

Experimental investigation of the thermal performance of impinging jet cooling in electronic component cooling

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Abstract

Fluid impingement jet cooling is considered a suitable solution for the thermal management of electronic components such as microprocessors with high production heat fluxes, to prevent damage and malfunction of these types of equipment. In this experimental research, the effective factors on the performance of an impinging jet cooling device with dual surface side exits were investigated experimentally. With the help of the Taguchi optimization method, the effects of the jet nozzle diameter and its height from the cooling surface at the same flow rate and water-ethylene glycol joint fluid in three different heat fluxes were investigated in this set-up, and the most optimal operating mode of the device was seen the results collected by several thermocouples were presented as stable temperatures of the cooling surface and fluid. The obtained results showed that the way the fluid flow exits can play a role in the influence of the mentioned parameters.

Keywords:

Cooling of electronic components, Fluid impingement jet, Taguchi optimization, Surface side exits, Microprocessors

Introduction

With the advancement of electronic technologies, there is a growing need for microprocessors with improved and quicker performance, which will increase production heat flux and, as a result, the danger of device damage and malfunction [1]. According to studies undertaken by the US Department of Defense [2] on estimating the dependable temperature range for the appropriate operation of microprocessors, the proper temperature for processor operation has been established as less than 75 degrees Celsius.

Forced air convection cooling is still the most prevalent way of cooling electronic components since it eliminates the need for pipes and auxiliary complicated equipment such as pumps and it is economically efficient [4,3]. However, as the number of electrical devices grows, so

does the amount of heat produced by these devices, leaving these systems incapable of cooling the CPUs¹. In response, scientists developed more technologically advanced cooling techniques, the majority of which concentrate on lowering the thermal resistance of cooling apparatuses by employing strategies such as substituting liquid fluid for air fluid. Heat pipes, microchannels, and jet and spray impingement coolers are a few examples of these devices [6, 5].

The fluid jet cooling method involves shooting the fluid through one or more nozzles at high speed before hitting the target plate for cooling. The most typical way of jet collision is to utilize a single jet, as there is no risk that its flow may interfere with the flow of other jets. However, the jet impact angle will remain a significant factor in thermal performance. A 90-degree angle is appropriate for ensuring that the cooling effects of the impinging fluid are symmetrical in all sections of the plate. The ratio of the nozzle diameter to the height of the surface is another factor that can be looked into. This indicates that as the nozzle gets farther away from the cooling surface, the impact of the jet decreases, and losing this much momentum in the fluid can result in the loss of potential heat transfer from impinging jets. The way the fluid flows out and the type of chamber design can affect these factors, though [7].

Martin [8] states that a fluid impingement jet typically consists of three main areas: 1. The departure segment of the flow from the nozzle to the point of impact where the flow's speed is greater than the speed of its surroundings; Now, if the surrounding environment is the jet fluid itself, it is referred to as a submerged jet, and if it is the air inside the chamber, it is known as a free stream jet. 2. A collision zone up to the hydraulic jump point. In this zone, the largest heat transfer with the fluid occurs because of the thin thermal and hydraulic boundary layers caused by the drop in axial velocity and increase in radial velocity. 3. The area after the hydraulic jump to the outlet sees a sharp decline in heat transfer as the radial fluid velocity drops and the boundary layers thicken.

Salem et al. [9] conducted an experiment to assess the impact of nozzle geometry on jet cooling performance.

¹ central processing unit (CPU)

They compared three circular nozzles with differing chamfered edges to a square-edged nozzle at five different Reynolds numbers. They determined that the changing geometry had no obvious effect on the local Nusselt number in the flow direction. They also discovered that the nozzle with square edges had the highest average Nusselt number when compared to the other nozzles evaluated.

Baghel et al. [10] examined the effects of an inclined free surface liquid jet at four distinct angles (0, 15, 30, 45 degrees) under four different Reynolds numbers on a flat surface using both experimental and computational methods. They indicate that for angles larger than 30 degrees and Reynolds values greater than 25611, the Nusselt number will grow. Another discovery of his study team was that the maximum value of the local Nusselt number reduces from zero to 15 degrees and then grows as the angle increases.

In a similar experimental approach to this research project, Stevens and Webb [11] investigated the effects of an axially symmetric water jet impinging on a smooth, stationary circular thermal plate, with fluid outflow possible from all directions around the plate. Afterward, the effects of nozzle height and diameter on changes in local heat transfer coefficients were determined. This study found that extending the distance between the nozzle and the plate somewhat decreased heat transmission in the range of 0 to 1.5 nozzle diameter to plate diameter and that decreasing the nozzle diameter had a higher effect on raising the local Nusselt number.

The next section includes the construction of an experimental setup for investigating the impact of the nozzle height and diameter variables on thermal performance, as well as an examination of their interactions with the kind of flow exit from the side outlets. It is anticipated that after the experiment, we will identify the device's best-performing conditions at the highest heat flux employed.

Experimental setup

1. design

The major component of the jet cooling setup, as shown in Figure 1, is a copper plate that is 6 by 5 square centimeters in size and 0.2 mm thick. It is linked to a ceramic plate heater using silicone paste. As per Figure 2(b), a k-type thermocouple with a measurement error of 1.1 °C is used to measure the temperature beneath the copper plate. The thermocouple is placed two centimeters away from one corner of the plate. Additionally, the same kind of thermocouples is used to monitor the three temperatures of the fluid's entrance and output as well as the wall of the jet device. A brass jet nozzle is set at a particular height from the plate, allowing the incoming flow to hit the copper plate at a steady volume rate of 8 liters per hour. This flow is regulated via a control valve and a flow meter with an inaccuracy of 0.5 liters per hour.

The diaphragm pump which have respective powers of 30 W and 4.8 W are utilized for suction and blowing in the circulation system. In order to preserve the health and effectiveness of the blower pump, a return flow channel to the tank is taken into consideration. A radiator that operates at an ambient temperature of 25 degrees Celsius is utilized to maintain the temperatures mentioned in each test.

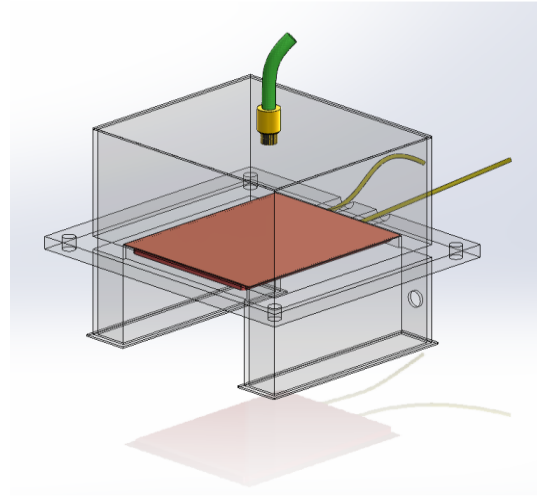


Figure 1: Overview of the jet cooling device

Throughout an average of 20 minutes, the temperature outcomes of three different nozzle heights 25, 15, and 10 mm and diameters 0.6, 0.8, and 1 mm were investigated from the plate in each experiment. The heat fluxes used were 20,000, 35,000, and 50,000 W/m². It should be mentioned that a 20% volume ratio of water to ethylene glycol is utilized in each test; this was done to avoid sedimentation in the radiator and nozzle.

2. Taguchi method

Taguchi's approach was used to identify their number and order in these experiments. The Taguchi method-based experiment design provides us with several advantages [12]; 1. Cutting down on the number of tests to find the ideal levels to save money and time. 2. Figuring out how the factors under investigation affected the experiment. 3. Forecasting of more and uncharted tests.

The Taguchi technique uses a loss function called the signal-to-noise ratio (S/N) to calculate the difference between the experimental and intended values. Taguchi proposes three types of signal-to-noise ratio: greater is better, smaller is better, and minimal changes, which are appropriate for the fluid jet impingement process in this experiment, which strives to achieve the lowest plate temperature. Based on this situation, the loss function equation is as follows [13]:

$$\frac{S}{N} = -10 \log \left(\frac{1}{n} \sum_{i=1}^n Y_i^2 \right) \quad (1)$$

In this equation, S/N represents the signal-to-noise ratio for each experiment, n is the number of repetitions, and Y_i is the quality-measurement characteristic. Thus, Table 1 represents the design and execution of the Taguchi technique experiments.

3. Validation

Experimental science places a particular value on statistical computations, error, and uncertainty. These elements enhance the validity and analytical ability of the test results and contribute to a more accurate analysis. Using these techniques for error evaluation is the step that enables us to examine experiment data more accurately and offer a more reliable interpretation.

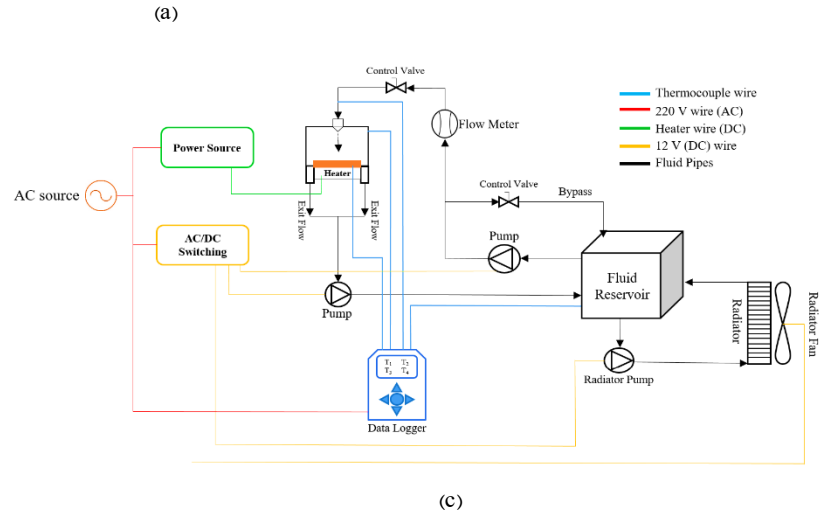
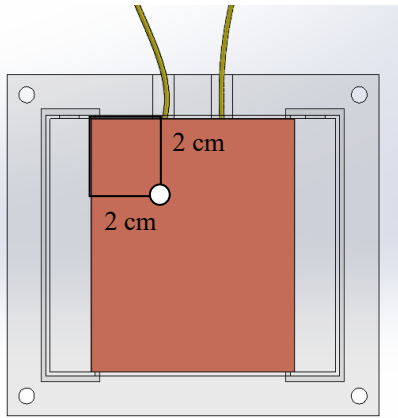
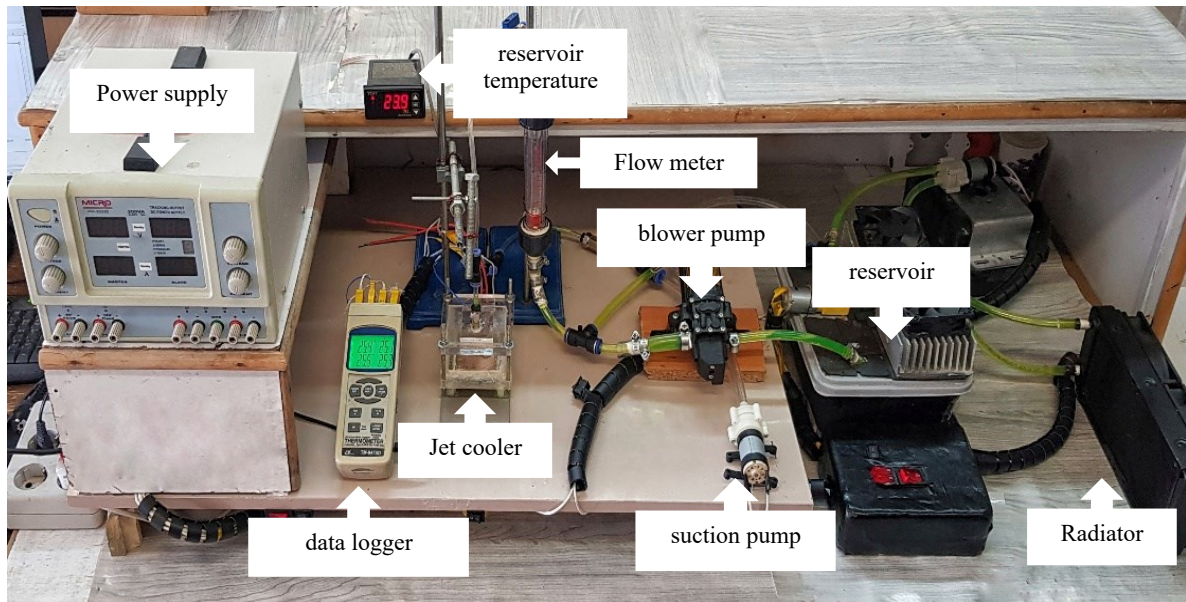


Figure 2: (a) Overall view of the jet cooling set-up cycle; (b) installation location of the plate temperature measurement thermocouple. (c) setup diagram

Table 1: Arrangement and outcomes of experiments using the Taguchi technique

experiment	Nozzle diameter (mm)	Height (mm)	heat flux (W/m ²)	steady temperature of the plate (°C)
1	1	25	50000	64
2	1	15	35000	52
3	1	5	20000	40
4	0.8	25	35000	50
5	0.8	15	20000	42
6	0.8	5	50000	62
7	0.6	25	20000	38
8	0.6	15	50000	62
9	0.6	5	35000	52

Table 2 shows the standard uncertainty and probable error of the maximum and average readings obtained from the repetition of these three tests for their steady temperature. These steps were taken to validate the test. First, we checked the maximum and average uncertainty for three test repetitions of a 1 mm nozzle with a height of 25 mm under a heat flux of 50,000 W/m². The following equations were utilized in the calculation of these values:

3.1. standard deviation:

The following equation was used to calculate the standard deviation due to the low number of data:

$$S = \sqrt{\frac{\sum_{i=1}^n Y_i^2}{n-1}} \quad (2)$$

In this equation, Y_i is the temperature data and n is the number of data.

3.2. Possible reading error:

$$PE_1 = 0.6745 \times S \quad (3)$$

3.3. Standard uncertainty due to repetition of the experiment:

$$u_{st} = \frac{S}{\sqrt{n}} \quad (4)$$

Table 3 also includes values for the tool's error and uncertainty. The uncertainty of each measurement equipment is estimated using the formula below:

$$u_{tool} = \frac{a}{\sqrt{3}} \quad (5)$$

In this relationship, a is half of the measurement accuracy.

Table 2: Standard Uncertainty and Probable Error of the Maximum and Average Readings Resulting from Repeating Three Tests of a 1mm Nozzle with a Height of 25 mm under a Heat Flux of 50,000 W/m²

value	Average	Maximum
standard uncertainty	0.80766905	1.00166528
Possible reading error	0.943574123	1.170213764

Table 3: Uncertainty and possible error of equipment measurement

value	Flow meter	Electric voltage	electricity flow	Thermocouple
error	0.5 (L/H)	0.05 (V)	0.005 (A)	1.1 (°C)
uncertainty	0.288675	0.02886	0.00288	0.635081

Finally, the highest and average overall uncertainties for the experiments' dependable temperature are 1.186029792 and 1.03479, respectively. This value is determined based on the following relationship:

$$u_{total} = \sqrt{u_{tool}^2 + u_{st}^2} \quad (6)$$

Results and Discussion

Looking at the graph of the acquired data (for example, Figure 3), it is obvious that, on average, in each of the experiments, all temperatures are very close to their steady value after about 5 minutes. In this diagram, the measured temperatures are as follows: T_1 is the temperature of the plate, T_2 is the temperature of the device wall, T_3 is the temperature of the inlet fluid, and T_4 is the temperature of the outlet fluid. The temperatures continue to climb rather slowly because

the heated fluid takes roughly 1000 seconds to circulate through the device's cycle and enter the reservoir. Table 1 shows that the screen temperature remained steady below 75 degrees Celsius in all circumstances.

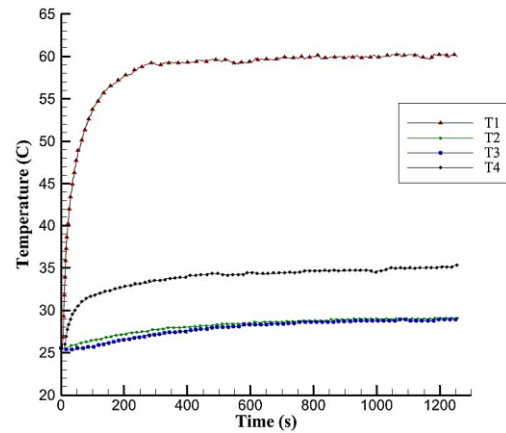


Figure 3: Temperature graph in terms of time in the test of 1 mm nozzle, 25 mm height and heat flux of 50,000 W/m²

By analyzing the constant temperature obtained from the experiments using Taguchi simulation in Minitab software. According to what is shown in Figure 4, which shows the amount of signal to noise for each of the factors affecting the cooling of the jet. As expected, the reduction in nozzle diameter was one of the positive factors in cooling. Its contribution in increasing the speed of the fluid in contact with the plate is the reason for this. Reducing the height of the fluid from the surface has also been one of the positive factors of cooling.

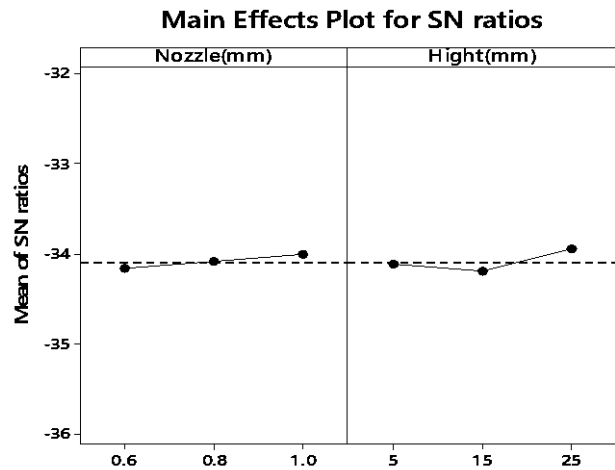


Figure 4: Diagram of the temperature effect of each of the factors affecting the test, based on the selected plan, the lower value is better.

In comparison with a free-flow jet [11], the exit fluid can freely depart the screen in any direction. However, because the device used in this experiment had dual side outputs, some of the fluid flows back from the wall has also made the effect of reducing the height of the nozzle from the surface less than 15 mm less noticeable. It is anticipated that the return flow after striking the walls

would rise as the height of the nozzle reduces and as a result of the increased impact momentum and speed upstream of the flow on the surface. The observation of Figure 5 makes it visible that these return flows have the ability to change the area before the hydraulic leap from circular to elliptical, which effectively lowers the quantity of heat transfer in this region and, consequently, lowers the nozzle's height. So, it can be concluded that the way the jet fluid flows out is effective in its cooling performance.

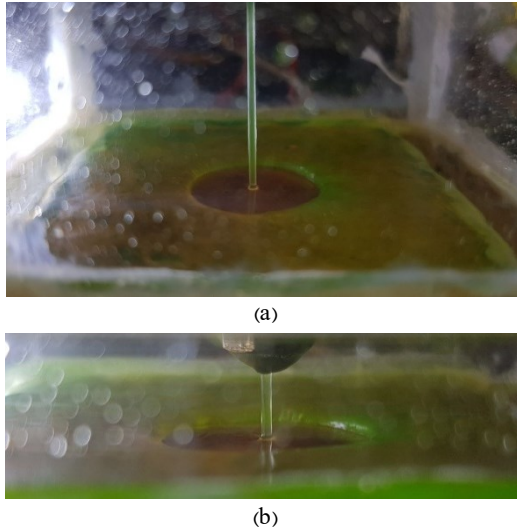


Figure 5: A view of the impact jet with a 0.6 mm nozzle at two heights (a) 25 mm and (b) 5 mm

In the end, the most efficient operating mode with the largest heat flux could be determined by using the ability to anticipate the Taguchi method. This state included using a 0.6 mm nozzle at a height of 5 mm, and the temperature obtained in this mode was introduced as 61.5 degrees Celsius.

Conclusions

In the study, an experimental investigation was conducted to determine the impact of effective factors on the impinging fluid jet's heat transfer and how these factors interacted with the device housing design under three heat flux conditions, with a maximum value of 50,000 W/m². The nozzle's diameter and height from the surface serve as a summary of those factors. The experiments were designed using Taguchi's optimization method, which allowed for the ultimate prediction of each factor's impact and the device's most efficient working mode. Here is an overview of the outcomes that were attained:

- There is an effective increase in heat transfer when the nozzle's diameter is reduced.
- Reducing the nozzle height from the surface is thought to improve cooling effectiveness, however, in this case, the existence of fluid return flows from the wall has a detrimental impact on this process.
- The device is anticipated to operate in its optimal mode at 61.5 degrees Celsius, with a nozzle diameter of 0.6 mm and a height of 5 mm.

Nomenclature

S/N: Signal to noise in Taguchi method
 S: standard deviation
 Y_i: The data examined in the Taguchi method
 PE₁: Possible reading error
 u_{st}: Standard uncertainty
 u_{tool}: Tool uncertainty
 a: Tool measurement error
 u_{total}: Total uncertainty

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