Investigation of Rotating Cylinder Cooling by Multiple Cold Air Impacting Jets for Enhanced Tool Performance

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Abstract- This study investigates the optimization of cooling systems for cylindrical cutting tools by examining how multiple cold air jets impact a rotating cylinder, applicable to milling and grinding operations. The research employs the realizable k-ε turbulence model to analyze turbulent flow governed by Navier-Stokes equations, with numerical results validated against existing experimental data.

The study evaluates various configurations: a single nozzle at 4 diameters distance, two nozzles symmetrically arranged, three nozzles at 120° intervals, and four nozzles at 90° intervals, each tested at different Reynolds numbers. The finite volume method is used to discretize the governing equations for turbulent jet flow.

Results demonstrate that a three-nozzle configuration achieves optimal heat transfer with uniform distribution of the local Nusselt number across the cylinder's surface. This arrangement provides effective cooling while preventing thermal shock, ensuring sustained cutting tool performance during machining operations.

Index Terms- Cooling process, Rotating cylinder, Cold air impinging jets, Turbulent flow, Numerical simulation, Finite volume method, Heat transfer, Nusselt number, Tool performance, Machining operations.

I. INTRODUCTION

Numerous studies have explored the interaction between turbulent jets and flat or curved surfaces, with the goal of enhancing localized heat and/or mass transfer within system components. To achieve this objective, a thorough comprehension of the fluid's dynamic behavior and its consequent impact on local heat and/or mass transfer phenomena is essential. Various parameters significantly influence heat transfer and fluid flow characteristics in distinct regions of an impinging jet, such as the free jet, impact zone, and wall jet. These parameters include the jet slot geometry (circular, elliptical, or rectangular cross-sections), the distance between the jet exit and the impingement surface, Reynolds number variations, jet inclination angles, turbulence intensity, swirling effects, jet temperature, surface curvature, surface roughness, and the number of nozzles employed. Notably, impinging jets find extensive application in various industrial sectors, including paper, glass, metallurgy, textiles, aeronautics, and manufacturing. Examples encompass air curtains for water evaporation in pulp (paper industry), cooling glass sheets (glass industry), cooling molten metal (metallurgy), drying textiles (textile industry), cooling turbine blades and combustion chambers (aeronautics), and cooling cutting tools and cleaning machined parts (manufacturing). Jet cooling offers an efficient solution for intense heat extraction or delivery to surfaces in industrial settings.

The objective of this research is to numerically analyze jet cooling applied to a cylindrical surface subjected to a heat flux of 3950 W/m². The investigation focuses on the cooling performance of single and multiple nozzle configurations, specifically examining cases with 2 nozzles, 3 nozzles, and 4 nozzles.

This review examines multiple studies conducted by various researchers on heat transfer in jet impingement systems. The work of Hammami et al. (2016) focused on numerical simulations of heat transfer using an air jet impinging on a rotating cylinder. Their findings revealed that the highest local Nusselt number shifted in the direction of the surface target's movement, with the maximum value obtained at a nozzle-to-target distance ratio of H/d=6 for all investigated Reynolds numbers. Fountain effects, as highlighted by Neil Zuckerman and Noam Lior (2007), played a significant role in heat transfer, covering up to one-third of the target surface. Increasing the Reynolds number had a more pronounced effect on average Nusselt number (Nuavg) than the number of jets. The study also indicated that reducing the number of jets (n = 2 or 4) yielded the highest Nuavg per unit of power. Furthermore, Julien SENTER and Camille SOLLIEC (2007) validated the results of the k-ω model by comparing them with experimental measurements of kinematics and local Nusselt number. The impact of the jet angle and surface mobility on Nusselt number distribution was analyzed. Additionally, M. Attalla and Eckehard Specht (2009) investigated convective heat transfer in a multiple-jet system experimentally, examining the influence of nozzle-to-sheet distance and nozzle spacing on heat transfer. It was found that the multiple-jet configuration outperformed a single nozzle arrangement, with the highest heat transfer achieved at a normalized spacing of S/d=6.0, while the normalized distance H/d had minimal impact within the range of $2 \leq H/d \leq 4$.

Eckehard Specht (2004) demonstrated that nozzle fields offer the potential for achieving the highest convective heat transfer coefficients in drying processes, leading to intensified drying and cost savings through reduced apparatus size and energy consumption. Restricting the nozzle diameter to the smallest feasible value ensures a minimum distance of four diameters between the nozzle and the product. Lower air velocities result in higher hot air temperatures, with a maximum limit of 500°C imposed by steel strength. However, for the protection of delicate items, maintaining significantly lower hot air temperatures is advisable. The optimal nozzle pitch for heat transfer in single-nozzle arrays and hole channels is found to be six diameters, while perforated plates show improved thermal transfer at nozzle pitches of four and reduced specific energy consumption at nozzle pitches of eight to ten. In an experimental investigation by S. A. Nada (2006) on slot jet air impingement cooling of a cylinder, two distinct jet-cylinder configurations were studied. Comparing a single slot jet aligned with the cylinder's axis and multiple slot jets orthogonal to the cylinder's axis, it was observed that cooling the cylinder with multiple slot jets results in higher and more uniformly distributed heat transfer rates around the cylinder. This paper aims to define the governing equations describing the studied flow characteristics, followed by the selection of an appropriate model. The computational domain, boundary conditions, geometry, and meshing details will be elucidated. Subsequently, the results of numerical calculations will be discussed. Finally, a comprehensive conclusion will be presented, highlighting the significance of the obtained results and emphasizing the search for optimal parameters to maximize thermal transfer.

2- **Governing equations**:

The ultimate kinematic equations that describe the motion of Newtonian fluids are highly intricate. For the purposes of this study, the flow field can be regarded as incompressible and steady-state. The influences of heat transfer, radiation, and momentum are neglected. The velocity and pressure components are categorized into mean and fluctuating components

The continuity equation is:

$$\frac{\partial U_i}{x_i} = 0 \qquad (1)$$

where

Ui is the component of speed. The equations of amount of motion and energy are decoupled. Assuming that the properties of the fluid are constant these two equations are:

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{\partial P}{\partial x_j} + \nu \frac{\partial}{\partial x_j} \frac{\partial U_i}{\partial x_j} - \frac{\partial \overline{u'_i u'_j}}{\partial x_j} \qquad (2)$$

$$\frac{\partial T}{\partial t} + U_j \frac{\partial T}{\partial x_j} = \alpha \frac{\partial}{\partial x_j} \frac{\partial T}{\partial x_j} - \frac{\partial \overline{u'_j T'}}{\partial x_j} \qquad (3)$$

Where P, T, ν and ρ are respectively the pressure, temperature, kinematic viscosity and fluid density

$$\alpha = \frac{\lambda}{\rho C_P} \qquad (4)$$

The numerical resolution of the governing equations of an incompressible turbulent stream will be done by the finite volume method using a commercial code.

2-1 Choice of turbulence model:

The selection of the turbulence model is guided by specific criteria, including: The nature of the fluid, which is considered an incompressible Newtonian fluid with a density of ρ = 1.1225 kg/m3, dynamic viscosity of μ = 1.7894 kg/m·s, specific heat at constant pressure of Cp = 1006.43 J/kg·K, and thermal conductivity of λ = 0.0242 W/m·K. Additionally, the complexity of the flow, where an isothermal jet impinges on a rotating target, resulting in flow separation, recirculation, vortices, and near-wall effects, is considered.

The standard k-ε model is not recommended to satisfy the aforementioned requirements. To close the set of equations, the choice is made between first-order and second-order models. Considering the computational cost and the nature of the studied flow, the Realizable k-ε model is selected.

Utilizing formal investigations, the current calculations were conducted with the aid of the realizable k-ε turbulence model coupled with the standard wall function. The momentum, energy, and turbulence model equations are solved using the second-order upwind solution scheme. The pressure-velocity coupling is solved using the SIMPLE algorithm. The flow is modeled as an incompressible ideal gas, and the normalized residuals for continuity and momentum equations, 10^{-5} for turbulence equations, and 10^{-8} for the energy equation were always less than 10^{-6} at convergence. To obtain optimal resolution, cell density was modulated, with the highest y^+ on external walls ranging from 30 to 300.

3- Computational domain and boundary conditions

This study focuses on the turbulent impingement of an air jet on a rotating cylindrical surface, considering four different geometric configurations at a nozzle-to-target distance ratio of H/d = 4. This choice is based on previous analyses by Hemmami (2016) [1], which indicated that the configuration with a ratio of "h/d = 4" corresponds to the highest maximum Nusselt number, aligning with experimental findings by Arun et al. (2013) [2].

The four investigated configurations include: (1) a single nozzle at different Reynolds numbers (Re = 6410, 9615, 12820, 16025, and 19230), as reported by Hemmami et al. (2016) [1], (2) two nozzles symmetrically positioned with respect to the cylinder axis for three different Reynolds numbers (Figure 1-c), (3) three nozzles distributed at 120° intervals for three Reynolds numbers (Figure 1-b), and (4) four nozzles arranged at 90° intervals for three Reynolds numbers (Figure 1-a). The cylinder is assumed to be at a constant temperature of T = 500 K, while the air jet is at a temperature of Tj = 273 K. The cylinder rotates at a frequency of ω = 450 rad/s. Due to the focus on heat transfer analysis on a section of the cylinder, the study is limited to a 2D geometry instead of 3D.

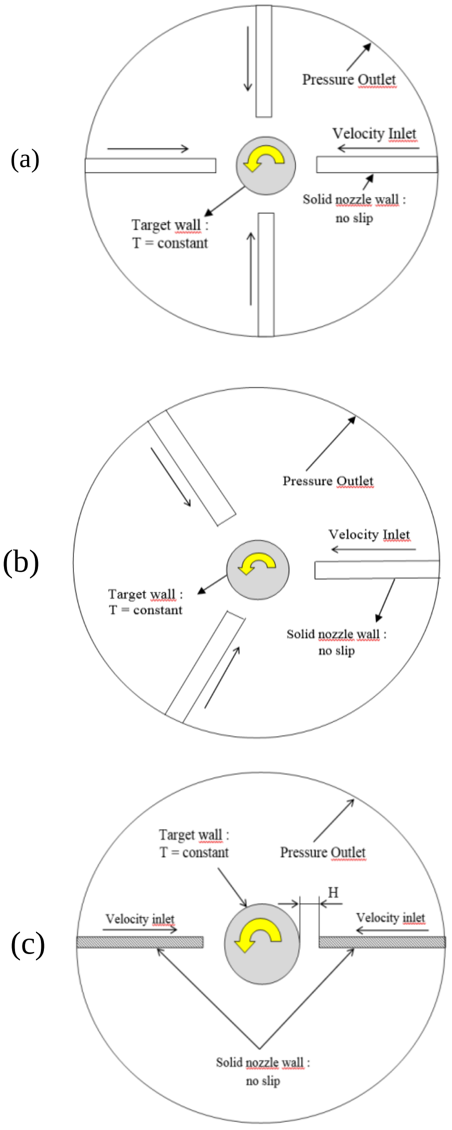

Figure-1- Computational domain and boundary conditions: (a) 4 nozzles, (b) 3nozzles, (c) 2 nozzles

Nusselt Number

For similar types of fluids, this relates to the difference between convective and conductive heat transfer. It also improves convective heat transfer through a fluid layer when compared to conductive heat transfer for the same fluid. It can be used to calculate the heat transfer coefficient of a fluid. It aids in identifying the factors that provide resistance to heat transfer and aids in improving the factors that can improve the heat transfer process.

$$h = \frac{Q}{A(T-T_\infty)} \qquad (5)$$

Where Q designates the net heat amount after accounting for the heat transfer rate to the plate and thermal radiation, A denotes the smooth impingement wall area, T is the impingement wall temperature, and T indicates the room temperature.

The mean heat transfer coefficient $\bar{h}$ was defined as shown in (6)

$$\bar{h} = \frac{1}{A}\int h(x)dx \qquad (6)$$

Where x is the distance from the stagnation point

The local Nusselt number was defined as follows:

$$Nu = \frac{h.d}{\lambda} = \frac{Q.D_h}{\lambda_a.A(T-T_\infty)} \qquad (7)$$

Where λ_a is the air thermal conductivity and the characteristic length is the hydraulic diameter.

4- Results and discussions

4-1- Two nozzles:

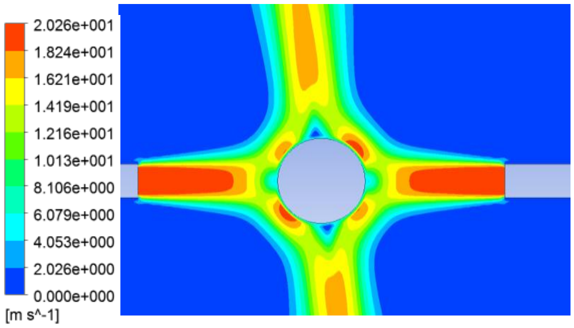

Figure – 2- Velocity magnitude contours, m/s, for the Re=19230 for the case of two nozzles

the This study investigates the distribution of the Nusselt number and velocity field in the impingement of air jets on a rotating cylinder. Two distinct impact positions, slightly offset due to the rotational speed, exhibit different maximum Nusselt number (Numax) values. The maximum Nusselt number varies across different Reynolds numbers. Notably, the average Nusselt number (NuAvg) increases with increasing Reynolds number, consistent with experimental observations by Hemmami et al. (2016) [1].

Figure 2 illustrates the velocity field for Re = 19230 in the case of two nozzles, showcasing the offset impact points resulting

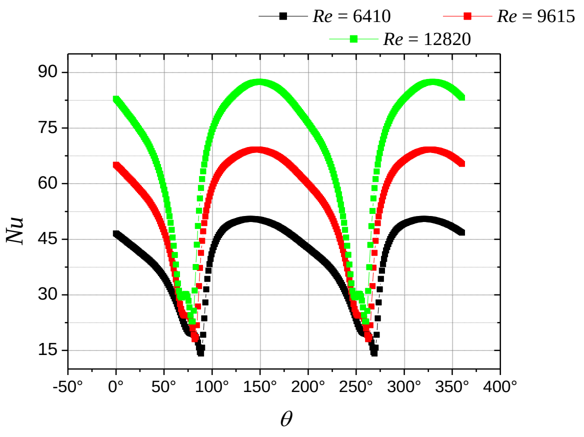

Figure – 3- Reynolds number effect on the distribution of the local Nusselt number, the case of two nozzles from the cylinder's rotation. The interaction of the two jets generates a backflow fountain with induced vortices beneath, as depicted in Figure 7.

4-2- Three nozzles:

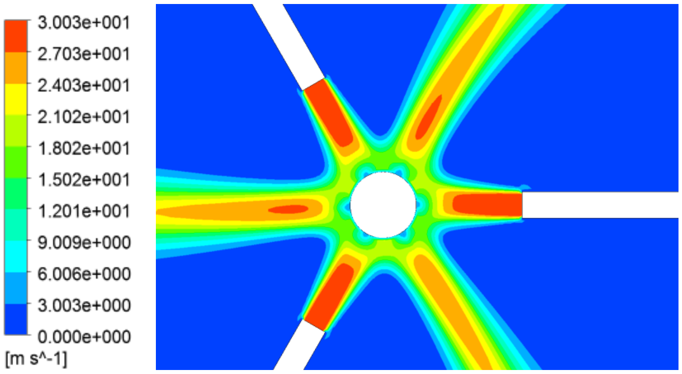

Figure – 4- Velocity magnitude contours, m/s, for the Re=19230 for the case of three nozzles

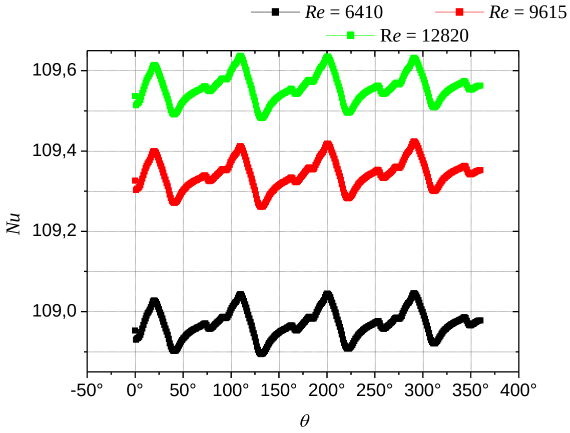

Figure – 5- Reynolds number effect on the distribution of the local Nusselt number, the case of three nozzles

Figure 5 reveals the presence of three distinct maximum Nusselt number values in the impact zones, accompanied by an additional maximum Nusselt number value with a comparatively lower magnitude than the main impact positions.

The observed maximum Nusselt number values are attributed to the presence of residual vortices near the point of impact. Notably, the average Nusselt number (Nu_{Avg}) exhibits a considerable increase. Furthermore, the Nusselt number curve exhibits a flattening trend, indicating a uniform cooling effect over the entire surface of the cylinder.

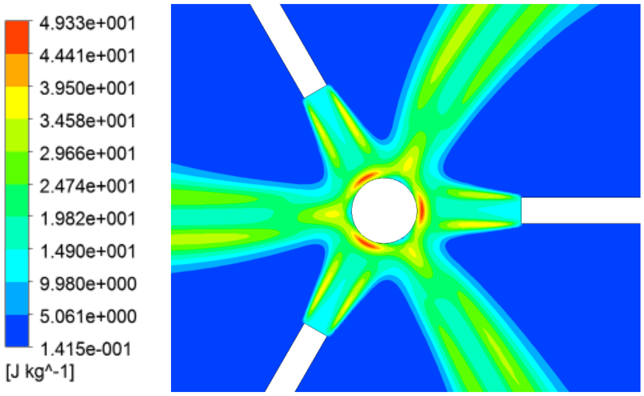

Figure – 6 Specific turbulent kinetic energy k in the free jet in J/kg for the Re = 19230, for the case of three nozzles.

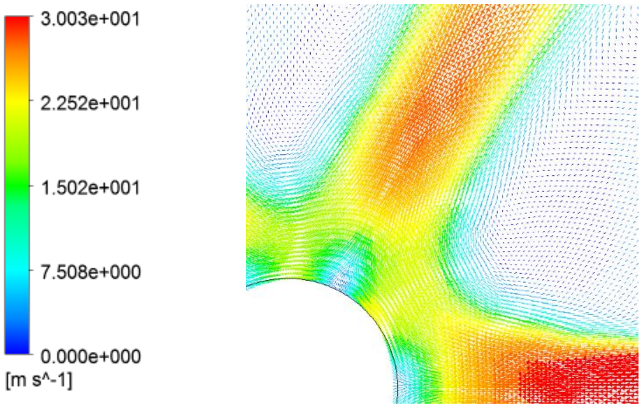

Figure – 7- Velocity vectors in the recirculation region around the impinging jet (fountain region) shown for the Re = 19230, for the case of three nozzles

This study presents an analysis of velocity vectors and turbulence kinetic energy in the recirculation region of impinging air jets. Figure 7 depicts the velocity vectors for Re = 19230 in the case of three nozzles. The generated vortices in the recirculation region scrub the surface, particularly in the region of reversed flow beneath the fountain. These vortices effectively transport energy away from the wall, preventing the hindrance of a thick developed boundary layer.

Figure 6 displays the contours of turbulence kinetic energy (k) in the flow field. Notably, three distinct areas with significant turbulence levels can be observed. The k-ε model, chosen for its tendency to overpredict turbulence in the center of the jet, is appropriately utilized in the shear layer at the edge of the free jet region, the middle of the wall jet adjacent to the wall, and the fountain zone beneath the separated jet.

4-3 Four nozzles :

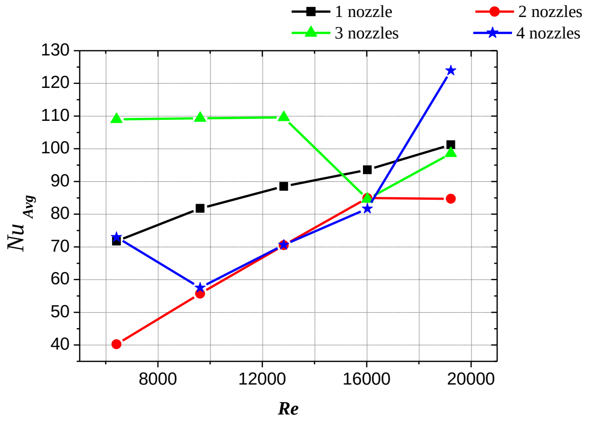

Figure – 8- the variation of the nozzle number effect on the average Nusselt for different Re

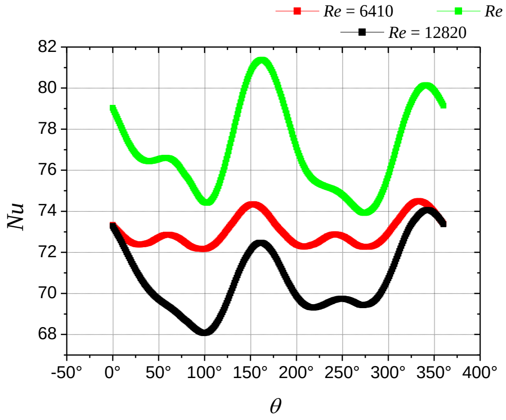

Figure – 9- Reynolds number effect on the distribution of the local Nusselt number, the case of four nozzles

This study investigates the variations in maximum (Nu_{max}) and average (Nu_{Avg}) Nusselt numbers with respect to Reynolds number (Re) in the context of jet cooling of rotating cylinders. Figure 9 reveals that Nu_{max} is highest at the lowest Re value, indicating an increase in Nu with increasing Re. Notably, Nu_{Avg} in this particular case shows a decrease compared to the other cases studied, specifically between Re = 6410 and 9615, as depicted in Figure 8.

Furthermore, the results demonstrate that for Re = 19230, the configuration with four nozzles exhibits the maximum Nu_{Avg}. However, in the case of three nozzles, there is a considerable decrease in Nu_{Avg} between Re = 12820 and 16025. In comparison, the cooling efficiency of the rotating cylinder is lower for the two-nozzle configuration when compared to the other cases.

5- Conclusion:

This study focuses on the numerical analysis of air jet cooling on a rotating cylinder, considering various configurations. The investigated cases include a single nozzle at different Reynolds numbers based on a previous study (Hammami & Al, 2016) [1], two nozzles symmetrically positioned along the cylinder axis at three Reynolds numbers, three nozzles distributed in a 120° arrangement at three Reynolds numbers, and four nozzles in a 90° configuration at three Reynolds numbers. The turbulent flow is governed by the Navier-Stokes equations, and the realizable k-ε turbulence model is employed due to its suitability for high-Reynolds number jet flows.

The results demonstrate that the three-nozzle configuration exhibits significant heat transfer (Nu_{max}) and leads to a broader distribution of the Nusselt number (Nu) curve, indicating uniform cooling over the entire cylinder surface. Notably, the case with Re = 12820 yields a higher average Nusselt number (Nu_{Avg}) compared to the other two Reynolds numbers studied.

From a technological standpoint, the cooling system with three nozzles demonstrates improved resistance to thermal shocks for milling tools. This finding highlights the potential advantages of utilizing the three-nozzle configuration in industrial applications requiring enhanced thermal management.

Data availability statement :

The data that support the findings of this study are not available due to privacy restrictions. Further inquiries regarding data availability should be directed to the corresponding author.

Competing Interest declaration : No

Ethical statement :

This study was conducted in accordance with ethical guidelines and principles. All procedures involving human participants were in compliance with the ethical standards of the institutional and/or national research committee.

Informed consent was obtained from all individual participants included in the study. Participants were made aware of their right to withdraw from the study at any time without consequence. All data collected were treated confidentially and anonymized to protect participant privacy.

Funding Declaration : No

Author Contribution Statement:

- Zineb HEMMAMI.: Conceptualization, - original draft. Data curation, Software, Visualization, Validation.
- Azzeddine HAMMAMI.: Methodology, Formal analysis, Investigation, WritingWriting - review & editing.

All authors have read and agreed to the published version of the manuscript.

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The preferred spelling of the word "acknowledgment" in American English is without an "e" after the "g." Use the singular heading even if you have many acknowledgments.

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