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Study of Heat transfer characteristics of Synthetic Jet

Manoj Rajale[1] , Shekhar Khedkar[2], Prakash Tripathi[3] , Ganesh Kerkal[4]

([1234]Assistant Professor, Mechanical Engineering department, Dr D Y Patil Institute of Engineering , Management and Research, Akurdi,, Pune, Maharashtra, India)

***Abstract:** A synthetic jet actuator is a device which moves a fluid in and outside a cavity, through a small orifice, by the continuous oscillation of a diaphragm which is frequently a piezoelectric disk. This paper represents a numerical study of an electronic cooling module using a periodic jet flow at an orifice with net zero mass flux. The two-dimensional time-dependant numerical simulation models used for the unsteady synthetic jet behavior, the flow within the cavity and the diaphragm movement while accounting for fluid turbulence using the (RNG) k-ε turbulence model. High formation frequency synthetic jets were found to remove heat better than low frequency jets for small z/d_o, while low frequency jets are more effective at larger z/d_o. In given numerical simulation Nusselt number is varies from range 0.16 to 5.25. In this paper study of synthetic jet flow and effect of different parameters resembling varying orifice dimensions and axial distance among orifice exit to top surface of heated wall and effect of frequency and cavity height on heat transfer coefficient is studied numerically via Ansys FLUENT 14.5 software.*

Keywords - Actuators; Synthetic jets; Zero net mass flux

NOMENCLATURE

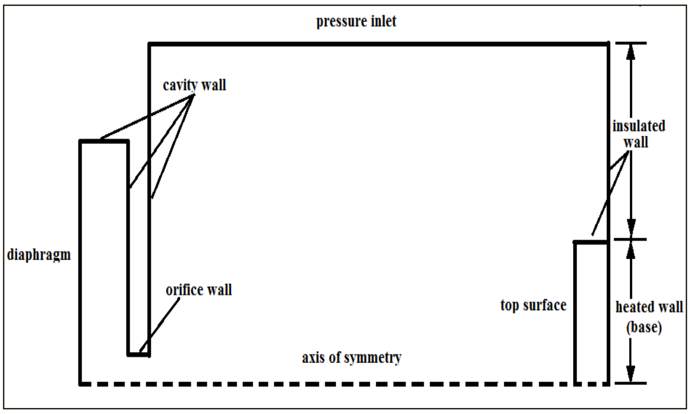
f = Frequency,
H_c = Cavity Height (m),
D_c = Diaphragm diameter (m),
h_o = Orifice Height (m),
d_o = Orifice diameter (m),
z = Axial distance between orifice exit to top of heated wall (m),
A_o = Orifice area (m^2) ,
r = Radial distance (m),
$\delta(r, t)$= Diaphragm displacement (m) ,
δ_c = Peak-Peak diaphragm center displacement (m),
h_{avg} = Average heat transfer coefficient(W/m^2K),

1. Introduction

Computational fluid dynamics can play a vital role in the design of micro-electromechanical systems based actuators, allowing an investigation of the underlying physical behavior of devices before proceeding to expensive manufacturing processes. In its most common implementation, a piezoelectric disk is bonded to a metal diaphragm, which is sealed to form a cavity. Smith and Glezer [1] was studied experimentally development of a synthetic jet made by the time-harmonic formation and interaction of a train of vortex pairs that are produced at the edge of the orifice. Synthetic jet has enhanced heat transfer characteristics as compare to continuous jet because of two reasons: First, because of vortex formation increases the wall normal velocity fluctuations, thereby increasing the momentum transfer in the layers closest to the wall which results increases the heat transfer rate. Second, the synthetic jet entrains more fluid when compared to an equivalent continuous jet, which increases the volume of fluid impinging upon a surface augmenting the heat transfer capacity [3]. Chaudhari et. al. [7] conducted heat transfer experiments using electromagnetic actuator and found that the square and circular orifices behave qualitatively similarly, while the behavior of the rectangular orifice is different. Mane et. al. [10] presented both experimental and numerical study of axisymmetric synthetic jet but heat transfer is not taken into consideration. Manu Jain et.al [11] presented numerical investigation of effects of cavity and orifice parameters on the characteristics of a synthetic jet flow. Subsequently present paper focuses on numerical analysis of synthetic jet with considering heat transfer.

2. NUMERICAL METHODOLOGY AND VALIDATION

For numerical study of synthetic jet and heat transfer characteristics, consider a two dimensional model which contains heated wall maintained at higher temperature



equal to 340K and atmospheric conditions were assumed for the thermodynamic variables. Air at an initial temperature of 300K was considered as the working fluid. The

Figure 1. Geometry and boundary conditions

compressibility effects come into picture because of the rapid change in pressure/density due to the movement of the diaphragm [11]. The diaphragm is defined

separately from the other walls so that time varying geometry equation can be used to describe its movement.
For the logarithmic profile the instantaneous displacement is shown below by equation,

$$\delta(r,t) = \pi\delta_c f\left[1 - \frac{4r^2}{D_c^2} + \frac{8r^2}{D_c^2}\ln\frac{2r}{D_c}\right] \text{--------Equation (1)}$$

At first for validation standpoint compare numerical results with results of Mane et. al. [10] for same configuration and boundary condition. The grid independency study shown in fig. (2) is done in order to obtain the results for validation cases.

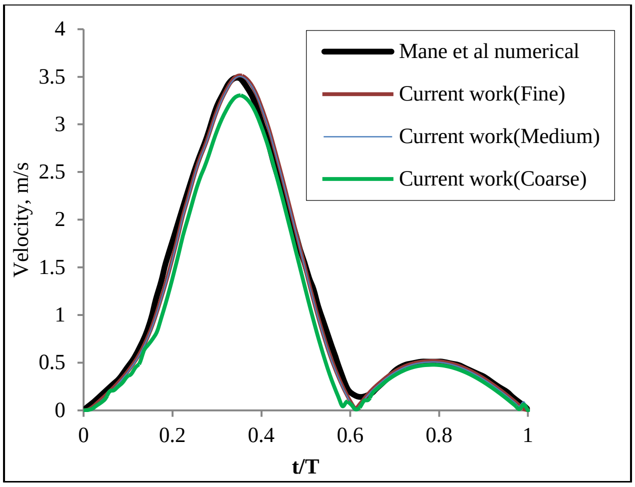
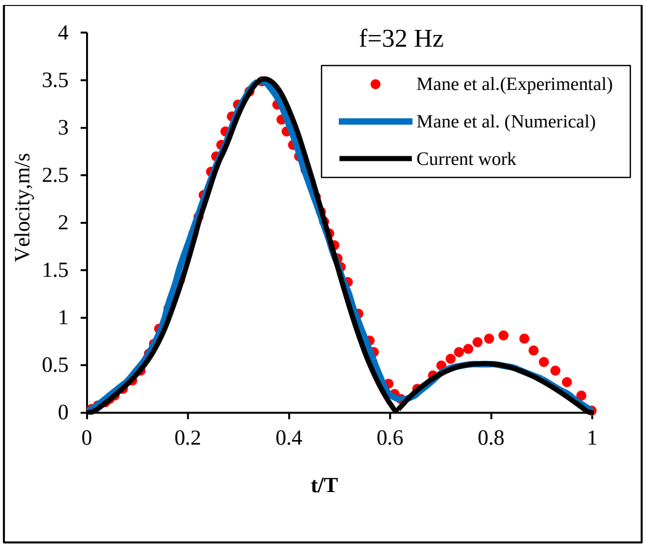
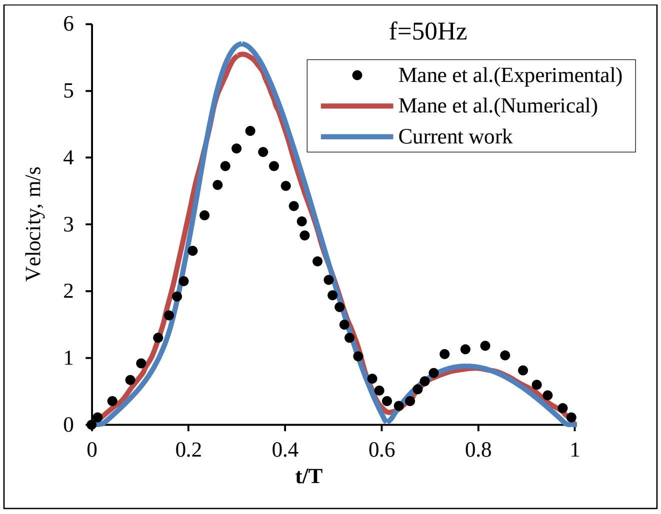


Figure 2. Study of mesh refinement (for f= 32 hz) [10]

Mane et al. [11] have performed a synthetic jet simulation for a bimorph actuator with a logarithmic approximation for the motion of diaphragm.



(a)



(b)

Figure 3. Velocity versus time curves for bimorph actuator at different frequencies of excitation (a) 32 Hz and (b) 50 Hz [10].

Using identical numerical conditions, simulation results are compared with those of Mane et al. (Experimental and numerical data) as shown in fig. (3). Jain et. al. [11] performed numerical simulation to investigate the effect of various cavity parameters and orifice/cavity shapes on the ensuing synthetic jet flow.

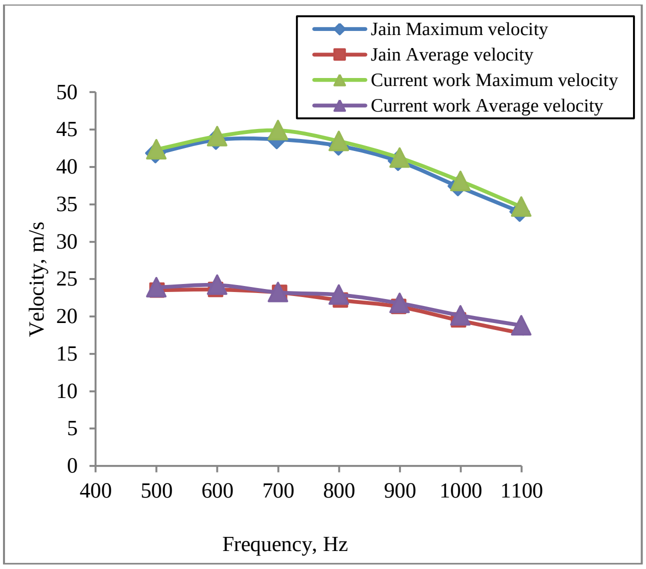


Figure 4. Maximum velocity/average velocity versus frequency [11]

Again by using similar numerical boundary conditions, simulation results for maximum velocity and average velocity are compared with those of Jain et al (numerical data) as shown in fig.(4). Validation results shows that technique and boundary conditions used for numerical simulation have good agreement with percentage deviation in results up to 3%.

3. RESULTS AND DISCUSSION

3.1. Effect of frequency on velocity

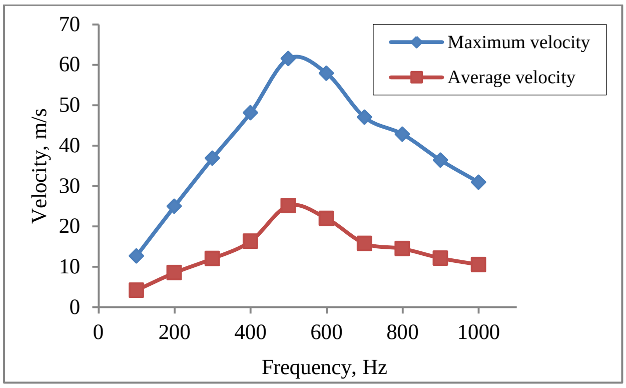


Figure 5. Maximum velocity/average velocity versus frequency (D_c=50mm, H_c=5mm, d_o=2mm, h_o=1.6mm) (Velocity is measured 1mm away from orifice exit at centerline)

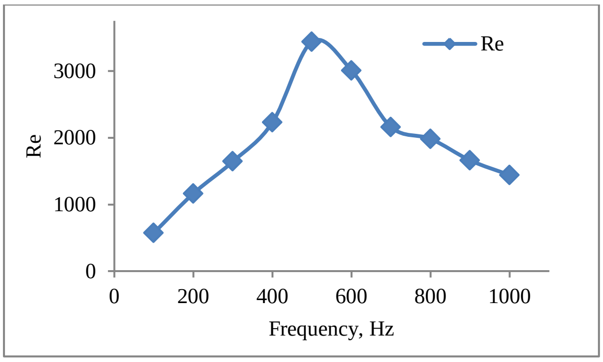


Figure 6. Variation in Re number with respect to frequency (D_c =50mm, H_c =5mm, d_o=2mm, h_o=1.6mm)

From simulation it is perceived that with respect to excitation frequency velocity get increases linearly upto frequency f=500 Hz subsequent to that it gets reduced with increase in frequency as shown in fig. (6). The cause for diminishing velocity is occurrence of two resonance frequencies: the Helmholtz frequency of the orifice and the diaphragm natural frequency [6].The Helmholtz frequency suggested by the simulations is between 500 Hz and 600 Hz. The maximum velocity succeeded is 61.514 m/s at f=500 Hz for configuration D_c=50mm, H_c=5mm, d_o=2mm and h_o=1.6mm.The maximum Re number achieved is equal to 3440.

3.2. Average temperature (T_{avg}) distribution of heated wall

The fig. (7) shows the contours of the bulk temperature of air inside the cavity. From fig. (7) it is clear that increase in the bulk temperature of air near the heated portion, and the extent of its migration into the quiescent air, because of impinging of jet on top surface of plate it gets cooled.

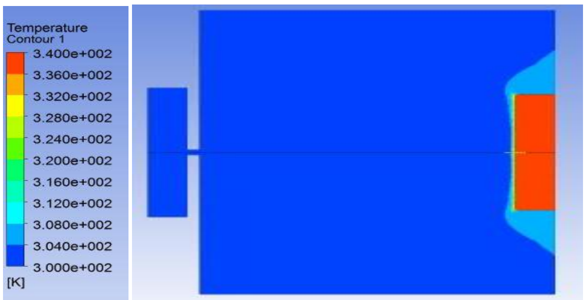


Figure 7. Temperature contours (D_c= 50mm, H_c= 5mm, d_o= 2mm, h_o=1.6mm, f=500Hz)

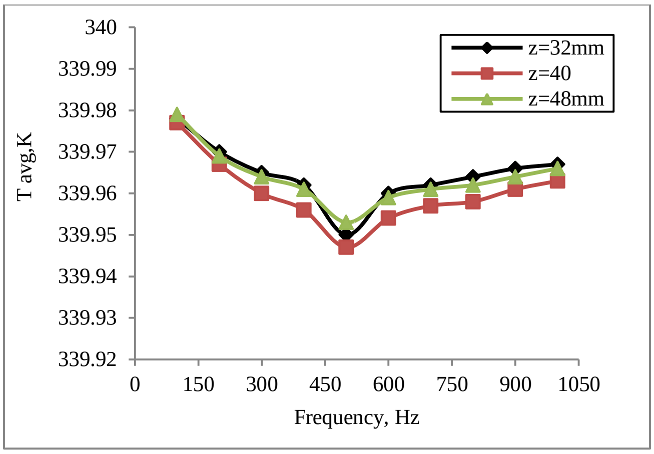


Figure.8. Average temperature (T_{avg}) versus frequency (D_c= 50mm, H_c= 5mm, d_o= 2mm, h_o=1.6mm)

The fig. (8) shows that variation in average temperature of heated wall surface with respect to change in frequency for different axial distance. Fig. (8) shows that, as frequency increases, temperature drop in heated wall surface increases upto frequency 500Hz further increase in frequency it gets decreases. It is observed that at 500Hz, maximum drop in average temperature of heated wall top surface arises for axial distance equal to z = 40mm.

3.3. Effect of frequency on h_{avg}:

Fig. (9) shows the variation of average heat transfer coefficient with varying axial distance between orifice outlet to top surface of copper block, for different frequencies. Numerical simulation is done for same size of orifice and cavity dimensions only axial distance is varying. The maximum heat transfer coefficient is achieved for given configuration is 72.51 W/m^2K at z= 40 mm. It is observed that average heat transfer coefficient increases upto frequency equal to 500Hz, further it get reduced. The equivalent trend of curve is observed for all frequencies. Chaudhari et. al. [7] have found experimentally same type of results for electromagnetic actuator for different size of configuration.

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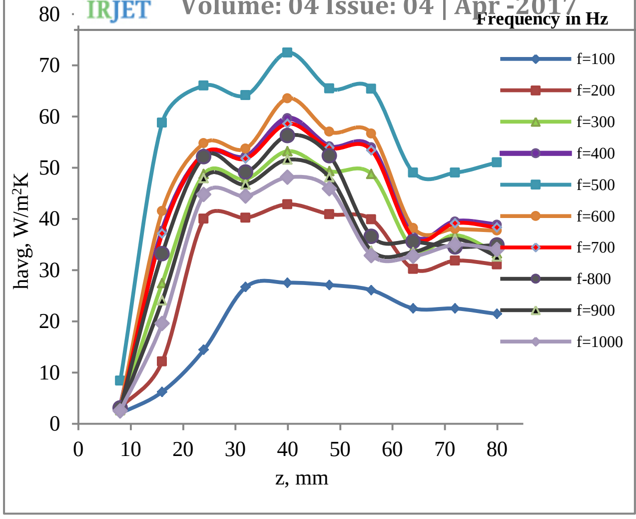

Figure 9. Variation of average heat transfer coefficient with axial distance for different excitation frequency, and for the same orifice diameter, length of orifice and length of orifice plate, and cavity depth (D_c=50mm, H_c=5mm, d_o=2mm, h_o=1.6mm)

3.4. Effect of orifice diameter on h_{avg}:

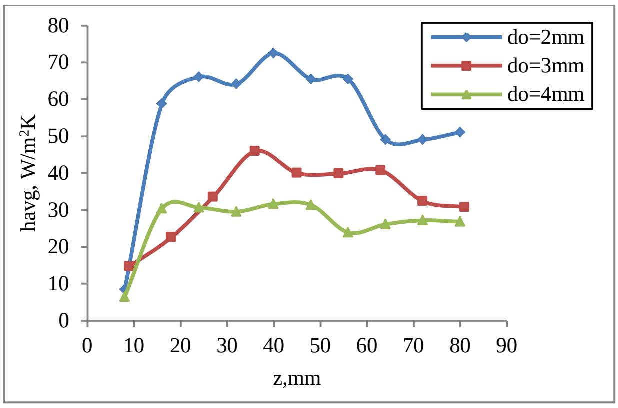

Figure 10. Variation of average heat transfer coefficient with axial distance for different orifice diameters, and for the same excitation frequency, length of orifice and length of orifice plate, and cavity depth (D_c=50mm, H_c=5mm, h_o=1.6mm, f=500Hz)

Fig. (10) shows that variation of average heat transfer coefficient with axial distance for different orifice diameters by keeping other parameters invariable. From simulation results it is clear that increasing diameter of orifice, h_{avg} get reduced and for simulation select sizes of orifice diameter i.e. (2mm, 3mm, 4mm). It is observed that location of maximum h_{avg} is changes with orifice diameter. For example the location of maximum h_{avg} is z = 40mm for d_o= 2mm, z =36 for d_o=3mm and z =40mm for d_o= 4mm. It observed that small change in orifice diameter that causes large change in heat transfer coefficient.

3.5. Effect of cavity height on h_{avg}

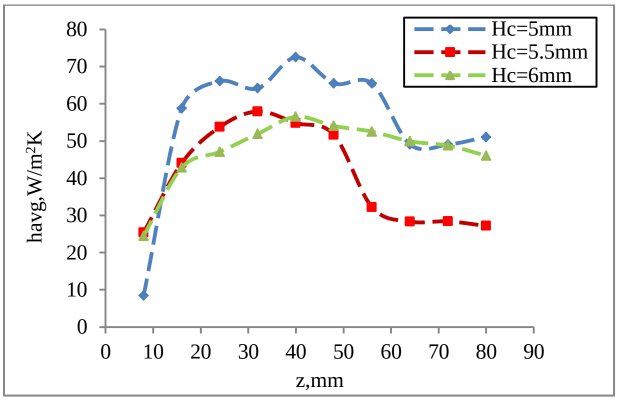

Figure. 11. Variation of average heat transfer coefficient with axial distance for different cavity depth, and for the same orifice diameter, length of orifice and length of orifice plate, and excitation frequency (d_o=2 mm, h_o = 2.4 mm, f = 500 Hz).

Fig. (11) shows the variation of average heat transfer coefficient with axial distance, for different cavity depths (5mm, 5,5mm and 6 mm) and keeping the value of all other parameters the same. It is noticed that the cavity height have a significant effect on the average heat transfer coefficient. Increase in cavity height decrease in heat transfer coefficient i.e. at H_c=5mm, f=500Hz, the heat transfer coefficient is h_{avg}=72.52 W/m²Kand it decreases at H_c= 6mm, f=500Hz equal to h_{avg}=56.52 W/m²K.

3.6. Non-dimensional results

This section discusses the variation of average Nusselt number with respect to the various non-dimensional parameters.

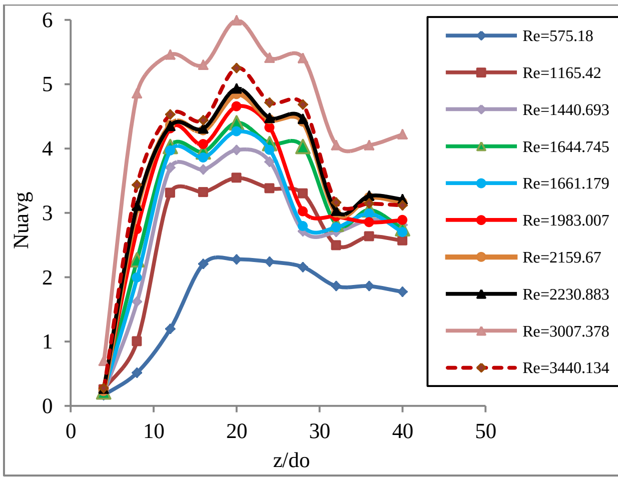

Figure 12. Variation of average Nusselt number with axial distance for different Reynolds number (D_c=50mm, H_c=5mm, d_o=2mm)

Fig. (12) shows that variation of Nusselt number with changing axial distance between orifice exit and top surface of heated wall. Chaudhari et. al. [7] have done experimental work on this non dimensional parameters using an electromagnetic actuator and found that same types of results. With reference to that results above results are plotted for piezoelectric diaphragm. From simulation result it is observed that the average Nusselt number rapidly increases upto $z/d_o \approx 20$ and then gradually decreases with an increase in z/d. Also it is observed that with increase in Reynolds number, average Nusselt number increases for any given z/d. The maximum value of average Nusselt number is 5.25 at a Reynolds number of 3440.1. The maximum Nusselt number is observed at the same location ($z/d_o \approx 20$) for all Reynolds numbers.

4. CONCLUSIONS

This study provides a thorough numerical simulation of an axisymmetric synthetic jet. The numerical modeling utilized a moving boundary condition with oscillating deflection logarithmic profile applied to the diaphragm. The present work focused on the heat transfer characteristic of synthetic jet. To find the effect of parameters of orifice and cavity height on the synthetic jet flow, different cases were designed and compared with a baseline case. With the help of numerical simulation and literature survey it is cleared that average heat transfer coefficient is exaggerated by the orifice diameter, and it increases with a decrease in the height of the orifice plate. In case of piezoelectric actuator required small size of orifice diameter (d_o=2mm) to get maximum heat transfer coefficient. The heat transfer first increases and then decreases with an increase in axial distance. From simulation it is cleared that the location of the maximum heat transfer coefficient depends on the geometric parameters. For non dimensional parameters, as Reynolds number increases, Nusselt number also increases upto $z/d \approx 20$. High formation frequency synthetic jets were found to remove heat better than low frequency jets for small z/d, while low frequency jets are more effective at larger z/d.

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