Synthetic Air Jet for Electronics Cooling

Jet impingement is one of the more effective solutions for cooling electronic devices, as it can create a very high heat transfer rate on the impacting surface. As the power density of modern chips keeps increasing, using fluid jets as a thermal management method shows great potential. In most air jets cooled electronic systems, continuous jets are created by using fans, blowers or a high pressure air source. For the continuous jets, parameters such as jet configuration (free-surface jet, submerged jet or confined jet), the spacing between the jet outlet and the impingement surface, the magnitude of the jet velocities, the angle of impingement etc. are major factors affecting the jets' cooling performance. To enhance jet impingement heat transfer, a pulsed air jet impingement configuration was investigated by some researchers who are looking for exciting the coherent structures in the jet flow and breaking the boundary layer on the impingement plate. However, creating pulsed jet impingement by traditional methods requires complicated mechanical design and flow routing arrangement.

Synthetic jets are pulsed jets generated by a flexible membrane/diaphragm driven by an electromagnetic driver, a piezoelectric driver or even a mechanical driver such as a piston. Figure 1 illustrates how synthetic jets are generated by the movement of a membrane/diaphragm. The membrane/diaphragm is fixed at one end of a chamber. A small opening/orifice at another end of the chamber allows for the passage of the jets. When the membrane/diaphragm moves up and down at a certain frequency, it sucks the surrounding air into the chamber and then expels it out in each cycle, creating jets at the operating frequency of the membrane/diaphragm. The pulsating jet can be directed at a heated surface to dissipate heat generated by the electronic device. Although the mechanism is fairly simple, extremely fast cycling requires high-level engineering to produce a device that will last in industrial applications.

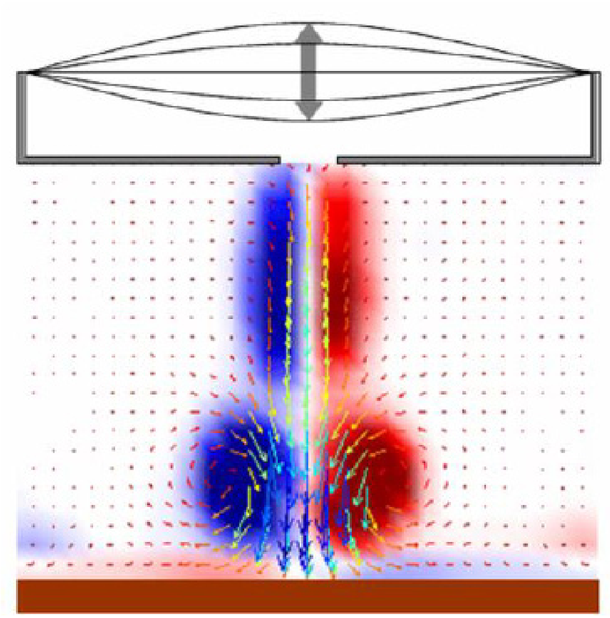


Figure 1. Synthetic Air Jet [1]

McGuinn et al. [2] studied the synthetic jet cooling performance by using a Particle Image Velocimetry (PIV) system to measure the velocity and a heated impingement surface to measure the local heat transfer. Figure 2 shows the testing bench McGuinn et al. used for their study. An acoustic speaker was mounted on one side of an enclosed cavity; an orifice plate was located on the opposing side. A TTi TG315 Signal Generator provided the driving signal for the speaker and the signal was amplified using a Kemo 40 Watt power amplifier. The speaker was supplied with a sinusoidal wave of specific amplitude and frequency to obtain the desired frequency and stroke length. The impingement surface was composed of three layers. The top layer was 5mm thick flat copper plate. The bottom layer was a 1.1mm thick silicon rubber heater mat. The mat was glued to a copper plate with a thin layer of adhesive. The whole impingement surface was insulated from the bottom. The top surface of the copper plate worked as an approximate uniform wall temperature boundary condition for the synthetic jets. During tests, the copper plate surface temperature was maintained at 40°C. An RdF Micro-Foil heat flux sensor was used to measure the local heat flux at different location.

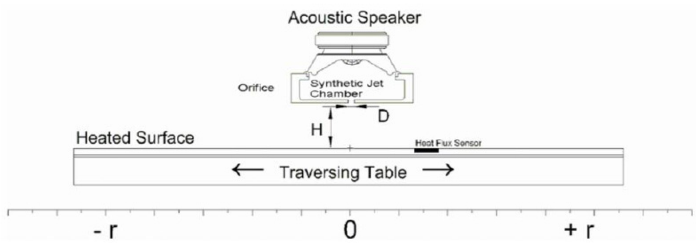


Figure 2. Experimental Setup [2]

In their study, the stroke length of the jet is defined as

$$L_o = \int_0^{\tau/2} u(t)dt \qquad (1)$$

Where τ is the jet period, u(t) is the jet centerline velocity. The Reynolds number is,

$$Re = \frac{U_0 D}{\gamma} \qquad (2)$$

Where U_O is the area-averaged orifice velocity, D is the orifice diameter, and y is the air kinematic viscosity.
The Nusselt number is

$$Nu = \frac{hD}{k} \qquad (3)$$

Where h is the heat transfer coefficient, k is the air thermal conductivity.

Figures 3 shows phase-locked dimensionless vorticity fields $\omega D/U_0$ for the synthetic jet for H/D=1. The starting phase had been chosen to correspond to maximum ejection. In the figure, the positive values (blue) indicate clockwise rotation and the negative values (red) indicate counterclockwise rotation. The locations of peak vorticity correspond to a vortex ring, propagating down towards the heated plate. The vortex ring form at r/D=1 with maximum flow velocity occurring in the center of the jet. Its evolving and dissipation with time are clearly shown in the figure.

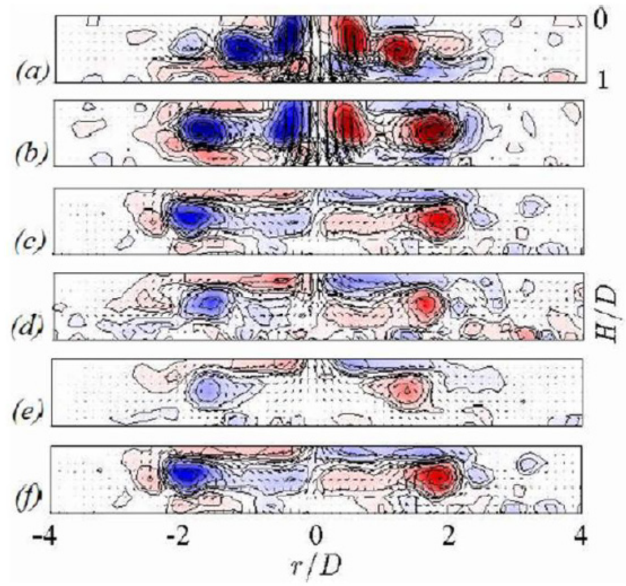


Figure 3. Phase Locked Vorticity Plot for H/D=1 and Re=3700 and L_o/D=17 for (a)φ=120 (b) φ=180 (c) φ=240 (d) φ=300 (e) φ=0 (f) φ=60 [2]

Figure 4 shows phase-locked dimensionless vorticity fields $\omega D/U_0$ for the synthetic jet for H/D=2. Again the vortex ring emerges at a radial distance of approximately r/D=1.

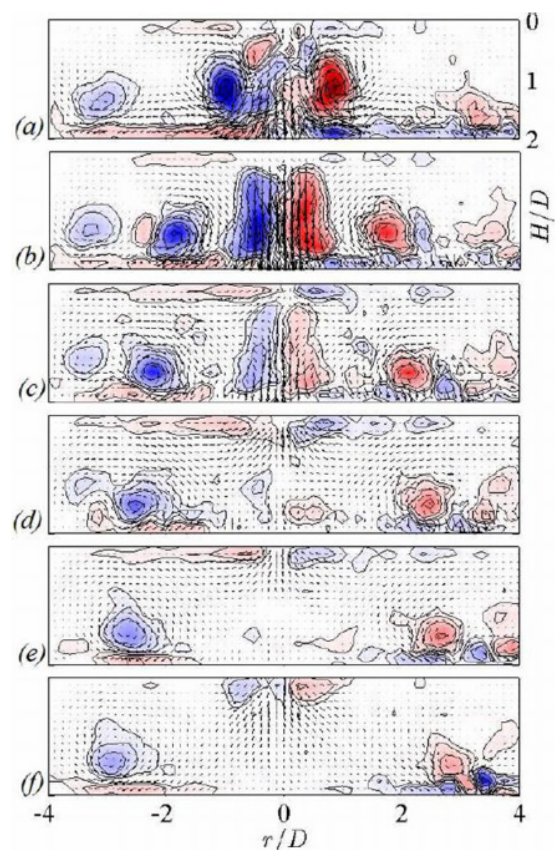


Figure 4. Phase Locked Vorticity Plot for H/D=2 and Re=3700 and L_o/D=17 for (a) φ=120 (b) φ=180 (c) φ=240 (d) φ=300 (e) φ=0 (f) φ=60 [2]

Figure 5 shows the measured Nusselt number at different radial locations for different H/D values. In McGuinn et al. test, generally the peak Nusselt number decreases as the H/D value increases. But the H/D=4 case has a higher Nusselt number than that of H/D=6. McGuinn et al. think that this is due to the interaction and subsequent breakdown of the coherent vertical structures as they approach the plate, resulting in increased mixing and hence the “spreading” of the heat transfer curve.

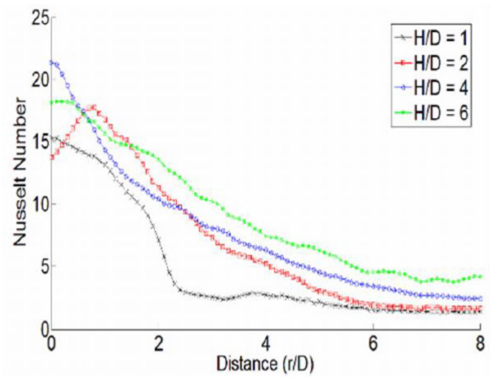


Figure 5. Nusselt Number Distributions with Re=2300 [2]

Figure 6 shows the measured Nusselt number at different Reynolds numbers for H/D=2. The higher jet velocity results in a better heat transfer on an impingement surface. In some cases, the peak Nusselt number is not at a stagnation point. For example, for Re= 2300, 3700, and 4900, the peak Nussult number was measured at r/D=1. Figure 7 shows the measured Nusselt number at different Reynolds numbers for H/D=4. For all cases, the highest heat transfer happens at stagnation point. So the convection on an impingement surface is very sensitive to the H/D ratio and jet velocity, due to the complicated flow and heat transfer interaction between jet and impingement surface.

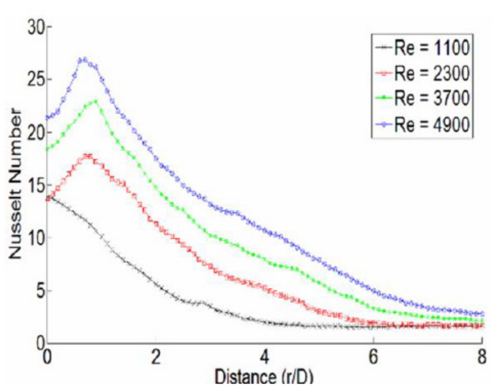


Figure 6. Nusselt Number Distributions with H/D=2 [2]

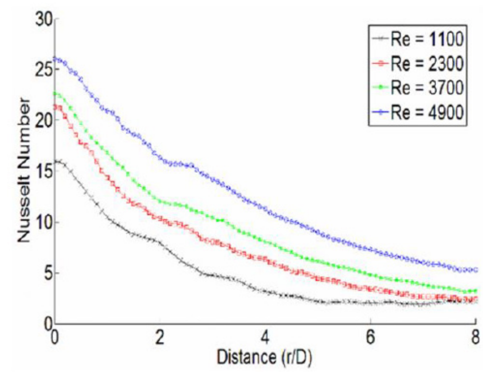
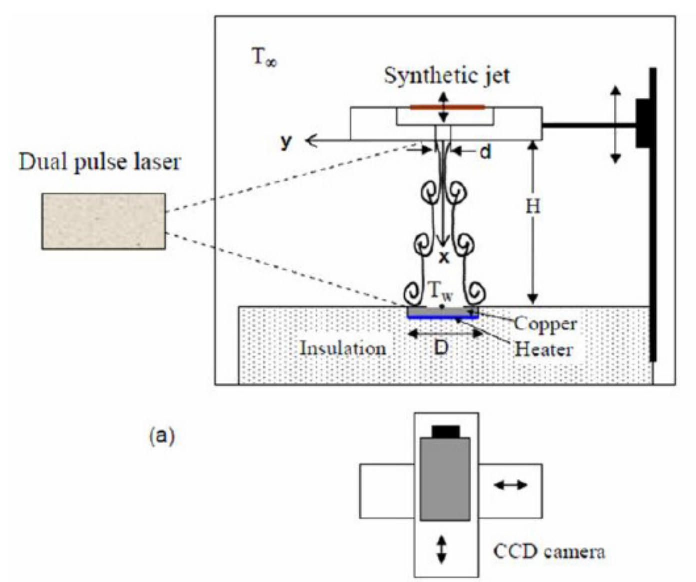


Figure 7. Nusselt Number Distributions with H/D=4 [2]

Pavlova and Amitay [3] studied synthetic jets with a different frequency, H/D configuration and velocities. Figure 8 shows the test setup for their study. The synthetic jet was driven by a single commercially available 32 mm diameter piezo-electric disk having the nominal resonant frequency of 1000Hz. The heated jet impingement surface includes a copper plate and a surface heater. The copper plate (12.7mm in diameter and 6mm in thickness) was made of oxygen-free copper. A round kapton heater was attached underneath the copper plate. The heated surface assembly was centrally mounted into a block of nylon insulation to minimize heat losses through the sides and bottom. Pavlova and Amitay concluded that the heated surface provides a constant heat flux boundary condition for the jet cooling test. The copper plate temperature was measured with a small diameter T-type thermocouple which was placed at the center of the copper disk just below the surface. The air jet velocity profile was measured by Particle Image Velocimetry (PIV) system and complemented with hot-wire anemometry.



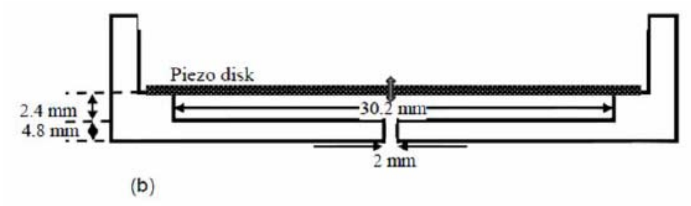


Figure 8. (a) Experimental Setup, (b) Synthetic Jet [3]

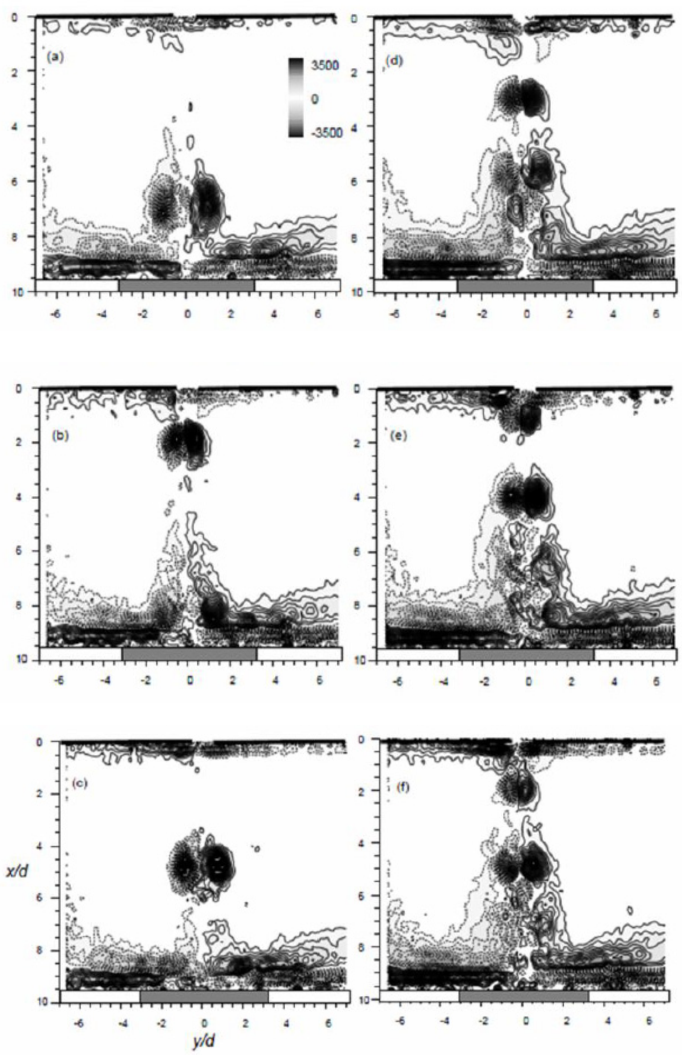


Figure 9. Phase-averaged Spanwise Vorticity Fields for f=420Hz (a-c) and f=1200 (d-f). φ=0° (a and d), 120° (b and e) and 240° (c and f). Re=445 and H/D=9.5 [3]

Figure 9 shows the phase-locked dimensionless vorticity for the synthetic jet for Re=445 and H/D=9.5 at different jet frequencies. In the figure, the positive vorticity contours are represented by a solid line and the negative vorticity contours are represented by dash lines. The difference between the two frequencies is apparent in these figures. For the f=420 Hz jet (Figures 9a-c), there is only one vortex ring at any time. For f=1200 Hz jet (Figures 9d- f), there are always two vortex rings which effect each other.

Pavlova and Amitay measured the surface temperature at a stagnation point and calculated the stagnation point Nusselt number as a function of H/D and Reynolds numbers for operating frequencies of 420Hz and 1200Hz. The results are shown in Figure 10. In the figure, is the free convection Nusselt number and Δ is the difference in Nusselt number between the synthetic jet and free convection cases for the same condition. Pavlova and Amitay found that when the synthetic jet is operated at a frequency of 420Hz (Figure 10a), the improvement of the stagnation Nusselt number with respect to free convection is up to 78%, with optimal cooling occurring for an H/D of 6 to 18 for all Reynolds numbers. For H/D>18, the performance degrades, as it does for normalized distances below 6. At a higher operating frequency (f=1200Hz), the enhancement in the Nusselt number is up to 113%, where the best cooling performance is obtained for H/D in the range of 3 to 11. Outside of this range, the cooling effectiveness decreases. The data show that the H/D range corresponding to better cooling at the higher frequency of the synthetic jet is closer to the surface, compared to the lower frequency jet. Increasing the jet velocity also significantly enhances the cooling on the impingement surface.

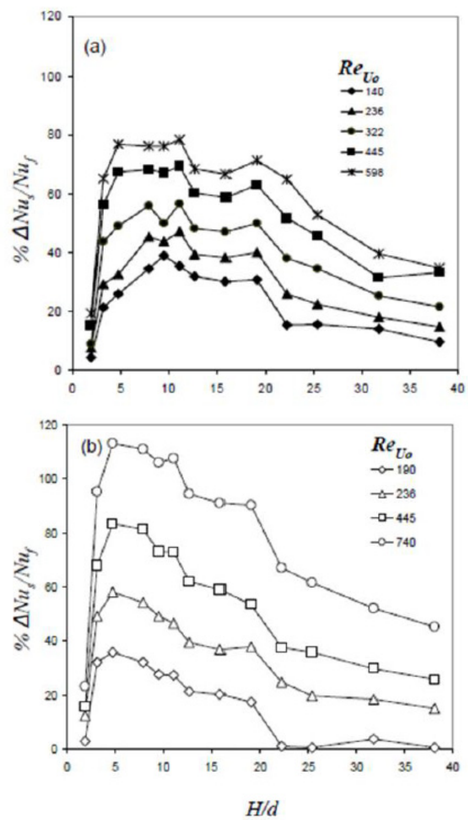


Figure 10. Stagnation Nusselt Number with Respect to Free Convection as a Function of the Normalized Distance, H/d, for Different Reynolds Numbers: (a) f=420 Hz and (b) f=1200 Hz [3]

The synthetic jet is a very good way to enhance the heat transfer on the impingement surface. Many researchers have found that the local heat transfer coefficient can be more than doubled. However, the enhancement is highly dependent on the synthetic jet configuration, such as jet frequency, jet speed and the orifice size/orifice-to-plate distance ratio etc., because the energy used to drive the membrane/diagram is small compared to a conventional fan and blower; synthetic jets have higher cooling efficiency. If their packaging and control system can be improved and manufacturing cost be reduced, synthetic jets will find more applications in electronics cooling in the future.

References:

1. O'Donovan, T. S., "Development of Synthetic Air Jet Technology for Applications in Electronics Cooling ", Presentation of 27th HEXAG Meeting, Heriot-Watt University, Edinburgh.

2. McGuinn, A., Persoons, T., Valiorgue, P., O'Donovan, T. S., Murray, D. B., "Heat Transfer Measurements of an Impinging Synthetic Air Jet with Constant Stroke Length", 5th European Thermal-Sciences Conference, Netherlands, 2008.

3. Pavlova, A. and Amitay, M., "Electronic Cooling Using Synthetic Jet Impingement", J. Heat Transfer, vol. 128, p.897-907, 2006.