International Journal of Technology 16(1) 46-71 (2025)

International Journal of Technology

http://ijtech.eng.ui.ac.id

Review Article

Heat Transfer Characteristics of Passive, Active, and Hybrid Impinging Jets: A Review

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Abstract: In engineering applications, there is a need to reform the excitation methods used for jet impingement to achieve simpler and more effective thermal exchange. Jet impingement is a highly effective method for enhancing heat transfer, characterized by its ability to create high heat transfer coefficients. These characteristics make it a preferred method in applications requiring efficient thermal management, such as cooling of electronic components, turbine blade cooling in jet engines, and material processing. However, traditional excitation methods for jet impingement can be complex and challenging to implement. Therefore, there is a growing interest in developing new excitation methods that are simpler and more effective. The methods used can be categorized into three groups, including passive self-excited jets, active excited jets, and hybrid methods. Passive methods, such as annular, swirling, and sweeping jets, utilize the inherent characteristics of jet flow without requiring additional energy consumption. Active systems, on the other hand, involve supplementary devices such as fans or pumps to intensify heat transfer. Examples of active excited jets include synthetic and pulsed jets. Hybrid methods combine two or more methods to further thermal improvement that can reach more than 20%. This paper reviews experimental and numerical hybrid methods to enhance heat transfer to impinged surfaces. Experimental tools, including high-speed imaging, methods, such as Computational Fluid Dynamics (CFD), are reviewed. The efficacy of these methods is evaluated by comparing their performance, highlighting the potential for optimization and innovation in jet impingement heat transfer.

Keywords: Flow dynamics; Heat transfer; Hybrid methods; Impinging jets

1. Introduction

Efficient thermal management is an important aspect of various engineering applications, ranging from electronics cooling to industrial processes. A very efficient method for enhancing heat transfer is jet impingement, which involves directing a jet of fluid onto a target surface. Many studies were performed numerically and experimentally with different methods to highlight heat transfer and flow dynamics interactions. The efficiency of this method largely depends on the excitation method employed to generate and control jet flow (El Hasan et al., 2024; Zohbi et al., 2024; Assoum et al., 2023; Aldossary et al., 2022; Susmiati et al., 2022; Mrach et al., 2020; Hassan et al., 2020; Assoum et al., 2020; Jani et al., 2019; Zhang 2009).

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https://doi.org/10.14716/ijtech.v16i1.7255
Received August 2024; Revised September 2024; Accepted October 2024; Published January 2025

1.1. Simple Jets

Over the past few decades, numerous experimental and numerical studies have focused on enhancing heat transfer to cool heated surfaces using impinging jets. The interest in this area stems from the critical need to improve thermal management systems across various industrial applications. Researchers have identified several key parameters that significantly influence heat transfer performance. These parameters include the composition of the fluid, the material and geometry of the plate, the shape and geometry of the nozzle, the impact distance between the nozzle and the surface, and the role of resonance effects. Each of these factors contributes uniquely to the efficiency of heat transfer, making them vital considerations for optimizing impinging jet systems (Matar et al., 2024).

1.1.1. Fluid Composition

The thermal properties of the working fluid play a pivotal role in heat transfer performance. Fluids with higher thermal conductivity, such as water-based nanofluids, have been shown to enhance heat dissipation. The addition of Al_2O_3 at a concentration range between 0.15% and 0.6% can enhance thermal transfer by up to 128%. Hybrid nanofluids can further improve the fluid's ability to transfer heat by mixing additional nanoparticles, which increase turbulence and thermal conductivity. Additionally, the specific heat capacity and viscosity of the fluid influence its flow behavior and cooling effectiveness (Ranga Babu et al., 2017; Modak et al., 2015).

1.1.2. Plate Modification

The material and geometry of the target plate significantly affect the flow dynamics and heat transfer characteristics. Surface roughness can enhance heat transfer by disrupting the boundary layer and promoting turbulence. However, excessive roughness may lead to higher pressure drops and energy losses. Surface modification can be achieved by adding pin fins of different geometries (rectangular, square, circular, and elliptical) to the surface, which impact both the velocity distribution and the magnitude of the backflow area near the pins, thereby enhancing heat transfer. Among these, elliptical fins demonstrate the highest enhancement in Nusselt number, with an increase of up to 54%. On the other hand, surface modification can also be achieved by applying linear or radial microgrooves, which show significant enhancement compared to a flat, smooth plate (Ravanji and Zargarabadi,2021; Jenkins et al., 2017).

The composition of the plate plays a crucial role in enhancing heat transfer by altering flow dynamics and thermal interactions. Studies have investigated the application of a magneto-fluid coating on hot surfaces, which resulted in a significant enhancement of heat exchange, influenced by jet velocity and reaching up to 32%. This improvement is attributed to the presence of vortices within the ferrofluid. Additionally, the use of porous materials, such as aluminum foam and resin foam on a plain wall, has been explored. These materials were found to increase hydraulic resistance against the incoming jet, as evidenced by the distribution of static pressure along the surface, further contributing to improved heat transfer performance (Yogi et al., 2022; Chen et al., 2001).A flat plate provides a uniform surface for jet impingement, whereas curved plates, as illustrated in Figure 1, create complex flow structures, including secondary vortices, which enhance mixing and significantly improve heat transfer (Kim et al., 2019; Li et al., 2019; Taghinia et al., 2016).

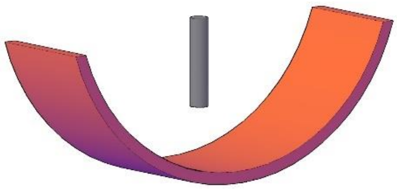


Figure 1 Concave surface

Adjusting the inclination angle of the plate redistributes the impingement region, influencing heat transfer performance. Studies have shown that using jets at different wall inclinations enhances heat exchange. This improvement is due to the formation of vortical structures, which disrupt the laminar flow pattern and promote more effective heat transfer (Yousefi-Lafouraki et al., 2014; Baffigi and Bartoli, 2010).

1.1.3. Nozzle Geometry

The nozzle shape and geometry significantly influence the velocity profile, turbulence, and jet spread. Chamfered nozzles improved the heat transfer to pressure drop ratio by up to 30.8% compared to square-edged nozzles. Among orifice geometries, square nozzles outperformed circular ones, increasing cooling efficiency by 42% due to better flow penetration. Rectangular nozzles with an aspect ratio of 5 achieved the best performance, covering 14 times the nozzle area. Using grid patterns, higher thickness ratios enhanced localized heat transfer at shorter nozzle-to-plate distances by amplifying flow disturbances (Wang et al., 2022; Cafiero et al., 2017; Brignoni and Garimella 2000).

1.1.4. Impact Distance

The standoff distance, defined as the distance between the nozzle exit and the target plate, significantly affects heat transfer efficiency. Studies show that this region typically spans 4 to 6 jet diameters and influences jet intensity. For instance, at H/De = 2, chaotic flow near the surface enhances heat transfer, while at H/De = 4, increased turbulence in the stagnation zone further improves performance (He and Liu, 2018; Zou, 2001).

1.1.5. Resonance

Resonance phenomena, caused by acoustic or fluid dynamic instabilities, can significantly enhance heat transfer in impinging jet systems. Oscillations or vibrations introduced into the jet increase turbulence and mixing, improving thermal performance. Resonant flow involves the formation of standing waves within a cavity, generating intense fluid motion that boosts convective heat transfer. One study found that a single fin could disrupt flow near the front edge, amplifying downstream vibrations and increasing heat convection by up to 23%. Another study experimentally investigated periodic jets, where controlling the mass flow rate improved performance. The combination of triangular (or sinusoidal) and rectangular signals yielded the best results, outperforming other configurations (Geng et al., 2015; Xu et al., 2009).

1.2. Self-Exciting Jets

To improve the efficiency of jet impingement in heat exchange applications, various methods can be utilized. These methods can be broadly classified into three categories such as passive, active, and hybrid. Subsequently, passive methods do not require additional energy to refine thermal exchange, while 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, thereby being cost-effective and more reliable than active methods. While hybrid systems involve the use of multiple passive or active systems to enhance thermal performance. (Saha et al., 2020; Pati et al., 2017; Webb and Kim 2005).

Hybrid systems use a combination of methods to enhance heat transfer and are becoming more significant in engineering. By blending different techniques, these systems achieve better cooling and thermal management. Hybrid methods are highly valuable in industries like electronics for effective heat dissipation and in energy systems to improve thermal efficiency. For instance, combining jet impingement with multilayer microchannel heat sinks is a proven approach to manage high heat fluxes while maintaining low pressure drops. These hybrid heat sinks provide adaptable designs that can be fine-tuned to achieve specific thermal performance goals, ensuring efficient heat dissipation with minimal pressure loss. Moreover, studies show that using square multiple impinging jets with hybrid nanofluids under optimal conditions can enhance the Nusselt number by approximately 35%. Another research focused on cooling an oscillating hot square object with a double slot jet impingement system under a magnetic field. In this setup, the use of hybrid nanofluids, coupled with the object's oscillation, led to a substantial improvement in cooling efficiency. Compared to using a base fluid without a magnetic field, cooling performance increased by 62.9% at Reynolds Number (Re) = 100 and 77.6% at Re = 500 when both hybrid nanofluid and object oscillation were applied (Ajeel et al., 2024; Selimefendigil et al., 2024; Mostafa et al., 2023). Recently, the use of AI (Artificial Intelligence) has gained significant importance in predicting, optimizing, and monitoring designs with high accuracy. A numerical study using an Artificial Neural Network (ANN) assisted Computational Fluid Dynamics (CFD) method was conducted on a hybrid cooling system that combines channel flow and slot jet impingement to cool an elastic plate. The results show that this combination significantly improves the cooling performance of both the upper and lower sections of the plate, while also addressing its deflection. Another study achieved an accuracy of 99.03% for the average Nusselt number and 94.82% for the Sherwood number when analyzing the magneto-bioconvective behavior of hybrid nanofluid in an inclined porous annulus with oxytactic microorganisms using ANN and CFD. (Swamy et al., 2024; Selimefendigil and Oztop 2024)

The flow chart presented in **Figure 2** illustrates heat transfer enhancement through active and passive excited jets, with further improvement achieved by combining excitation jet methods with other methods such as fluid diode, surface modification, piezoelectric fan, nanofluids, and nozzle geometry which will be the focus of this study. The use of passive or active methods to excite turbulent jets has a significant interest in thermal engineering due to its theoretical and practical importance for enhancing jet turbulence and mixing characteristics. Numerous experimental and theoretical analyses have explored both passive and active excitation jets, examining the impact of different shapes and working conditions on fluid flow and heat exchange properties (Sabato et al., 2019; Persoons et al., 2011; Chaudhari et al., 2010a; 2010b; Tesař et al., 2006; Lee et al., 2003).

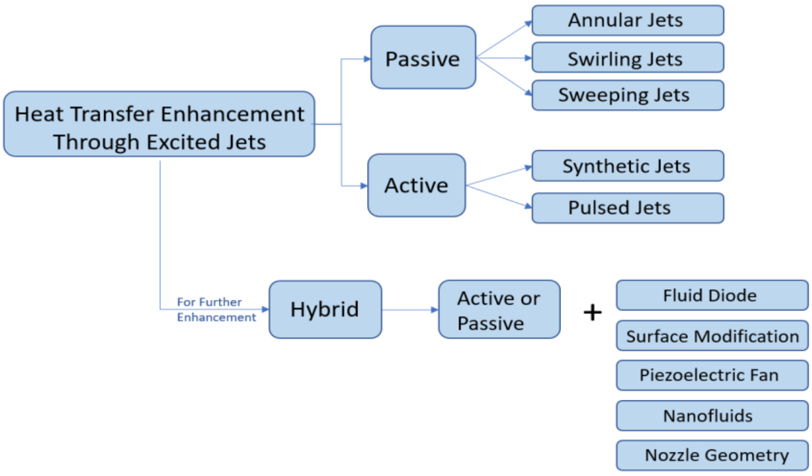


Figure 2 Flow chart of the study

1.2.1. Passive Self-Exciting Jets

Passive self-excited jets leverage the inherent characteristics of jet flow to enhance heat exchange without requiring additional energy input. Among the most notable examples are annular, swirl, and sweeping jets (Khan et al., 2023; Fénot et al, 2021; Eghtesad et al., 2019; Ikhlaq et al., 2019; Park et al., 2018; Trávníček and Tesař, 2013; Bakirci and Bilen 2007; Lee et al., 2002).

1.2.1.1. Annular Jets

Annular jets, produced by a ring-shaped nozzle, generate a hollow cylindrical flow. This configuration enhances the surface area of the impinging fluid, thereby improving heat exchange rates. The structure of an annular jet involves the creation of a vortex region beyond the nozzle outlet, featuring two axisymmetric shear layers: one at the outer boundary of the annular flow and another on the inner surface. The interaction of the flow between these different regions leads to significant large-scale turbulent disturbances. Studies have shown that at identical mass flow rates, the annular jet displayed notably greater velocity and turbulent fluctuations compared to the circular jet (Terekhov et al., 2016; Patte-Rouland et al., 2001).

In specific configurations of jet exit Re, critical impact distance (H), and a specific blockage ratio (BR), thermal exchange for the annular jet was enhanced by 10-15% relative to the circular jet. The optimal thermal improvement relative to the circular jet occurred at approximately BR=0.4. Additionally, the impact of extending the central shaft of the annulus past the exit point of jet, considering three different shapes including cylindric, conic, and half-ellipsoid was examined. Thermal exchange was influenced differently depending on the configuration and size of the bullet extension. Relative to the standard case, the ellipsoidal extension had a slight positive impact on average heat transfer, particularly at higher Re, with improvements of about 1- 2%, the cylindrical extension provided thermal enhancement for longer extensions (more than the outer jet diameter), while the conic extension reduced thermal exchange regardless of the extension length. As the extension length increased, there was a slight increase in maximum Nu values (Afroz and Sharif 2022; 2018).

1.2.1.2. Swirling Jets

Swirl jets are created by introducing a tangential component to the fluid flow, causing jet to spin around its axis. The dynamic interplay between the upstream and downstream flow regions was examined, focusing on the impact of impingement on vortex breakdown induced by swirl and the intricate relationship between thermal exchange and the downstream flow domain. In the upstream region, under minimal swirl conditions around 0.3, free and impinging jets each exhibit an absence of vortex failure. However, at a higher swirl rate of around 0.74, vortex failure is observed only in Re range between 11,600 and 24,600. At close-range interaction distances of H/D = 2 and 4, the recirculation bubble associated with vortex breakdown appears more spherical and exhibits greater size and strength at lower Re, diminishing at higher Re (Ikhlaq et al., 2021).

The emergence and evolution of organized vortical patterns, influenced by the submerged impinging swirling jet, play a significant role in shaping flow characteristics and the conveyance of thermal energy, acting as a passive variable in the given operational parameters (Contino et al., 2022).

The intensity of swirl diminishes as jet-wall distance increases. Conversely, the impact of swirl becomes more pronounced at a larger jet-wall distance, resulting in a wider affected area along the wall. Furthermore, although swirl motion contributes to turbulence increase, thermal coefficient declines with a higher swirl number. Swirl motion improves the uniformity of thermal exchange for both jet-wall distances, except near the stagnation region at H/D = 2, where variations in Re influence the enhancement (Huang et al., 2022).

A numerical method showed a better swirling enhancement (at L/D = 6 and 8). At higher Re, thermal exchange rate increases because of the high rate of momentum transfer. Notably, the use of two jets with identical flow rates can raise heat rate by 10% (Amini et al., 2015).

1.2.1.3. Sweeping Jets

Sweeping jets, which oscillate back and forth across the target surface, can effectively cover a significantly larger area, extending to nearly half of a large curved surface, with a robust impingement effect. In addition, as Re increased and the gap between the nozzle and the wall decreased, thermal exchange of the sweeping jet experienced a boost. At a high Re of 15,000, the sweeping jet demonstrated notable improvements in the domain at H/D ratios of 0.5 and 1.0, reaching up to a remarkable 40% increase around the stagnation zone. Additionally, by excluding the outer diffuser at a distance ratio (X/D) of 4.5 and Re of 60,000, a 140% enhancement in thermal exchange was observed. Conversely, increasing the distance ratio and divergence angle leads to a decrease in thermal exchange coefficient. In the confined impingement scheme, the sweeping jet demonstrates superior overall cooling efficiency relative to the steady jet. However, in the unconfined impingement configuration, the steady jet exhibits a slight advantage (Abdelmaksoud and Wang 2023; Joulaei et al., 2022; Wen et al., 2019; Zhou et al., 2019a).

1.2.2. Active Exciting Jets

Actively excited jets require external energy sources, such as fans or pumps, to enhance heat transfer. They include synthetic and pulsed jets, which offer precise control over jet flow characteristics (Ergur and Calisir 2023; Castellanos et al., 2023; Kim et al., 2022; Kurian et al., 2021; Gil and Wilk 2020; Travnicek and Antosova 2020; Raizner et al., 2019; Zhang et al., 2018; Larasati et al., 2017. Kosasih et al., 2016).

1.2.2.1 Synthetic Jets

Synthetic jets are generated by the cyclic ejection and suction of fluid through an orifice, typically driven by a diaphragm or piezoelectric actuator. The sinusoidal waveform exhibits a significantly higher average Nusselt number, outperforming the square waveform by 20.86%. However, in the region of no flow separation, the square waveform surpasses the sinusoidal waveform by 18.94% in thermal exchange. Notably, the sinusoidal waveform achieves a 73.68% higher mass flow rate relative to the square signal at a resonance frequency of 150 Hz. These jets operate without the need for a continuous supply of external fluid, making them both efficient and compact. Meanwhile, investigations into the effect of orifice plate thickness on thermal transport behavior revealed that the peak heat transfer coefficient was 16.1 times higher than that of natural convection (Singh et al., 2022; 2020).

Experiments conducted using synthetic jets emerging from a star-shaped nozzle with lobes ranging from 3 to 10 revealed that the 6-lobed star orifice demonstrated optimal thermal performance at distance to target over diameter z/d ratio ranging from 2 to 14. At z/d = 2, the 6-lobed orifice outperformed the round orifice by 7.6% and the 10-lobed star orifice by 10.1%, due to the generation of vortices along the edges of the lobes, resulting in a subsequent shift of the axis between the primary and secondary planes. The square nozzle shape and sinusoidal wave frequencies provide a wider coverage area compared to the circular nozzle. This results in a higher entrainment rate, which enhances heat transfer performance (Sharma et al., 2023; Harinaldi et al., 2013).

Increasing the pulse frequency in the synthetic impinging jet led to the development of local velocity and gas disturbances, enhancing thermal exchange and increasing stagnation of thermal conductivity. The stagnation Nusselt number increased for short orifice-to-wall distances (H/d < 4), with peak thermal conductivity observed at distances of H/d from 3 to 5. Further increases in distance resulted in inhibited thermal exchange (Lemanov et al., 2022).

1.2.2.2 Pulsed Jets

Pulsed jets involve the intermittent discharge of fluid at high velocities, with control over frequency and amplitude. The introduction of pulsation caused jet to spread, resulting in a reduction of the potential core length compared to a normal jet. Pulsation amplified the mixing and diffusion processes with the surrounding fluid, thereby enhancing thermal exchange in the potential cone area. Using a pulsating jet operating at a frequency range of 40 to 160 Hz resulted in a 2 to 8% increase in the time-mean Nusselt number in the wall jet zone. In addition, the impacts of square-signal pulsating frequency and amplitude were investigated, providing detailed insights into the interaction of these parameters on cooling performance (Wang et al., 2023; Marzouk et al., 2022; Zargarabadi et al., 2018).

Introducing a pulse frequency of 100Hz to jet resulted in a notable 22% enhancement in the convective heat transfer coefficients for round/square jets and a 15% improvement for elliptical/rectangular jets. The pulsation exhibited a dual effect on the average Nusselt number, leading to a reduction at low frequencies and an increase at high frequencies compared to steady jets (Rakhsha et al., 2023).

After introducing all types of excitation jets, the focus shifts to hybrid methods, which combine elements from both passive and active methods to optimize thermal performance and are the main focus of this review. This review study explores the potential of hybrid methods in providing superior heat transfer by integrating the advantages of various excitation methods. The subsequent sections will explore specific hybrid configurations, their influence on thermal enhancement, and how they combine the strengths of passive and active jets to optimize efficiency. Through detailed analysis and experimental results, the next section aims to demonstrate how hybrid methods can be effectively employed for advanced thermal management solutions.

2. Hybrid Methods for Enhancing Heat Transfer

In the search for improved heat transfer performance, hybrid methods have emerged as a compelling solution. These methods combine the strengths of different thermal enhancement strategies to achieve superior results. By integrating various passive and active methods, such as advanced fluid dynamics, innovative materials, and external control mechanisms, hybrid methods can significantly enhance the efficiency of thermal management systems. These combinations lead to increased turbulence, better mixing, and more efficient heat dissipation, making them highly effective for a wide range of applications in fields such as electronics cooling, industrial processes, and energy systems. The synergy between different approaches in hybrid methods represents a powerful method to overcoming the limitations of traditional heat transfer methods and achieving optimal thermal performance (Bai et al., 2020; Lyu et al., 2019a; 2019b; Chouaieb et al., 2017).

2.1. Heat Transfer Enhancement by Combining Excited Jets with Fluid Diode

In the pursuit of advanced heat transfer solutions, hybrid methods that integrate various enhancement strategies have gained significant attention. One such innovative method is the combination of synthetic jets with fluid diode technology. The implementation of fluid diodes is designed to regulate oscillating airflow, thereby suppressing the reversal of hot air through the nozzle exit during the suction phase. Studies have highlighted the superior cooling capabilities of hybrid synthetic jet, which reduces the average Nusselt number by 54.7% relative to a simple synthetic jet configuration, offering valuable insights guiding the development of novel hybrid synthetic jets and emphasizing their potential for high-efficiency impingement cooling applications. On the other hand, the use of pulsation with the fluid increases Re, optimizing heat and mass exchange and enhancing flow oscillations, resulting in a 12 to 40% improvement in heat and mass transfer. Additionally, hybrid synthetic jet achieved an 18% enhancement in heat transfer rate due to a 26% greater flow rate compared to the standard synthetic jet (Yu et al., 2019; Trávníček and Vít, 2015).

2.2. Heat Transfer Enhancement by Combining Excited Jets with Surface Modification

Using a pulsating jet with frequencies between 50 and 100 Hz towards a rough wall equipped with 12 elliptical pins significantly amplifies heat transfer rate, making it more effective compared to a round pin. The optimal placement for mounting the pin on a flat wall is at a distance equal to three times the diameter of jet ($r = 3D$). Another study, examining a rough surface featuring 36 elliptical pin-fins of varying diameters, reported a significant 35% improvement in thermal exchange as the orifice-to-wall distance increased under pulsating flow conditions. In contrast, under steady-state flow conditions at Re of 10,000, a reduction of approximately 12% was observed, with the effect of the impact distance being minimal at higher Re. The aspect ratio played a significant role in improving thermal exchange, showing a 20% Improvement in average Nusselt number with a rise in pin height, while a reduction in average Nusselt number was observed with a rise in pin diameter for $AR > 1$. Additionally, introducing oscillation at a frequency of 100 Hz, relative to the normal state, was found to boost thermal exchange by up to 17% (Yousefi-Lafouraki et al., 2023; 2022).

Another study assessed the efficiency of heat dissipation by combining the use of single and multiple synthetic jets with hollow cylindrical fins filled with PCM. The performance improved with this incorporation, and the best results were achieved when using Eicosane in the impinging wall and exposing it to multiple orifices synthetic jets. The configuration yielded thermal resistance of 0.91 K/W, thermal coefficient of 420.4 W/m^2, and a Coefficient of Performance (COP) of 2.1. These results provide a valuable enhancement to thermal efficiency in such systems (Arumuru et al., 2023).

2.3. Heat Transfer Enhancement by Combining Excited Jets with Piezoelectric Fan

Thermal efficiency improvement can be achieved by combining excitation jets with piezoelectric fans. The addition of a piezoelectric fan to the circular jet has an advantage on thermal performance, leading to a 20% improvement in the area-averaged Nusselt number at a small impact distance relative to the circular jet. This combined method optimizes heat transfer process for more efficient and compact cooling solutions (Zhou et al., 2019a).

The integration of a piezoelectric fan with a continuous circular jet was investigated, as illustrated in Figure 3. A similar configuration utilizes the fan's vibrations to introduce pulsating excitations to jet impingement while maintaining its continuous flow. The results indicate that in the axial arrangement, the average thermal exchange optimization factor is improved by 13%, and thermal exchange uniformity factor by 0.5%, relative to the transverse system (Li et al., 2024).

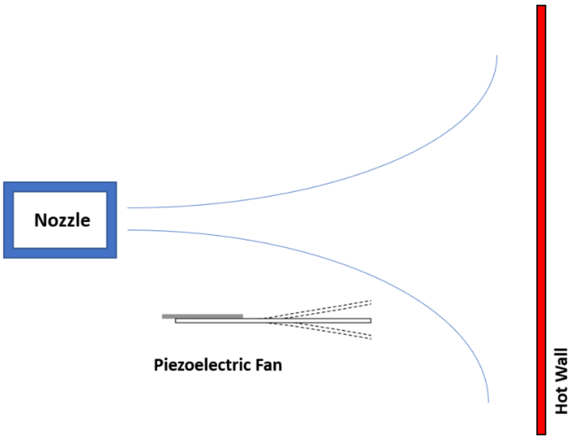


Figure 3 Configuration of a nozzle with the piezoelectric fan

Jet excitation leverages fluid flow to disrupt thermal boundary layer, while piezoelectric fans induce mechanical vibrations that enhance fluid mixing and promote heat transfer. The integration of synthetic jets with a piezoelectric fan exemplifies the effectiveness of this interaction. Combining synthetic jets with a piezoelectric fan demonstrates this effective interaction. The synthetic jet, produced by the piezoelectric actuator, achieves the peak performance when operated at its optimal frequency. Additionally, studies have explored the combination of pulsed jets with a piezoelectric micropump. By adjusting the signal applied to the piezoelectric micropump, they were able to control the pulsating jet frequency, ranging from 10 Hz to 40 Hz. These results revealed that a high-frequency pulsating jet could substantially enhance the critical heat flux, achieving a value of 245.2 W/cm^2 at a flow rate of 60 ml/min. This represents an 84% increase relative to a steady jet (Fan et al., 2024; Tan and Zhang, 2013).

2.4. Heat Transfer Enhancement by Combining Excited Jets with Nanofluids

Combining pulse jets with nanofluids has shown significant potential in enhancing thermal exchange rates due to the synergistic effects of fluid pulsation and the superior thermal properties of nanofluids. Studies explored the combination of Al_2O_3-H_2O nanofluid, with volume fractions ranging from 0% to 3.5%, and periodic pulse jets with pulsation frequencies (f) between 10 and 50 Hz, employing various waveforms (Rectangular-wave and Triangular-wave). The results indicated that the Triangular-wave conducts a better enhancement of heat conductivity with medium frequency and large Re and nanoparticles volume fraction (Li et al., 2019).

Further investigation has underscored the effectiveness of hybrid nanofluids in pulse jet systems. A study highlighted the use of Al_2O_3-MWCNT/water hybrid nanofluid with volume fractions ranging from 0.05-0.3% in a pulse jet with pulsating frequencies between 0.2-20 Hz, employing sine, square, and triangular waveforms. The results indicated a maximum heat transfer improvement of 24% for a 0.3% volume fraction of Al_2O_3-MWCNT/water relative to de-ionized water under continuous jet impingement. Moreover, a 20% improvement was observed with a sine waveform at a 0.3% volume fraction and a frequency of 0.2 Hz. Pulsating jet impingement generally produces greater cooling rates, offering valuable insights for optimizing thermal exchange through pulsating hybrid nanofluid jet impingement cooling (Atofarati et al., 2024).

2.5. Heat Transfer Enhancement by Combining Excited Jets with Nozzle Configuration

Innovative jet configurations can significantly enhance heat transfer rates by leveraging various fluid dynamics and cooling mechanisms. A study combined a water circular jet with an air annular jet in the form of a mist. When the mist concentration is significantly reduced, the primary heat transfer mechanism is identified as intermittent heat perturbations resulting from the impingement of mist droplets. As the mist concentration rises, the significance of evaporative cooling from the liquid film on the wall and convective cooling due to the flow of the film grows more pronounced in the overall heat transfer process (Quinn et al., 2017).

In air coaxial jet configurations, enhanced mixing and flow dynamics are important for superior thermal performance. The local thermal exchange distribution displayed two peaks, one at the stagnation point and another near a unitless radial distance of 1. The increased involvement of the annular jet led to enhanced flow mixing, the extension of the dynamic regions towards the outer edges of the impingement plate, and a thinner heat gradient layer. Consequently, the use of a coaxial jet demonstrated significant advantages over a conventional single-round jet, particularly in achieving greater consistency and efficiency in thermal exchange. Alternatively, the impact of the combined swirl and circular jets reveals the complex dynamics affecting heat transfer uniformity, convective intensity, and pressure distribution in the studied impinging jet configuration. Nusselt number is enhanced by 22.2% with a rising flow ratio and by 9.3% with a lowering orifice-to-wall distance (Markal 2018; Markal and Aydin 2018).

Different nozzle shapes, such as chevron nozzles, can significantly influence synthetic jet thermal exchange performance. A study examining the combination of the synthetic jet with the pipe transmission and exit nozzle shape showed that the chevron nozzle proves to be beneficial for enhancing synthetic jet thermal exchange. Its impact varies with different orifice-to-wall distances and functional frequencies. At lower functional frequencies, the presence of the chevron exit alters the optimal orifice-to-wall distance for synthetic jet impingement thermal exchange relative to the circular exit nozzle (Lyu et al., 2019a).

Incorporating a central synthetic jet in the square-shaped array-jet assembly effectively enhances total thermal exchange efficiency, specifically when Re of the synthetic jet matches or exceeds that of the array-jet, practically making it suitable for applications. The results showed that thermal exchange enhancement persists at Re = 5000, with Nusselt numbers increasing by 30%-60% across impinging distances. Even at Re = 7000, a rise of 10%-30% was observed, and at Re = 10,000, there was an increase of less than 20% (Tan et al., 2023).

3. Evaluation of Hybrid Heat Transfer Techniques

Table 1 shows an overview of all studies discussed in hybrid section. Fluid diodes improve jet flow control, disrupting the thermal boundary layer for localized cooling and higher heat transfer rates. Piezoelectric fans amplify fluid mixing through mechanical oscillations, with optimal operation significantly boosting the heat transfer coefficient. Nanofluids enhance thermal conductivity and reduce resistance, enabling efficient energy distribution. Surface modifications, such as microstructures or conductive coatings, increase the effective heat transfer area and improve dissipation. Optimized nozzle designs further refine jet impingement patterns, ensuring uniform cooling and maximizing thermal efficiency.

Table 1 Summarize the various hybrid methods in impinging jets used to enhance heat transfer

Author (s)	Study type	Method (s)	Hybrid		wall	fluid	Main findings
Section 2.1 Jet + Fluid Diode							
(Yu et al., 2019)	Numerical	CFD The turbulence model SST/k-ω	Synthetic jet nozzle diameter Do=4 mm; Cavity diameter of 7.5Do Cavity height of 2.5Do; Nozzle length of 1 Do; Nozzle-to-wall gap of 4Do; Oscillations with 500 μm amplitude and 250 Hz frequency	Fluid diode To control oscillating airflow, effectively preventing the reverse flow of hot air through the nozzle exit during the suction cycle.	Heated surface uniform heat flux of 5000 W/m^2 Diameter of 10Do; With the length of 20 Do.)	Air Re = 1150 Re = 4180	The increased volumetric efficiency, facilitating the introduction of cooler external air and minimizing the rotation of hot air. Hybrid jet achieves an impressive volumetric efficiency of up to 95.8%. Amplifies Nu_{avg} by 54.7%
(Trávníček and Vít 2015)	Experimental	Smoke-wire hot-wire naphthalene sublimation method	Hybrid synthetic jet		Heated wall	Air 4000 ≤ Re ≤ 6000	18% enhancement in heat transfer rate attributed to the 26% greater flow rate achieved by hybrid synthetic jet The pulsation causes a rise in Re, leading to an improvement in heat/mass exchange and flow oscillations, resulting in a 12% to 40% improvement in heat/mass exchange.

Table 1 Summarize the various hybrid methods in impinging jets used to enhance heat transfer (Cont.)

			Synthetic jet: diaphragms of diameter D_D=53 mm and driving mechanism MONACOR SP-7/4S loudspeakers (nominal impedance of 4 Ω, RMS of 4 W, and peak power capacities of 8W and frequency of 95Hz)	Fluidic diodes			
			Mixed pulsed jet				
			The same actuator of hybrid synthetic jet described above	Fluidic diodes			
Section 2.2 Jet+ Surface modification							
(Yousefi-Lafouraki et al., 2022)	Numerical Experimental	CFD The (RNG) k - ε model. Hotwire Infrared Camera	Pulsating with a rotating disk Frequency ranging between 1 and 200 Hz. The pulse jet frequency is double that of the rotation of the disc.	rough target surface with 12 elliptical pins	An aluminum plate (200×200×2 mm	Air Re= 10000, 15000, 20000	Employing a pulsating jet with frequencies ranging between 50 and 100 Hz significantly amplifies heat transfer rate. The elliptical pin was found to be more effective than the round pin. The best pin positioning is set at a distance of three times the diameter of jet (r = 3D).

Table 1 Summarize the various hybrid methods in impinging jets used to enhance heat transfer (Cont.)

(Yousefi-Lafouraki et al., 2023)	Numerical Experimental	CFD RNG k – ε Hotwire IR camera	Pulsating with a rotating disk Frequency ranging between 1 and 200 Hz. The pulse jet frequency is double that of the rotation of the disc. The diameter of the round jet is 12 mm.	Rough surface with 36 elliptical pin-fins.	An aluminum base plate (20×20x2 cm2)	Air 10000 ≤Re ≤ 20000	A 35% enhancement in thermal exchange due to pulsating flow. The aspect ratio demonstrates a 20% improvement in mean Nu with a rise in pin height, while a decline in average Nu was observed with a rise in pin diameter for AR > 1. Introducing oscillation at a frequency of 100 Hz enhances thermal exchange by as much as 17%.
(Arumuru et al., 2023)	Experimental	A 16-channel data acquisition system 12 T-type thermocouples	Synthetic jet with single and multiple orifice cavity volume (50 mm diameter, and 11 mm height) orifice diameter of 3 mm diaphragm with a piezo (lead zirconate titanate PZT)	Aluminum heat sinks with 16 hollow cylindrical fins PCM (Eicosane and 1-Hexadecanol)	Aluminum heat sink	Air	The performance improved by incorporating Phase Change Material (PCM) in the hollow fins. The best results were achieved when using Eicosane with multiple orifices synthetic jet. This configuration yielded thermal resistance of 0.91 K/W, thermal coefficient of 420.4 W/m², and a Coefficient of Performance (COP) of 2.1.
Section 2.3 Jet + Piezoelectric fan							

Table 1 Summarize the various hybrid methods in impinging jets used to enhance heat transfer (Cont.)

(Zhou et al., 2019b)	Experimental	PIV Temperature Sensitive Paint Method	Circular jet 300 mm long 15 mm diameter	Piezoelectric fan thin metal blade (0.2 mm thickness and 15 mm width)	a thin foil of 400 mm×230 mm×30 µm.	Air Re=5000, 10,000, 18,000	A 20% improvement in the area-averaged Nusselt number at a small impact distance.
(Li et al., 2024)	Experimental	Infrared camera	Continuous circular jet 8 mm nozzle diameter 600 mm long 0.3 mm wall thickness (75 length to diameter ratio)	Piezoelectric fan piezoelectric fan of 51 Hz as 1st resonance frequency	heater foil of heat flux 2000 W/m2	Air 2,500 ≤ Re ≤7,500	The axial arrangement achieves a 13% improvement in the mean thermal transfer efficiency and a 0.5% increase in heat transfer uniformity factor.
(Tan and Zhang 2013)	experimental	PIV, hot-wire anemometer infrared camera	Synthetic jet A cylindrical cavity (30 mm diameter and 5 mm height), diaphragm (0.2 mm thickness). Four different orifices: single-slot, single-hole, three-slots, and three holes align in x-direction.	A piezoelectric ceramic disk (PZT-5) OF 20 mm diameter	a thin constantan foil of 100×150× 0.01 mm, mounted on the transparent plastic plate with a size of 200 mm × 150 mm × 20 mm	Air 1000 ≤ Re ≤ 2600	The synthetic jet, produced by the piezoelectric actuator, achieves the peak performance when operated at its optimal frequency.

Table 1 Summarize the various hybrid methods in impinging jets used to enhance heat transfer (Cont.)

(Fan et al., 2024)	Experimental	High-speed camera Thermocouples Data acquisition system Flow meter	Pulsating jet	piezoelectric micropump	A copper block (with four heating rods of 1000 W).	Deionized water $42 \leq Re \leq 252$	The critical heat flux with a high-frequency pulsating jet reaches 245.2 W/cm^2 at a flow rate of 60 ml/min, representing an 84% enhancement compared to a steady jet.
Section 2.4 Jet + Nanofluid							
(Li, Guo, and Liu 2019)	Numerical	CFD RANS SST- k-ε and k-ω	Pulsed Jet Pulsation frequency f= 10-50 Hz Rectangular wave Triangular wave Jet exit width W= 6 mm	Nanofluid The use of Al_2O_3-H_2O with volume fraction ϕ= 0-3.5%	Adiabatic wall of length 120 mm with constant heat flux	Al_2O_3-H_2O nanofluid $10000 \leq Re \leq 20000$	The T-wave demonstrates superior improvement in heat conductivity with moderate frequencies at higher values of ϕ and Re. When f=20 Hz, the rate at which Nu_{ave} increases starts to slow down.

Table 1 Summarize the various hybrid methods in impinging jets used to enhance heat transfer (Cont.)

(Atofarati et al., 2024)	Experimental	thermocouples, data-logger, and computer	The pulsed jet frequency is between 0.2 and 20 Hz. Amplitude between 4 and 20 Vp. Waveform (sine, squared, triangular). Wave offset between 0 and 4.	Al2O3-MWCNT/water hybrid nanofluid of volume fraction (0.05 vol% ≤ φ ≤ 0.3 vol%)	a constantly heated copper cylindrical block	Al2O3-MWCNT/water hybrid nanofluid 500 ≤ Re ≤ 7000	A maximum heat transfer improvement of 24% was realized with a 0.3% volume fraction of Al_2O_3-MWCNT/water compared to de-ionized water during continuous jet impingement. A 20% improvement was observed with a sine waveform at a 0.3% volume fraction and a frequency of 0.2 Hz
Section 2.5 Jet + Nozzle geometry							
(Quinn et al., 2017)	Experimental	high-speed shadowgraph hot film sensor with a TTL (Transistor-Transistor Logic)	Annular air jet With inner diameter D_i =1.3 mm and outer diameter D =1.7 mm	Circular water jet of diameter D_w =0.4 mm	heated copper block	Air and Water Re= 4500	When mist concentration decreases, heat transfer is mainly driven by intermittent perturbations from droplet impingement. As mist concentration rises, evaporative cooling from the liquid film and convective cooling due to film flow become dominant.

Table 1 Summarize the various hybrid methods in impinging jets used to enhance heat transfer (Cont.)

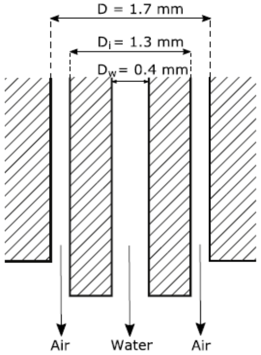
			The mist jet is produced using a Spraying System nozzle.  				
(Markal and Aydin 2018)	Experimental	Flexible heater Micro thermocouples connected to a data logger	Annular jet 10 mm outer diameter and 5 mm inner diameter	Circular jet Diameter (Di =4 mm) and 1 mm wall thickness.	For the pressure experiments: A polycarbonate circular plate (46 mm diameter and 5 mm thickness) For thermal experiment: A copper circular plate (46 mm diameter and 1.5 mm thickness)	Air 12000 ≤ Re ≤28000	In air coaxial jets, enhanced mixing and flow dynamics improve thermal performance. The thermal exchange peaks at the stagnation point and a radial distance of 1. The annular jet boosts flow mixing, extends dynamic regions outward, and reduces the heat gradient layer. Coaxial jets outperform single jets in thermal consistency and efficiency.

Table 1 Summarize the various hybrid methods in impinging jets used to enhance heat transfer (Cont.)

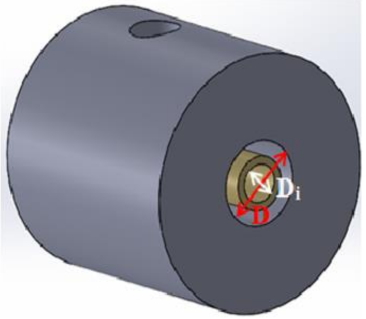
			The length of the nozzle (L =29 mm) Delrin holder of 30 mm outer diameter 				
(Markal 2018)	Experimental	Pressure tests: scanning valve Differential digital manometer Thermal measurement: a flexible heater powered by an AC power supply Micro thermocouples connected to a data logger	Swirl jet Three symmetrical outer helical grooves (width: 2 mm, height: 1.5 mm) are spaced 120° apart around a brass nozzle (D: 10 mm, L: 29 mm) housed in a Delrin holder (outer D: 30 mm). The nozzle has a swirl angle of 45° and a swirl number of 0.86.	Coaxial jet Nozzle with the inner round passage of 4.5 mm diameter	A copper circular plate (46 mm diameter and 1.5 mm thickness)	Air $10000 \leq Re \leq 26000$	The Nu enhanced by 22.2% with a rising flow ratio and by 9.3% and lowering orifice-to-wall distance. The heightened contribution of outer swirling flow positively impacted both the consistency and overall magnitude of heat transfer. Marked enhancement in heat convection was observed as the orifice-to-wall gap decreased.

Table 1 Summarize the various hybrid methods in impinging jets used to enhance heat transfer (Cont.)

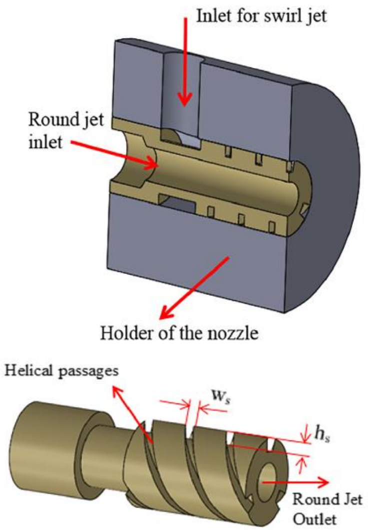
							
(Lyu et al., 2019a)	Experimental	Infrared camera	Synthetic jet A motor (3000 rpm and 50 Hz). Five frequencies of (5, 10, 15, 20, and 25 Hz). Stroke length of 1.24m Strouhal number of 0.008.	Transmission pipe and exit nozzle shape Three transmission pipes (short, moderate, and long pipe) two nozzle exit configurations (round and chevron)	A transparent plastic plate with a 5 mm thickness and a thin stainless-steel sheet of 0.05 mm thick),	Air Re = 3910, 7820, 11,740, 15,650 and 19,550	The chevron nozzle enhances synthetic jet thermal transport, with effects varying by orifice-to-wall distance and frequency. At low frequencies, the chevron exit alters the optimal orifice-to-wall distance compared to circular nozzles. At high frequencies, the circumferential Nusselt number trends align for both chevron and circular jets.

Table 1 Summarize the various hybrid methods in impinging jets used to enhance heat transfer (Cont.)

(Tan et al., 2023)	Experimental	Infrared camera	a square-layout continuous-jet array Four identical jet pipes of 8 mm inner diameter and 120 mm length Pitches including X/d = Y/d = 4, 5 and 6. Impinging spacing 2-10 mm	center-positioned synthetic-jet loudspeaker Diaphragm of 24 mm diameter Actuator cavity of 24 mm inner diameter and 5 mm depth. Orifice of 2 mm thickness and 6 mm diameter Frequency of 250 Hz.	A nickel-based super alloy sheet (100 mm ×100 mm ×0.025mm)	Air 3000 ≤ Re ≤ 1000T0	A central synthetic jet boosts heat transfer, especially when its Re matches or exceeds the array-jets. • At H/d ≥ 6 and Re=3000, Nu rises over 100%. • At Re=5000, Nu increases 30%-60%. • At Re=7000, gains are 10%-30%. • At Re=10,000, sparse arrays (X/d=Y/d=6) see <20% improvement.

4. Conclusions

In conclusion, the incorporation of a fluid diode significantly improves the directional control of the impinging jet, leading to more efficient disruption of thermal boundary layer. This leads to improved localized cooling and a significant increase in heat transfer rates. Incorporating a piezoelectric fan adds mechanical vibrations that enhance fluid mixing, further boosting heat dissipation. Operating the fan at its optimal frequency maximizes the cooling effect, significantly boosting the overall heat transfer coefficient. Utilizing nanofluids in the impinging jets improves thermal conductivity and heat capacity compared to conventional fluids. The nanoparticles in nanofluids contribute to better energy distribution and reduced thermal resistance, leading to a more efficient heat transfer process. Surface modifications, such as micro-structuring or coating with thermally conductive materials, enhance thermal properties of the surface and increase the effective surface area for heat transfer. These modifications result in improved heat dissipation and lower thermal resistance. The optimization of the nozzle configuration, including the shape and size, enhances jet impingement pattern and improves the uniformity and intensity of cooling. This leads to a more effective distribution of cooling across the target surface and maximizes heat transfer efficiency. This study shows that a multifaceted method incorporating fluid diodes, piezoelectric fans, nanofluids, surface modifications, and optimized nozzle configurations can significantly enhance heat transfer performance. Each component contributes uniquely to the overall system, leading to a synergistic effect that maximizes thermal efficiency and cooling capacity. The combination of these advanced methods offers a robust solution for high-performance thermal management in various applications. Future research should focus on exploring new hybrid combinations and understanding their dynamic interactions. Potential areas of investigation include assessing the stability and thermal performance of nanofluids under extreme conditions and prolonged use. Additionally, the development of innovative surface treatment techniques that improve durability and thermal properties can further enhance heat transfer. Leveraging computational optimization tools and artificial intelligence to create advanced nozzle geometries can also improve cooling performance and uniformity. Hybrid impinging jet techniques represent a step-change in the field of thermal engineering. By addressing challenges related to implementation, cost, and scalability, these methods have the potential to meet the growing demands for efficient and sustainable cooling solutions. Artificial intelligence can play a transformative role in this field by enabling the design of optimized jet configurations and hybrid systems through machine learning algorithms. AI can analyze large datasets from experiments and simulations to predict heat transfer performance, identify optimal operating conditions, and even automate real-time adjustments in complex thermal management systems. Interdisciplinary collaboration, incorporating AI tools, and continued innovation will be key to realizing the full potential of these approaches in future applications.

Acknowledgements

The authors wish to thank FEDER, the 'Region of Nouvelle Aquitaine'.

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Conceptualization, Michel Matar, Hassan H. Assoum, Anas Sakout, Mohammad El Hassan; methodology, Michel Matar, Hassan H. Assoum, Mohammad El Hassan; writing-original draft preparation, Michel Matar, Hassan H. Assoum, Mohammad El Hassan, Nikolay Bukharin; writing-review and editing, Michel Matar, Hassan H. Assoum, Mohammad El Hassan, Nikolay Bukharin; project administration, Hassan H. Assoum and Ali Hammoud; and funding acquisition, Anas Sakout. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare no conflict of Interest.

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