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A Review of Active Techniques for Improving Heat Transfer in Heat Exchangers Using the Impingement Jet Approach and the Potential Future of Nanocoating

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ABSTRACT

Impingement jets have several industrial uses, and their efficiency has been greatly increased. Heat transfer properties were significantly enhanced by jet impingement. The literature on the impingement jet system's heat transfer characteristics is reviewed in this research. Different control parameters characterise impinging air jets, and it is necessary to look into how these characteristics depend on performance-defining criteria. Increasing turbulent intensity, using nanofluid and improving surfaces by nanocoating, increasing heat transfer area, and creating vortex or secondary flows are all factors that must be taken into account in order to arrive at the optimal impinging jet geometry, which creates one or a combination of the following conditions that are favourable for heat transfer enhancement. One crucial concern is the possibility of improving certain traits. In order to optimise control factor combinations for an ideal impinging jet design, the current review looks at the thermodynamic behaviour of impingement jet techniques and reviews experimental and numerical studies published in the literature to investigate the dependence of control factors on heat transfer, flow characteristics, and decision-making techniques. By optimising heat transfer and system flow characteristics, this review offers researchers in the same sector a platform to construct a noble heat transfer enhancement contrivance in the form of jet control elements for enhancing thermal performance. This paper's primary contribution is its comprehensive discussion of the steady jet impingement heat transfer problem. According to the literature, using nanofluid technology and the ideal concentrations of the influencing elements can improve heat transfer characteristics. The choice of an appropriate impingement mechanism and surface coating with the nanosolution have a favourable impact on the rate of heat transmission.

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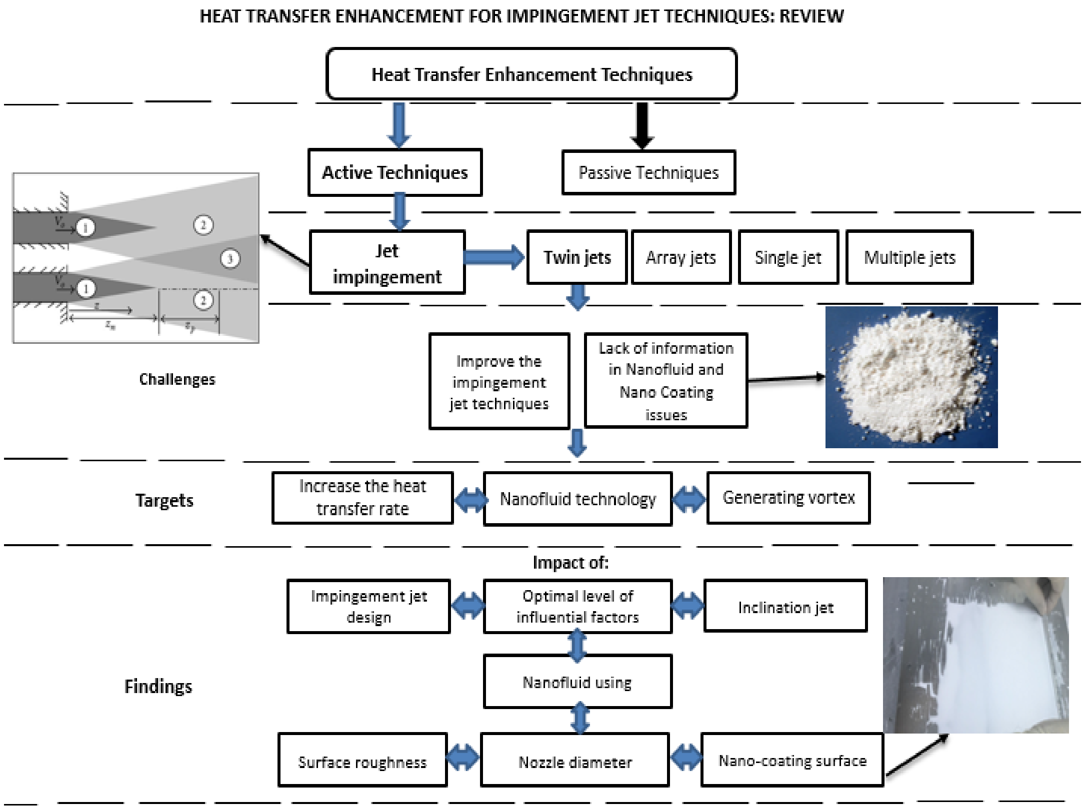
GRAPHICAL ABSTRACT



1. Introduction

One of the most promising approaches to improving heat recovery in engineering and industrial applications, as well as optimising heat transfer equipment [1-5], is to enhance heat transfer. Jet impingement systems' high heat and mass transfer rates allow them to successfully increase convective processes, although in recent decades, researchers have been more interested in the challenges of boosting heat transfer [6-10]. Such an upgrade method minimises work and expenses, lowers energy consumption, and significantly increases heat transfer efficiency. Additionally, it has a variety of uses in heating and cooling that could assist lower costs associated with materials, energy use, weight, and size, therefore increasing the effectiveness or performance of heat exchange [11], [12]. Since the technology is directly associated with numerous industrial applications, it is necessary to identify the mechanism that enhances heat transmission [13-16].

Impinging jets are currently being used in an increasing variety of industrial applications. Impinging jet systems are used for drying paper and textiles as well as chilling hot metal, plastic, or glass sheets. Compact heat exchangers are used in the automotive and aviation industries and frequently employ many impinging jets in dense configurations. In microscale applications, impingement systems are frequently used to cool electronic components, especially in electronic chips.

Gas turbine applications have historically made extensive use of jet impingement. Demands are being made for lower emissions and higher power production and efficiency. By raising compressor ratios and turbine inlet temperatures, high thermal efficiency can be achieved. Consequently, a number of gas turbine parts, including rotor discs, turbine vanes and blades, and combustion chamber walls, are kept at temperatures significantly higher than the maximum acceptable material norms. The intricate design and high turbulence of the turbine system necessitate the development of efficient cooling systems for these heavily loaded components in order to guarantee longevity and extended working periods. Moreover, nanofluid technology can be used to achieve excellent thermal efficiency. By expanding the surface area and improving the plate feature, nanocoating surfaces also plays a significant role in heat transfer by improving flow characteristics and heat transfer. Nevertheless, comprehending flow and heat transfer properties is still a difficult topic. [17-21].

Figure 1. Taxonomy of enhancement Heat transfer techniques

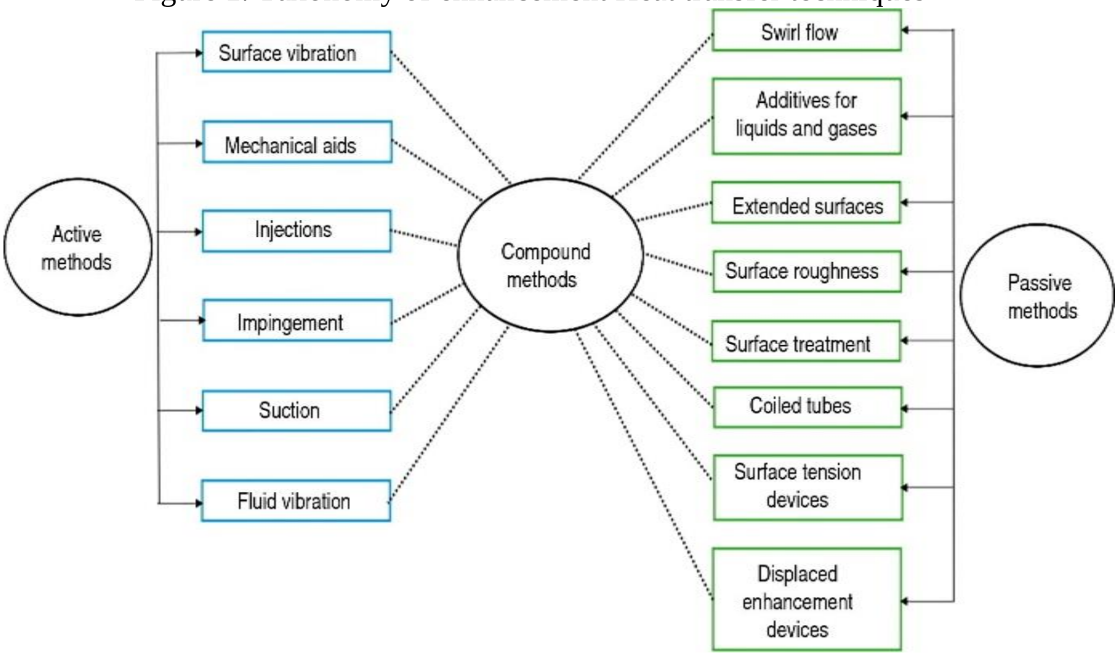


Figure 1 shows the taxonomy of heat transfer improvement methods.

1.1 Classification of heat transfer enhancement techniques

There are two types of heat transfer augmentation techniques: passive and active [22]. Either surface amendment on hot plate surfaces or swirl devices in the flow domain are used in passive approaches, which don't require any external power. Because they need an external power source, these methods perform better than sophisticated active methods. However, active methods provide significant thermal control and potency. These include of injection, suction, jet impingement, surface and fluid vibration, mechanical assistance, and electrostatic fields. Passive approaches include fluid additives, flow disturbance, out-of-plane mixing, secondary flow, re-entrant blockage, channel curvature, and surface roughness. Figure 1 shows the taxonomy of heat transfer improvement strategies. Passive approaches include surface roughness, channel curvature, secondary flow, and re-entrant blockage [22].

1.2 Impingement jet

One active method for capturing the flow field and forecasting jet efficiency is jet impingement. According to this assessment of the literature, the jet impingement mechanism is a significant method that has drawn the attention of numerous researchers, particularly in the past 20 years. In engineering applications, impingement jets offer an efficient and flexible way to transmit mass or energy. When directed gas or liquid flow is unleashed on a surface, significant quantities of mass or thermal energy can be effectively exchanged between the fluid and the surface [23]. A Statistical Method Using Response Surface Methodology to Enhance Heat

Transfer and Evaluate TiO2 Nano Concentration and Twin Impingement Jet to Improve Heat Transfer and Flow Characteristics into Various Zones [24] (Figures 2). A submerged impingement jet travels through a number of different zones. The upstream flow determines the turbulence characteristics when the jet emerges from a nozzle or opening with a specific velocity and temperature profile.

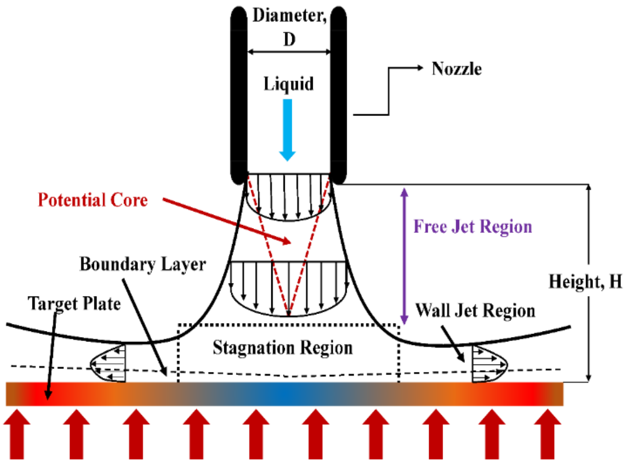


Figure 2. Jet flow properties: (a) single flow; (b) single impinging jet arrangement

stagnation points of twin impingement jets

In many applications, increasing fluids' thermal conductivity is necessary to increase heat transfer efficiency [25]. Because forced convection action produces high heat transfer coefficients, the jet impingement heat transfer technique has garnered significant scientific interest [26]. Jet impingement technology (JIT) can be used to develop a wide range of applications, particularly in the food sector, textile drying, turbine blade cooling, electronic chip cooling, metal annealing, and glass tempering. The effects of using single and multi-impinging stable jets on flow and heat transfer properties have been extensively studied. There has been extensive research on the impact of varying the Reynolds number (Re), which is defined as ρv d/μ, where ρ is the fluid's density (kg/m3), μ is its dynamic viscosity (in N·s/m2), and v is its mean velocity (in m/s).

Numerous works, including [27,28], have examined the effects of conduction and convection, varying velocities, distance between nozzles, and spacing between nozzle and plate on jet flow shape and impingement heat transfer rates. Inadequate information is available in the literature regarding the combined impact of twin jets on flow and heat transfer behaviour. The purpose of this review is to highlight the information gaps regarding the heat transfer of impingement jets, identify essential parameters involved, and validate the lack of knowledge regarding the flow and heat transfer enhancement of dual jets. When the right impingement system and ideal amounts of the influencing parameters are chosen, the literature on the heat transfer properties of impingement jets can be enhanced. Although many areas require more research to improve thermal performance, previous studies clarified the flow and heat transmission properties of constant impingement jets.

1.3 Research gaps and questions

One important feature of impingement jets is their high convective heat transfer coefficient. The following is a presentation of the research challenges:

1. How do nano coatings like TiO2, CNT, AL2O3, ZNC, and CU affect the flow properties and heat transfer rate in various applications?
2. The mechanism of dual impingement jets is poorly understood.
3. How may the radial distance from the stagnation point be used to maximise the heat transfer rate?
4. How does heat flux cover every hole in the transaction area, and how does the cross-flow region impact the two nozzles?
5. How can computational fluid dynamics (CFD) be used to improve the dual impingement jet technique using numerical and experimental methods?
6. There is insufficient (yet unreported) information on the twin impingement jet system.
7. How can the radial distance from the stagnation point be maximised in terms of heat transfer rate?

2. Flow characteristics of multiple steady jets

Establishing a foundation for comprehending the behaviour of impingement heat transfer requires analysing the flow characteristics of several jets. By displaying a zone of interference between jets, one may differentiate between the flow characteristics of numerous jets and a single jet. This interference between nearby aircraft takes place prior to the jets' impact on the target. On the impingement surface, jets create different flow configurations. The flow structure of several jets can be characterized using the impact of the interference zone on a single jet. Turbulence intensity can be greatly impacted by interfering jets. Other impacts on flow parameters were acknowledged in related publications [29].

To differentiate between single and double impinging jets, the flow structure of each system was presented for additional analysis [30]. For both jet systems, the effects of low Re and nozzle–plate distance (H/De) on velocity and pressure distribution were investigated experimentally. Velocity was measured using hot-wire anemometry. Double jets showed an increase in secondary stagnation pressure with increasing Re. When Re exceeded 2,700 or the nozzle–plate distance approached 2 (H/D), a sub-atmospheric zone was seen on the impingement plate. Therefore, the primary distinction between single and double jets is the interference effect. Convective heat transfer accumulation and fluid flow architectures for numerous jet impingements were covered in reference [31]. In order to provide a better understanding of the impact of near-wall flow patterns on convective heat transfer accretion, the results for these intricate flow phenomena are examined.

Particle image velocimetry (PIV) was used to examine the effect of jet interference for a hexagonal array of circular jets that impinged a flat plate [32]. The impact of that plate impingement on turbulence kinetic energy and jet-jet interference on the length of the jet core were also covered in the study. The findings showed that due to differences in interference levels, the array's central jet had a shorter core length than its lateral jets. The upwash produced by wall jet collisions raised the axial velocity gradient in the shear layers of the jets, which enhanced the conversion of mean flow momentum into turbulent stress.

Numerical analysis was performed to investigate the effects of Re, nozzle–nozzle centerline distance, nozzle–plate spacing, and jet angle on 2D impinging circular twin jets [33]. The governing mass, momentum, turbulent kinetic energy, and turbulent kinetic energy dissipation rate were all calculated using the finite volume method. The findings indicate that when the jet angle increased or the Re decreased, the pressure at the secondary stagnation point fell. As the jet angle and nozzle–plate separation grew, the strength of the recirculation zone between two jets decreased. In addition, each vortex region's turbulent kinetic energy rose.

Taghinia et al. numerically investigated the impingement of a turbulent jet on a curved plate using CFD [34]. For different jet–surface (h/B) distances at different Re of 2,960 and 4,740, hydraulic diameter (2B) and jet exit velocity (U) were calculated. The Reynolds averaged Navier-Stokes (RANS) k-ϵ model results were obtained by comparing the results with experimental data published in the literature. The comparisons demonstrated that the two models (e.g., k-ϵ and RANS) could produce results that were reasonably excellent. The one-equation model (OEM) yielded accurate findings, especially at the impingement zone at small jet-to-surface distances. The OEM was able to accurately forecast heat transfer across a range of tiny jet-to-surface widths. At high h/B ratios, the two models performed similarly. [35] investigated numerically the fluid flow and heat transmission of non-Newtonian multiple impinging jets. The findings demonstrated that high wall Nusselt number (Nu) and impingement velocity were caused by a rise in the power law index. For high jet plate spacing, environmental entrainment vortices were created to round the jet's body. These vortices vanished when the separation was reduced. The numerical findings demonstrated that wall Nu increased significantly as the jet–plate gap was decreased.

In order to boost turbulent kinetic energy, the oblate jet shape was taken into consideration and contrasted with the circular arrangement in a jet array system [36]. Additionally, instantaneous velocity fields obtained along the cross-flow direction using digital PIV were examined. The energetic content of the flow revealed that the oblate jets produced more kinetic energy, or turbulent kinetic energy.

Using the instantaneous velocity recorded at the axial jet's centerline, the turbulent intensity of twin jets was calculated [27]. The measurements were performed using hot-wire anemometry. Additionally, measurements were made of the pressure distribution on the impingement plate and confinement surface. High values for Re (30,000 to 50,000) were used along with various nozzle–nozzle and H/De. The centerline turbulence levels increased during the development, according to the data. Jet–jet and nozzle–plate spacing, rather than Re, determined the pressure distributions on confinement and impingement surfaces. Using a large-eddy simulation (LES), Taghinia et al. [37] numerically investigated the twin-jet impingement in conjunction with hybrid-type turbulence models. The hybrid model of shear stress transport (SST)–scale-adaptive simulation (SAS) (SST–SAS) was used to impinging twin jets for the first time. The idea behind the SST–SAS $k - \omega$ model was to add the SAS term, an additional production term, to the ω equation. This new word was susceptible to variations that were either resolved or unsettled. A numerical analysis was carried out for different spacings and Re. A range of values for Re, H/D spacing, and S/D spacing were taken into consideration in the study. The recirculation structures were composed of two stagnation areas due to the H/D spacing. The zones between two impinging jets with an upwash fountain-like structure were the locations of the first and second regions at the impinging area.

A model with a rough surface served as the foundation for the fluid flow, entropy formation, and heat transfer in air jet impingements [38]. Surface roughness, jet impingement dimensions, and jet flow Re all had quantifiable effects. Additionally, the temperature differential between the jet flow and the impinging target on the heat transfer from the jet impingement was measured. Roughness had a noticeable impact on the wall jet area but was less noticeable in the impingement area. Additionally, the amplification factor of the heat transfer rate was more influenced by surface roughness than by the geometrical dimension of the jet.

By altering the jet flow rates, a prior work [39] examined the heat transfer efficiency of an internal cooling channel with a single-row impingement jet array. The results showed that overall flow deviated from the baseline by about 65%. About 35% more heat was transferred to the objective plate surface. Additionally, due to the complex cross flow effect and the plenum's flow distribution, this improvement was minimised after switching to the varying-diameter jet plate. A turbulent impingement jet on a vibrating, heated wall was investigated using large eddy simulation (LES) in a prior study [40]. When the wall's displacement was positive or negative, the mean radial velocity rose and fell, accordingly. The secondary Nu peak showed periodic changes. Vibration had a positive impact on heat transfer, but only in the impingement area did it improve heat transfer in the stagnation region.

For a cooling turbine blade application, the flow field of many jets was examined. Liu et al. built an extended model of a trapezoidal duct close to the blade's leading edge [41]. After that, two lines were opened into the duct, each with 40 staggered circular side impingement holes of two diameter sizes. Impingement jet, cross flow, swirl flow, and effusion flow effects were taken into account. There were two impingement angles for detailed flow structures: 35° and 45°. To record the intricate flow in the tunnel, a seven-hole pressure probe was designed and calibrated. A 2D interpolation approach was used to replicate the flow's angle and velocity. The findings showed that whereas large jets mostly concentrated on driving and creating the vortex, small jets had an effective effect on the target wall.

The physics of impinging jets for a low Re regime in a wide array was covered in Reference [42]. There was a significant lack of knowledge about the pressure drop that happened in impinging jets. Moreover, no information could improve our comprehension of the physics of flow in various jet impingement arrays. The outcome demonstrated that viscous losses and the contraction effect at the nozzle entrance resulted in a significant drop in system pressure. The sensitivity of pressure drop, heat transfer properties, and anticipated manufacturing tolerances in real-world engineering applications of these jet arrays were all investigated through simulations. Reference [43] investigated heat transfer in air-assistant jet impingement and the impact of volumetric quality on fluid flow parameters. The findings demonstrated that as volumetric quality increased, the stagnation Nu rose as well, reaching a maximum value at about 0.8 of the volumetric quality. Nu then started to decline after that. The stagnation Nu of the air-assistant water jet impingement was determined by the stagnation pressure. The boiling heat transfer rate of thermal water for a turbulent jet impingement positioned on a heated surface was studied statistically in Reference [44]. The findings demonstrated an increase in a fluid's water velocity and convective heat transfer coefficient at the stagnation point. Furthermore, as the fluid jet temperature drops, the convective heat transfer coefficient would rise. In order to address the three-domain conjugation heat transfer problem, Reference [45] looked at the fluid jet's flow and heat transfer properties. The findings were derived from research on the solid-air interface's wall temperature.

The behaviour of the flow field produced by jet interference was investigated using various configurations of multiple jets. At various Re, steady jets often displayed nearly identical interference features, such as fountain vortices and secondary stagnation point development. On the other hand, velocity profiles and turbulence intensity may behave differently. In conclusion, research has shown that the interference zone modifies the impingement heat transfer response and characterizes the flow field of numerous jets.

3. Multiple steady jet impingement heat transfer

Impingement heat transfer with numerous jets has opened up a broad field of study in a number of areas. The most important parameters related to multiple jets were examined both experimentally and theoretically. Numerous works have addressed various impingement target configurations and consequences. In certain instances, the impact of angled multiple-jet impingement on heat transport was taken into account. Several multiple-jet configurations were used to study impingement heat transfer. In multiple-jet impingement heat transfer difficulties, the impact of nozzle configuration was examined. The multiple-jet impingement heat transfer problem may be limited by all of these problems. To validate and contrast experimental techniques, single-jet impingement heat transfer was nevertheless taken into consideration [46, 47].

3.1 Influential parameters of multiple-jet impingement

By examining all studies that addressed the impacts of flow and geometrical factors as well as any parameters that are anticipated to have a significant impact on heat transfer, this section of the literature review seeks to identify the most important parameters related to multiple-jet impingement heat transfer. Despite the fact that many applications have been employed in various studies, this research shared the goal of examining the influential aspects.

For multiple-jet impingement heat transfer, optimisation of several important parameters was investigated [48], and nozzle spacing showed optimal values due to the influence of jet interference [49]. How a parameter affects local stagnation Five jets in equilaterally staggered arrays were used to experimentally investigate nu. It also took into account different nozzle–target distances (H/Dn) and the Re of 10,000, 20,000, and 30,000. The findings showed that one important component influencing the heat transfer properties is jet interference. Some uses, like compressed air in a turbine's internal cooling system, only need a small amount of coolant. Brevet et al. [48] carried out an experimental investigation utilising thermal imaging. In order to minimise the amount of cooling air that was taken from the compressor, the findings were evaluated in terms of averaged and local Nu. The measurements showed the ideal impingement distance and spanwise spacing. Because increasing heat transfer was less expensive than the amount of cooling air needed, large spanwise spacing was suggested. Can [49] demonstrated the optimisation of the nozzle array under impinging air jets for practical purposes. In addition to the effects of velocity and air temperature, this work showed an ideal combination of design characteristics (such as nozzle height, shape, width, and pitch in terms of the free area). Practically speaking, it would be beneficial to look at the nozzle design cost, fan power consumption, and operating and capital costs. On the basis of CFD [50]. Each jet's heat transfer performance was reduced by the jet contact at the region where the wall jets collided. The performance of a single jet was superior than that of its twin counterpart. Under twin jets, average heat transfer was injected alternately, making each pair of jets act similarly to a single jet. This strategy is seen to be superior to issuing the twin jets at the same time. A novel and easy method of enhancing the thermal performance of the jet pairs in a twin jet system is to switch up the jet flows. The effects of the significant temperature differential between the target surface and jet air during heating, as well as the target surface's model roughness, were evaluated in addition to the parametric studies of geometric and important flow parameters. Because of the potential for fluid to become trapped in the hollow portion of the rough surface, roughness can reduce the effectiveness of heat transmission in the impingement zone. The physics of impinging jets given a wide array inside a low-Re scheme was covered in Reference [52]. LES and RANS data were used in numerical simulations to determine the heat transfer characteristics of a number of impingement jets. The heat transfer coefficient increased by about 10%, according to CFD calculations and experimental research. At X/D = 1, the local heat transfer increased as a result of the surface renewal impact upstream of the jets caused by the upwash of the primary vortices and wall jets. The average heat transfer rate would drop by roughly 6% and the pressure drop would rise by 15% if it blocked a jet that produced the fastest local heat transfer rate.

For impinging laminar multiple square jets, the flow and heat transfer properties were investigated at various nozzle–nozzle spacing (S/D) and H/De [51]. The 3D Navier-Stokes and energy equations were solved in steady state using a numerical simulation. The findings shown that the H/De has a significant impact on the flow structure of several square jets impinging on a heated plate. S/D has no effect on the local maximum Nu at the stagnation point. Additionally, Wang et al. [52] used several parameters to improve the impinging jet's cooling performance for effective power transfers and machining. Additionally, they added more design parameters for the cooling system. A larger convective heat transfer coefficient with the same flow rate can be obtained by decreasing the nozzle diameter while increasing the oil supply pressure or the number of nozzles. The impact of geometric factors on the axisymmetric impingement heat transfer jet was investigated in reference [53]. According to the analysis, every model has a unique dependency style. The turbulence model for H/D=2 was validated through the observation of a secondary peak at the precise position. The findings on the impact of grooves based on averaged Nu and surface Nu were briefly reviewed by the authors.

Reference [54] used CFD to anticipate the heat transfer of two and three jets impinging on two and three cylinders beneath one another. The two important factors taken into account in this investigation were Re and S/D. The findings demonstrated that increased Nu arises from an increase in Re. It is beneficial when two jets interact. Compared to a single jet, two jets transmit heat more efficiently on average. Under three jets, the cylinders' individual heat transmission would also vary. The core cylinder's heat transfer distribution is different from the outside cylinders'.

The impact of an experimental technique on the distribution of heat transfer coefficients on the target surface of jet impingement in a confined chamber was examined in reference [55]. A 1D technique utilising hue angle and a 3D inverse transient conduction scheme were compared with a transient liquid crystal technology. An 8 × 11 array of restricted impinging jets was used for the study, and Re ranged from 1,039 to 5,175. The total heat transfer was overrated by about 12%, the local maximum and minimum heat transfer values were inflated by around 15% to 20%, and the 1D findings were greater than the 3D results. The heat transfer coefficient's surface mapping shifted from a columnar to a horizontal pattern with a return to the columnar pattern when the Re increased. The findings showed that while greater cross flow improved homogeneity, it decreased heat transfer performance.

Based on the Re of 1,000 [56], the effects of S/D and H/De on the heat transfer and shape of a single and an array of three laminar. The local heat flux from the flame to the plate was measured using a heat flux transducer with an effective detecting area of 6 mm2. As S/D and H/De increased, the interference between the jets diminished. At S/D = 1 and H/de = 2, strong interference was observed. When the S/D was modest, the central jet of a multiple-slot jet system had a larger resulting heat flux distribution than a single-slot jet. As the S/D increased, this thermal performance advantage decreased.

Experimental research was done on free-surface and constrained submerged impinging cooling water jet arrays [57]. This work used rectangular jet arrays with varying volumetric flow rates, H/Dn, and hole–hole spacings. Three thermocouples mounted at the impingement plate centerline were used to measure the heat flux and surface temperature. The outcomes of the submerged jet arrays demonstrated a significant reliance on S/D and nozzle–target spacing. On the other hand, the free-surface jets displayed a local minimum in the heat transfer coefficient at around H/Dn = 10 along with a nonmonotonic shift with the nozzle–target separation. For a specific pumping power requirement, the submerged jets generally achieved a high heat transfer coefficient. Using the transient liquid crystal approach, Liu et al. [58] experimentally examined the heat transfer distributions on array impingement jets on a target surface that was half smooth and half rough. Three exit flow orientations—a jet Re between 2,500 and 7,000, a jet-to-jet spacing of 4, and a jet-to-surface spacing of 3—were used to investigate the effects of cross flow in comparison to a fully rough target surface.

The impact of the nozzle-plate spacing on the heat transfer rate for the five impinging confined and inline laminar square jets was investigated numerically [59]. The energy and Navier-Stokes equations were also solved for a simulation with a nozzle-plate spacing value of 2 B to 20 B and a S/D value of 4 B, where B is the jet width. The cross-flow impact caused by confinement was also taken into account in this investigation. The anticipated outcomes showed that the interaction between the two jets caused a horseshoe vortex to form at different points between the orifice and the impinging plates. The magnitude of the local Nu of the combined impinging jets was independent on the number of combined jets. As H/De dropped, the local Nu peaks rose. When the jet-to-cross flow ratio dropped, the maximum local Nu rose downstream while maintaining the same nozzle–plate separation.

An analysis of the impact of Mach and Re numbers on a variety of impinging jets was carried out [60]. The information was given as local and spatially averaged recovery factors, discharge coefficients, and local and spatially averaged Nus. From 5200 to 8200, the Re values ranged. In addition, the Mach number varied between 0.16 and 0.74. The power produced by the thermofoil heater and the outcome of the energy balance study were used to calculate the heat flux. Additionally, nine copper-constantan thermocouples positioned at different spanwise and streamwise positions in the impingement plate were used to assess the surface temperature. When the Re is held constant, the experimental results showed significant and independent Mach number effects. Additionally, the averaged Nu values were found in the local peak line, and the locally and spatially resolved Nu data showed that there was only one local maximum value beneath each jet. Under and close to the impingement jets' impact areas, the local recovery factor data reached a high of 1.03.

Three interacting methane/air flame jets that were impinged on a level surface were studied by Chander and Ray [61]. Given a Re of 800, the surface heat flux distributions were calculated using various burner–target separation and interjet spacing distances. A row of K-type thermocouples uniformly spaced in one radial direction was used to detect the surface temperature. The local heat flow was then measured using a heat flux microsensor. Because of the intense interaction between the jets and their modest separation and interjet spacing distances, the results demonstrated an outward deflection of flames that arise from the centroid of the triangle configuration. At large and small separation and interjet spacing distances, the heat flux pattern varied.

The effects of confinement on the impinging array and liquid circular jets were investigated by comparing confined submerged and unconfined free-surface water jets [62]. 48 K-type thermocouples were soldered along the centerline on the heater's dry side, or back side. Additionally, an offset line was used to guarantee that it was possible to measure the impingement plate's temperature. This configuration was demonstrated by the planar jet-like structure created by the inline array-circular jet in the wall jet, which, rather than providing a monotonic decrease in the convection coefficient, led in the absence of a transition area in all examined cases. Additionally, the single-circular jet experienced a $V \geq 6.1$ m/s transition. The constraining circular jets pushed the radial flows to become two-way channel flows, which significantly increased mixing and turbulence. Consequently, within $1 \leq r/d \leq 2$, the switch to turbulence occurred. Additionally, the standstill region saw a considerable increase in convection coefficients.

On a row of circular jets impinging a concave surface, the parameters of Re, C/D, and H/Dn were examined [63]. The FLUENT 6.2.16 software was used to conduct a computer analysis of the flow and heat transfer properties. The findings showed that entrainment, the presence of two counterrotating vortices, and the upwash fountain flow could all be used to describe the flow field. Only until current geometries (H/D = 1, 3, 4 and C/D = 3.33, 4.67) impinged could jet contact take place. Furthermore, when the designated range exceeded the jet–jet distance, interference between the jets was seen. The heat transfer coefficients were significantly impacted by H/d. High heat transfer coefficients were found when H/d = 1.

1.The flow structure and heat transfer properties in a variety of impinging slot jets were examined by Ozmen and Ipek [64]. They took into account the jet-jet centerline separation (S/D) of 9. Secondary peaks in the Nusselt division were found to be strongly correlated with the subatmospheric zone. The experimental results for suitable nozzle-plate spacing values were in agreement with the numerical results obtained using the realisable k–ε turbulence model. The process of conjugate heat transfer of the impingement jet was thoroughly examined by Zhu et al. [65], who found that various parameters changed the thermal condition and the Nu at the fluid–solid interface. The thermal conjugate effect transformed the border heat flux into thermal boundary by redistributing it. The conjugation effect caused a decline in the Nu.

Goodro and Park [66] used an array of jets impinging a flat plate to show how hole spacing affects spatially resolved heat transport, where D stands for the hole diameter. To measure the surface temperature, ten calibrated copper-constantan thermocouples were then positioned at different spanwise and streamwise points inside the impingement plate. The findings showed that the spatially averaged Nu values were typically greater than the 12D jet spacing values in the 8D jet spacing.

Double jets impinging on the isothermal wall were used to study the effects of H/Dn, Re, and S/D on the flow field and heat transfer [67]. Using a modified basic approach. On the isothermal surface, the mean Nu increased nearly linearly as Re increased. When the Re of the first jet exceeded that of the second, a notable improvement in the heat transfer rate was noted.

The impact of spanwise jet–jet spacing on the local heat transfer distribution in a restricted array of circular jets was examined by Katti and Prabhu [68]. The spanwise pitches were 2, 4, and 6 d, where d is the nozzle diameter; the jet-plate spacing varied from 1D to 3D; and the mean Re of the jet varied from 3000 to 10000. Thin metal foil composed of stainless steel was used to create the flat heat transfer surface. The findings demonstrated that those with spanwise pitches of 2 d and 4 d had lower stagnation Nu than those with a spanwise pitch of 6 d. Because of the increased spanwise jet interaction at low spanwise pitches, there were significant spanwise fluctuations in the coefficient of local heat transfer at various streamwise lines at high spanwise pitches. In low spanwise pitches, the stagnation point's heat transfer coefficient was much lower than the impingement brought on by a single jet. The spanwise jet–jet contact and cross flow may be the cause of this degradation. Using liquid crystal thermography, the experimental study on the heat transfer of jet impingement of the inlet condition [69] visualised the temperature distribution over the impingement surface. As a function of the separation distance and Re, the correlations advanced to the Nu.

A review of related studies is used to illustrate the influential factors connected to the impingement heat transfer of numerous jets. As a result, the following is a list of the most crucial parameters examined:

1. Reynolds number (Re)
2. Nozzle–nozzle spacing (S/D)
3. Nozzle–target distance (H/Dn)
4. Surface roughness

In multiple-jet impingement difficulties, these five typical elements drastically change the interference between the jets. The improvement in flow characteristics may have an impact on or improve the interference zone's heat transfer properties. Therefore, when examining the impingement heat transfer of twin jets, these characteristics should be taken into account.

3.2 Multiple jets with different impingement target configurations

An essential component of the jet impingement heat transfer system is the impingement target. A homogeneous temperature distribution on an impingement-cooled or -heated target is desired in the majority of applications. When the effects of various impingement target qualities, such as moving, rough, and nonflat surfaces, are taken into account, heat transfer characteristics should be improved. Numerous research has examined the impact of impingement target features using the same influential parameters that were previously identified. The impact of heat and fluid flow properties on the solar air passage of a circular impingement jet was examined by Nadda et al. [70]. According to the results, heat transfer and friction were optimally enhanced by 6.29 and 9.25 times, respectively, compared to a smooth absorbent plate. For a Re value of 13,000, the ideal thermal hydraulic efficiency was 3.64. Using LES, Draksler et al. [71] conducted experiments to investigate the fluid flow dynamics and heat transfer conditions of a multiple-impingement jet under varying Re values up to 20,000. The dynamics and complexity of the immediate flow field were analysed using numerical models. The effectiveness of jet impingement in quick food freezing and cooling systems is controlled by a number of factors [25]. JIT is a technique for improving heat transfer. The extensive use of JIT in key turbine parts, glass technology, electronic components, drying paper, textiles, biomaterials, and food preservation is demonstrated by the literature. JIT's fluid dynamics and heat transfer characteristics are intriguing. It is a significant research issue because of its relative simplicity, low cost, air abundance, fast heat transfer generation, and quick freezing rates. Jet impingement in rapid food freezing and cooling systems has been studied using a variety of methods, including factorial and mathematical modelling, computational simulation, experimental, visualisation, and numerical analysis. The literature on the governing parameters of jet impingement in systems for quick food freezing and cooling is reviewed in this work.

The arrangement of a moving impingement plate and its impact on flow and heat transfer due to multiple impinging jets were studied by Yang and Hao [72] and Aldabbagh and Mohamad [73] In order to avoid local hot (or cold) spots, it is necessary to choose the geometry and flow parameters in multiple-jet impingement systems [63]. The design of multiple-impingement jets was studied statistically by examining three turbulent slot jets impinging on a sliding flat plate. Parameters,

Dimensionless pitch, entry Re, dimensionless velocity ratio (plate-to-jet), and dimensionless nozzle–surface space were all taken into account. The findings showed that interference effects were amplified in closely spaced jets. When a surface was moving, the impinging surface's skin friction coefficient had a significant impact on the surface motion. The heat transfer feature, however, had no discernible impact within the velocity ratio range that was being examined. Similar factors were taken into account numerically for an array of square jets that impinge on a moving heated flat plate in another study. This study aims to explore the effect of flow structure on the parameters of heat transmission [73]. The current moving plate case and the fixed-plate scenario were compared using a 3D simulation. The findings showed that the cross flow was enhanced by the moving plate's velocity ratio. Whether the plate was stationary or moving had no effect on the oscillatory behaviour of Nu profiles. Prior research has demonstrated that surface motion has a negligible impact on heat transfer properties, leading to the use of stationary plates in multiple-jet heat transfer systems.

Even though [74] had previously examined the features of flat plate transient heat transfer for circular air–jet impingement, the local Nu quickly rose when air jet impingement started. Nu's growing speed reduced when the jet impingement continued to cool (at the 50–80 s area). Reference [75] examined the heat transfer and fluid flow during the heat transfer of slot jet impingement numerically. A secondary peak was noticed in the Nu at a tiny value of the nozzle–plate distance. The mean velocity profile in the stagnation region deviated from the usual law of the wall, according to the results. In the absence of disturbances, the Nu was greater. Near the secondary Nu summit, large-scale vortical formations were seen.

In [76], the heat transfer performance and microgrooved surfaces of boiling jet array impingement were investigated. Under fully developed boiling conditions, the impinging jet's heat transfer efficiency is independent of the Re. The radial microgroove surface conveyed a significant heat flow of 380 W/cm2 while achieving the greatest heat transfer coefficient of h = 230 kW/m2 K. Additionally, [77] assessed the impingement heat transfer on a cylindrical surface using various jet shapes. The condition of Nu distributions in a cylindrical surface was examined using the transient liquid crystal technique. They assessed how the form of the hole and the variation in the hole inlet affected things. The exit conditions were studied using cylindrical and racetrack-shaped holes. For the cylindrical and racetrack-shaped holes, Nu is connected to Re. Compared to the cylindrical holes, the racetrack-shaped holes achieved a greater heat transmission rate. A method for creating a mechanistic heat transport model that permits steel cooling was provided in Reference [78]. This work was based on systematic experimental examinations. Heat fluxes that occur in stationary plates during jet impingement boiling were computed, and was investigated. Farahani et al. [79] used the adjoint equation in conjunction with a conjugate gradient approach to investigate the slot jet impingement's heat transfer coefficient. Heat transfer coefficients decreased with increasing separation space and increased with increasing Re. This approach might be used to determine how the local Nu changed over time. Furthermore, the effect of employing different plate materials was tested in [80] during examining the rectangular step scenario. The local Nu rose with the Re, according to the results.

Rough surfaces with various configurations, such as dimpled and ribbed surfaces, were studied to address the problem of jet impingement in the context of further increasing the levels of heat transfer enhancement. [81]. Heat transfer was measured using the transient liquid crystal technique. Regarding the location of the jet impingement hole, this study took into account the two-dimple configurations of inline and staggered arrangements. The findings showed that when dimples were present on the target surface, the heat transfer coefficients were lower than when the target surface was not dimpled. The impact of surface ribbing on the impingement heat transfer caused by an elliptic jet array was examined by Yan and Mei [82]. The broken and continuous V-shaped rib configurations with three angles were covered in this study. Heat transmission was measured using the liquid crystal thermograph technique in Additionally, the research showed that the ribbed surface may either accelerate or slow heat transfer. When the rib angle was 45° and the ribs were continuous, the best heat transfer was achieved. In order to further investigate the impact of dimple shape on heat transfer resulting from several impinging jets, convex [83] and concave [84] surfaces as well as the fusion of both shapes [85] were introduced. Uniformity also improved over the convex-dimpled surface. Regarding the concave-dimpled surface, it may be possible to increase heat transmission in the average Nu from the smooth-walled level across the dimpled surface if Re, E/H, and S/Dj ratios are sufficiently chosen. Dimpled-concave and -convex surfaces with and without effusion were investigated. The findings demonstrated that a surface with concave dimples had a lower average Nu than a surface with convex dimples when effusion was absent. The variations in the average Nu between the noneffusion and effusion findings for each dimpled surface demonstrated a steady decline as Re increased. Two impingement surface topologies were examined by Rallabandi et al [86]. A variety of circular jets impinging on porous and ribbed surfaces were shown in this study.

Investigations were conducted into the flow and heat transfer properties of numerous jets impinging on nonflat impingement surfaces, namely concave surfaces [87] The cooling of a spinning semi-cylinder passage caused by a row of impinging jets was experimentally studied by Iacovides and Launder [88]. The flow was visualised using laser Doppler anemometry and PIV techniques, while the local Nu was measured using the liquid crystal method. High rates of Nu were found near impingement spots and midway between them, according to the stationary case results. However, because of the rotation impact, which accelerated jet spreading rates, the Nu decreased in certain regions. The nonrotating situation of this work was simulated for turbine blade cooling applications by T.J. Craft [87]. Both linear and nonlinear eddy viscosity models with wall function were taken into consideration. The simulation's findings showed that heat transport could not be adequately predicted using the conventional log law-based form of the wall function. Moreover, it was essential to approximate convective terms precisely. By changing the jet tube diameter (d) while keeping the impinging surface diameter (D) constant, the impact of high relative curvature (d/D) was investigated given the same surface design [80]. Infrared thermal imagers and the heat foil technique were used to measure the heat transfer characteristics. Linear regression was used to get the local heat transfer coefficient. The Nu distribution was found to be comparable to the distribution of a concave surface across a flat plate. As the relative curvature increased, so did the heat transfer close to the impinging zone. Nonetheless, the general decrease in the Nu was caused by the variation in confinement. As a result, the nonflat impingement surfaces showed different effects on the heat transfer behaviour when numerous jets were impinging.

Three different scenarios of an impingement target being struck by different jet configurations were shown in this study. The impingement heat transfer and flow pattern were impacted differentially by the nonstationary, nonflat, and rough surfaces. When the goal of the study was to examine the impact of interference between the features of impingement heat transfer and jets on flow, fixed, flat, and smooth plates were frequently used. In order to guarantee that the issue could be contained solely within the influence of the twin-jet features, our analysis disregarded the effects of the impingement surface parameters. Investigations were conducted into the flow and heat transfer properties of numerous jets impinging on nonflat impingement surfaces, namely concave surfaces [87]. The cooling of a spinning semi-cylinder passage caused by a row of impinging jets was experimentally studied by Iacovides and Launder [88]. The flow was visualised using laser Doppler anemometry and PIV techniques, while the local Nu was measured using the liquid crystal method. High rates of Nu were found near impingement spots and midway between them, according to the stationary case results. However, because of the rotation impact, which accelerated jet spreading rates, the Nu decreased in certain regions. The nonrotating situation of this work was simulated for turbine blade cooling applications by T.J. Craft [87]. Both linear and nonlinear eddy viscosity models with wall function were taken into consideration. The simulation's findings showed that heat transport could not be adequately predicted using the conventional log law-based form of the wall function. Moreover, it was essential to approximate convective terms precisely. The impact of high relative curvature (d/D) was investigated given the same surface design [80]. The Nu distribution was found to be comparable to the distribution of a concave surface across a flat plate. As the relative curvature increased, so did the heat transfer close to the impinging zone. Nonetheless, the general decrease in the Nu was caused by the variation in confinement. As a result, the nonflat impingement surfaces showed different effects on the heat transfer behaviour when numerous jets were impinging.

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3.3 Inclined multiple jet impingement

When the inclination angle in a jet impingement system interacts with other multiple-jet parameters, it is anticipated that the flow and heat transfer properties will change. On the one hand, this parameter was examined by taking into account the angle between the jets and the impingement surface; on the other hand, the orientation of the entire system (jets and impingement target) was examined. The selection of an effective system configuration that concentrates on the common characteristics associated to impinging twin jets is where the significance of examining such pertinent studies lies.

In order to ensure that the static wall pressure decreased and the coefficients of local heat transfer in cutting-edge triangular ducts could be determined, three inclination angles (such as 30°, 45°, and 60°) of jets impinged within a duct were taken into consideration during the experimental study. Heat transfer experiments were conducted at various jet Re ($3000 \leq Re \leq 12600$) and jet spacing values ($s/d = 3.0, 6.0$) using the transient liquid crystal technique. Because Duct C had the highest jet centre velocity and the shortest jet inclined angle, the results demonstrated that it achieved the maximum rate of wall-averaged heat transfer. Heat transfer was not as effective as typical impingement. A pair of jets impinged on an inclined surface were the subject of a numerical investigation into the impact of the jet impingement angle () on average and local Nu. FLUENT 5.2 software and the finite volume method were used to solve the 3D Navier-Stokes equations. The range of the Re was 500–20,000. Additionally, the impingement angle varied in 15° increments from 30° to 90°. Two scenarios—Case A with wall boundary conditions and Case B with atmospheric pressure boundary circumstances—were taken into consideration. According to the computation findings, Case A Outperformed Case B in terms of peak Nu. Nuavg might be improved by nearly four times the value of Re at 20000 by increasing the jet impingement angle. In conclusion, the two works' inclination angles had comparable effects on heat transport. Self-similar behaviour in local heat transfer was investigated using jet impingement of the laminar slot and submerged jets [92].

An array of slot jets impinging on a heated flat plate was used to demonstrate various multiple-jet impingement system orientations

[93]. The impacts of cross flow and buoyancy induced flow and hot surface orientation with respect to gravity. The Re and Rayleigh numbers on heat transfer characteristics were all examined in this work. Type T thermocouples were utilised to measure the surface temperatures after the impingement plate was heated using a panel heater driven by a regulated DC power source. For best results in real-world applications, the hot-surface orientation is crucial. The Nu was independent of the hot-surface direction in Re ≥ 400 and Ra ≥ 10000. With a hot surface facing up, the Nu of vertical and horizontal orientations were roughly comparable. Nonetheless, Nu was higher in both orientations than in the horizontal orientation with the hot surface pointing downward. Due of the associated high Nu and design constraints, the vertical orientation was practical for convection heat transfer measurements.

In order to demonstrate that the stream-wise development of a short impingement distance surface would raise the Nu but decrease it with a large impingement distance, Reference [94] provided data on local and averaged heat transfer coefficients. The Re would be impacted by any changes (increase or reduction in span-wise and stream-wise spacing). In the row of averaged Nu, the Nu of impingement jets with an inclined angle showed high prediction performance and were consistent with the conventional impingement jets. The crucial conclusion that the vertical impingement plate is the effective configuration that generates the features of high heat transfer in many impinging jets was disclosed by the findings of earlier studies pertinent to the influence of inclination angle. As a result, this configuration is taken into account in the current study for an effective twin-jet impingement heat transfer system.

3.4 Impact of the individual nozzle geometry in multiple impinging jets

To improve the impingement properties of heat transmission, the nozzle arrangement in a multiple-jet system was changed. In addition to the elements pertaining to each individual nozzle, several nozzles were set up in the configuration of related nozzles. Various criteria are used to construct a single nozzle, along with other geometrical factors pertaining to multiple jets, the impact of nozzle size on heat transfer and jet impingement flow was examined. Su and Chang [95] used a grooved orifice array plate with different nozzle sizes to increase the impingement heat transfer. Re ranged from 1000 to 4000, and a small S/D (S/D < 1) was measured. The combined effect of the nozzle and groove size was taken into consideration for the three examples (e.g., A, B, and C).

Heat transport was measured using infrared thermography. The findings demonstrated that jet-array C consistently produced high average values at S/D = 0.5. No. The impact of nozzle diameters on the flow characteristics and heat transfer of divertor cooling at the power plant of conceptual fusion was investigated numerically by Koncar et al. [96]. Around the central nozzle, the nozzles were arranged in four circles. Then helium jets from a cartridge struck a target in the shape of a thimble. The governing equations were solved using the ANSYS CFX 11.03D code. While the overall areas of the jets stayed constant, the four scenarios with different nozzle diameters were taken into consideration. The results showed that by lowering the temperature to formulate equal nozzle diameters, it attained the best divertor efficiency. Terri B. Hoberg [97] examined the impact of nozzle size on the heat transfer of a staggered array of jets with fusion holes in a different study. Three scaled models were used, each with a different nozzle diameter and Re between 500 and 10,000. A k-type thermocouple was used to detect the surface temperature after the impingement plate was heated using an electrical resistance heater. The findings showed that high transfer coefficients of dimensional heat might be attained by using small-scale arrays.

Due to the impingement of many jets, the nozzle form is anticipated to have a noteworthy effect on heat transmission. For an array of jets [99] and as three lines of circular jets against a single-slot jet at the same Re [100], circular and slot nozzle shapes were taken into consideration. The highest heat transfer coefficient peaks for circular jet arrays are more noticeable than those for slot jet arrays. Additionally, compared to slot jets, three-row jets have a greater heat transfer increase. Other studies used liquid crystal thermography to experimentally examine the elliptic nozzle shape's aspect ratio (AR) influence [101], [102].

Various Res were used for the experiments. The findings show that the elliptic jets of AR = 0.5 impact on a flat surface at the maximum mean heat transfer rates at Re = 3000 and 4500; jet arrays with AR = 2 and 1 outperform those with AR = 0.5 in the low-Re situation of 1500. A circular jet with AR = 1 provides the best heat transfer performance for an array of elliptic jets that impinge on a foil hole target [103]. According to their experimental findings, a moving nozzle reduces the maximum temperature differential between a heated surface and the mean thickness of the liquid sheet more effectively than a settled nozzle, leading to constant temperatures and heat transfer rates. Temperature uniformity and improved heat transmission can be attained with a high nozzle speed.

The authors evaluated the two-phase flow patterns, heat transfer, and jet impingement in a Hele-Shaw cell during the boiling process in [104]. Excellent heat transfer results were obtained along with a pressure drop with a diameter of 10 mm, a spacing of 0.1 mm, and a jet diameter of 1 mm. For a heat flux, the equivalent flow boiling pattern is 327 W/cm2. Similarly, a prior work [105] investigated the cooling process on both stationary smooth discs and high-speed reciprocating discs with uniform heat flux and no phase shift using an impinging oil jet situated in a cylindrically restricted region. A high stagnation zone Nu and a modest overall surface average Nu were found for jet impingement on a stationary disc at short impingement distances, Authors in [106] performed a numerical analysis of the turbulent round jet impingement heat transfer on the high temperature difference. According to the numerical results, the heat transfer coefficient rose as each thermal attribute was increased, but it dropped with density.

Different edge forms can be used to construct the nozzle, which could have an impact on the impingement heat transfer properties in a multiple-jet system. Four-nozzle arrays with four edge configurations were examined by Royne and Dey [98]. A digital camera and liquid crystal thermography were employed. According to their findings, the average heat transfer coefficients of countersunk nozzles are higher than those of the other geometries.

Choo et al. [108] looked at how the nozzle-to-plate separation affected the fluid flow and heat transmission during submerged jet impingement. According to their findings, three zones were distinguished between the pressure and the Nu:

1. Zone I: zone of jet deflection ($H/d \leq 0.6$)
2. Potential core region ($0.6 < H/d \leq 7$) is zone (II).
3. Free jet zone (III) ($7 < H/d \leq 40$)

As the nozzle-to-plate distance decreased in Zone I, a notable rise in pressure and the Nu was noted. The nozzle-to-plate distance has very little effect on the pressure and Nu in Zone II. As the nozzle-to-plate spacing increased in Zone III, a monotonic drop in pressure and the Nu was noted. Wang et al. [109] used jet impingement at a high-temperature plate surface to assess the heat transfer properties. Taking into account various industrial uses, they investigated the impact of water temperature, beginning surface temperature, and jet velocity on the heat transfer characteristics. Heat flux seemed to be primarily affected by jet velocity, water temperature, and surface temperature.

In addition to the four designs mentioned above, two additional dense and nine/spare nozzles with straight edges were taken into consideration [110]. The findings show that four-nozzle arrays outperform nine-nozzle arrays. Geers and Tummers [111] looked into the curved nozzle shapes and the sharp-edged orifices. In comparison to the curved nozzle geometries, the sharp-edged orifice jets successfully generated a greater initial core velocity at the same Re, which led to a higher impingement-point heat transfer.

Impingement heat transport is significantly impacted by the geometrical arrangement of numerous jets. Compared to the other jet shapes, the circular jet shape performs more efficiently. Furthermore, in a jet array configuration, the sharp edge outperforms the other edge types. Additionally, effective jets with good heat transfer properties on a flat plate are delivered by nozzles of equal size. Circular equal-size jets typically signify appropriate design choices.

4. Multiple jet arrangement effect

The performance of heat transfer at the impingement target is anticipated to be impacted by the geometrical arrangement of many jets, particularly the array of jets, which will also affect the behaviour of interference between jets. Numerous researchers with varying multiple jet impingement system setups and scales have examined this problem. The parameters of interference between jets are essentially the same in all configurations, even if the geometrical arrangement relates to the array of jets. Nonetheless, crucial design choices could be guided by the effective arrangement.

Nakabe et al. [112] conducted an experimental study on the duct, which measured 21 mm in height and 432 mm in width. They measured heat transfer using the thermochromic liquid crystal method and the neutral network algorithm, and they looked at the flow visualisation using fluorescence dyes and PIV techniques. Their findings show that the geometrical configuration of the jets had an impact on the interference between them, which in turn affected the heightened zones of heat transmission. Only three longitudinal vortices were created in the inline arrangement scenario, compared to four in the staggered jets example. Additionally, in the inline example, the Nu has a higher peak upstream than downstream. The behaviour of staggered jets was different.

The improvement in heat transfer of a slot jet impingement with numerous nozzles and different duty cycles was investigated numerically in [113]. The numerical results demonstrate that the heat transfer performance of steady impingement jets is better than that of unsteady impingement jets in the case of double-slot impingement jets under the same Re and a phase difference (θ) of 0°. Heat transfer is best achieved with robust impingement jets.. The worst heat transfer performance occurs above a threshold frequency of 50 Hz and below a duty cycle of 0.5. Experimental research on the many uses of a solar air heater on a corrugated absorber plate was conducted by Aboghrara et al. [114]. To ascertain the impact of jet impingement on the corrugated absorber flat plate, they examined the efficiency and outlet temperature of a solar air heater. Their results show that heat transfer efficacy in solar air heaters is strongly influenced by the mass flow rate of air. Additionally, compared to a smooth duct, the suggested duct design's thermal efficiency was about 14% higher.

In order to anticipate the flow and heat transfer characteristics, several configurations of the square and circular arrays of nine impinging jets were taken into consideration [115]. The governing differential equations were solved using the finite volume approach with the SIMPLE scheme. The numerical results indicated that although the square configurations displayed an asymmetric flow pattern, the circular array of jets exhibited symmetrical behaviour. With the exception of the central jet in a circular arrangement at high heat transfer, this flow pattern produced similar heat transfer characteristics of separate jets because one jet was developed at the expense of the other in the square array scenario.. The authors of [116] investigated the effects of vortex generators on jet impingement heat transfer at various cross-flow Res. To increase the impingement heat transfer rate, a vortex generator pair (VGP) was positioned between the crossflow channel and the upstream of the jet outlet. At varying heights, delta winglets (DW) and rectangular winglets (RW) were deployed. Next, the flow structures and heat transfer processes were investigated.

The heat transfer characteristics and the impact of the jet Reynolds of imping jet arrays [117] were investigated numerically and experimentally for a variety of geometrical arrangements and parameters, such as the non-corresponding slot widths for the local Nu division, the non-corresponding nozzle-to-plate and jet-to-jet spacings, the local Nu that corresponds to the impingement region, the stagnation point and relative minimum for any configuration when the Re increases, and the low ratios of the plate spacing-to-jet hydraulic diameter. The stationary Nus reduced as the jet-to-jet distance increased while the Re stayed constant.

The effects of various micro-jet configurations and the ratio of total jet area to surface area on impingement heat transfer were investigated by Michna et al. [118]. The difference between the heater's heat dissipation and the heat losses was used to calculate the heat flux. There was no indication that the jets differed at the micro and macro dimensions. Additionally, an inline array with an area ratio of 0.159 showed the highest Nus. Furthermore, the area ratio's ideal value revealed a staggered arrangement. Similarly, [119] investigated the slot jet impingement heat transfer for the moving nozzle and plate. The investigation showed that as the nozzle or plate velocity increased, the Nu decreased. There was a big impact from the moving nozzle.

Numerous research, including [14], [28], have examined experimentally the effects of employing the twin impingement jet mechanism (TJIM) on improving fluid flow characteristics and heat transmission in order to increase the heat transfer rate in the passive heat transfer approach. Heat flux-temperature micro foil sensor readings and infrared thermal imaging (Fluke Ti25) were used in earlier research. While the nine models on the target's impinged flat were used to gather heat flux-temperature data, the results show a discernible and significant improvement in the localised heat transfer coefficient regarding the steady flow at radial distance positions on the measured aluminium surface at various Res and with the gradual decrease when moving away subsequently from the interference area's centre. We can take into account the distance between the nozzles and the space between the nozzles and the jet to determine the best condition for establishing higher heat transfer rates for the current issue. The impact of the many chosen models in various configurations on the heat transfer characteristics related to the twin jet impingement mechanism might therefore be defined by the various results that are presented. Furthermore, for all Re values utilised, the best heat-transfer coefficient is found in the vicinity of the nozzles and the aluminium plate, as well as the closest distance between the nozzles, particularly in the first five spots at the plate.

The experimental and numerical simulations of the heat transfer enhancement in the twin impingement jet system were investigated in earlier research [13], [26]. In order to enhance heat transmission and examine the impact of distance between nozzles and plates on the Nu (Nu) and the heat transfer coefficient (nu), this paper includes numerical and experimental evaluations. The computational examination of the heated plate was investigated by simulating electronic components using the RNG k-μ turbulence model. At various distances, the jet-plate's position was altered. We also looked at the heat transfer coefficient, the local and average Nus, the static pressure, and the primary flow structure. The findings support a novel approach to enhancing the TJIM's flow and heat transfer capabilities. The optimum model for the heat transfer coefficient and the maximum Nu is found at the closest spacing between the nozzles and the nozzle and the plate, according to the results of research conducted at different TJIM positions.. In this instance, the researchers used the TJIM of 9 models to perform a numerical simulation based on the RNG k-μ turbulence model. The Nu and thermal enhancement factor for the impacts of the nozzle-nut distance (S / D), H/De, and the Re number were further examined in the computation of the heat transfer coefficient. It has been demonstrated that Model 1 works well for determining the Nu number of S / D = H / D = 0.5 in all jets. Model 9 showed the worst results, with S/D = 1.5 and H/D = 5.5. The findings demonstrate that the local Nu number (Nu) is distributed unevenly onto the damaged area as a function of flow turbulence. This work examined the flow structure on a flat wall and the heat transfers of sweeping jet impinging. Analysis was done on the unstable flow structure with an appropriate orthogonal composition. Two separate local Nu areas form along the wall. Near the wall, there is a correlation between the flow structure and the Nu distribution. The effects of the nozzle-to-plate spacing and the Re are examined. The transfer heat from a moving surface with a uniform wall temperature caused by the impingement of a number of slot jets was investigated numerically by Kadiyala and Chattopadhyay [18], using the transition–SST model. For both turbulent and laminar slot jets, there was good agreement with the available data. In order to comprehend how surface velocity affects the flow regime, the heat transfer was further investigated. The range of Re is 100–5,000. At high surface velocity, the moving wall transfers more heat than it would in a stationary situation. At the Re of 400, the regime starts to change from laminar to turbulent, and at the Re of 3,000, it is fully turbulent.

The shape and dimensions impacts of impingement synthetic jets on the flow field and heat transfer were investigated by Hatami et al. [17]. We looked at how the flow field and heat transfer rate were affected by confined and unconfined geometric patterns. Heat transport and the flow field were investigated in relation to the restricted synthetic jet of impingement distances. We looked at the Re's flow field and heat transfer effect. The flow and heat transfer behaviour of the variations in stroke length were examined. The vortex and, thus, the heat transmission structure are impacted by increasing the distance between the jet and the surface.

[120] conducted both numerical and experimental research to examine how the impingement dimples on the surface affected the heat transmission properties in a circular test plate. The dimple shape and the impingement jet approach can accelerate the rate of heat transfer brought on by the high intensity of turbulence. In this piece, the dimple's cylindrical shape was employed. The experimental data collected from four different kinds of test plates was used to validate the simulation results. The complicated flow and heat transfer properties are provided by the simulated data, which also shows the test plate's contour temperature surface and flow structure. According to the experimental data, the maximum heat transfer rate was obtained when the dimple diameter (d) was equal to the jet diameter (Dj) and the distance between the jet and the test plate (B) was double that of Dj. When compared to a flat plate at Rej = 14,500, the heat transfer rate was increased by up to 200%.

Due to the impinging row of jets in various configurations, narrow channels were constructed in order to monitor the heat transfer [121]. The transient liquid crystal technique was used to measure the temperature distribution on the impingement target. The findings show that the distribution of the convection coefficients is strongly influenced by the jet arrangement. Additionally, the cooling jets may effectively cover the impingement area thanks to the inline arrangement. As a result, compared to a staggered design, the heat transfer coefficients show higher rates.

One important issue is the geometric shape of impinging jets. Using an elliptical form resulted in a better heat transmission. Compared to rectangular jets, elliptic jets have higher heat transfer coefficients. The Re of 10,000 and the H/d of 2 had the highest heat transfer efficiency. The jet geometries improve the AR, Re, and jet–plate gap while increasing the heat transfer coefficient on the target plate by roughly 6.01% to 16.8% at the major surface. The turbulent kinetic energy distribution at (x/d, y/d) = (0.0, 0.0) is then shown, showing similar distributions for all nozzle geometries [122-124].

Because several impinging jets can be arranged differently, impingement heat transfer exhibits a variety of behaviours. The various configurations result in varying numbers of each nozzle's closest neighbours and impinged areas. Consequently, the way the jets interfere with one another is determined by the multiple-jet pattern. In general, an inline arrangement of several jets results in optimal performance. To investigate the interference between two nearby jets, twin-jet configurations might be chosen as a standard setup.

5. Effect of nanotechnology in impinging jets techniques

The application of nanotechnology to impingement heat transfer has opened up a large field of study in a number of areas. Twin-jet impingement heat transfer is still taken into consideration while validating experimental techniques, despite the availability of numerous kinds of nanofluids and nanocoating materials [19]. The multiple-jet impingement heat transfer problem may be limited by these problems. Three distinct methods for heat transfer enhancement were used in our earlier study [125] to examine the impact of the concentration of TiO2 nanosolution on the double impingement jet of a heated aluminium plate. A twin jet impingement system, the heat sink, and the TiO2 nanosolution coat were taken into consideration. A number of other factors were also examined, including the separation between the nozzles, the concentration of the nanosolutions, and the distance between the nozzle and the plate. We then used field emission scanning electron microscopy (FESEM) and X-ray diffraction (XRD) to examine the structure and uniform surface coating of our nanosolutions. After analysing every outcome, we concluded that the twin impingement jets' flow structure in the interference zone was the main cause of the increase in heat transfer rate. The Nu was impacted by the ratio of nanoparticle size to surface roughness. The heat transmission properties could be enhanced by choosing the right impingement mechanism and the ideal concentrations of additional variables. The rate of heat transmission was positively impacted by the TiO2 nanosolution surface coating as well.

The effect of jet–plate spacing to jet diameter ratios on the heat transfer and pressure drop of TiO2 nanofluids through jet impingement was examined by Nakharintr et al. [15]. Using a wire electrical discharge machine, the heat sink was constructed from aluminium with dimensions of 50 mm for length, 50 mm for breadth, and 3 mm for base thickness. The jet-plate spacing to jet diameter ratios (H/D = 0.8–4.0), mass flow rates (8–12 g/s), and nanofluid concentrations (0.005%–0.015% by volume) are among the parameters and ranges that are being examined. The temperature and flow characteristics of jet impingement, which enhanced turbulent intensity and heat transfer rate, are strongly influenced by the jet–plate spacing to nozzle diameter ratios. In the meantime, LV et al. [126] used three heat transfer enhancement techniques—jet impingement, micro-channel heat sink, and nanofluids—to study the continuous TiO2 nanofluids jet impingement heat transfer and flow in a micro-channel heat sink. The obtained results demonstrate that, at a concentration of 0.015% nanofluid, the suspension of nanoparticles in the base fluid significantly enhanced the convective heat transfer by 18.56%. Furthermore, as the nozzle level height decreased and the nozzle diameter increased, the acquired heat transfer coefficient tended to rise.

[20] presented the numerical study of heat increase and fluid flow from a heated surface utilising nanofluids with three impinging jets. Numerical analysis was used to examine the impacts of various volume ratios, heat fluxes, and nanofluid types (such as CuO-water, Al2O3-water, Cu-water, TiO-water, and pure water) on heat transfer and fluid flow. The average Nu rises by 10.4% when the volume changes from μ = 2% to 8%. The six increase in heat flux had no effect on the average Nu. CuO-water, TiO-water, Al2O3-water, and pure water increased by 2.2%, 5.1%, 4.6%, and 9.6%, respectively, as a result of using Cu-water nanofluid. Heat transfer properties were experimentally investigated by [127]. To examine the quantitative effects and raise the critical heat flux, the impact mechanism of the surface differentiating parameters was investigated. The shifting nanoscale had little effect on the heat transmission properties. The detraction of solid-liquid might improve the heat transfer coefficient, but the critical heat transfer obviously declined.

[128] and [129] looked into how nanofluids affected the augmentation of heat transmission. The magnetic field influence of a confined impingement jet in a mini-channel heat sink on the improvement of nanofluid heat transfer was demonstrated by Nakharintr et al. [128]. Their findings demonstrate that, in contrast to the concentration of thin nanofluid without a

magnetic field influence, the Nu rises with the magnetic field effect. The test findings, however, show that the concentration of nanofluid has no appreciable impact on pressure decrease. Tiara [129] investigated the effects of an alumina nanofluid jet on the enhancement of heat transfer on a steel plate. The results demonstrate an improvement of about 7.74% following the nanofluid jet impingement on the plate surface roughness, which increases the number of nucleation sites.

In their second study [130], the researchers freely used nanofluid (SiO_2-water) to evaluate a single impingement jet. According to their experimental findings, using nanofluid significantly improves heat transfer efficiency. The SiO_2-water nanofluid with a 3.0% nanoparticle volume fraction and Re between 8,000 and 13,000 had a convective heat transfer coefficient that was 0.04 higher than that of pure water. In subsequent studies, the authors suggested examining the effects of dispersed nanoparticles and the impingement jet's condition. In their third investigation [131], the CuO-water nanofluid in circular impingent jet cooling was used to experimentally analyse the heat transfer properties of a heated surface; the Nu increases were 14% for $\varphi = 0.15\%$ and 90% for $\varphi = 0.60\%$. Using scanning electron microscopy, the properties of the test plate surface following nanofluid jet impingement were examined. A unique array cone heat sink was quantitatively investigated in a prior study [132] to improve the cooling and heat transfer effects of fluid impingement; the results demonstrate that the impact of fluid impingement on a cone heat sink is better than that on a traditional flat plate heat sink. The following parameters produced the best cooling effect: $A = 50°$, $d1/d = 2$, and $H/d = 5$. Nu− rose significantly as Re increased within the range of 16,000–32,000. The heat transfer coefficient h rose with the Nu in a study on improving cooling in central processing with jet impingement with and without nanofluid [133]. Nevertheless, the Nu was constant at 831 between Re = $23*10^3$ to $50*10^3$ and a jet impingement angle of (30) and (75), indicating that the area was turbulent.

There are numerous methods to increase heat transfer and flow properties [134], [135]. Since strong convective heat transfer has a notable impact on impingement heat transfer, nanotechnology involving nanofluid and nanocoating is frequently used. Furthermore, the impact of twin jet impingement on various jet flow and heat transfer configurations was ascertained. The heat transmission of dual impingement jets is influenced by a number of important parameters, including the Re, S/D, H/De, plate or nozzle inclinations, and heat flux.

6. Discussion

A literature review is a systematic, repeatable, and explicit design that aims to rectify, analyse, and differentiate the available publications. These days, the process for creating review articles is shared by many other fields (such as social science, engineering, and medical).

The successful search and acquisition of research papers is primarily made possible by online journal databases like Science Direct, Scopus, Google Scholar, and Emerald. These databases show the proportion of the exercised database and include works from a variety of publishers, such as Taylor, Elsevier, ASME, Springer, Emerald, and IEEE. If all of the papers are indexed in ISI and Scopus, only English papers are taken into consideration, and no selection was made based on journal rating. The project or study may be defined by the use of designated keywords, such as heat transfer enhancement, impingement jets, numerous jets, nano fluid, and nano coating. To establish the study standard for the analysis, we downloaded a large number of pertinent published articles based on research methodology, study objectives, simulation, conclusions, data gathering techniques, and data analysis tools. In order to categorise the articles, the research approach was taken into account for each study by highlighting its philosophical foundation. By weighing the methods' benefits and drawbacks, the authors conducted a constructive review of the approaches.

This paper provides a comprehensive analysis of the numerical, theoretical, and experimental research that identify the variables impacting twin jet impingement and the associated flow and heat transfer performance. The numerous research that have focused on steady impingement jets have only considered the most relevant examples of twin impinging jets. However, there is still little research on twin impingement jets. As far as the authors are aware, there aren't many papers that use experimental and numerical evaluations of twin jets.

There is a dearth of knowledge on heat transfer increase through twin jet impingement, despite the existence of numerous pertinent articles. To create twin impingement jets (Figure 3), a unique system that regulates all of the previously listed parameters must be created and tested.

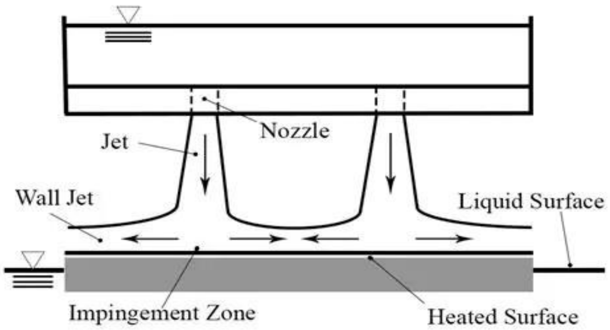

Figure 3 Twin-Jet Effect.

Additionally, there hasn't been enough research done on the interference zone between two nearby jets and the impact of twin impingement jets in this area on flow structure and heat transfer. The Nu and the important characteristics identified in the literature have not been shown to be correlated. Furthermore, the linked factors' interactions have not been thoroughly examined. To increase understanding of heat transfer characteristics in cooling and heating applications, all of these flaws must be fixed.

Additionally, we looked over a number of research regarding how various jet shapes affect flow characteristics and heat transfer enhancement. To concentrate on a topic that hasn't been studied before, a thorough investigation was carried out to ascertain how twin jet impingement affected various jet flow and heat transfer configurations. Important variables pertaining to the heat transmission of dual impingement jets include the Re, S/D, H/De, nozzle or plate inclinations, and heat flux. Insufficient consideration has been given to the interference zone between two nearby aero planes. Not enough research has been done on how impingement affects the flow structure and heat transfer in this area. Furthermore, the linked factors' interactions have not been thoroughly examined. To address a previously unexplored field of research, a thorough investigation into the impact of twin jet impingement in multi-jet flow and heat transfer was carried out.

The importance of advancing nanotechnology-based research for various heat transfer-related applications should also be emphasised by researchers. It is also necessary to discuss how the jet designs affect the heat flux factor and how the concentration of nanoparticles affects the Nu. At the interference zone's centerline, a velocity increase was seen, which improved heat transmission and raised Nu. According to the research, choosing the right impingement system and the ideal concentrations of the contributing elements can improve the heat transfer characteristics. Only the most pertinent instances of dual impingement jets are covered in this study, however several research have looked into occurrences of steady impingement jets. There is not much literature about twin jets. The list of the most pertinent studies on stable impingement jets is shown in Tables 1 through 4. This article's conclusions are supported by the information that is now accessible as well as other possibilities.

4. Conclusions

This article provides a thorough analysis of the experimental and computational studies that were used to determine the key variables influencing the flow and heat transfer performance of multiple impingement jets. A comprehensive study of the research on multiple, single, array, and twin impingement jets for flow behaviour and heat transfer enhancement is provided, along with an identification of the important variables involved. The review highlights the dearth of information regarding the heat transfer issue in jet impingement. The many impingement jet setups are covered in the pertinent literature. Crucial challenges are those that affect how flow and heat transfer behave as well as the possibility of improving these properties. There is little study on impingement jet methods. No experimental or numerical research has been done on the improvement of heat transmission using dual impingement jets at a radial distance for stagnation points. It was examined how jet impingement affected the improvement of heat transfer. By choosing an appropriate impingement system and taking into account the ideal amounts of the influencing elements, the heat transfer characteristics can be improved. Research on stable impingement jets can shed light on the behaviour of jet flow and improve heat transfer. To further understand the thermal behaviour of impingement jets, flow properties should be investigated. We don't know enough about how created vortices behave. Therefore, we recommend more research on this subject using visualisation methods like PIV and high-speed cameras. Given the paucity of information on this topic, it is worthwhile to investigate how nozzle geometry affects heat transfer and fluid flow. Given the substantial influence of wall jet features, measuring the turbulence intensity close to the impingement wall in the event of heat transfer is crucial. It is necessary to look into the relationship between the Nu and the important elements. Furthermore, the linked factors' interactions have not been thoroughly examined. There is little data on how high pressure temperature, spray, and jet impingement affect the rates of heat transfer in different nanofluids. Applications of nanofluids in impingement jet techniques are very promising and require more research.

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