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Modeling and computation of turbulent slot jet impingement heat transfer using RANS method with special emphasis on the developed SST turbulence model

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ABSTRACT

Based on the Reynolds-Averaged Navier-Stokes (RANS) method, this work has developed a combinational turbulence model for the numerical simulation of turbulent slot jet impingement heat transfer. The combinational model is constructed by taking the original Shear Stress Transport (SST) turbulence model as the parent model and coupling with the Kato-Launder model, the intermittency transition model and the crossflow transition model, which has been abbreviated as SST-KIC model. Detailed study has been conducted for the effect of different component models in terms of the turbulent kinetic energy, the local Nusselt number as well as the flow structures including the mean velocity, skin friction and the law of wall. By comparing with both experimental data and available numerical results of other researchers, it has been found that the proposed model possesses good performance in terms of different parameters for both two nozzle-plate spacing of 4 and 9.2. Finally, the effect of Reynolds number on the flow field characteristics was studied and it is noted that the positive gradient of turbulent intensity has similar variation tendency as the positive gradient of the Nusselt number.

1. Introduction

Jet impingement problem, by itself, usually involves a strong heat transfer characteristics. It is directly relevant to many different applications, such as the typical heating and cooling processes of papermaking, spinning, food product, steelmaking and air-conditioning. Moreover, it is also widely used in fast cooling of high speed flight vehicles and anti-icing application for aircraft. Furthermore, the application of generating lift by impinging jets into the surfaces is applied to the vertical takeoff and landing (VTOL) aircraft. Consider the complexity of the jet impingement, numerical simulation has been considered as an effective way to study the mechanism of the problem. However, the flow field characteristics of impinging jets include the streamline curvature, flow separation, and vortex formation and breakdown, which make it a challenge to simulate the heat transfer of impinging jets accurately. Accurate numerical model and effective prediction of the impinging jet phenomenon are the goals that researchers have long been pursuing.

Among varies numerical methods, the RANS has been popularly used in recent years [1–5]. In the early studies of RANS models, it has been shown that the standard eddy viscosity models usually generate higher turbulent kinetic energy k in the stagnation region [6,7]. Yap [8] developed the Yap correction which is added in the dissipation ε equation as an extra source term. The Yap correction corrects the turbulent length scale and improves the prediction of heat transfer in the stagnation region. The effect has also been observed by other researchers [7,9,10]. Kato and Launder [11] also developed a correction called Kato-Launder model which corrects the production term P_k. In the Kato-Launder model, one of the strain rate S in P_k has been replaced by the vorticity rate Ω, which is almost zero in the stagnation region because the flow is nearly irrotational. Hence, the k is reduced in a Kato-Launder model. Selvam [12] used the standard k-ε model and Kato-Launder k-ε model to simulate the flow around Texas Tech building. He found the Kato-Launder k-ε model predicts the lower turbulent kinetic energy than the standard k-ε model. Wienand et al. [13] studied an impinging jet for different nozzle-plate spacing using SST k-ω

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Nomenclature

B	slot jet width
H	the impinging spacing
L	the length of impinging plate
T	temperature
k_{in}	inlet turbulent kinetic energy
U	the mean velocity in x component
V_{in}	inlet velocity
I	turbulent intensity
k	turbulent kinetic energy
l_c	the characteristic of length scale
Pr	Prandtl number
Re	Reynolds number
y^+	the dimensionless distance of node to wall
u^+	the dimensionless velocity
Nu	local Nusselt number
T_w	temperature of impinging plate
T_{in}	temperature of inlet
C_f	skin friction

Greek symbols

ε	turbulent dissipation rate
ω	specific dissipation rate
Ω	vorticity rate
ω_{in}	inlet specific dissipation rate
μ_t	turbulent viscosity
μ	molecular viscosity
τ_w	the wall shear

with and without Kato-Launder model. They pointed out that the effect of Kato-Launder model depended on the nozzle-plate spacing. For lower nozzle-plate spacing, the correction reproduces more accurate results; while for higher values, the Kato-Launder model was not recommended.

Numerous studies have shown that the low Reynolds number models and transition models have the ability to predict the second peak. Dutta et al. [14] carried out a detailed investigation for the confined impinging jets by using different available numerical models, which include the SST k-ω model [15], the standard k-ω model with or without the low Reynolds number correction [16], the standard k-ε model and the Launder and Sharma (LS) model [17]. Most of the low Reynolds number models generate the second peak in the nozzle-plate spacing of 4. But the SST k-ω model with low Reynolds number correction gets much closer to the experimental data. Studies on low Reynolds number models also include the work of Craft, Launder and Suga model (CLS) [18] and Yang and Shih (YS) [19]. However, Dutta et al. [14] pointed out that the standard k-ω model and the standard k-ε model performed better than the low Reynolds number models, which computed a false secondary peak of Nu in the case of high nozzle-plate spacing of 9.2. In addition, based on the laminar-turbulence transition theories, Laundry and Menter [20] developed a transition model coupled with the SST k-ω model called the *Gamma-Theta* model (also known as the Transition SST). This model adds two transport equations for intermittency and the transition momentum thickness Reynolds number, respectively, which have been found to be useful in wall-bounded flows. Alimohammadi et al. [21] carried out the Transition SST model to investigate the Nu distribution in the range of Reynolds number $600 \le Re \le 14000$ and nozzle-plate spacing $1 \le H/D \le 6$ for the round impinging jets. Their results showed robust performance for Transition SST model in terms of heat transfer. Papadrakakis et al. [22] also carried out the Transition SST model to study the round impinging jet and also got good results. However, for a turbulence model, a good performance in the round impinging jets does not guarantee a good performance in the flat impinging jets and vice versa [23].

Based on early studies on RANS models, Zuckerman and Lior [24] compared various turbulence models for heat transfer of impinging flows. They found the k-ε model shows poor ability to predict the second peak of Nu and the SST k-ω model has a fair performance in obtaining the second peak. Dewan et al. [23] pointed out that the poor performances of RANS based models are due to arbitrary coefficients, wall functions and damping functions. Further, the v^2-f model of Durbin [25] and Direct Numerical Simulation/Large Eddy Simulation (DNS/LES) models have excellent performances in the prediction of both Nu in the stagnation point and the secondary peak. But the above two kinds of models generally demand high computational cost. To get the accurate results and reduce the computational cost, the hybrid models such as RANS/LES model has drawn attention over years [26–29]. However, these hybrid methods are not computationally efficient enough for industrial design and engineering environment.

From the published literatures, we can find that although various turbulence models have been evaluated for heat transfer of impinging jet, there is lack of a robust and highly efficient computational strategy to address the rich physical characteristic. To achieve the goal of exploring a robust numerical model for the impinging jet, the SST k-ω model is recommended as a based turbulence model in the present study. To predict the correct secondary peak of Nu which is affected by laminar-turbulence transition process and reduces the computational cost, the one equation intermittency transition model developed from the *Gamma-Theta* model is tested in this work. The Kato-Launder model is used for testing the validation of reducing the turbulent kinetic energy in the stagnation region. In the stagnation region, the crossflow instability, which the *Gamma-Theta* model is not able to predict, may be induced because of the low turbulent intensity ($Tu \le 0.5\%$). Hence, a crossflow transition model [30] is also presented in this work. Based on established numerical method, two cases of flat impinging jet are studied in Reynolds number of 20,000. The local Nusselt number distribution and the flow structure are presented by comparing with both the experimental data from the work of Ashforth-Frost et al. [31], Zhe and Modi [32] and the numerical results of others found in the literatures.

Section 2 describes the numerical methodology including the governing equations, turbulence models, numerical setup, the grid independence and the effect of turbulent intensity. Section 3 reports the two cases with nozzle-plate spacing of 4 and 9.2 including heat transfer, the mean velocity profiles, the skin friction and the law of wall in Reynolds number of 20,000 for the turbulent slot confined impinging jets. The effect of Reynolds number is also reported in Section 3. Finally, the main findings and conclusions are presented in Section 4.

2. Numerical methodology

2.1. Governing equations

The RANS governing equations include the conservation of mass, momentum, and energy which are given as: