Computational Study of Turbulent Slot Jet Impingement on a Ribbed Surface

Anuj Kumar Shukla  
Department of Applied Mechanics  
Indian Institute of Technology Delhi  
Hauz Khas, New Delhi - 110016  
Email: anujshukla.cest@gmail.com

Anupam Dewan  
Department of Applied Mechanics  
Indian Institute of Technology Delhi  
Hauz Khas, New Delhi - 110016  
Email: adewan@am.iitd.ac.in

Balaji Srinivasan  
Department of Applied Mechanics  
Indian Institute of Technology Delhi  
Hauz Khas, New Delhi - 110016  
Email: balaji@am.iitd.ac.in

Abstract
A computational study was carried out to assess the suitability of various RANS based turbulence models for slot jet impingement. We have considered flat and ribbed surfaces to predict the flow and heat transfer characteristics for Re = 5500, 20,000 and non-dimensional nozzle to plate spacing (H/B) = 4, 9.2 and 8. We have compared the computed result with the reported experimental data. It is observed that none of the turbulence models considered predicts the quantitative heat transfer data accurately. On the other hand, some models predict the experimental data with good trends, e.g., secondary peak in Nusselt numbers for low H/B values and spikes in Nusselt number for ribbed surface. It is shown that the standard k-ε model predicts heat transfer more accurately than the SST k-ω turbulence model with several spikes in Nusselt number for ribbed surface.

Keywords: Slot Jet impingement; Heat Transfer; Ribs; Turbulence Modelling; Nusselt Number.

I. INTRODUCTION
Jet impingement heat transfer is an interesting flow configuration to study because of its industrial as well as fundamental importance. Some important industrial applications are cooling/heating of electrical equipment, drying requirement associated with textile and paper industries, cooling of turbine blades, cooling of outer combustor wall, etc. Although jet impingement on a plate is geometrically simple, it involves a number of interesting complex physical flow configurations, namely, free-shear region (formation of large scale vortex structures), stagnation region (with strong streamline curvature) and a wall jet region. Several parameters were found that affect the characteristics of slot jet and have been found special attention in the literature either experimentally or numerically [1-3].

Majority of the RANS based turbulence models considered in the literature were not able to predict impinging flows accurately and its complexities except a few [4-7]. A small number of literature dealing with jet impingement heat transfer on a rib fitted surface either experimentally or numerically exists in the literature [7]. Katti and Prabhu [8] observed that the addition in the rib height may lead to a reduction in Nusselt number in the downstream from the first rib. Gau and Lee [9, 10] observed that the flow and heat transfer features with rib-roughened walls were different from the flat plate configuration and reduced heat transfer near the impingement region were obtained for ribbed surface. Recently Tan et al. [11] experimentally observed 30% enhancement in heat transfer with the rib roughened wall than that with a flat plate.

II. METHODOLOGY
All the computations in the present study were performed using an unstructured and cell centred finite volume code FLUENT 15, which employs a co-located grid arrangement. The diffusive terms of the governing equations were discretized using the second-order central difference scheme and the convective terms were discretized using the second order upwind scheme. The Semi Implicit Pressure Linked Equations (SIMPLE) method was used for the pressure-velocity coupling. Fig. 1 shows the details of the computational domain considered in the present study.

For a statistically steady flow, every variable can be written as the sum of average value and a fluctuation about the average value. The averaged continuity, momentum and energy equations for a steady, incompressible flow without body forces can be written in the tensor notation in Cartesian coordinates as:

$$\frac{\partial (\rho \overline{U})}{\partial x_i} = 0$$  \hspace{1cm} (1)

$$\frac{\partial}{\partial x_i} (\rho \overline{U} \overline{U}) = \frac{\partial \overline{P}}{\partial x_i} + \rho \frac{\partial \overline{T}}{\partial x_i} = \mu \left( \frac{\partial \overline{U}}{\partial x_i} + \frac{\partial \overline{U}}{\partial x_j} - \rho \overline{u' u'} \right)$$  \hspace{1cm} (2)

$$\rho c_v \overline{U} \frac{\partial \overline{T}}{\partial x_i} = k \frac{\partial^2 \overline{T}}{\partial x_i^2} + \rho \overline{c_v} \overline{u' u'}$$  \hspace{1cm} (3)

where $\rho$ denotes the density of the fluid and $\overline{U}$ the mean component of velocity in $x_i$ direction and $u'$ the fluctuating component of velocity. The other symbols used here have their standard meanings. The term $-\rho \overline{u' u'}$ in the momentum equation (2) is called the Reynolds stress and its existence leads to a closure...
problem. Readers are referred to any comprehensive book for details on turbulence models used in the present work such as Dewan [12].

III. RESULTS AND DISCUSSION

In the present study we have considered two cases of jet impingement, i.e., on a flat surface and on a ribbed surface. For the ribbed surface the jet impinges directly upon one of the ribs. We have considered \( Re \) (based on the slot width) of 5500 and 20000 and \( H/B \) values of 4, 9.2 and 8. For the ribbed surface we have considered the non-dimensional rib pitch \( p/e \), where \( e \) (= 3 mm) is the rib thickness. Various turbulence models, namely, SST \( k-\omega \) model, standard \( k-\omega \) model, transitional SST model (4 equation), \( k-kl-\omega \) model, Spalart–Allmaras model, RSM and variants of \( k-\epsilon \) model were considered. The grid independence studies were carried out for all the cases considered. We have maintained \( y^+ \) values at the first grid in the vicinity of walls less than 1 for all the computations.

We can observe from Fig. 2 that the predictions of the surface Nusselt number are in good agreement with the predictions of [1] and [4]. Though some mismatch can be observed with the experimental data, the predictions follow the experimental trend. The present prediction of the surface \( Nu \) shows a dip nearly at the same location as in the experimental data but everywhere it over predicts the surface \( Nu \). We can observe from Fig. 2 (a) that the standard \( k-\omega \) and SST \( k-\omega \) turbulence models predict the secondary peak in the Nusselt number. It is well known that the occurrence of the secondary peak in \( Nu \) is due to the transition of laminar to turbulent flow in wall jet regions. The SST \( k-\omega \) turbulence model works well under adverse pressure gradients and separating flow situations [12]. Other turbulence models, such as, the transitional SST model, \( k-kl-\omega \) and Spalart–Allmaras model also predict the secondary peak in the surface Nusselt number.

A similar trend is captured by the transitional SST model because of the interaction of transition model with the SST turbulence model by a modification in the \( k \)-equation. The transition SST model uses two extra equations with the two-equation SST model (thus a total of four equations). The two extra equations involved are the intermittency and the transitional momentum thickness \( Re \) that controls the transition criterion. Fig. 2(b) shows the surface \( Nu \) predictions using various turbulence models for \( H/B = 9.2 \) and \( Re = 20000 \). We observed that the prediction of the surface \( Nu \) with the standard \( k-\epsilon \) model follows the precise trend as in the reported experimental [1] and computation results [4]. However, except for the standard \( k-\epsilon \) model all other models show a false secondary peak.

We have observed that the flow pattern is different for impingement on a ribbed surface than that on a flat surface. For the first case the rib projection helps to promote turbulence in the wall jet region. A higher pressure in the rib cavity in the vicinity of the stagnation region was observed and it decreased downstream. Air bubbles in the cavities were also observed downstream [Fig. 3(a)] until the jet became turbulent after impingement and was strong enough to infiltrate these air bubbles formed in the cavity. Infiltration of turbulent wall jet occurs due to the low pressure at the downstream location. Further flow separation from the rib surface, recirculation and reattachment in the cavities at the downstream location can be observed [Fig. 3(a)].

We can observe a significant decrement in \( Nu \) along the downstream for a ribbed surface (Fig. 4). This behaviour is due to the rib projection which reduces the horizontal momentum and increases wall jet layer thickness. For the case of \( H/B = 8 \) the maximum values of \( Nu \) were observed in the vicinity of the stagnation region. This behaviour is due to the fact that at high \( H/B \) the jet becomes turbulent before impingement. Hence enormous amount of jet flow can impinge on the surface and infiltrate in to the cavity near the impingement region. As a result heat transfer is large in this region. Further we can observe several spikes in
undershootings in the prediction of local modelling assumptions involved. Such overshootings and able to capture these complexities accurately due to several experimental study [9]. This behaviour could be due to several underpredicted, though it follows the same trend as in the experimental result [9] except in the vicinity of the rib, where it is the present predictions of local $\text{Nu}$ for jet impingement on a ribbed surface. We can observe that the standard k-e model predicted $\text{Nu}$ with more accuracy than the SST k-ω turbulence model but undershootings are present in both the models. The standard k-e model predicts the stagnation $\text{Nu}$ close to the impingement region more accurately than the SST k-ω which underpredicts it (Fig. 4).

IV. CONCLUSIONS

It was observed that the standard k-ω and SST k-ω turbulence models were able to predict the secondary peak in the Nusselt number for low nozzle to plate spacing ($H/B$) value and standard k-e model for high $H/B$ value. Further we have investigated the effect of ribbed surface on flow features and heat transfer characteristics for non-dimensional pitch ($p/e$) = 3 and $Re$ = 5500. We observed that the standard k-e model predicted $\text{Nu}$ number with more accuracy than the SST k-ω turbulence model. Several spikes in $\text{Nu}$ number due to the rib projection were observed and the present trend is similar to the experimental result with some under-prediction due to the weaknesses of turbulence models considered. It was observed that the prediction of local $\text{Nu}$ was more with ribbed surface than that of flat surface everywhere.

REFERENCES


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