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A Numerical Investigation of the Influence of Sidewalls on the Flow-field of a Slot Synthetic jet

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Abstract

The influence of sidewalls for continuous jets has been widely investigated, using numerical and experimental methods. It has been observed that the presence of sidewalls significantly influence the flow-field characteristics of the jet flow field. However, the influence of sidewalls on the synthetic jet flow-field characteristics remain unexplored. Synthetic jets are generated through the orifice of a synthetic jet actuator made of a cavity driven by sinusoidally oscillating one of its walls. Synthetic jets are increasingly being investigated for their impingement heat transfer enhancement characteristics.

In this study, a slot synthetic jet is investigated using Large Eddy Simulations (LES) and validated using experimental data to understand the influence of sidewalls on the synthetic jet flow-field behaviour. The sidewalls are attached to the shorter side of the slot, extending in the streamwise direction of the jet to constrain the flow entrainment along the spanwise direction of the jet. The jet characteristics are examined and compared for both configurations under similar operating parameters. The results suggest that the flow-field characteristics of the synthetic jet may be significantly altered due to restricted flow entrainment from the spanwise direction. This may have a significant impact on synthetic jet impingement heat transfer.

Introduction

In the last two decades, the research on synthetic jets (SJ’s) has been geared up because of their versatile potential applications ranging from active flow-control [1], heat and mass transfer enhancement [2-5], underwater jet propulsion [6], and turbulence mixing enhancement [7, 8]. Unlike conventional jets (CJ), a SJ does not need an additional supply of fluid but is synthesized from the same fluid in which the SJ actuator (SJA) is deployed. Hence, it is also known as a zero-net-mass-flux (ZNMF) jet.

A SJA setup generally consists of a cavity bounded by a flexible membrane or diaphragm on one end and an orifice on the other. The shape of the cavity and orifice can vary according to requirements. When the membrane oscillates periodically by some means (piezoelectric, mechanical or electromagnetic), the accompanying change in volume of the cavity results in successive and periodic suction and ejection of fluid through the orifice. Consequently, vortical structures are developed at the orifice exit, which subsequently advect, coalesce, trigger radial instability and ultimately experience transition to turbulent flow and impart net positive momentum to the flow field in the streamwise direction.

Contrary to the CJ, the SJ does not need any continuous supply of fluid or any complex fluid packaging. Therefore, it has attracted the attention of researchers and numerous studies have been reported for characterizing the flow-field of the SJ considering various parameters: such as geometrical (cavity and orifice shape), operational (frequency, amplitude) and different fluids.

However, two derived dimensionless parameters, i.e. Reynolds number (*Re*) and dimensionless stroke-length (*L*) based on all the important parameters were found to influence the SJ flow-field significantly [9] and consequently its performance in various applications.

Rizzetta et al. [10] have numerically investigated the influence of the cavity depth and *Re* on the flow-field of the SJ in a quiescent environment. From their experimental work, Cater, and Soria [11] have further characterized the flow behaviour of SJ’s based on *Re* and Strouhal number (*St*) into four regimes, namely: laminar jet, laminar rings, transitional jet and turbulent jet. Holman et al. [12] formulated jet formation criteria for both two-dimensional and axisymmetric SJ’s. From their particle image velocimetry (PIV) and numerical investigation, Jabbal et al. [13] showed that the geometrical properties of the synthetic jet actuator such as orifice plate depth and cavity depth can influence the performance of the SJ. According to Jabbal et al. [14], *Re* does not affect the spreading and decay rate of the SJ; it only controls the coherence, strength, and stability of the vortex-rings while *L* influences the relative streamwise spacing between the vortex rings. Jain et al. [15] have numerically found that the flow-field of the SJ is more sensitive to change in orifice dimensions than to that of cavity dimensions under similar operating conditions of frequency and amplitude.

In contrast to the SJ, a CJ is formed under the continuous supply of fluid with top-hat velocity profile in the potential-core region (known as the zone of establishment) followed by Gaussian velocity profile in the established flow zone. Depending on the initial conditions at the orifice exit, a CJ is termed as a plane or rectangular jet. An ideal plane jet is a statistically two-dimensional jet with no entrainment of the surrounding fluid in the spanwise direction [16]. To the best of our knowledge, Hitchman et al. [17] were the first to compare directly the flow-field of the rectangular and planar jets using similar experimental facilities. Deo et al. [18] have further extended the experimental work of Hitchman et al. [17] and found increment in the length of the potential-core in the presence of sidewalls with the corresponding extension of the two-dimensionality region in the downstream ascribed to the low entrainment of the ambient fluid.

The flow-field of the free SJ emerging in a quiescent environment have been investigated exhaustively, both numerically and experimentally, with consideration of different parameters. However, to the best of our knowledge, the flow-dynamics associated with the SJ emerging in a confined space i.e. bounded by sidewalls along the minor axis of the slot has not been established yet. For avoiding confusion in understanding both configurations, the SJ with sidewalls is called as plane SJ and that without sidewalls as free SJ in the subsequent sections. This paper presents the numerical investigation of the influence of sidewalls on the flow-field behavior of the SJ. The objective of the current paper is to provide a perspective for the comparison of the flow-field features of SJ considering both configurations and to identify the relative merits for the design of future experiments.

Experimental Setup

The synthetic jet in the current research was generated by using a permanent magnetic shaker driven loudspeaker. The center of the loudspeaker diaphragm was connected to the magnetic shaker via a steel rod. The diaphragm was actuated in a sinusoidal manner at a constant frequency and amplitude via a function generator and amplifier. The SJA had a cylindrical cavity with a height of 95mm and diameter of 202mm with a slot of aspect-ratio 25 and slot-width of w = 6.4mm. The velocity measurements in the flow-domain were made using a single probe hot-wire (55P16). The hot-wire was precisely traversed in the three-dimensional space in the flow domain using a Dantec dynamics traverse system. It was calibrated against a known velocity before the measurements, and a third order polynomial equation was used for data processing. The sampling frequency of 8 kHz was used with a sampling duration of 60s at each location.

Numerical Setup

Numerical simulations were carried out using the ANSYS CFX software package. Figure 1 represents the numerical model used for the SJ with and without sidewalls. The numerical model has been developed similar to the experimental setup employed for the current research. The computational domain of the free SJ was mainly categorized into two zones, i.e. a cylindrical cavity with a slot (representing the experimental SJA) and a rectangular box (60w x 60w x 60w) representing the ambient located at the downstream of the slot, where the jet flow takes place. The sides of the ambient domain were modeled as openings with zero relative pressure. Whereas, in the case of the plane SJ, two no-slip wall boundary conditions were used to represent the sidewalls running along the minor axis of the slot, as shown in Figure 1. The domain size in the downstream and transverse direction are more than sufficient to capture the desired results [19]. The main parameters used in the simulation are summarized in Table 1**.**

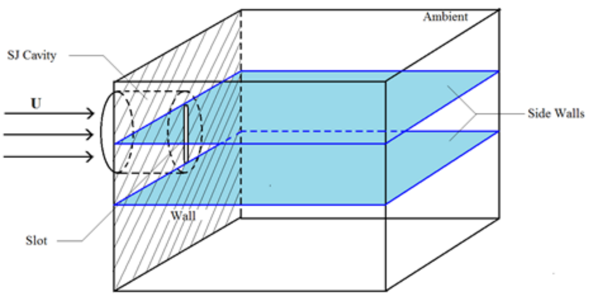

Figure 1 Schematic of the numerical model

The oscillating diaphragm was modelled as an oscillatory inlet boundary condition with the help of a user-defined function (equation 1),

$$U = U_o sin(2\pi f t) \quad (1)$$

Here, U is the instantaneous velocity at the inlet, U_o is the forcing velocity amplitude, f is the actuation frequency, and t represents time.

Parameters	Values with units
Slot *AR*	25
f	40Hz
Re (Based on w)	≈3900
Orifice plate thickness t_o	6mm

Table 1 Parameters used

Three-dimensional transient state Large-Eddy simulations of the free and plane SJ configurations were carried out. The fluid was air at 25°C. The convergence criterion was set to normalised RMS residual target of 10^{-6}. The geometries for both configurations were generated and meshed in ICEM-CFD using unstructured hexahedral grids. Multi-body grid approach has been employed in the current simulations [19, 20]. Since most of the applications are more concerned about the near-field of the SJ, more emphasis was given in this region with finer grid resolution. Therefore, the slot mesh was generated by providing the first near-surface layer thickness based on the $y+$ value of 1 while all the grids used in the cavity and the other regions were non-uniform in all directions and were generated with an expansion factor of 1.2 outside the slot.

Mesh independence analysis was carried out at various mesh densities. At the end of analysis, mesh with 8.9 and 14.32 million number of elements were found showing almost similar results for the centreline velocity as shown in Figure 2. For optimizing the computation time, mesh with 8.9 million elements was adopted for the analysis.

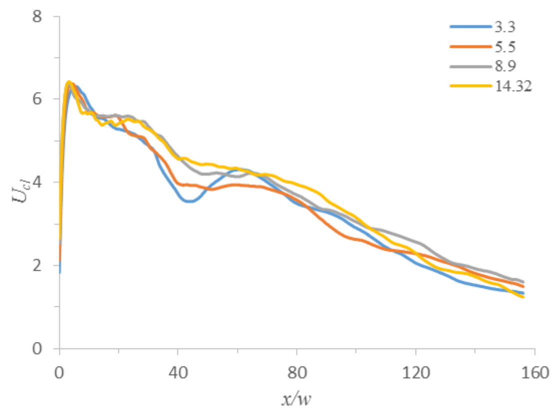

Figure 2 Mesh independence analysis for centreline velocity. The numbers in legends represent the number of elements in million

For adequate and accurate capturing of the flow-field characteristics of both the configurations, the timestep distribution should be sufficiently fine. Thereby, the statistical calculations related to the SJ flow-field can be accurately obtained as these are dependent on the average results of the velocity distribution. Therefore, the time step size of 0.0001 s i.e. t_{step} = $T/250$ (where T is actuation time-period, $T=1/f$) was found sufficient to capture the desired results. For both the configurations, LES-WALE, Central Difference advection scheme, and Second Order Backward Euler Transient scheme were used to run the three-dimensional simulations. The solver was run in double precision as it makes the round-off error suitably small and makes the iterative error to the level of the round-off error.

Results and Discussions

Figure 3 shows that the jet centreline velocity (U_{cl}) for both configurations diminishes in the downstream. The centreline velocity decay is presented by normalizing the centreline velocity with the average orifice exit velocity during the ejection phase ($U_{cl,o}$) – the reciprocal of this $U_{cl,o}$ / $U_{cl,}$ is plotted. The experimental and numerical results for the free SJ are almost consistent with each other. However, it appears to deviate in the far-field believed to be due to the increase in experimental uncertainties in the far-field (low velocities). In contrast to conventional jets with and without sidewalls, the centreline velocity for the plane SJ decreases more rapidly in the downstream compared to the free SJ. This is attributed to the interaction of the rolled up vortex during the ejection phase with the wall boundary layer resulting into the corresponding decrease in the vortex strength in the downstream [21].

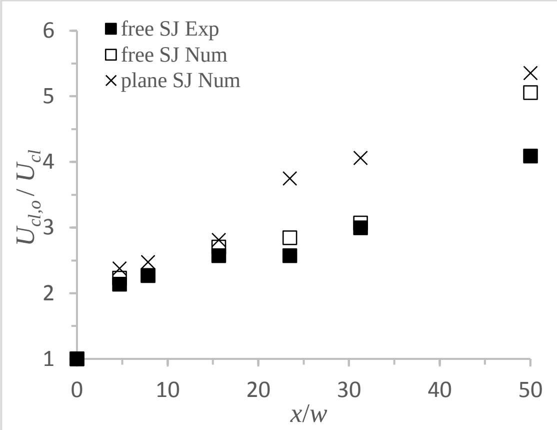

Figure 3 Centreline velocity decay from numerical (Num) and experiment (Exp)

However, in the case of the free SJ, the vortex structure ejected during the ejection phase entrains the ambient fluid and due to azimuthal instabilities undergoes the phenomenon of axis-switching in the downstream to attain a more stable shape [19].

To further assess the differences in the flow field characteristics between the two configurations, jet spreading in the minor plane is illustrated in Figure 4. The jet spreading has been evaluated by plotting the jet half-width, b_j at different streamwise locations in the downstream along the minor axis of the slot. Jet half-width is the lateral distance from the jet centreline to the point where the velocity drops to half of the average centreline velocity. It is evident from the profile that the free SJ spreads rapidly across the slot in the downstream whereas the SJ with sidewalls remains concentrated near the jet centerline, with a much slower spread rate. This outcome is consistent with the conventional jet literature, where the presence of sidewalls significantly influenced the jet spreading in the minor plane [18]. This profile further supports our claim that the presence of the sidewalls along the shorter side of the slot has suppressed the phenomenon of axis-switching from the flow-field of the SJ.

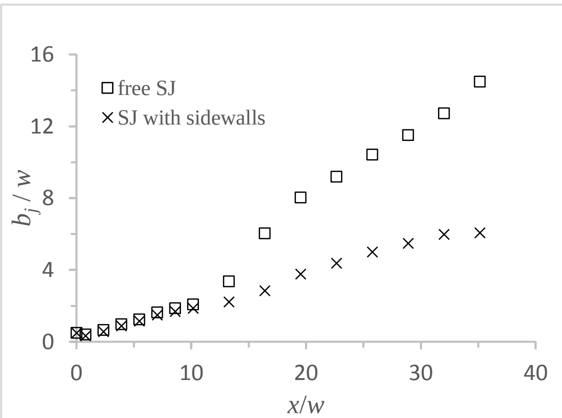

Figure 4 Comparison of jet spreading

The above results can be further realized from the time-average velocity contours for the both configurations shown in Figure 5 (a)-(d), where the difference in the time-average velocity profiles along the major and minor sides of the slot shows that the presence of the sidewalls significantly influences the flow-field of the SJ.

Figure 5(a) and Figure 5(c) show a glimpse of the expansion of the free SJ along the minor and major axis of the slot respectively.

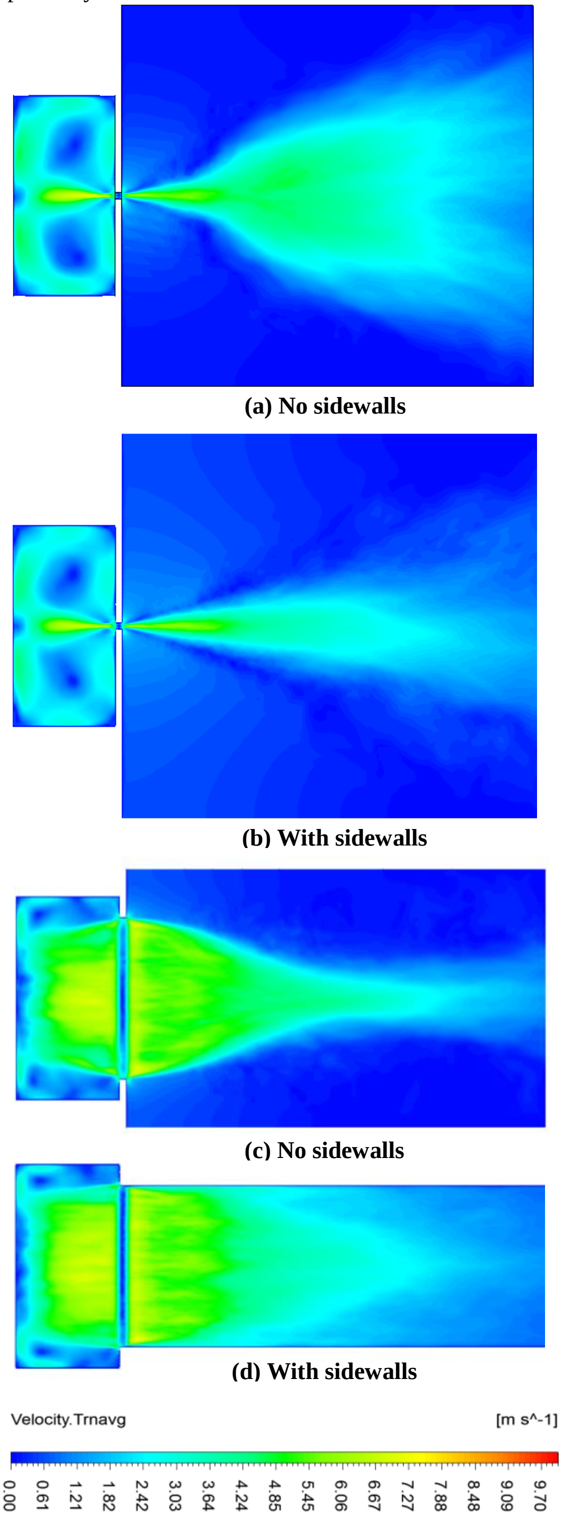

Figure 5 Time-average velocity contours (a) Along minor axis, free SJ (b) Along minor axis, plane SJ (c) Along major axis, free SJ (d) Along major axis, plane SJ

It can be observed from Figure 5(a) that the free SJ spreads remarkably in the minor plane and shrinks along the major plane in the downstream. This can be again attributed to the phenomenon of axis-switching occurring as a result of the non-uniform curvature of the slot.

However, in the case of the plane SJ, the presence of the sidewalls does not allow the vortex structure rolled up during the ejection phase to interact with the surrounding fluid from the third plane. The vortex structure remains attached to the sidewalls at its ends, and is sheared causing distortion, preventing the axis switching observed with no sidewalls. This can be confirmed from time-average velocity contour plots along the major axis of the slot shown in Figure 5(d). The ejected vortex structure directly comes in contact with the wall boundary layer at the slot exit, and due to the no-slip condition, it induces a boundary layer of opposite nature on the wall surface by losing part of its vortex strength [21]. This process carries on with the subsequent vortex and in the downstream, the vortex ultimately breaks into smaller vortices, and eventually, the jet strength vanishes rapidly.

Conclusions

This work is the first step to determine the influence of sidewalls on the flow-field features of the slot synthetic jet. This has been attained by modeling two different configurations, i.e. a free slot SJ and a plane slot SJ (i.e. with sidewalls). In the case of the plane SJ, the flow is constrained from the lateral plane by attaching two parallel sidewalls with the no-slip condition to the shorter sides of the slot. Due to the presence of the sidewalls, there is significant change found in the flow-field of the SJ. One of the remarkable features of axis-switching in slot SJ flow-field is suppressed due to the presence of the sidewalls. Simulations further revealed that the plane SJ grows slowly relative to the free SJ in the lateral plane due to the continuous interaction of the vortex with the wall boundary layer in the spanwise plane. In the context of heat transfer enhancement by SJ impingement, the presence of the sidewalls would significantly influence the heat transfer capacity of the SJ as it is strongly affecting its flow-field.

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