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ORIGINAL ARTICLE

Optimization of thermal characteristics of axisymmetric synthetic air jet impingement on flat surface

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ABSTRACT – The local heat transfer of axisymmetric synthetic air jet impinging on flat surface is investigated experimentally. Acoustic speaker is used for generation of synthetic air jet with cavity of cylindrical shape.The experiments is conducted for actuator frequency ranging from 50Hz to 400Hz, orifice diameter 2mm to 10mm, orifice plate thickness 2mm to 10mm, cavity diameter 50mm to 75mm, cavity depth 30mm to 60mm, jet to plate distance 16mm to 112mm. A steady heat flow is maintained on the flat surface. Local heat transfer characteristics on flat surface is found by thermal images using IR thermal imaging and thin foil technique.The experimental results reveals that the heat transfer is highly effected by frequency, orifice diameter, orifice plate thickness, jet to plate distance. However, cavity depth and cavity diameter has small influence on thermal performance.The higher cavity volume show more influence on heat transfer characteristics. An optimization of synthetic jet performance parameters is studied for maximum thermal performance interms of heat transfer characteristics.

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INTRODUCTION

Due to technological improvements, the density of electrical components is increasing every day. The thermal stress is parameter for the failure of electronic components which in turn decreases the efficiency of the system. Hence, cooling is required for the proper functioning of the electronic system. Conventional cooling methods like fin and fans already exist which are not that effective because of lower heat transfer coefficient and also occupy more specific space. In addition, conventional cooling techniques must be continually improved to meet the difficulties of increased heat power dissipation. Hence, researchers focused their research on newly method of cooling of electronic components. Synthetic jet is one of the latest effective methods which may be used for such cooling applications. Synthetic air jet is simple and doesn't require additional plumbing system which makes it an effective technology for cooling of electronics components as compared to conventional methods.

Synthetic jet is obtained when the flow is sucked, expel out through an orifice by the displacement of actuator diaphragm as reported by Smith & Glezer [1]. Due to pulsating flow behaviour of synthetic jet, entrainment of secondary air into the primary air jet is more when it is compared with continuous jet, which may lead to efficient cooling. Hence, synthetic air jet is used for heat transfer enhancement of electronic systems.

Pavlova & Amitay [2] reported influence of z/d and frequency. At low z/d, high actuator frequency is effective and at high z/d, low frequency is more effective.Garg et al.[3] reported the influence of actuator voltage, orifice to surface distance of mesoscale synthetic jet. The actuator with voltage ($50V_{rms}$) and z/d of 8 is observed maximum heat transfer. Gillespie et al. [4] experimentally reported effect of slot jet on the heat transfer. Average Nusselt numbers were maximized for orifice to surface distance between 14 and 18, jet frequency close to cavity frequency. Mahalingam and Glezer [5] studied thermal characteristics of heat sink, which results in 40% heat dissipated using synthetic jet.Chaudharu et al. [6 - 9] reported influence of orifice shape of varying aspect ratio.At $z/d > 5$, square orifice shape was found effective.They also studied the multiple orifice effect on synthetic jet performance. At lower z/d, satellite orifice with central orifice was observed effective. Jain et al. [10] numerically investigated influence of cavity, orifice shape. The cavity and orifice height doesn't change the maximum velocity but changes the behaviour of velocity variations. Liu et al.[11] reported effect of a diffusion shaped orifice. At low z/d, diffusion shaped orifices are more effective than round orifices. Ziade et al. [12] reported the effect of cavity shape.The sharpest nozzle cavity shape observed more momentum than all other cavity shape.

The local heat transfer study of an axisymmetric synthetic jet impinging on a flat surface is investigated using the IR thermal imaging method.The experiments is studied for different configuration i.e excitation frequency of the actuator, orifice diameter, orifice plate thickness, cavity diameter, cavity depth,orifice plate to jet distance on the target plate keeping the diameter and amplitude of the actuator as constant. For the system's maximum thermal performance, the performance characteristics of the synthetic jet are also optimized.

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Experimental Layout and Measurement Methodology

Figure 1 illustrates the experimental setup. An acoustic speaker of diameter (50mm) with power capacity (5W) is used for the generation of synthetic jet. The input voltage of 5.5V to acoustic speaker is kept constant throughout the experiment. The frequency and waveform of actuator is controlled by signal generator.

The stainless steel foil (180mm × 91mm × 0.05mm thick) is used as a target plate.It is tightly attached between two copper bus bars and is coupled to a regulated DC power supply indirectly. The temperature of the back and front surfaces of the target surface are considered to be the same due to the thinness of the foil according to Lytle & Webb [13]. Matt finish Asian' paint was used to paint the back surface black. The emissivity of back surface is obtained by method as stated by Talapati et al. [14] and is 0.98. The local temperature distribution on the flat plate is measured with 2^0C accuracy by an IR thermal camera model "Fluke" Ti 200.The controlled DC power supply is utilised to keep the heat flux on the target plate constant. A voltmeter is used to measure the voltage drop on the target plate by inserting voltage taps at the proper distance.The regulated DC power supply panel records the current to the target plate.A calibrated K-type thermocouple (Chromel-Alumel) is used to measure the jet and ambient temperatures. The cavity air temperature is considered as jet air temperature as reported by Talapati and Katti [15]. The assembly of entire target plate is placed on a 2-D traversing table.The distance between orifice plate and flat plate can be adjusted using a 2-D traversing table with a minimum count of 0.05mm.Experimental estimates of heat loss owing to free convection at back, radiation at both the front and back surfaces are explained in the data reduction section.

DATA REDUCTION

The local temperature distribution on a flat surface is determined using thermal images from an IR thermal camera. The Nusselt number and heat transfer coefficient is obtained by Eqs. (1) and (2):

$$Nu = \frac{hd}{k} \tag{1}$$

$$h = \frac{q_{conv}}{(T_s - T_j)} \tag{2}$$

The rate of heat transfer between the impingement jet and the flat surface (q_{con}) is computed using the energy balance (Eq. (3) and Eq. (4)

$$q_{con} = q_s - q_{loss} \tag{3}$$

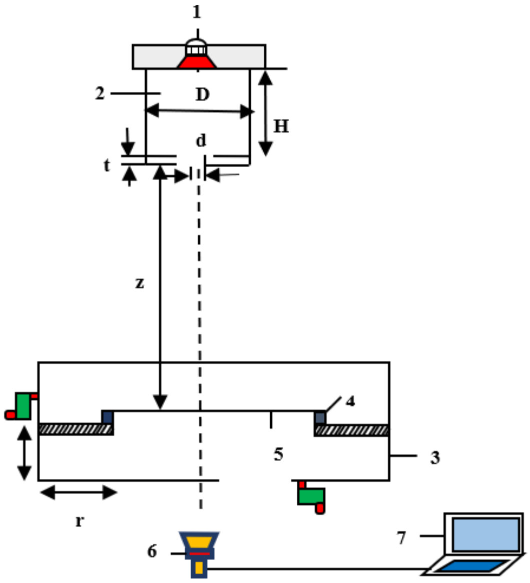
$$q_s = \frac{VI}{A} \tag{4}$$

$$q_{loss} = q_{r(f)} + q_{r(b)} + q_{n(b)} \tag{5}$$

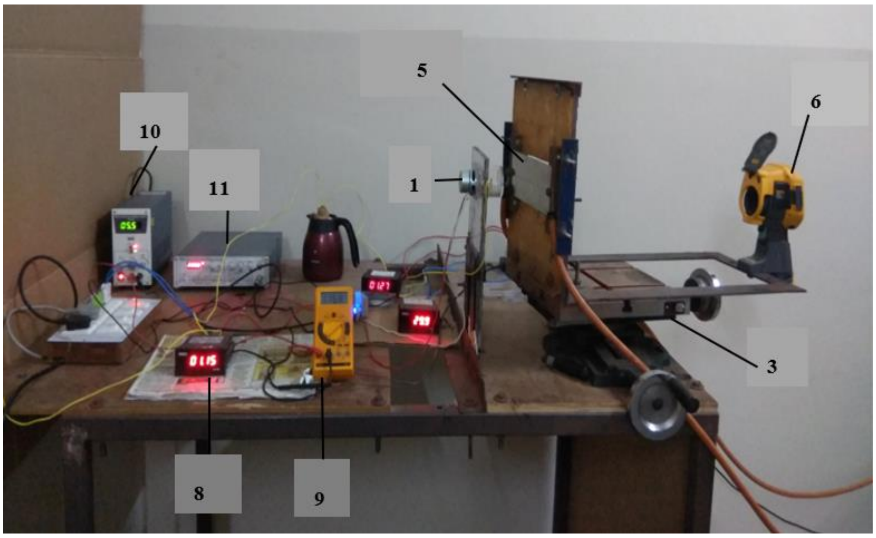
q_{loss} is estimated experimentally using Eq. (5).

MEASUREMENT OF UNCERTAINTIES

The temperature difference between the flat surface and the jet was maintained above 40^0C in this study, resulting in a maximum error of less than 2%.The heat flow uncertainty on a flat surface is the same as the power supply uncertainty, which is around 4%.The uncertainty measurement of Nusselt number reported by Moffat [16] are less than 9 % in the present paper.



(a) Schematic diagram of synthetic jet



(b) Photographic view of synthetic jet experimental setup

(1) Acoustic speaker	(2) Synthetic jet cavity	(3) 2-D Traversing table	(4) Copper bus bar
(5) Target plate	(6) Thermal camera	(7) Laptop	(8) Millivoltmeter
(9) Multimeter	(10) DC power supply	(11) Signal generator	

Figure 1. Layout of experimental set up of synthetic jet

RESULT AND DISCUSSIONS

Local Heat Transfer Characteristics

The local heat transfer study of an axisymmetric synthetic jet impinging on a flat surface are investigated using the IR thermal imaging technique.The experiments are carried for actuator frequency ranging from 50Hz to 400Hz, orifice diameter 2mm to 10mm, orifice plate thickness 2mm to 10mm, cavity diameter 50mm to 75mm, cavity depth 30mm to 60mm, jet to plate distance 16mm to 112mm and obtained results are represented in terms of *Nu*. An optimization of synthetic jet parameter is studied for the maximum heat transfer of the system.

Effect of Actuator Frequency

The effect of actuator frequency on heat transfer performance is studied by varying actuator frequency from 50Hz to 400Hz. Figure 2 shows h_{avg} for different actuator frequencies with varying z value for 8mm orifice diameter.When the actuator frequency is increased, the h_{avg} also increased until it reaches 200Hz, after which it drops.The actuator frequency (200Hz) produces maximum heat transfer characteristics compared to other actuator frequencies because the momentum flux of synthetic jet flow will be high at resonance frequency which is 200Hz in the present study.The *Nu* distribution for different actuator frequency is shown in Figure 3.

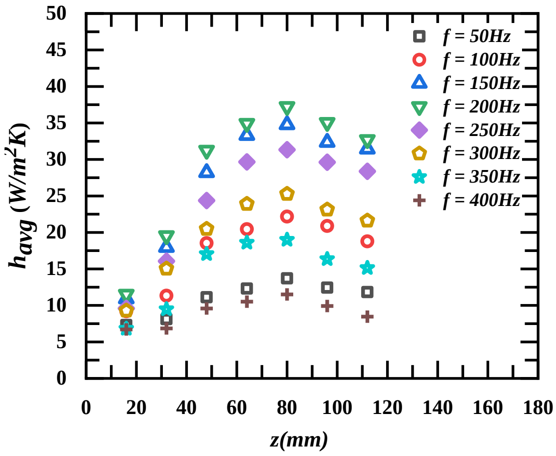
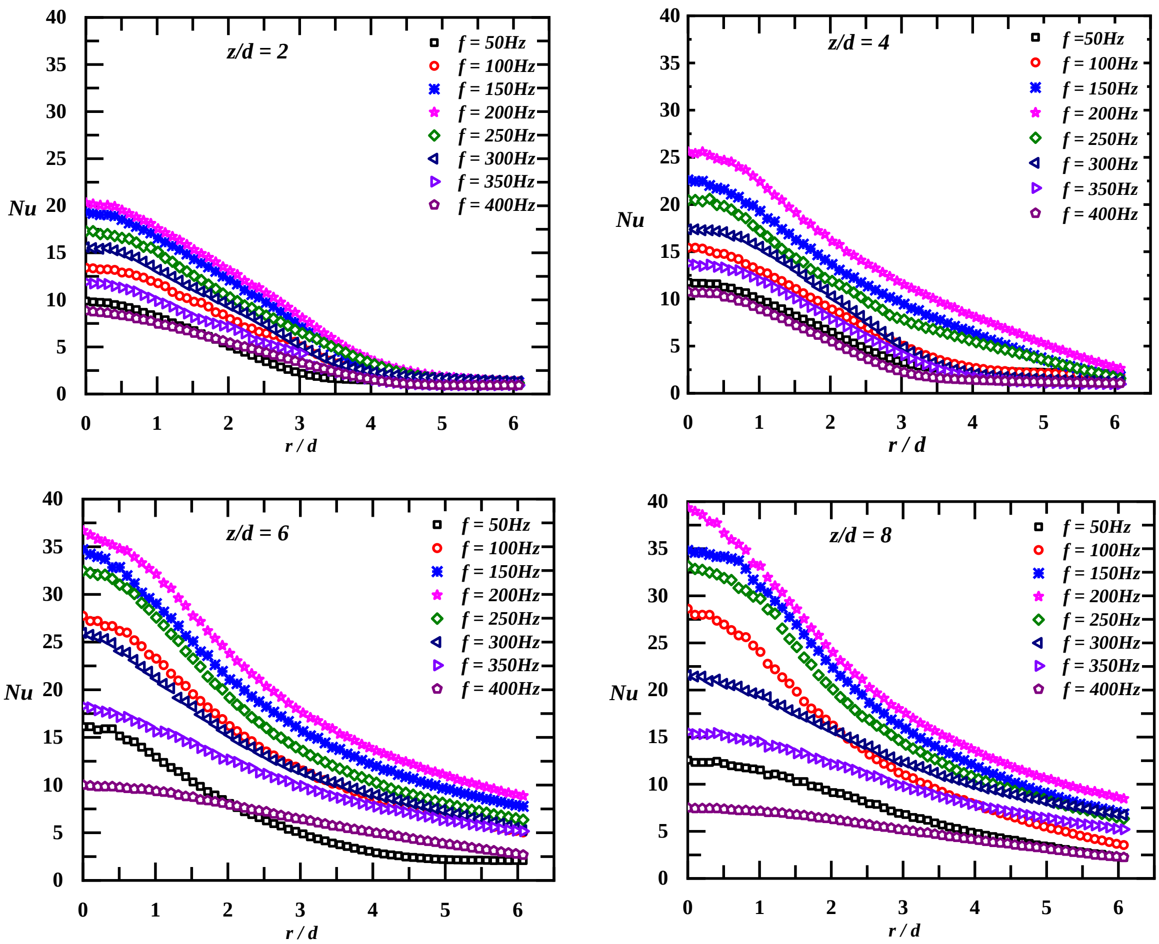


Figure 2. h_{avg} for different z and actuator frequency, *f* for d =8mm

The *Nu* of lower frequency (*f* = 50Hz) actuator increases with increase in *z/d* distance and decreases as the *z/d* distance increases with a higher frequency (*f* = 350Hz) actuator. Due to vortex ring structure in flow path, lower frequency are effective at higher *z/d* distance, while higher frequency provides effective heat transfer at lower *z/d* distances as result of breaking of vortex rings into smaller vortex rings before jet impingement. Nu_o is maximum for the resonance frequency (*f* = 200Hz) of the actuator at all *z/d* distance. The frequency (200Hz) is effective at stagnation region and away from the stagnation region. But at higher frequency (*f* = 400Hz), the heat transfer is minimum due to lower momentum of sythetic jet impingment. The *Nu* distribution contours for varying actuator frequencies at *z/d* =10 is shown in Figure 4. At *z/d* =10, the actuator frequency (*f* = 200Hz) has maximum heat transfer characteristics and actuator frequency (*f* = 50Hz) has minimum heat transfer characteristics. Hence for effective synthetic jet, the actuator is desired to be driven at resonance frequency.The optimum condition for maximum heat transfer characteristics occurs at 200Hz actuator frequency at all *z/d* distances in the present experiment.



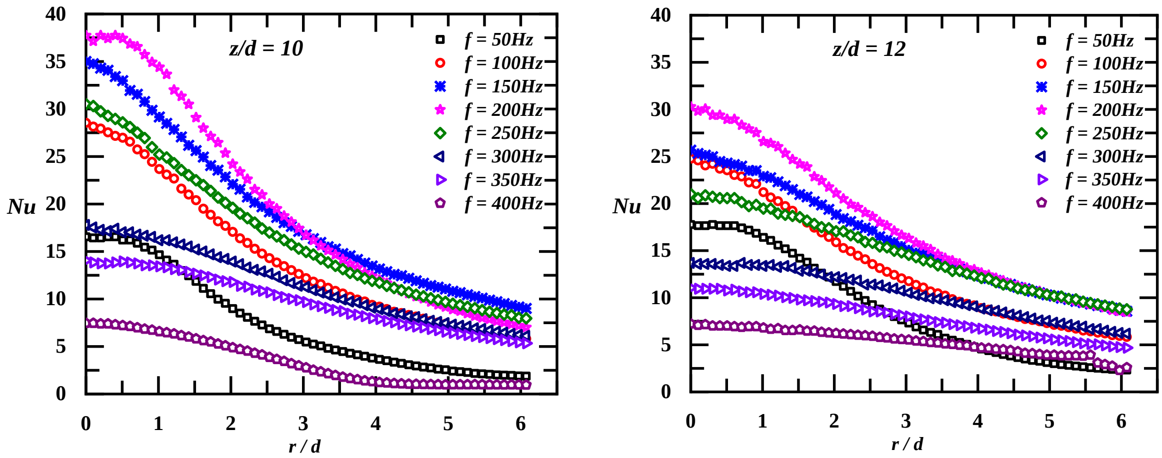
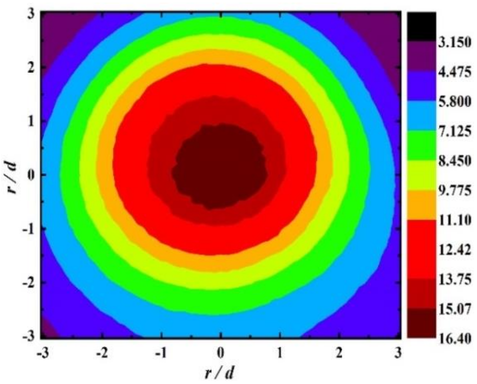
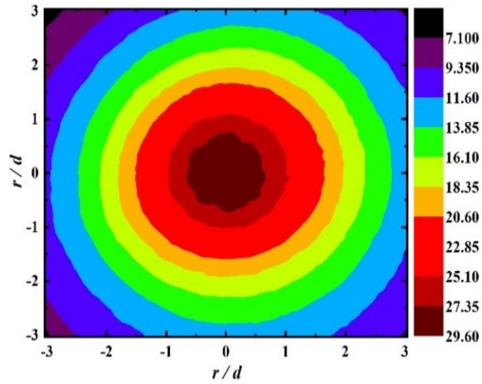


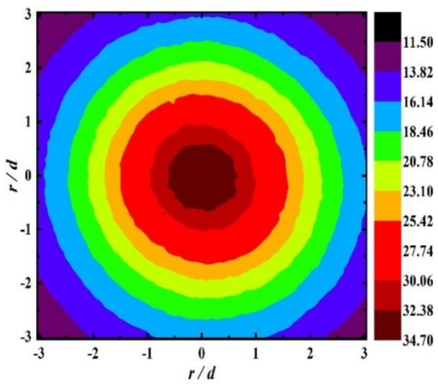
Figure 3. Nu distribution for different z/d distance and frequency, *f* for d = 8mm



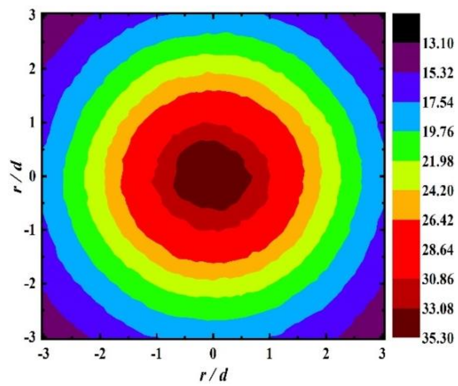
(a) *f* = 50Hz



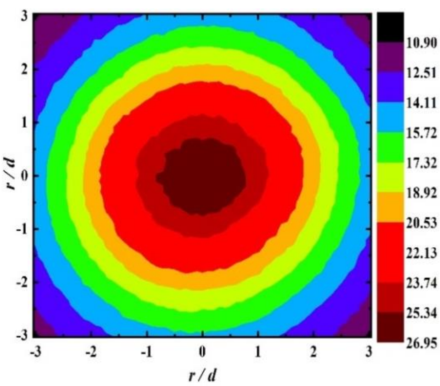
(b) *f* = 100Hz



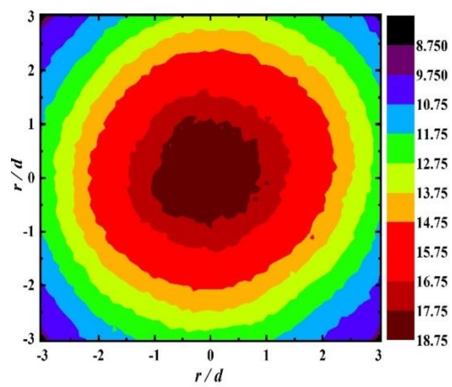
(c) *f* = 150Hz



(d) *f* = 200Hz



(e) *f* = 250Hz



(f) *f* = 300Hz

Figure 4. Nu contours for different frequency, *f* at z/d =10 for d = 8mm

Effect of Jet to Plate Distance

Figure 5 shows the h_{avg} characteristics with varying *z* and frequency(*f*) for 8mm orifice diameter. For all actuator frequencies, the h_{avg} increases up to 80mm plate to jet distance (*z*) and then drops. The heat transfer characteristics will be more effective at *z/d*=10 for resonance frequency (*f* =200Hz). This could be due to the development of high-potential tiny vortex rings before they collide with the target plate.At lower plate to jet distance,the heat transfer is minimum due to increase in flow confinement.The optimum *z/d* distance for maximum average heat transfer reported by Utturkar et al.[17] is *z/d* =10. The *Nu* distribution for different *z/d* is shown in Figure 6.

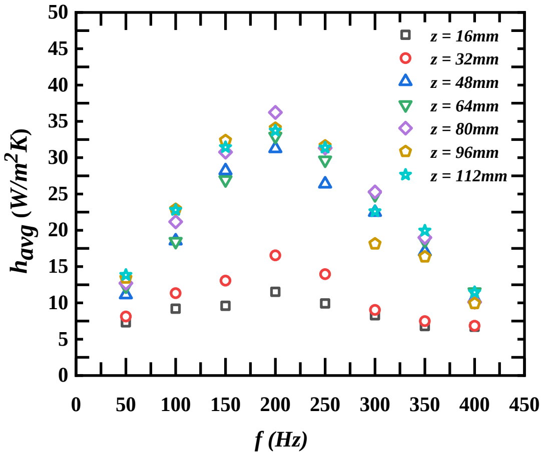
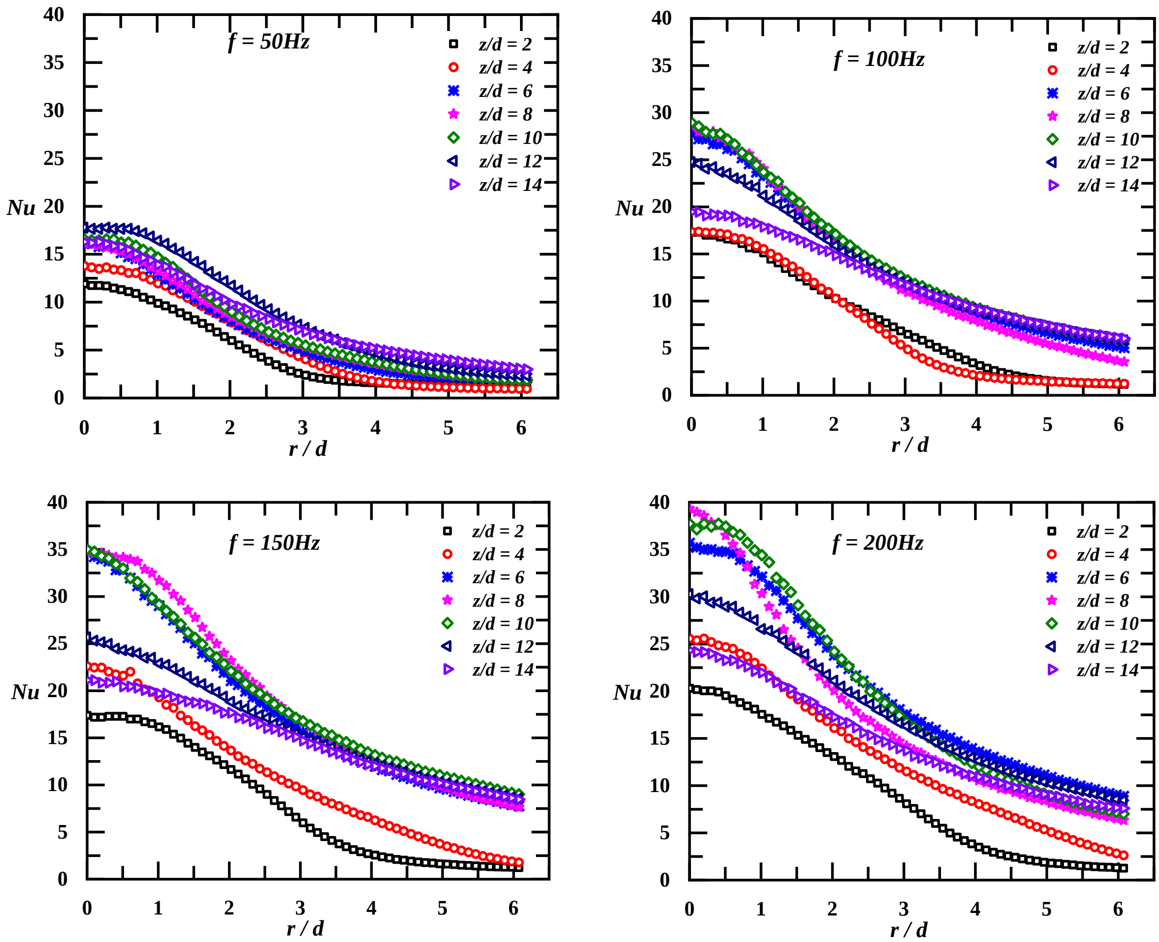


Figure 5. h_{avg} for different frequency, *f* and z for d = 8mm



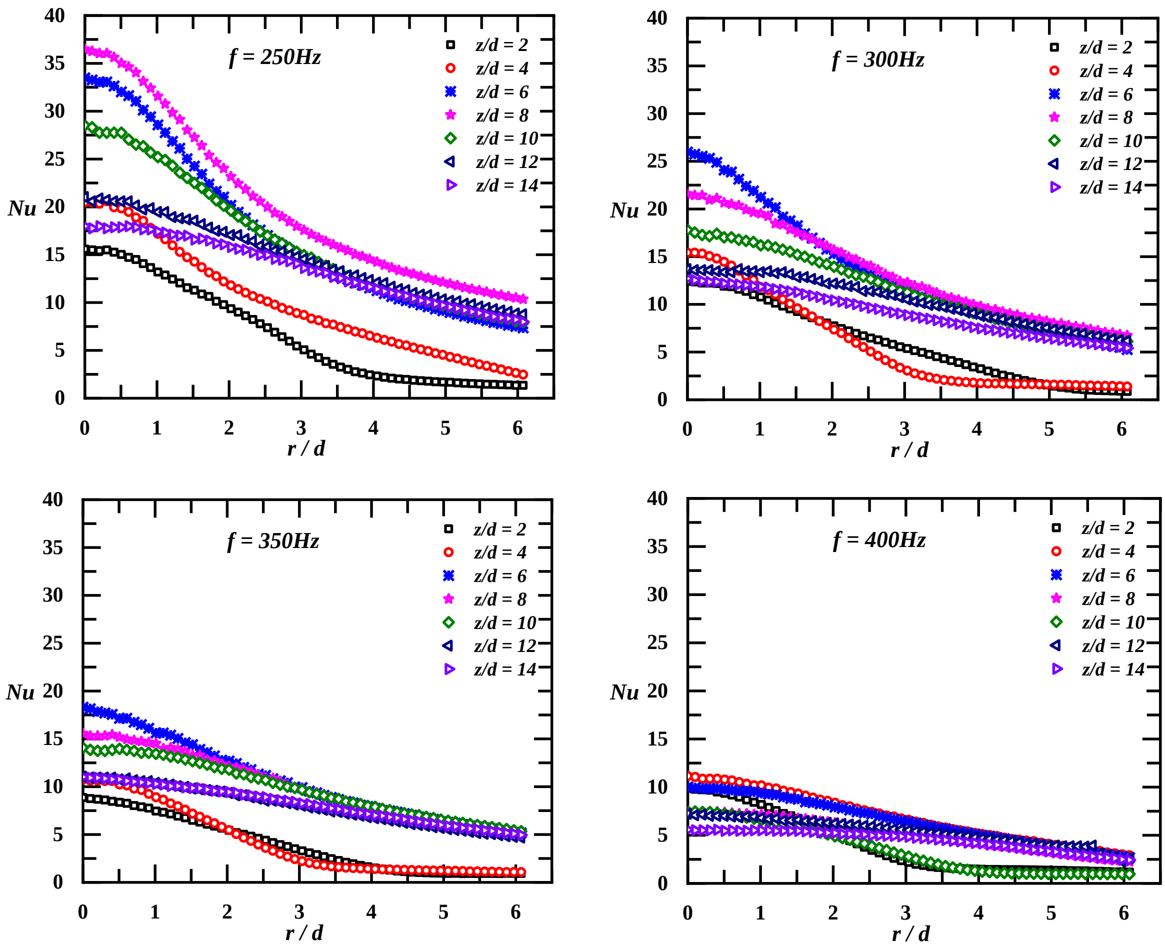


Figure 6. Nu distribution for different frequency, *f* and z/d for d = 8mm

The maximum value of *Nu* for actuator frequency (f = 50Hz) is found at z/d =12 distance. However for z/d = 8 distance, *Nu* has maximum value for all other actuator frequencies except f = 50Hz & 100Hz. At the stagnation point, the variation in Nu_o is small at lower frequency (f =50Hz) and increases at higher frequency. This may be due to vortex ring structure in flow path, lower frequency are effective at higher z/d distance, while higher frequency provides effective heat transfer at lower z/d distances as result of breaking of vortex rings into smaller vortex rings before jet impingement. The optimum z/d distance for maximum heat transfer on an average basis (for the entire target surface) when the actuator is excited at 200Hz is at z/d =10, which is similar to the results of Utturkar et al. [17] and on stagnation point basis it is at z/d = 8.

Effect of Orifice Diameter

The influence of orifice diameter on h_{avg} of synthetic jet at different z values and 200Hz actuator frequency is shown in Figure 7. Compared to continuous jet, momentum of flow is not conserved. The synthetic jet occurs when the flow is sucked and expel out through an orifice, hence the potential of synthetic jet depends strongly on orifice geometry[1].The momentum of synthetic jet flow at suction stroke will be less compared with ejection stroke because higher pressure is obtained in the cavity due to the compression by actuator diaphragm. The synthetic jet velocity will be more effective when actuator resonance frequency closely with the Helmholtz frequency. The Helmholtz frequency depends mainly on cavity geometry i.e. orifice diameter, cavity volume and orifice plate thickness. The orifice diameter is varied from 2mm to 10mm. According to Lee et al.[18] the calculated orifice diameter for which actuator resonance coincides with Helmholtz resonance frequency is 3.3mm. In the present work, the actuator frequency is not driven at Helmholtz frequency. Figure 8 shows the *Nu* distribution for different orifice diameter's at z/d =10 and 15. As orifice diameter increases, the local heat transfer characteristics increases up to 8mm orifice diameter and beyond that, it will decrease. It is found that the orifice diameter (8mm) has maximum heat transfer characteristics and orifice diameter (4mm) has least influence on heat transfer characteristics due to low potentail of synthetic jet flow. The orifice diameter (d = 8mm) was observed maximum heat transfer as reported Chaudhari et al.[8] and similar results are found in the present study. Hence, optimum orifice diameter for the maximum heat transfer is 8mm at 200Hz.

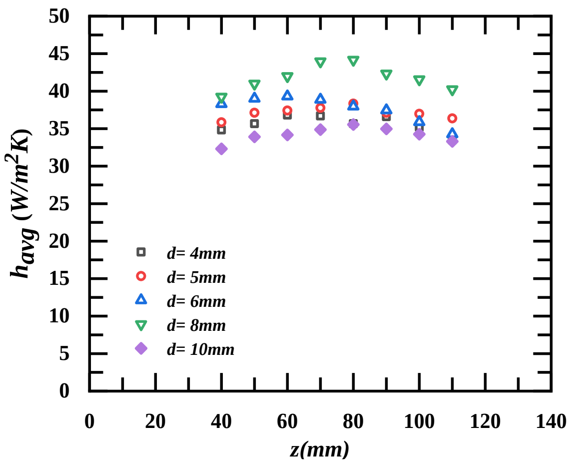


Figure 7. h_{avg} for different z distance and orifice diameter

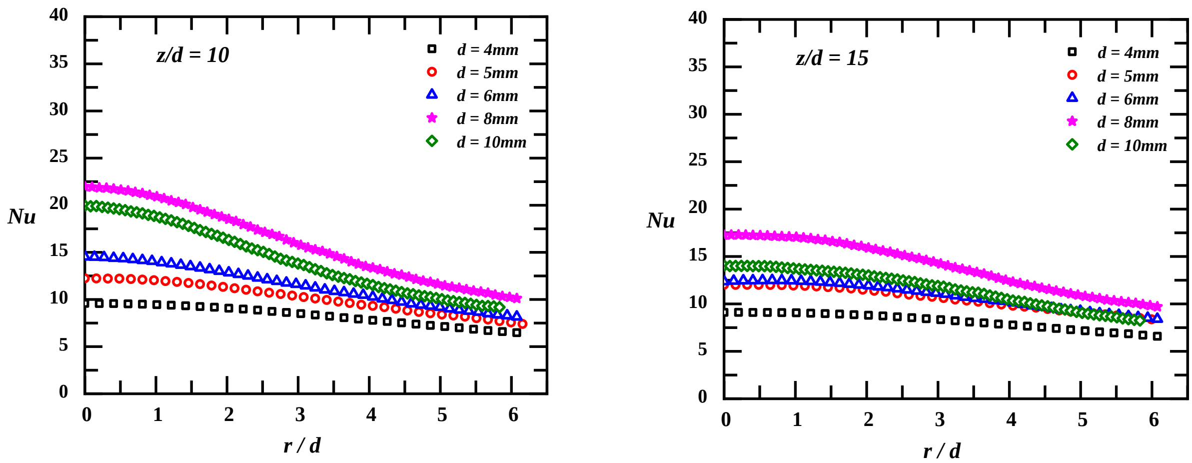


Figure 8. Nu distribution for different orifice diameter and z/d =10, 15

Effect of Cavity Depth

Figure 9 shows the influence of cavity depth on h_{avg} characteristics of synthetic jet at different *z* value and 200Hz actuator frequency for 8mm orifice diameter. The cavity depth is strong function of Helmholtz frequency. Cavity depth ranging from 30 mm to 60mm is used for study. According to Lee et al. [18] the calculated value of Helmholtz frequency for the cavity depth of 30mm, 40mm, 50mm and 60mm is 550Hz, 476Hz, 426Hz and 389Hz respectively.

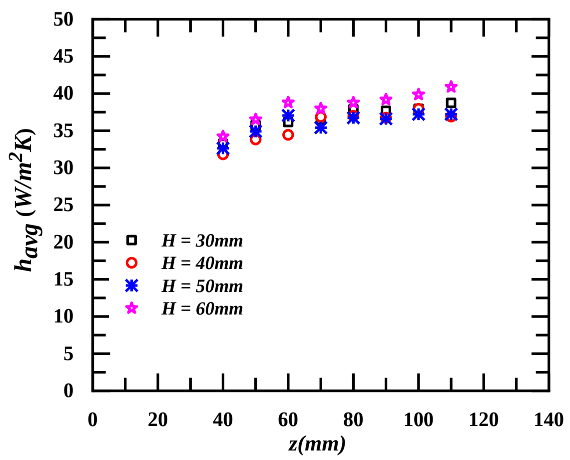


Figure 9. h_{avg} for different z distance and cavity depth for d = 8mm

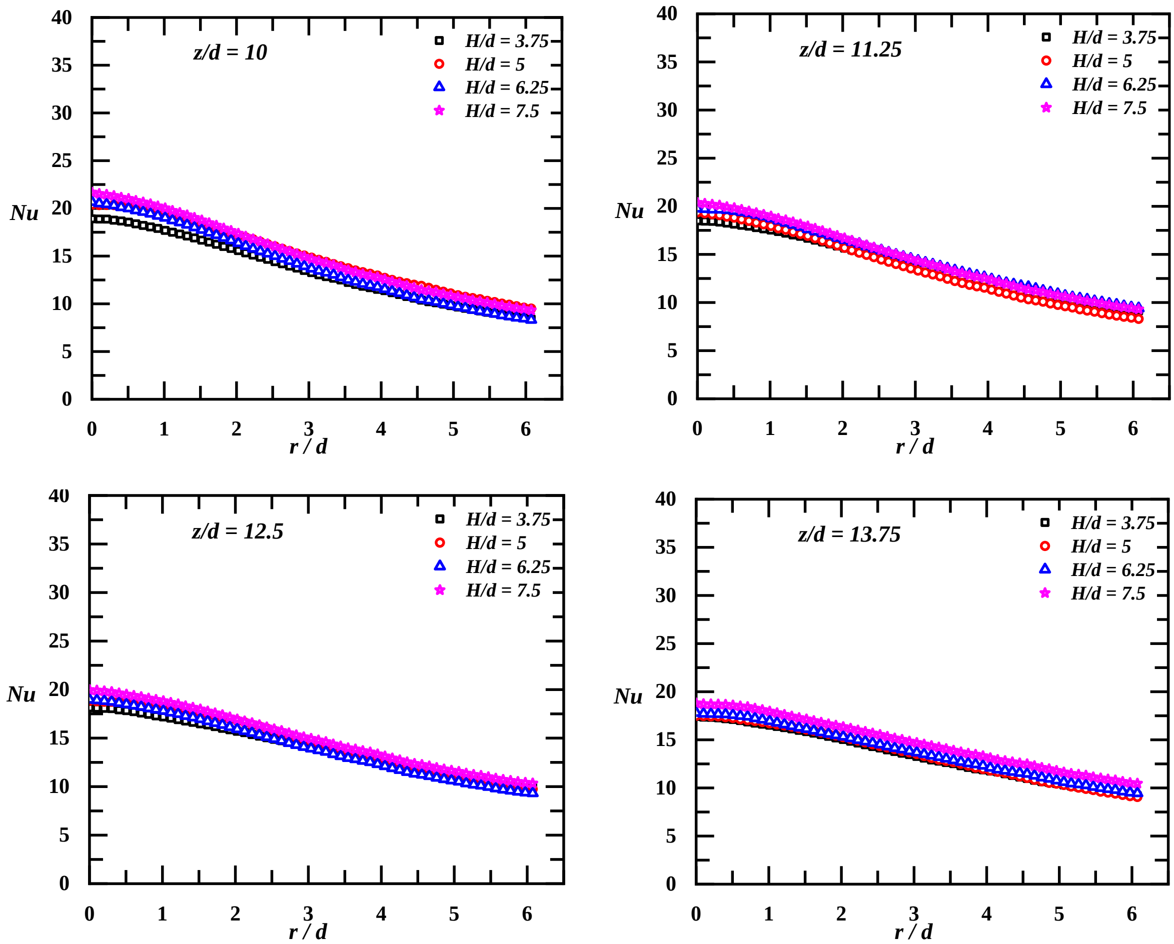


Figure 10. Nu distribution for different z/d distance and cavity depth for d = 8mm

With increase in *H/d*, the heat transfer characteristics increases because at high cavity depth (*H/d* =7.5), the calculated value of Helmholtz frequency (389Hz) is nearer to the resonance frequency (200Hz) of the actuator. For a given actuator frequency, when the cavity depth is high, the cavity pressure generated in the cavity will be high which results in increase in potential of synthetic jet. Figure 10 shows the *Nu* distribution for different cavity depth, *z/d* distance. The *Nu* of high cavity depth is maximum at stagnation point. The cavity with high depth increases the potential of vortex, in turn increases the velocity of synthetic jet. Thus, to increase the potential of fluid inside the cavity a high cavity depth is used compared to small cavity depth. The optimum value of cavity depth for maximum heat transfer may be calculated for which the resonance frequency coincides with Helmholtz frequency. Hence for the maximum heat transfer, optimum cavity depth (*H/d* =7.5) is preferable.

Effect of Cavity Diameter

Figure 11 shows the effect of cavity diameter on h_{avg} characteristics of synthetic jet for different *z* value and 200Hz actuator frequency for 8mm orifice diameter. The cavity diameter is varied from 50mm to 75mm. According to Lee et al.[18] the calculated value of Helmholtz frequency for the cavity diameter of 50mm, 60mm and 75mm is 402Hz, 335Hz and 268Hz respectively. With increase in cavity diameter, the Helmholtz frequency is moving close towards the resonance frequency of actuator and hence higher cavity diameter has slightly higher heat transfer characteristics. Figure 12 show the *Nu* distribution for different cavity diameter, *z/d* distance. High cavity diameter has maximum local Nusselt number at stagnation point. The maximum difference in *Nu* for different *z/d* and cavity diameter is nearly 4 W/m^{2}K which means that the cavity diameter has marginal influence on performance of synthetic jet. Hence, the optimum value for the maximum heat transfer when the actuator is driven at 200Hz is *D/d* = 9.37 in the present work.

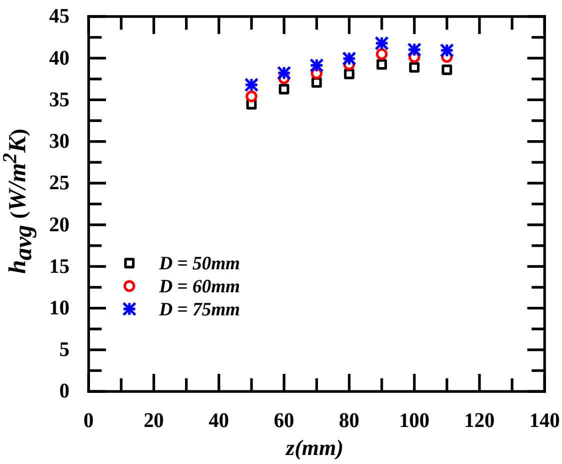


Figure 11. h_{avg} for different z distance and cavity diameter for d = 8mm

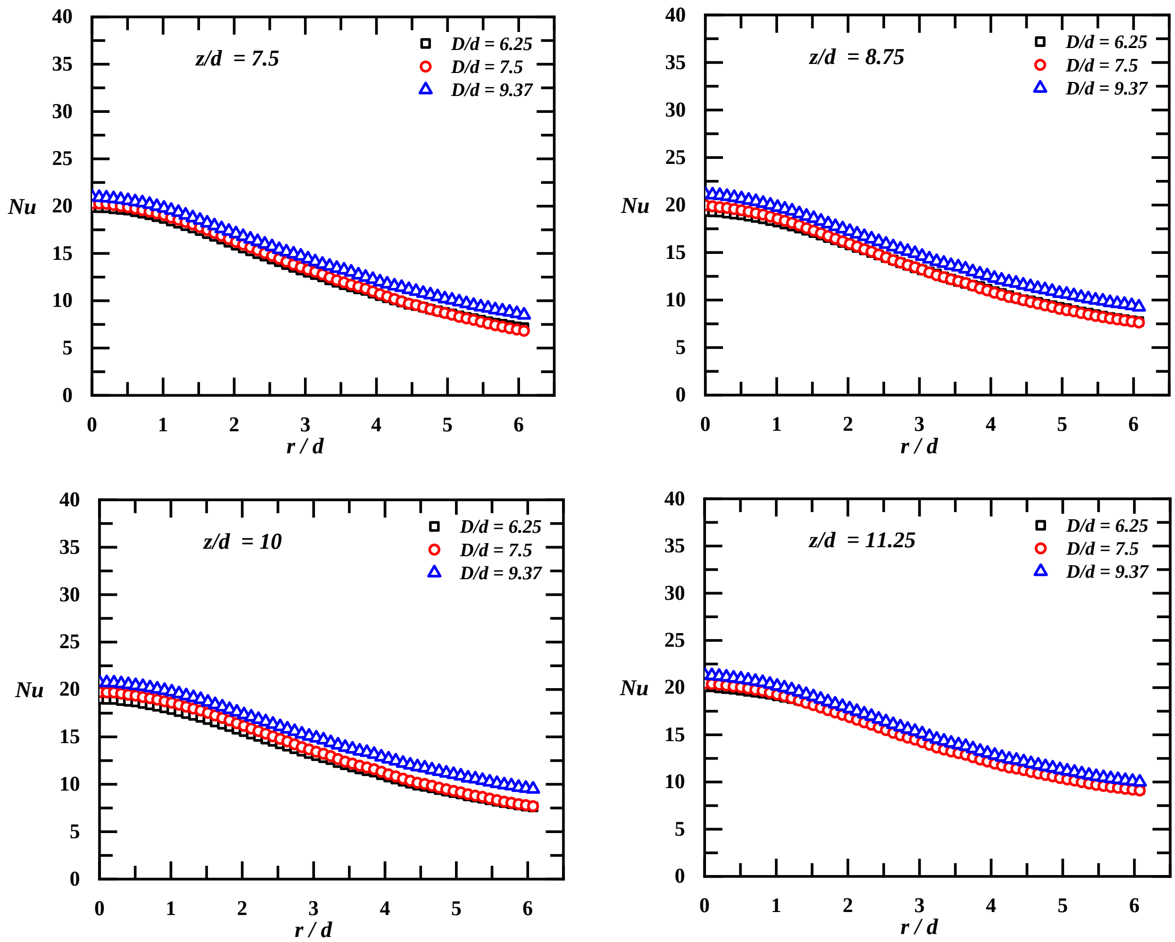


Figure 12. Nu distribution for different z/d distance and cavity diameter for d = 8mm

Effect of Thickness of Orifice Plate

Figure 13 shows the effect of orifice plate thickness on h_{avg} characteristics of synthetic jet for different *z/d* and 200Hz actuator frequency. When orifice plate thickness increases, the resistance to fluid flow increases due to increase in contact area between fluid flow and plate surface area which may results in low momentum of synthetic jet. The formation of vortices at the orifice exit mainly depends on the contact area between the fluid and plate surface area. The h_{avg} tends to increase with increase in orifice plate thickness up to (*t* = 4mm) and then decreases beyond it.

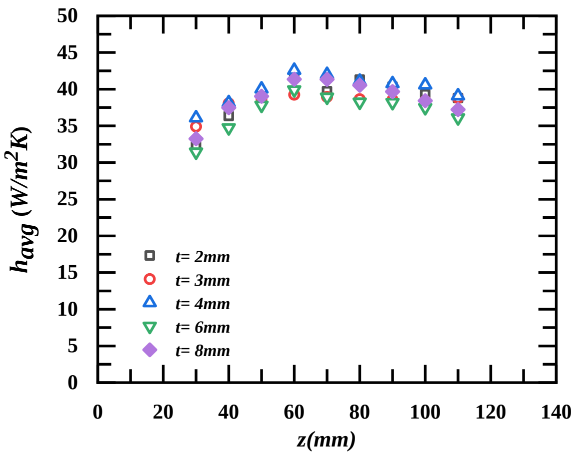


Figure 13. h_{avg} for different z distance and orifice plate thickness for d = 8mm

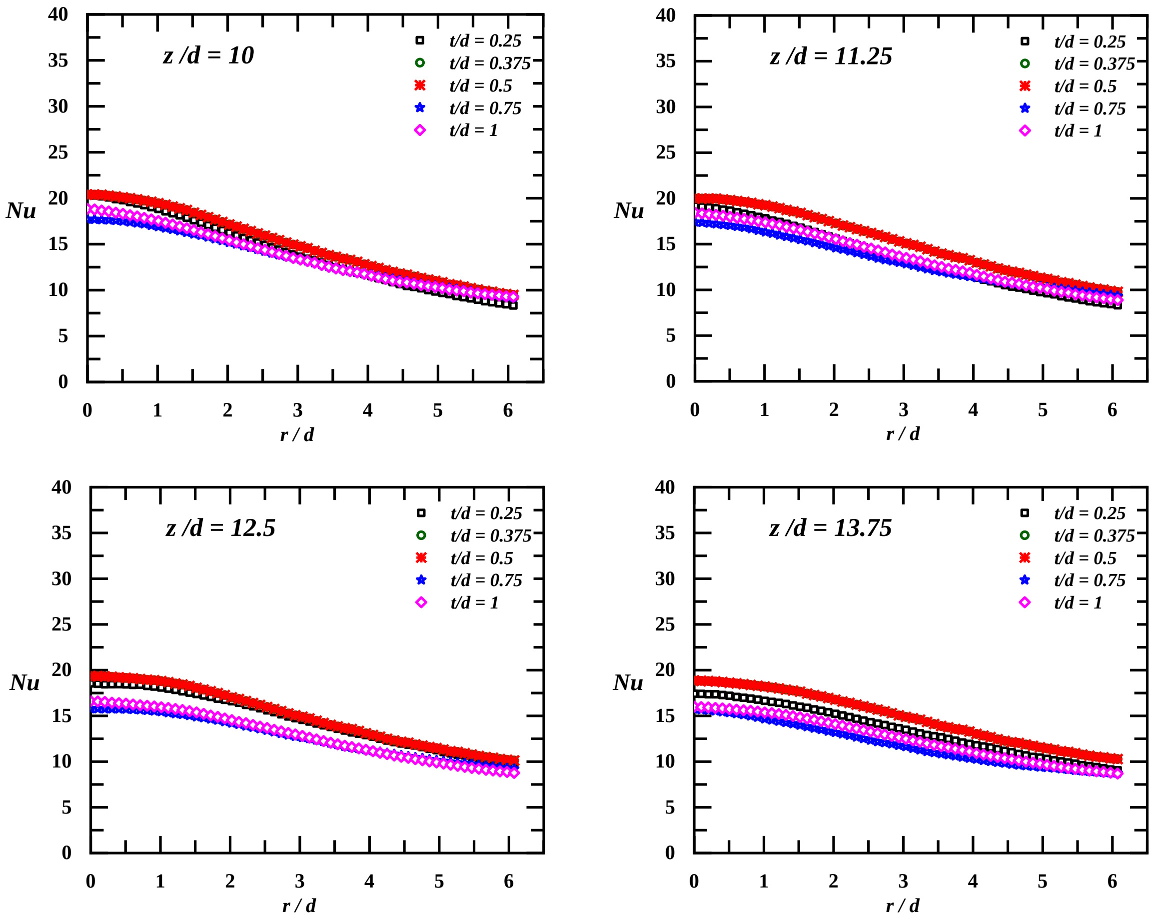


Figure 14. Nu distribution for different t/d and z/d for d = 8mm

Hence the h_{avg} is maximum for orifice plate thickness of 4 mm. From the Figure 14, the local heat transfer coefficient is maximum for *t/d* = 0.5.The optimum value of orifice plate thickness for maximum vortex formation has been reported by Jabbal et al. [19] is *t/d* = 0.5.The similar results at orifice plate thickness (*t/d* = 0.5) is reported for maximum heat transfer .

CONCLUSIONS

The local heat transfer of axisymmetric synthetic jet with a cylindrical cavity impinging on a flat plate is studied. The effect of frequency, orifice plate to jet distance, orifice diameter, cavity depth, cavity diameter and orifice plate thickness on local heat transfer are investigated experimentally. An optimization of synthetic jet parameter are studied for maximum thermal efficiency of the system. Following conclusions are drawn from the experiments which are mentioned below:

1) Actuator frequency, orifice plate to jet distance, orifice diameter and orifice plate thickness have a significant impact on local heat transfer characteristics. The cavity depth and diameter has least influence on the local heat transfer characteristics of synthetic jets.
2) The average heat transfer characteristics of synthetic jet has maximum value at its resonance frequency (*f* =200Hz) of the actuator.
3) At the critical distance (z/d = 10), the average Nusselt number reaches its greatest value. However, high actuator frequency (350Hz) is efficient at shorter jet to plate distances (z/d = 6) while low actuator frequency (50Hz) is effective at longer distances (z/d = 12).
4) As orifice diameter increases, the *Nu* increases up to 8mm orifice diameter and beyond that it will decrease. The *Nu* with orifice diameter 8mm is found to maximum at and away from the stagnation when compared with other orifice diameters.
5) The increased heat transfer characteristics are observed for higher cavity depth and higher cavity diameter than that of lower cavity geometry.

ACKNOWLEDGMENTS

Not applicable

NOMENCLATURE

A	surface area of flat plate (mm^2)
d	diameter of orifice (mm)
D	cavity diameter (mm)
f	frequency of actuator (Hz)
h	local heat transfer coefficient (W/m^2K)
h_{avg}	average heat transfer coefficient (W/m^2K)
H	depth of the cavity (mm)
I	current (A)
k	air thermal conductivity (W/mK)
Nu	local Nusselt number (hd/k) (-)
Nu_o	stagnation Nusselt number (-)
q_s	heat flux (W/m^2)
q_{con}	total convective heat flux to impinging jet (W/m^2)
q_{loss}	net heat loss from flat plate (W/m^2)
$q_{r(f)}$	heat loss by radiation from front face of flat plate(W/m^2)
$q_{r(b)}$	heat loss by radiation from back face of flat plate (W/m^2)
$q_{n(b)}$)	heat loss by natural convection from back face of flat plate (W/m^2)
r	radial distance from stagnation point (mm)
t	orifice plate thickness (mm)
T_j	temperature of jet air (^0C)
T_s	temperature of the flat plate at radial location (^0C)
T_r	ambient air temperature (^0C)
V	voltage (V)
z	plate to jet distance (mm)

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