Severity assessment of circular orifice synthetic jet based on sound pressure level

Mahesh KANASE; Laxmikant MANGATE; Mangesh CHAUDHARI[1]

Department of Mechanical Engineering, Vishwakarma Institute of Technology, Pune 411037, India

ABSTRACT

Severity Assessment from the viewpoint of noise exposure is the preliminary stage for application of noise reduction technique to solve noise problems. In this paper, the severity assessment of circular orifice synthetic jet is presented based on sound pressure level. Synthetic jet generates substantial noise when operated in air as surrounding fluid. The effect of orifice diameter, orifice height and excitation voltage on sound pressure level of circular orifice synthetic jet is experimentally documented here. The excitation frequency to the synthetic jet actuator for the present study is 100 – 700 Hz. This parametric study is valuable from viewpoint of selection of synthetic jet configuration without violating Environmental Protection Agency standard and for obtaining maximum jet velocity and minimum sound pressure level.

Keywords: Synthetic Jet, Acoustic Test Chamber, Sound level meter

NOMENCLATURE

dB	decibel
dB(A)	decibel (A-weighting)
S	Signal [Wanted Sound], dB
N	Noise [Unwanted Sound], dB
P	Number of microphone positions.
W	Sound Power, Watt
d	Orifice diameter, mm
t	Orifice height [plate thickness], mm
h	Synthetic jet cavity height, mm
D_p	Diameter of bore on actuator plate, mm
D_h	Diameter of the hole drilled for screw, mm
V	Excitation voltage, V
f	Frequency, Hz

Abbreviation

SPL	Sound Pressure Level (dB)
SLM	Sound Level Meter
B&K	Bruel and Kjaer
USEPA	The United States Environmental Protection Agency

[1] chaudharimb@gmail.com

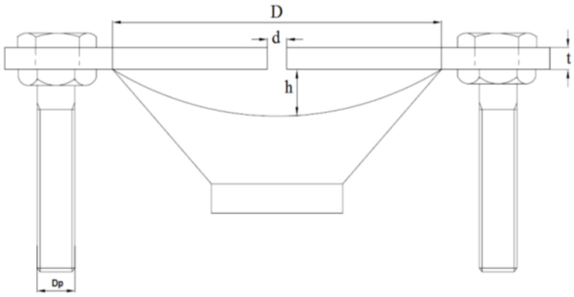


Fig. 1. Geometric parameters of synthetic jet module

Smith and Glezer [1] reported the formation and evolution of the two dimensional synthetic jet through Schlieren imaging and velocity measurements. The vortices were formed at the edge of an actuator orifice without net mass injection by the motion of a diaphragm in a sealed cavity. Mallinson et al. [2] investigated the flow generated by a synthetic jet actuator with a circular orifice. Cater and Soria [3] presented experimental study to determine the structure and mean flow quantities of round zero-net-mass-flux (ZNMF) jets. These jets were generated by a piston oscillating in a cavity behind a circular orifice and different flow patterns were observed with dye flow visualization. Cross-correlation digital particle image velocimetry was used to measure instantaneous two dimensional in-plane velocity fields in a plane containing the orifice axis. Chaudhari et al. [4] documented heat transfer characteristics of synthetic jet impingement using an electromagnetic actuator and compared it with continuous jet. Also a correlation for different configurations is suggested from the measured data. In other study, Chaudhari et al. [5] has explored the effect of square, circular and rectangular shapes of orifice on impingement cooling of heated surface. In further investigation, Chaudhari et al. [6] have improved the impingement heat transfer using multiple orifice synthetic jet and found that the maximum heat transfer coefficient is 30% more as compared to that obtained with a conventional single orifice jet. Utturkar et al. [7] examined the sensitivity of synthetic jets to the design of the jet cavity using the numerical simulations. The primary focus was to examine the effect of change in the cavity aspect ratio and the placement of piezoelectric diaphragm on the flow produced by the jet. Experimental measurements and flow visualization of synthetic jets and continuous jets is reported by Smith and Swift [8]. In the far field, the synthetic jets bear much resemblance to continuous jets. However, in the near field, the synthetic jets are dominated by vortex pairs that entrain more fluid than continuous jets. Pavlova and Amitay [9] obtained the efficiency of synthetic jet impingement cooling. The mechanisms associated with the removal of heat from a constant heat flux surface were investigated experimentally using thermocouples and particle image velocimetry. The effects of jet formation frequency and Reynolds number at different nozzle-to-surface distances are investigated and compared to that of continuous impingement jet cooling. Tan and Zhang [10] discussed the utility of a synthetic jet driven by piezoelectric actuator for impingement on a heated surface. In addition they have used particle image velocimetry (PIV), hot wire anemometer to measure the jet velocity field to describe characteristics and flow field database of the synthetic jet.

Chaudhari et al. [11] discussed the design aspects of synthetic jet cavity viz. geometric parameters and control parameters. Geometric parameters considered were cavity depth and actuator diameter along with orifice diameter and length. Control parameters considered were frequency and excitation voltage. Upper and lower bound frequencies for the formation of jet and two resonance frequencies corresponding to diaphragm frequency (250 Hz – 300 Hz) and Helmholtz frequency (1200 Hz) were reported. In addition Chaudhari et al. [12] also documented the experimental performance of a heat sink in the presence of synthetic jet for square, circular and rectangular shapes of orifice. The heat transfer coefficient was found to be approximately four times higher in the presence of a heat sink than that for the bare surface at same excitation frequency. Arik [13] experimentally obtained a maximum sound pressure level of 73 dB for synthetic jet and stated that it could be reduced to 30 dB by employing noise reduction technique such as muffler.

Literature suggests that studies reported earlier are mostly on synthetic jet flow and heat transfer measurements with very little thought on its acoustic aspects. It is found that, the severity assessment of synthetic jet based on sound pressure level measurement has not been dealt in detail. This gap in the literature of synthetic jet has been addressed in the current research paper.

2. EXPERIMENTAL SETUP AND PROCEDURE

This section presents a low cost, miniature acoustic test chamber which is designed and manufactured for noise measurements of synthetic jet giving emphasis on Green Technology. Different validation methods have been adopted and presented here to ensure free – field conditions and noise reduction of acoustic test chamber.

2.1 Design and manufacturing of acoustic chamber

Fig. 2 shows the acoustic chamber which has been designed according to ISO 3745 [14] and is constructed with gross dimensions of 2.44m X 2.44m X 1.22m where the last term indicates the height of the chamber. Pioneering work on the design, construction and validation of anechoic sound chamber has been done by Beranek and Sleeper [15]. Though the work on anechoic chamber was started much earlier and researchers have put efforts for its better acoustic performance; only a few technical institutes and industries can afford such costly acoustic facility. This underlines the fact that the most restrictive factor for severity assessment of noise is the cost. In order to overcome this hurdle, acoustic chamber has been designed and manufactured by giving emphasis on Green Technology and multilayer absorption treatment. In acoustics, absorption occurs as a result of incident sound penetrating and becoming entrapped in the absorbing material. It loses its vibration energy that converts into heat through friction. Absorption treatment by more thin layers assists more loss of sound energy because such layers can be easily set into vibration. Also, Multilayer absorption treatment acts in the form of insulating sections which break the sound path and assures high extraneous noise reduction. Materials selected based on their already available sound absorption characteristics are Jolly Bitulex acoustical ceiling tiles and open cell polyurethane foam. According to Green Technology, wastes are used instead of generating them. Therefore, eco-friendly plant based innocuous waste viz. coir fiber obtained from coconut husk is used. Another such fibrous material which is the most economical used in acoustic treatment is the cotton waste. Multilayer sound absorption treatment applied to 18 mm plywood and consists of polyurethane foam of 2 inch thickness, coir, cotton waste and jolly bitulex acoustic ceiling tiles of 12 mm thickness. The entire absorption treatment of total thickness of 80 mm is supported by chicken mesh wire grid.

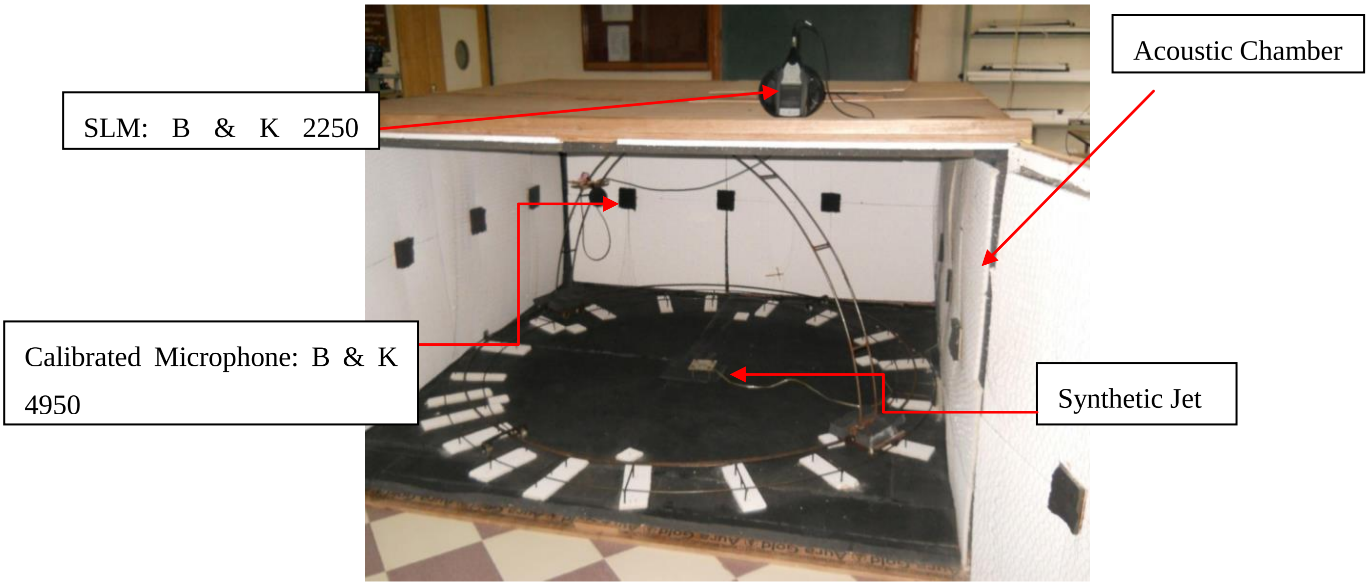


Fig. 2. Acoustic test chamber and hemi-spherical track along with synthetic jet

2.2 Validation

Acoustic measurements of synthetic jet are obtained in validated acoustic chamber. Different methods of validation such as S/N, 1 Watt, 1 kHz, 1m and Inverse Square Law [14 - 16] are mentioned in this section.

2.2.1 Validation by S/N ratio

S/N is the ratio of wanted sound (signal) to the unwanted sound (noise). Signal (S) is measured inside acoustic chamber at a distance of 1m from reference sound source under investigation. Without changing microphone position, same reference sound source is moved around acoustic chamber in order to avoid the effect of room position on noise (N) measurement. The S/N ratio is obtained using following equation:

$$\text{S/N} = \frac{\textit{Wanted Sound}}{\textit{Unwanted Sound}} = SPL_A - SPL_R = 10\log(\frac{W_A}{W_R}) \qquad \text{Eqn.(1)}$$

From S/N validation method for pure tones of signal and random noise, observed errors in the measurement of 1 Watt sound power are 0.0083Watt and 0.00023Watt respectively.

2.2.2 Validation by 1 Watt, 1 kHz, 1m method

Absolute maximum spatial deviation from mean surface sound pressure level of thirteen measurement points in fig. 4 has been recorded as 0.805 dB which is less than 1dB. The 3 dB doubling rule gives relation between sound pressure level and sound power level. Sound power is the cause and sound pressure is an effect. A doubling of sound power results in a measured increase of 3 dB. According to 3 dB doubling rule the maximum error involved is 0.781% for 1 Watt signal power in the acoustic measurement with 1 kHz frequency at 1 m.

2.2.3 Validation by inverse square law

In Inverse square law method, a point source of sound, radiating spherical waves in a free space, gives rise to sound intensity inversely proportional to square of distance from sound source. For the frequency range of 100 – 700 Hz, the observed deviations are found to be within permissible limit i.e. < 2.5 dB.

3. ACOUSTIC MEASUREMENT PROCEDURE

For the present experiment, an acoustic speaker of 50 mm diameter and 8 Ω impedance is employed as an actuator for creating the synthetic jet flow. A half inch microphone (B & K, Type: 4950) located at 1m from the sound source is used to measure the noise and is recorded on sound level meter (B & K, Type: Hand – held Analyzer 2250 Light). To curtail the directivity effect of reference actuator, its diaphragm is kept facing perpendicular to microphone and SPL measurements at different microphone locations (see Fig. 3) on hemisphere are taken. All sound generating sources outside the anechoic chamber were put off intentionally during acoustic measurements so as to keep background noise as low as possible. Background noise recorded in the experiment is 21 dB which is less than noise in empty auditorium or whisper at 1 m. Acoustic measurements are obtained for different synthetic jet orifice diameter and orifice height at different excitation voltages to the synthetic jet actuator in frequency range of 100 Hz – 700 Hz (see Table 1). Under realistic conditions of ambient noise the background noise level observed is in the range of 21-23 dB. The corresponding background noise level is added as a correction for SPL measurement of synthetic jet.

Table 1: Parameters varied in the present study

Parameter	Value	Dimension
d	3,5,8,12,14	mm
t	3,5,8,12	mm
h	6.3	mm
f	100 – 700	Hz
V	2,4,6,8	V

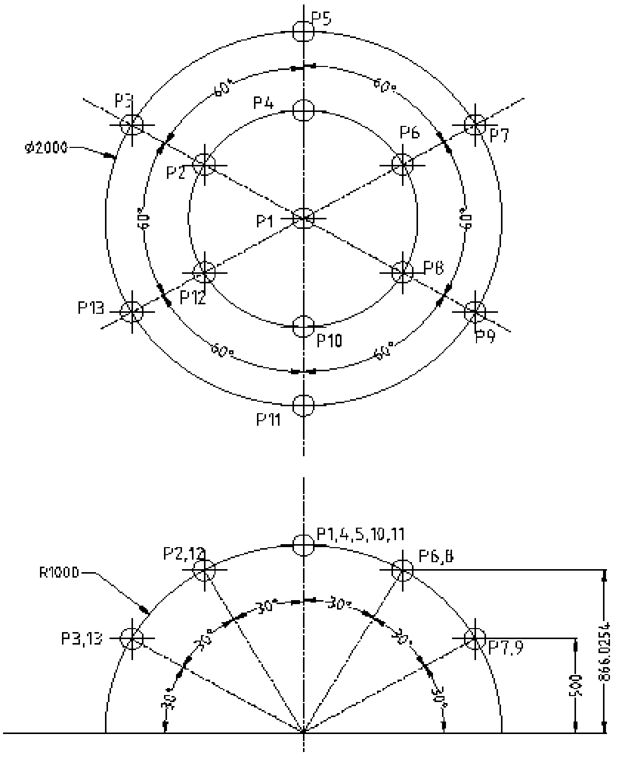


Fig. 3. Microphone positions on equal areas on the surface of test hemisphere in free-field.

4. ACOUSTIC DATA REDUCTION

Sound pressure level of Synthetic Jet is dependent on orifice diameter, orifice height (thickness), excitation frequency and voltage. Experimental data has been represented in the form of dimensionless group viz. Acoustic Reynolds number and thickness to the diameter ratio.

The group $\frac{\rho}{\mu}\omega L^{2}$ is denoted as Acoustic Reynolds number (Res_a), is the ratio of inertia force to the viscous force[17]. It shows the effect of hydraulic diameter (d_h) and frequency (f) on SPL of Synthetic Jet.

$$Res_a = \frac{\rho}{\mu}\omega L^{2} \qquad \text{Eqn.(2)}$$

$$Res_a = \frac{\rho}{\mu}(2\pi f)L^{2} \qquad \text{Eqn.(3)}$$

$$Res_a = \frac{\rho}{\mu}(2\pi)(fd^{2}) \qquad \text{Eqn.(4)}$$

$$Res_a = 0.392278(fd^{2}) \qquad \text{Eqn.(5)}$$

Where,

L = characteristic dimension = orifice diameter = d

ρ = air density = 1.165kg/m^3, at 303°K

μ = dynamic viscosity of air = 1.866X$10^{-5}kgm^{-1}s^{-1}$, at 303°K

Thickness to the diameter ratio (t/d) is another dimensionless parameter useful to present effect of variation of thickness and diameter on SPL of synthetic jet. Indirectly, a particular group of t/d ratios indicate an orifice diameter under investigation as shown in Table 2.

Table 2: Thickness to diameter ratios (t/d) considered for the present study.

t(mm)	d=3mm	d=5mm	d=8mm	d=12mm	d=14mm
3	1	0.6	0.375	0.25	0.214
5	1.667	1	0.625	0.417	0.357
8	2.667	1.6	1	0.667	0.571
12	4	2.4	1.5	1	0.857

5. RESULTS AND DISCUSSION

In this section, the effect of orifice diameter, orifice height, excitation voltage, excitation frequency on sound pressure level of circular orifice synthetic jet is discussed.

5.1 Effect of Excitation Voltage On SPL without orifice plate

Fig. 4 shows the variation of SPL with excitation frequency at different excitation voltages to synthetic jet actuator. It is observed that there is increase in sound pressure level for frequency range of 100 Hz – 400 Hz and 600 Hz – 1100 Hz. Further it is observed that there is drop in sound pressure level at 500 Hz and 1200 Hz. SPL is further observed to be increasing with increase in excitation voltage 2V to 8V.

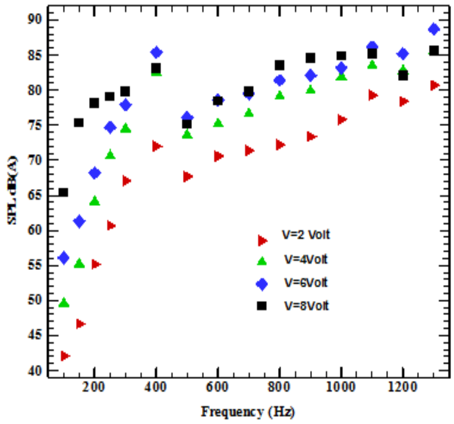
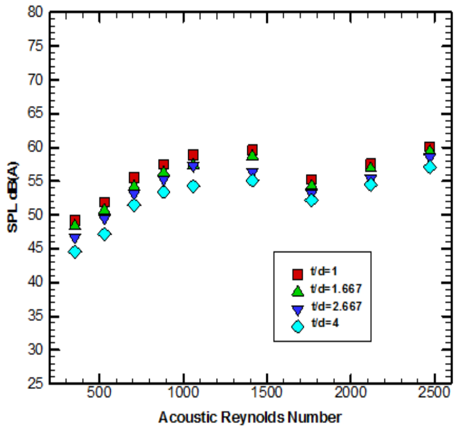


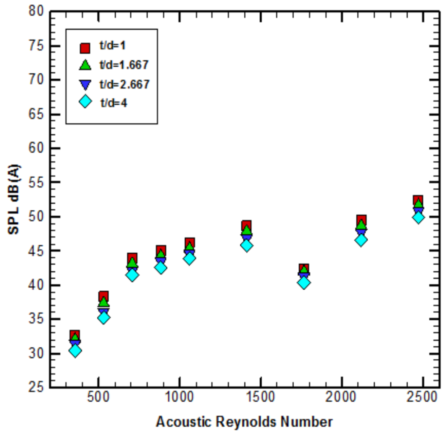
Fig. 4 Variation of SPL for different excitation frequency to synthetic jet actuator (Without orifice plate) at different excitation voltage.

5.2 Effect of Excitation Voltage on SPL with orifice plate (d = 3mm)

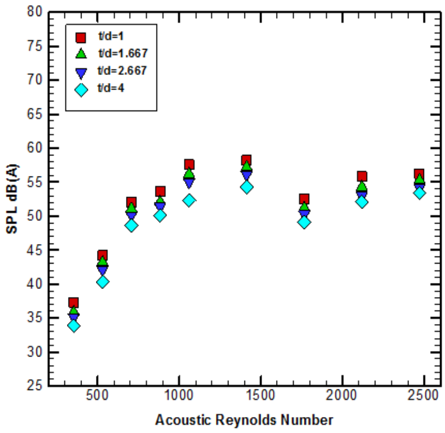
Fig. 5 shows the variation in SPL with acoustic Reynolds number at various t/d ratios for synthetic jet orifice of 3mm. Acoustic measurements are obtained for different excitation voltages to the actuator .



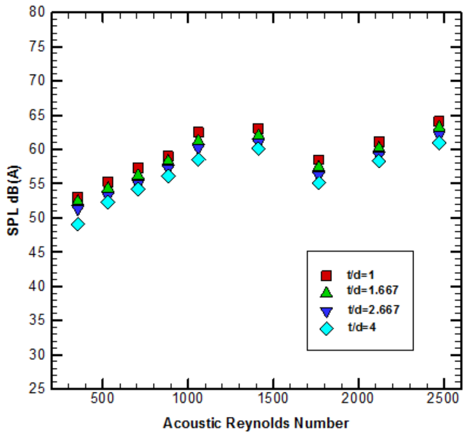
(a)



(b)



(c)



(d)

Fig. 5 Variation of SPL with Acoustic Reynolds Number for orifice diameter of 3 mm at (a) 2 V (b) 4 V (c) 6 V (d) 8 V for different t/d ratio.

It is observed that the SPL increases with increase in orifice length for constant orifice diameter. It is also observed that there is gradual increase in the value of SPL as the excitation voltage to the actuator is increased. This trend is observed for all the values of t/d considered for the present experiments. For higher excitation voltage, the amount of power supplied to the actuator will also be high. Part of supplied input power is used for motion of diaphragm due to which back pressure will be generated in synthetic jet cavity. As excitation voltage increases, diaphragm displacement and thus back pressure increases which will lead to increase in jet velocity. The rest of the supplied power will be converted into sound energy and other losses. Therefore, SPL is expected to increase with increase in excitation voltage.

5.3 Effect of Orifice Diameter on SPL of Synthetic Jet

Fig.6 shows the variation in SPL with acoustic Reynolds number for different orifice diameter. The results are obtained for different orifice lengths at constant excitation voltage of 4V. It is observed that the value of SPL increases with increase in orifice diameter as well as the orifice length for the range of acoustic Reynolds number considered for the present study.

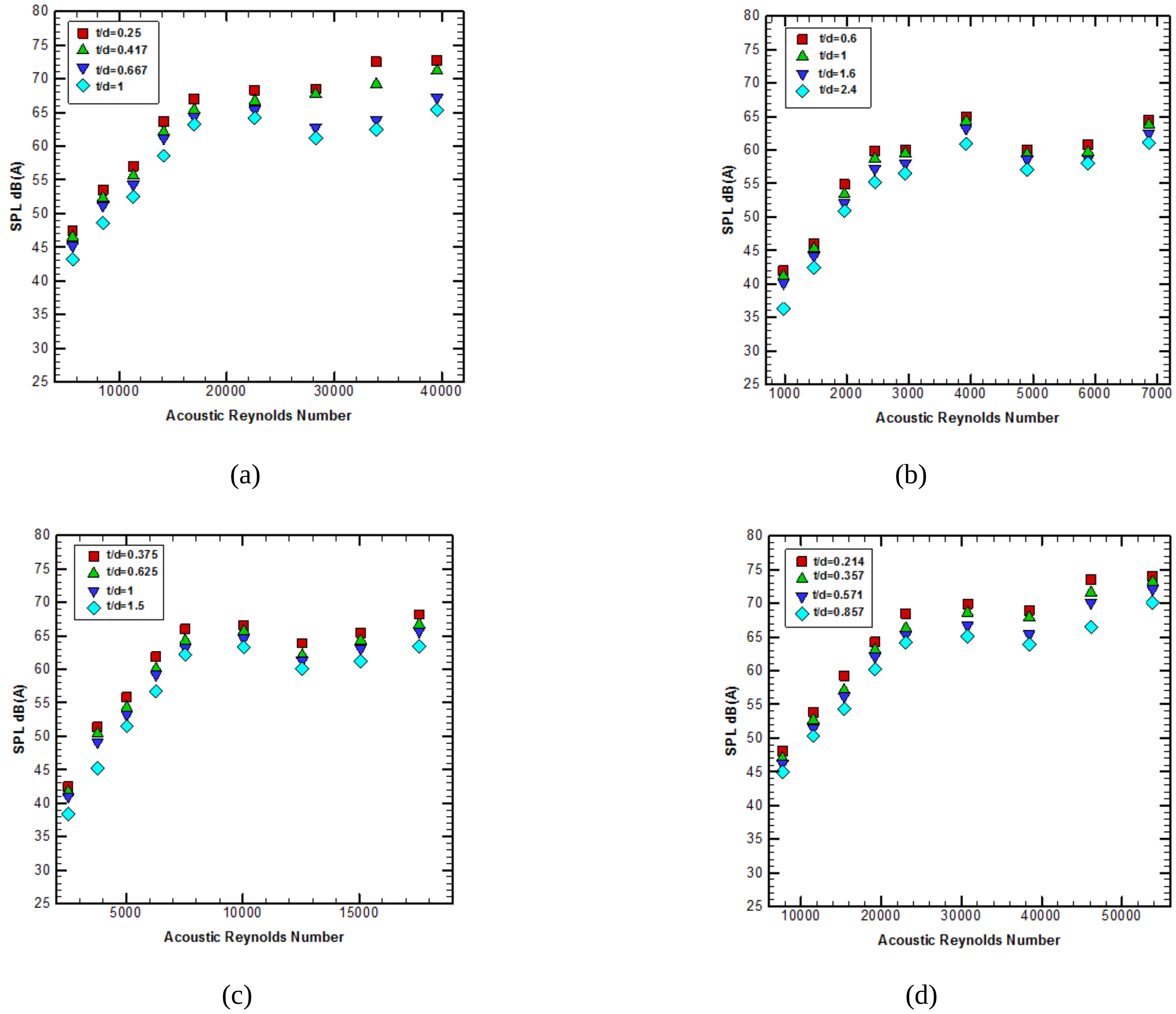
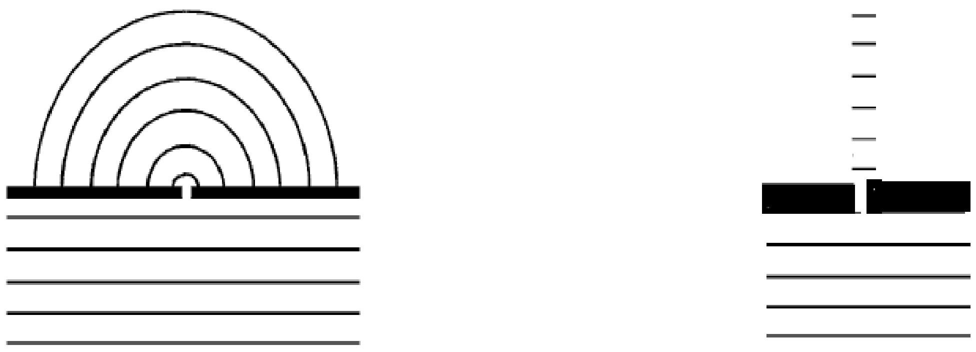


Fig. 6 Variation of SPL with Acoustic Reynolds Number at an excitation voltage of 4 V for orifice diameter of (a) d=5mm (b) d=8mm (c) d=12mm (d) d=14mm for different t/d ratio.

For larger orifice diameter, the value of SPL increases due to increase in orifice cross sectional area. This trend of rising value of SPL is observed for all t/d ratios. Here, the effect of oscillating air mass on SPL has been observed. With increase in orifice diameter the mass of an air volume in a restricted cross – sectional area increases which lead to higher SPL. Furthermore, SPL is also found to be increasing with increase in acoustic Reynolds number. This is primarily due to the fact that at lower frequency power consumed will be more for the same distance travel. It is also observed that there is drop in SPL at 500Hz for loudspeaker (actuator) for all orifice diameters of all heights.

5.4 Effect of orifice (acrylic plate) height on SPL of synthetic jet

Fig 7 shows that there is decrease in SPL with increase in orifice height. The obvious reason for this is that there is less hemispherical spreading of sound wave with increase in orifice height. It leads to more loss of sound energy due to multiple reflections in orifice cavity.



(a) (b)

Fig. 7 Dependence of spherical spreading of sound wave on orifice height (a) and (b).

6. CONCLUSION

The effect of voltage, frequency, orifice diameter and height on sound pressure level of circular orifice synthetic jet is addressed. This information on severity assessment of circular orifice synthetic jet is valuable from viewpoint of

(i) Parametric selection of synthetic jet without violating EPA standard,

(ii) Parametric selection of synthetic jet for maximum jet velocity and minimum sound pressure level.

These are frequently opposing requirements and an optimum design represents a balanced compromise between them. A judicious choice of design and control parameters dictates the frequency range for which circular orifice synthetic jet can be used for intended cooling purposes without violating EPA standard. Severity assessment of synthetic jet shows that increase in orifice diameter leads to increase in sound pressure level while contradictory condition is found in case of orifice height as an investigating parameter. Sound power level of circular orifice synthetic jet with 12 mm plate thickness is found half as that of with 3 mm. 3 dB increase in sensitivity means that it needs half input power to achieve a given sound pressure level.

ACKNOWLEDGEMENT

Authors are grateful to Department of Science and Technology (D.S.T.), New Delhi, India for providing funding to this research work in the field of acoustics. The authors are also thankful to Mechanical Engineering Department of Vishwakarma Institute of Technology, Pune for providing consistent encouragement.

REFERENCES

1. Smith BL, Glezer A. The formation and evolution of synthetic jets. Phys. Fluids, 10 (1998), pp. 2281-2297.
2. Mallinson SG, Reizes JA, Hong G. An experimental and numerical study of synthetic jet flow. Faculty of Engineering, University of Technology, Sydney, Australia (2001).
3. Cater JE, Soria J. The evolution of round zero-net-mass-flux jets. J. Fluid Mech., 472 (2002), pp. 167-200.
4. Chaudhari M, Puranik B, Agrawal A. Heat transfer characteristics of synthetic jet impingement cooling. International Journal of Heat and Mass Transfer, 53 (2010), pp. 1057-1069.
5. Chaudhari M, Puranik B, Agrawal A. Effect of orifice shape in synthetic jet based impingement cooling. Experimental Thermal and Fluid Science, 34 (2010), pp. 246-256.
6. Chaudhari M, Puranik B, Agrawal A. Multiple orifice synthetic jet for improvement in impingement heat transfer. International Journal of Heat and Mass Transfer, 54 (2011), pp. 2056-2065.
7. Utturkar Y, Mittal R, Rampunggoon P, Cattafesta L. Sensitivity of Synthetic jets to the design of the jet cavity. AIAA (2002), pp. 0124.
8. Smith BL, Swift GW. A comparision between synthetic jets and continuous jets. Experiments in Fluids, 34 (2003), pp. 467 – 472.
9. Pavlova A, Amitay M. Electronic cooling using synthetic jet impingement. Journal of Heat Transfer, 128 (2006), pp. 897 – 907.
10. Tan XM, Zhang JZ. Heat transfer characteristics of a synthetic jet impingement. Heat and Mass Transfer Conference, IIT Guwahati, (2006), pp. 140 – 145.
11. Chaudhari M, Verma G, Puranik B, Agrawal A. Frequency response of a synthetic jet cavity. Experimental Thermal and Fluid Sciences 33 (2009), pp.439 – 448.
12. Chaudhari M, Puranik B, Agrawal A. Heat transfer characteristics of a heat sink in presence of a synthetic jet. IEEE Transactions on Components, Packaging and Manufacturing Technology, 2(3) (2012), pp. 457–463.
13. Arik M. An investigation into feasibility of impingement heat transfer and acoustic abatement of meso scale synthetic jets. Applied Thermal Engineering 27 (2007), pp.1483–1494.
14. ISO 3745. Acoustics – determination of sound power levels of noise sources using sound pressure – precision methods for anechoic and hemi-anechoic rooms. International Organization for Standardization, Geneva, Switzerland 2003.
15. Beranek LL, Harvey P, Sleeper Jr. The design and construction of anechoic sound chamber. The Journal of the Acoustical Society of America 18 (1946), pp.140–150.
16. Beranek LL. Noise and Vibration Control Engineering. John Wiley & Sons, Inc. (1992).
17. I. Carl Romer Jr. Dimensionless parameters for use in presenting acoustical data. J. Acoustical Society of America 59 (1976), pp.1227-1229.