Review Paper on the Behaviour of Circular Synthetic Jet in Quiescent Air at Low Reynolds Number

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Abstract— **The present paper discuss overall study of the behaviour of circular synthetic jet in quiescent air at low Reynolds number. This study carried out based on brief literature review to understand behavior of circular synthetic jet in quiescent air at low Reynolds number. 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**

I. INTRODUCTION

A Synthetic jet is a mean fluid motion created by an oscillating flow through an orifice or a slit. The fluid oscillations necessary to synthesize the jet are typically provided by intermittent suction and blowing through the jet orifice or slit. The device which produces the jet usually consists of a neck driven by a pulsating diaphragm in a cavity as shown in Figure 1.1. When the diaphragm moves towards the orifice, a vortex pair (for a 2-D slit) is formed at the edge of the orifice and is advected by its own self-induced velocity such that when the diaphragm moves away from the orifice, the vortex pair is far enough and is not affected by the fluid that is drawn into the cavity. Therefore, a synthetic jet has a zero net mass flux but it allows momentum transfer to the flow. A synthetic jet is produced by the interactions of a train of vortices that are typically formed by experimentally using PIV. The synthetic jet was produced over a broad range of length and time scales at various Reynolds numbers, stroke lengths, slit widths, and formation frequencies. The velocity and vorticity fields were measured in two planes, across the slit (i.e., along the short axis of the orifice) and along the slit (i.e., along the long axis). The measurements in the plane along the slit revealed a unique flow pattern, where near the orifice the flow is two dimensional, while farther downstream the vortex pair lines develop secondary counter rotating structures. The stream wise and span wise spacing between these structures vary with stroke length and formation frequency. As the orifice aspect ratio increases the effect of the slit edges decreases, thus the secondary structures are less pronounced alternating momentary ejection and suction of fluid across an orifice such that the net mass flux is zero. A unique feature of these jets is that they are formed entirely from the working fluid of the flow system in which they are deployed and thus can transfer linear momentum to the flow system without net mass injection across the flow boundary.
Synthetic jets can be produced over a broad range of length and time-scale and their unique attributes make them attractive fluidic actuators for a broad range of flow control applications. Over the last few years, the stream wise and span wise evolutions of finite span synthetic (zero net mass flux) jets were investigated.

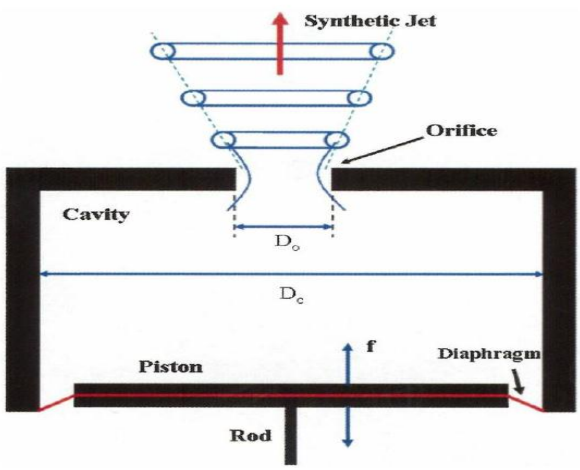
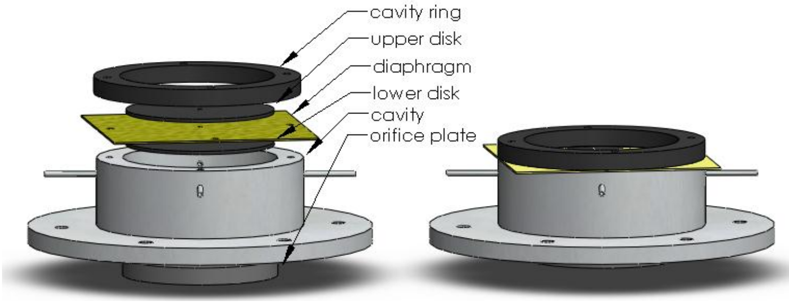


Figure1.1 Schematics of Synthetic Jet Actuator [24]



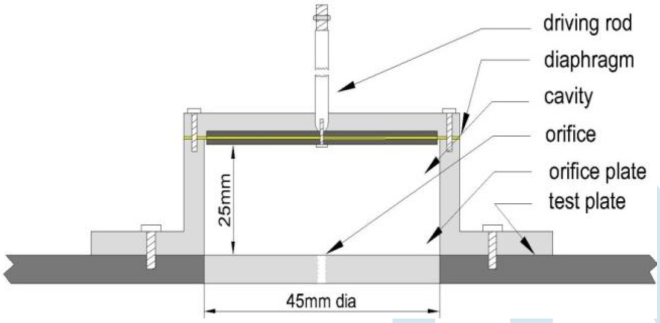


Figure 1.2 synthetic Jet Actuator Assembly[3]

II. Formation of a Synthetic Jet

A synthetic jet is generated by a membrane oscillation in a relatively small cavity (Figure 1.1), which produces a periodic cavity volume change and thus pressure variation. As the membrane oscillates, fluid is periodically entrained into and expelled out from an orifice connecting the cavity with the external ambient (to be controlled). During the expulsion phase of the cycle, due to the flow separation, a vortex ring forms near the orifice exit section which, under favorable operating conditions (Holman et al. [11]), convects away towards the far field and breaks up due to the viscous dissipation eventually "synthesizing" a turbulent jet always directed downstream.

Since the jet formation depends on the ability of the vortex ring to escape to the subsequent ingestion phase, following Smith and Glezer [10], a basic parameter characterizing the jet strength is the so called stroke length L, namely the integral of the (spatially averaged) velocity at the orifice exit over the ejection phase only of the cycle

$$\overline{L} = \int_0^{\frac{T}{2}} U(t)dt \tag{2.1}$$

where T is the actuation period and U(t) is the fluid velocity at the exit section. The stroke length can also be expressed conveniently as the product $\overline{L} = \overline{U}T$, where $\overline{U}$ is a proper reference velocity defined as

$$\overline{U} = \frac{1}{T}\int_0^{\frac{T}{2}} U(t)dt \tag{2.2}$$

Therefore, it is natural to expect that the jet is formed or not according to whether the parameter $\overline{L}/d_0$ is greater or less than 0.16π, with d_0 being the orifice diameter. In the literature the parameter $\overline{L}/d_0$ is generally referred to as the reciprocal of the Strouhal number). The importance of the stroke length, or of the average velocity $\overline{U}$, lies in the fact that to compare the performance of a synthetic jet with that of a continuous jet, it is usual to refer to a Reynolds number based on the velocity $\overline{U}$,

$$\mathrm{Re} = \frac{\rho \overline{U} d_o}{\mu}$$

(2.3)

where ρ and μ are respectively the air density and the air dynamic viscosity.

The formation and evolution of synthetic jets have been the subject of a number of experimental and numerical investigations of plane and round jets with emphasis on near field formation, evolution and advection of the jet vortices and on scaling of the time averaged flow (examples of experimental investigations: plane jets (Smith and Glezer [9], round jets (Shuster and Smith [21]).

III. Non Dimensional Number

REYNOLDS NUMBER (Re)

The Reynolds number of exit air jet produced by SJA is mostly defined based on exit air jet velocity U_j, orifice or slot diameter d_o and fluid kinematic viscosity v,

$$\mathrm{R}_e = \frac{u_j d_o}{v} \tag{3.1}$$

In particular, the Reynolds number gave a clear meaning of physical where if the value drops below 50, the jet produced are not separated from the edge of the orifice, means that the air jet that comes out from the orifice is not satisfactory for the flow separation control application.

NON-DIMENSIONAL STROKE LENGTH

Stroke length was non-dimensional parameter for exit air jet produce by SJA called as a simple slug-velocity-profile model. During the membrane oscillates a little amount of fluid is forced inside the cavity and ejected out through the orifice. The distance of a slug of the air velocity that travels away from the orifice will build. This distance called stroke length of fluid, L_o and can be approximated as:

$$L_o = U_j T_o \tag{3.2}$$

Where T_o is the time or the inverse of the oscillating frequency. The relationship between the variation of exit air jet velocity and geometry of orifice will be used to define the non dimensional parameter for SJA, the non-dimensional stroke length

$$L_s = \frac{L_o}{D_o} \tag{3.3}$$

From the previous studies (Shuster and Smith, 2004) suggest that L_s>1 for asymmetric jet formation.

STOKES NUMBER (ST)

The effect of unsteady flow generated by the SJA through orifice can be explained by Stokes number.

$$S_t = \frac{\omega d_o^2}{v} \tag{3.4}$$

where u`=2ð f is the radian oscillating frequency. The effects of viscosity are not occurring at the orifice if the Stokes number is large. The orifice will influence by viscous effects if the Stokes number is small and the exit air jet can be choking.

STROUHAL NUMBER (SR)

Strouhal number is one of non-dimensional parameter that is important to evaluate SJA ability which it depends on membrane oscillating frequency, f and exit air jet velocity pass through the orifice

$$S_r = \frac{f d_o}{U_j} \tag{3.5}$$

During SJA operates, oscillating membrane has certain frequency which will cause the air in the cavity are going out and entering through orifice. The relationship between rate of airflow and the frequency used to assess Strouhal number. Based on literature, most SJA operate in Strouhal number that is relatively low, i.e. S_r< 1 (less unsteadiness and more directivity) and in Reynolds number that is relatively high, i.e.R_e> 50 (lower viscous losses). Suitability of the combination of this non-dimensional parameters will make momentum flux is quite high that greatly needed for flow separation control use.

NON-DIMENSIONAL FREQUENCY (F^+)

Non-dimensional frequency can be defined using membrane oscillating frequency, f and a distance c^+), that is about the order flow size of the area to be influenced (i.e. distance from the location of orifice actuator to the trailing edge of airfoil in percent chord), and also free-stream velocity, U_∞)

$$F^+ = \frac{f_c^{\,+}}{U_\infty} \tag{3.6}$$

Basically, the maximum exit air jet velocity produce is determined by the actuation frequency. There are generally two options oscillating frequency accepted for the application of flow separation. The SJA operates at the same frequency as the natural frequency of the main flow, i.e. $F^{+}\sim 1$ (Seifert and Pack, 1999). Another option is the actuator operated at higher frequency, i.e. $F^{+}\sim 10$ for vortex shedding suppression. Latest design of synthetic jet show device which gives a different resonance frequency that usually higher than application requested. This is to achieve control of vortex shedding and delay flow separation.

JET MOMENTUM COEFFICIENT (Cµ)

Interaction between the air jets produced by the SJA with external cross-flow at a surface can be determined by the jet momentum coefficient parameter and can be estimated as:

$$c\mu = \frac{2\rho_j U_j^2 d_o}{\rho U_\infty^2 c} \tag{3.7}$$

Where ρ and ρ_j are the fluid densities of free-stream and jet, U_j is exit air jet velocity and U_∞ is the velocity of free-stream, c is normally the airfoil chord length and d_o is diameter or width of the orifice (Smith et al., 1998). Jet momentum coefficient, $c\mu$ for the certain application is usually on the order of 10^3. A minimum number of 0.002 are needed for the SJA to have any effect on the flow separation control. Effectiveness of synthetic jet in separated flow will be better if the coefficient of momentum jet is increasing. These phenomena were illustrated by McCormick (2000) where the separation occurs badly for without actuator, and the size of separation reduced when the momentum jet coefficient increases until eventually very good for 0.04. Broadly, the higher momentum's coefficients jet are needed if the actuator located further from separation location. A non-dimensional parameter associated closely that commonly used to define the synthetic jets efficiency in cross-flow known as the synthetic jet to free-stream velocity ratio and it compare the peak magnitude of synthetic jet and free-stream velocities. Usually for low subsonic speed the ratio could be R = U_∞ / U_j of three and for the micro UAV's applications (very low subsonic speed) the ratio could be as high as ten, so active flow control is sensitive for a usual Reynolds number of the vehicles. The optimum velocity ratio depends on the type of flow control strategy usage.

IV. Literature Review

Crook Andrew, Amit M. Sadri and Norman J. Wood [5] carried out this experimental investigation for the development and implementation of synthetic jets for control of separated flow. Here author have carried out two approaches analytical and experimental for the synthetic jets used on the cylinder have been successfully developed and constructed by the authors, with mean jet, velocities of the order of 20 ms^{-1} measured at ten orifice diameters from the jet exit. A piezoceramic actuator bonded to a circular diaphragm is used to create unsteady cavity pressure fluctuations and is driven at resonance using a square wave signal, with a peak to peak potential difference of 8OV.

The analytical model successfully predicted the maximum jet velocity at the orifice for the optimum parameters of the previous device, and was very close to the experimentally measured mean jet velocity at an orifice diameter from the exit. The model was less successful in correlating the predicted maximum jet velocity at the orifice with the measured mean velocity for the current device. And also has not predicted well. the optimum values of d and H, for the maximum jet, velocity. Viscous effects clearly are the cause of the poor predictions for smaller orifice diameters at higher forcing levels.

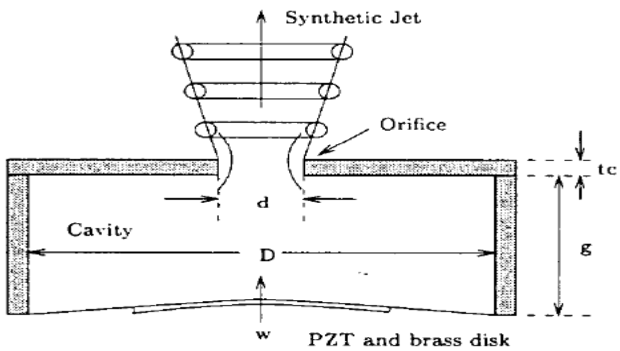


Figure 3.1 Schematic diagram of a synthetic jet formed using an oscillating diaphragm clamped in a cavity [5]

Crook Andrew, W.J Crowther and Norman J. Wood [4] has carried out parametric study of synthetic jet in cross flow. Preliminary research using synthetic jets to control the separation line of a turbulent boundary layer on a circular cylinder, has revealed that periodic ejection and suction through an orifice leads to a time averaged jet structure, and a time averaged delay of the separation line. To answer the question of how a periodic ejection and suction can produce this effect, research has been undertaken to study the behavior of the vortex rings in quiescent, cross flow and shear flow condition.

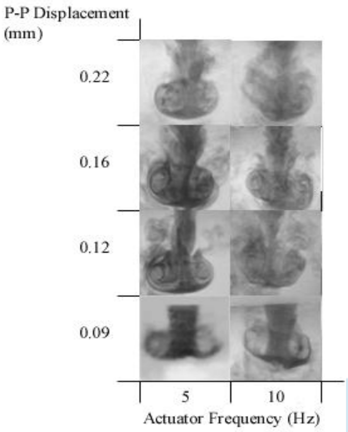


Figure 3.2 Effect of frequency and amplitude for a speed of 4 cm/s [4]

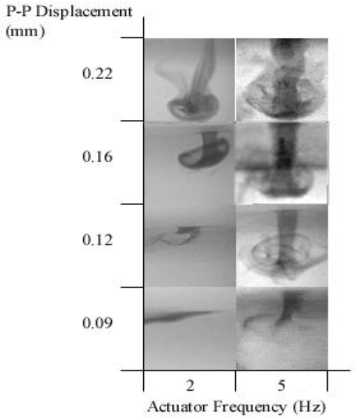


Figure 3.3 Effect of frequency and amplitude for a speed of 6 cm/s [4]

Chaudhry, Ishtiaq A and S. Zhong [2] have carried out this work of "A single circular synthetic jet issued into turbulent boundary layer". In this research work an experimental investigation has been undertaken to study the behaviour of a single circular synthetic jet issued into turbulent boundary layer produced on a flat plate in cross flow. At the given free stream conditions, the jet is also issued into laminar boundary layer so that an effective evaluation on the interaction of the vortices with the changing boundary layer could be made. The flow visualization technique is used in conjunction with the stereoscopic imaging system to reveal a unique quasi three-dimensional recognition of the vortices formed in either type of boundary layer under varying synthetic jet actuator (SJA) operating conditions. Firstly, the laminar boundary layer is produced on the flat plate with zero pressure gradient and later on the same boundary layer is triggered to turbulence using a trigger device. The free-stream conditions are justified by PIV measurements, in that the velocity profiles are drawn at given stream wise locations for both laminar and turbulent boundary layers. The parametric map is given to identify and bound the SJA operating parameters to produce the explicit vortical structures at the given conditions.

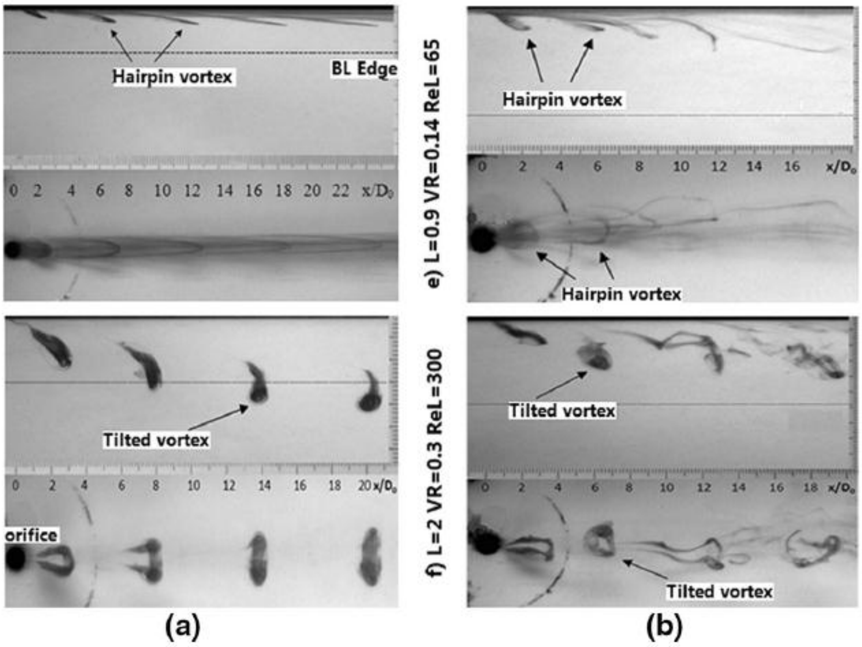


Figure 3.4 Vortex formation (a) Laminar boundary layer (b) Turbulent boundary layer [2]

Xia Qingfeng and Shan Zhong [24] in their research work they have presented the behaviour of circular synthetic jets issuing into quiescent surrounding fluid at low Reynolds numbers is experimentally studied for potential mixing applications of synthetic jets at micro-scales or in highly viscous fluids. Sugar solutions and silicone oil are used as the flow media in order to achieve the required low Reynolds numbers. The conditions for jet instability, vortex rollup and synthetic jet formation are investigated using both flow visualisation techniques and particle image velocimetry, and the typical behaviour of synthetic jets at a Reynolds number around unity is also illustrated. The roles of Reynolds number, dimensionless stroke length and Stokes number in determining the characteristics of synthetic jets are examined and found to be largely consistent with the finding obtained at higher Reynolds numbers. Finally, a parameter map of synthetic jet flow patterns is produced based on the results from this study, which can be used to aid the choice of synthetic jet operating conditions for specific applications or anticipate if a desired vortex structure can be obtained at a given synthetic jet operating condition.

Jain Manu, Bhalchandra Puranik, Amit Agrawal [15] have carried out numerical investigation of effects of cavity and orifice parameters on the characteristics of a synthetic jet flow. In this research work a synthetic jet is a quasi-steady jet of fluid generated from the periodic motion of a diaphragm enclosed in a cavity with opening/s on one or more walls. In this study, numerical simulations are performed to investigate the effect of various cavity parameters and orifice/cavity shapes on the ensuing synthetic jet flow. A circular orifice synthetic jet is simulated assuming axisymmetric behaviour. The quality of results is verified by time, grid, and domain independence studies, and the results are validated against existing experimental and numerical data. The moving diaphragm is modelled with a velocity boundary condition, with a moving piston boundary condition as well as with a moving wall boundary condition. The results obtained using these approaches are compared and it is concluded that the moving wall boundary condition provides the most realistic representation of the motion of the diaphragm. The simulation results show that synthetic jets are more affected by changes in the geometric parameters of the orifice than those of the cavity. The most significant parameters are determined to be the orifice and cavity radii and the orifice length. Two new parameters - volumetric efficiency and orifice utilization factor, are introduced; different types of diaphragms can be compared with the help of these parameters. The results obtained in this study are significant because they provide basic design guidelines for cavity and orifice, and can be used for optimization of the cavity and orifice shape for maximum velocity or mass flow rate.

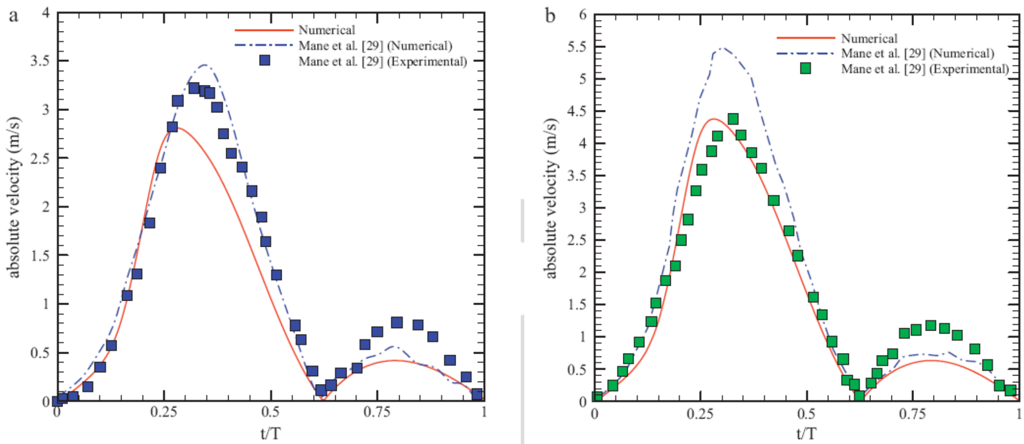


Figure 3.5 Velocity versus time curves for bimorph actuator at different frequencies of excitation (a) 32 Hz and (b) 50 Hz [15]

Xia Qingfeng, ShenghuiLei, Jieyan Ma, Shan Zhong [25] showed us the numerical study of circular synthetic jets at low Reynolds numbers through this research work. In this paper, the flow patterns of circular synthetic jets issuing into a quiescent flow at low Reynolds numbers are studied numerically. The results confirm the presence of the three jet flow regimes, i.e. no jet formation, jet flow without rollup and jet flow with rollup reported in the literature. The boundaries of the different jet flow regimes are determined by tracking the structures produced by the synthetic jets in the near field of the jet orifice over several actuation cycles and examining the cycle-averaged stream wise velocity profiles along the jet central axis. When the Stokes number is above a certain threshold value appropriate for the corresponding flow regime, a good correlation between the flow patterns and the jet Reynolds number defined using the jet orifice diameter, Do, is also found. Furthermore, the flow structures of synthetic jets with different suction duty cycle factors are compared. The use of a high suction duty cycle factor strengthens the synthetic jet resulting in a greater penetration depth into the surrounding fluid. Overall, the finding from this study enables the flow regimes, in which a synthetic jet actuator with a circular orifice operates, to be determined. It also provides a way of designing more effective synthetic jet actuators for enhancing mass and momentum transfer at very low Reynolds numbers.

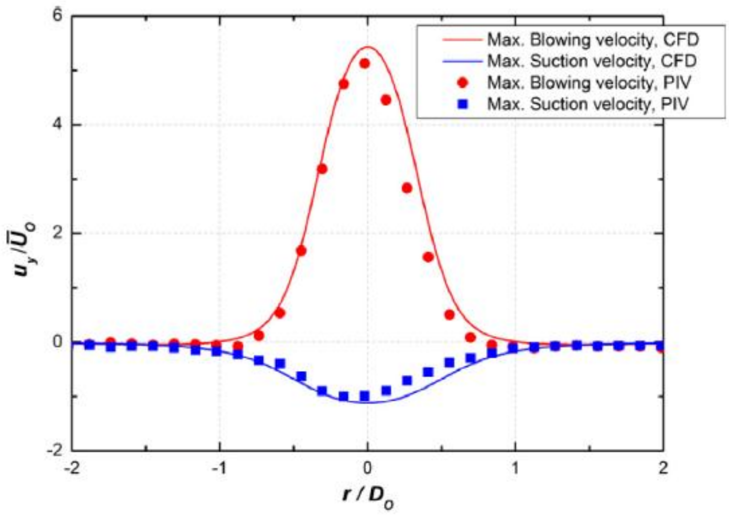


Figure 3.6 Velocity profiles [25]

IV. CONCLUSION

The overall study of the behaviour of circular synthetic jet in quiescent air at low Reynolds number. This study carried out based on brief literature review to understand behavior of circular synthetic jet in quiescent air at low Reynolds number. The study understood that lot of study had been carried out to assess the behavior of vortex rings at different diaphragm displacements, free stream speeds and driving frequencies. The key factor in the behavior of the jet appears to be the ratio of the jet velocity to the cross flow speed and also the separation distance between the vortex rings. Most of numerical and experimental investigations are based on cross flow boundary layer separation.

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