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THE EFFECT OF ORIFICE SHAPE ON CONVECTIVE HEAT TRANSFER OF AN IMPINGING SYNTHETIC JET

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ABSTRACT
A greater heat load due to the miniaturization of electronic products causes the need for a new cooling system that works more efficiently and has a high thermal capacity. A synthetic jet is potentially useful for the cooling of electronic components. This paper reports the results of our experimental studies and the influence of orifice shape for Impinging Synthetic Jet cooling perfomance. The effect of shape of the orifice of an impinging synthetic jet assembly on the apparatus cooling of a heated surface is experimentally investigated. It will be seen that the characteristics of convective heat transfer will occur by moving the piezoelectric membrane. The prototype of the synthetic jet actuator is coupled with two piezoelectric membranes that operate by 5 volt electrical current and create a sinusoidal wave. The orifice shapes considered are square and circular. The results show the significant influence of orifice shape and sinusoidal wave frequencies on the heat transfer rate that were obtained. The temperature drop with a square orifice is found to be larger than that with circular shapes. A square orifice has a larger covered area if compared to the circular orifice at the same radius, thus resulting in a larger entrainment rate that leads to an increase of heat transfer performance.

Keywords: Cooling; Impinging synthetic jet; Orifice; Temperature drop

1. INTRODUCTION
The requirement for adequate thermal management, which is perhaps the most crucial part of the electronic system design due to miniaturization is emphasized in this experiment. One of the major causes for failure of electronic components is thermal overstressing. A major challenge for thermal engineers is to develop new alternative cooling systems for such high heat flux components. In this study,of a synthetic jet with an impingement type, which can potentially be used for the cooling of a heated plate is investigated. A synthetic jet works as a jet vortex generated from the continuous vibration of the piezoelectric membrane, which is driven by a function generator to produce flow separation at the outlet orifice of a cavity. A synthetic jet can be defined as a zero-net-mass flux device commonly generated by suction and blowing of fluid from a small cavity (Smith & Glezer, 1998). Due to the pulsating nature of the flow, the entrainment of ambient fluid into the jet is high as compared to that in a continuous jet, which helps in effective cooling performance (Chaudhari et al., 2009). The synthetic jet was driven by a couple of piezoelectric actuator membranes that have a zero net mass input, but produce non-zero momentum output. In a previous study about the orifice parameter, Gulati et al. discussed the effect of shape of the orifice on local convective heat transfer enhancement for different jet impinging distances and average Reynolds numbers (Gulati et al., 2009).

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Moreover, Pavlova and Amitay experimentally investigated the performance and mechanism of cooling at a constant heat flux surface by an impinging synthetic jet (Pavlova & Amitay, 2006). In their investigation, high frequency (1200 Hz) jets were found to be more effective at smaller impinging distances and the low frequency (420 Hz) jets were found to be more effective at larger impinging distances. In that report, a comparison with a continuous jet was also presented. Chaudhari et al. discussed the effect of different shapes of orifices on the convective heat transfer characteristics of an impinging synthetic jet (Chaudhari et al., 2010). It was noticed that the rectangular orifice gives better heat transfer performance as compared to both a square and/or a circular orifice, at smaller impinging distances. However, at larger impinging distances the square orifice outperformed the other orifice shapes investigated. Lee et al. studied the effects of orifice configuration on impinging jet heat transfer and fluid flow. They concluded that local Nusselt numbers in the region corresponding to $0 \leq r/d \leq 0.5$ increased with increasing orifice diameter (Lee et al., 2004). Many prior studies were focused on the role of orifice configuration on the impingement heat transfer. Lee & Lee investigated the effect of orifice configuration for l/d of 0.2 with three different types of profiles at the outlet orifice: square-edged, sharp-edged and standard-edged orifices. The tests were carried out for unconfined air jets impinging normally on smooth surfaces with a heated plate. The convective heat transfer results agree that at the stagnation region a sharp-edged orifice performs better than the others (Lee & Lee, 2000). Convective heat transfer is a very important aspect in synthetic jet cooling systems since the generated vortices tend to dissipate the heat from the surface of the heated plate to be cooled. McGuinn et al. investigated a synthetic jet as a current potential technology for the microelectronics cooling system by focusing on the distribution of flow and heat transfer characteristics from a jet sprayed on the surface by blowing with a jet at the average Reynolds number (Re_{avg}) range of 1100-4900 and an orifice diameter of 1-6 mm. As a result a relationship occurs between the measured average and fluctuating heat transfer distributions and local acceleration of the synthetic jet (McGuinn et al., 2008). Travnicek and Tesar recommended that the basic goal in convective heat transfer is to mobilize the cooling fluids as near as possible to the surface to be cooled and the synthetic jet being used as the impinging mechanism is influenced by the actuator configuration such as the orifice configuration and cavity parameters (Travnicek & Tesar, 2005).

In the present work, a comprehensive study was done by a computational and an experimental method on an original design of a synthetic jet actuator that operates based on a couple of piezzoelectric membranes which are driven by the function generator. In the current stage, the main focus of the research was to characterize the temperature field of an impinging flow configuration with the variation of orifice shapes and driving wave function frequency of the membranes to generate turbulence flow.

2. METHODOLOGY

The present study was done comprehensively by a computational simulation and experimental works in order to investigate the effects of orifice shape related to the cooling performance of an impinging synthetic jet in cooling systems for microelectronic components. The details of each the works are explained as follows.

2.1. Computational Work

This computational work is used to analyze the thermal flow at an impinging synthetic jet by using a mathematical model k-ω SST (Shear Stress Transport). Ambient temperature is assumed to be 27^{o}C and the temperature of the bottom of the heatsink is heated and maintained isothermally at temperature of 60^{o}C. Boundary walls on both sides of the actuator are assumed to have a constant static pressure with an atmopheric pressure of 1 atm. After that, the movement of the piezoelectric diaphragm is modeled with a user-defined function (UDF). In this modeling, it will be seen there are some turbulent flow regions, while others remain at the laminar flow conditions indicated by the low value of the average Reynolds number (Re_{avg}). The parameters used at this computational study are model arrangement, boundary conditions, and fluid properties.

At the beginning (t = 0), the position of the diaphragm is at the bottom of the cavity. The diaphragm movement is modeled like a piston moving in a cylinder, in which the upper and lower membranes use variations of square and *sine* wave functions. The motion of the upper and lower membranes is approached with the Equations (1) to (4).

The deflection of the membrane with square function is expressed as:

$$Y(t) = \frac{4k}{\pi}\left(Sin(2\pi ft) + \frac{1}{3}\sin(2\pi ft) + \frac{1}{5}Sin(2\pi f)\right) \tag{1}$$

Therefore, the velocity of the membrane with square function is expressed as:

$$V(t) = \frac{4k}{\pi}\left(2\pi fCos(2\pi ft) + \frac{2\pi f}{3}Cos(2\pi ft) + \frac{2\pi f}{5}Cos(2\pi f)\right) \tag{2}$$

Whereas, the deflection of the membrane with a *sine* function is expressed as:

$$Y(t) = k\left(Sin(2\pi ft)\right) \tag{3}$$

Therefore, the velocity of the membrane with a *sine* function is expressed as:

$$V(t) = k\left(2\pi fCos(2\pi ft)\right) \tag{4}$$

Where k represents the amplitude actuated by the oscillating motion of the piezoelectric membranes in a cavity, t is time operation for both of the membranes, and f is the frequency of wave function that is given by the function generator.

2.2. Experimental Work

The quality of cooling results is verified by a chronological history of convective heat transfer studies, and the results are validated against existing experimental data. Experimental activities were carried out by measuring the temperature at the heatsink using a digital thermometer for 120 minutes. The heatsink module used in this study has a circular form with 32 fins made from aluminum material. The heatsink diameter was 11 cm and the height was 5 cm. The heat source was obtained from the heater mat at 60^{o}C which was controlled by using a thermostat. Measurements were performed using a k-thermocouple under open conditions at an ambient temperature of 30^{o}C. The impinging synthetic jets modul used in this study was constructed in the form of a cylinder cavity having a couple of piezoelectric membranes at the top and bottom. The piezoelectric membranes were working to move the surrounding fluid in order to remove the air from the nozzle, with square and circular shapes of orifices. The casing was made of nylon material that could be assembled easily. Sinusoidal and square wave functions were generated by a sweep function generator with the frequencies of 80 Hz, 120 Hz and 160 Hz. The experimental work was conducted using variations of orifice shapes, that is square and circular orifices at the same diameter, 3 mm.

Figure 1 shows the detail of the experimental apparatus used in this study which consisted of the thermostat, heater mat, an impinging synthetic jet module, heat sink and DAQ (Data Acquisition).

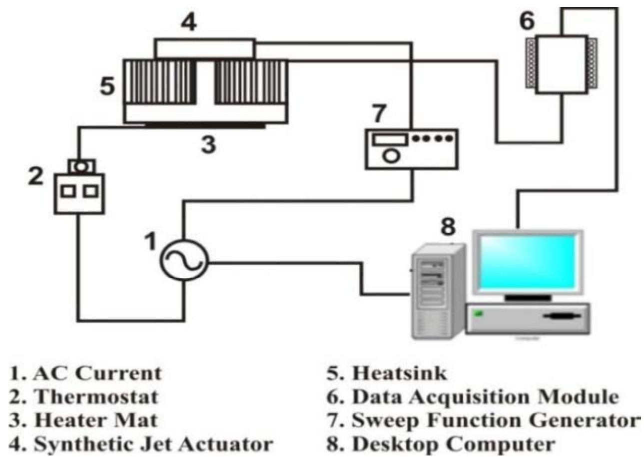

Figure 1 Experimental apparatus

More details for Synjet cooling apparatus and the point of temperature measurement are depicted in Figure. 2. The experimental results were obtained under open space conditions with a collection of data for 3600 seconds at 1 second intervals.

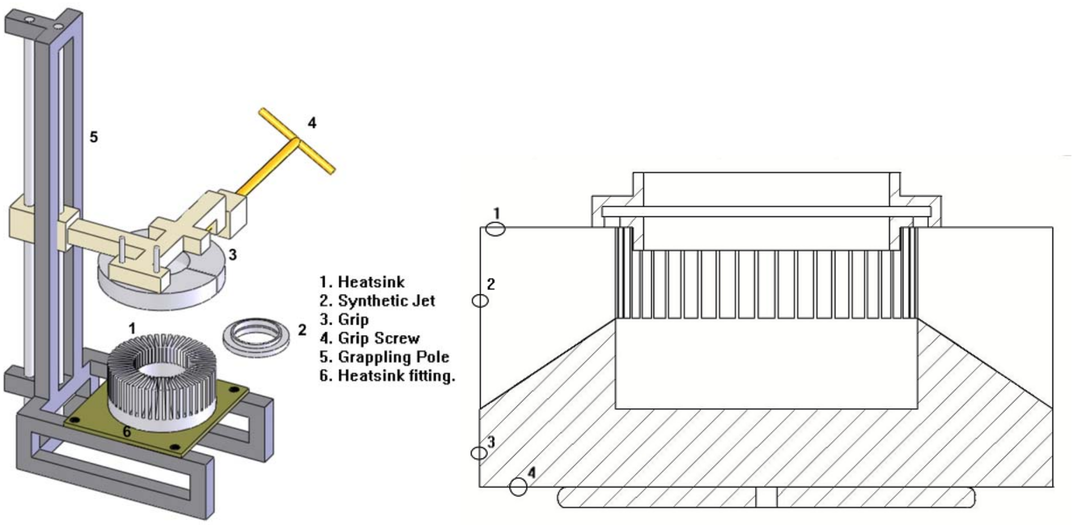

Figure 2 Synthetic jet cooling apparatus & point of temperature measurement

3. RESULTS AND DISCUSSION

3.1. Computational Work

Figure 3 depicts the static temperature contour inside a cavity, inside a heatsink, and an outer field outside the heatsink using a circular orifice with a 120 Hz of Sinusoidal wave function. Simulation was made for a 1/16 condition under the assumption that the suction phase and blowing phases were uniformly implemented at every nozzle.

In Figure 3, it can be seen that the heat flow is moving up from cavity heatsink toward the heatsink fins. In the condition at the ¼ cycle, the heat that is produced by heater mat starts to move up inside the heatsink. And then, at the condition of the ½ cycle, it seems that heatflow is moved toward the heatsink fins. Furthermore, at the condition of the ¾ cycle, the heatflow moves faster than before to go out from the heatsink fin. As in a full cycle, the heatflow is released from the heatsink to the environment gradually.

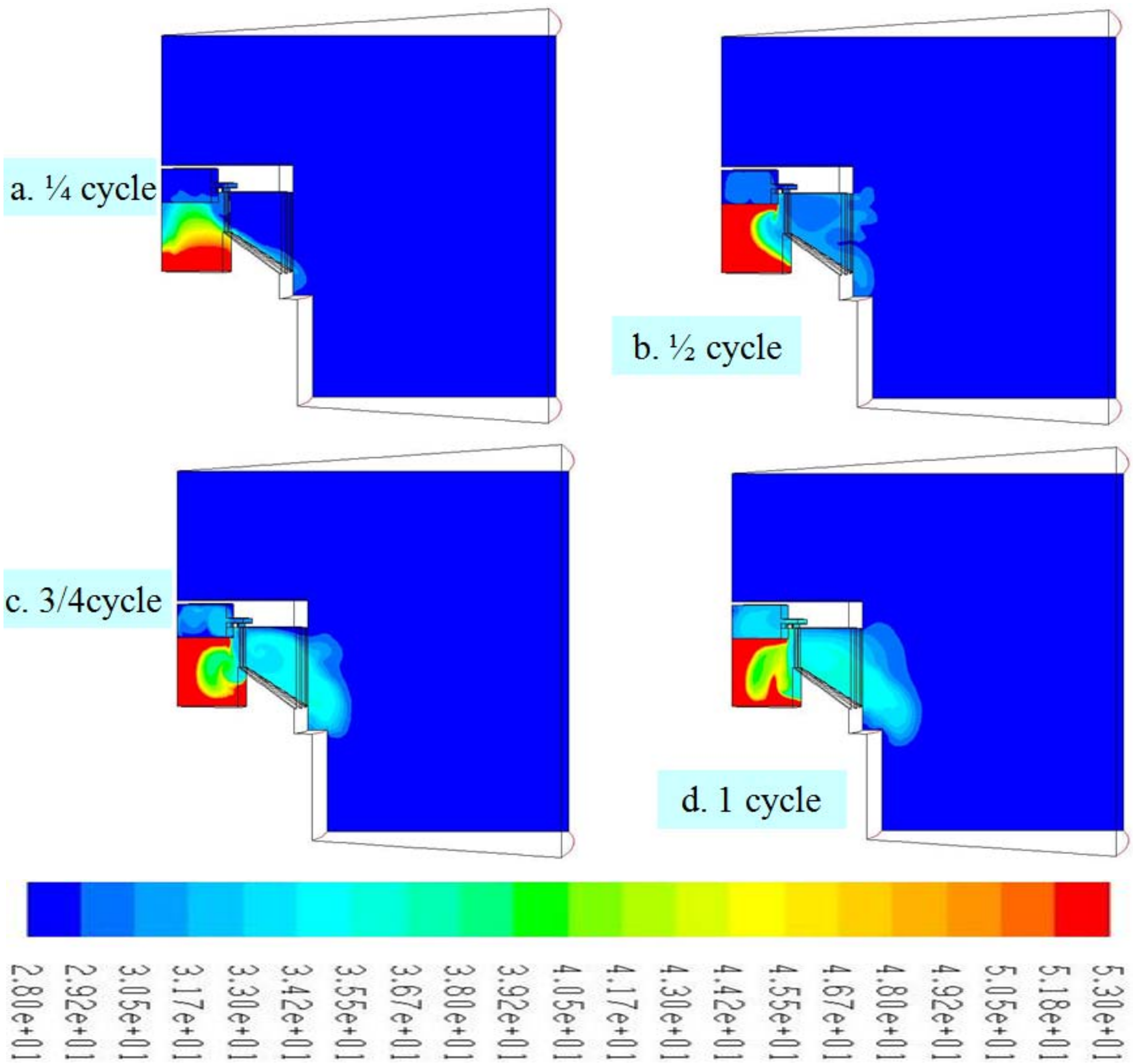

Figure 3 Temperature contour with circular orifice (120 Hz of square function)

Figure 4 shows the static temperature contour inside the cavity, inside the heatsink, and in the outer field as well as outside the heatsink using a square orifice with a 120 Hz of square wave function. A simulation was made for a 1/16 condition with the assumption that the suction phase and the blowing phase were uniformly implemented at every nozzle.

In Figure 4, it can be seen that the heat flow moves up from the cavity heatsink toward the heatsink fins, but it is at a faster rate if compared with the sinusoidal wave function. At the condition of the ¼ cycle, ½ cycle, and full cycle, it seemed that using the sinusoidal wave function, but with the exception of using faster moving fluid and the contour of static temperature inside cavity, the inside heatsink was dominated by a low temperature region, if compared with the sinusoidal driven membrane.

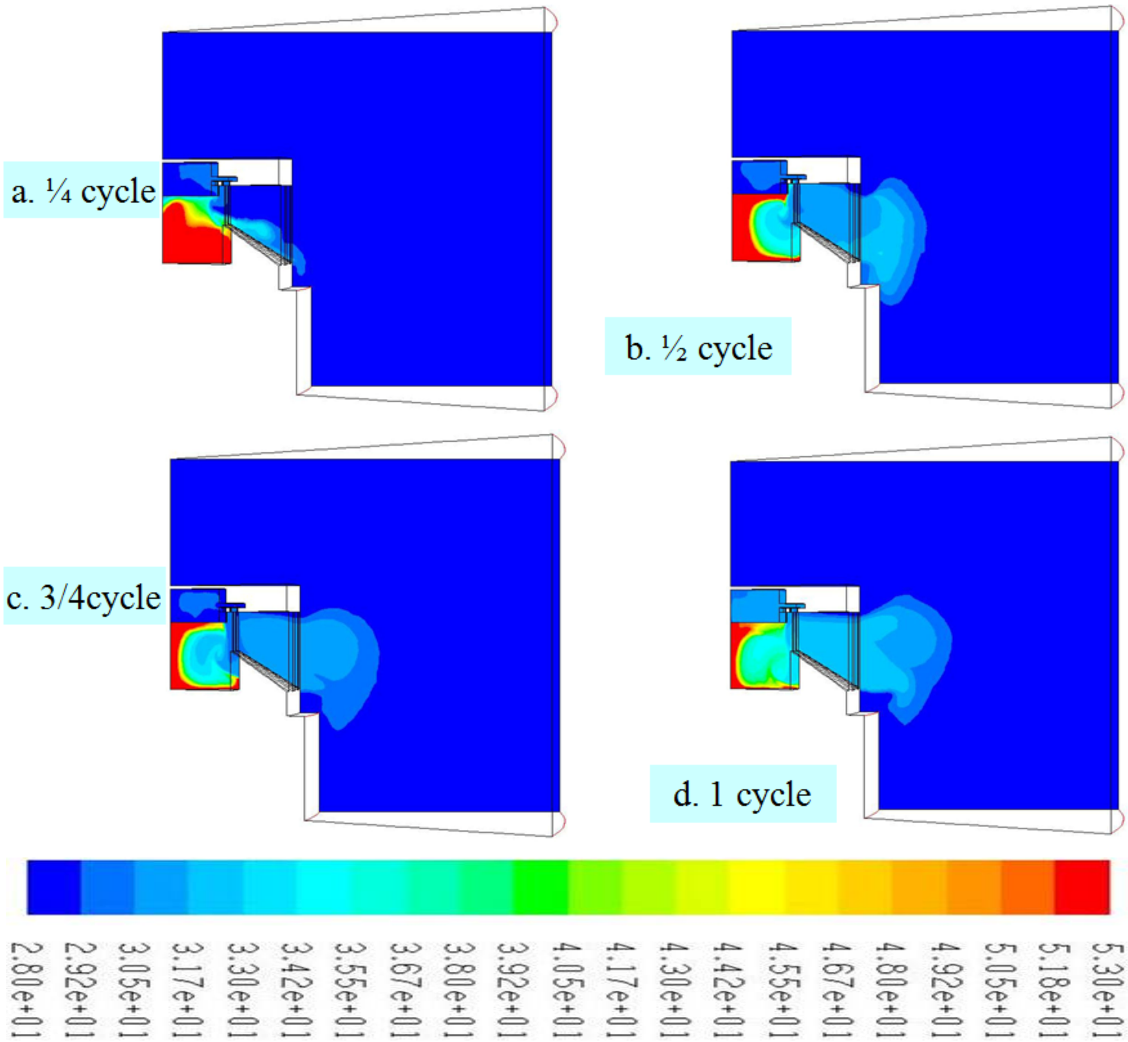

Figure 4 Temperature contour with square orifice (120 Hz of square function)

3.2. Experimental Work

Figure 5 shows the temperature history for a 3,600-second experiment with a variation of orifice shapes at the same diameter using a 120 Hz of square wave function. In that figure, it can be seen that at both of orifice shapes, the cooling performance becomes remarkably better after a 1,000-second activation of a synthetic jet. The apparatus with a square orifice was decreased to a 2.8°C temperature during the experimental work, while the circular orifice at the same diameter was decreased to 1.5°C. Moreover, after a 2,500-second interval with a circular orifice, the temperature of the heatsink tended to rise, whereas with a square orifice, the temperature of the heatsink still decreased, although with a lower temperature gradient. So it follows that a 120Hz of a square with a square orifice has better cooling characteristics than a circular orifice at the same condition. The tendency of the temperature to rise as well as the improved cooling performance with a lower gradient temperature at any given time indicated the significant effects of recirculation due to the confinement effect. Agrawal et al. have explored that the confinement effect that can be dissipated, if we increase the impinging distance at a certain number. However, at larger impinging distances, the jet velocity is reduced due to the entrainment of the still ambient air, which again reduces the heat transfer coefficient (Agrawal et al., 2010). Gulati et al. have discussed that besides recirculation, another possible reason and this needs to be investigated in further detail for the higher cooling performance with a square orifice at the smaller impinging distances is that the Nusselt number contours retain the shape of the orifice from which the flow emerges at lower impinging distances (Gulati et al., 2009). So that, a larger surface area is covered by the flow with a square orifice at smaller impinging distances, if compared to a circular orifice with the same hydraulic diameter. From the previous investigation that was done by Grinstein and DeVore, the entrainment flow rates for the square orifice are significantly larger than for those in relation to the circular orifice (Grinstein & DeVore, 1996). Due to a large entrainment factor, the square orifice attains a larger mass flux rate at the same impinging distance from the orifice. The mass flux rate has a direct bearing on the heat and momentum transport between the jet and the ambient air. This can be seen as a possible argument in favor of a square orifice synthetic jet outperforming its circular orifice counterpart.

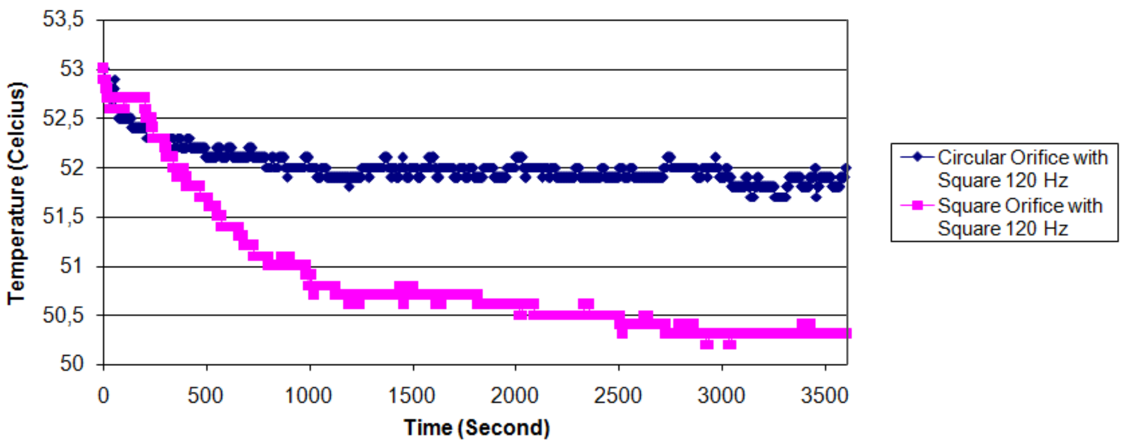

Figure 5 Temperature history of experiment with square & circular orifice (120 Hz of square function)

4. CONCLUSION

The heat transfer experiments and CFD simulation were conducted using a synthetic jet with various types and frequencies of wave functions and shapes of orifice. From variations of the sinusoidal waves and the square 80 Hz, 120 Hz, and 160 Hz and orifice shape variations for the square and circular orifices, it was found that the cooling effect for a 60-minute measurement was optimum with a 120 Hz square function and a square orifice. Both of the experimental and the computational results revealed that by using shape orifice variations on same aspect ratio, the results point significantly toward the development of a synthetic jet as the new alternative cooling system of microelectronic components. The square orifice has a larger covered area, if compared to circular orifice at the same radius, thus resulting in larger entrainment rate that leads to an increase of convective heat transfer performance.

5. ACKNOWLEDGEMENT

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