International Journal of Thermal Sciences 118 (2017) 139–151

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

An analysis of turbulence models for prediction of forced convection of air stream impingement on rotating disks at different angles

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ARTICLE INFO

Article history:
Received 17 December 2016
Received in revised form
5 April 2017
Accepted 21 April 2017

Keywords:
Jet impingement
Rotating disk
Turbulence modelling
Heat transfer
DES

ABSTRACT

In this study, the performance of seven turbulence models for the prediction of the flow and heat transfer in forced convection of jets and air streams impinging on a disk in different stationary, rotating and inclined rotating conditions are compared using a large number of experimental case studies. These models include four RANS models, i.e. k-ε RNG, k-ω SST, transition k-ω SST and RSM and three hybrid models, i.e. SAS, detached eddy simulation with transition k-ω SST and detached eddy simulation with realizable k-ε (DDES-RKE). Based on a detailed comparison and error analysis, it is shown that while no RANS model is found to perform well in all regions of the flow, DDES-RKE model can capture all flow, i.e. velocity and kinetic energy fields, and heat transfer, i.e. mean Nusselt number, features of the problem in excellent agreement with experiments in all regions of the flow and for all stationary, rotating and inclined rotating conditions. In addition, the local Nusselt number distribution predicted by these models are compared and analyzed carefully. It is observed that the presence and interaction of the swirling vortex and leading-edge flow bubble result in a complex local Nusselt number distribution with several extrema.

1. Introduction

Forced air stream impinging on a moving or rotating surface is an important engineering problem used in various applications, such as cooling of gas turbine blades, cooling of electronic parts, tempering of glass and some metal sheets, disk brakes and so on. Owing to this widespread usage, this problem has been studied extensively, both experimentally and numerically. Interesting reviews on this topic have been carried out by Jambunathan et al. [1], Weigand and Spring [2], Harmand et al. [3] and Carlomagno and Ianiro [4].

Many experimental researches have been conducted on this topic. One of the first experimental works was done by Dennis et al. [5]. They studied the heat transfer from a rotating disk in parallel air stream and developed empirical correlations for the mean Nusselt number, *Nu*. The effect of different parameters, including the cross flow Reynolds number, *Re*, rotational Reynolds number, Re_ω, and ratio of the nozzle-to-surface distance, *h*, to the nozzle hydraulic diameter, *d* (see Fig. 1), on the heat transfer from a flat surface or disk subjected to an impinging air jet or stream have been investigated experimentally by many researchers [6–11]. The configurations with an inclined rotating disk in airstream were first studied by Trinkl et al. [12] experimentally for a wide range of air crossflow velocities and rotational speeds. The effect of the incidence angle on the flow over a stationary and a rotating disk subjected to forced air streams was studied experimentally by Helcig and Wiesche [13,14] covering the whole range of 0–90° and a large number of crossflow and rotational Reynolds numbers.

Computational prediction of the flow field and heat transfer associated with the forced airflow on a surface has long been a challenging task in turbulence modelling due to the nature of turbulence and boundary layers. In case of a jet or stream impinging a stationary surface, Cziesla et al. [15] reported the flow structures of an impinging jet at a moderately high *Re* using a dynamic sub-grid scale (SGS) model for large eddy simulation (LES). Their computed results agreed favorably with the experimental observations, especially in the stagnation zone. Through the review of a large number of studies using RANS models, Lior and Zuckman [16] reported that even with high-resolution grids the various implementations of the k-ε, k-ω, Reynolds stress model (RSM) and

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http://dx.doi.org/10.1016/j.ijthermalsci.2017.04.021
1290-0729/

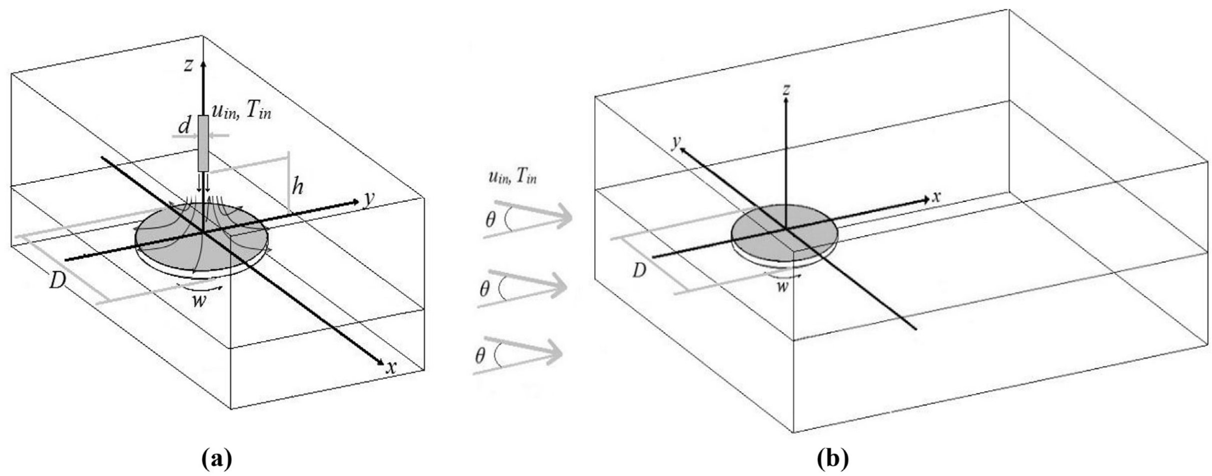

Fig. 1. Schematics of a rotating disk subjected to (a) perpendicular jet or (b) air stream at angle θ. The 3D computational domain is depicted by a rectangular box.

algebraic stress model (ASM) give large errors compared to experimental data. They pointed out that v^2-f model is the most accurate RANS model in case of heat transfer prediction. Jaramillo et al. [17,18] investigated the performance of different RANS models based on k-ε and k-ω platforms, including two-equation linear and non-linear models and ASM, for plane and round turbulent impinging jets through comparison with direct numerical simulation (DNS) results. The authors mourned the lack of generality of these models and observed that each model was only able to accurately capture a particular region of the flow field. Nevertheless, they mentioned that the use of better damping functions and/or additional terms, such as the Yap's correction [19], seems to play an important role. Sharif and Mothe [20] applied four turbulence models, namely RSM, standard k-ε, RNG k-ε and shear stress transport (SST) k-ω, to simulate the air flow impingement on a curved surface. All these models failed to accurately predict the local *Nu* distribution along the surface. However, RSM showed relatively better performance in recreating the flow features. Kubacki et al. [21] examined k−ω based RANS and hybrid RANS/LES models for the simulation of plane jets impinging on a flat plate. They showed that the hybrid models, due to their ability to resolve the evolution and break-up of the vortices in the shear layer of the jet, give much better prediction of the wall shear stress and the *Nu* number along the plate. In their later work, Kubacki et al. [22] did a detached eddy simulation (DES) and a partially-averaged Navier−Stokes (PANS) hybrid RANS/LES model based on the k−ω RANS turbulence model for the simulation of plane impinging jets. Authors announced that the flow prediction with DES and PANS models is much better than with the RANS model, however the skin friction prediction with DES outweighs the one with PANS. Taghinia et al. [23] investigated the heat transfer and flow characteristics of air jet impingement on a curved surface using two models, a one-equation SGS closure for LES and a k-ω SST scale adaptive simulation (SAS). Comparisons showed that the one-equation model produced more accurate results especially at impingement region and lower nozzle-to-surface distances. It is also observed that both models show similar performance at higher ratios of *h*/*D*. Bovo and Davidson [24] showed the ability of LES method to capture the physics of the impinging jet on a surface.

There are much fewer computational studies in the case of the forced convection on a rotating or moving surface. Chattopadhyay and Saha [25] used LES with a dynamic SGS model to study the flow and heat transfer of single slot jet impingement on a moving hot isothermal plate. Badra et al. [26] analyzed various turbulence models for single and multiple circular jets impinging perpendicularly on a moving flat plate for heating and cooling purposes. They announced the SST k-ω and v^2-f turbulence models succeeded with a reasonable accuracy (within 20% error) in reproducing experimental results. Benmouhoub and Mataoui [27] used k-ω turbulence model to predict the effect of Re number and surface-to-jet velocity ratio on the heat transfer of 2D plane jet impingement on a moving wall.

In the case of rotating surface, the predictions are even more challenging due to additional complexities like the flow curvature effect. Wiesche [28] investigated the heat transfer of a rotating disk in an air crossflow parallel to the disk surface using LES. They proposed different correlations in order to predict convective heat transfer on the disk. In the case of dominant rotational Reynolds number, the agreement is good but higher values has been noticed for the mean *Nu* in comparison to experimental data [5] in the cases with dominant crossflow *Re*. Benim et al. [29] investigated jet impinging on a rotating disk with different RANS turbulence models. They announced that the performance of RSM is rather unsatisfactory while the best overall agreement with the experiments is obtained by the k-ω model. Using a k-ε model, Abdel-Fattah [30] examined the influence of wall rotation on the characteristics of an impinging jet under varying rotational speeds and *h*/*d*. Their results showed that the pressure coefficient depends on the centrifugal force and decreases as *h*/*d* increases. Saidi et al. [31] studied the performance of the cooling process of a circular jet impingement on a rotating disk using RNG k-ε. Manceau et al. [32] compared five turbulence models for this problem. They noticed a poor prediction of the velocity field in the jet region and attributed it to an overestimation of the free-jet spreading before its impingement on the rotor. They pointed out the need of more advanced models accounting for the effect of rotation. Poncet et al. [33] examined an advanced RSM model in comparison with the k-ω SST model and pointed out that RSM does not capture the secondary peak in the *Nu* distribution while it better predicts the turbulence intensities. Recently, Manceau et al. [34] examined more advanced RANS models and showed that the considered models predict well the wall jet region, while they fail to predict the mean and turbulent flow fields in the free-jet area. A DNS study on a confined jet impingement on a rotating disk was performed by Oguic et al. [35] and the *Nu* secondary peak was observed in the DNS results. They also proposed correlations for the mean *Nu* number.

Despite the previous efforts to study and compare the ability of