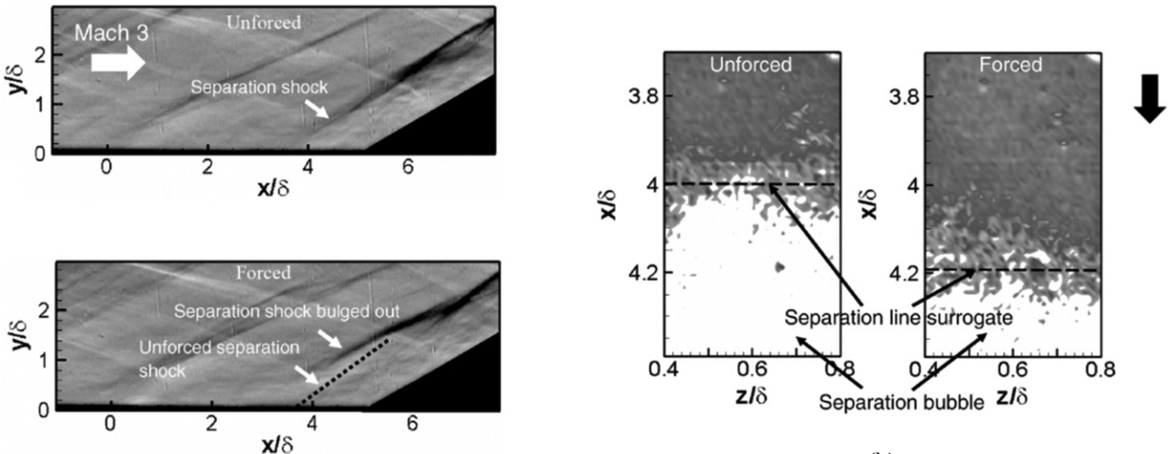


Figure 7. (a) Hairpin vortices, (b) Stretched vortex rings, and (c) Tilted vortex rings[29].



(a) (b)

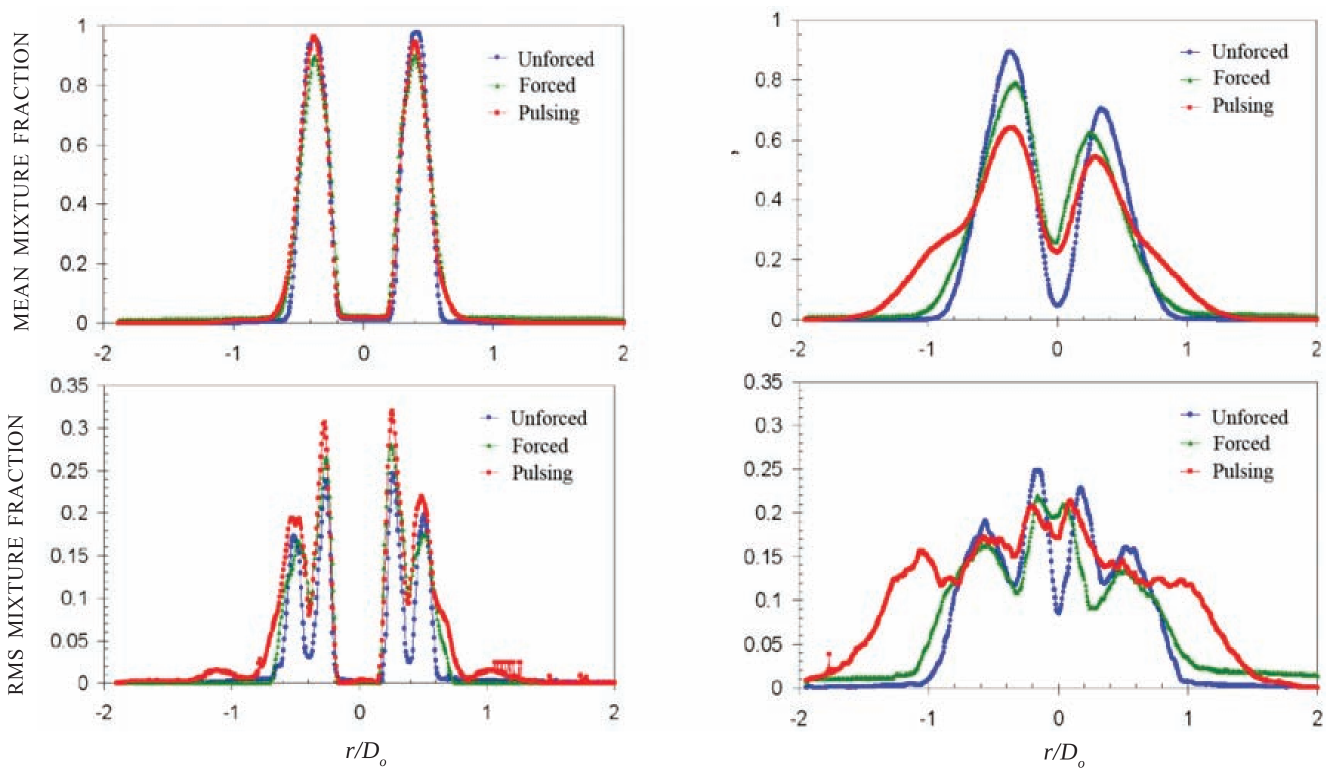
Figure 8. (a) Schlieren (b) phase-locked planar laser scattering (PLS) images showing the separation-scale reduction[32].

3.2 Jet Mixing

Mixing is an essential process in automobile, aerospace, chemical, medical, plastics, and paints industries etc. A basic and conventional method for improving the mixing is to change the geometry of the flow. The other processes include static mixers, mechanical stirrer, agitation and different fluid jet impingements. Davis and Glezer[33] examined the utility of SJ for the modification and control of small-scale motions and mixing processes in the shear layer of a round turbulent jet. The jet shear layer spread faster with downstream distance and the excitation resulted in a substantial increase in the rms velocity fluctuations compared to the unforced flow.

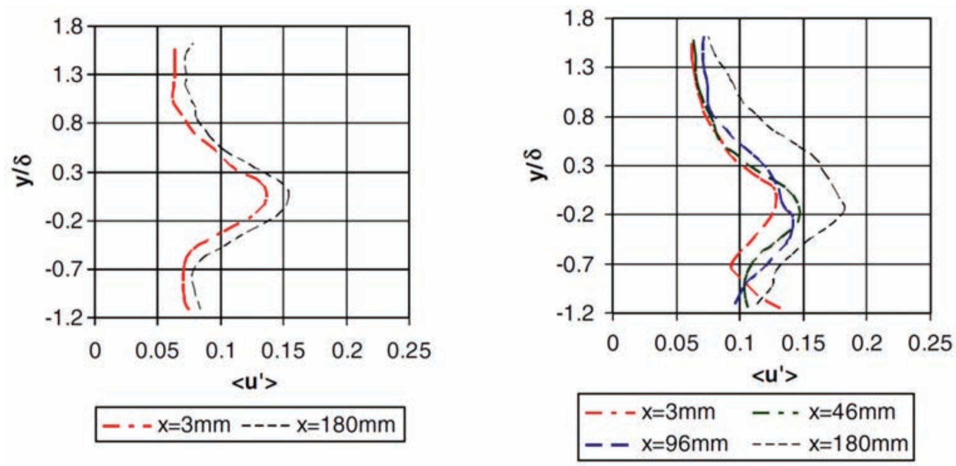
Ritchie[34], *et al.* used nine SJ circumferentially around the jet and controlled the entrainment by varying the actuation frequencies. The mean mixture fraction profiles near the exit showed a slight broadening of the outer mixing layer (Fig. 9). Forcing had slightly lowered the peak mixture fractions and increased the rms fluctuations. However, the pulsing spread the jet more than the forced case and unforced cases on the outside of the outer mixing layer. At downstream location ($x/D_o = 2$), the mixing was primarily controlled by the small-scale excitations. The rms values of the fluctuations showed that both forcing and pulsing had increased the fluctuations at the jet axis, however the outer mixing layer was significantly influenced only by the pulsing.

Wang and Menon[35] had investigated the effects of forcing amplitudes, frequencies and different configurations of the MEMS-based SJ on the enhancement of fuel-air mixing. It



(a) (b)

Figure 9. Comparison of mean and rms mixture fraction profiles (a) x/D_o=0.25 (b) x/D_o=2[34].



(a) (b)

Figure 10. Streamwise velocity fluctuations (a) uncontrolled (b) controlled flow[36].

was seen that the normal forcing had a superior mixing as the periodic pulsing resulted in local entrainment of the air and fuel stream. The SJ was also observed to abruptly destroy the large-scale coherent structures[36] in the turbulent mixing layer. Streamwise velocity fluctuating components (Fig. 10) showed a downward shift of the maximum fluctuation due to the deviation of mixing layer towards the wall.

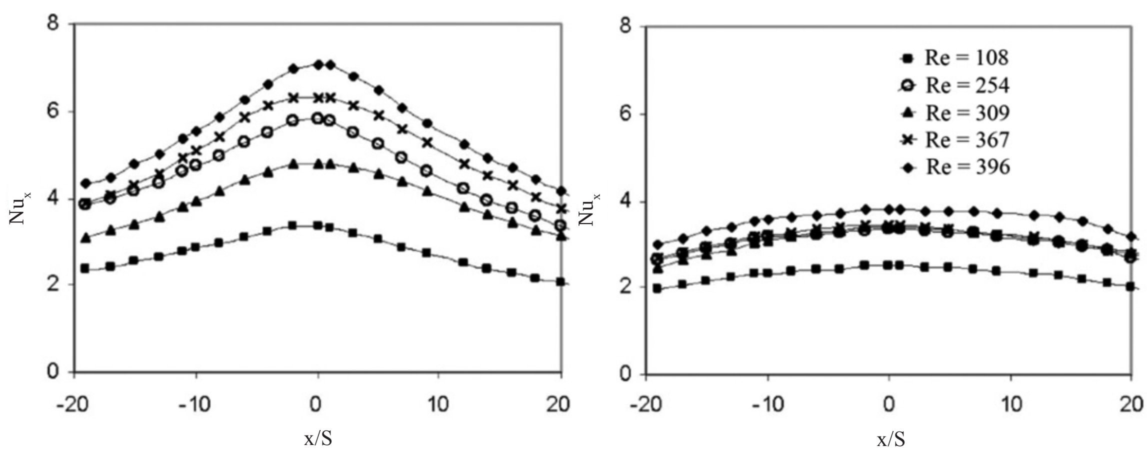
Al-Atabi[37] used SJ for mixing in vessels for Re up to 50 and proposed that the SJ mixing appeared to be a promising technique for mixing of shear sensitive materials such as enzymes and bio-fluids. Xia and Zhong[38] examined the effect of SJ pairs operated at 180° out of phase on mixing of two fluid streams in a planar channel. They proposed a functional relationship between actuation frequency and amplitude using PLIF data ($St\,L^{2.24} = 14.2$). The mixing was enhanced due to folding and stretching of fluid elements, sequential segmentation, and the stretching of fluid elements due to shear force.

3.3 Heat Transfer Enhancements

Cooling of miniature electronic devices with less power is a major concern in many MEMS applications. Conventionally, small fans are being used for cooling the electronic components. The uniform flow generated by the fans helps in augmenting the heat transfer through forced convection. However, a steady thermal boundary layer is developed over the heated surfaces. The cooling can be further enhanced if the boundary layer is disturbed which allows the higher velocity fluid streams to penetrate close to the wall.

This can be achieved using the SJ which produces a jet with a highly unsteady velocity fluctuations. Many studies are being performed for enhancing the heat transfer using SJ which showed promising results compared to the continuous jets. Mahalingam and Glezer[39] developed few air cooled heat sink configurations using SJ for cooling electronic components. It was found that the thermal effectiveness of the heat sink increased close to 70 per cent which was more than twice that of a typical fan-heat-sink combination. Garg[40], *et al.* developed a 0.85 mm diameter rectangular SJ actuator at GE global research which produced 90 m/s jet velocity. They found that the heat transfer increased approximately 10 times over natural convection.

Gillespie[41], *et al.* examined the effects of spacing between rectangular SJ and heat surface on heat transfer coefficient and identified three distinct flow regimes for Re 1000 to 10000. The Nusselt number (Nu) depended on the optimum jet to plate spacing and the Gaussian distribution became flatten as the heated surface moved farther from the orifice (Fig. 11). The



(a) (b)

Figure 11. Spanwise distributions of Nu at the normalised spacing of (a) 14.5 and (b) 22.7[41].

average Nu got maximised when the dimensionless spacing was in between 14 and 18. Timchenko[42], *et al*. studied numerically the control of 2-D micro-channel laminar flow by varying the SJ actuator frequencies. It was seen that SJ increased the rate of heat transfer however the overall rate of heat transfer did not change with frequency. A heat transfer enhancement of 37 per cent was observed with SJ compared to the steady flow.

Valiorgue[43], *et al*. tried to correlate the heat transfer characteristics with impinging SJ flow structure for different non-dimensional stroke length (1 to 22) and Re (1000 to 4300). They found a power law relationship between Re and Nu with an exponent of 0.32 ± 0.06 for a constant stroke length greater than 2.5. Chandratilleke[44], *et al.* used SJ in micro-channel flow for heat transfer enhancement at low Re and simulated flow field using URANS equations and the Shear-Stress Transport (SST) κ-ω turbulence model. It was found that the SJ increased the heat dissipation by about 4.3 times compared to the normal channel flow. For a given Re of SJ, increasing the cross-flow velocity decreased the average Nu as the jet was displaced downstream from the heated surface.

Chaudhari[45], *et al.* examined the impinging heat transfer characteristics for a longer non-dimensional spacing (0 to 25) between SJ and the heated plate. It was observed (Fig. 12(a)) that Nu rapidly increased up to a normalised spacing of 6, and then gradually decreased with increasing in spacing. The SJ performance was found to be comparable with the continuous axisymmetric jet (Fig. 12(b)) for Re up to 4000 and expected to be better at high Re. Qayoum[46], *et al*. investigated the role of excitation amplitude and frequency of the SJ on heat transfer enhancement over a flat plate by perturbing the laminar boundary layer over the flat plate for Re = 5500. They observed that the average heat transfer coefficient increased with increase in amplitude and a maximum enhancement of 44 per cent was noticed. SJ produced a number of ring vortices which got deflected towards the wall and swept downstream while merging with the main flow. These vortices increased the turbulence contents inside the boundary layer and responsible for the heat transfer enhancement.

Travnicek[47], *et al*. used a system of four SJ distributed around the circumference of a primary nozzle for studying the heat transfer. They observed that the excitation enhanced the fluid mixing, and increased the spreading angle of the jet. The excitation had led to the highest increase in heat transfer (40 per cent) in the stagnation area and the suppression of the secondary peaks in Nu distribution at the small spacing (x/D = 2). A numerical study of multiple SJ[48] interacting with the cross flow in a micro-channel showed that a better cooling enhancement could be obtained with an out-of-phase configuration of SJ. Two SJ operating at 180º out-of-phase resulted in 3.32 K reduction in microchip temperature. Whereas it showed a 2.32 K reduction for synchronised jets.

McGuinn[49], *et al*. examined the various flow regimes of the SJ during cooling of a heated plate as a function of stroke length (3-32) and non-dimensional spacing (2-16) using PIV and hotwire wire anemometry. They had identified four SJ flow morphology regimes (vortex ring, vortex ring with a weak trailing jet, vortex ring with strong trailing jet and the turbulent intermittent jet flow) based on the stroke lengths. Bhapkar[50], *et al*. studied the effect of orifice diameters, actuator frequencies, spacing and inclination angle of a jet on noise and heat transfer characteristics of SJ impinging on a heated flat plate. Sound pressure level increased with increase in orifice diameters as the mass of air associated with the orifice increases. The maximum Nu was obtained during direct impingement (90º) for all normalised axial distances. The flow behaved like a direct impingement for an angle between 40° to 90°. Hence, SJ could be used up to an angle of 40° (where space is a main constraint) with less than 10 per cent reduction in heat transfer coefficient compared to the normal impingement.

Yu[51], *et al.* combined the piezo-electrically driven agitator and SJ in a heat sink to study the heat transfer performance at three mean flow regimes namely laminar (1332), transition (1832) and turbulent (2448). They have shown that the above combination had raised the heat transfer coefficient by 82.4 per cent and established a correlation between Nu and Re. The active augmentation was attributed to the combined turbulence and vortices introduced in the channel flow by the agitator and SJ. Impingement cooling obtained by varying the orifice and

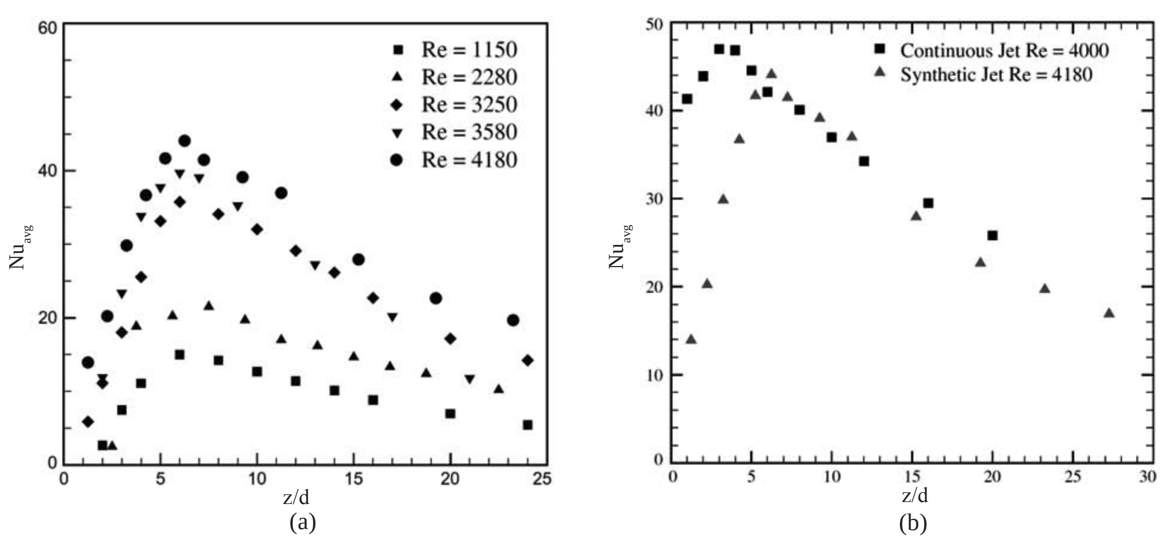


Figure 12. (a) Nu variation with axial distance (b) Nu for synthetic and continuous jet[45].

slot diameters[20] of the SJ showed that the single-slot SJ had a stronger entrainment and vigorous penetration compared to the single-hole SJ. Competitive heat transfer was achieved from multi slots/holes arrangement only when they are arranged in an optimal mode.

A numerical simulation performed with an obstruction at the SJ orifice[52] in a cross flow for Re varying from 5 to 20 showed that the SJ with obstruction could penetrate the cross-flow much deeper compared to a regular SJ. The heat transfer coefficient increased with increase in the percentage of obstruction up to 50 μm amplitude. However, the SJ without obstruction had performed better at higher values of amplitude.

4. CONCLUSIONS

Synthetic jet is a zero-net-mass flux jet and it is synthesised from the ambient fluid. It consists of periodic vortex rings in the developing region. The vortex rings do not get paired up or undergo leapfrogging instead the individual vortex rings collapse into turbulent structure due to circumferential instability. The vortical structures break down into turbulence in the developed region. The fluid parameters, geometrical and operating parameters of the actuators govern the SJ characteristics. A formation criterion of SJ ($K < 1/St = \mathrm{Re}/S^2$) was established using non-dimensional parameters. The compressible SJ was dominated by a strong starting jet similar to the impulsive flow generated from shock tubes.

Synthetic jet is becoming an essential and important device for aerodynamic flow control in many critical applications. It has been widely used for energising the boundary layer flows and controlling the separation over the wings in subsonic flight. Significant improvement in drag reduction and delay in separation due to Coanda-like attachment were noticed with the application of synjet at higher actuation frequencies[23]. It was also observed that the airfoil stalled at the small angle of attack continued to increase the lift coefficient up to 25° when SJ was deployed[27]. The wall pressure fluctuations and the mean shear stress over a turbulent boundary layer were reduced up to 15 per cent and 7 per cent, respectively by incorporating an array of SJ[24]. When SJ is applied in a laminar boundary layer[29], the stretched vortex rings identified in the flow are the most useful vortical structure for separation control. Plasma SJ[30,32] is used for controlling the shock-boundary layer interaction in supersonic flow and its velocity depends strongly on plasma temperature. It has a huge potential to control the separation in both subsonic and supersonic flows.

Synthetic jet is also used for enhancing both mixing and heat transfer. The folding, sequential segmentation and stretching of fluid elements due to shear are responsible for increasing the mixing. A normal forcing[35] within the fuel injector had a superior performance on mixing as the periodic pulsing results in local entrainment of the air and fuel stream. The presence of higher level of fluctuations in the flow makes the synjet as a potential contestant for fans for cooling the miniature electronic devices. Since the turbulent contents in the flow break the thermal boundary layer and penetrate much closer to the heated surface of the devices, SJ effectiveness is much higher than the continuous flow fans. By optimising driving frequency, amplitude, jet axial distance, heater size, and heat flux[40], it was observed that the heat transfer of SJ was increased approximately 10 times over natural convection.

A comparative study[45] between the continuous jet and SJ showed that the continuous jet (consumes more energy) gave a higher value of Nu at small spacings and both became comparable at larger spacings. The synjet performance was found to be comparable with the continuous jet for Re upto 4000 and expected to be better at high Re. SJ can be used up to an angle of 40° with less than 10 per cent reduction[50] in heat transfer coefficient compared to normal impingement where space is a main constraint. The slot type SJ was observed to have a stronger entrainment and vigorous penetration compared to the circular orifice. A competitive heat transfer from multi slots/holes arrangement[20] was achieved only when they are arranged in optimal mode compared to the single jet. The present review showed that there is a scope for improving the aerodynamic control and enhancing the mixing and cooling through innovative design. Plasma SJ can be used to alter the vortical flow structure over delta wings for delaying the bursting. We are presently working on the coaxial synthetic jet which is expected to increase the turbulent contents and help in improving the heat transfer.

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