Enhancement of heat transfer in a synthetic jet actuated by piston cylinder

Arun Jacob, KA Shafi and KE Reby Roy

Abstract
Modern electronics demand more powerful cooling systems due to an increase in heat dissipation. The traditional cooling techniques reached their limit and the synthetic jet impingement arises as a promising method for cooling of modern electronic systems. This paper presents the experimental studies on the heat transfer characteristics of a synthetic jet. The synthetic jet is driven by a piston actuator. The effects of dimensionless parameters like the distance between the orifice and heater plate (Z/D), the ratio of stroke length to diameter of orifice (L/D), Stokes number, and Reynolds number are discussed. The effect of orifice geometry, number of orifices are also presented. The results indicate that the Z/D and Stokes number have a significant influence on the heat transfer rate. As the Stokes number increases the heat transfer increases due to an increase in axial momentum and turbulence in the flow direction. For circular orifice and at high Z/D, the L/D ratio should be higher for better heat transfer. Rectangular orifice performs better than square and circular geometries. When compared to single jet multiple jets have a higher heat transfer rate. Maximum and minimum values of normalized pressure (Pnr) are achieved for high Stokes number and smaller areas of the orifice.

Keywords
Frequency, jet impingement, Reynolds Number, Stokes number, synthetic jet

Introduction
In the fast-growing technology, the demand for compact and high-speed electronic devices has increased dramatically. Moore predicted the exponential growth of the number of transistors on an IC. As the transistor density on integrated circuits increases in response to this demand, a high heat flux will be produced. One of the most common causes of electronic failures is thermal overstress. Therefore, effective cooling techniques are required to avoid the failure due to thermal stress.

The jet impingement method emerges as a promising method for the cooling of high-powered electronic devices. When compared to other jet impingement cooling methods, the synthetic jet performs better. It is a simple structure with low power requirements that can produce unsteady turbulent impinging flow with zero net mass flux. The synthetic jet can be produced using flexible membrane or a diaphragm. It is positioned on one side of a closed chamber. The nozzle or orifice can be attached opposite to the diaphragm. Air from the surroundings is sucked into the cavity and forced out through the nozzle when the diaphragm vibrates. The synthetic jet can also be produced using a piston actuator. The periodic motion of the diaphragm/piston produces a series of coherent vortex rings. These vortex
rings impart a hydrodynamic impulse to the system ensuring zero net mass flux and then roll down, coalesce, develop radial instability, and ultimately undergoes transition to turbulence.3

Smith and Glezer4 investigated the flow characteristics of synthetic jet and found that the evolution of jet at jet plane is dominated by the time periodic formation and moving of vortex pairs away from the orifice. These vortex pairs are turbulent in nature, gradually undergoes transition, slow down and lose their coherence. Zhang and Tan5 experimentally investigated the effect of excitation frequency on the synthetic jet flow field. The mean velocity and vorticity of the synthetic jet are maximized at two frequencies, especially at higher resonance frequencies.

The heat transfer coefficient of synthetic jet impingement depends on several parameters like the geometry of orifice, multiple orifices, and dimensionless numbers like Z/D ratio, L/D ratio, Stokes number, and Reynolds number. Lot of research works are done in this area and an overview of previous studies is presented. From all these studies it is noted that a small change in any of these parameters influences the heat transfer capacity of synthetic jet highly.

Wu and Breuer6 experimentally studied the dynamics of synthetic jet actuator arrays. The near-wall turbulent layer was studied with Reynolds numbers ranging from 15 to 70, a Strouhal number of around 1, and a high Stokes number of 40. A discrete vortex is generated at each cycle to form a steady jet as close as five orifice diameter from the actuator. Lee et al.7 carried out an experimental study to identify the influence of nozzle diameter on heat transfer and fluid flow characteristics of synthetic jet. The nozzle shape was circular and the Z/D was in the range of 2 to 14. The experiments were limited to jet Reynolds numbers of 23000. The local Nusselt numbers improved in their investigations with an improvement of the nozzle diameter in the region of stagnation.

Pavlova and Amitay8 studied the effect of the Z/D ratio of synthetic jet for different frequencies 420 Hz and 1200 Hz. For frequency 420 Hz the improvement of Nusselt number as compared to free convection was up to 78% and optimum cooling is obtained at Z/D 6–18. At frequency 1200 Hz the enhancement in Nusselt number with respect to free convection was up to 113% and optimum cooling was obtained at Z/D 4.75–11. They concluded that high frequencies remove heat better at a small Z/D ratio than low frequencies. This is due to the breakdown and mixing of vortices. Crittenden and Glezer9 reported that piezo electrical synthetic jet actuators have many disadvantages such as their volumetric displacement performance varies significantly with frequency, driver size, and material. Piston/cylinder actuators can be utilized to address all of these issues, providing a stroke which is independent of frequency.

Arik10 experimentally studied the heat transfer and acoustic aspects of synthetic jet over small and large heaters. They investigated the effect of jet location, driving voltage, driving frequency, and heater power on heat transfer rates. It was observed that depending on the heater size, the enhancement can range from 4 to 10 times, indicating that smaller heaters provide the most effective jet. McGuinn et al.11 studied the impact of frequencies on the overall heat flux profile. The presence of high turbulent intensity at high frequency is the reason for high heat transfer at a low Reynolds number.

The effects of nozzle shape, Z/D ratio, and Reynolds number on the local heat transfer distribution of a synthetic jet were investigated by Puneet et al.12 The Nusselt number distribution along the horizontal axis of the rectangular jet is higher in the stagnation region than for circular and square jets up to Z/D of 6. Oren et al.13 conducted experimental studies on orifice shapes of synthetic jet to identify which shape is better for thermal management application. The studies showed that the spreading and mixing of jets is higher for rectangular orifices makes it a preferable design configuration for the synthetic jet actuator.

The heat transfer characteristics of synthetic air jet impingement was studied experimentally by Chaudhary et al.14 For all frequencies, the coefficient of heat transfer rapidly raises up to an axial distance of 48–50 mm and gradually decreases as the distance increases. Rylatt and O’Donovan15 studied the heat transfer effect of confined, ducted, and un-ducted impinging synthetic air jets experimentally. At all radial distances, ducting outperforms confined and unconfined impingement in terms of heat transfer. When comparing different ducting diameters, the 1.6 ducting produces better results than the others. Bhupkar et al.16 performed acoustic and heat transfer analysis to investigate the effect of frequency, jet to plate spacing and inclination angles on noise level and synthetic jet heat transfer capabilities. The maximum heat transfer coefficient is obtained at an angle of 90°. They observed that at an angle of inclination of 40° and Z/D of eight the synthetic jets can be used with a heat transfer coefficient reduction of less than 10% compared to an angle of 90°.

Dahalan et al.17 compared different orifice shapes and diameters on the heat transfer characteristics of synthetic jet. They concluded that the smaller circular orifice produces higher maximum pulse jet velocity. Lee et al.18 experimentally studied the effect of cavity sizes and the aspect ratio of a rectangular orifice on synthetic jets. The heat transfer is improved by orifices with a smaller aspect ratio and larger hydraulic diameter. Peña Fernández and Sesterhenn19 numerically investigated the compressible starting jet and observed
that the trailing jet and the vortex rings have great influence on heat transfer. When the flow is impacted by Kelvin–Helmholtz instabilities, the shear layer–vortex interaction causes a rapid breakdown of the head vortex ring.

Hiroyuki et al.\textsuperscript{20} tested four orifice plates, each with a single hole or multiple holes of varying diameters. The influences of total orifice area are well explained by larger/smaller values of maximum/minimum cylinder pressure. Mangate et al.\textsuperscript{21} experimentally investigated the heat transfer characteristics of multiple orifices with different shapes such as circular, diamond, and oval at different stokes number, pitch ratio, and $Z/D$ ratios. They discovered that a multi orifice jet with the best orifice shape can transfer 75% more heat than a single orifice synthetic jet.

Although numerous studies have been carried out by various researchers to investigate the flow and heat transfer characteristics of synthetic jets, the idea of using synthetic jets to transfer heat with a piston-cylinder actuator is relatively new. A small change in any parameters may affect its performance. In this experimental study, the heat transfer and flow characteristics of a synthetic jet actuated by a piston-cylinder arrangement are presented. The effects of cylinder pressure and multi orifice on heat transfer are also discussed.

**Experimental system**

Figure 1 shows the experimental setup schematically, while Figure 2 shows the heater plate assembly and piston-cylinder arrangement. The main components of the experimental setup are a piston-cylinder arrangement for producing the synthetic jet and a heater plate for the thermal environment. The actuator is positioned so that the jet strikes the heater plate orthogonally. The periodic movement of the piston within a cylinder cavity generates the synthetic jet. The cylinder has a bore of 20 mm and a stroke of 26 mm. The piston is driven by a brushless DC motor. By varying the electric motor’s speed, the frequency of the synthetic jet can be altered. A copper plate measuring $50 \times 50 \times 5$ mm with a heater underneath simulates the thermal environment. A hook gage is used to alter the distance between the heater surface and orifice exit. The dimmerstat is used to control the heater’s power input, and a voltmeter and an ammeter indicate the corresponding voltage and current, respectively. Temperature is measured using thermocouples (T type, 32 SWG) placed at various locations on the copper plate. A multi-channel temperature scanner is connected to the thermocouple output. Calibrated hot wire anemometer is placed at the orifice exit to measure the exit velocity of the jet.

For placing a pressure transducer, the cylinder head is replaced by a copper plate of thickness 10 mm, and shown in Figure 3. The gage pressure is measured by the transducer and using an oscilloscope it is stored in the computer. The overall volume of the cylinder is 8.5 cc, and the pistons displacement volume is 8.1 cc.

Five different orifice plates of circular geometry are used in the experiment as shown in Figure 4. The plates A, B, and C each have orifice holes of diameter 3, 4, and 5 mm, respectively. The plates D and E have multiple holes of numbers two and four, respectively and the diameter is 3 mm. The distance between the centers of the two holes is 5 mm as shown in Figure 4.

Three orifice geometries were used in this study, as shown in Figure 5. The different geometries used are circular, square, and rectangular of the same orifice area.
**Experimental procedure**

Before being used in the experiments, the calibration of thermocouples was done with the help of a constant temperature bath (Jula-boF25). Experiments were conducted by varying the Stokes number and $Z/D$ ratios. The power input to the heater is 20 W and it generates an 8000 W/m² heat flux. The parameters used in this experimental studies are Stokes number, $Z/D$ ratios, $L/D$ ratios, multi orifice, and the geometries of the orifice. The pressure measurements were also performed for different orifice diameters and multi orifices at different frequency. The $Z/D$ ratio varies from 2 to 16. The Stokes number ranges from 6.18 to 13.82. The $L/D$ of the circular orifice is varied from 5.2 to 8.66. For the comparative study on orifice geometry, different geometries of the same orifice area are used. The temperatures are continuously noted until it reaches the steady-state. Additional details are available in Jacob et al. 22

**Data reduction**

The heat transfer coefficient is defined as

$$h = \frac{q}{T_s - T_j}$$

Where $h$ is the heat transfer coefficient, $q$ is the applied heat flux, $T_s$ is the heated surface temperature, and $T_j$ is the jet temperature. The net heat flux ($q$) is defined as

$$q = \frac{IE\cos\phi - \text{losses}}{Ap}$$

Where $E$ is the applied voltage, $I$ is the current, $\cos\phi$ is the power factor, and $Ap$ is the area of the plate. The Reynolds Number (Re) is defined as

$$Re = \frac{\rho v D}{\mu}$$

Where

- $\rho$ is the density of fluid
- $v$ is the velocity of fluid
- $D$ is the Diameter of orifice
- $\mu$ is the Dynamic viscosity of fluid

The Stokes Number is defined as

$$St = \sqrt{\frac{2\pi fD^2}{\vartheta}}$$

Where

- $f$ is the Frequency of jet
- $D$ is the Diameter of orifice
- $\vartheta$ is the Kinematic viscosity of fluid

An experiment in which the system is brought to a steady state is used to estimate the heat loss due to conduction. 3.31 W is estimated to be the total loss. During
the experiment, the total heat loss is assumed to be constant. Between the inlet air jet and the atmosphere, a small temperature difference is also assumed.

**Uncertainty analysis**

The Kline and McClintock method was used to perform an uncertain analysis. The sources of uncertainties considered in the current study were the heat input, heat loss, wall temperature, ambient temperature, and material properties. The uncertainty in net heat flux and the heat transfer coefficient was calculated as follows

\[
\frac{\sigma q}{q} = \frac{1}{q} \sqrt{ \left( \frac{\partial q}{\partial E} \sigma_E \right)^2 + \left( \frac{\partial q}{\partial T} \sigma_T \right)^2 + \left( \frac{\partial q}{\partial P} \sigma_P \right)^2 }
\]

(5)

\[
\frac{\sigma h}{h} = \frac{1}{h} \sqrt{ \left( \frac{\partial h}{\partial q} \sigma_q \right)^2 + \left( \frac{\partial h}{\partial T} \sigma_T \right)^2 }
\]

(6)

The maximum uncertainty in heat flux and heat transfer coefficient was 4.13% and 5.91% occurring at Stokes number 13.82 and approximately at 5.2, 6.5, and 8.66. It is noted that, at low Z/D ratio, the recirculation effect is reduced and the vortices impinging on the target plate separately enhances the heat transfer.

**Result and discussions**

This section presents the findings of experimental studies on various parameters that affect the heat transfer characteristics of synthetic jets. The influence of cylinder normalized pressure on the total orifice area is also discussed.

**Effects of Stokes number and orifice to surface distance on heat transfer coefficient**

Figure 6 shows the heat transfer coefficient with Z/D ratios at different stokes numbers from 6.18 to 13.82. The L/D ratio is 8.66, and the geometry is circular. As the stokes number increases, the heat transfer coefficient also increases. There is an increase of 41% in heat transfer coefficient when the stokes number is raised from 6.18 to 13.82. At all stokes number the heat transfer coefficient increases with the Z/D ratio reaches an optimum and then decreases. It was also noted that when the stokes number increases, the Z/D ratio for optimum decreases. The optimum Z/D ratio achieved for 6.18 and 13.82 stokes numbers are 14 and 8, respectively. At low Z/D ratio jet with high stokes number is more suitable as the vortices can accumulate and achieve their strength when it impinges the surfaces. At high Z/D ratio and high stokes number there is a chance of merging of vortices losing their coherence that results in less heat transfer rate. But in the case of low stokes number and low Z/D ratio the recirculation of fluid may cause less heat transfer. At high stokes number and high Z/D ratio the heat transfer rate increases as the vortices merges. Therefore, at low stokes number, a high Z/D ratio achieves the maximum heat transfer coefficient. At low stokes number and low Z/D ratio, the chance for the recirculation is more that reduces the heat transfer. At low stokes number and high Z/D ratio the recirculation effect is reduced and the vortices impinging on the target plate separately enhances the heat transfer.

**Effects of stroke length to orifice diameter ratio and orifice to surface distance on heat transfer coefficient**

Figure 7 represents the impact of the ratio of stroke length (L) to circular orifice diameter with Z/D ratios on the heat transfer coefficient. The heat flux, jet frequency, and stroke length is maintained constant as 8000 W/m², 50 Hz, and 26 mm, respectively. The L/D used in this study are 5.2, 6.5, and 8.66. It is noted that, the L/D of 8.66 has maximum heat transfer coefficient as compared with other two ratios. While all other parameters remain constant, the Reynolds number increases with an increase in L/D ratio. The velocity of the fluid ejected from the orifice increases with an increase in L/D according to Bernoulli’s principle. It is observed that the Z/D ratio for optimum decreases with an increase in L/D.
ratios, the maximum heat transfer coefficient obtained at \( Z/D \) ratio of 4, 6, 8, respectively. As the pressure field strength is dependent on the \( L/D \), it has the greatest impact on jet parameters.

**Table 2.** Effect of orifice geometries on heat transfer.

| \( Z/D \) | Heat transfer coefficient (W/m\(^2\) K) |
| --- | --- |
|   | Rectangle | Square | Circle |
| 2 | 248.06 | 234.02 | 172.84 |
| 4 | 328.00 | 305.95 | 189.65 |
| 6 | 416.02 | 393.96 | 229.62 |
| 8 | 431.97 | 386.06 | 190.61 |
| 10 | 368.15 | 357.36 | 188.81 |

**Dependence of heat transfer on the geometry of the orifice**

Different orifice geometries, circular, square, and rectangular, are used in experimental study to find their impact on heat transfer. The variation of heat transfer coefficient distribution on heater plate with different orifices circular, square, and rectangular at 50 Hz frequency is shown in Table 2. Here the orifice area is maintained constant. At all axial distances, the maximum heat transfer coefficient is achieved for rectangular orifice as compared with other two geometries.

According to Oren et al.\(^1\) the axial velocity increases at the exit of the orifices due to an increase in aspect ratio. Here the rectangular orifice has the highest aspect ratio that results in higher heat transfer coefficient. By comparing the circular and square orifice synthetic jet a strong secondary vortices are produced by the excess vorticity in the corner of the square orifice. These secondary vortices interact with the primary vortices and enhance the momentum transport ability of the synthetic jet of square orifice.

**Effect of Reynolds number on heat transfer**

Figure 8 represents the variations of heat transfer coefficient with various Reynolds number. The \( L/D \) is 8.66. The heat transfer coefficient increases by 41.4\% if the Reynolds number is increased from 2500 to 12940. As the stokes number increases from 6.18 to 13.82 the velocity of the fluid ejected from the orifice also increases from 13.28 m/sec to 65.13 m/sec which in turn the Reynolds number. The turbulence levels increase as the Reynolds number increases, and the spread of the jet also increases. The net amount of fluid that comes out of the jet increases as the Reynolds number increases, resulting in better heat transfer performance.

**Effect of multiple orifice on heat transfer**

Figure 9 represents the variation of heat transfer coefficient with \( Z/D \) ratio for multi orifices. The stokes number and the diameter of the jet is maintained constant as 13.82 and 3 mm, respectively. The number of orifices
varied as 2 and 4. It was observed that multi orifice exhibits a higher heat transfer coefficient than single orifice. For a single orifice, the heat transfer coefficient increases with $Z/D$ ratio reaches a maximum of $Z/D$ 8 and then decreases. But in the case of multi orifices the maximum heat transfer coefficient occurs at two different $Z/D$ ratios, one at a lower $Z/D$ ratio and the other at an intermediate $Z/D$ ratio. The multi orifices has higher heat transfer coefficient at all $Z/D$ ratios. The impingement of large vortices and high mass flow rate results in high heat transfer rate for multi orifices. At $Z/D$ ratio 2 there is less recirculation effect as compared with $Z/D$ ratio 4. With the increase of $Z/D$ ratio >4 there is an increase in the availability of fresh air and also the vortices achieve higher momentum.

**Effect of pressure**

The flow field of synthetic jet with piston cylinder arrangement, is characterized by the absolute pressure

![Figure 10. Time history of cylinder pressure for various frequency: (a) diameter of orifice = 3 mm, (b) diameter of orifice = 4 mm, (c) diameter of orifice = 5 mm, (d) diameter of orifice 3 mm and number of orifice = 2, and (e) diameter of orifice 3 mm and number of orifice = 4.](image)
$P$ inside the cylinder. The time history of normalized cylinder pressure is shown in Figure 10(a) to (e) for different orifice diameters and multi orifices. The absolute pressure inside the cylinder is normalized by the atmospheric pressure $P_a$. It is represented as $P_{nr} = P/P_a$. The time $t$ is also normalized by a time period of one cycle $T$, where $T = (1/f)$. As the frequency increases the $P_{nr}$ reaches a maximum and minimum for all orifice plates. If the plate has more than one holes and at higher frequency the suction and ejection processes over a cycle becomes asymmetric and it is shown in Figure 10(d) and (e). At higher frequency the effect of orifice area $A$ is more significant for $P_{nr}$ max.

Figure 11(a) and (b) represents the maximum normalized pressure ($P_{nr}$ max) and minimum normalized pressure ($P_{nr}$ min) against the frequency of various orifices. $P_{nr}$ max shows the blowing process and $P_{nr}$ min shows the suction processes in a cycle. At a given frequency the $P_{nr}$ max and $P_{nr}$ min depends on orifice diameter and number of orifices. The normalized maximum and minimum pressure inside a cylinder are highly influenced by the total orifice area. Maximum and minimum values of $P_{nr}$ is achieved for high frequency and smaller area of orifice.

Figure 12 shows the variation of the heat transfer coefficient with the maximum pressure. The $L/D$ ratio is 8.66. The Stokes number is varied from 6.18 to 13.82. As the Stokes number changes keeping the $L/D$ ratio constant the normalized pressure changes. It can be seen that as the normalized pressure increases the heat transfer coefficient also increases. This is due to the fact that as the normalized pressure increases the jet acquires more strength.

**Conclusions**

Experiments were conducted on a constant heat flux surface to evaluate the performance of a synthetic jet powered by a piston cylinder arrangement. The axial momentum and turbulences in the flow direction increases as the Stokes number is increased. As a result, the heat transfer coefficient increases as the fluid velocity increases. At small $Z/D$ ratios, high Stokes number synthetic jets remove heat more efficiently than low
Stokes number jets and low Stokes number jets are more effective at larger $Z/D$. At low $Z/D$ ratios, there is a recirculation and air entrainment effect, which affects heat transfer ability. However, when the $Z/D$ ratio and Stokes number are high, the effect is reduced and uniform heat transfer occurs. Due to recirculation, synthetic jets cannot be used for very low $Z/D$ ratios, according to studies. The $L/D$ ratio determines the optimum $Z/D$ ratio, and heat transfer increases as the $L/D$ increases. All orifice geometries behave qualitatively similarly for a given set of boundary conditions, with the rectangular orifice providing the maximum heat transfer. The increase in Reynolds number causes an increase in the amount of fluid, resulting in improved heat transfer performance. In comparison to a single orifice of equivalent diameter, the multi orifice has a higher heat transfer rate. For a high Stokes number and a smaller orifice area, maximum, and minimum Pnr values are achieved. The experimental studies show that the synthetic jet is an alternative for the cooling of microelectronic devices.

**Declaration of conflicting interests**

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

**Funding**

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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**Appendix**

**Notation**

| Symbol | Description                        |
|--------|------------------------------------|
| $Ap$   | Surface area of the impingement plate, $m^2$ |
| $D$    | Diameter of orifice, $m$           |
| $E$    | Voltage, $V$                       |
f  frequency of oscillations, Hertz
I  current, A
h  heat transfer coefficient, W/m² K
 hav average heat transfer coefficient, W/m² K
Ka thermal conductivity of the fluid, W/m K
L stroke Length, m
Nu Nusselt number
P  absolute pressure
Pa atmospheric pressure
Pnr normalized pressure
q applied heat flux, W/m²
Re Reynolds number
St stokes number
T time period of one cycle
Tj temperature of the jet, K
Ts temperature of the heated surface, K
t time period, sec
Z spacing between the target plate and orifice

Greek symbols
μ dynamic viscosity, Ns/m²
τ stress, N/m²
ρ density, kg/m³
θ kinematic viscosity of fluid, m²/s