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Research Article

Effect of Ribbed Target Plate on Impingement Cooling

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ABSTRACT

This study experimentally investigates the heat transfer characteristics of an air jet impinging on smooth and ribbed target plates. Key variables examined include jet velocity, orifice diameter, and orifice-to-plate distance ratio (Z/D). Results show that the maximum heat transfer rate occurs at the stagnation point on the target plate. Increasing jet velocity significantly enhances heat transfer due to heightened turbulence, while larger orifice diameters yield higher heat transfer rates by covering a greater impact area. The optimal Z/D ratio for maximum heat transfer was determined to be 6 for all Reynolds numbers tested. However, introducing ribs to the target plate reduces heat transfer due to flow redirection and kinetic energy loss. These findings contribute to optimizing impingement cooling systems for various industrial applications.

1. INTRODUCTION

The fundamental comprehension of jet impingement cooling originated from investigations concentrating on the heat transfer processes at the stagnation point when the fluid jet first interacts with the surface [1]. Martin's study [2] offered an exhaustive analysis of heat and mass transmission in impinging jets, establishing a foundation for future research.

Single jet impingement has been thoroughly investigated owing to its simplicity and efficacy in attaining high localized heat transfer. Initial experimental research conducted by Gardon and Akfirat [3] showed that the heat transfer rate peaks at the stagnation point and diminishes radially outward, a conclusion supported by subsequent investigations. Jambunathan et al. [4] comprehensively analysed experimental and computational investigations on single jets, emphasizing the significance of flow characteristics such as Reynolds number, Prandtl number, and nozzle shape. These investigations established the foundation for enhancing single-jet designs for industrial applications. Many jets, or jet arrays, have garnered interest for applications necessitating homogeneous cooling over extensive surfaces. Beitelmal et al.[5] investigated the interaction between nearby jets and determined that the distance between jets is critical in influencing total heat transfer efficiency. Their research shows that insufficient spacing may result in interference effects, including crossflow and jet coalescence, which reduce heat transfer efficiency. San and Lai [6] conducted complementary numerical studies to improve jet configurations for enhanced heat transfer and reduced negative flow interactions.

The design of the nozzle profoundly influences the efficacy of impinging jets. Circular nozzles are often used because of their simplicity; alternative forms, such as slot nozzles, provide distinct benefits in certain applications. Zuckerman and Lior [7] examined the effect of nozzle exit configuration on local heat transfer distribution, revealing that slot nozzles provided more consistent cooling over extended surfaces. Moreover, improvements in 3D printing have facilitated the production of intricate nozzle geometries, resulting in breakthroughs such as micro-jet arrays and fractal nozzles. Comprehending the turbulence properties in jet impingement is crucial for forecasting and enhancing heat transfer. Cooper et al. [8] performed a seminal investigation on the turbulence structure in impinging jets, using sophisticated laser-based measuring methods to delineate the velocity and turbulence fields . The change from laminar to turbulent flow near the nozzle exit significantly affects the heat transfer efficiency at the target surface. Multi-phase jet impingement, using mist, droplets, or other phase-change events, has become an effective technique for improved cooling. Recent research, like that of Li and Dunn-Rankin [9], has shown the enhanced cooling efficiency of mist jets, which integrate convective cooling

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with latent heat absorption. Furthermore, investigations into nanofluid jet impingement have shown potential, with researchers such as Nguyen et al. [10] indicating substantial enhancements in thermal conductivity and cooling efficacy upon incorporating nanoparticles into the working fluid. Real-world applications often include intricate target geometries, including curved surfaces or obstructions. McDaniel et al. [11] investigated jet impingement on concave and convex surfaces, finding that curvature may augment or reduce heat transfer based on the flow circumstances. Goldstein and Behbahani [12] investigated heat transfer in scenarios where the target surface is roughened or textured to enhance turbulence, noting a substantial improvement in cooling performance.
The emergence of advanced computational tools has enhanced the comprehension of jet impingement cooling. Recent simulations conducted by Gardon et al. [13] using large eddy simulation (LES) methodologies provide novel insights into unsteady flow structures and their influence on heat transport. CFD analyses have investigated combining impinging jets with other cooling techniques, including micro-channel heat sinks, to develop hybrid cooling systems. Al-Dulaimi et al. [14,15] investigated experimentally and numerically the heat transfer and flow structure of an air-sand impinging jet from a cylindrical nozzle. The results revealed that adding sand particles decreases the heat transfer rate from the target plate and dampens the jet's kinetic energy.
The main objective of this research is to examine the heat transfer efficiency of air jet impingement on both smooth and ribbed heated target plates. The study seeks to examine the influence of critical factors, including jet velocity, orifice diameter, and the orifice-to-plate distance ratio (Z/D), on both local and average heat transfer properties. Furthermore, it aims to evaluate the impact of ribbed surface shape on flow dynamics and heat transfer efficiency, offering insights for the optimization of jet impingement cooling systems in real applications.

2. EXPERIMENTAL SETUP

The primary parts of the setup are the test section, measurement devices, power supply unit, air supply unit, and power supply unit. The air supply unit includes a blower, flow UPVC pipe, injection pipe and the orifice. A centrifugal blower has a port to connect the blower to the pipe. The specifications of the blower are speed (2800 rpm), power (0.4 kW), and air flow rate (0.028 m3/min). A PVC pipe with a length (0.8) m and a diameter of 4 inches (10 cm) connects the blower to the orifice. It is used to emerge the air jet. Two sizes of orifices were manufactured from Teflon, which are 10 and 20 mm. The power supply unit comprises a voltage regulator and voltage-current monitors. This device provides electrical power and regulates the current and voltage supplied to the heater. It comprises a voltage regulator and a voltage-current digital monitor. The LCD digital display measures the voltage and current supplied to the heater. An LCD monitor measures current with a range of AC (0-50) A, while another LCD monitor measures voltage with AC (0-500) V. The test section, shown in figure (1), comprises a target plate, an aluminium plate, an insulation layer made of polyurethane, and a wooden frame. The parts that make up the assembly are as follows: a wooden frame, a pan of polyurethane foam, thermocouples, a flat heater, and a target plate made of aluminium. A stainless-steel plate is used as a target plate with dimensions (20x20) cm^2 and a thickness of (5) mm. Stainless steel material is used for the plate to reduce heat conducted in the lateral direction. Six thermocouples of type (K) are welded to the back face of the target plate by Epoxy resin to measure the plate temperature. Vane-meter were used to measure the and the velocity. A schematic diagram and a photo of the rig are shown in Figure (2). Three ribs of different diameters, 60mm, 102 mm, and 150 mm, are used to roughen the target plate. The ribs are denoted as R1, R2, and R3 for small, medium and large ribs, respectively, as shown in figure (3).

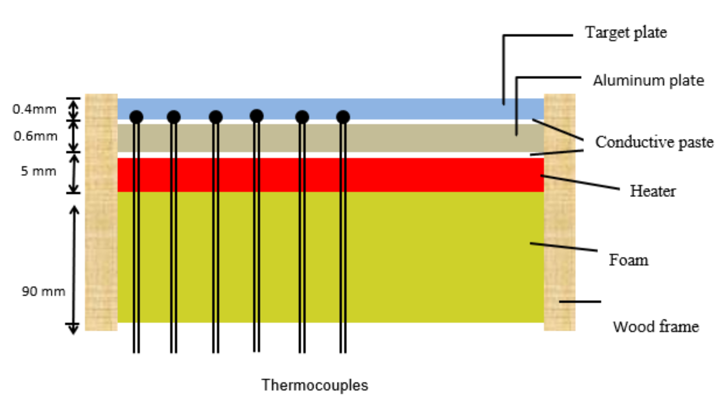

Fig. 1. Section of the test section

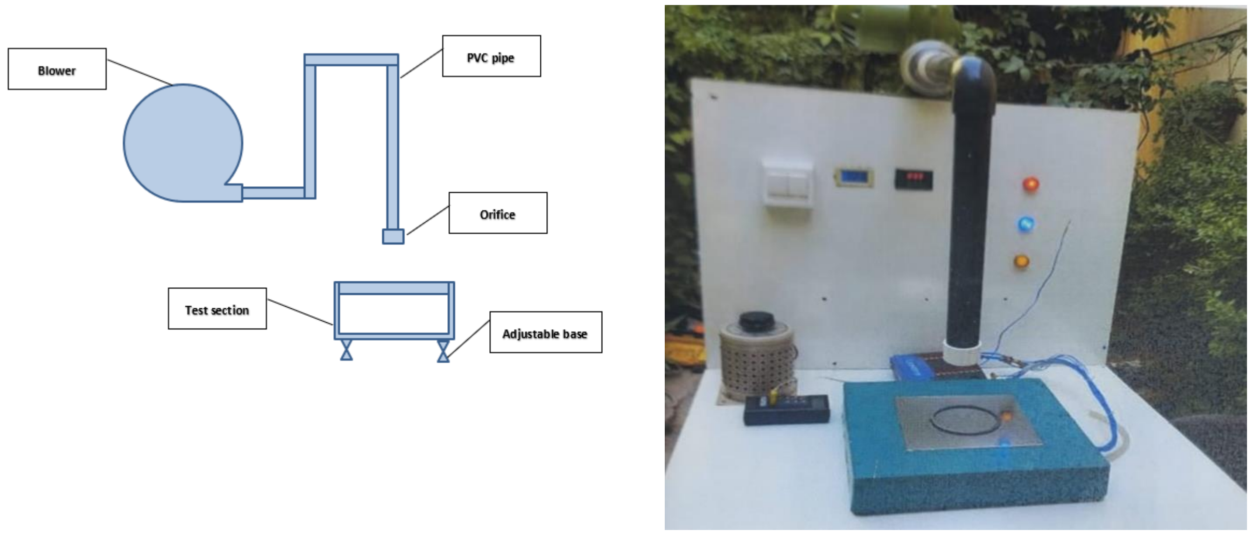

Fig. 2. Schematic and photo of the rig.

Fig. 3. The ribs

3. CALCULATION

The following processes have been executed to calculate the heat transfer coefficient and Nusselt number.

a. Calculation of film Temperature

The properties of air are computed based on the mean film temperature. T_f (°C) of the plate:

$$T_f = \frac{T_S+T_J}{2} \tag{1}$$

Where T_s and T_J are the plate and jet temperatures, respectively.

b. Calculation of Reynolds Number *Re*

$$Re = \frac{\rho_f\, U_J D}{\mu_f} \tag{2}$$

Where ρ_f is the density of the jet air (kg/m^3), U_J is the jet velocity (m/s), D is the jet diameter (m) and μ_f is the dynamic viscosity of the jet air (Pa. s).

c. Calculation of heat flux *q″*

The heat flux on the target plate is calculated as :

$$q'' = \frac{VI}{A_s} \quad (3)$$

Where V is the supplied voltage (volt), I is the supplied current (amp) and A_s is the area of the target plate (m^2)

d. Calculation of local heat transfer coefficient h_x

The local convective heat transfer coefficient h_x ($W/m^2.^oC$) is computed as :

$$h_x = \frac{q``}{T_x - T_f} \quad (4)$$

where T_x : temperature of the surface at a certain point.

e. Calculation of Nusselt Number Nu

The Nusselt number quantifies the augmentation of heat the transfer in a fluid layer due to convection compared to conduction within the same layer and is calculated as:

$$Nu_x = \frac{h_x D}{K} \quad (5)$$

Where k is the thermal conductivity of air at film temperature (W/m.K)

4. RESULTS

The experimental data were collected for different jet velocities (V), orifice diameters (D) and orifice-to-plate distance ratios (Z/D) for smooth and ribbed target plates. The tested values are presented in Table (1).

TABLE I. EXPERIMENTAL VARIABLES

Variable	Values
Jet velocity (V)	3,5,7.2 m/s
Z/D	2,5,6,8
Diameter (D)	10,20 mm

4.1 Smooth Plate

4.1.1 Effect of Z/D ratio

A peak can be observed at the stagnation zone for all cases, as shown in Figure (4), due to the high turbulence level of the flow at this zone. The convective heat transfer coefficient declines in a radial direction away from the stagnation zone. This is because as the fluid flows radially, it loses kinetic energy, and the boundary layer thickness increases. Also, it can be seen that the (Z/D) ratio significantly affects the heat transfer rate.

Figure (5) presents the local distribution of the heat transfer coefficient for different Z/D ratios at V= 3 m/s. Z/D = 6 achieves the optimum ratio of the highest heat transfer rate for both V=1 m/s and V=3 m/s, as shown in figures (4) and (5). It can be determined that the variation of the convective heat transfer coefficient is insignificant after a distance of L= 5D from the stagnation point.

Figure (6) shows the values of the Average Nusselt number (Nu_{av}) for different Z/D ratios and Reynolds number (Re). The figure shows that the optimum Z/D ratio is 6 for all Reynolds numbers.

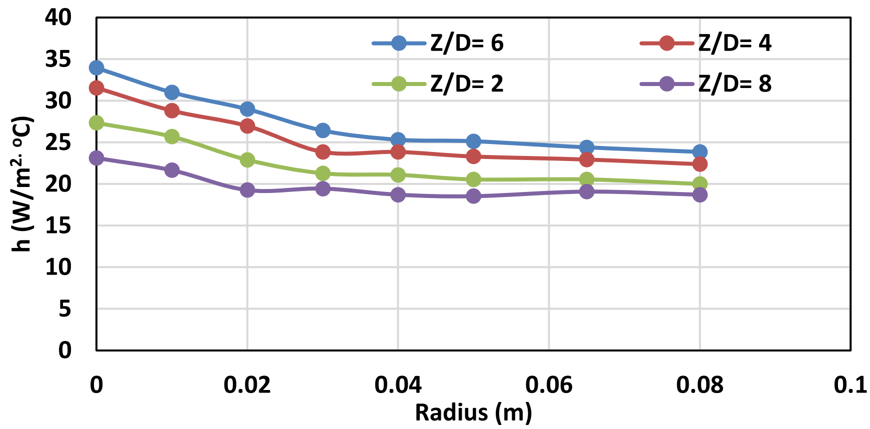

Fig. 4. Effect of Z/D ratio on local heat transfer coefficient (V=3 m/s, D = 10 mm).

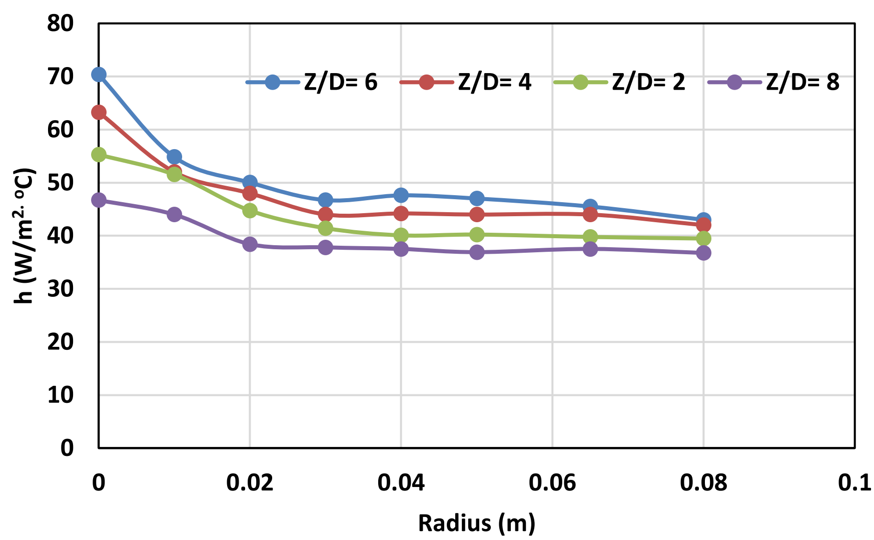

Fig. 5. Effect of Z/D ratio on local heat transfer coefficient (V=7.2 m/s, D = 10 mm).

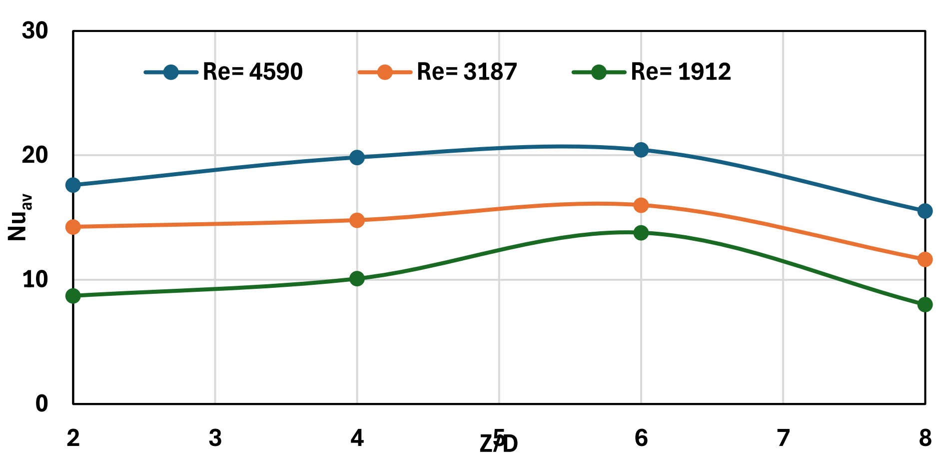

Fig. 6. Variation of Average Nusselt number with Z/D and Reynolds number.

4.1.2 Effect of Velocity

Figure (7) shows the effect of jet velocity on the local heat transfer coefficient. The effect of velocity is strong and significant. The higher the velocity, the higher the heat transfer rate due to the increased turbulence and kinetic energy in the flow.

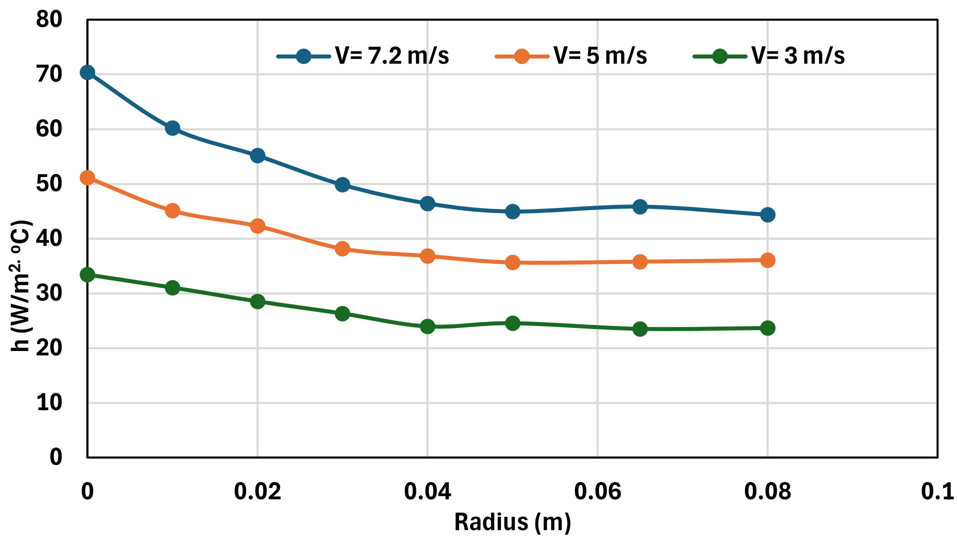

Fig. 7. Effect of velocity on local heat transfer coefficient.

4.1.3 Effect of The orifice Diameter (D)

The impact of the orifice diameter on the local heat transfer coefficient is shown in figure (8) for the same mass flow rate. It reveals that the larger the diameter, the higher the heat transfer coefficient due to the larger area subjected to the direct jet flow.

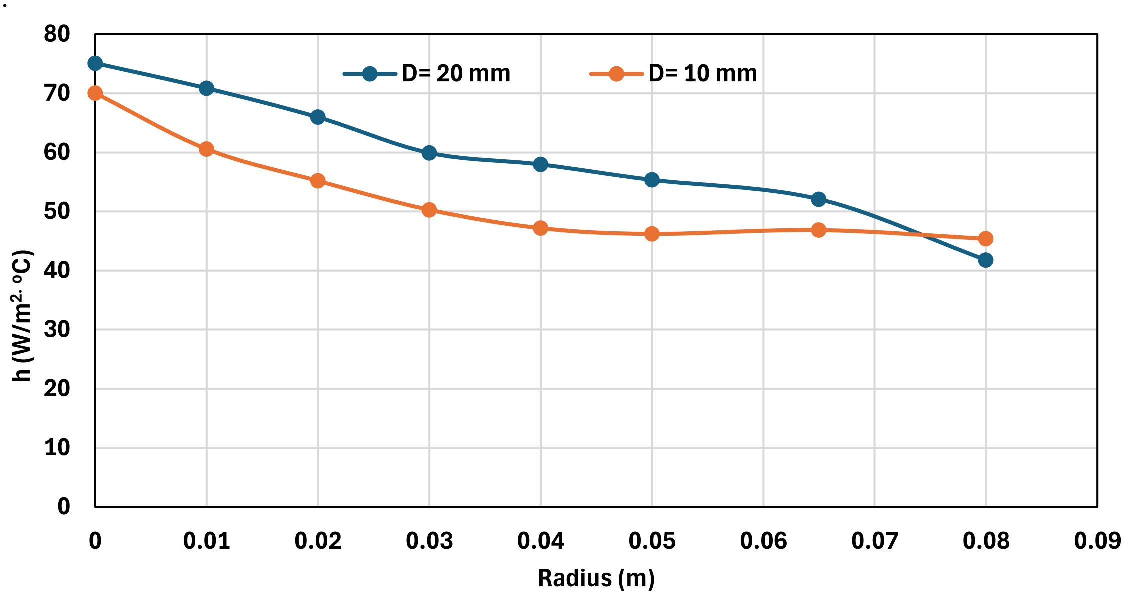

Fig. 8. Effect of diameter on local heat transfer coefficient.

4.2 Ribbed plate

Figures (9) demonstrate the effect of the rib's presence on the local heat transfer coefficient for the case of different diameter single ribs. Figure (10) exhibits the effect of two ribs, R1 R3 and three ribs R1R2R3. Compared to a smooth target plate, the presence of ribs decreases the heat transfer from the target plate. The ribs dampen the flow's kinetic energy over the plate. Also, the flow is believed to be directed upward from the plate. The reduction effect in heat transfer is higher for the cases of using two ribs together and the highest for three ribs together. This is due to the increased effect of ribs

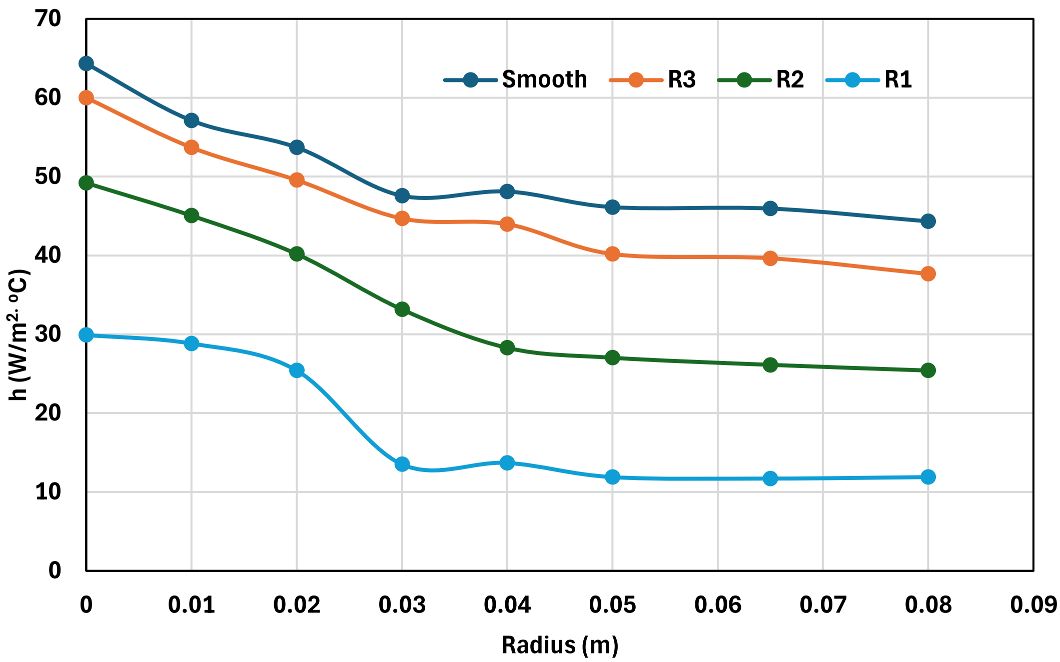

Fig. 9. Effect of rib size on the local heat transfer (V=7 m/s, Z/D= 5, and D=10 mm)

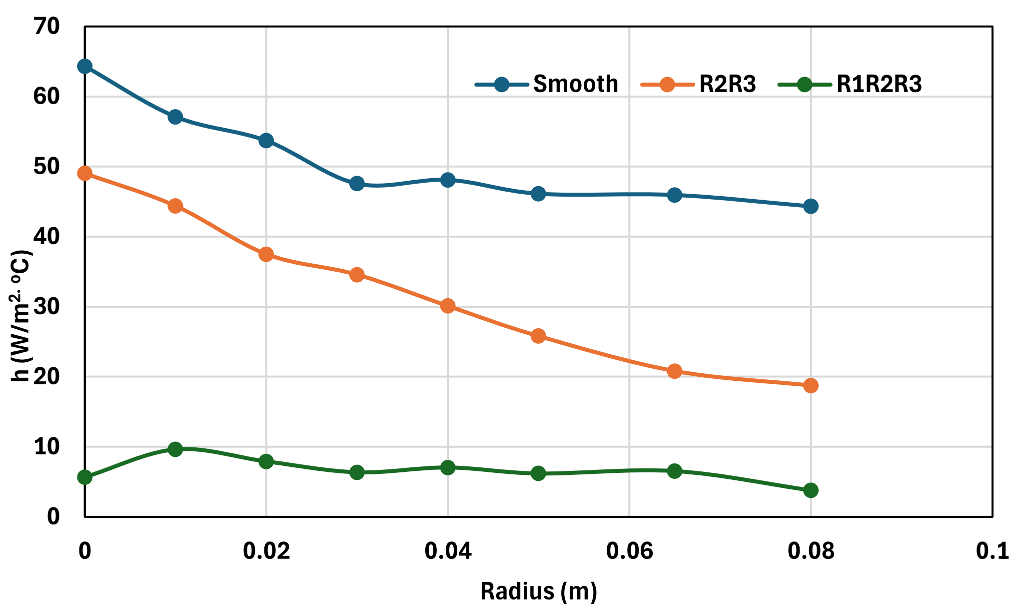

Fig. 10. Effect of rib arrangement on the local heat transfer (V=7 m/s, Z/D= 5, and D=10 mm)

5.CONCLUSIONS

The present study concerns the heat transfer measurement of a smooth and ribbed heated target plate subjected to an air jet emerging from an orifice. The main conclusions can be summarized as follows:

- The stagnation zone has the highest heat transfer rate.
- A higher heat transfer rate is achieved with a larger diameter.
- The orifice-to-plate distance ratio (Z/D) significantly impacts the heat transfer rate.
- The presence of ribs reduces the heat transfer from the target plate.

Conflicts Of Interest

The author's paper explicitly states that there are no conflicts of interest to be disclosed.

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References

[1] A. Abdul Rasool and F. Hamad, "Flow structure and cooling behavior of air impingement on a target plate," Open Engineering, vol. 3, no. 3. Walter de Gruyter GmbH, pp. 400–409, Jul. 28, 2013. doi: 10.2478/s13531-013-0103-z.

[2] H. Martin, "Heat and mass transfer between impinging gas jets and solid surfaces," *Advances in Heat Transfer*, vol. 13, pp. 1-60, 1977.

[3] R. Gardon and J. Akfirat, "The role of turbulence in determining the heat-transfer characteristics of impinging jets," International Journal of Heat and Mass Transfer, vol. 8, no. 10, pp. 1261-1272, Oct. 1965.

[4] K. Jambunathan, E. Lai, M. A. Button, and B. E. Ashforth-Frost, "A review of heat transfer data for single circular jet impingement," International Journal of Heat and Fluid Flow, vol. 13, no. 2, pp. 106-115, Apr. 1992.

[5] H. Beitelmal, F. Patel, and J. S. Heffington, "Effects of jet-to-jet spacing on the heat transfer characteristics of impinging jet arrays," International Journal of Heat and Mass Transfer, vol. 43, no. 6, pp. 1161-1172, Mar. 2000.

[6] S. N. San and M. C. Lai, "Optimum jet-to-jet spacing for heat transfer enhancement in impinging jet arrays," International Journal of Heat and Mass Transfer, vol. 44, no. 19, pp. 3997-4007, Sep. 2001.

[7] N. Zuckerman and N. Lior, "Jet impingement heat transfer: Physics, correlations, and numerical modeling," Advances in Heat Transfer, vol. 39, pp. 565-631, 2006.

[8] D. Cooper, D. J. Jackson, B. G. Launder, and G. X. Liao, "Impinging jet studies for turbulence model assessment—I. Flow-field experiments," International Journal of Heat and Mass Transfer, vol. 36, no. 10, pp. 2675-2684, Jul. 1993.

[9] P. W. Li and D. Dunn-Rankin, "Heat transfer enhancement using mist jet impingement," International Journal of Heat and Mass Transfer, vol. 48, no. 24-25, pp. 5275-5285, Nov. 2005.

[10] T. Q. Nguyen, A. Deshmukh, and Y. E. Zhang, "Heat transfer enhancement in nanofluid jet impingement cooling," Journal of Heat Transfer, vol. 132, no. 10, p. 101005, Oct. 2010.

[11] D. McDaniel, T. Mikic, and S. Rohsenow, "Heat transfer from jet impingement on concave and convex surfaces," ASME Journal of Heat Transfer, vol. 120, no. 1, pp. 197-202, Feb. 1998.

[12] R. J. Goldstein and A. I. Behbahani, "Impingement of a circular jet with and without cross flow," ASME Journal of Heat Transfer, vol. 104, no. 4, pp. 719-724, Nov. 1982.

[13] R. Gardon et al., "Large eddy simulation of jet impingement cooling with application to gas turbines," Journal of Turbomachinery, vol. 143, no. 4, p. 041003, Apr. 2021.

[14] Al-Dulaimi, Mustafa J., Adnan a. Abdul Rasool, and Faik A. Hamad. "Investigation of impingement heat transfer for air-sand mixture flow." The Canadian Journal of Chemical Engineering 94, no. 1 , 2015): 134–41. https://doi.org/10.1002/cjce.22364

[15] Al-Dulaimi, M. J., F. A. Hamad, A. a. Abdul Rasool, and K. A. Ameen. "Effect of sand particles on flow structure of free jet from a nozzle." JOURNAL OF MECHANICAL ENGINEERING AND SCIENCES 13, no. 3,2019, 5542–61.https:/doi.org/10.15282/jmes.13.3.2019.21.0447.