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Review Article

# Surface modification techniques for cooling by impinging jets-a review

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## ABSTRACT

The following paper is a review of the recent published literature on these three techniques for heat transfer augmentation. With global trend of the miniaturization of today's systems and the rapid development due to innovative equipment on a rise, the associated heat generation rates are increasing. As a result, the need to develop techniques to achieve faster and efficient cooling are also increasing., Heat transfer by impinging jets poses a good and economical solution to this problem since, among all the processes used for heat removal, heat transfer by impinging jets have the highest rates associated with them. Although, the heat generation rates have increased over period of time, jet impingement is in the industrial use for quite a long time and is still relevant for the field. This is because overtime the impingement heat transfer effectiveness has been improved by various innovations. Innovations such as surface modifications, use of flow control techniques etc. The modifications reported had seen actual use of them in industries, thus bringing more interest of the researchers towards them. The need to achieve higher heat transfer rates and efficient working of the systems is still seeing numerous interactions pertaining to surface modifications integrated with jet impingement reported on them. Primarily, the use of various types of extended surfaces such as pin fins, plate fins, ribs etc., inducing the roughness elements on the surface by employing dimples, protrusions etc., applying specific surface coatings found a plethora of research work reported on them. For any work, it is necessary to study these modifications and their interactions in details. This paper thus presents the above stated three surface modifications in detail.

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## INTRODUCTION

With rapid advancements and miniaturizing, the need for faster heat removal rates is becoming a necessity nowadays. Heat transfer enhancement, though can be achieved by many mechanisms but various techniques such as use of fins, increasing the surface roughness or employment of various types of surface coating are used primarily to increase the convective heat transfer. Use of extended surfaces such as pin fins, plate fins, vortex promoters are intended to cause enhanced mixing of the fluid by providing turbulence to the flow. This is turn increases the secondary flows and more vortex regions are generated. These vortex regions and secondary flows result in increased secondary

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advection of the heat from the surface. Moreover, higher turbulence levels cause increased shear and create velocity gradients for notable flow volumes. This further causes an increase in the turbulence production which then causes higher heat removal rates. Also, the added increase in the convective surface area results in heat transfer enhancement to some extent.

Heat transfer enhancement by roughness elements can be understood by visualizing the flow patterns and turbulence intensity. Roughening up the surface includes employing dimples, protrusions, ribs of various shapes and sizes, use of pedestals etc. For low values of Reynolds number, roughness elements have a little effect on the Reynolds number. The flow is then considered aerodynamically smooth. But, for higher Reynolds numbers, the roughness elements dominate the momentum transport so much so, that the viscous effects are eventually nullified. Roughening increases, the swirl which in turn, affects the turbulence characteristics of the flow. With increase in the degree of the swirl, the rate of entrainment of surrounding fluid and the rate of jet velocity decay are all increased, resulting in higher heat transfer. But, as much as the roughening of the surface increases the heat transfer rate, the associated friction factor also increases. Thus, the higher heat transfer rates should also justify the added pumping power requirement. Additionally, the increased convective surface area provided increased number of nucleation sites which in turn also plays a role in the higher heat removal rates.

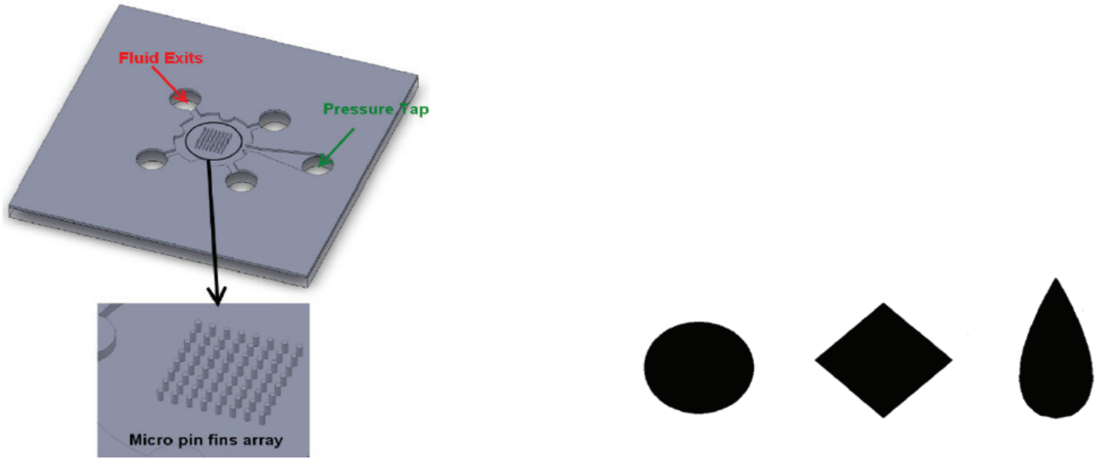
Enhancement by applying the surface coating occurs by establishing finer and finer control over porosity and surface roughness. Thinner coating layers over the surface reduce thermal resistance and thermal stresses. This in turn has been proven to enhance Critical Heat Flux. Coating materials including nanoparticles have higher thermal conductivity due to the presence of suspended solid particles. They have displayed that the liquid surface temperature gets reduced near the non-wetting region, resulting in the formation of a surface temperature gradient, thus leading to a secondary flow. These secondary flows are responsible for additional turbulence, enhancing the rate of heat dissipation.

Fabis et al. [1] in their study confirmed that nearly 60% of failures of electronic components are caused due to thermal stresses. Management of thermal stresses is of prime importance, especially at elevated rates of the order of 1MW/m2. Lee et al. [2] stated that for every 10 degrees rise in the junction temperature, the failure rate of the component nearly doubles. Jet impingement heat transfer poses a good solution to the problem at hand. Impinging jets are used in numerous applications ranging from cooling of electronic equipment [3], cooling involved in glass manufacturing [4], food processing [5], Nuclear Power plants in case of Loss of Cooling Agent (LOCA) [6], Steel industries during strip rolling [7], manufacturing of optical fiber [8], Fire Suppression mechanism [9], Cooling of Turbine blades [10] and plenty more. For systems that use nucleate boiling as extensive heat transfer mode such as Pressurized Water Reactor (PWRs) or cooling as an Emergency Core Cooling System (ECCS), the critical heat flux provides an upper restriction to the Nucleate boiling. It has been stated that a 32% increase in the Critical Heat Flux would result in a 20% power density uprate in current plants [11]. A lot of reviews have been presented in this context, but application-based techniques still have a limited number of comprehensive and detailed literature published on them. The following paper thus presents a review on the three types of surface modification techniques for impinging jets, possible applications, and future scope of the techniques.

## USE OF EXTENDED SURFACES (FINS)

Heat sinks being one of the most important parts of the structure of a microchannel has seen various developments over the years. These incudes use of pin fins [12–17], use of plate fins [18–20] and various other types of extended surfaces[21–23]. Increasing the surface area leads to increase in number of nucleation sites which consequently results in increase in the rate of heat transfer. Using R134a as a coolant, Ndao et al. [12] conducted experiment to study the effect on flow boiling when micro pin fins of various shapes are attached to the surface (See Figure 1). Heat transfer at elevated rates was observed. The effect was even more pronounced for high velocity coolant impingement. In fact, increase in the diameter of the pin fins led to faster heat transfer rates. This happened due the smaller flow area and consequent higher velocity. But smaller flow areas result in pressure drop. Thus, for the constant pressure drop, the pin fin with larger flow area will perform better. Circular and square micro pin fins resulted in better thermal behavior than the hydrofoil micro pin fin. Ndao et al. [13] later in their study conducted a study for cross flow using circular, square, hydrofoil and elliptical (See Figure 2) pin fin arrangements (See Figure 3). The comparative results were plotted (See Figure 4). The circular followed by the square pin fins presented the highest heat transfer coefficients at given Reynolds number. Lack of significant secondary flows were coined as a possible cause for low heat transfer coefficient observed in elliptical and hydrofoil pin fins, but presence of pin fins of any shape resulted in enhancement of heat transfer coefficient.

For extended surfaces, the enhanced cooling is mostly achieved by geometric modifications. Kim et al. [20] optimized the plate fin height and which resulted in a 50% increment for the fin heat sink performance than the conventional heat sink (See Figure 5). Wong and Indran [18] analysed the effect of fillet profiles on heat transfer for a plate fin heat sink. Mesalhy and Sayed [19] in their study using an entropy generation minimization technique reported that using the narrow jets are better for short fins with lower fin number. The studies concerning pin fin and plate fin do however pose one question, which one has the better thermal performance? Few studies in the past have tried to shed some light on this area with respect to



(a) (b)

**Figure 1.** (a) Micro device(b) Micro pin fin geometries-circular, square, hydrofoil [12]

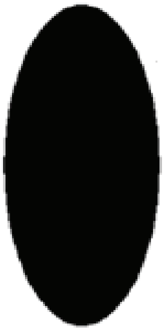


**Figure 2.** Elliptical Pin Fin[13].

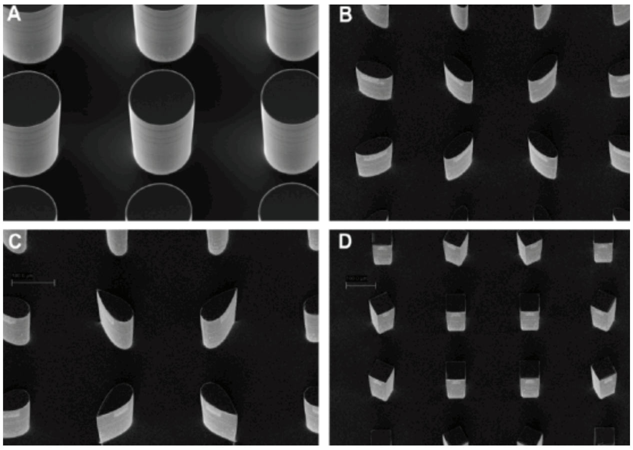


**Figure 3.** 3-D view of pin fins A) Circular B) Elliptical, C) Hydrofoil D) Square [13].

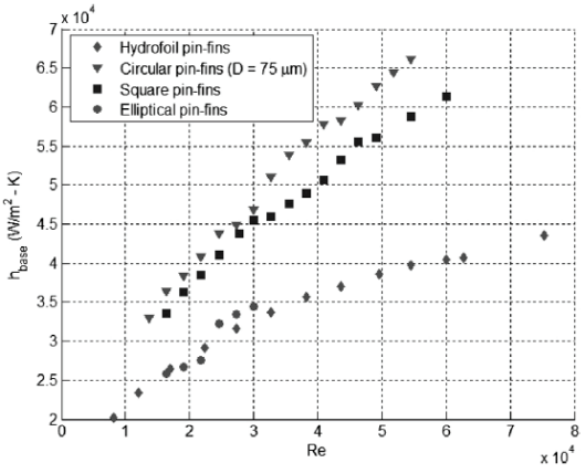


**Figure 4.** Effect of pin fins on heat transfer coefficients [13].

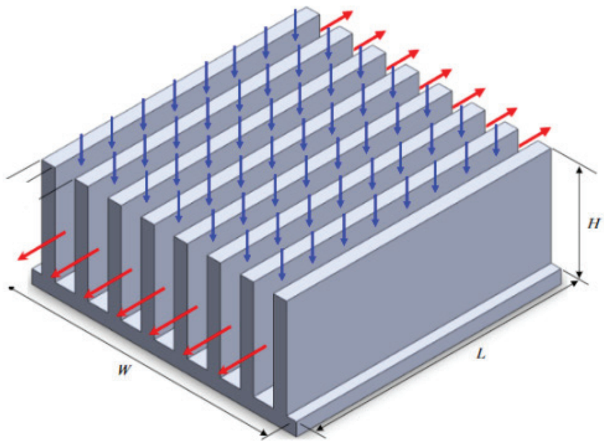


**Figure 5.** Plate fin heat sink [20].

jet impingement [24–26]. Kondo et al.[24] in his analysis stated that the optimized pin fin heat sinks have 40% more thermal resistance than the optimized plate fin heat sinks. Li et al. [25] stated that pin fins are superior to plate fins. However, these conflicting conclusions were later answered later by Kim et al. [26] when they compared the thermal resistance. It was concluded that pin fin heat sinks are better for smaller dimensionless pumping power and larger dimensionless length of heat sink and vice- versa.

Pin fin porosity gives an advantage of favorable flow condition and less pressure drop. Thus, it plays an important role in heat augmentation studies. Increase in the porosity leads to increase in the surface area which consequently leads to better heat transfer performance. Zhao et al. [14] in their numerical study stated that the pin fin porosity value of 0.75 and the pin fin location angle of 30 degrees for a micro square pin fin for cooling are the optimum values. Chiu et al. [15] studied pin fin arrangement and concluded that the arrays of smaller pin diameter offer better heat transfer with lower thermal resistance and hence are suitable for thinly dispersed devices. Consequently, arrays of large pin diameters were advantageous for denser devices. They also concluded that the porosity above 0.7 had an impact on the thermal resistance.

Prajapati [16] conducted a parametric study to optimize the pin fin height in a rectangular parallel microchannel numerically. For heat flux varied between 100 to 500 kW/m$^2$, Reynolds number from 100 to 400 and fin height ranging from 0.4 to 10mm, he concluded that increasing fin height up to 0.8mm displayed heat transfer enhancement and the best possible results were obtained at this value (See Figure 6) and further increase in fin height resulted in decrement of heat transfer. The fin height of 0.4 and 0.9mm showed minimum and maximum pressure drops respectively (See Figure 7). This was because of the fact that increase in fin height will cause more obstruction to the flow and hence the Pressure drop. Kosar and Peles [27] in their study provided an insight on staggered vs in-line arrangement of micro scale pin fins. He concluded that for fixed pressure drop and pumping power, in-line arrangement displayed better results while for fixed mass flow rate, staggered arrangement showed more promising results. Naphon and Wongwises [28] investigated the effect of jet impingement cooling by observing the working temperature of a CPU and observed comparatively lower temperatures. Mohammed and Razuqi [29] studied effects on heat transfer coefficient for a rectangular pin fin heat sink subjected to jet impingement. They concluded that with an increase in the Reynolds number, the thermal resistance decreased, which in turn led to an increase in the average Nusselt number. This resulted an increase in the heat rejection from the sink. DoĞan et al. [30] studied numerically the heat transfer and pressure drop characteristics due to variation in the bending of the fin for a heat exchanger. Increment in the heat transfer coefficient from 58 to 76 W/ (m2. K1) was reported in the research. Lee et al. [21] studied the heat transfer characteristics for a flat surface on and around a central and a secondary pedestal (Figure 8). Unaffected from the height of the secondary pedestal, the average Nusselt number displayed an increment than the case with no secondary pedestal. The flow visualization at Reynolds number (Re)= 2300 was conducted by varying the distance between the centerlines of both pedestals(p) to central pedestal diameter ratio(D). p/D= 2.0,2.5,3.0 were studied. The formation of two vortices (recirculation zones) between the central pedestal and the flat surface were observed (See Figure 9). The size of the secondary vortex (formed between the secondary pedestal and the flat surface) was observed to be increasing with increase in p/D ratio. This formation of the vortex was accused for the enhancement in the Nusselt number. It should be noted that the impinging jets although have high heat removal rate but for a wider surface, number of jets need to be increased. This further adds complexities

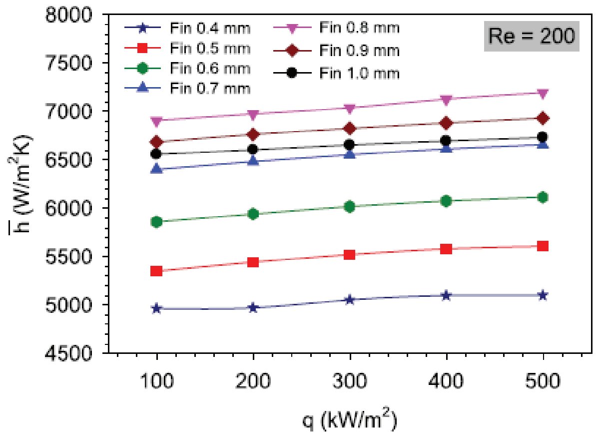


**Figure 6.** Effect of various fin heights on average heat transfer coefficient [16].

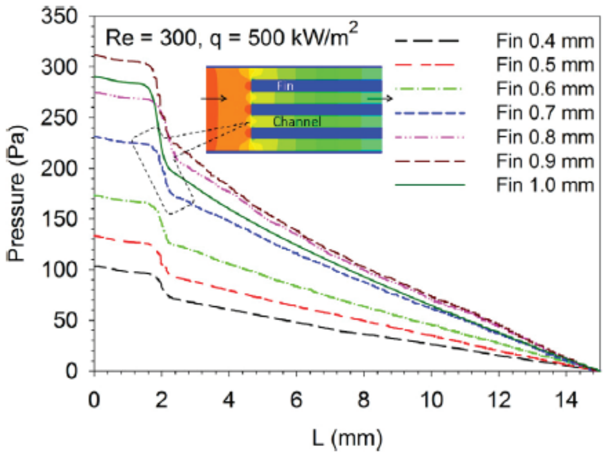


**Figure 7.** Pressure drop due to varying fin height [16].

in the cooling arrangement and studies pertaining to the use of multiple jets in electronic cooling are limited. In conjunction with the Nano fluids, a lot of studies are being carried out on recent times. Kilic et al. [31] studied effects of vortex promoter inside a rectangular channel both experimentally and numerically. The location, length and angular position of the vortex promoter was found to have a direct impact on the heat transfer. Han et al. [22] studied the heat transfer augmentation for a 90° and 45° attack angled ribs and concluded that for the same Heat transfer through the target surface, the angled ribs had low Pressure drop than the orthogonal ribs. Park et al. [23] studied the effect of various rib angles (90°, 60°, 45°, 30°) on the heat transfer performance in a channel and concluded that for 60° angled ribs, the heat transfer augmentation was best among all the channels. Ali and Arshad[17] conducted an experiment using water-based graphene nanoparticles (GNPs) to find the angle effect of pin fin heat sink channel.

They reported that for pin fin channel angle of 22.5 degrees, convective heat transfer coefficient observed was 84.30% higher than that of 90 degrees. Further, using GNPs resulted in enhancement of heat transfer coefficient by 23.86% and 19.68% for 22.5- and 90-degrees pin fin geometry respectively. Liu et al. [32] displayed the impinging jet cooling with Copper- water Nano fluid with the volume concentration of 3%. They reported that the convective heat transfer coefficient was 52% higher as compared with the pure water. Furthermore, no additional pressure loss was reported. Sun et al. [33] performed an experiment using Silver–multiwall carbon nanotube (Ag-MWCNT) and found out that heat transfer coefficient is enhanced by 29.45% than standard water as a coolant. Zhen-Hua Liu et al. [34] investigated experimentally the Critical Heat Flux (CHF) and showed that the jet boiling heat transfer for water-based Copper (II) oxide (CuO) nanoparticle is significantly different than that for water as a coolant and the CHF for Nano fluid increased compared with that of water. The properties of the Nano fluid were measured where it was found out that the surface tension of the nanoparticle was about 75% that of water (which hardly changed with concentrations) and although the viscosity of the nanofluid was almost the same as that of water, the thermal conductivity of the nanofluid increased linearly with increase of the nanoparticle concentration which was about 8% for every 2% weight increase in CuO concentration that water. Thus, use of the nanoparticle in conjunction with the modified surface leads to higher heat removal rates and are currently being used in our modern world.

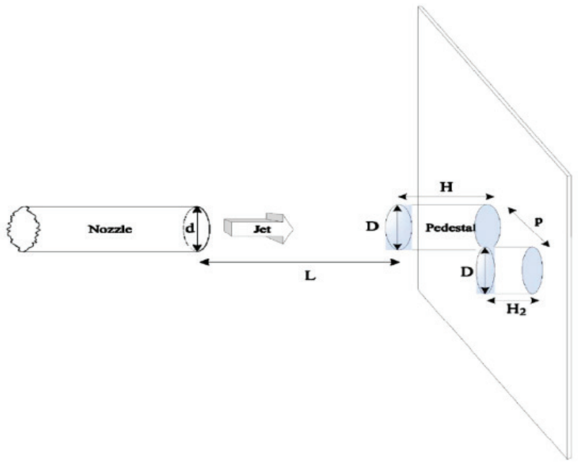


**Figure 8.** Schematic of impinging jet and multiple pedestal impinging jet [21].

**Figure 9.** Flow visualization at Re= 2300(p/D=3.0) [21].

Gaikwad and Mohite [35] studied experimentally and numerically thermal characteristics for a microchannel heat sink. Enhancement factor of 1.24 was obtained when disrupting pins were used in the study. Krishnayatra et al. [36] numerically studied the effect of fin parameters such as length, thickness, number of fins and material of fins from a horizontal cylinder. Heat transfer enhancement was characterized by effectiveness and maximum effectiveness of 4.34 was recorded for the system. Rana et al. [37] carried out numerical simulations to investigate the effect on the thermal and hydraulic performance due to baffles in a microchannel. Enhancement in Nusselt Number as high as 164% was reported. However, higher value of Nusselt number was accompanied by an increase in friction factor. Kilic and Ali [38] studied numerically the effects of different volume ratio, heat flux and different types of Nano fluids using CuO-water as the coolant for varying other parameters. Volume ratio increase from 2 to 8% saw an increase in the average Nusselt Number of 10.4%. For Cu-water Nano fluid, an increase of 2.2%,5.1%, 4.65 and 9.6% Nusselt number was found with respect to CuO-water, TiO-water, Al2O3-water, and pure water. Kilic et al.[39] studied effects on local and mean Nusselt number as a function of jet to plate distance and Reynolds number. The constant heat flux boundary condition was used for their numerical investigation. The results were in aligned with the experimental observations.

## USE OF ROUGHNESS ELEMENTS

Augmentation in heat transfer through use of extended surfaces happen due to increase in convective surface area and increased flow turbulations. Another way of enhancement in heat transfer is by increasing the wetted are This can be achieved by roughening up the surface. By doing that, viscous sublayer gets disturbed and transition to turbulence happens faster thus leading to higher values of heat transfer coefficients. Celik [40] in his experimental study analysed the effect of roughening up the surface for the circular and co-axial impinging jets. The roughness elements used were 20 dimples of 0.5 mm base, 0.5 mm height and 1.8 mm spacing between them. Nusselt number increment up to 6% were reported for circular jets. Furthermore, 27% enhancement in the Nusselt number was also reported for co-axial impinging jet as compared to the circular impinging jet when using the rough surface. The impingement cooling performance very strongly depends upon the arrangement, pattern, and distribution of the roughness elements along with the Jet Reynolds number. Khan et al. [41] studied effect of dimple protrusion in a rectangular channel and reported heat transfer enhancement for various rages of Reynolds number. Buzzard et al. [42] employed eight different sizes of rectangular roughness elements in combination with large pins (see Figure 10) for laminar (Reynolds number 900 and 1500) and turbulent (5000 and 11000) flow types. The results showed that there was an increase in 60- 120 % of wetted surface area with addition of roughness elements. For turbulent jets, plates with the combination of roughness elements and pins gave higher value of Nusselt number at the same Reynolds number due to increase in local mixing. However, for smaller values of Reynolds number, surfaces with small roughness elements alone resulted in better values of Nusselt number than the ones with both roughness elements and large pins due to the insulating effect of the latter which causes less overall heat transfer. Figure 11 shows the ratio of enhanced Nusselt number (Nu) with addition of roughness elements as compared to the one with the smooth surface (Nuo) at Reynolds number 11000 and various jet to plate distance(x) and jet diameter(D) ratio.

Singh et al. [43] studied the effect of an array of roughness elements of cylindrical, cubic and concentric shape on surface (See Figure 12). Reynolds number was varied between 2500 to 10000. They concluded that the concentric type elements showed the highest heat transfer as compared

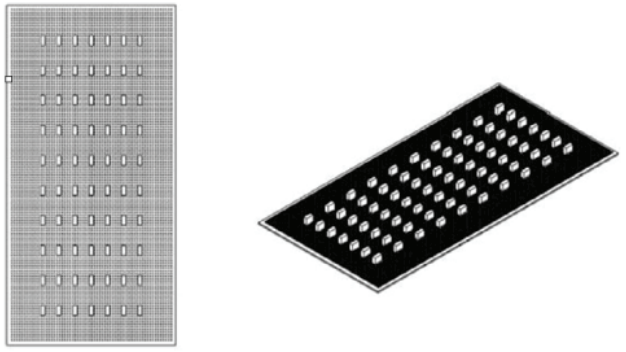


**Figure 10.** Rectangular roughness Elements with large pins [42].

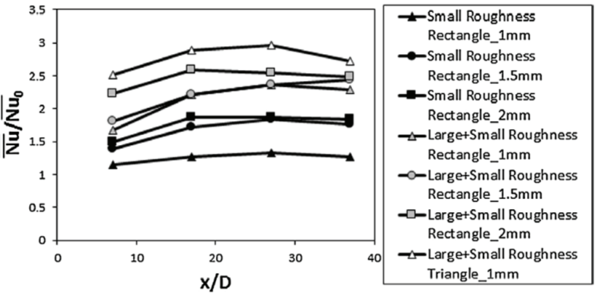


**Figure 11.** Comparison of Nusselt number (Nu) w.r.t Nusselt number for a smooth plate ($Nu_o$)for different roughness elements at Reynolds number 11000 [42].

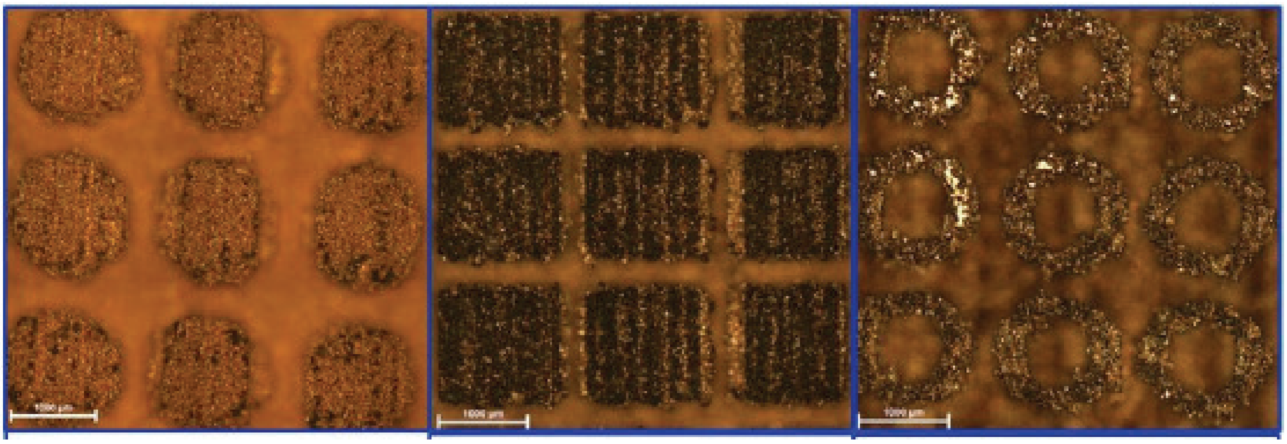


**Figure 12.** Microscopic image of roughness elements (top): a) cylindrical, b) cubic, c) concentric [43].

to the elements of other geometries. An increase of 20-40% for concentric, 20-40% for cubic and 10-30% for the cylindrical roughness elements in fin effectiveness was found as compared to smooth surface. K Nagesha et al. [44] performed experiments to characterize the heat transfer to a jet impinging normally on a heated surface modified along with multi protrusions or V grooves. For Reynold's Number in the range 10000 to 27500, enhancement in heat transfer over that of a flat plate for V-groove type surface elements which was attributed to the increase in surface area due to roughness.

The analysis of the near wall turbulence characteristics for a micro ribbed channel was presented by Zhao et al. [45]. In their study, Reynolds number was kept at 20000. Ribs of various heights were chosen such that height of all the ribs were located between the viscous layer and the log law layer with a dimensionless height of h+=8-40(See Figure 13). This was done to study the thermal performance within the boundary layer and to find out the optimal height interval for maximum heat transfer and minimum pressure loss. For h+ < 40. Nusselt number and the friction factor rose at the similar rates. But, for h+>40, the near wall turbulence due to the large rib height caused a sharp increase in the resistance growth rate. At the same time, the heat transfer rate was found to be falling. With rise in rib height, the bursting process of coherent structures were stated as the main reason for increase of pressure drag behind this observation. h+ values lying between the range of 30-60 in the log law layer and the buffer layer was suggested as the optimal rib height for minimum pressure loss and the maximum heat transfer enhancement. T. Çalışır et al. [46] presented a study for heat removal under triangular and square ribbed surfaces for array of impinging jets. The effect of Reynolds number, jet to plate distance and rib arrangement on heat transfer was studied numerically for two different arrangements. The major difference between the arrangement was the direction of the nozzle, where one being towards the ribs and other being towards the centreline of the cavity of the ribs. Nusselt number for the former arrangement was found significantly higher than the latter. In a follow up study, T. Çalışır et al. [47] studied numerically the effects on the flow field of triangular and square ribbed surface under rectangular array of impinging jets. Tang et al. [48] proposed use of array cone heat sink for heat transfer enhancement (See Figure 14). The jet flow and heat transfer mechanism were explored and explained by use of a single cone. On a broader level, parameters such as effect of cone angle (0°-70°), cone diameter to nozzle diameter ratio (1-3), Reynolds number (16000-32000) were studied. A significant enhancement in heat transfer performance due to the presence of surface cones was reported. This observation was in complete agreement with observations of Li et al. [32]. Cone angle of 50° saw the best heat transfer characteristics (11.7 % higher than the flat plate heat sinks i.e., 0° angle). Moreover, this effect was even more pronounced at higher values of Reynolds number (See Figure 15). This was due to the presence of an additional impact zone (the transition zone) in addition to the impact zone. The thickness of the Temperature boundary layer was drastically reduced due to the presence of this additional zone causing heat transfer to happen at elevated rates.

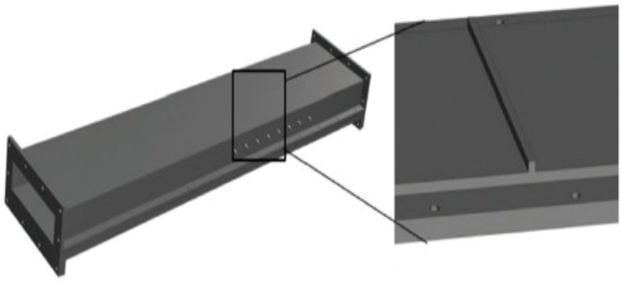


**Figure 13.** Experimental setup with micro rib attached [45].

Froissart et al. [49] validated numerically the study conducted by Tang et al. [48] and reported the effect of the varying cooling channel height along with the deformation of the cone side surface. A total of sixty-two cases were compared and the optimum one saw an enhancement on 11% in heat transfer than the standard flat plate heat sink. Use of dimples and protrusions are also being used on the target wall to achieve faster heat transfer rates. Kim et al. [50] by use of Kriging model found an increase of 0.68% in the average Nusselt Number for a corresponding Pressure loss of 5.43%. Jing et al. [51] did a numerical investigation for concave dimples, protrusions, and triangular tabs. The dense arrangement of the protrusions resulted in higher heat transfer enhancement. The triangular tabs were found to worsen the heat transfer.

Singh et al. [52] experimentally investigated to analyze the effects of artificial roughness on heat transfer and friction in a solar air heater duct. Triangular protrusion elements were used as the roughness geometry. An Increment in both the heat transfer coefficient and friction factor was

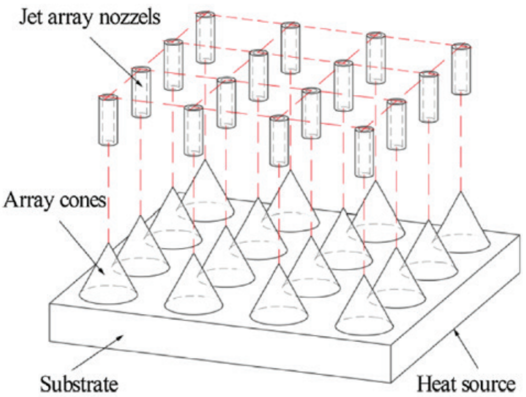


**Figure 14.** Array cone heat sink [48].

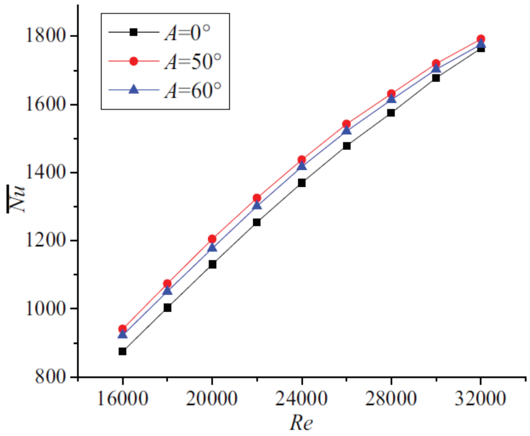


**Figure 15.** Effect on Avg. Nusselt Number (Nu) due to cone angles with varying Reynolds number (Re) [48].

observed for the roughened case over the smooth case. Thus, an agreement for both the heat transfer coefficient and friction factor must be made before such that the added pumping power costs justify the enhancement in heat transfer. Yıldırım and Özdil[53] investigated the thermohydraulic efficiencies of a solar air collector with a roughened absorber and compared the results with that of a flat plate solar collector. Reynolds number from 3,000 to 21,000 was investigated for their study. Relative roughness height was found to increase thermal and hydraulic efficiency. Tepe et al. [54] studied the effects of extended jet holes on a rib roughened surface. For the test section (See figure 16), an increase up to 40.32% was possible by use of the extended jet holes. A direct dependence of the heat transfer was found with the fluid jet velocity. Xie et al. [55] observed in his study that no flow separation happened in the dimpled space and reported an enhancement of up to 50% in Nusselt number in one of his arrangements.

Choi et al. [56] conducted an experimental and numerical study on heat transfer augmentation for the internal cooling of turbine blades by using angled ribs and dimples. Since, the Turbine Inlet Temperature (TIT) has been exceeding the permissible operating temperature of the blade material for the desire of high efficiency and power output, a cooling technique is a must for the turbine blade. So, the study consists of an experimental setup to mimic the internal coolant passage of a gas turbine blade fir Reynold's Number ranging from 10000 to 60000 with aspect ratio 2 and 4 and Rib pitch, Rib angle, Dimple diameter and Dimple center- to- center distance as 6mm, 60°, 6mm, 7.2mm respectively. With dimples fabricated within the ribs, an increase in heat transfer coefficient was found with an acceptable increase in Pressure drop. It was noted that the heat transfer enhancement through different jet impingement techniques is usually accompanied by an increase in pressure drop of the flow across the targeted surface because of enhanced fluid–surface interactions. Therefore, it is always desirable to have such a system that yields the maximum heat transfer enhancement at a minimum Pressure loss and to measure the overall performance of a system, simultaneous considerations of heat transfer and the friction factor are necessary. For this very purpose, the Thermal Performance Factor (TP) is proposed by Choi et al. [56] as:

$$\mathrm{TP} = \frac{Nu/Nu_0}{(f/f_0)^{\frac{1}{3}}} \tag{1}$$

Where, Nu, f and $\mathrm{Nu}_0$, $\mathrm{f}_0$ are the Nusselt number and friction factor of the targeted surface of the enhanced case and the reference case respectively. Also, TP is a function of Reynold's number as well since both the Nusselt number and the friction factor are a function of it. TP > 1 is desirable since it specifies that the enhancement of the heat transfer rate over the required pumping power.

Pachpute and Premachandran [57] took a circular cylinder as their target surface shape with Reynold's Number ranging

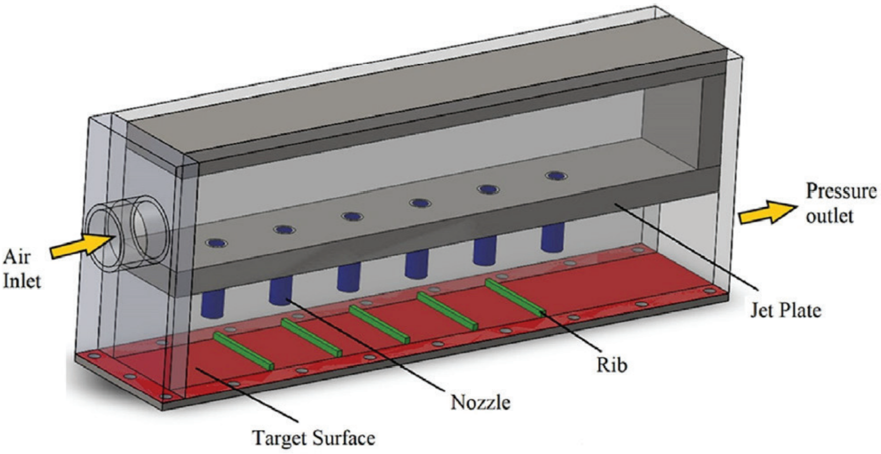


**Figure 16.** Test section used by Tepe [54].

from 5000-20000 and H/D ranging from 2-12 and found that the average heat transfer was enhanced by 14% for Reynold's Number 20000 and H/D =2 for staggered jet arrangement as compared to the inline jets thus concluding that the arrangement of the jets also affects the heat transfer rate.

## SURFACE COATING

Various methods of surface coating have been studied for the heat transfer phenomenon over the years, but lack of comprehensive and detailed studies was found concerned with the use of jet impingement. Surface properties like wettability, porosity and coating thickness can be easily controlled by this technique and significant enhancement in the heat transfer is achievable owing to these parameters. Nazari and Saedodin [58] used the electrochemical coating- anodizing process to coat a metallic layer of aluminum oxide on an aluminum surface. Gupta and Misra [59] used Copper-Aluminum oxide nanocomposite coatings. An increase in the Critical Heat Flux was reported by both studies. In a follow up study by Gupta and Misra [60], effects of two- step electrodeposition technique was studied. An enhancement of 86% with respect to bare copper surface was reported when Copper- Titanium dioxide was developed on a copper surface. Owing to enhanced wettability, similar observations were made when the coating was done by Physical Vapor Deposition (PVD) process. Das et al. [61] found an enhancement of 58% in heat transfer coefficient for the coating of silicon oxide layer. Owing to increase in surface to volume ratio, 80% enhancement in the heat transfer coefficient was obtained with Silicon dioxide coating in another study by Das et al. [62]. The Atomic Vapor deposition process for heat transfer enhancement is also employed by a few researchers. Feng et al. [63] reported a two-fold enhancement on a Platinum wire in de- ionized water when coated with Alumina. Similar observations were also made for surface modifications during a study of pool boiling by Ha and Graham [64]. Dip coating methods are also prevalent for heat transfer enhancement because they provide a greater number of nucleation sites. Ray et al. [65] explored the Titanium dioxide thin film coating (100nm and 200nm) on a copper surface experimentally (See Figure 17). Plane and film thickness Nano coated type of copper heating surfaces of diameter 9mm were prepared. A maximum of 36.91% and 44.93% enhancement in heat transfer coefficients was reported on 100nm and 200nm Titanium dioxide coated surface.

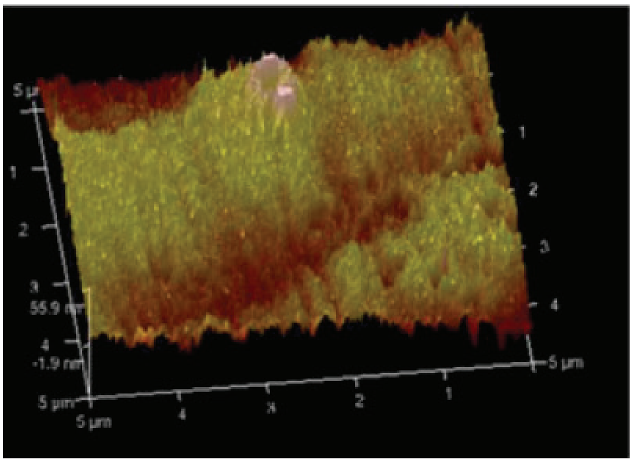


**Figure 17.** Atomic Force Microscopic image of $TiO_2$ surface [65].

Hendricks et al. [66] in their experiment used Zinc oxide nanostructures deposition on Aluminum and Copper substrate. Superior heat transfer characteristics were observed in both the samples for nanostructured surfaces. A 10x times enhancement in heat transfer and 4x times improvement in critical heat flux was reported for nanostructured surfaces over the bare Aluminum substrate. Wang et al. [67] reported an increase in the Critical Heat Flux through controlling the surface chemical properties. Hu et al. [68] reported an increment of 160% in the Critical Heat Flux due to the presence of the Nano porous surface coatings. Liu and Wang [69] reported heat transfer enhancement and avoided fouling by studying the effects of coating a Titanium dioxide layer. Joseph et al. [70] used Nano Copper (II) oxide coating on Stainless Steel 316 and reported a maximum of 30% increment in the boiling heat transfer coefficient on the coated surface as compared to its uncoated counterpart. Increase in the number of nucleation sites (Figure 18 clearly shows more nucleation sites in (a) as compared to its counterpart in (b) and (c)) since it was rougher and had more Nano sized coating. This led to the enhancement in the heat transfer. Compared to the uncoated surface, a 30% heat transfer enhancement was reported. Zhao et al. [71] prepared a porous surface by diffusion bonding on a copper mesh surface. The rest of the surface was then heated and subjected to jet impingement cooling. The results displayed an enhancement in the heat transfer over the standard untreated copper mesh. Joshi and Dede [72] investigated effect of multi-scale porous surfaces. The heat transfer coefficient and pressure drop parameters were reported. Results were reported for Porous coated flat; pin-fin, open tunnel, and closed tunnel structures and the porous coated pin fin surfaces displayed the highest heat transfer enhancement.

Negeed et al. [73] studied the impact of a small droplet and its behavior on a heated hydrophilic surface. Empirical relations for the effect of surface wettability, contact angle, droplet velocity and droplet size are presented in their study. Forrest et al. [74] studied nanoparticle thin film coating effects when applied layer by layer to a nickel wire. The surfaces showed hydrophobic and hydrophilic properties depending on their final treatment. A 100% enhancement in Critical Heat Flux was found when the wire was treated with fluorosilane. This effect is visible in Figure 19 where (a) is the bare nickel wire and (b) is a coated nickel wire. The boiling heat transfer was found to be increasing with

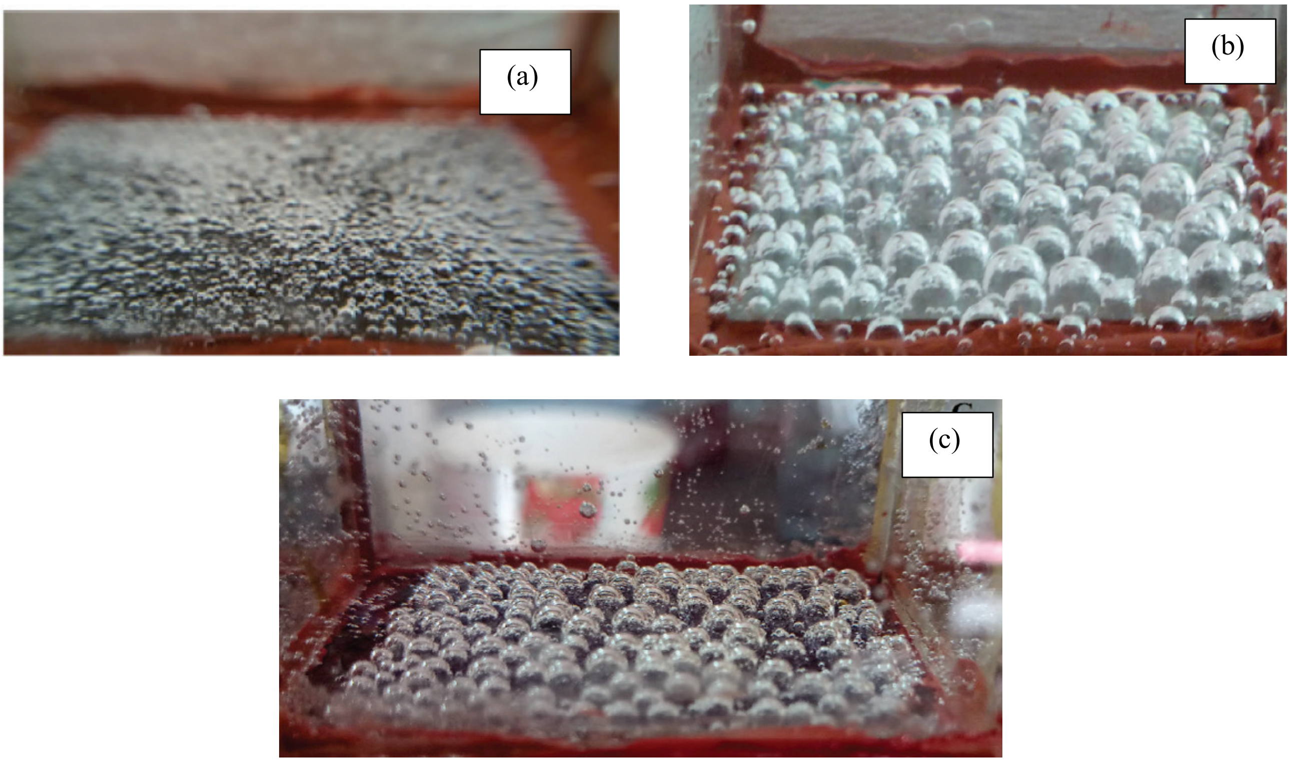
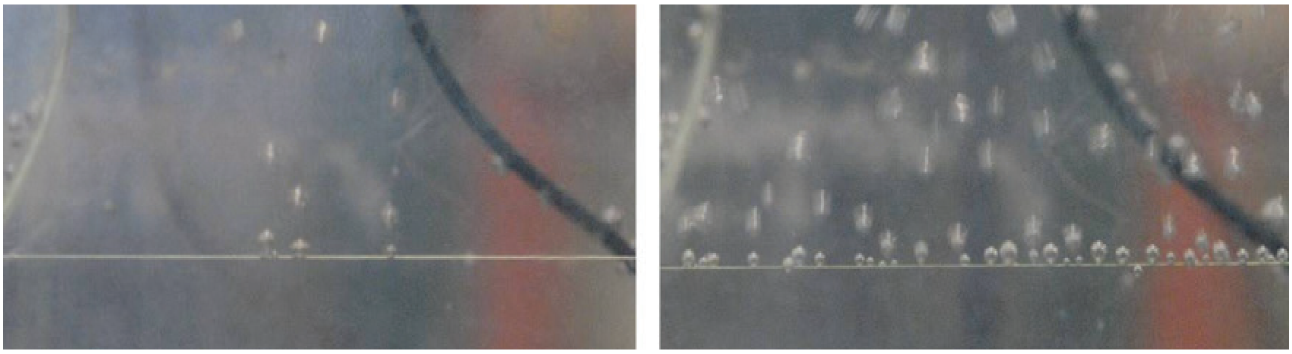


**Figure 18.** Smaller grain size leading to a greater number of nucleation sites [70].

decrease in surface wettability. Change in wettability or induction of roughness are the two effects which are studied the most when surface coatings are applied. Mohammadi et al. [75] studied effect of wettability on a silicon block. Significant changes in the critical heat flux were reported. Maynes et al. [76] brought forward the comparative study on hydraulic jump for hydrophobic, hydrophilic, and Super hydrophobic surfaces with ribs and cavities pattern on them and presented a local film thickness model to describe his results. Akdag et al. [77] reported the effect of the synthetic jet on the heat transfer for a flow over the flat plate. The smoke wire method was used for flow visualization of the heat transfer mechanism. The disruptive behavior of the hydrodynamic boundary layer on the heat transfer actuator was revealed in the experiment.

## CONCLUDING REMARKS

A review on heat transfer by impinging jets has been presented in this paper. This review includes various surface modifications for impinging jets. Three modifications are presented in this paper. On a broader look, all three modifications stated above had displayed higher degree of enhancements. Now, the question here lies that which modification is best suited for which type of application. Extended surfaces



**(a)** **(b)**

**Figure 19.** Nickel wire- (a) bare and (b) hydrophobic at same heat flux [74].

like pin fins, plate fins, pedestals result in secondary flows and an increment in the convective heat transfer area. The research work is motivated for the areas such as microelectronics fabrications like transistor chips, small heat sources like thermoelectric generators, or use in the Integrated circuits by passive methods. Though not possible everywhere due to space constraints, other techniques have to be looked upon. Induction of the roughness elements on to the targeted surface area to disturb the flow cause early turbulence which in return leads to faster cooling rates. Roughness induction techniques are used primarily in the duct of solar air heater, solar dryer, gas turbine airfoils and blades etc. Use of surface coatings provides versatility in its use. Application areas stated for the above two methods, heat exchangers etc. see use of coatings to achieve higher heat transfer rates. One of the most recent innovations i.e., Use of special surface coatings by methods like nanoparticle coatings, Physical Vapour Deposition (PVD), Atomic Layer Deposition Method, Vacuum Glancing method, applying coating coatings to make the surface hydrophobic, hydrophilic leads to higher heat transfer rates and is being used more and more due to simplicity associated with its use.

## CONCLUSION

The advantages that the modifications during the nanoparticle coating presents are huge, but details regarding the nanoparticle-surface adsorption phenomenon still needs to be understood. Porous coatings such as by film condensation have provided good temperature drops and are an interesting field for possible future, but micromanaging the parameters like thickness, which influences heat transfer rate directly still provides new difficulties. Integration of two or more techniques such as nanoparticle coatings over a dimpled surface, a dimple-protrusion array, vortex turbulators and surface coatings presents an interesting area of research and numerous possibilities. Primarily, the use of such hybrid techniques can in turn, give us better results. Use of dimples and protrusions to induce the roughness has displayed good results but further details like optimum depth, shape, angles etc. still need some work to be reported on them. Use of other techniques like nanoparticles in the coolant fluid is also a field of interest for the researchers nowadays. Various techniques like encapsulation of the nanoparticles are being studied and reviewed. Various Phase Change Materials (PCMs) can be used as a heat storage medium for the targeted surface thus reducing the frequency of the jet. Use of PCM's in conjunction with the impinging jets to effectively bring down the economics of the cooling mechanism. Thus, making it a more viable solution to address heat removal problems. The use of dimples and protrusions to induce the roughness has displayed good results but further details like optimum geometric parameters and application-specific roughness elements still need some work to be conducted on them. The use of other techniques like nanoparticles in the coolant fluid is also a field of interest for researchers nowadays. Various techniques like an encapsulation of the nanoparticles are being studied and reviewed. Various Phase Change Materials (PCMs) can be used as a heat storage medium for the targeted surface thus reducing the frequency of the jet. Use of PCM's in conjunction with the impinging jets to effectively bring down the economics of the cooling mechanism. Thus, making it a more viable solution to address heat removal problems.

## AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

## DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

## CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## ETHICS

There are no ethical issues with the publication of this manuscript.

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