NUMERICAL STUDY OF THE TURBULENT SLOT JET IMPINGEMENT HEAT TRANSFER USING THE MODIFIED SST K-W MODEL BASED ON OPENFOAM

HUAKUN HUANG[1], GUIYONG ZHANG[1,2,3*], ZHI ZONG[1,2,3]

[1]*Liaoning Engineering Laboratory for Deep-Sea Floating Structures, School of Naval Architecture, Dalian University of Technology, huanghuakun@mail.dlut.edu.cn*

[2]*State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, gyzhang@dlut.edu.cn*

[3]*Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, zongzhi@dlut.edu.cn*

***Keywords*:** jet impingement, heat transfer, Nusselt number, transition, modified SST *k-ω* model

Abstract: Jet impingement heat transfer has been applied in many industry fields due to its high heat and mass transfer rate. A numerical simulation about the turbulent slot steady jets has been carried out using the modified SST- *k-ω* model based on OpenFOAM. The cases studied are of nozzle-plate spacing of 4 and 9.2, respectively, and the Reynolds number is 20,000. The modified SST *k-ω* turbulence model is constructed based on the Kato-Launder mode. To test the modified SST *k-ω* model's validation for jet impingement, the velocity profiles, skin friction and Nusselt number distribution are investigated in detail. By comparing with both experimental data and other numerical results, the good agreement between the present model and the experimental data has indicated the model's ability for predicting the transition in slot impinging jets.

1 Introduction

The SST *k-ω* model proposed by Menter [1] which blends the standard *k-ε* model and *k-ω* model is very popular in many applications. However, the complex impinging jet flows are also challenges for various turbulence models, due to the complex phenomena including the vortex developing, separation and high adverse pressure gradient [2, 3]. For a typical impinging jet, there are a dip and second peak of the Nusselt number along the impinging plane at low nozzle-plate spacing ($H/B \leq 4$), which disappear at high nozzle-plate spacing. This phenomenon is affected by the laminar to turbulence transition [2]. Thus, the turbulence models with the ability of predicting the transition have been carried out to investigate the jet impingement problems in recent years [3-5]. Based on earlier studies, the SST *k-ω* model has been recommended due to its appropriate performances [6]. And the SST *k-ω* model has been used in many studies, which shows good performances in jet impingements [7-10]. However, the SST *k-ω* model predicted the second peak and dip of Nusselt number earlier than the experiment and provided a false secondary peak of the Nusselt number at high nozzle-plate spacing [3, 11]. These findings imply that there is not a single turbulence model which shows best for different conditions, which leads to the importance of studying the new modifications using the same framework to assess their relative performances.

The work of this paper modifies the SST *k-ω* model based on the Kato-Launder model to the available reference data [3, 12-14] for different nozzle-plate spacing of 4 and 9.2. The Kato-Launder modification has been succeeded in improving the flow structures not only in the stagnation region but also in the wall jet region [15]. Various comparisons against the experimental data and numerical results in terms of velocity profiles, skin friction and Nusselt number distribution are presented in this work.

Section 2 describes the modified work for SST *k-ω* model. Section 3 shows the results of the velocity profiles, skin friction and Nusselt Number distribution. Section 4 presents the conclusions draw from the present study.

2 The modified SST *k-ω* model

The modifications based on the Kato-Launder model are carried out using the open software OpenFOAM platform to ensure the codes' accuracy and robustness. The eddy viscosity for modified SST *k-ω* model is defined as:

$$\mu_t = a_1 k \frac{1}{\max\left(a_1\omega, b_1\sqrt{S}F_2\right)} \tag{1}$$

where a_1 is 0.31, b_1 is 1.0, k is the turbulent kinetic energy, ω is the specific dissipation rate, S is the strain rate and F_2 is the blending function.

The equation k and ω are modified as following:

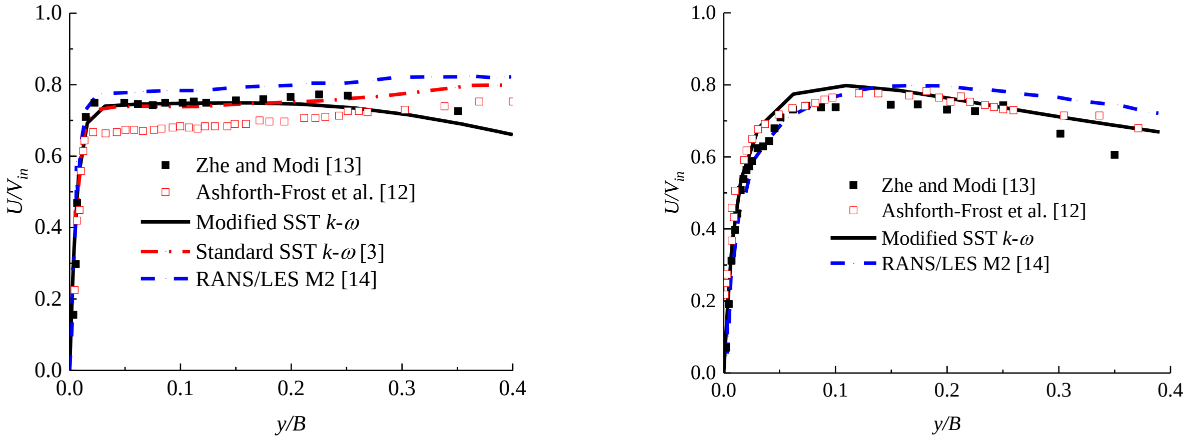
$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \min\left(P_k, 10\beta^* k\omega\right) - \beta^* k\omega + \frac{\partial}{\partial x_j}\left[\left(\mu + \sigma_k \mu_t\right)\frac{\partial k}{\partial x_j}\right] \tag{2}$$

$$\frac{\partial \omega}{\partial t}+U_i\frac{\partial \omega}{\partial x_i}=\alpha\frac{\omega}{k}\min\left(Gu,\frac{c_1\beta^*\omega}{a_1}\max\left(a_1\omega,b_1F_{23}\sqrt{S}\right)\right)$$
$$-\beta\omega^2+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\omega}\right)\frac{\partial \omega}{\partial x_j}\right]+2\left(1-F_1\right)\frac{\sigma_{\omega 2}}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \tag{3}$$

where $P_k = 2S\Omega$, Ω is the vorticity rate, β_0^* is 0.09, $Gu=\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij}$, $\beta^* = 0.09$.

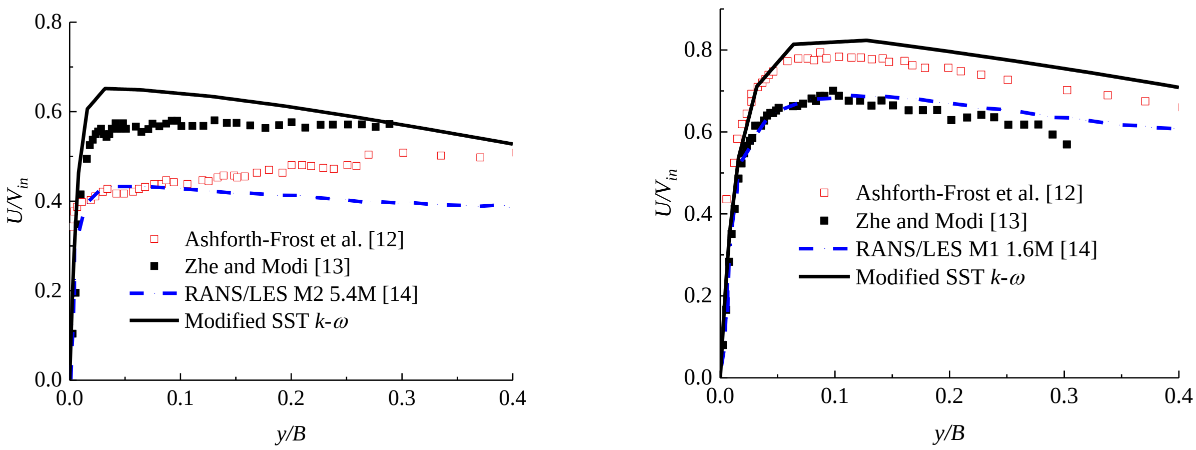
3 Results and discussion

3.1 The velocity profiles



(a) x/B=1 (b) x/B=7

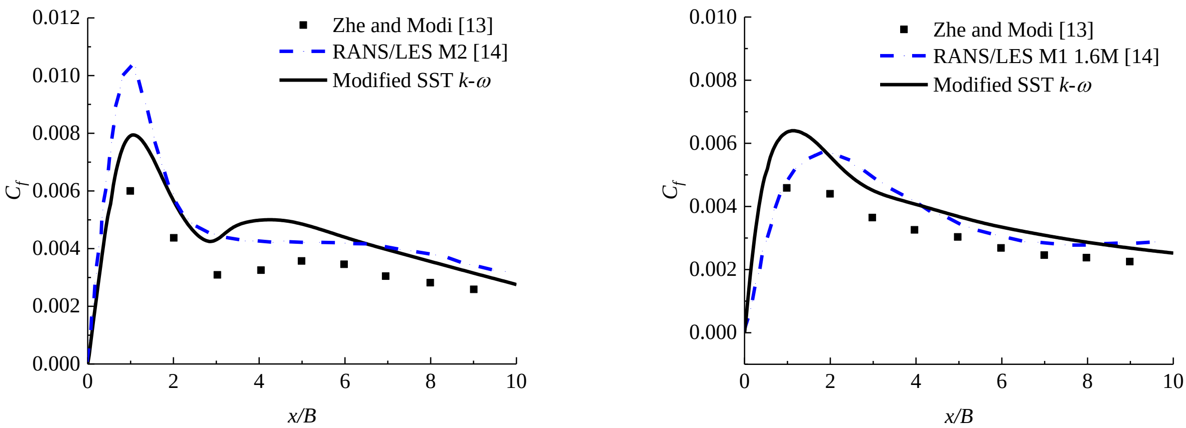
Figure 1. The comparison of velocity profiles against the experimental data and numerical results for H/B = 4



(a) x/B = 1 (b) x/B = 5

Figure 2. The comparison of velocity profiles against the experimental data and numerical results for H/B = 9.2

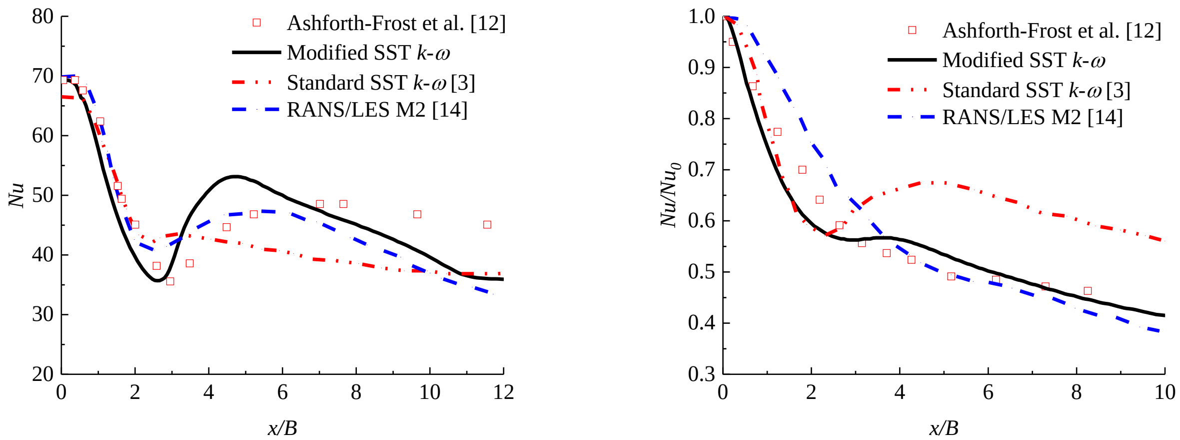
3.2 The skin friction



(a) *H/B* = 4 (b) *H/B* = 9.2

Figure 3. The comparison of skin friction against the experimental data and numerical results

3.3 The Nusselt Number distribution



(a) *H/B* = 4 (b) *H/B* = 9.2

Figure 2. The comparison of Nusselt Number against the experimental data and numerical results

4 Conclusions

The modified SST *k-ω* model has been assessed in this work for turbulent slot impinging jet with two different nozzle-plate spacing of 4 and 9.2. The results are compared with the standard SST *k-ω* model, the RANS/LES model and the experimental data in terms of fluid structures including the velocity profiles, skin friction and Nusselt number distribution. It is observed that the modified SST *k-ω* model improves the ability of predicting the transition process and overcomes the false secondary peak of the Nusselt number at high nozzle-plate spacing (*H/B* = 9.2) which is predicted by the standard SST *k-ω* model. In general, the modified SST *k-ω* model provides fair performances using low computational resources comparing with the RANS/LES model.

Acknowledgements

Thanks all those involved in the organization of OFW13 and all the contributors that will enrich this event.

Reference

[1] F. R. Menter, "Two-equation eddy-viscosity turbulence models for engineering applications," *Aiaa Journal*, vol. 32, pp. 1598-1605, 1994.

[2] E. Khalaji, M. R. Nazari, and Z. Seifi, "2D numerical simulation of impinging jet to the flat surface by k-ω-v2-f turbulence model," *Heat and Mass Transfer*, vol. 52, pp. 127-140, 2015.

[3] R. Dutta, A. Dewan, and B. Srinivasan, "Comparison of various integration to wall (ITW) RANS models for predicting turbulent slot jet impingement heat transfer," *International Journal of Heat and Mass Transfer*, vol. 65, pp. 750-764, 2013.

[4] S. Alimohammadi, D. B. Murray, and T. Persoons, "Experimental Validation of a Computational Fluid Dynamics Methodology for Transitional Flow Heat Transfer Characteristics of a Steady Impinging Jet," *Journal of Heat Transfer*, vol. 136, p. 091703, 2014.

[5] S. Pramanik and M. K. Das, "Numerical characterization of a planar turbulent offset jet over an oblique wall," *Computers & Fluids*, vol. 77, pp. 36-55, 2013.

[6] N. Zuckerman and N. Lior, "Jet Impingement Heat Transfer: Physics, Correlations, and Numerical Modeling," vol. 39, pp. 565-631, 2006.

[7] J. Ortega-Casanova and S. I. Castillo-Sanchez, "On using axisymmetric turbulent impinging jets swirling as Burger's vortex for heat transfer applications. Single and multi-objective vortex parameters optimization," *Applied Thermal Engineering*, vol. 121, pp. 103-114, 2017.

[8] M. Papadrakakis, V. Papadopoulos, and G. Stefanou, "Uncertainty Quantification and Modelling og CFD Simulations of Swirling Turbulent Jet Created by A Rotating Pipe for Application to Heat Transfer from A

Heated Solid Flat Plate," presented at the Proceedings of the 1st International Conference on Uncertainty Quantification in Computational Sciences and Engineering, Crete, Greece, 2015.

[9] A. Dewan, R. Dutta, and B. Srinivasan, "Recent Trends in Computation of Turbulent Jet Impingement Heat Transfer," *Heat Transfer Engineering*, vol. 33, pp. 447-460, 2012.

[10] M. Wae-hayee, P. Tekasakul, S. Eiamsa-ard, and C. Nuntadusit, "Effect of cross-flow velocity on flow and heat transfer characteristics of impinging jet with low jet-to-plate distance," *Journal of Mechanical Science and Technology*, vol. 28, pp. 2909-2917, 2014.

[11] M. A. R. Sharif and K. K. Mothe, "Evaluation of Turbulence Models in the Prediction of Heat Transfer Due to Slot Jet Impingement on Plane and Concave Surfaces," *Numerical Heat Transfer, Part B: Fundamentals*, vol. 55, pp. 273-294, 2009.

[12] S. Ashforth-Frost, K. Jambunathan, and C. F. Whitney, "Velocity and Turbulence Characteristics of a Semiconfined Orthogonally Impinging Slot Jet," *Experimental Thermal and Fluid Science*, vol. 14, pp. 60-67, 1997.

[13] J. Zhe and V. Modi, "Near Wall Measurements for a Turbulent Impinging Slot Jet " *Journal of Fluids Engineering*, vol. 123, pp. 112-120, 2000.

[14] S. Kubacki and E. Dick, "Simulation of plane impinging jets with k–ω based hybrid RANS/LES models," *International Journal of Heat and Fluid Flow*, vol. 31, pp. 862-878, 2010.

[15] J. Wienand, A. Riedelsheimer, and B. Weigand, "Numerical study of a turbulent impinging jet for different jet-to-plate distances using two-equation turbulence models," *European Journal of Mechanics - B/Fluids*, vol. 61, pp. 210-217, 2017.