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Turbulent Flow and Heat Transfer Characteristics of Resonant Impinging Jets - State of the Art Review

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ABSTRACT

Impinging jets are encountered in many industrial applications. Previous studies have considered different parameters that affect the flow and enhance mass and energy transfer of these flows, such as Reynolds number, nozzle geometry, nozzle-to-plate distance, wall material and angle, and the flow regime at the jet exit. Furthermore, the dynamics of these jets could be a source of a high level of noise when the transfer of energy is optimized between the aerodynamic and acoustic fields. This can lead to a resonant jet producing self-sustained tones. Self-sustained tones are related to aero-acoustic coupling and occur in impinging jets when a feedback loop is present between the jet exit and the impinged plate. Few studies that deal with the heat transfer of an impinging jet in the presence of an acoustic resonance have been conducted. This state of the art review and discussion will focus on the heat transfer and flow dynamics in such noisy and resonant configurations. Such investigation will allow us to understand how a similar regime characterized by acoustic instabilities could be useful in enhancing heat transfer at the wall.

1. INTRODUCTION

An impinging jet into a wall refers to the flow of fluid, such as a gas or liquid, which is directed towards a solid surface or a wall [1]. This system is commonly used in various engineering mechanisms, including chemical reactors, heat exchangers, and combustion systems. The jet's influence can enhance heat transfer, mixing, or chemical reactions within the system.

The impinging jet into a wall can be analyzed using various mathematical and computational techniques, such as Computational Fluid Dynamics (CFD) simulations or mathematical analysis of the fluid dynamic equations. These techniques can be used to predict the velocity and pressure distributions of the fluid jet and the wall impact, as well as the thermal exchange in the system [2-5]. Also, the impinging jet into a wall can be analyzed using experimental techniques to measure the flow characteristic, like Particle Image Velocimetry (PIV), pressure-sensitive paint, flow visualization and hot wire anemometry ...etc. The heat transfer can be experimentally measured, such as heat flux sensors, thermocouples, Liquid Crystal Thermography, Infrared Thermography, Pressure Sensitive Paint, Particle Image Velocimetry … etc. All these techniques were performed to clarify all phenomenon and correlations that can take place between the flow entering the jet and the wall [6-8].

To improve the efficiency of jet impingement in heat exchange applications, there are various techniques that can be utilized. These techniques can be broadly classified into three categories: passive, active, and hybrid [9]. Passive techniques do not require additional energy to refine the thermal exchange, whereas active methods incorporate supplementary devices such as fans or pumps to enhance fluid circulation and intensify thermal exchange. Passive methods do not incorporate moving components, making them cost-effective and more dependable than active methods. Whereas hybrid systems, involve the use of multiple passive and/or active systems to enhance the thermal exchange [10-12].

This study will focus on how these parameters enhance the flow dynamics and heat exchange close to the impinged plate.

Depending on various parameters, the thermal conductivity of a jet impingement represents a wide range subject in thermal engineering, some of which include:

- Target plate (moving, steady [10])
- Surface properties (plane, concave [13], roughness [14], composition [15], etc.)
- Convection type (natural or forced [16])
- Flow regime (laminar [17], turbulent [18])
- Fluid type (Newtonian [19] or Non-Newtonian)
- Phase (single or two phase)
- Jet number (single [20] or array [21])

- Geometrical properties (H/D, jet angle, Reynolds number) [17]
- Jet type (circular, elliptical, slot, etc. [13])
- Impingement type (free surface [22], confined jet [17] or submerged jet)

Figure 1 schematic representation of an impinging jet into a wall typically shows a nozzle that directs the fluid jet towards a flat or curved surface [23]. The fluid typically flows through a pipe or a duct before being discharged from the nozzle. The nozzle is often designed to create a coherent and stable jet, which can penetrate through the boundary layer of the surface and produce a high-velocity impact on the surface.

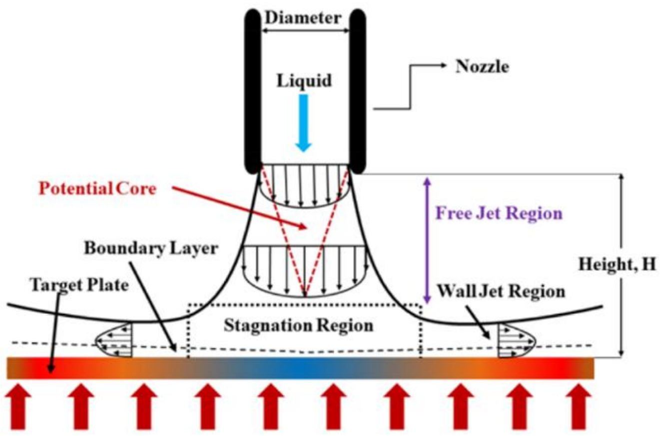

Figure 1. Different regions of jet impingement flow

The fluid dynamics area can be categorized into four different zones. The initial mixing zone is where the air is drawn into the current flow, reducing its speed and contributing to the development of the flow. This zone surrounds the jet core, where the flow motion is almost equal to the nozzle exit speed. The potential core zone lies beyond the mixing zone and is characterized by interactions among the jet and the surrounding air that lead to mass incorporation, flow energy intensification, and force exchange. In the designated jet area, the along-axis speed of the jet diminishes as the gap widens between the jet exit and the wall. The diverted jet area, closest to the impingement plate, experiences a fast reduction in the along-axis speed of the jet and an increase in static pressure. Ultimately, the wall jet area is characterized by a rapid rise in transverse velocity reaching its peak near the wall, followed by a decrease further distances from the wall. This region is associated with high levels of thermal exchange due to the high turbulence intensity (Tu) caused by the high intensity shear between the impacted plate and the surrounding air [24].

At low nozzle-to-surface distances, fluctuations in along-axis velocity and stress within the incoming jet were approximated [25].

Numerous studies have been conducted show that self-sustained tonal sounds in impinging jets are caused by aero-acoustic coupling, which occurs when there is a reciprocal interaction between the nozzle exit and the wall. To maintain these signals, it is crucial to understand the relationship among the sound signals and vortical structures. When the acoustic level is low, only a singular trajectory of the vortices is observed. However, when the highest level occurs, double vortical trajectories may exist [14].

When the acoustic level reaches a peak, there is a noticeable jump in the self-sustained frequencies signals, leading to a change in the aerodynamic mode. This modulation is mainly associated with the aero-acoustic frequency, amplifying the acoustic waves and facilitating the energy exchange toward the sound field. Furthermore, optimizing the feed-back loop and installing it within the jet leads to the structured progression of the two-dimensional turbulent flow characteristics, which is in sync with the acoustic signal and facilitates its transfer to the acoustic field.

Further study concerned submerged jets establishes a link among heat flux and vortical structures, and it is noted that these dissipative phenomena are extremely sensitive to even minor changes in medium viscosity [20].

2. ENHANCING JET IMPINGEMENT HEAT TRANSFER THROUGH FLUID TYPE

Researchers have conducted numerous experiments to improve the thermal exchange employing the cooling mode impinging jet, exploring various coolants including water, air, fluoro-chemicals, liquids, nanofluids, and mixtures of nanofluids. A relative analysis was carried out to identify the optimal fluid choice for each specific application. Air was primarily employed for applications with low surface temperatures. However, the restricted utilization of air is directly associated with its limited thermal conductivity. Water was found to be the most suitable fluid in high temperature applications, due to its direct impingement to the wall. The enhancement of heat transfer rate can be more significant when water combined with nanofluids, this combination should be based on specific application requirements, considering factors such as specific heat, heat conductivity and other properties of the fluid [26-28]. Modak et al. [29] investigated the use of Al_2O_3 nanoparticles suspended in water at concentrations of 0.15% and 0.60% (Φ) as a nanofluid. The nanofluid was directed onto a copper sheet with a range of Reynolds numbers between 5000 to 12000. They observed a marked thermal advancement, with a rise of 128%. Moreover, at $\Phi = 0.60\%$, the peak heat flux experienced a notable increase of 112%.

Over the past two decades, researchers have shown significant interest in using nanofluids for thermal enhancement due to their unique attributes that are adjustable according to specific needs. Mono nanofluids, made with one type of nanoparticle, offer many advantages attributed to the characteristics of the nanoparticle constituent. In contrast, for further improvement, Scientists have created an innovative heat transfer fluid, known as hybrid nanofluid, representing a new generation in thermal management technology. Hybrid nanofluids are formulated by mixing different nanoparticles either as separate components or by dispersing nanocomposite particles within the host fluid (such as Al_2O_3-Cu, TiO_2-CNT …etc.). These hybrid nanofluids possess the potential for superior thermal and flow characteristics due to an enhanced interaction between the different types of nanoparticles. Thus, hybrid nanofluids have found a crucial place in designing new thermal systems for various engineering applications [30]. In the work of Yarmand et al. [18], study was conducted where they developed a Nano-composite by coating graphene with silver (Ag-graphene nanofluids), using water as the host fluid with a mass content of 0.1% nanoparticles. The investigation revealed that at a T = 40°, the thermal exchange enhanced by 22.22%.

3. ENHANCING JET IMPINGEMENT HEAT TRANSFER THROUGH SURFACE MODIFICATION TECHNIQUES

3.1 Roughness

The occurrence of flow boiling in two-phase thermal exchange is characterized by elevated thermal coefficients (h), attributed to the enthalpy of vaporization and the turbulence caused by vigorous bubble detachment from the heated surface. Surface texture is a critical factor in the creation of these gas pockets, with high roughness resulting in a greater density of nucleation sites that promote flow boiling heat transfer [13]. Altered surfaces can take on various forms, including textured and extended surfaces or turbulence promoters. The primary purpose of these geometries is to enhance the outcome of h×A by expanding the touching region (A) and boosting thermal exchange rates (h) via chaotic movement and prevention of boundary layer development. Wall modification techniques can include producing micro, macro, or nanostructures. Ravanji and Zargarabadi [31] made a macrostructure modification by incorporating a pin fin onto the surface (Figure 2), each of the four different geometries featuring equivalent wetted areas, were evenly placed in a circular pattern. According to the results, the pin geometry exerts a notable impact on both the speed distribution and the magnitude of backflow area very close to pins. Elliptical pin fins outperformed other shapes, demonstrating higher velocities and smaller backflow regions around the pin, as well as leading to a significant reduction in local temperatures along the plate. Additionally, an increase of 47-54% in the average Nusselt number relative to the flat wall, with variations dependent on the Reynolds number.

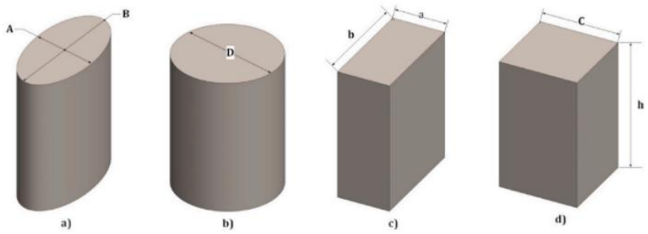

Figure 2. Visualizations of assorted pin-fin design. a) Elliptical, A=3.22 mm, B=6.46 mm b) Circular, D=2 mm c) Rectangular, a=4.84 mm d) Square, C=6.16 mm, h=280 mm

Jenkins et al. [16] investigated a flat wall, as well as linear and radial microgroove surfaces (as shown in Figure 3). The grooved surfaces demonstrated better enhancement in heat transfer attributed to increased nucleation sites than the flat wall. The study concluded that the radial microgroove surface offered superior enhancement of high heat flux in comparison to the linear multi-groove surface due to its larger surface area.

Hsieh et al. [21] conducted three different microstructured surfaces presented in Figure 4, namely 50 µm SiC, 10 µm CNT, and 50 µm diamond thin films, were examined for their cooling performance. The results showed that the 50 µm diamond thin film exhibited a good enhancement, achieving up to 610 W/cm^2 for the studied cases.

The micro-, macro-, and multiscale-structured shapes were conducted by Xie et al. [22] to test the effectiveness of enhanced surfaces, compared to a smooth, flat surface. The study's findings showed that the enhanced surfaces led to improved thermal exchanged and pressure drop efficiency compared to the smooth surface. In the study of Nirgude and Sahu [15], an experiment was conducted to examine how different orthogonally intersecting tunnel structured surfaces affected nucleate boiling thermal efficiency. Findings indicate that changing the dimensions of the tunnels had a notable effect on the efficiency. By evaluating thermal rate, it was noted that the used configurations enhanced the efficiency of heat transfer during boiling. Furthermore, they facilitated the flow of liquid towards active regions on the surface where nucleation occurs, thereby retarding evaporation and enhancing the interaction between liquid and vapor at the surface. The use of pillared surfaces was conducted by Sahu et al. [32], it was found that using a spray cooling jet with a pillared wall resulted in better heat transfer enhancement.

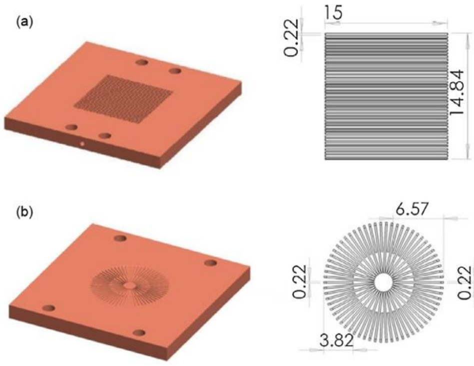

Figure 3. Improved microgroove finishes (a) linear and (b) radial (units are in mm) [16]

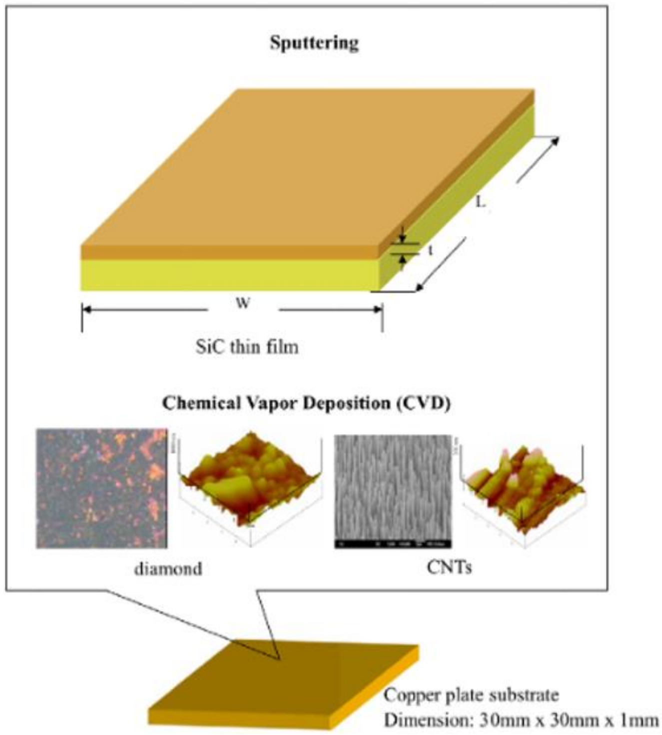

Figure 4. Microstructured surfaces [21]

3.2 Curved surface

The flow topology can be substantially affected by the wall curvature, which creates a dominant fluid transport and considerable curved flow lines in the wall jet zone. Additionally, it can modify the thermal conductivity along the impact zone. Taghinia et al. [17] investigated a Computational Fluid Dynamics (CFD) approach that incorporated a curved wall. Rakhsha et al. [33] analyzed the relationship between nozzle shape and flow behavior, as well as heat transfer, when a pulsed jet impacts a concave wall (Figure 5). They found that the spacing ratio had a substantial impact in reducing the effects of nozzle geometry, as it increased the amount of entrained air.

Figure 5. Concave surface [33]

The heat convection rate exhibited an optimum at intermediate curvature levels regardless the surfaces were concave or convex. This observed behavior was closely associated with the mean velocity distribution of the wall jet and the levels of turbulence. In the case of curved-in surfaces, an increase in curvature led to enhanced bonding among the jet and the wall, accompanied by a narrowing near the nozzle, due to the influence of centrifugal forces. Unexpectedly, the turbulence kinetic energy was more pronounced at moderate curvature levels than at the highest curvature levels, resulting in superior heat transfer performance, despite the thicker wall jet. Conversely, on convex surfaces, the negative impact of centrifugal forces caused a more dominant flow attachment at moderate curvatures. However, the Coanda effect on convex surfaces led to reduced turbulence kinetic energy, explaining the relatively insignificant heat transfer enhancement compared to concave surfaces [34].

Li et al. [35] investigated confined concave surfaces, as shown in Figure 6. The unique bend of the plate had a significant effect on the flow characteristics. the investigation reveals the presence of significant trapped vortices in the lateral recirculation zones when the jet hits on the highly bended wall (R = 10Dh), in opposition to the flat surface scenario (R infinity). These large eddies exert a notable influence, intensifying turbulent velocity away from the main jet hit. For the medium bend wall (R = 20 Dh), the boundary layer displayed transitional behavior.

3.3 Effusion holes

Choi and Kim [36] examined the thermal enhancement of an impingement wall with effusion cavities that employed a jet array of effusion cavities with five different arrangements to reduce the heat of a gas-turbine enclosure. It was discovered that impingement heat transfer was notably affected by the radial acceleration and vortical motion near to the target surface, alongside the length of the central region of the jet. In addition, the Eq. (1) was realized to predict the average Nusselt number of the used configuration within ±15% error band including the conditions of the ratio hole pitch to jet diameter P/D of range 5 to 20, the ratio of wall- jet distance to jet diameter H/D of range 1 to 10, the ratio of total jet area to heat transfer area Ar of range 0.001967 to 0.035931, and Re of range 3500 to 35000.

$$Nu_{avg} = 4.9\left(\frac{P}{D}\right)^{2.77} e^{-\frac{0.04H}{D}} A_r^{2.47} Re_D^{\left\{-0.07+\left[e^{\left(A_r^{1.3}-1.97A_r\right)}\right]^{\frac{P}{D}}\right\}} Pr^{\frac{1}{3}} \tag{1}$$

3.4 Coating surface

Chen et al. [37] investigated the application of a magneto-fluid coating onto the hot surface. The utilization of magnetic fluid coating led to a noticeable enhancement in heat exchange, which was influenced by the jet velocity, reaching up to 32%. This observed effect can be attributed to the presence of vortices within the ferrofluid. Yogi et al. [19] investigated the use of porous aluminum foam and resin foam on a plain wall. Their outcomes showed that the pore existence in the material contributed to increased hydraulic resistance against the incoming jet, as indicated by the arrangement of static pressure along the surface. Additionally, there was an enhancement in heat conduction facilitated by the metal foam, while a drop in thermal exchange, attributed to the supplementary hydraulic resistance. On the other hand, the resin foamed surface exclusively underwent a drop in thermal exchange attributed to the added hydraulic resistance.

3.5 Inclined surface

Baffigi and Bartoli [38] focused on enhancing the thermal conductivity from inclined walls to air through free convection using expired jets. The results revealed that the heat exchange increased with the use of jets at various wall inclinations. The jets introduced vortical structures, transitioning beyond the laminar pattern and enhancing heat transfer. The peak of heat transfer coefficient reached at an inclination of 15 degrees and then gradually decreased. Yousefi-Lafouraki et al. [39] conducted a numerical study on a confined jet within a converging channel. They varied the converging angle to examine its thermal impact, performing at angles of 0 and 5 degrees. The findings indicated that increasing the jet-wall distance ratio (H/W), flow velocity, and converging angle all contribute to higher intensity and larger vortex structures.

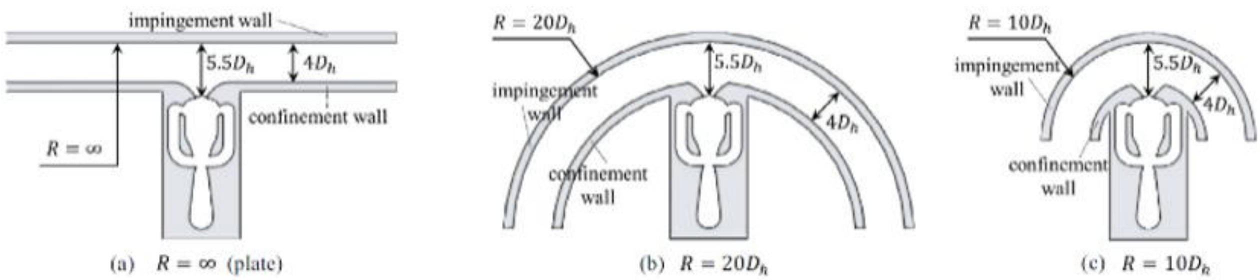

Figure 6. Confined impinging jet with impinging wall (Dh = 5 mm)

4. ENHANCING JET IMPINGING HEAT TRANSFER THROUGH IMPACT DISTANCE

The relation of jet-wall distance to the jet diameter (H/D) is a critical factor in jet impingement thermal exchange. This relation determines the strength attributed to the jet that hits a hot surface, which is influenced by the development of the central jet region. According to several studies, this region typically appears far from the jet, extending across 4 to 6 jet diameters and affects the intensity of the impinging jet. The distance at which the jet is fully developed is characterized by the potential core. At this point, the mean average speed is equivalent to jet speed. Changes in H/D result in variations in velocity, with either a decrease or an increase depending on the specific distance [40]. He and Liu [41] explored the impinging jet on a wall with varying the H/D factor. The primary objective was to analyze the distribution of the mean Nusselt number on the hot wall. Their findings indicated that elevated chaotic flow levels in the surface-jet region at H/De = 2 and the stagnation region at H/De = 4 were responsible for enhanced heat transfer.

5. ENHANCING JET IMPINGING HEAT TRANSFER THROUGH JET INCLINATION

The orientation of the jet plays a significant function in jet impingement heat transfer, affecting the overall heat transfer rate. Various angular positions, including oblique and orthogonal orientations with respect to hot surfaces, have a direct impact on the efficiency of the jet's impact on the wall, minimizing energy losses in the process. Lv et al. [42] explored the influence of different jet inclinations on a hot wall. They observed that as the jet angle decreased along the radial direction, the coefficient of heat transfer decreased as well. On the other hand, when the jet is at right angle, the gravitational attraction aids in enhancing the impact energy on the disc, thereby enhancing the thermal exchange. Singh et al. [43] investigated the impact of a tilted swirling jet on a wall located at a particular distance (z/d = 4). Their findings revealed a decrease in the dead zones due to the unbalanced positioning of swirl passages with respect to target surface. Mondal et al. [44] found that a 45° tilted air curtain with a speed of 3.5 m/s achieved a value of 4.19% reduction in natural convective heat losses from an isothermal hot surface. Lv et al. [42] investigates the performance of a 45 to 90-degree tilted swirling impinging jet (SIJ) on an inclined surface. This inclination has significant effect on the vortical particles in the jet space, while Reynolds number has minor influence. Beyond 45 degrees, the thermal enhancement region of the swirling jet lies within r/d < 3, with weak Nusselt numbers (around 20) in the wall jet area. Meanwhile, as the inclination angle (a > 45 degrees) increases, the average Nusselt number on the wall stabilizes. Beneath an inclined orientation, the thermal enhancement increases with rising Reynolds numbers, but the rate of enhancement diminishes once Re surpasses 18,000.

6. ENHANCING JET IMPINGING HEAT TREASFER THROUGH RESONANCE

The enhancement of thermal exchange rate through resonant flow in cavities and walls offers a promising approach to improve thermal management in various applications. Resonant flow refers to the generation of standing waves within a cavity, which creates vigorous fluid motion and facilitates convective heat transfer. Xu et al. [45] discovered that a single fin has the ability to disturb the flow characteristics near the front edge, leading to intensified vibrations downstream and improved heat convection covering a wide expanse. This enhancement was significant, reaching an increase of 23%. Geng et al. [46] experimentally investigated the use of periodic jet, by controlling the mass flow rate, onto a hot wall. The enhancement of multiple use signals related to the performance of each signal. The combination of triangular (or sinusoidal) and rectangular signals, demonstrating superior results compared to the reverse combination. The raise of Strouhal number consistently led to observed improvements in heat transfer for impinging jets with these combined signals. In particular, triangular jets with balanced parameters of 0 and 1 exhibited a thermal enhanced, with the latter showing moderately superior outcome. The rate of momentary velocity change also played a role in thermal transmission enhancement, with a duty cycle of 1:2 proving to be the most effective in enhancing heat transfer in this investigation.

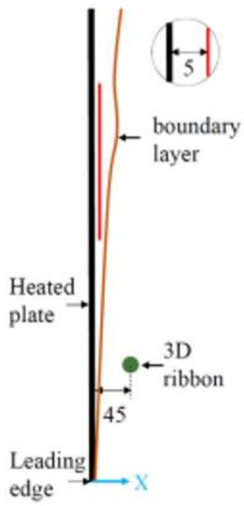

Figure 7. The perturbation mechanism, and the ribbon relative to the heated plat

Methods driven by flow resonance have significant potential for enhancing heat transfer over large surface areas. Importantly, these methods require only a small amount of energy to drive an actuator located near the leading edge (Figure 7). During the transition period of the thermal boundary layer and eventually becomes the prevalent frequency domain. To gain a deeper understanding of this high-frequency band, the researchers introduced mono-frequency disturbances with varying rate near the leading edge of the shear layer. They discovered that this signal at the maximum frequency within the high-frequency band elicited the best response from the thermal boundary layer. This finding suggests that the highest frequency corresponds to the characteristic or resonance frequency of the thermal boundary layer [47].

A series of experimets were conducted in the study of Zhao et al. [48] to investigate controlled flow transitions and their impact on thermal behavior in free convection mode. They utilized particle image velocimetry (PIV) to visualize these transitions in water and analyze numerically [49] the transmission of fluctuations through the boundary layer and their efficacy on thermal efficiency. Additionally, they investigated the employment of thermal disturbance near the wall edge to enable the thermal exchange improvement in an air thermal boundary layer [36]. Their findings revealed that the enhancement was highly sensitive to disturbance frequencies, with the greatest improvement observed when the disturbance frequency aligned with the aspect frequency of the free convection boundary layer. Furthermore, they observed that the disturbance amplitude influenced the thermal exchange improvement, but its impact varied based on the signal amplitude and was significant only when the disturbance frequency closely matched the aspect frequency.

7. ENHANCING JET IMPINGING HEAT TRANSFER THROUGH NOZZLE SHAPE

Optimizing the nozzle's layout is essential for enhancing the thermal exchange in impinging jet systems onto a target plate. The geometry of the nozzle, including its shape, size, and arrangement, significantly influences the stream characteristics and the thermal performance. Brignoni and Garimella [50] compared the performance of chamfered nozzles to square-edged nozzles of the same diameter, varying parameters such as turbulent Reynolds numbers, nozzle-to-plate spacing and chamfer angles and lengths. Their findings revealed that machining the nozzle significantly enhanced the mean convective coefficient to pressure drop ratio, with an improvement of up to 30.8% observed. Narrow chamfering was identified as the more effective configuration, highlighting the potential for improving heat transfer efficiency by modifying nozzle design in such systems. In the study of Wang et al. [51], five different orifice geometries with different aspect ratio (AR) were studied. The findings indicated that the square geometry exhibited superior stagnation cooling performance compared to the circular configuration. The maximum stagnation cooling coefficient increased by 42% in the square orifice case because of the high speed and increased infiltration into the boundary shear layer. Additionally, the rectangular orifice with an AR of 5 achieved the best cooling efficiency, with the peak time-averaged cooling coverage exceeding 14 times the area of the jet nozzle. Dano et al. [52] examined confined jet array with cross-flow, highlighting the influence of circular and cusped ellipse orifice geometries on flow dynamics and thermal exchange. The findings indicated that the cusped ellipse nozzle had a higher influence on the stream in the wall zone due to cross flow interactions, compared to the circular nozzle. Additionally, under consistent heat flux, the cusped ellipse nozzle demonstrated a rise in total thermal conductivity, indicating improved thermal efficiency relative to the circular nozzle. He and Liu [41] analyzed the impact of geometrical configurations of the lobed nozzle by adjusting the ratio of the nozzle center deviation to the nozzle radius while maintaining a constant equivalent diameter (De) for all configurations, ensuring consistent cross-sectional area of the nozzles. Their findings revealed that lobed jets exhibited enhanced heat transfer when H/De is less than or equal to 4. When H/De equals 2, the maximum Nu was achieved with a lobed nozzle having a ratio of a/b equal to 0.8 in the range of r/De between 1 and 4, resulting in a 10% improvement compared to a circular jet. When H/De equals 4, the radial-averaged Nu consistently increased by up to 16% in the zone where r/De is less than 0.5 with an increase in a/b, whereas a slight decline was observed in the range of r/De between 2 and 4. In the study of He and Liu [41], the impact of geometrical configurations of the lobed nozzle was stufied by adjusting the ratio of the nozzle center deviation to the nozzle radius while maintaining a constant equivalent diameter (De) for all configurations, ensuring consistent cross-sectional area of the nozzles. Their findings revealed that lobed jets exhibited enhanced heat transfer when H/De is less than or equal to 4. When H/De equals 2, the maximum Nu was achieved with a lobed nozzle having a ratio of a/b equal to 0.8 in the range of r/De between 1 and 4, resulting in a 10% improvement compared to a circular jet. When H/De equals 4, the radial-averaged Nu consistently increased by up to 16% in the zone where r/De is less than 0.5 with an increase in a/b, whereas a slight decline was observed in the range of r/De between 2 and 4. Trinh et al. [53] analyzed three distinct injection methods: reference tube, circular nozzle, and cross-shaped nozzle on a hemispherical surface. The aerodynamic results revealed that the hemispherical surface produced a "vena contracta" impact, which was more pronounced in the circular nozzle compared to the cross-shaped nozzle. The velocity field at the nozzle exit displayed a parabolic configuration for the tube, a reversed parabolic pattern for the circular nozzle, and a three-dimensional structure for the cross-shaped nozzle because of the existence of two boundary regions. As a result, the circular nozzle exhibited a higher thermal efficiency than the other injection methods. Cafiero et al. [54] explored the thermal impact using an alternative grid shape, considering the grid thickness ratio, the effect of secondary grid iterations, and the selection of the first pattern. They demonstrate that an increased thickness ratio results in an earlier manifestation of the highest point in the disturbance strength profile, resulting in a localized high convective thermal exchange rate at shorter distances among the nozzle and plate. On the other hand, if a uniform distribution of the convective rate is preferred, either a single square grid or an alternative initial pattern such as a round fractal grid should be chosen. The findings highlight the importance of grid geometry in controlling and optimizing heat transfer characteristics in impinging jet systems.

8. CONCLUSION

In conclusion, the study of impinging jets into walls includes a wide range of parameters and techniques aimed at enhancing heat transfer in various engineering applications. The analysis of fluid dynamics and heat exchange near impinged plates involves complex interactions that can be optimized through different approaches.

One significant area of improvement lies in fluid selection, where researchers have explored various coolants and nanofluids to enhance heat transfer rates. Nanofluids, in particular, offer unique advantages due to their adjustable properties and potential for superior thermal characteristics. Hybrid nanofluids, combining different nanoparticles, represent a promising frontier in thermal management technology.

Surface modification techniques also play a crucial role in improving heat transfer. These techniques include roughness alterations, curved surfaces, effusion holes, coating surfaces, inclined surfaces, and resonance-driven methods. Each of these techniques offers specific advantages in enhancing heat transfer efficiency, whether through increased surface area, optimized flow patterns, or resonant flow effects.

Additionally, nozzle shape optimization has been explored as a means to enhance thermal exchange efficiency in impinging jet systems. Various nozzle geometries and configurations have been studied to understand their impact on flow dynamics and heat transfer rates. These studies have highlighted the importance of nozzle design in achieving higher convective coefficients and improved thermal performance.

Overall, the advancements in fluid selection, surface modification techniques, nozzle design, and resonance-driven methods offer promising avenues for enhancing heat transfer in impinging jet systems. Continued research in these areas will contribute to the development of more efficient and effective thermal management solutions in engineering applications.

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NOMENCLATURE

Ar	Aspect ratio
Re_D	Reynolds number
Nu_{avg}	Average Nusselt number

Greek symbols

Φ	% Concentration of nanofluid in water