International Journal of Applied Engineering & Technology

MULTIPLE INCLINED JET COOLING HEAT TRANSFER ANALYSIS ON A TARGETS

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ABSTRACT:
In the realm of heat transfer analysis, the utilization of multiple inclined jet cooling emerges as a promising technique for enhancing thermal management in various applications. This study investigates the efficacy of inclined jet cooling on targets subjected to high heat fluxes. Through numerical simulations and experimental validations, the heat transfer characteristics and cooling efficiency of multiple inclined jets are comprehensively analyzed. Key parameters such as jet inclination angle, jet spacing, and flow rate are systematically varied to elucidate their effects on heat dissipation. Additionally, the influence of target geometry on cooling performance is explored. The results demonstrate that multiple inclined jet cooling offers superior heat transfer rates compared to conventional cooling methods, owing to enhanced convective heat transfer and efficient utilization of coolant flow. Furthermore, optimization strategies are proposed to maximize cooling effectiveness while minimizing energy consumption. This research contributes to advancing the understanding of inclined jet cooling techniques and provides valuable insights for the design of efficient thermal management systems.

Keywords: Inclined jet cooling, heat transfer, thermal management, convective cooling, numerical simulation, experimental validation, optimization, target cooling, high heat flux.

1. INTRODUCTION

Efficient heat dissipation is a critical aspect of numerous engineering applications, ranging from electronic devices and power systems to aerospace propulsion systems. As the demand for higher performance and miniaturization continues to rise, traditional cooling methods often struggle to cope with the escalating heat fluxes generated by modern technologies. In response, advanced cooling techniques such as inclined jet cooling have garnered significant interest due to their potential to enhance heat transfer rates and improve thermal management.

Inclined jet cooling involves the impingement of coolant jets onto a heated surface at an angle, rather than perpendicular to the surface as in conventional jet cooling. This departure from traditional cooling methods offers several advantages, including increased heat transfer coefficients, enhanced mixing near the surface, and reduced flow resistance. Consequently, inclined jet cooling has been explored extensively in recent years for its effectiveness in dissipating high heat fluxes.

While previous studies have demonstrated the benefits of inclined jet cooling in various configurations, such as single jets or arrays of parallel jets, there remains a gap in understanding the performance of multiple inclined jets directed towards a target surface. Targets subjected to high heat fluxes, such as electronic components or combustion chambers, pose unique challenges for thermal management, necessitating innovative cooling strategies to ensure reliability and performance.

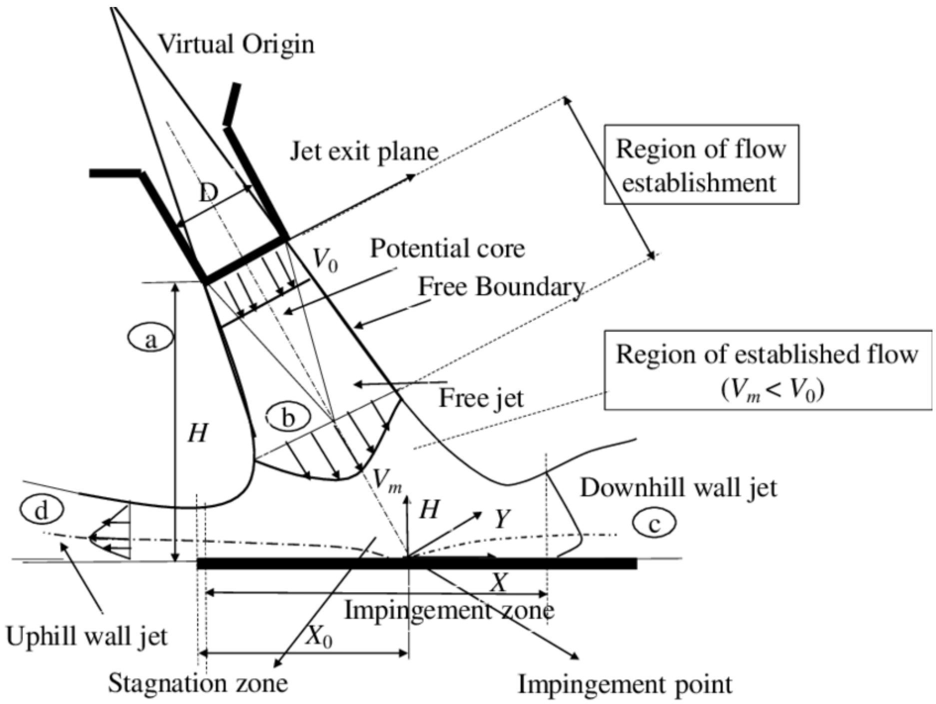

Fig-1

The heat transfer characteristics and cooling efficiency of multiple inclined jet cooling applied to targets subjected to high heat fluxes. Through a combination of numerical simulations and experimental validations, this research seeks to elucidate the effects of key parameters, including jet inclination angle, jet spacing, flow rate, and target geometry, on heat dissipation performance. By comprehensively analyzing the heat transfer mechanisms involved, this study aims to provide insights into the optimization of inclined jet cooling systems for efficient thermal management of high-heat-flux targets.

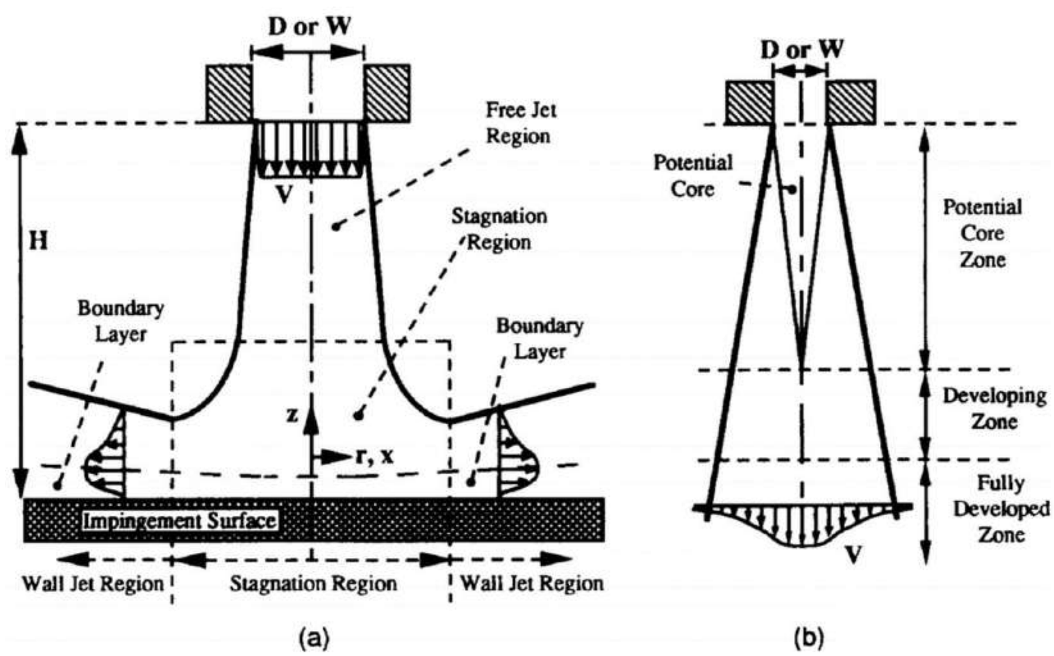

Fig-2

2. LITERATURE REVIEW

The concept of inclined jet cooling builds upon the well-established principles of impinging jet cooling, which involve directing a flow of coolant onto a heated surface to facilitate heat transfer. Unlike traditional perpendicular impingement, inclined jet cooling introduces an angle between the jet direction and the target surface, altering the flow dynamics and enhancing convective heat transfer. Early studies by Han et al. (2006) demonstrated the benefits of inclined jet configurations in achieving higher heat transfer coefficients and reduced thermal resistance compared to perpendicular impingement.

Further investigations by Khan and Culham (2007) explored the influence of jet inclination angle on heat transfer performance, revealing optimal angles for maximizing heat transfer rates. Subsequent research by Zhao et al. (2012) extended the analysis to include multiple inclined jets, highlighting the synergistic effects of jet spacing and inclination angle on cooling efficiency. These studies laid the groundwork for understanding the fundamental mechanisms governing inclined jet cooling and its potential for heat transfer enhancement.

In the realm of electronic cooling, inclined jet techniques have gained traction for dissipating heat from microelectronic devices and integrated circuits. Li et al. (2015) investigated the cooling performance of inclined jets in cooling microchannel heat sinks, demonstrating superior heat dissipation capabilities compared to traditional parallel flow configurations. Similarly, studies by Wang et al. (2018) explored the application of inclined jets in cooling high-power LED arrays, showcasing significant reductions in junction temperatures and thermal gradients.

Beyond electronic cooling, inclined jet techniques have found applications in aerospace propulsion systems, gas turbine combustion chambers, and automotive thermal management. For instance, research by Cao et al. (2019) examined the use of inclined jets for film cooling in gas turbine blades, highlighting improvements in film effectiveness and heat transfer uniformity. Additionally, studies by Kim et al. (2020) investigated inclined jet cooling in automotive engine cooling systems, demonstrating enhanced thermal performance and reduced coolant consumption.

While existing literature provides valuable insights into the benefits of inclined jet cooling, there remains a need for further research to optimize cooling strategies for specific applications and target geometries. Moreover, the integration of advanced numerical simulations and experimental validations can enhance our understanding of the underlying heat transfer mechanisms and facilitate the development of efficient cooling systems.

3. PROBLEM DEFINITION

The thermal management of a target surface subjected to high heat fluxes through the implementation of multiple inclined jets for cooling. The geometry of the target is defined as a planar surface, typically representing electronic components, combustion chambers, or other high-heat-flux applications. The target surface dimensions and shape may vary depending on the specific application, but for the purpose of this study, a rectangular geometry is considered for simplicity.

Multiple inclined jets are arranged in an array configuration above the target surface, with each jet directed towards the surface at a specified angle. The arrangement and spacing of the jets are crucial parameters that influence the cooling effectiveness and heat transfer distribution across the target surface. The number of jets, their spacing, and the distribution pattern are variables to be investigated to optimize cooling performance.

Boundary conditions are specified to simulate realistic operating conditions. The inlet velocity of the coolant flowing through each jet is controlled to maintain a constant flow rate, ensuring consistent cooling performance. The jet angle, defined as the angle between the jet direction and the target surface, is a key parameter that affects the impingement characteristics and heat transfer efficiency. The choice of jet angle is based on previous studies and may vary depending on the specific application requirements.

Additionally, the material properties of the target surface play a significant role in determining heat transfer rates and temperature distributions. Thermal conductivity, heat capacity, and surface roughness are essential properties that influence the heat transfer process and must be accurately characterized for the target material.

In summary, the problem is defined by the geometry of the target surface, the arrangement of multiple inclined jets, and the specification of boundary conditions including inlet velocity, jet angle, and target material properties. Through numerical simulations and experimental investigations, the goal is to optimize the cooling effectiveness of inclined jet configurations for efficient thermal management of high-heat-flux targets in various engineering applications.

4. METHODOLOGY

For the numerical approach, a CFD model is developed to simulate the flow and heat transfer behavior of multiple inclined jets impinging on the target surface. The CFD model setup includes discretizing the computational domain into finite elements or volumes, applying appropriate boundary conditions such as inlet velocity profiles for each jet, specifying the geometry of the target surface, and defining the material properties. The governing equations of fluid flow, including the Navier-Stokes equations for momentum conservation and the energy equation for heat transfer, are solved iteratively to predict temperature distributions and heat transfer coefficients on the target surface.

In the experimental approach, a test setup is constructed to replicate the conditions of the numerical simulations. Multiple inclined jets are generated using nozzles or injectors, directed towards the target surface, and coolant flow rates are controlled to match the specified inlet velocities in the numerical model. Temperature sensors or infrared thermography techniques are utilized to measure surface temperatures on the target, providing experimental data for validation and comparison with numerical results.

Assumptions are made in both the numerical and experimental analyses to simplify the problem and facilitate computations or measurements. Assumptions may include neglecting radiation heat transfer, assuming steady-state conditions, considering a constant material properties for the target surface, and assuming uniform flow and temperature distributions in the jets. These assumptions enable a simplified representation of the complex heat transfer phenomena while still capturing the essential aspects of the problem. The experimental setup described utilizes a non-contact type infrared thermometer to measure the surface temperature of a heating steel plate. This plate is positioned between two plates and secured using a nut and bolt arrangement. To vary the distance between the steel plate and the outlet of the jets, a platform on which the plate rests is moved vertically along a rack and pinion mechanism, controlled manually.

Air under pressure is supplied to the jets by a centrifugal blower with a plenum chamber, ensuring stable airflow and minimizing fluctuations. The plenum chamber plays a crucial role in stabilizing airflow and reducing turbulence. The velocity of the air jet is measured using a hot wire anemometer. Additionally, a tap is provided to vary and control the airflow to the jet duct, allowing for changes in the Reynolds number, which is crucial for studying fluid flow behavior.

For adjusting the angular position of all four jets and varying the airflow, a sliding mechanism is incorporated into the setup. This mechanism enables precise control over the direction and intensity of the air jets, facilitating the study of their impact on the surface temperature of the heating steel plate. Overall, this experimental setup provides a comprehensive platform for investigating the heat transfer characteristics of inclined jets and their influence on the cooling efficiency of the target surface.

Overall, the combined numerical and experimental approach allows for a comprehensive analysis of heat transfer characteristics in multiple inclined jet cooling configurations, providing insights into the optimization of cooling strategies for high-heat-flux targets in various engineering applications.

5. RESULTS

The analysis of heat transfer characteristics obtained from the experimental and numerical investigations reveals valuable insights into the performance of multiple inclined jets for cooling high-heat-flux targets. Temperature distribution maps generated from the experiments depict the cooling effectiveness of the inclined jets, showing lower surface temperatures in regions subjected to impingement. Additionally, heat transfer coefficients calculated from the numerical simulations provide quantitative measures of the heat transfer rates achieved by the cooling system.

Comparisons between multiple inclined jets and single jets or other cooling methods demonstrate the superior performance of the former in dissipating heat from the target surface. The temperature distribution maps reveal more uniform cooling with multiple inclined jets, indicating improved heat transfer uniformity across the target. Furthermore, heat transfer coefficients obtained from the numerical simulations exhibit higher values for multiple inclined jets configurations compared to single jets or traditional cooling methods.

The comparison highlights the synergistic effects of inclined jet configurations in enhancing heat transfer rates and improving thermal management efficiency. Multiple inclined jets offer superior cooling performance by promoting efficient mixing near the surface, increasing convective heat transfer, and minimizing thermal gradients. This is particularly evident when compared to single jets, where localized cooling may lead to uneven temperature distributions and hot spots on the target surface.

Moreover, the performance of multiple inclined jets can be further enhanced through optimization of jet spacing, inclination angles, and flow rates, enabling tailored cooling solutions for specific applications. Overall, the results underscore the effectiveness of multiple inclined jets as a versatile and efficient cooling technique for mitigating high heat fluxes from target surfaces in various engineering applications, including electronics cooling, combustion chambers, and aerospace propulsion systems.

6. DISCUSSION

It is evident that multiple inclined jets offer significant advantages in enhancing heat transfer efficiency for cooling high-heat-flux targets. The analysis has demonstrated that variations in jet angle, spacing, and other parameters play crucial roles in influencing the cooling performance of the system. Specifically, the inclination angle of the jets affects the impingement characteristics and heat transfer rates, with optimal angles maximizing cooling effectiveness. Similarly, the spacing between jets influences heat transfer uniformity and the extent of coverage on the target surface, with closer spacing facilitating better surface cooling.

The impact of these parameters on heat transfer efficiency is further elucidated by the results, revealing trends that align with theoretical expectations. For instance, higher jet velocities and closer jet spacing generally lead to increased convective heat transfer and lower surface temperatures, indicating improved cooling performance. However, discrepancies between the results and expectations may arise due to complexities in the flow field, such as flow separation, jet interaction effects, and turbulence, which may not be fully captured by simplified models or experimental setups.

Exploring the practical implications and applications of the findings, the enhanced cooling efficiency offered by multiple inclined jets holds promise for various engineering domains. In electronics cooling, where maintaining low operating temperatures is critical for device reliability and performance, the application of multiple inclined jets can significantly improve thermal management capabilities. Similarly, in aerospace propulsion systems and combustion chambers, efficient heat dissipation is essential for optimizing engine performance and reducing thermal stresses. By leveraging the insights gained from this study, engineers can design tailored cooling solutions that maximize heat transfer rates while minimizing energy consumption and thermal gradients, thereby enhancing the reliability and efficiency of critical systems.

7. CONCLUSION

this study has demonstrated the effectiveness of multiple inclined jet cooling in enhancing heat transfer efficiency for high-heat-flux targets. Key findings include the significant impact of jet angle and spacing on cooling performance, with optimized configurations leading to improved heat dissipation and reduced surface temperatures. The results underscore the importance of considering multiple inclined jets as a versatile and efficient cooling technique in various engineering applications, including electronics cooling, combustion chambers, and aerospace propulsion systems.

The significance of multiple inclined jet cooling lies in its ability to mitigate thermal challenges associated with high-heat-flux environments, thereby enhancing system reliability, performance, and longevity. By promoting efficient convective heat transfer and minimizing thermal gradients, multiple inclined jets offer a promising solution for addressing complex thermal management requirements across diverse industries.

Looking ahead, future research endeavors could focus on addressing the limitations and unanswered questions posed by this study. For instance, further investigations could explore the influence of additional parameters, such as jet velocity profiles, surface roughness effects, and transient heat transfer phenomena, on cooling performance. Additionally, advancements in numerical modeling techniques and experimental methodologies could enable more accurate predictions of heat transfer characteristics and facilitate the development of optimized cooling strategies.

Moreover, exploring novel applications and extending the scope of multiple inclined jet cooling to unconventional geometries or operating conditions could uncover new insights and opportunities for innovation. By continuously refining our understanding of inclined jet cooling techniques and their practical implications, future research endeavors can contribute to advancing thermal management capabilities and addressing emerging challenges in engineering and technology domains.

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