Enhanced Transport under Annular Jet by Introducing Rib

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Abstract: This work concern studies for the transport enhancement of impinging annular jets. The ribs are introduced on the impingement surface and higher heat transfer could be obtained using rib compared to plane surface. Comparison is made with circular jet to predict the enhancement of heat transport for same Reynolds number and mass and momentum efflux at jet outlet. The model used for solving the problem is Shear Stress Transport (SST) model, while the Reynolds numbers of jet varies from 100 to 50000. Square rib is used in this study. This study reveals that the ribs will increase the heat transfer for both circular and annular jets. Annular jet provides 20–30% lower heat transfer than that of the circular jet.

Keywords: Annular jet, Ribbed Surface, Heat transfer, Turbulent flow.

1. Introduction
Impinging jets are used either heating or cooling in many applications where heat transfer takes place between the impinging fluid jet and surface. The performance of knife jet where the jet emanates at an angle with the axis has been studied numerically by Chattopadhyay and Saha \cite{1} and results are compared with axial slot jet on moving surface under laminar conditions. It has been found that knife jet always under-performs than axial jets and velocity at the surface also reduces heat transfer. Chattopadhyay \cite{2} has been performed laminar annular jet with jet location at $r_i = 0.5$. Heat transfer in case of circular jet is more and it is about 20% in comparison to the annular jet. Heat transfer drops in case of moving surface, noted by Chattopadhyay \cite{3}. Heat transfer on ribbed surface is investigated by Yan et al. \cite{4}. They have observed that heat transfer depends on rib orientation. Tan et al. \cite{5} have studied heat transfer characteristics for ribbed regions and observed 30% heat augmentation in this zone of rib. Nakod et al. \cite{6}, Studied the effect of circular air jet impinged finned (rough) flat surface on the local heat transfer coefficient for different Reynolds number. The local heat transfer coefficient for finned surface was increased up to 77%.

This work is divided into two parts. The first part show the study of heat transfer on ribbed surface and comparison is made with pane surface. The second part discusses the comparison of heat transfer between circular and annular jet.
2. Mathematical Formulation

The schematic configuration of an annular jet is shown in figure 1. The governing equations for continuity, momentum and energy transfer are solved using finite volume formulation. A wide range of Reynolds from 100 to 50000 is investigated with a fixed height of impingement. The location of jet of the annular zone is, \( r_i = 0.5 \). The distribution of Nusselt number and turbulent intensity has been found to be strongly influenced by these parameters.

The flow has been considered steady and incompressible. In this study of fluid flow and heat transfer phenomena for annular jet, transition Shear Stress Transport (SST) based model is chosen to solve the constitutive equations.

The Reynolds-averaged Navier-Stokes (RANS) equations in dimensionless form are now presented.

The pressure, velocity and temperature have been non-dimensionalised by \( \rho \), \( \beta \), and \( \alpha \), respectively.

Continuity equation:

\[
\frac{1}{r} \frac{\partial}{\partial r} (ru) + \frac{\partial w}{\partial z} = 0
\]

(1)

Momentum equation along radial direction:

\[
\frac{1}{r} \frac{\partial}{\partial r} (ruu) + \frac{\partial (uw)}{\partial z} = -\frac{\partial p}{\partial r} + \frac{1}{Re} \left( 1 + \frac{v_t}{\nu} \right) \left( \nabla^2 u - \frac{u^2}{r} \right)
\]

(2)

Momentum equation along axial direction:

\[
\frac{1}{r} \frac{\partial}{\partial r} (ruw) + \frac{\partial (uw)}{\partial z} = -\frac{\partial p}{\partial z} + \frac{1}{Re} \left( 1 + \frac{v_t}{\nu} \right) \nabla^2 w
\]

(3)

Energy equation:

\[
u \frac{\partial T}{\partial r} + w \frac{\partial T}{\partial z} = \frac{1}{Re \cdot Pr} \left( 1 + \frac{\alpha_t}{\alpha} \right) \nabla^2 T
\]

(4)

In figure 1, axi-symmetric part shows the annular jet at the inner radius of \( r_i \). In our present study, Reynolds number varies from 100 to 50000, jet position from the axis is \( r_i = 0.5 \), and from the plate, \( h = 1.0 \). H is the vertical distance from the enclosing plate to the surface of impingement.

![Figure 1 Physical configuration for annular jet with rib](image)

Present study is carried out by considering air as working fluid having \( Pr = 0.71 \). Reynolds number is calculated based on width of annular part [2]. The constitutive equations are described in cylindrical polar coordinated. For stationary surface, no slip boundary with uniform temperature is chosen. Adiabatic walls are assumed at top and bottom wall. The simulations are performed in 2D and axi-symmetric, therefore axi-symmetric boundary conditions are imposed in the axis. The characteristic length and velocity to achieve non dimensionalization is designated as \( d_i \) and \( w_{in} \), respectively and fixed pressure at the exit plane has been assumed.

For non-dimensionalization, the skin friction coefficient can be represented by velocity gradient i.e.,

\[
C_f Re = \frac{\delta u}{\delta z}, \quad Nusselt number estimates the heat transfer and expressed by local temperature difference as \( Nu = -\frac{\partial T}{\partial z} \).
\]

The average Nusselt number is acquired by \( Nu_{av} = \frac{-\partial T}{\partial z} \). The average Nusselt number is acquired by \( Nu_{av} = \frac{-\partial T}{\partial z} \).
along r direction of computational domain i.e., 5d. The dimensionless temperature of the impinging plate is chosen as unity i.e., \( T_s = 1.0 \), and the jet temperature is taken atmospheric (i.e., \( T_a = 0.0 \)). A typical value of 5% is chosen for inlet turbulent intensity [7-8]. In the present study, the axi-symmetric governing equations are solved by finite volume method. Non uniform staggered grid is used for discretization of the equations. The most popular scheme, SIMPLE [9] is used for predicting pressure and velocity. QUICK scheme is adopted for interpolation of temperature and velocities gradients; second order accurate upwind scheme for gradients of intermittency, turbulent kinetic energy, specific dissipation rate, and momentum thickness. The equations were solved iteratively with ANSYS Fluent [10]. For achieving convergence, residual level of \( 10^{-6} \) is prescribed for all equations except for continuity which was set at \( 10^{-4} \).

3. Results and Discussion
The present study is conducted for different Reynolds numbers ranging from 100 to 50000 at jet location \( (r_i = 0.5) \) on rib surfaces. Jet is taken circular and annular along with ribbed impinging surface. To show the improvement of heat transfer, average Nusselt number and skin friction coefficient are investigated.

The velocity contours for our considered cases of jets have been shown in Fig.2. It is revealed from the figure that two fluid streams are discharge from two concentric sections and the outer portion of stream forms an annular jet. The physical feature differentiating the flat surface and ribbed surface impinging from annular jet is related with the outlet flow structure on surface. The impingement on the target plate creates reverse flow zone along the jet axis. This may be attributed to flow streams reversing towards the jet axis [Fig.2 (a) & (b)]. An impinging of simple circular jet is configured by high momentum flow discharging from the jet and impinges on surface. Peak momentum region coincides with the jet axis [Fig.2 (c) & (d)].

![Figure 2 Velocity contour (a) annular jet without rib and (b) annular jet with rib (c) circular jet without rib and (d) circular jet with rib](image)

Figure 3 shows the distribution of \( C_f \) for different Reynolds numbers for an annular jet \( (r_1 = 0.5) \) with single rib \( (0.15 \times 0.15) \) at rib location \( r = 0.5 \). It is observed that the jet divides either towards the central core i.e., axis or radially outwards after impingement. Negative value of skin friction indicates that the flow moves inward adjacent to plate. Skin friction coefficient is zero at the axis and then reduces up to \( r = 0.2 \) for annular jet, beyond that it starts to increase. \( C_f \) value again becomes zero at about \( r = 0.4 \) after which it is in positive range. \( C_f \) reaches its maximum peak value on rib then it is zero at about \( r = 0.6 \). However \( C_f \) reaches its peak value at \( r = 1.0 \) and then drops.
Figure 3 Variation of $C_f$ at different Re (annular jet with single rib) at rib location $r=0.5$

The distribution on Nu on ribbed surface is shown in Fig. 4. The local heat transfer appears low at below jet as the jet impinges the rib at the stagnation point. It is also observed from the figure that heat transfer rises and becomes maximum behind the rib and decays gradually downstream. Local heat coefficient occurs maximum at the stagnation point. This value occurs minimal and maximum at the rib and behind the rib respectively. The heat transfer studies on flat surface are conducted in our earlier studies Pal et al.[8] in order to understand the heat transfer characteristics on the impingement plate but from the present study it is evident that by introducing of ribs on surface overall heat transfer is increased.

Figure 4 Distribution of Nu at different Re for an annular jet ($r_1 = 0.5$) single rib (0.15x0.15) at rib location $r=0.5$

Figure 5 shows variation of Nusselt number for jet impingements with Reynolds numbers for circular and annular jet for both surfaces, though for annular jet, Nusselt number is comparatively lower than that of circular jet. It is noted that heat transfer for annular jet is about 20 - 30% less compared to the circular jet. Also from the study, it can be concluded that the Nusselt number value increases on ribbed surface. Nusselt number values for the ribbed surface can be increased by 5% to 20% than that of plane surface.

Figure 5 Variation of Nu with Re for an annular jet ($r_1 = 0.5$) and circular jet with or without single rib.
Table 1 shows that enhancement of heat transfer at different Re when rib is used for annular jet. The difference in percentage of Nusselt number is also shown in the table. From the table, it is observed that the Nu for plane surface is less than that of ribbed surface.

| Re  | Nu for Plane Surface | Nu for Rib Surface | Difference (%) |
|-----|----------------------|--------------------|----------------|
| 100 | 3.18509              | 3.369135           | 5.46%          |
| 500 | 7.152728             | 7.618556           | 6.11%          |
| 750 | 9.132468             | 9.933756           | 8.06%          |
| 1000| 10.93725             | 11.9253            | 8.28%          |
| 5000| 36.65586             | 40.14501           | 8.69%          |
| 10000| 56.14009             | 67.62579           | 16.98%         |

4. Conclusion
In our earlier study Pal et al. 2019 [8] showed that an annular jet underperforms circular jets in terms of heat transfer. In this work, strategy of enhancing transport from annular jet is investigated. Augmentation is brought by using ribs on surface. The result reveals that for ribbed surface the Nusselt number becomes higher compared to flat surface in our considered study. But the Nusselt number is lower in case of annular jet compare to circular jet. Therefore, it concludes that enhancement is occurred in case of ribbed surface and the heat transfer distribution may be lower in case of annular jet. This enhancement can be increased 5%-20%.

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