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A Review on Aero-Acoustics and Heat Transfer in Impinging Jets

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Abstract. A summary of key discoveries regarding the industrial applications of impinging jets on a vertical plate. The summary explores the link between the dynamics and heat transmission on one hand and the relationship between heat exchange and acoustic coupling on the other hand. The objective of this research work is to investigate the vortex dynamics and heat transfer mechanisms in impinging jets. The jet impingement technique finds widespread use in the industry, it serves purposes such as drying, cooling, and heating. The impinging jet system involves directing a fluid jet with high-velocity onto a surface. The jet impingement results in high heat exchange rates and mass transfer rates, making it an attractive technique in various industrial processes. To investigate these mechanisms, a combination of experimental and computational methods was used, including flow visualization and numerical simulations. The study of vortex dynamics in impinging jets is crucial for understanding the heat transfer mechanisms involved. The flow characteristics of impinging jets, such as the Reynolds number (Re) of the jet, the distance from the blowing mouth to the impinged wall, and the geometry of the blowing mouth, significantly affect the vortex dynamics and heat transfer rates. Therefore, optimizing these parameters can result in significant improvements in heat transfer efficiency. Several methods were proposed to enhance heat transfer, these methods can affect the flow dynamic, the surface of impingement, the nozzle's shape and size, and the impingement parameters such as the impact distance and the jet angle. For example, investigations have identified that optimal heat transfer took place at an inclination angle between 40 and 90 degrees. In addition, studies have reported enhancement in heat transfer with diamond orifices that reached up to 17%. The key findings of this paperwork include the identification of optimal impingement parameters that maximize heat transmission rates and the understanding of the significant relationship between the dynamics of the flow and the acoustic emissions. For instance, studies showed that synthetic jets can enhance convective heat transfer by 3 times compare to natural convection. The correlation between the flow dynamic and the heat transmission on one side, and the flow dynamics and acoustic emission on the other side, emphasizes the researcher to present acoustic-thermal coupled studies on the impinging jet; this topic needs more effort to understand the relation between the two phenomena. The conclusion highlights the significance of previous findings in industrial applications, suggesting control mechanisms capable of reducing noise and enhancing heat transmission.

Keywords: Aero-acoustics; Flow control: Heat transfer; Impinging jets; Vortex dynamics

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1. Introduction

Most impinging jets present complex flow dynamics as shown by several authors (Dairay *et al.*, 2015; Duda, Lagor, and Fleischer, 2008; Beaubert and Viazzo, 2003). Despite the large number of experiments and studies conducted on impinging jets in the past decades (Matsuda, Fukubayashi, and Hirose, 2017), this research topic is still one of the most active research areas in thermofluid because of its fundamental and applied importance (Moghadam, 2017). One of the most active research areas is the mechanism of heat transmission in jets impinging at subsonic speeds. It is of high importance due to its widespread use in the industry, like cooling of turbine blades, annealing of glass, and drying of papers, among others.

Quite a few geometric and flow properties affect the performance of heat transmission in impinging jets, including the Reynolds number (Re) of the jet, geometry of the blowing mouth, flow regime, angle at which the jet is impinging in addition to the distance separating the blowing mouth and the wall being impinged, etc. (He and Liu 2018a; 2018b; El Hassan and Nobes, 2018; Nuntadusit *et al.*, 2012; Gardon and Akfirat, 1965).

It is important to note that the complexity of this flow is mainly determined by certain characteristics (Weidman, 2017; Zerrout, Khelil, and Loukarfi, 2017). These characteristics include the development of boundary layers along the impinged wall's surface, as well as the presence of jet instabilities and their interaction with the impinged wall. Therefore, a thorough understanding of the flow dynamics and its correlation with the transfer mechanisms is of high importance in order to define proper flow control techniques both passive and active for particular industrial uses (Nastase and Bode, 2018; Hong and Cho, 2005; Hwang, Lee, and Cho, 2001).

This paperwork presents a literature summary of the latest experimental and numerical investigations on jet flows impinging a plate. The first industrial applications of impinging jets are represented. Second, the link between the dynamics of the flow and the transmission of heat in addition to the control methods that enhance heat transfer are the main topics of this literature review. Third, the impact of the aero-acoustics on the transfer of heat is discussed. Finally, perspectives on further analysis of impinging jets and the development of control systems suitable for industrial uses are proposed. Therefore, it is of interest to understand the underlying phenomenon between the flow dynamics and heat transfer on one side, in addition to the relation between aero-acoustics and heat transfer on the other side, in order to find a control mechanism capable of enhancing heat transfer and reducing the produced aero-acoustics.

2. Industrial Applications of Impinging Jets

Jet Impingement technique finds widespread use in the industry, including cool cooling down of electrical components and turbine blades, glass tempering, cryosurgery freezing of tissues, and paper drying, among others.

In gas turbines, the blades are subject to extremely high temperatures due to the combustion of fuel. Therefore, if the blades are not adequately cooled, they can deform or even melt, which can lead to engine failure. The impinging jets can be designed to create different flow patterns on the surface of the blade, such as radial or crossflow (Zuckerman and Lior, 2007; Chambers *et al.*, 2005). These flow patterns can be optimized to provide maximum cooling while minimizing the amount of coolant required. Overall, impinging jets are a highly effective cooling technique for turbine blades, and they are commonly used in modern gas turbines to ensure reliable and efficient operation. To assess the effectiveness of jet impingement in various industrial applications, multiple experiments and numerical studies have been conducted (Forster and Weigand, 2021; Liu and Feng, 2011).

Moreover, impinging jets are often utilized and employed for cooling electrical equipment, such as computer chips and power electronics. Electronic devices generate heat during operation, and if this heat is not dissipated properly, it can reduce the device's performance and even cause damage. Several experiments were conducted to identify the performance of impinging jets in cooling electrical components (Kercher *et al.,* 2003; Cheng, Tay, and Hong, 2001). Results from previous studies show that higher jet speeds with larger jet diameters led to a substantial rise in rates of heat transfer. Moreover, the utilization of microjet cooling devices suggests that they can adhere to traditional jet correlations with necessary adjustments made to correlation parameters. The usage of cooling devices that employ microjets may be particularly appealing in situations that require localized cooling, as they can be targeted toward specific hot areas within a system.

Solar energy technologies have shown great potential as a replacement for fossil fuels in electricity generation. However, solar collectors often suffer from overheating and poor heat transfer, which can limit their performance. To address this issue, cooling applications like jet impingement cooling can be used to improve heat exchange rates and boost performance as prescribed by Ewe *et al.* (2022). It is important to highlight the potential of jet impingement cooling for improving the efficiency and reliability of solar energy systems and provide valuable insights into the key factors that influence its performance. Authors mentioned that, by optimizing different factors like the velocity of the jet, the jet/surface separation distance, the shape of the nozzle, and the rate of coolant flow, it is possible to enhance the effectiveness and efficiency of jet impingement cooling. Moreover, jet impingement cooling can also be used for other solar energy applications, such as cooling solar cells, inverters, and battery systems.

Impinging jets are also found in drying processes where jets of air or other gases having The high-velocity are directed onto the surface of a material to be dried. The impact of the jets can help to break up surface moisture and promote faster drying. Turkan *et al.* (2019) examined the thermal properties of a continuous industrial drying process for semi-porous textile composites; impinging jets were employed as a mean of enhancing the drying rate of a moist porous solid. The authors aimed to investigate the effect of various parameters, such as nozzle-to-target distance and jet velocity, on the heat exchange rate and drying rate of the moist porous solid. The moist porous solid drying rate was found to be significantly enhanced by impinging jets compared to natural convection drying.

In some food products freezing, refrigerant jets with high-velocities are addressed onto the food product surface to be frozen. The impact of the jets can promote faster and more efficient heat transfer, resulting in faster freezing times and higher-quality frozen food products as stated by Anderson and Singh (2006). Marazani, Madyira, and Akinlabi (2017) provided an overview of research on impinging jets used for fast freezing and cooling systems, including experimental, computational, and theoretical models. It examines the key factors that govern the performance of these systems.

Based on the literature review on impinging jets in different industrial applications, further understanding of the dynamics of the flow and its relationship with the transmission of heat in such flows would be helpful for system optimization and for developing proper control methods for heat transfer enhancement.

3. The Interaction Between The Dynamics Of The Flow And Resultant Heat Transmission In Impinging Jets

Dairay *et al.* (2015) mentioned that impinging jets are characterized by four main regions, as illustrated in Figure 1:

- Region I, where the flow is initiated to then reach the potential core's apex downstream from the blowing mouth exit. This area, referred to as the potential core region located in the flow central portion, maintains a consistent velocity where the speed of the jet stays constant and equals to the blowing mouth exit speed.
- Region II develops downstream from region I where the centerline jet velocity is lower than in the jet core and the flow starts to spread in the transversal direction.
- Region III where the jet is diverted from the axial direction. This region contains the stagnation region near the impinging plate.
- Region IV, also called the wall jet region, is where the driven flow thickens as the flow boundary layer starts to develop within the impinging wall.

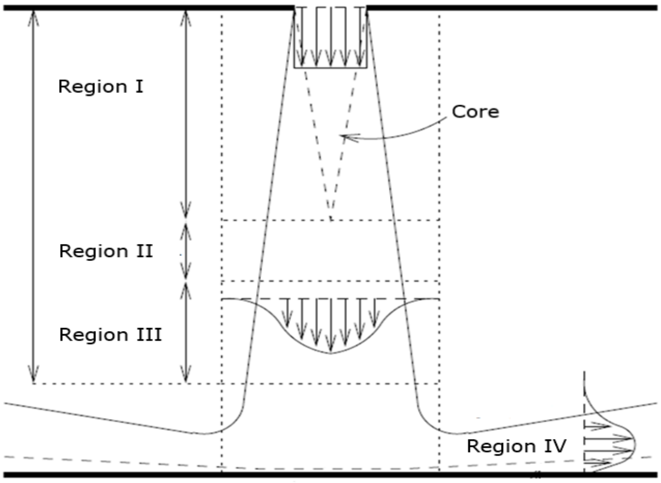

Figure 1 Flow jet regions of jet impinging a solid wall

3.1. Large Coherent Structures in Impinging Jets:

Many experimental and numerical investigations were done for the purpose of analyzing the correlation between vortex dynamics and the transfer of heat at the wall. In this section, some of these studies are discussed.

Experimental investigations of the near-wall vortical structures in impingement jets have been extensive (El Hassan *et al.*, 2013; 2012; Hall and Ewing, 2006; Jambunathan *et al.*, 1992; Martin, 1977). For example, Didden and Ho (1985) analyzed the unsteady separation of the boundary layer that occurs when the flow impinges on a solid surface. The authors noted that primary vortices develop in the jet shear layer and are advected radially in the near-wall flow (region IV), while vortices rotating oppositely conveyed along the radial axis and located closer to the wall are also observed, which are referred to as secondary vortices. However, the emergence of these secondary vortices occurs downstream of where the primary vortices were initially detected. The viscous-inviscid interaction theory, as described by Didden and Ho (1985), elucidated the mechanism behind the impinging jet flow's unsteady separation. The primary vortices, situated in the flow inviscid area, generate a fluctuating pressure gradient downstream, resulting in an upward fluid motion. Consequently, an unstable boundary between the viscous and inviscid areas emerges, which leads to the roll-up of an oppositely rotating vortex. This vortex is associated with an unsteady boundary layer separation caused by the shear-layer instability. While, the previous experimental studies provided valuable insights into the vortical structures formed near the wall, the study conducted by Martin (1977) is limited due to the advancements in both experimental and computational techniques since then. Moreover, the analysis regarding the boundary layer separation conducted by Didden and Ho (1985) could include simplifications in the assumptions that could affect the accuracy of the proposed mechanism.

Moreover, over the past twenty years, several computational investigations have been conducted to enhance our understanding of the formation of large coherent structures in impinging jet flows (Lodato, Vervisch, and Domingo, 2009; Beaubert and Viazzo, 2003; Tsubokura *et al.,* 2003). The main focus of the author's work is to compare the vortical structures of planes and round jets. Specifically, their simulations identify secondary small coherent structures near the wall. In their LES study, Hadžiabdić and Hanjalić (2008) investigated a turbulent jet with a Reynolds number of 23000 and a separation length between the blowing mouth exit and the wall being impinged H/D = 2. The authors' findings suggest that the predominant flow dynamics event controlling the flow is the vortex roll-up taking place at the wall being impinged. This event is closely linked to the creation of oppositely rotating smaller vortices and the unstable boundary layer detachment phenomenon, all of which directly influence the distribution of the mean heat exchange. Besides the valuable insights into the dynamics of large coherent structures in impinging jets provided by the previous computational investigations. However, the accuracy of the conducted simulations depends on factors like turbulent model, resolution of the grid, and boundary layer conditions, all of which have a direct influence on the fidelity of the predicted flow characteristics.

3.2. The Transfer of Heat at The Impingement Wall:

To investigate the relationship between flow dynamics and the transfer of heat, the authors recommend examining the pattern of the average heat transfer and the primary velocity metrics within the studied flow, as suggested by Dairay *et al. (*2015). On the impingement plate, the coefficient of the mean heat transmission (h) is defined as the heat flux density (Q_p) divided by the variance in temperature between the mean wall temperature (T_w) and the jet impinging temperature (T_j), where the radial distance from the jet axis is represented by 'r'. The mean Nusselt number ($\overline{Nu}$), commonly used to quantify heat transfer in impinging jets, is defined as: Nusselt(r) = h(r)D/k; k is the thermal conductivity.

As previously mentioned, there are quite a few geometric and flow factors that can control the performance of heat transfer of impacting jets including, the Reynolds number (Re) of the jet, shape of the blowing mouth from which the jet is issued, flow regime, angel of impingement, and distance separating the plate from the nozzle's exit, etc. Gardon and Akfirat (1965) demonstrated that the heat transfer rises as the Reynolds number grows, while maintaining a descriptively comparable geometry. Two peaks in the local mean heat transfer were observed after surpassing Re ≥ 2800 at around radial distances of 0.5 and 2. Figure 2 illustrates the two local maxima of the mean heat exchange for various Reynolds numbers at a distance from the blowing mouth to the surface being impinged equal to 2. Lee and Lee (1999) found that the magnitudes of the 2 local peaks rise with increasing Re. Other experimental investigations have explored the impact of nozzle type (Roux *et al.* 2011), nozzle to plate distance (He and Liu, 2018a; Baughn, and James, 1989) and confinement (Ashforth-Frost, Jambunathan, and Whitney, 1997) on mean heat exchange. It can be inferred from these investigations that the secondary maximum in the Nu distribution is more pronounced when using a convergent nozzle instead of a long tube for small separations between the blowing mouth of the nozzle and the impinged plate (H/D < 4). Despite being a common configuration in practical applications, the installment of a plate with confinement can restrict the transfer of heat on the impingement surface (Figure 3).

In order to understand the emergence of primary and secondary peaks in the distribution of the mean Nusselt number, many investigations were done. Chung and Luo (2002) and Chung, Luo, and Sandham (2002) studied the relationship between the vortex patterns and the fluctuation of heat transmission using Direct Numerical Simulations (DNS). Results revealed that the changes in stagnation heat transmission are primarily due to the impact of the primary vortices that emerge from the blowing mouth exit. The nearly periodic variations in the impingement heat exchange are caused by the quasi-periodic production of the primary vortices as a result of Kelvin-Helmholtz instability, although more complex and non-linear changes occur as Reynolds numbers increase. According to Lee and Lee (1999), the primary peak is linked to the accelerated radial flow at the nozzle's edge.

Roux *et al.* (2011) linked the primary peak shown in the distribution of the mean Nusselt number to the increase in turbulence intensity that happens as a result of shear layer impingement. Several authors focused on understanding the emergence of the secondary peak in the distribution of the mean Nusselt number, as for most authors, the primary peak in heat transfer rate in jet impingement is primarily caused by the impingement of the primary vortices. However, many authors disagreed in determining the origin of the secondary peak.

According to Gardon and Akfirat, (1965), the appearance of a second optimum in the $\overline{Nu}$ distribution can be assigned to the fact that the laminar boundary layer is transitioned to a turbulent boundary layer. Lee and Lee (1999) supported the idea that the second maximum was due to the change that occurred within the boundary layer from a smooth and laminar layer to a turbulent one. However, this explanation has been called into question by the study conducted by Cooper *et al.* (1993), which found that the secondary peak can also appear in a fully turbulent boundary layer.

Jambunathan *et al.* (1992) proposed that the formation of annular structures, which are generated by the jet shear layer, is responsible for the experience of a second peak in the distribution of the mean Nusselt number. They suggested that these structures contribute to the intensification of heat exchange in the region of the secondary peak. Additionally, several other studies, such as those conducted by Buchlin (2011), and Roux *et al.* (2011) and Vejrazka *et al.* (2005), supported the idea that a presence of a second extreme in the distribution of Nusselt number is closely linked to the large-scale vortical structures that form in the jet flow (region II).

In Popiel and Trass (1991) authors used smoke-wire flow visualizations to obtain a more profound understanding of the typical vortex pattern in both free and impinging circular subsonic jets. They observed a development of smaller near-wall vortices in the vicinity where a second peak in the mean distribution of heat transmission is detected. These structures were found to be related to the large-scale vortical structures, and the authors suggested that they could be in charge of enhancing heat transmission in that region. On the other hand, according to Chung and Luo (2002), the distribution of Nusselt numbers, which measure heat exchange far from the area of jet/wall contact, is affected by the smaller near-wall vortices, also known as secondary vortices, that result from the primary vortices and the wall jets interactions.

However, additional research is required to completely comprehend the underlying mechanisms of the secondary maximum occurrence. Hadžiabdić and Hanjalić (2008) and Uddin, Neumann, and Weigand (2013) both used LES to investigate the link between heat transmission and vortical structures in turbulent jet impingement. Hadziabdic and Hanjalic found a correlation between the mean Nusselt number second extreme and the location of the secondary vortex, while Uddin, Neumann, and Weigand (2013) observed regions of significant heat transfer, referred to as cold spots, which were directly related to radially elongated coherent structures. Table 1 presents a summary of the key findings from previous studies that examine the direct connection between heat transfer and flow dynamics. The collection of experimental and computational investigations presented in this section provides a thorough comprehension of the intricate relationship between flow dynamics and heat transmission in impinging jet flows. However, it is crucial to critically evaluate the conducted studies to draw reliable conclusions that can effectively guide future research.

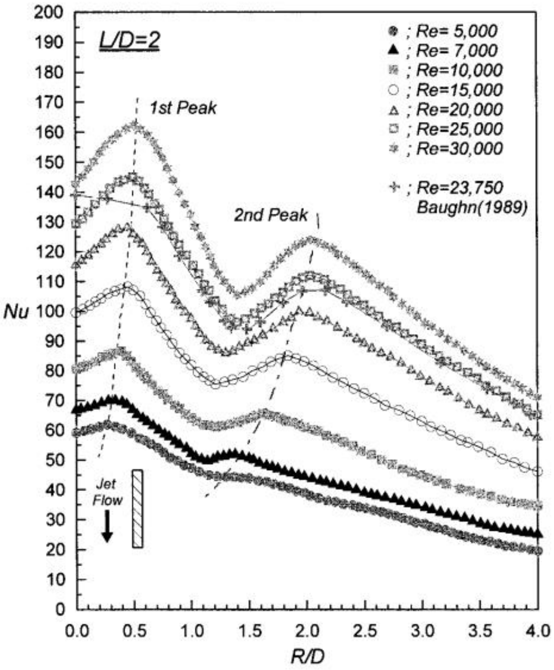

Figure 2 Local Nusselt number for different Reynolds numbers at H/D = 2.

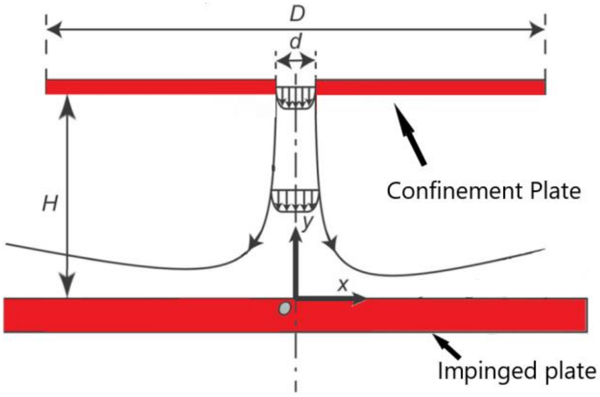

Figure 3 Jet impingement confinement plate is installed

Table 1 Summary of the main studies on the relationship between heat transfer and flow dynamics

Paper	Objectives	Methods	Results
Gardon and Akfirat, (1965)	To examine how turbulence impacts the transfer of heat characteristics when a jet impinges a solid surface.	•Re-examined the velocity measurements and turbulence distributions.	•2 distinct spikes in the local mean heat transfer were noticed after surpassing Re ≥ 2800 at around radial distances of 0.5 and 2. •The 2nd peak in the average Nu distribution can be assigned to the fact that the laminar boundary layer is transitioned to a turbulent boundary layer.
Lee and Lee (1999)	To explore the features of heat transmission when a jet impinges on a flat surface symmetrically to examine the impacts of various flow characteristics such as Re, the separation that exists between the blowing mouth and the impinged flat surface, and the diameter of the blowing mouth on the rate of heat transfer within the stagnation region.	•Utilized thermo-chromic liquid crystal (TLC) and digital image processing techniques. •Re ranging from 5,000 to 30,000. The separation distance between the plate and the nozzle used is H/D = 2, 4, 6, and 10.	•The heat transfer rate rises as Re grows, nozzle diameter decreases, and H/D decreases. •The primary peak is linked to the accelerated radial flow at the nozzle's edge. The 2nd peak contributed to the boundary layer transition from a smooth, laminar boundary layer to a turbulent one.
Cooper *et al.* (1993)	To provide hydrodynamic data for impinging jet flow conditions that can be used for turbulence-model evaluation. Also to assess the performance of turbulence models for impinging jet flows.	•Two Reynolds numbers were studied experimentally (2.3 x 10^4 and 7 x 10^4), at different separation distances between the impinged wall and the blowing mouth (varying from 2 to 10). •Computational simulations to compare with experimental data.	•Models that exhibit poor (or good) predictions of the mean flow also demonstrate corresponding poor (or good) predictions for the turbulence data. •The secondary peak can also appear in a fully turbulent boundary layer, calling into question the study done by Lee and Lee (1999).
Roux *et al.* (2011)	To examine how acoustic excitation affects both the flow parameters and the transfer of heat when a jet strikes a solid flat surface.	•Circular nozzle that produced a laminar jet that impinged onto a flat plate. •Thermocouples to measure surface temperature. •Particle Image Velocimetry (PIV). •The jet was subjected to acoustic excitation by a loudspeaker.	•The coefficient of heat transfer rises when the excitation amplitude and frequency are increased. •In the near-wall region, the size and number of vortices of the jet have changed due to excitations. •Authors linked the primary peak to the increase in turbulence intensity that happens when the shear layer impacts the solid flat surface. The second peak is linked to the smaller-scale vortical structure formed near the solid flat surface.
Chung and Luo (2002)	To investigate the unstable transfer of heat-induced when a jet impinges on a flat plate from a confined nozzle configuration. The authors aim to comprehend how both vortical structures (primary and secondary vortices) formed when the jet impacts the flat surface influence the distribution of Nu.	•Applied Direct Numerical Simulations (DNS) to simulate the dynamics of the flow and the transfer of heat. •Reynolds numbers are varied and two separation distances between the plate and the blowing mouth (nozzle) are tested to investigate the effects on the heat transmission.	•The quasi-periodic generation of primary vortices which results from the Kelvin-Helmholtz instabilities was responsible for the nearly periodic fluctuations observed in heat transmission of the jet impingement. •As the Reynolds numbers increased, the fluctuations became more chaotic and non-linear. •The changes in the stagnation transfer of heat are primarily due to the impact of the Kelvin-Helmholtz vortices that emerge from the blowing mouth exit. •The 2nd optimum in the distribution of mean Nusselt number is linked to secondary vortices formed as a fact of primary vortices/wall interaction.

Table 1 Summary of the main studies on the relationship between heat transfer and flow dynamics (Cont.)

Paper	Objectives	Methods	Results
Jambunathan *et al.* (1992)	To review and critically analyze experimental data concerning the heat exchange rate when a jet impacts a solid surface in turbulent conditions, encompassing Re within the range of 5,000-124,000. The authors aim to derive a correlation for the Nusselt number that accurately predicts heat transfer coefficients for this system.	•Experimental data from various literature sources were collated and critically reviewed. •Extrapolation of data was implemented to obtain coefficients of wall jet heat transmission.	•Up to a certain value and at a certain distance from the stagnation point the Nu does not depend on the distance separating the blowing mouth and the solid surface. •The authors derived a new correlation for the Nusselt number able to accurately predict heat exchange coefficients for the system. •The formation of annular structures, which are generated by the jet shear layer, is responsible for experiencing a 2nd peak in the distribution of the average Nu.
Hadžiabdić and Hanjalić (2008)	To investigate the vortical and turbulence patterns in jet impinging a solid wall and examine their relation with the heat transfer at specific locations.	•Large-Eddy Simulations (LES) to generate instantaneous velocity and temperature fields of a round jet issued from a long pipe and impinges normally on a solid wall at Re = 20,000 and a separation distance between the impinged plate and the orifice equals to 2.	•The predominant flow dynamics event controlling the flow is the vortex roll-up taking place at the wall being impinged. •The primary flow dynamics event is linked to the creation of opposing smaller vortices and the intermittent separation of the boundary layer, both of which directly influenced the distribution of the average Nu. •A direct link between the mean Nu second extreme and the location of the secondary smaller vortical structure is found.
Uddin, Neumann, and Weigand (2013)	To examine the flow properties and the characteristics of heat transmission when a cold jet strikes normally on a heated plate to clarify the factors that contribute to the emergence of the 2nd optimum in the radial distribution of the target wall Nu.	•Large-Eddy Simulations (LES) were employed for Re varying between 13,000 and 23,000, estimated based on the jet's diameter and bulk velocity. The non-dimensional separation between the blowing mouth and the surface of the impingement was set at 2.	•The 2nd optimum in the radial distribution of Nu at the target wall is due to the formation of a secondary vortex that promotes the transfer of heat from the stagnation zone toward the impingement wall. •The authors observed regions of significant heat transfer, referred to as cold spots, which were directly related to radially elongated coherent structures.

4. Control Methods To Enhance Heat Transfer In Impinging

Since striking jets are widely used for industrial purposes, the enhancement of heat exchange in striking jets is of significant importance. Several studies proposed control mechanisms for the enhancement of heat transmission by impinging jets.

The control of the heat exchange between the flow and the plate consists generally of controlling the flow on one hand or varying the surface properties on the other hand. One of the methods to control the flow dynamic was proposed by Cho, Lee, and Kim (1998), who added a coflowing stream around the main nozzle periphery. This method leads to disturbing the shear layer and enhances the heat transmission on the plate by up to 20%. Another flow control was proposed by Zumbrunnen and Aziz (1993) who demonstrated that the convective heat transfer coefficient for intermittent flows is two times that of the steady flow. In addition, they examined the effect of the frequency of intermittency on the convective heat transmission enhancement and found a monotonical dependence between the two parameters.

Several studies found the advantage of oscillating jets on the heat transfer compared to stationary jets. This proposition was proved by Camci and Herr (2002). Liu and Sullivan (1996) studied the heat transmission for a jet excited with its natural frequency and the subharmonics, for an impact ratio H/D < 2. The authors found that the excitation of the jet can raise or reduce the heat transmission, depending on the excitation frequency: a frequency near to the natural frequency produces random vortical structures, which are responsible for the transfer enhancement. However, the excitation with the subharmonic gives a stable vortex pairing which generates the unsteady separation of the surface boundary layer and results in a reduction in the transfer of heat rate. Similar work was made by Poh *et al.* (2004), who demonstrated that, after testing different Reynolds numbers, impact ratio H/d, and pulsation frequency f, the configuration of Re=300, f=5 Hz, and H/d=9 gives the maximum heat exchange.

Hwang, Lee, and Cho (2001) proposed control of the vortex structures by acoustic excitation, they found that for Strouhal numbers equal to 2.4 and 3 (blowing case), the length of the potential core of the jet increases and the turbulence intensity decreases, which leads to reduction of the local heat transfer and the formation of secondary peak. However, for Strouhal number equal 1.3 (suction case), the flow has a shorter potential core and higher turbulence intensity, and then stronger heat transfer.

All the previous studies explore various flow control techniques like coflowing streams, intermittent flows, and oscillating jets capable of enhancing heat transfer in impinging jet systems. Even though, these methods show promising increases in heat transmission rates, it is very important to evaluate their practicality and efficiency for previously mentioned industrial applications.

The transfer of heat in impinging jets depends on the geometry of the nozzle. Lee and Lee (2000) studied the effect of the aspect ratio (AR) of an elliptic nozzle on heat exchange enhancement. Experiments were carried out for 5 values including AR = 1 (axisymmetric jet). For a small impact distance, the heat exchange rate increases when the aspect ratio increases. Similar work was made by Koseoglu and Baskaya (2010), who tested the aspect ratio for both elliptic and rectangular jets, and found that the transmission of heat increases in the stagnation point when the aspect ratio increases, for both types of jet. Gao, Sun, and Ewing (2003) examined the performance of adding triangular tabs to the round nozzle. Different nozzle-to-plate distances have been examined. This system was found to give rise to the transfer of heat rate by more than 25% for small impact distance.

Other methods of heat enhancement consisting of controlling the surface properties were proposed by Rallabandi *et al.* (2010) and de Lemos and Fischer (2008). de Lemos and Fischer (2008) simulated numerically the effect of the presence of the porous layer on the impacted plate on the convective heat transfer. They found that the presence of the porous layer causes the disappearance of the second peak in the Nusselt number, and the total heat transfer is enhanced for a certain range of layer thickness, porosity, and thermal conductivity ratio between the layer and the plate. Rallabandi *et al.* (2010) Examined the effect of having element roughness on the heat transmission enhancement for impinging jet, using staggered and inclined ribs, and porous foam material. They found a 50 to 90% increase in heat change due to axial ribs, and a well noticed rise in the coefficient of heat exchange when the porous foam was used. In the same context, Ekkad and Kontrovitz (2002) examined the effect of surface dimples on heat exchange. The results obtained were normalized by those of the plane plate to compare the changes in heat that occurred. It was found that the dimpled surface has a lower heat exchange coefficient than the non-dimpled one. Another enhancement method consisting of a micro structured impingement surface was investigated by Ndao *et al.* (2012). The surface consists of 64 circular pin fins with a diameter of 125 µm and a height of 230 µm. A pitch of 250 µm with an enhancement area ratio A_Total/A_base =2.44has been chosen. They demonstrated an enhancement of 200% in the heat transfer compared to a plate without fins.

Surface properties described by previous investigations such as porous layers, ribbed surfaces, dimples, and micro-structured surfaces, provide innovative approaches to enhance the rates of heat transfers. However, it is of vital importance to assess the manufacturability, cost-effectiveness, and durability of implementing such modification on the surface for practical uses.

The heat transmission is also related to the impact angle between the jet and the plate, this topic was been studied by Beitelmal, Saad, and Patel (2000). Experiments were carried out for different parameters like the spacing between the wall of impingement and the blowing mouth, the Reynolds number, and the impact angle. The results show the Nusselt number's dependence on the impact angle for different Re and impact ratios. It shows that the highest Nusselt decreases when the angle of inclination at which the jet is impinging decreases, for all configurations, in addition to a shift in the diagrams to the left side of the plate.

Deberland and Rhakasywi (2014) examined how the shape of the orifice in an impinging synthetic jet affects the cooling performance pf a heated surface. Results showed that square orifices which covers a larger area and having a higher entrainment rate, resulted in a greater temperature drop and better heat transfer performance when compared to circular orifices.

Nguyen *et al.* (2009a) Investigated experimentally the convective transfer of heat for a confined and submerged impinging Al_2O_3-water nanofluid jet. The authors have tested different parameters such as Re, Pr, impact ratio, and size of Al_2O_3 particles. They found that, for specific values of impact distance and particle volume fraction, the use of nanofluids can enhance the heat exchange. In addition, for a particle volume fraction higher than 6%, the use of nanofluids was found not appropriate for transfer enhancement. Another study based on nanofluids was proposed by (Barewar, Tawri, and Chougule, 2019; Septiadi *et al.*, 2019), who compared the heat exchange between a ZnO nanofluids jet and a water jet, and demonstrated a considerable enhancement in the coefficient of heat exchange for ZnO nanofluids coolant.

Klein and Hetsroni (2012) Proposed a control mechanism that consisted of the actuating slab in the impinging plate. The study was carried out for steady impinging laminar microjets. They found that this mechanism can increase heat transfer by up to 34%. A passive control mechanism which consists of air-augmented ducts were investigated experimentally and numerically by Nuntadusit, Wae-hayee, and Kaewchoothong (2018). Different duct diameters and lengths have been tested. The results show that the air-augmented duct increases the heat transfer by 25.42% compared to the conventional jet.

Furthermore, Ai, Xu, and Zhao (2017) studied experimentally the heat transfer in the case of movable nozzle. Different nozzle velocities have been tested using a stepper motor. The results were compared to the fixed nozzle case. It was found that the nozzle movement enhances convection by increasing the transfer rate and the uniformity of temperature distribution. The increase in heat transfer can reach more than 40%ncomparing to the fixed nozzle.

Nuntadusit *et al.* (2012) studied the effect of the twist ratio in swirling imping jet on the heat transfer. Experiments were carried out for 5 ratios. Authors have found that the maximum enhancement is acquired at a low ratio of 3.64. Kaewchoothong *et al.* (2014) investigated experimentally and numerically the performance of expansion pipe nozzle with holes in the enhancement of heat exchange. Different impact distances and a number of holes were examined. Results revealed that the existence of holes can enhance the change of heat up to 6.4% for 4 holes at an impact ratio of 4. Dynamically, the presence of holes allows the ambient air to enter the duct and reduce its entrainment with the main jet.

More recently, Nimmagadda, Lazarus, and Wongwises (2019) studied the consequences of the magnetic field on the heat transmission of a water jet impinging on a stationary and vibrating plate. Results show an enhancement in the heat transmission in the case of the stationary plate by 36.18% in the presence of the magnetic field of Ha = 80. However, opposite results were obtained in the case of the vibrating plate and a reduction in the heat transmission was observed. Furthermore, Diop *et al.* (2022) investigated the result of adding mist to the flow of the heat exchange behavior. Different impact ratios and velocity inlet have been tested, the results show an enhancement in the case of the presence of the mist, which reaches 21% and 32% for a mist mass flow rate of 3 mg/s and 6 mg/s, respectively. Table 2 presents a summary of previous studies on the control methods used in the enhancement of heat exchange.

Overall, further research is needed for optimization of previously mentioned methods for specific industrial uses. Factors like energy efficiency, manufacturability, scalability, and cost-effectiveness should be considered especially when dealing with the industry.

5. Heat Transfer and Self-Sustained Tones in Impinging Jets

When a turbulent flow strikes a rigid wall, the fluid-solid interaction can generate, in certain configurations Rockwell and Naudascher (1979), acoustic waves which lead to acoustic discomfort. The acoustic waves, called self-sustaining tones, are generated by the wall pressure fluctuations which propagate backward as pressure oscillations, called feedback loops, disturb the shear layer and produce the self-sustaining tones Ho and Nosseir (1981). The first theory about aerodynamic noise Lighthill (1954) proves the direct relation between the turbulence and the emitted noise, and models mathematically the propagated wave taking the turbulence as a source of sound. This theory emphasizes the effort to describe the turbulence dynamics to understand the acoustic emission, as well as to control turbulence structure to reduce the generated noise (Alkheir *et al.,* 2021; Arya and De, 2021; Assoum *et al.* 2021; 2020; Hamdi *et al.,* 2020; Alkheir *et al.,* 2020; Hamdi *et al.,* 2019; El Hassan and Keirsbulck, 2017; Assoum *et al.,* 2017; Abed-Meraïm, Assoum, and Sakout, 2016; Assoum, Sakout, and Abed-Meraim, 2014; Dhamanekar and Srinivasan, 2014; 2013; El Hassan *et al.,* 2012; Miron *et al.,* 2012; Uzun *et al.,* 2011; Ramakrishnan *et al.,* 2009; Keirsbulck *et al.,* 2008; Henning *et al.,* 2008; Zhang, 2000). Whereas, the previous studies on the heat transmission by impinging jet (mentioned in section 3) found a direct link between the change of heat and the turbulence dynamics. This indicates the presence of an indirect relation between the acoustic field and heat transfer since the two phenomena are related to the turbulence behavior of the jet. From this point, several works have been proposed as acoustic-heat coupled studies of impinging jets.

Two scenarios can be distinguished in this domain: the enhancement of the heat exchange using the acoustic excitation, and the control of the acoustic emission by heating or cooling the impingement plate. In this context, Seeley *et al.* (2006) studied the effect of acoustic resonance on heat transfer enhancement, using synthetic jets obtained from two piezoelectric resonators. Based on CFD and acoustics models, they found that the synthetic jet increase the convection heat exchange more than 3 times that of natural convection. Similar work has been proposed by Arik (2007), which tested the effect of a synthetic jet, obtained from acoustic abatement with sine waves, on heat enhancement. Experiments were carried out at different operating frequencies between 3 and 4.5 kHz, and different parameters such as the impact ratio and the heater power, to find the best combination that gives the maximum heat exchange. In addition, the study also compared two different sizes of heaters. The results indicate that the enhancement can vary from 4 to 10 times compared to natural convection. Acoustic measurements revealed a noise level exceeding 65 dB, which prompted the authors to suggest exploring alternative techniques for generating the synthetic jet.

Oppositely, Gustavsson *et al.* (2010) investigated the consequences of the temperature of a jet on the acoustic generation, for jets impinging at supersonic speeds. This work is similar to that of Lepicovsky *et al.* (1988). In a previous test, the authors proved that the acoustic frequency varies with the jet temperature. The configuration was chosen to simulate a hot jet as used in aircraft landing, so a large-scale facility consisting of a 36.2 mm diameter nozzle and an operating temperature of up to 1030K was used. It was found that the temperature does not eliminate the tones, but transforms them to a high-frequency broadband noise. In the continuation of their study, the authors compared three geometric configurations on the acoustic emission for a supersonic jet with a Mach number equal to 1.5 and different temperatures. The three configurations were: normal impingement, oblique impingement, and jet blast deflector impingement. Results indicate that, differently from the normal impingement, oblique and jet blasts did not produce tones at low temperatures, however, the tones appeared at elevated temperatures. In addition, the unsteady load was found important at high impact distance, this is due to the reversed flow from the surface, entrainment in the shear layer of the main jet because of jet spreading, and interaction between the main jet and the deck surface which lead to grazing wall jet.

Table 2 Summary of previous studies on the control methods used in the enhancement of heat transfer

Authors	Control	Metrology	Method	Main results
Cho, Lee, and Kim (1998)	Co-flowing streams around the main jet.	HWA, Thermocouple.	A coflowing stream was added to a circular jet impacting a heated wall. The measurements of velocity and temperature were obtained by hot wire and thermocouples respectively.	Changing in the jet characteristics and enhancement of about 20% in heat transfer.
Zumbrunnen and Aziz (1993)	Intermittent flow.	Hot film probe, thermocouple.	Rotating wheels with blades were used to create intermittent circular jets. The measurements of velocity and temperature by hot fil probe and thermocouples respectively.	Enhancement in heat exchange by a factor of 2 compared to steady jet.
Camci and Herr (2002)	Self-oscillating jet.	Hot film probe, thermocouple.	A feedback tube creates the self-oscillation of a circular jet. Velocity and temperature measurements by hot fil probe and thermocouples respectively.	The oscillation enhances the heat transfer.
Liu and Sullivan (1996)	Acoustic excitation of the jet.	Temperature-sensitive fluorescent technique, hot film sensor.	Circular jet excited using speaker impinging on a heated plate. Velocity and temperature measurements by hot film sensor and fluorescent paint, video recording using CCD camera.	Enhancement in heat exchange when the jet is excited by its natural frequency. Reduction in the heat exchange when the jet is excited with subharmonic frequency.

Table 2 Summary of previous studies on the control methods used in the enhancement of heat transfer (Cont.)

Authors	Control	Metrology	Method	Main results
Poh *et al.* (2004)	Flow pulsations.	Finite Volume CFD.	A circular oscillating jet impinging on a heated plate was simulated using Fluent 6.0.	Best heat performance at Re=300, f=5Hz, and H/D=9.
Lee and Lee (2000)	Changing the aspect ratio of the elliptic jet.	Thermochromic liquid crystal thermometry, smoke wire technique.	An elliptic jet with different AR impinging on a heated plate was used. CCD cameras were used for temperature visualization of liquid crystals. Smoke wire with cameras was used for flow visualization.	The heat transfer increases with increasing the aspect ratio for small impact distance.
Koseoglu and Baskaya (2010)	Changing the inlet geometry.	3D low Reynolds number k-ε model. Thermochromic liquid crystal technique, LDA.	Elliptic, circular, and rectangular jets impacting a heated plate were tested. Numerical and experimental work was carried on to obtain velocity and temperature data.	Increasing AR of all types of nozzle with equal section area leads to an enhancement in the heat transfer.
Gao, Sun, and Ewing (2003)	Adding triangular tabs to the round nozzle.	Infrared thermography, AN anemometry, and HWA.	6, 10, and 16 tabs were added to a circular nozzle. Velocity and temperature measurements by AN2000 anemometer and IR camera respectively.	More than 25% enhancement in the heat exchange.
de Lemos and Fischer (2008)	Adding a cover of porous material to the plate.	CFD.	Simulation of rectangular jet striking a heated plate covered with a porous material layer	Decrease the peak in the Nusselt number distribution. Enhancement in heat flux for values certain values of layer thickness, porosity, and thermal conductivity ratio.
Rallabandi *et al.* (2010)	Adding ribs to the plate.	Transient liquid crystal, mass flowrate sensor. CFD.	Staggered and inline ribs were added to the impingement plate, and jets with different aspect ratios and flow channels were used.	50-90% increase in heat transfer in both configurations
Ekkad and Kontrovitz (2002)	Adding dimples to the plate.	Liquid crystal thermometry.	Inline and staggered dimples were tested using an image processing system (RGB camera, CCD camera ...).	TheThe heat exchange is reduced compared to the case without dimples.
Ndao *et al.* (2012)	Adding pin fin structures to impingement surface.	CFD.	A simulation of a circular jet impinging a plate with micro pins was carried out.	200% increase in the heat exchange rate.
Beitelmal, Saad, and Patel (2000)	Inclination of impinging plate.	Thermocouples.	The impacted surface was inclined between 45 and 90 degrees. The temperature was measured using thermocouples.	Shifting in the region of maximum heat transfer
Nguyen *et al.* (2009b)	Using of Al2O3-Water nanofluid.	Thermocouples.	36 nmAl_2O_3 particle water nanofluid was projected on a heated plate. The temperature measurements were carried out using thermocouples.	Nanofluid particles with a volume fraction higher than 6% were found not suitable for heat transfer enhancement.
Barewar, Tawri, and Chougule (2019)	Using nanoparticles with a water jet.	Thermocouples.	DI water and ZnO nanofluids with different concentrations were added to a circular jet striking a heated copper plate.	Significant enhancement in the case of using ZnO nanofluids.

Table 2 Summary of previous studies on the control methods used in the enhancement of heat transfer (Cont.)

Authors	Control	Metrology	Method	Main results
Klein and Hetsroni (2012)	Using actuating slab.	IR thermography.	Circular jet impacting a heated plate with an actuating slab that moves up and down.	34% enhancement in the coefficient of heat change.
Nuntadusit, Wae-hayee, and Kaewchoothong (2018)	Using of swirling jet.	TLC and bleu dye technique.	A swirling jet impinging a heated plate in a rig test was used. Different twist ratios were tested.	Enhancement in heat exchange was acquired for a swirl number of 0.4.
Ai, Xu, and Zhao (2017)	Moving nozzle.	Thermocouples.	Stepper motors with regulating speed were used to create a jet with a movable nozzle. The heated plate was fixed and thermocouples were used to measure the temperature.	Increase in the heat transmission and temperature uniformity at higher nozzle velocity.
Kaewchoothong *et al.* (2014)	Expansion pipe nozzle with air entrainment holes.	CFD.	A numerical simulation of a system consisting of an expansion pipe blowing mouth with a different number of air entrainment holes was performed to test the performance of the system on the heat exchange characteristics.	Enhancement up to 6.4% in case of 4 holes and impact ratio of 4.
Nimmagadda, Lazarus, and Wongwises (2019)	Magnetic field around the plate.	CFD.	The multi-physical simulation was carried out to study the impact of the magnetic field on the heat exchange in the case of a water jet striking on a fixed and vibrating plate.	Enhancement in the heat transfer in the case of fixed plate up to 36.18% with a magnetic field of 80 Ha. Reduction in the heat exchange rate in the case of vibrating plate.
Diop *et al.* (2022)	Mist adding.	Thermocouples.	A mist with different concentrations was added to a jet hitting a heated plate. Thermocouples were utilized to compute the surface temperature.	The addition of mist increases the heat transfer rate by 21% for a mist concentration of 3mg/s and 32% for a concentration of 6 mg/s.

A coupled study was investigated by Bhapkar, Srivastava, and Agrawal (2013), who studied the outcomes of operating parameters including orifice dimensions, Reynolds number, impact distance, stock number, and inclination angle on both acoustic fields, and transfer of heat, for a circular synthetic jet impacting a heated plate. The objective was a little different from the studies presented above. The authors were interested in finding a configuration that gives the maximum heat transfer enhancement and low acoustic noise. They proved that the maximum heat transmission was obtained for an inclination angle between 40 and 90 degrees, for all impact distances. Furthermore, the authors compared an elliptic jet to a circular, rectangular, and square jet with the same equivalent diameter, to find the out-turn of utilizing an orifice shape on the acoustic emission and heat exchange Bhapkar, Srivastava, and Agrawal (2014). They found that, for the elliptic jet, an aspect ratio of 1.4 gives a maximum heat transfer at an impact ratio of 3. Compared to other orifice shapes, the elliptic one has the best performance for an impact ratio lower than 6. However, for higher impact distances, circular and square orifices are better. Finally, the author highlighted the strong correlation between acoustic and heat transfer behavior, which needs more effort to relate the two phenomena.

A similar study was made by Mangate and Chaudhari (2015) who studied two other shapes: diamond and oval orifices. The excitation frequency of the synthetic jet was taken in the range of 100 to 250 Hz, and the impact ratio was between 0 and 16. They calculated the average heat transfer coefficient and the sound pressure level in order to inspect the acoustic properties in addition to the properties of heat transfer. Results show an enhancement in the heat transmission with a value of 17% for the diamond orifice and 7% for the oval orifice compared to the circular jet at the operating frequency of 200 Hz. However, there is a decrease in sound pressure level of 7% for both orifices, as compared to the circular jet. These findings are highly significant in terms of achieving an optimal balance between heat enhancement and noise reduction.

Recently, Mrach *et al.* (2020) studied the effect of the plate temperature on the acoustic noise produced in the event of a rectangular jet impacting a slotted plate. This configuration corresponds to a slot noise listed in Rockwell and Naudascher (1979). The authors found a change in the sound pressure level by 10% when the plate was heated, in addition to the change in the acoustic spectrum during the heating process. This study indicates a high correlation between thermal and acoustic characteristics of impinging jets, and needs further work to understand the change in the turbulence dynamic due to the plate heating.

Based on previous studies in this section, continued research in this area is essential for having the potential to improve both the fundamental understanding of the complex relationship between flow dynamics, heat transmission, and acoustics, especially in practical uses of impinging jet systems where many factors are capable of influencing the system's performance.

4. Conclusions

In conclusion, this review paper has provided valuable insights into impinging jet flow dynamics and their important role in various industrial applications. Controlling the flow dynamics by adjusting the design of the nozzle, the impingement distance, and flow rates, enhancement and improvement in heat transfer rates on the performance of previously mentioned industrial applications can be achieved. Synthetic jets were found to enhance convective heat transfer by over 300% compared to natural convection. Also, maximum heat transfer was achieved at inclination angles between 40 and 90 degrees of impinging jet. Additionally, heat transmission improved by 17% when jet impinges from a diamond orifices and the sound pressure levels decreased by 7% compared to jets impinging from a circular orifice. Moreover, this paperwork highlights the need for further research to explore the complex relationship between aero-acoustics emissions and heat transfer of jet impingement. Therefore, understanding the acoustic implications in industrial systems is very important to address concerns that are directly related to ensuring acoustic comfort in practical applications. As a result, future research in this field must focus on developing advanced computational techniques and conducting extensive experimental studies in addition to exploring control strategies to have more advanced knowledge in fluid dynamics, heat transfer, and aero-acoustics. This will pave the way for more efficient and sustainable industrial processes.

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