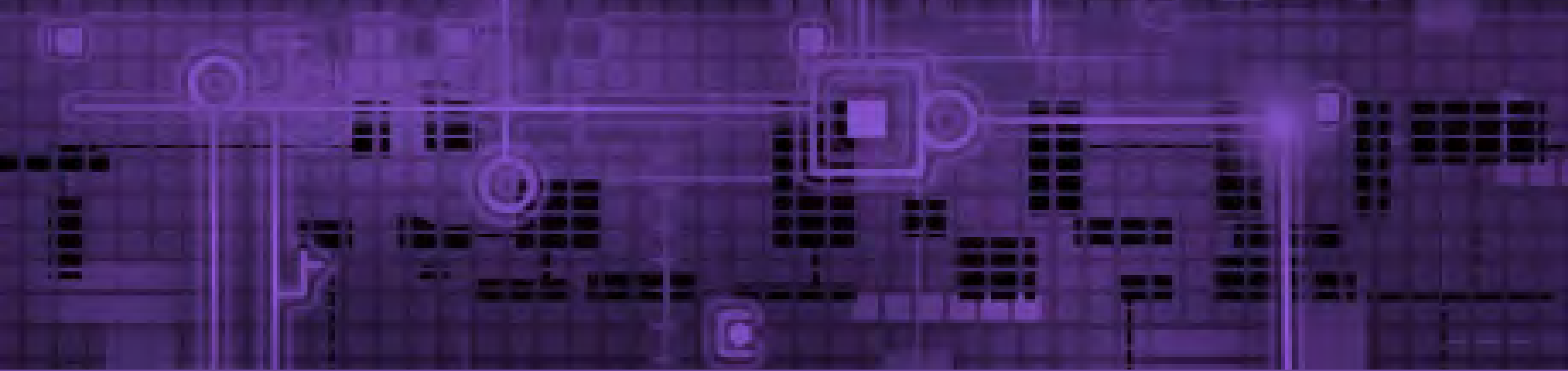


Enhancing Heat Transfer by Using

Single-Phase Self Oscillating Jets

Innovative cooling technologies are being developed as the power dissipation of electronic components is increasing rapidly over the years. In general a cooling technique is evaluated by a term called the heat transfer coefficient(HTC) which is a measure of heat removal.

Literature is rich with HTC values for different fluids. Figure 1 is such one example where it shows the comparison of different cooling techniques using the heat transfer coefficient as a parameter.

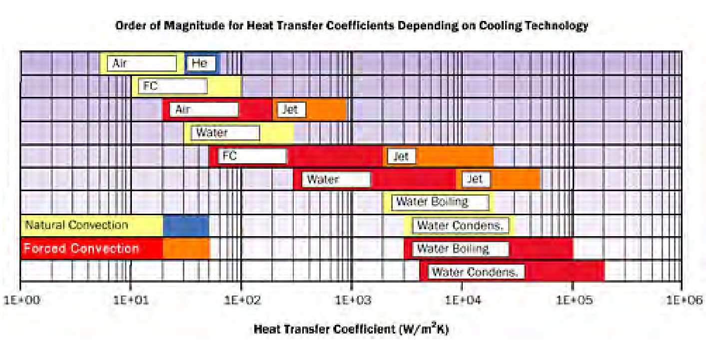


Figure 1. Heat Transfer Coefficient Range That Can Be Attained With Natural Convection, Single Phase Liquid Forced Convection And Boiling For Different Coolants [1]

As seen above, jet impingement cooling seems to offer a high heat transfer coefficient and is expected to result in better cooling than natural or traditional forced convection methods.

Jet impingement cooling is extensively used to enhance the local removal of heat from internal passages of gas turbine blades. When compared to the conventional convection cooling (e.g. flow over a flat plate) jet impingement enhances the heat transfer coefficient up to three times. The benefit is obtained by increasing the heat transfer coefficient by using impingement on the target surface. This is because the thinner boundary layer and the spent flow serves to enhance the turbulence in the surrounding fluid. In electronics cooling applications studies are being conducted to see how this technology can be used to cool high heat density devices. This sort of jet impingement is known as continuous jets. Much of the early research on the heat transfer enhancement using continuous jets was summarized by Martin[2].

In the quest for further enhancing the heat transfer by jet impingement some researchers looked into pulsating jets. Navin and Ball [3] in 1961 were among the first few researchers to analyze and study the effects of pulsed air jet impingement. However their studies concluded that no heat transfer enhancement was observed as the result of pulsations for an impinging circular jet with the Reynolds number range between 1200 and 120000. In 1993, Eibeck et al. found that the pulsations introduced into the flow resulted in heat transfer enhancement in excess of 100%. The researchers concluded that this was because of the intermittent vortex rings impinging on the surface. This phenomenon was also seen by Zumbrunnen and Aziz[4] who used water as their working fluid.

Further work on jets resulted in the concept of self oscillating jets – where in the oscillations in the jet impingement is obtained by a simple orifice nozzle combination without any moving parts. Viets [5] used fluidic nozzles as simple and effective mixing devices but Hermi and Carr[6] used the Self Oscillating jets as methods to enhance heat transfer. They studied the enhancements obtained by self oscillating jets over stationary impinging jets and concluded that the heat transfer zone on the impingement plate is enlarged effectively when compared to the stationary jet. The oscillating jet yields heat transfer enhancements which ranged from 20% to 70% over the stationary jets in an identical set up.

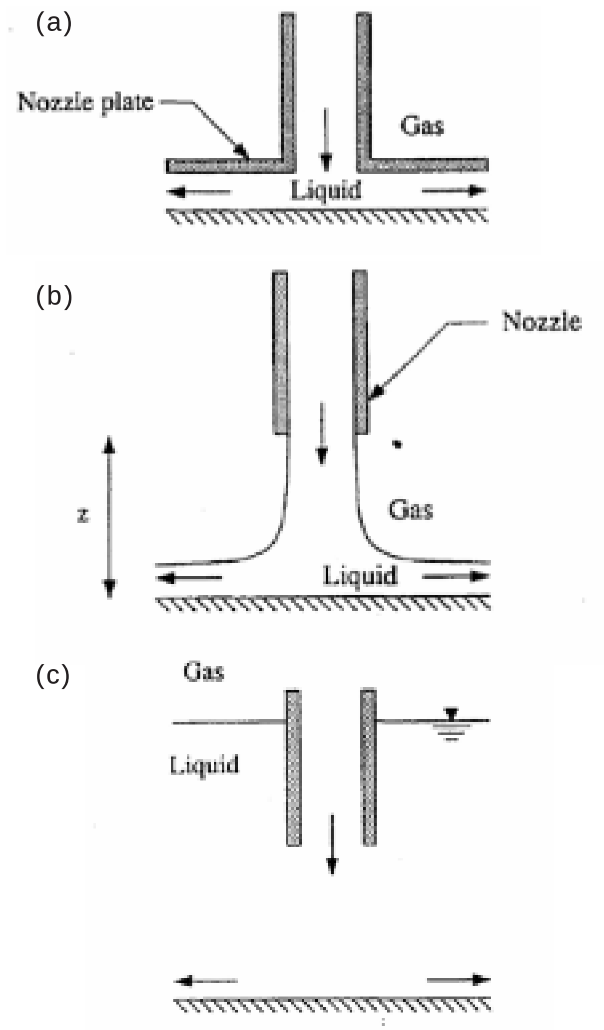


Figure 2. Different Configurations Of Jet Impingement [7] (a) Confined Submerged Jet (b) Free-Surface Jet (c) Submerged Jet

The self-oscillatory nature of these jets make it very attractive to use since there are no moving parts involved and can be used in virtually any situation related to cooling of high heat dissipating devices/ parts.

Sreekant et al [7] in their paper on Single-Phase Self Oscillating Jets for Enhanced Heat Transfer conducted a full factorial design of experiments to investigate the impact of nozzle design, oscillation frequency, jet flow rate, nozzle to target distance and jet configuration (free surface or submerged) on the heat transfer coefficient.

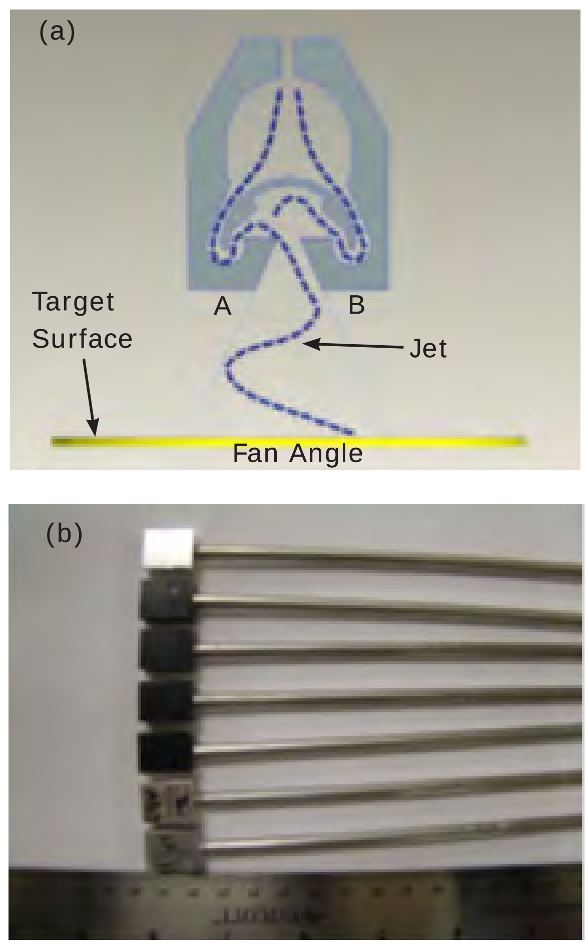


Figure 3. An Illustration Of The Principle Behind the Self Oscillating Jets (a) Cross Sectional Schematic and (b) Nozzles Tested At NREL

Figure 2 illustrates the concept behind self-oscillating jets, although this was not the exact geometry of the nozzles tested for the study. The oscillations are caused by the inherent geometry of the nozzle which causes vortices in the fluid. When these vortices interact the consequent pressure differences in the fluid results in oscillations in the liquid jet at the exit of the nozzle. The oscillation of the jet is restricted to the angle shown in Figure 2 (a), which is referred to as the fan angle. The frequency of the oscillations is determined by the time it takes for the jet to go from A to B and back to A. From a heat transfer point of view this sweeping motion within the fan angle has the potential to disrupt the boundary layer growth on the target surface resulting in heat transfer enhancement between the surface and the liquid.

In the experimental set up built by NREL, single phase heat exchangers were used in the high heat flux test loop. The schematic of the loop is shown in Figure 3 (a). Figure 3 (b) shows the test fixture that was used with the high-heat flux loop to characterize the heat-transfer performance of single-phase jets. The plane of oscillation is shown in Figure 4 (a). A total of four thermocouples were placed on the target surface as shown in Figure 4 (b) to adequately determine the temperature distribution on the target surface. An additional thermocouple was placed on the heater to monitor the heater temperature. Experiments were conducted with six different fluidic nozzles with an area of 1.1mm X 1.1 mm.

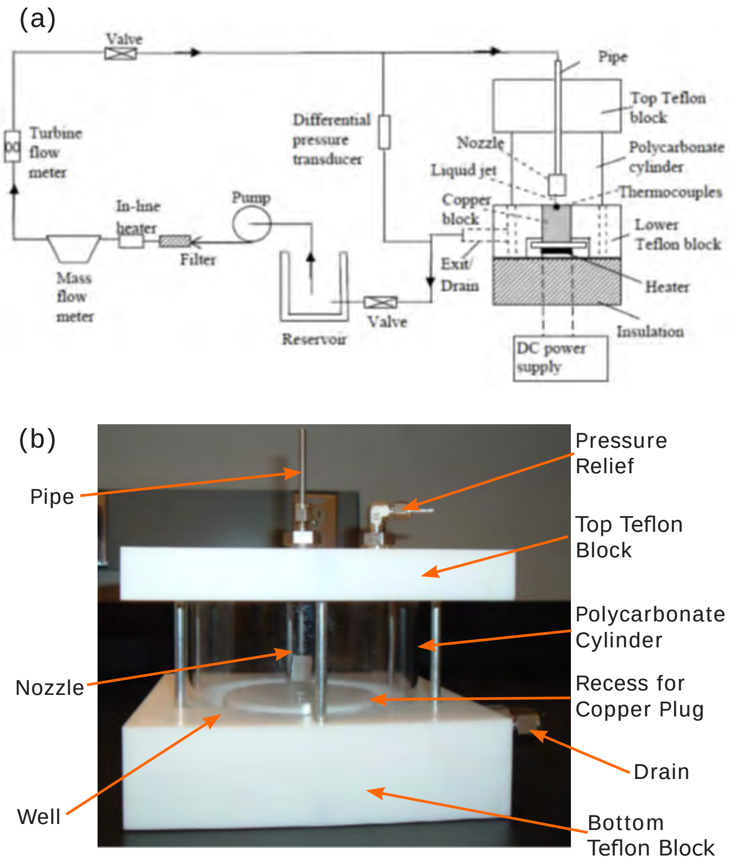


Figure 4. (a) Schematic Of The Experimental Test Loop (b) Experimental Test Fixture Set Up

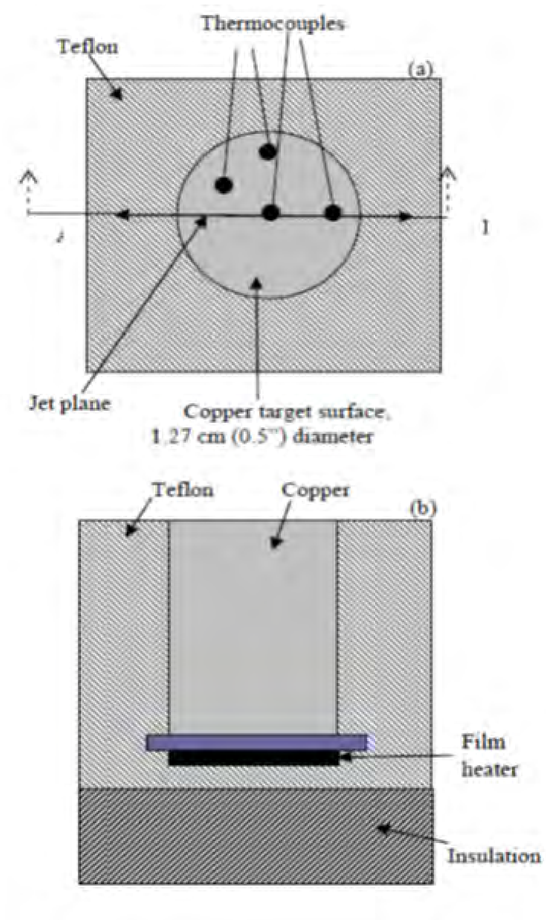


Figure 5. Top And Cross Sectional View Of The Copper Plug That Serves As The Target Surface For The Experimental Set Up

The authors used a three level (for velocity and target distance) full factorial design of experiments to evaluate three jet velocities (2, 7 and 12 m/s) and three target distances (1.1 , 4.4 and 7.7 mm) in the free surface and the submerged configurations. Sreekan et al. have analyzed the data and presented the data for the performance of the different fluidic nozzles for selected variables as a function of velocity and flow rate. However in this article we will limit the discussion to how the self-oscillating jets perform relative to steady jets in different configurations keeping in mind the heat transfer coefficient.

The heat transfer coefficient is defined as

$$h = \frac{Q}{A(T - T_{ref})}$$

where:

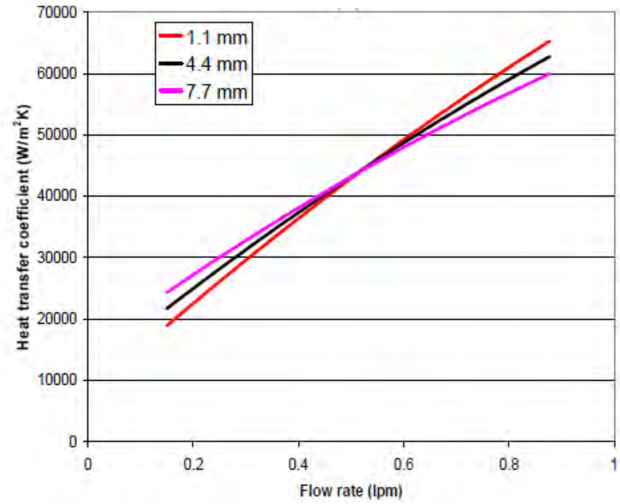
h is the heat transfer coefficient (W/m$^2 \cdot$ ºC)

Q is the power applied to the resistive heater (W)

T is the surface temperature (average of the readings from the four locations on the copper surface) (ºC)

T_{ref} is the jet inlet temperature which is set at 25ºC

Figure 5 (a) shows the impact of target distance on heat transfer coefficient for one of the tested nozzles (fluidic1) in the free-surface and submerged configuration. One can see that for the free-surface configuration at lower flow rates the heat transfer coefficients was slightly higher for larger Nozzle-to-target distance (H_D) which reverses at higher flow rates. However as seen in Figure 5 (b), we see that the impact of target-to-distance has a significant impact on the heat transfer performance of the fluidic nozzle. As H_D increases, irrespective of flow rate the heat transfer coefficient increases. At higher flow rates the increase is more pronounced. At low flow rates, the difference was only about 10% but at the highest flow rate the difference vary between 35 % to 40%.



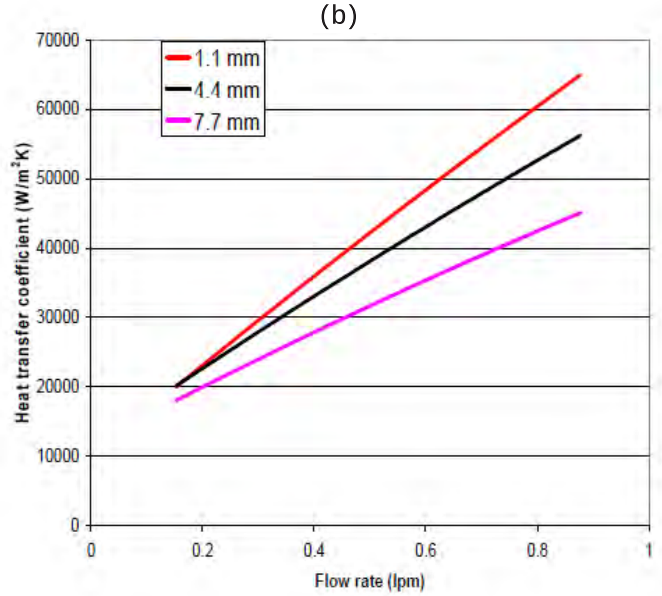


Figure 6. Impact of Target Distance on the Heat Transfer Coefficient with the Self-Oscillating (Fluidic) Nozzle in the (a) Free-Surface Configuration and (b) Submerged Configuration

The optimum H_D distance for most cases was found to be 1.1mm. Figure 6 shows the performance of the self-oscillating and the steady jet at this optimum H_D (1.1mm) at different flow rates for the two configurations (free-surface and submerged). As seen in figure 6 (a) in the free surface configuration the self-oscillating jets (fluidic

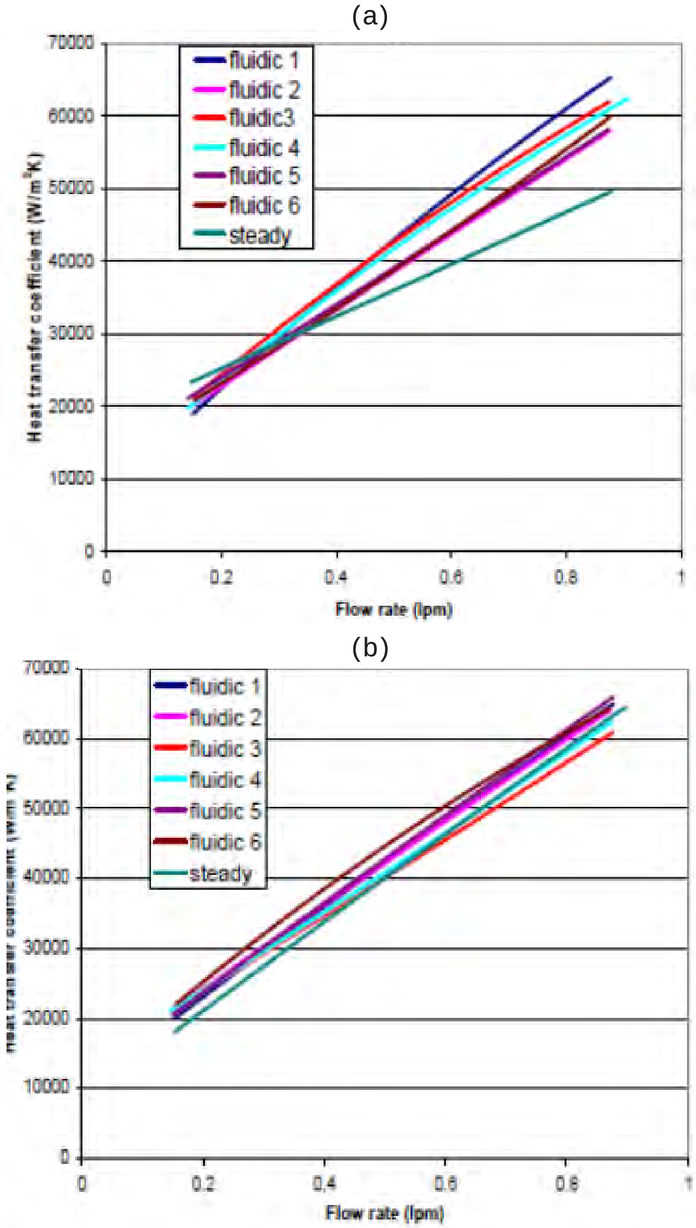


Figure 7. Plot of Heat Transfer Coefficient V/S Flow Rates At 1.1 Mm Target Distance (a) Free-Surface Configuration and (b) Submerged Configuration

nozzles) perform almost up to 30% better than the steady jet at comparable flow rates. However in the submerged configuration, Figure 6 (b) there is virtually no advantage in using a self-oscillating jet over a steady jet. The steady jet performs as well as the best performing self-oscillating jet.

The authors conclude that there might be two reasons for the behavior seen in Figure 6. In the submerged configuration since there is no splashing, which is a problem in the free surface configuration, there is no advantage of oscillating the jet. Additionally in the submerged configuration, the strength of the oscillations of the self-oscillating jets is somewhat dampened and attenuated which is particularly true at larger H_D. The authors [7] also concluded from their experiments that the steady free-surface jet was outperformed by the steady submerged jet by almost 30% which is believed to be the result of minimizing the splashing.

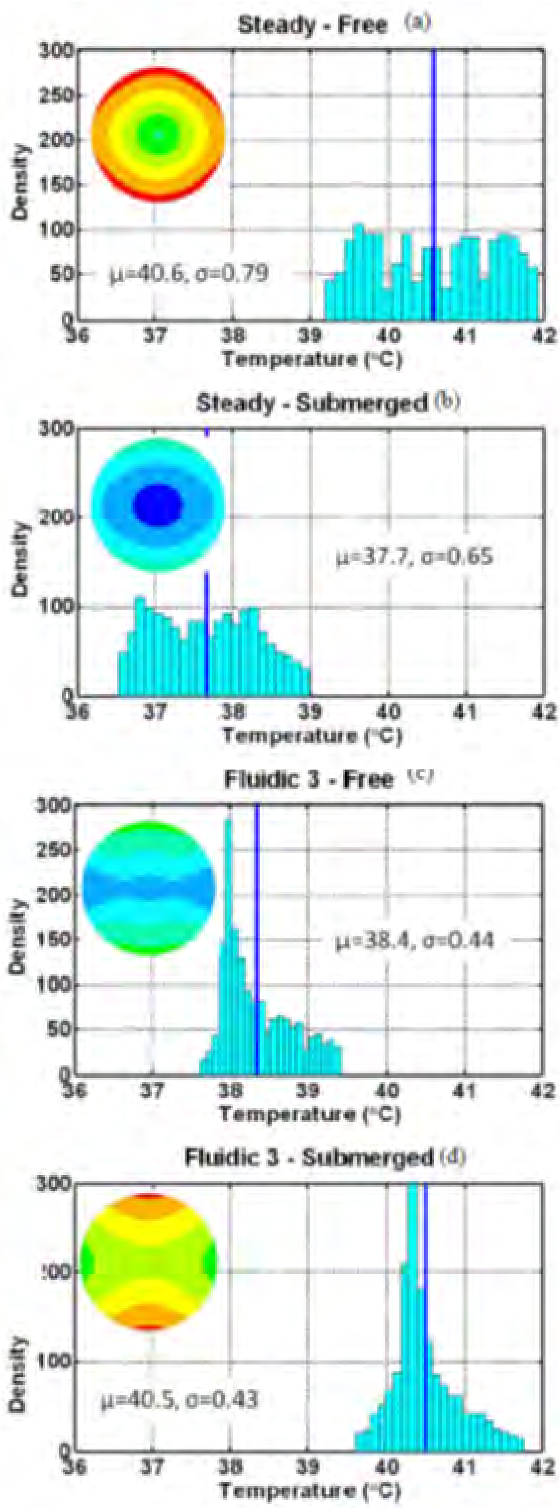


Figure 8. Temperature Distribution On The Target Surface For (a) Steady Free-Surface Jet (b) Steady Submerged Jet (c) Self-Oscillating Jet (Fluidic 3) Free-Surface Configuration (d) Self Oscillating Jet (Fluidic 3) Submerged Configuration

Figure 8 shows the temperature distribution across the target surface as measured by the four thermocouples. We see that the standard deviation of temperatures for the steady jet is much higher than that of the self-oscillating (fluidic3) jets. This suggests that self-oscillating jets are helpful in obtaining more uniform target surface temperatures in both the free-surface and submerged configurations.

This article primarily focused on the heat transfer performance enhancements obtained by using Self-oscillating jets over a steady jet based on the results presented in [7]. They have discussed other key parameters and results in their paper. The key point to note is that it is evident [7] that in the free surface configuration the self-oscillating jets showed heat transfer enhancements of nearly 30% over a steady jet. However this improvement vanishes in the submerged configuration where the steady jet performs as well as the self-oscillating jets. Results also suggest that the self-oscillating jets yield a more uniform surface temperature on the target surface which can be of immense help when cooling components where uniform surface temperatures are desirable.

It is of interest to extend the above results to array of jets. In most electronics cooling applications a single jet will not be sufficient to cool a component, rather, a multiplicity of jets are required. In the case of array of oscillating jets, their interaction becomes important. This topic requires further research which is of interest to electronics cooling applications.

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