International Journal of Future Engineering Innovations

# Convective chilling and heat transfer for different arrays of impinging jets

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## Article Info

**ISSN (online):** 3049-1215
**Impact Factor (RSIF):** 8.25
**Volume:** 03
**Issue:** 03
**May-June 2026**
**Received:** 25-02-2026
**Accepted:** 25-03-2026
**Published:** 28-04-2026
**Page No:** 11-19

**Abstract**
This paper investigates convective chilling and heat transfer characteristics for twelve different round jet array configurations impinging on a heated silver plate. The arrays, ranging from 3×3 to 12×12 with jet diameters between 0.5 mm and 1.7 mm, were tested at five volume flow rates (0.0000167 m³/s to 0.0003 m³/s) at a constant jet-to-target distance of 1.30 mm using an air jet impingement apparatus. For each pair of arrays with identical size, number of jets, and spacing, the array with the smaller jet diameter (0.5 mm) consistently achieved superior convective cooling and higher heat transfer coefficients compared to the larger-diameter array. For example, the 12×12 array with 0.5 mm jets cooled the target surface to temperatures as low as 20.25°C with a heat transfer coefficient of 98,765 W/m²°C at the highest flow rate, outperforming the 12×12 array with 1.7 mm jets under identical conditions. Furthermore, increasing the flow rate improved both chilling effectiveness and heat transfer coefficient across all configurations. These findings demonstrate that smaller jet diameters provide more effective impingement cooling for electronic thermal management applications.

**DOI:** https://doi.org/10.54660/IJFEI.2026.3.3.11-19

**Keywords:** Air jet impingement, jet-to-target distance, jet diameter, heat transfer coefficient, infrared thermometer

## 1. Introduction

When it comes to achieving a high heat/mass transfer rate on a surface, jet impingement works really well. Large heat fluxes may be extracted from high temperature components more effectively using the jet impingement approach (Ewe et al., 2022) [5]. For many years, jet impingement cases have been of interest. Impingement cooling is a method of cooling in which a cooling medium is sprayed in the form of a jet onto the surface of the cooled component in order to remove heat (Masip et al., 2020) [7]. Impinging jets can use any type of liquid or be driven by air. Dissipation of heat has become a common cause for the thermal runway and breakdown of several electronic devices (Tabassum et al., 2022) [12]. To effectively use these devices, it is required to extract heat from the dissipating parts. It is of utmost importance to maintain the electronic device temperature below a specified limit, as overheating may lead to performance degradation, and device failure. For achieving higher computing efficiency, the devices must be operated in conformity to the thermal safety guidelines. Traditional air-cooling methods often fail to transfer the heat produced by such devices; this impairs the reliability and lifetime of the devices. Badr et al (2020) [3] disclosed that multiple jet impingement is a widely implemented convective process for enhancing heat transfer over target surfaces. Applications of impinging jets include cooling of gas turbine blades and outer walls of combustion chambers, cooling of heated computer and electronic components, chilling in the food industries, cooling in the paper industries, tempering of glass, processing of some metals and glass, etc. Ren et al (2021) [10]. Numerous studies have been reported on round jet impingement heat transfer characteristics in an array of multi jets.

Niranjan et al., (2018) [9] investigated jet impingements cooling with multiple jets on a virtual microelectronic chip. In this investigation an experimental study of cooling capabilities of impinging air jet array is presented. Investigations were carried out using electrically heated test plate.

Heat flux in the range of 25 to 200W/cm$^2$, which is a typical requirement for cooling high power electronic components was dissipated using 0.5mm and 2mm diameter air jets arranged in $7 \times 7$ array with a pitch of 3mm. Tests were performed in the Reynolds number range of 1200 to 4500. Result shows higher values of heat transfer coefficient are obtained with the lower diameter jets.

A multi-jet impingement cooling design was investigated experimentally and numerically by Schroll et al. (2022) [14]. Heat transfer and flow are examined in relation to the jet Reynolds number (Re = 120-180). To produce a consistent heat flux on the flat surface, an electrically heated gold film intrex- extremely thin polyester substrate sheet coated with gold is utilized. Thermochromic liquid crystals and a digital color image processing system are used to measure the surface temperature. The local Nusselt numbers along the surface are then ascertained using captured color images of liquid crystals. The Nusselt number grows between Re = 120 and Re = 140, abruptly decreases at Re = 150-160, and then increases once again beyond Re = 160, according to the results, which exhibit an unusual trend. A sinusoidal oscillation of the jet flow could be the cause of this abrupt decrease in Nusselt number at about Re = 150–160.

Dae et al., (2020) [4] studied the jet diameter effect on the fluid flow and heat transfer. A single round turbulent air jet was used for this study. At the nozzle exit the flow has a fully developed velocity profile. The uniform heat flux boundary is created at the plate surface and the liquid crystals were used to measure the surface temperature of the plates. The following are the range of parameters used for the study, the distance between test plate surface to jet exit (Z/d) between 2 to 14, jet diameter from 1.36 to 3.4 cm and Reynolds number of 23000. In the stagnation point region corresponding to $0 \leq (r/d) \leq 0.5$, the Nusselt number increases with increase in jet diameter. It was observed that in the wall jet region corresponding to (r/d) =0.5, the effect of jet diameter on the local Nusselt number is very small. Increase in the intensity of turbulence and jet momentum with the larger jet diameter increases the heat transfer co-efficient.

Limaye (2021) [6] investigated influence of jet temperature and nozzle shape on the heat transfer distribution between a smooth plate and impinging air jets. Experiments are performed to study the effects of nozzle shape, jet temperature and nozzle to distance (z/d e) on heat transfer distribution due to impingement of air jet on a smooth flat plate. Thin metal foil technique is employed in this study for measuring local wall temperature. Influence of jet temperature (70e175 C) on local heat transfer and effectiveness is studied for different Reynolds numbers (5000 e23,000) and jet to plate distances (1e10) for circular jets. Influence of nozzle shape (circular, square and triangular) on local heat transfer distribution and effectiveness is studied for Reynolds number of 10,000 and 23,000 at different jet to plate distances. Reynolds number is calculated on the basis of equivalent diameter (10 mm). Nusselt number measured based on equivalent diameter is the highest for a circular nozzle in comparison with square and triangular nozzles. The effect of jet temperature on heat transfer is found marginal and axis switching is observed for non-circular jets.

Senol (2021) [13] studied the role of jet inlet geometry in impinging jet heat transfer, modeling and experiments. Effects of jet inlet geometry and aspect ratio on local and average heat transfer characteristics of totally nine confined impinging jets have been investigated experimentally using thermochromic liquid crystals and numerically by using a 3-D low Reynolds number ke3 model. Experimental study by using liquid crystals for temperature measurement was conducted for three different jet exit geometries (circular, elliptic, rectangular). In addition, simulations were performed at the same mass flow rate for totally nine jet exit geometries including circular, elliptic and rectangular jets with different aspect ratios for dimensionless jet to plate distances 2, 6, and 12. As the aspect ratio of equal cross-sectional area elliptic and rectangular jets increases, heat transfer enhancement in the stagnation region was obtained. As a result, higher aspect ratio jets can be used as a passive enhancement technique for localized heating or cooling especially at small jet to plate distances. Wall jet region comprises very large portion of the impinging plate under study and generally lower heat transfer rates were attained for higher aspect ratio jets in this region especially at small jet to plate distances. Therefore, as the aspect ratio increases, lower average heat transfer rates were acquired. The effect of aspect ratio on local and average heat transfer decreases with increasing jet to plate distance. Even though the mass flow rate is the same, heat transfer rate of rectangular jets was reduced with increasing the cross-sectional area. With increasing the separation distance between the jet and plate very similar heat transfer characteristics were observed along the major and minor axis directions.

Mohammad (2021) [8] examined computational study of multiple impinging jets on heat transfer.

This numerical study presents investigation of impinging jets cooling effect on a hot flat plate. Different configuration of single jet, 5-cross and 9-square setups have been studied computationally in order to understand about their behavior and differences behind their physics. Moreover, a specific confined wall was designed to increase two crucial parameters of the cooling effect of impinging jets; average heat transfer coefficient of impingement wall and average air temperature difference of outlet the domain and jet inlet. The 2-D simulation has been performed to design the confined wall to optimize the domain geometry to achieve project goals contains highest average heat transfer coefficient of hot plate in parallel to highest average air temperature difference of outlet. Different effective parameters were chosen after 2-D simulation study and literature review; Jet to wall distance H/D = 5, Radial distance from center of plate R/D = 20, jet diameter D = 10 mm. The 3-D computational study was performed on single jet, 5-cross and 9-square configurations to investigate the differences of results and find best setup for the specific boundary condition in this project. Single jet geometry reveals high temperature level in the outlet, but very low average heat transfer coefficient due to performance of a single jet in a domain (Re= 17,232). In the other side, 5-cross setup has been studied for Reynolds number of 9,828, 11,466, 17,232 and 20,000 and it was found that range of 11,466 to 17,232 performs very well to achieve the purposes in this study. Moreover, turbulence models have been used to verify the models (Re=17,232) with available experimental data for fully developed profile of the jets inlets and wall jet velocity and Reynolds stress components near the wall boundary condition. All three turbulence models predict well the velocity components for jets fully developed profile and for wall boundary condition of the target plate. But since model has been validated with the Reynolds stress components by experimental data, therefore is more reliable to continue the study with verified simulation. Finally, 9-

square configuration was investigated (Re=17,232) and the result compared with other setups. It was concluded that 5-cross multiple jets is best design for this project while 9-square multiple impinging jets also fulfils the project purpose, but for extended application in industry each setup is suitable for specific conditions. 5-cross multiple jets is good choice for large cooling area which can be used in number of packages to cover the area, while 9-square jets setup performs well where very high local heat transfer is needed in a limited area.

Sadek (2020) [11] researched on the thermal behavior of a turbulent impinging jet issuing from a nozzle with chevrons. A three-dimensional turbulent steady-in-the-mean round jet issuing from a nozzle and impinging on a heated flat plate is investigated numerically. The effects of the nozzle geometry and nozzle-to-plate distance on the dynamical and thermal behaviors are explored. Three nozzle geometries are considered: a circular nozzle, and nozzles with 4 and 6 chevrons. Three nozzle-to-plate distances are studied: H/D = 2, 4 and 6. The Reynolds number is fixed and equal to 5000 for all the flow cases. The results show that the chevrons improve the heat transfer near the area of stagnation. This improvement can reach up to 110% in specific regions. Such enhancement is probably due to the relatively intense turbulence observed in the vicinity of the stagnation region when a nozzle with chevrons is used. It is also found that the wall heat flux is appreciably non-uniform for the small nozzle-to-plate distance H/D = 2. Increasing the distance to H/D = 6 yields a somewhat axisymmetric thermal behavior.

Amina (2022) [1] investigated numerical simulation of heat transfer in an axisymmetric turbulent jet impinging on a flat plate. Computational study of the impingement of a thermally turbulent jet on a solid plate, using k e model, is reported. The possibility of improving the heat transfer is carried out according to the characteristic parameters of the interaction jet-wall. The close zone solid wall required a particular treatment using an economic method known as quot; wall functions quot;. The numerical resolution of the equations is carried out using the finite volume method. For a fixed nozzle–plate distance, the influence of the Reynolds number on the stagnation point heat transfer is investigated. Good agreement with experimental results is observed. The influence of the nozzle–plate distance on the stagnation point Nusselt number is also discussed.

## 2. Materials and Method

### 2.1. Materials

The materials used were copper plate of size 30mm x 30mm and thickness 1mm, heating element of capacity 1.8KW, air cylinder of volume 40m$^3$, 0.5hp centrifugal blower, PVC pipe of ¾ inch diameter, aluminum plate of thickness 1mm, strain gage-type pressure transducer of 5mA, 3Vdc, infrared thermometer (FLIR Lepton 3.0) and gage valve.

#### 2.1.1. Experimental Apparatus

An experimental apparatus consists of a heater assembly, a 0.5hp centrifugal blower, an air cylinder, PVC pipe, jet nozzle plate, flow control valves, pressure transducer, and infrared thermometer.

A plane jet of air impinging on a heated smooth flat surface is produced by the apparatus shown in plate 1. The jet emerged from a circular nozzle (30 mm diameter). The target surface which represents the surface of a typical electronic device was made of silver, of dimensions 30mm x 30mm and thickness 1mm and is heated using the heater of capacity 1.8KW. Silver is selected because of its high thermal conductivity. Jet nozzle plates having 0.5mm, 0.7mm, 0.9mm, 1.1mm, 1.3mm, 1.5mm, and 1.7mm diameter jets were used. The jets are laser drilled and arranged in a square array of $12 \times 12$, $9 \times 9$, $8 \times 8$, $6 \times 6$, $4 \times 4$, and $3 \times 3$. The distance between the jet nozzle plate and the test plate surface is maintained at 1.30mm. The air flow rate, and impingement plate were varied during the experiments.

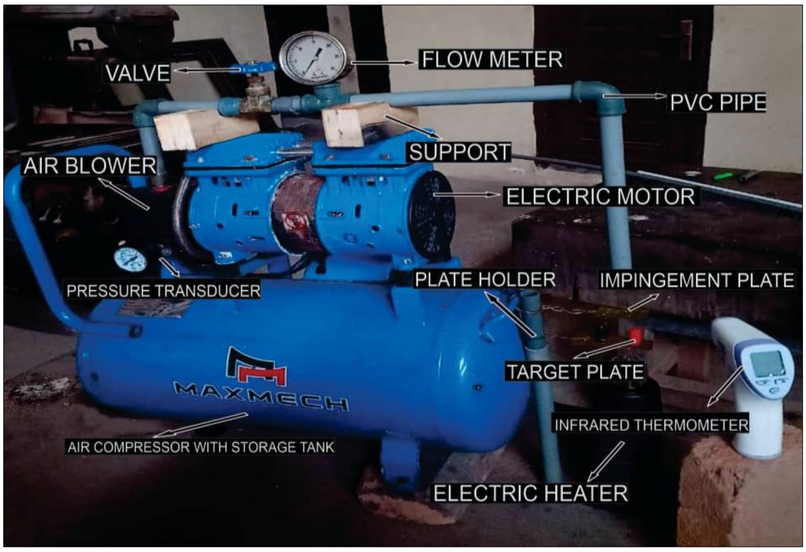


**Fig 1:** Experimental apparatus

Heat Transfer Measurement and Quantification

The heat transfer coefficient at the heated surface is giving as (Amjadian et al., 2020)

$$h = \frac{Q}{A\Delta T} = \frac{Q}{A\left(T_{s-T_j}\right)} \quad (1)$$

Where, h is heat transfer coefficient (W/m$^2$ $^o$C), Q is heat transfer in Watts, A is heat transfer surface area {m$^2$), $T_s$ is target surface temperature ( $^o$C), $T_j$ is the jet temperature ($^o$C),

### 2.1.2. Array geometries

The array geometries are listed in table 1 while their diagrams are shown in figure 1.

**Table 1. Array geometries In each pair of arrays, the jet spacing is same likewise the array size but their jet diameters vary.**

| Plate no | Array | d (mm) | s (mm) | l (mm) |
|---|---|---|---|---|
| 1 | 12 × 12 | 0.5 | 2.73 | 30 |
| 2 | 12 ×12 | 1.7 | 2.73 | 30 |
| 3 | 9 × 9 | 0.5 | 3.75 | 30 |
| 4 | 9 × 9 | 1.5 | 3.75 | 30 |
| 5 | 8 × 8 | 0.5 | 4.29 | 30 |
| 6 | 8 × 8 | 1.3 | 4.29 | 30 |
| 7 | 6 × 6 | 0.5 | 6 | 30 |
| 8 | 6 × 6 | 1.1 | 6 | 30 |
| 9 | 4 × 4 | 0.5 | 10 | 30 |
| 10 | 4 × 4 | 0.9 | 10 | 30 |
| 11 | 3 × 3 | 0.5 | 15 | 30 |
| 12 | 3 × 3 | 0.7 | 15 | 30 |

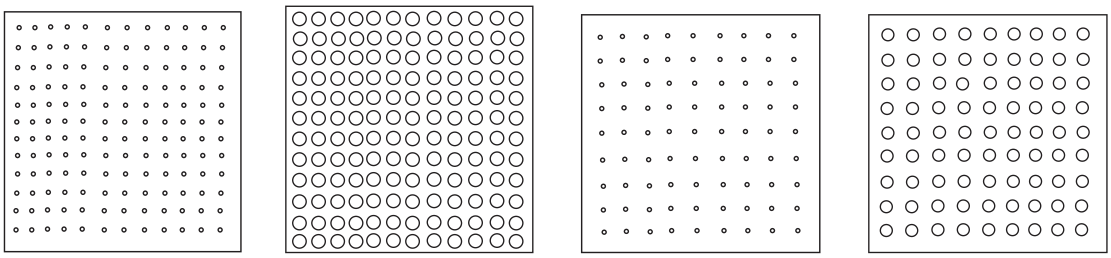

Plate 1: $12 \times 12$ ($d = 0.5mm$). Plate 2: $12 \times 12$ ($d = 1.7mm$). plate 3: $9 \times 9$ ($d = 0.5mm$). Plate 4: $9 \times 9$ ($d = 1.5mm$)

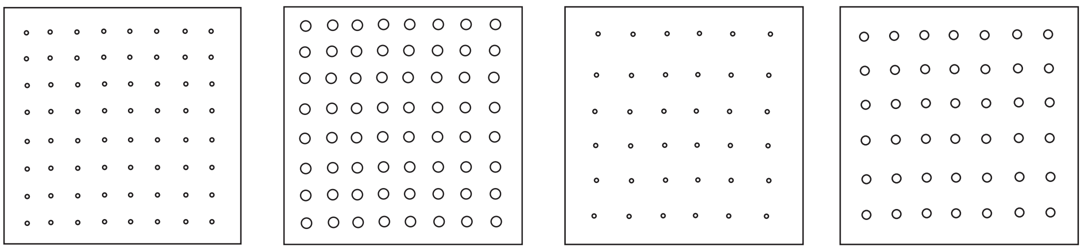

Plate 5: 8× 8 ($d = 0.5mm$) Plate 6: 8× 8 ($d = 1.1mm$) Plate 7: 6× 6 ($d = 0.5mm$) Plate 8: 6× 6 ($d = 1.1mm$)

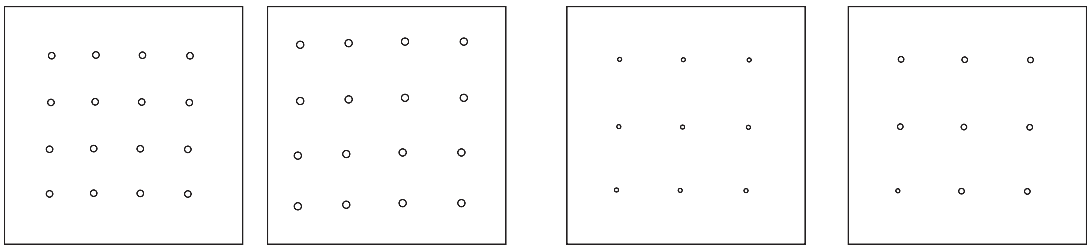

Plate 9: 4 × 4 (d=0.5mm). Plate 10: 4 × 4 (d=0.9mm). Plate 11: $3 \times 3$ ($d = 0.5mm$) Plate 12: $3 \times 3$ ($d = 0.7mm$)

**Fig 1:** Array of different jet diameters and jet spacings

Plates 1 and 2, plates 3 and 4, plates 5 and 6, plates 7 and 8, plates 9 and 10, plates 11 and 12 have array of $12 \times 12$, $9 \times 9$, $8 \times 8$, $6 \times 6$, $4 \times 4$, and $3 \times 3$ respectively. Each array is of size 30mm..Plate 1 and 2 have jet diameters of 0.5mm and 1.7mm respectively with jet spacing 2.73mm, plates 3 and 4 have jet diameters of 0.5mm and 1.5mm respectively with jet spacing 3.75mm, plates 5 and 6 have jet diameters of 0.5mm and 1.3mm respectively with jet spacing 4.29mm, plates 7 and 8 have jet diameters of 0.5mm and 1.1mm respectively with jet spacing 6mm, plates 9 and 10 have jet diameters of 0.5mm and 0.9mm respectively with jet spacing 10mm and plates 11 and 12 have jet diameters of 0.5mm and 0.7mm respectively with jet spacing 15mm. The arrays were tested to determine their convective chilling and heat transfer performances at flow rates of 0.0000167m$^3$/s, 0.0002m$^3$/s, 0.00023m$^3$/s, 0.000266m$^3$/s , and 0.0003m$^3$/s.

### 2.2. Experimental Procedure

We started by hanging a 12 × 12 array with jet diameter and jet spacing of 0.5mm and 2.73mm respectively on an aluminium holder at a jet-to-target distance of 1.30mm, and connected the heating element to the power to supply heat at the bottom side of the plate and the blower was turned on to impinge air on the smooth and flat target plate. We ensured that air was regulated to the desired flow rate using gate valve. We captured the jet temperature, $T_j$ before the air impinges on the target plate and captured also the surface temperature, $T_s$ after the target plate had reached a steady state using infrared thermometer. Temperature change, ΔT that is ($T_s - T_j$) was calculated.

We continued the experiment till every array listed in table 1 was tested at flow rates of 0.0000167m$^3$/s, 0.0002m$^3$/s, 0.00023m$^3$/s, 0.000266m$^3$/s, and 0.0003m$^3$/s. At each test performed, the required parameters were noted and calculated.

### 3. Results and Discussion

Figures 2a, 3a, 4a, and 5a are the plots of temperature rise of the silver plate versus jet diameters while figures 2b, 3b, 4b, and 5b are the plots of heat transfer coefficient against jet diameter at flow rates of 0.0000167m$^3$/s, 0.0002m$^3$/s, 0.00023m$^3$/s, 0.000266m$^3$/s, and 0.0003m$^3$/s respectively. The blue bars are array with jet diameter 0.5mm, the black bars are array with jet diameter 1.7mm, the dark orange bars are array with jet diameter 1.5mm, the yellow bars are array with jet diameter 1.3 mm, the green bars are array with jet diameter 1.1mm, the red bars are array with jet diameter 0.9mm and the purple bars are array with jet diameter 0.7mm. Results showed that in the pair of arrays, the blue bars which is array of jet diameter 0.5mm chilled the copper plate more effectively and transferred large amount of heat than every other array at every flow rate tested. For arrays of the same size, same number of jets, same jet spacing but of different jet diameters, the array with smallest jet diameter produced the best chilling and had the highest heat transfer coefficient on the plate. As the flow rate increases the more the chilling and heat transfer coefficient become better.

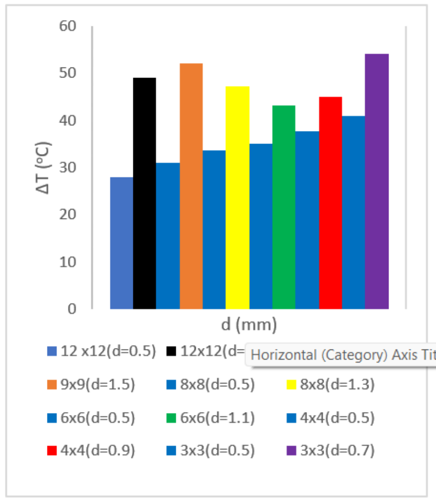


**Fig 2a:** Temperature rise versus jet diameter at flow rate of 0.0000167m$^3$/s

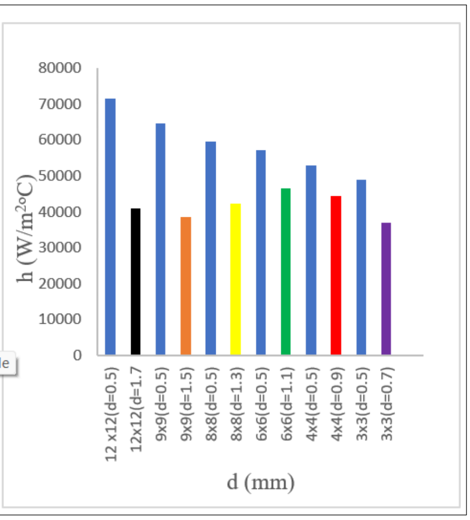


**Fig 2b:** Heat transfer coefficient versus jet diameter at flow rate of 0.0000167m$^3$/s

In each pair of arrays, the blue bar which is array of smaller jet diameter of 0.5mm chilled the silver plate more effectively and transferred larger amount of heat than the array of bigger jet diameter at flow rate of 0.000167m3/s

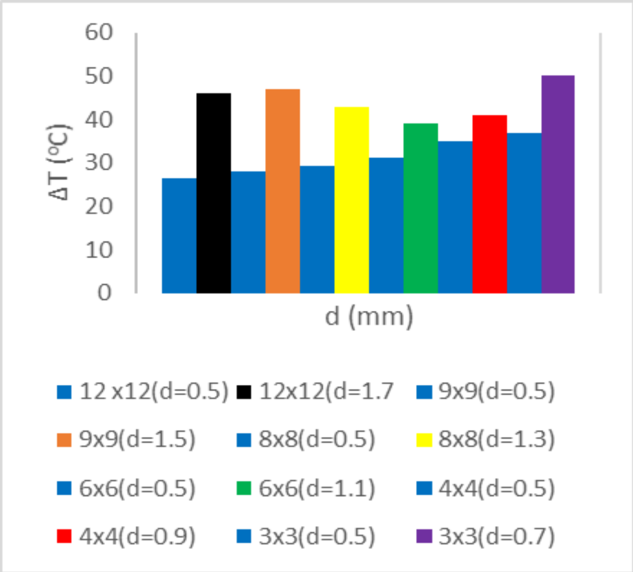


**Fig 3a:** Temperature rise versus jet diameter at flow rate of 0.0002m3/s.

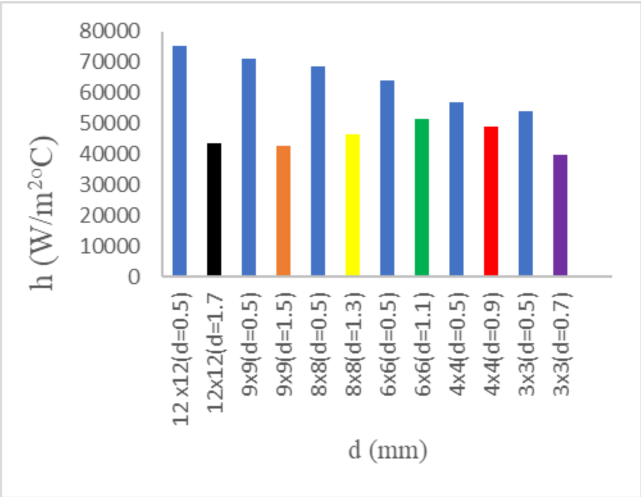


**Fig 3b:** Heat transfer coefficient versus jet diameter at flow rate of 0.0002m3/s

In each pair of arrays, the blue bar which is array of smaller jet diameter of 0.5mm chilled the silver plate more effectively and transferred larger amount of heat than the array of bigger jet diameter at flow rate of 0.0002m$^3$/s

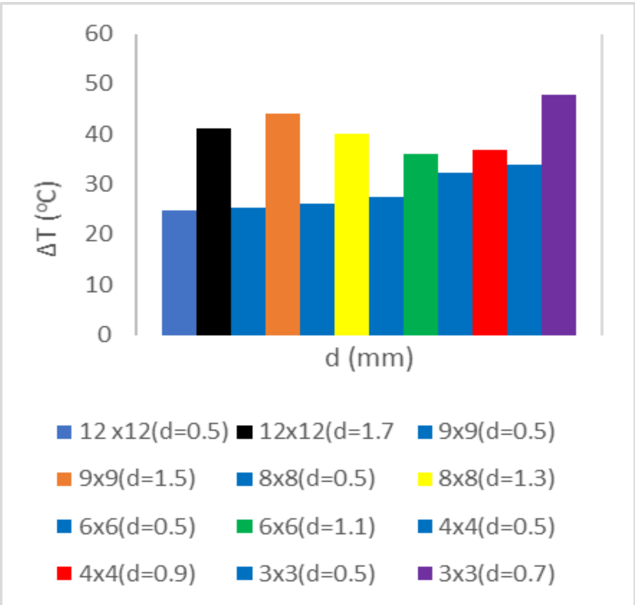


**Fig 4a:** Temperature rise versus jet diameter at flow rate of 0.00023m$^3$/s

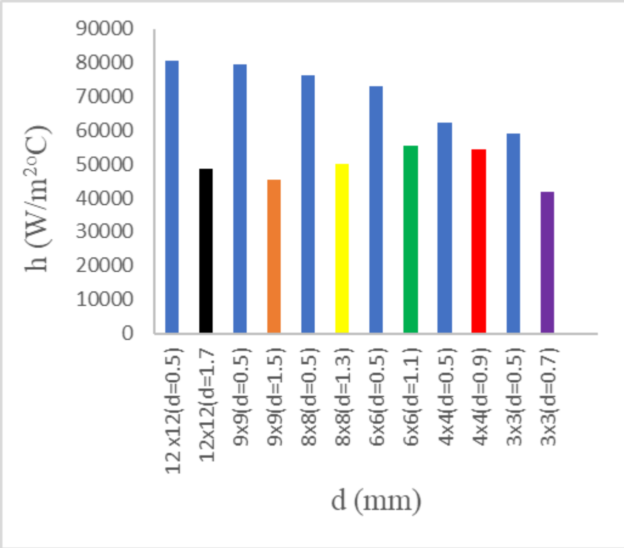


**Fig 4b:** Heat transfer coefficient versus jet diameter at flow rate of 0.00023m$^3$/s

In each pair of arrays, the blue bar which is array of smaller jet diameter of 0.5mm chilled the silver plate more effectively and transferred larger amount of heat than the array of bigger jet diameter at flow rate of 0.00023m$^3$/s

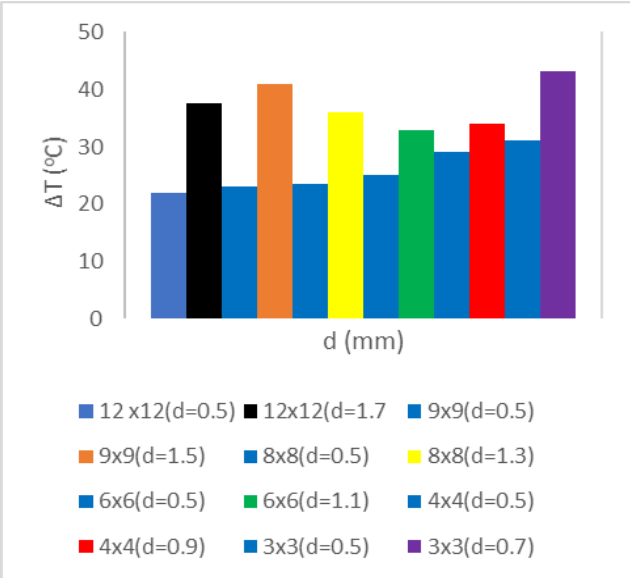


**Fig 5a:** Temperature rise versus jet diameter at flow rate of 0.00026m3/s

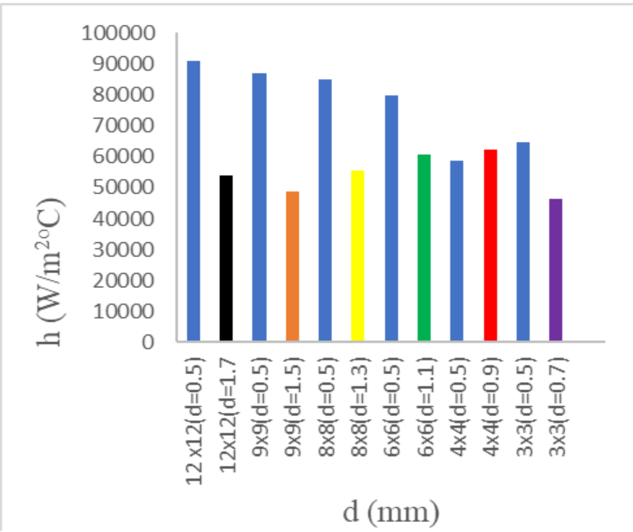


**Fig 5b:** Heat transfer coefficient versus jet diameter at flow rate of 0.00026m3/s

In each pair of arrays, the blue bar which is array of smaller jet diameter of 0.5mm chilled the silver plate more effectively and transferred larger amount of heat than the array of bigger jet diameter at flow rate of 0.00026m3/s

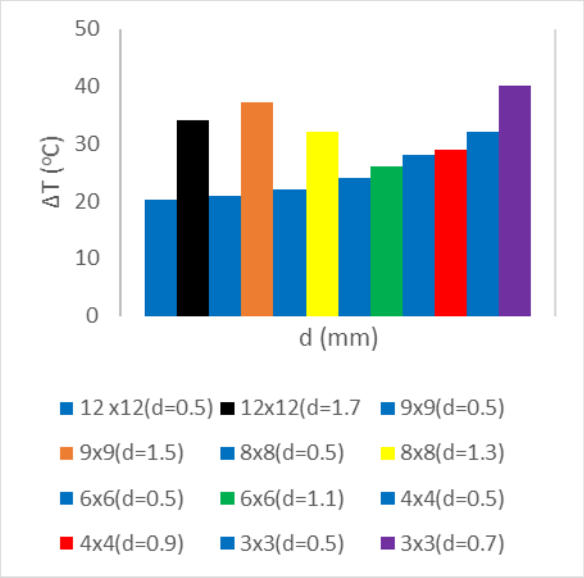


**Fig 6a:** Temperature rise versus jet diameter at flow rate of 0.0003m3/s

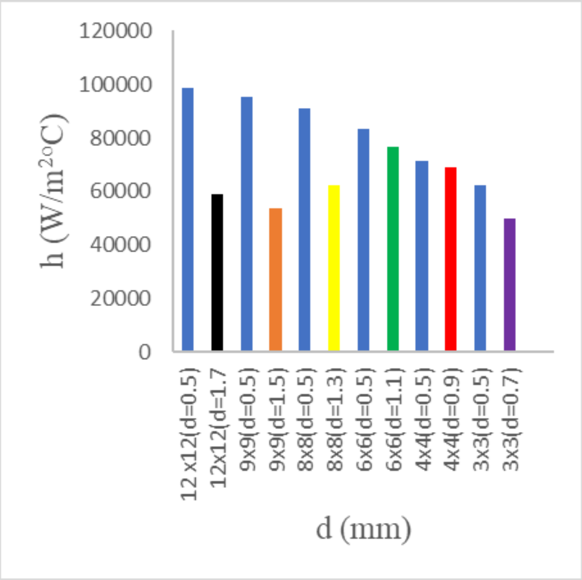


**Fig 6b:** Heat transfer coefficient versus jet diameter at flow rate of 0.0003m3/s

In each pair of arrays, the blue bar which is array of smaller jet diameter of 0.5mm chilled the silver plate more effectively and transferred larger amount of heat than the array of bigger jet diameter at flow rate of 0.0003 m³/s.

**4. Conclusion**

In each pair of arrays, the blue bar which is array of smaller jet diameter of 0.5mm chilled the silver plate more effectively and transferred larger amount of heat than the array of bigger jet diameter at every flow rate tested. As the flow rate increases the more the chilling and heat transfer coefficient become better.

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