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An experimental investigation of cooling behavior of liquid jet and liquid spray methods in high heat flux condition

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Abstract

The surface cooling of components with a high heat flux is one of the critical challenges for various industries. One of the techniques used is impingement cooling, in both forms of a liquid jet flow and a liquid spray. In this research, a comparison has been made between jet cooling and spray cooling in terms of flow rate, and nozzle height (distance from the nozzle exit to the target surface). It is observed that the time to reach the steady state and the time rate of temperature variations in the spray are lower than those of the jet cooling. For a typical heat flux of 40 W/cm^2, the use of spray instead of jet is found to reduce the surface temperature by 15.1%. The results show that using a liquid spray increases the convection heat transfer coefficient by almost 55% compared to that of a liquid jet for the same flow rate. However, both cooling methods exhibit an increase in the convection heat transfer coefficient with higher flow rates. The reduction of the nozzle height is found to reduce the surface temperature. In addition, the results show that spray cooling is more dependent on the nozzle height than jet cooling.

Keywords: High heat flux surfaces, Impingement cooling, Convection heat transfer coefficient, Jet cooling, Spray cooling

1. Introduction

Over the last three decades, the relentless micro miniaturization of electronic components has fueled the urgent need for cutting-edge cooling techniques to reliably keep device temperatures below those set by dependability and material limitations. By the beginning of the 1980s, this trend had caused a sharp increase in the rate at which heat was dissipated, leading to a switch from cooling methods that relied solely on the sensible heat rise of coolants to those that used dielectric liquid coolants instead of fan-cooled heat sink attachments. Nevertheless by the mid-1980s, most single-phase liquid cooling systems could not keep up with the heat dissipation from supercomputer processors, which surpassed 100 W/cm^2 [1]. In addition to initiatives to promote heat dissipation, several instances of applications exist in nuclear engineering [2], electronics [3,4], or refrigeration [5]. Another traditional application of high dissipation techniques [6,7] may be seen in metallurgy with water quenching, which involves rapidly cooling metallic pieces that are first heated to extremely high temperatures. This procedure can be carried out by impinging a jet or spray onto the surface of the part or submerging it in a liquid pool. In most cases, pool immersion is less costly and may be used for more significant components, simpler geometries, and higher production quantities. Sprays, on the other hand, are suggested, for example, for complex-shaped components or when higher heat fluxes are required, albeit it is difficult to guarantee homogenized heat dissipation [8].

The shrinking of high-performance computing processors and power electronics converters has been made necessary by the growing demand in the computing industry. As a result, the industry is increasingly embracing three-dimensional chip stacking and two-dimensional chips with strong heat flux dissipation. However, the chips must be operated in accordance with the thermal safety criteria [9] in order to achieve better computational efficiency, which is most frequently measured as performance per Watt [10]. The heat generated by such components is frequently not transferred by conventional air-cooling techniques [11], which reduces chip reliability and lifetime and raises the total cost of ownership (TCO). As a result, during the past few decades, both academics and businesses have devoted much study to alternate high heat-flux removal techniques. Because liquid cooling dissipates heat more effectively than traditional air cooling, it has received increased attention for direct contact cooling. Among these, spray cooling has been the subject of in-depth research [8,12]. The spray cooling technique coats the whole heating surface (insulating surface) of an electronic device with atomized droplets created by high-pressure pumps and nozzles. High heat transfer capacity, remarkable temperature homogeneity, and a sizable cooling surface are all benefits of spray cooling. While spray cooling requires droplet atomization, jet impingement cooling does not. Optimizing jet parameters, liquid properties, and heating surface structures are the main goals of the work on jet impingement heat transfer enhancement [13]. Additionally, the pool immersion cooling approach provides excellent cooling performance and may be used with servers [14] and data centers [15].

In this article, the comparison of the cooling performance of a liquid jet flow and a liquid spray is discussed, which includes a comparison of the surface temperature and convection heat transfer coefficient at different flow rates and different nozzle heights (distance from the nozzle exit to the target surface).

2. Experimental Setup

An experimental system, called a closed-cycle setup, has been developed for the investigation of heat transfer in jet impingement. The flow chart presented in Figure 1 outlines the sequential operations within this experimental system. A diaphragm pump propels the working fluid from a storage tank into the first enclosure, where heat transfer occurs through jet impingement. After heat exchange with the impingement surface, the fluid departs the experimental enclosure. It flows through a plate heat exchanger, where it undergoes cooling through the cooling water. Eventually, the chilled fluid is directed back to the storage tank, thereby finishing a complete cycle. Throughout each test, the flow rate of the operational fluid is measured using a flow meter, provided by Instrument Company in China (Flowmeter 100-500 ml/min). The temperature of the fluid is monitored at five specific points: at the entrance of the experimental enclosure, at three points located 15mm radially from the center of the impingement surface, and the last one in the storage tank. In order to evaluate the pressure decrease through the liquid nozzle, a differential pressure transmitter (Atek BCT-22-10B-A-G1/4-C-S30, Turkey) is installed upstream of the experimental enclosure. Additionally, the entire pipeline is insulated with a 10-mm thick polyethylene layer to minimize the effect of the surrounding temperature.

Figure 2(a) shows a schematic diagram depicting the configuration of the experimental enclosure assembled for this study. The experimental enclosure consists of plexiglass parts, including upper and lower plates, along with a cylindrical cavity. Within this arrangement, a centrally extended stainless-steel outer-threaded pipe, with a diameter of 12 mm, traverses through the upper plate and into the cavity. The jet or spray nozzle is attached to this outer-threaded pipe which is used to change the nozzle height. In this study, for the jet flow experiments, a nozzle with a 1mm exit diameter and for the spray tests, a conical spray nozzle with a 100^{o} spray angle is employed.

Below the nozzle, there exists an enclosed cavity housing a copper cylinder that performs as a heating element. Figure 2(b) presents a schematic of the copper cylinder. The copper cylinder consists of two main parts: a lower large column with a radius of 20mm and an upper small column with a radius of 10mm. To produce heat, the cartridge element is placed in the lower column from the bottom, and to regulate the heating power, a DC voltage regulator (Model: Laboratory DC power Supply GW Instek GPS-4303, Taiwan) is employed. The upper small column is designed to mimic high-power electronic components. The upper surface of the heating element, protruding through the top of the enclosed cavity, serves as the impingement surface that needs to be cooled. There are two k-type thermocouples for measuring temperature in the small column. The first one is located 1.5mm below the impingement surface, while the second one is positioned 10mm below the first. Mineral wool and polystyrene are used to fill the gap between the copper cylinder and the enclosed cavity, which minimizes heat dissipation.

Figure 2(c) depicts the storage tank used in the system. A control system is employed to keep the tank temperature constant at a desired value. This system constantly controls the temperature by a k-type thermocouple inside the storage tank. If the tank's temperature decreases, the 200-Watt AC element inside the tank is activated to bring the temperature back to the pre-established setting. Furthermore, when the tank's temperature increases, the cooling modules, which are thermoelectric type Tec 127-15, are activated to reduce the temperature of the tank and maintain it at the set level. To cool these modules, a combination of a fan, heat sink, and heat pipe is employed, and each module delivers a cooling capacity of 35 Watts.

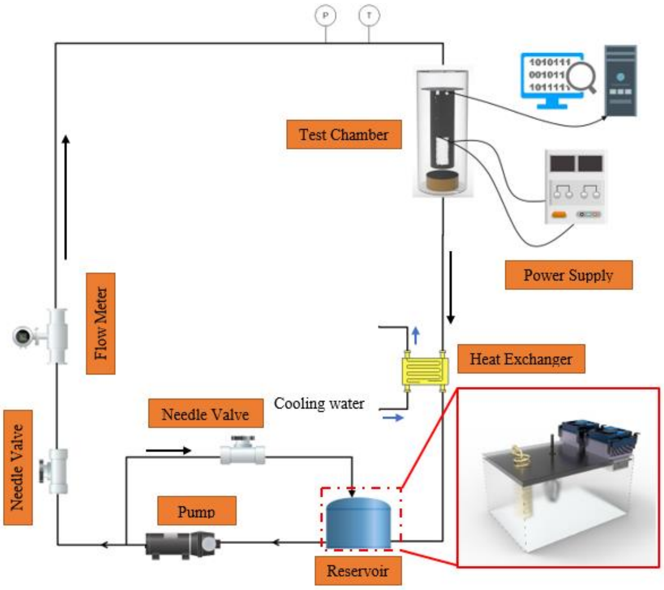

Figure 1: Flow chart of experimental system

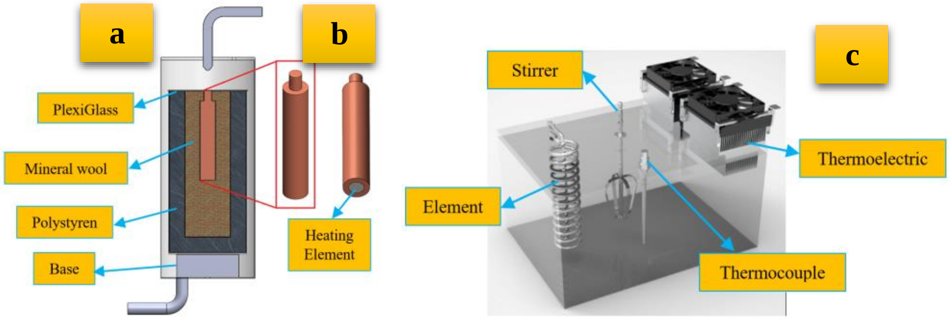

Figure 2: Schematics of (a) test chamber, (b) heating element and copper cylinder, and (c) reservoir.

3. Results and Discussion

The parameters reported in the succeeding results are calculated as follows. The heat flux (q'') is calculated based on the measured temperatures at two points in the small copper column located 1.5 and 11.5 mm below the impingement surface. Considering a linear temperature distribution in this column, the temperature of the impingement surface (T_s) can also be determined. Next, the convection heat transfer coefficient (h) is calculated by dividing the calculated heat flux by the difference between the surface temperature and the average temperature of the inlet and outlet fluid.

Figure 3 compares the convection heat transfer coefficient for jet and spray at two different flow rates. As observed, at a constant flow rate, a considerably better thermal performance of spray is obtained. On average, using a spray increases the convection heat transfer coefficient by 55% compared to that of a jet. It can be seen that in all investigated heat fluxes of 40, 60, and 80 W/cm^2, the use of spray has a higher convection heat transfer coefficient than liquid jet. Slight changes observed in the convection heat transfer coefficient against various heat fluxes may be attributed to the uncertainty in the measuring equipment and the repeatability of the experiments. In spray cooling, the overall surface area of liquid droplets exposed to heat and the dispersion of droplets over the entire surface enhances heat transfer. Moreover, the possibility of surface evaporation and heat absorption from the surface for droplet evaporation in spray cooling is significantly higher than that of the liquid jet cooling.

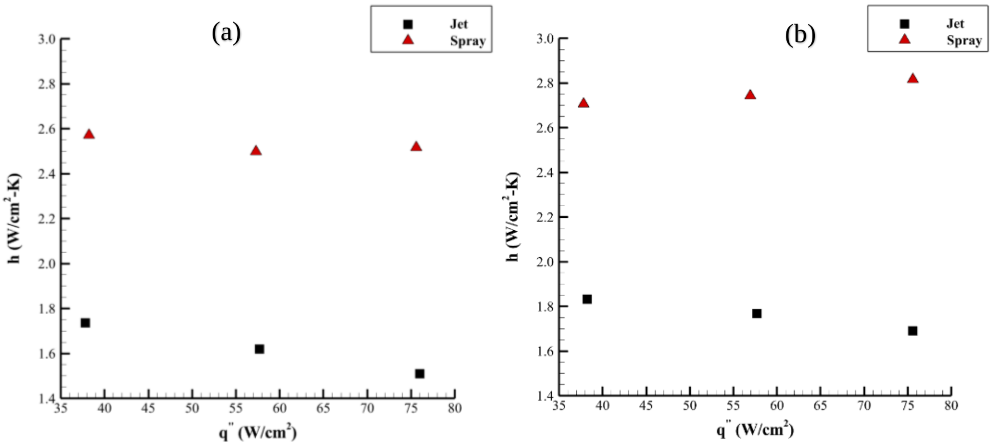

Figure 3: Convection heat transfer coefficient vs heat flux for jet and spray at a constant flow rate of (a) 140 ml/min, and (b) 180 ml/min.

Figure 4 illustrates the surface temperature vs. time for a constant heat flux of 40 W/cm^2 at two flow rates of 140 ml/min and 180 ml/min. The time evolution of the impingement surface

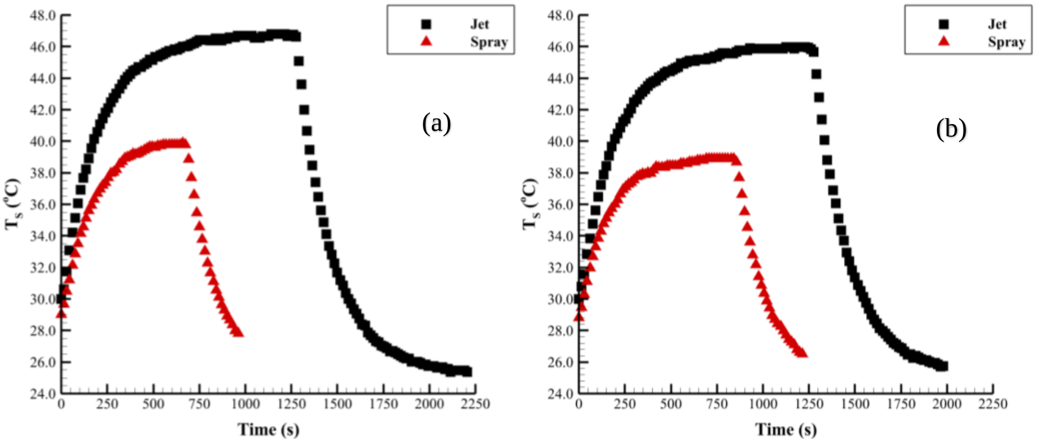

Figure 4: Surface temperature vs time for a constant heat flux 40 W/cm^2 at a constant flow rate of (a) 140 ml/min, and (b) 180 ml/min.

temperature for both jet and spray cooling is displayed in the figure. The results show that using the spray instead of the jet, reduces the temperature of the surface by 15.1%. As observed, using the spray not only reduces the surface temperature but also decreases the time required to reach the steady state, and also the cooldown time after the heat flux is suddenly turned off. It also reduces the time rate of surface temperature variations. The figure also shows that using a higher flow rate results in a lower surface temperature in both jet and spray cooling.

Figure 5 displays the effect of nozzle height (distance from the nozzle exit to the target surface) on spray and jet flow performance on cooling the surface. As observed for both jet and spray cooling modes, a decrease in the nozzle distance from the target surface leads to a slightly lower surface temperature which translates into a better cooling. Although, for the jet mode, the surface temperature in the steady state does not vary significantly with changes in the nozzle height from the target surface, in the case of using the spray mode, the nozzle height from the surface becomes a highly influential and essential parameter. If it is not positioned at an appropriate height, the cooling performance deteriorates even compared to the liquid jet (at a height of 4 mm). An increase in height from 2 to 4 mm causes a 40% increase in surface temperature. One of the reasons for the strong dependency of the cooling system's performance on the liquid spray is the variation in the positions of the points where droplets collide with the surface and the change in droplets momentum. Moreover, depending on the spray angle, the likelihood of droplet collision with the surface decreases with an increase in the nozzle height from the surface.

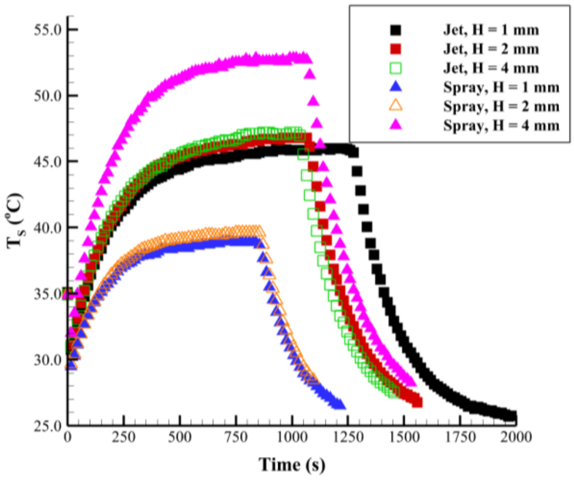

Figure 5: Effect of nozzle height on spray and jet cooling

4. Conclusions

This study compared the effect of using a jet flow or a liquid spray on convection heat transfer coefficient and surface temperature in an impingement cooling system. Based on the results at the same heat flux and flow rate, the convection heat transfer coefficient increases by approximately 55%. The findings of this study reveal that when subjected to the same heat flux and flow rate, the application of spray leads to a decrease in the steady temperature of the impingement surface and reduces the time required to reach that temperature. Furthermore, using spray also lowers the rate of variations in the impingement surface temperature.

Through this study, it was found that rising the nozzle height makes surface temperature increases. Although this change in the nozzle height does not considerably affect the jet thermal performance, it has a significant effect on the spray cooling. When the height increases from 1 mm to 2 mm, the surface temperature of the jet part experiences a slight increase. However, as the height is further increased from 2 mm to 4 mm, there is a significant 40% rise in the surface temperature. This phenomenon is associated with a reduced probability of droplet collisions, which, in turn, is influenced by the spray angle.

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