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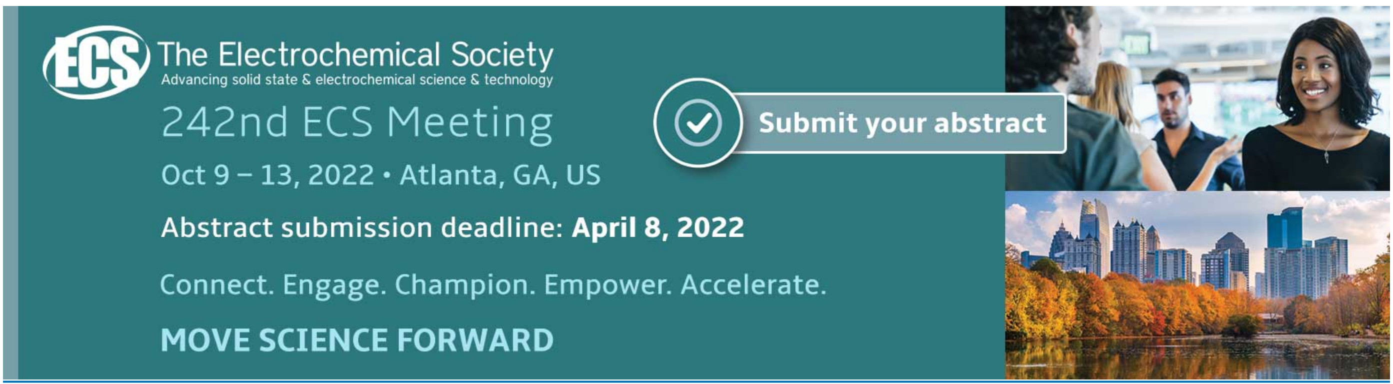

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RANS numerical simulation in in-line tube bundle: prediction of heat transfer

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Abstraction. This article analyzed three RANS turbulence models to predict heat transfer in a in-line tube bundle. The numerical simulations were based on the commercial product AnsysFluent. The RNG k-epsilon model with enhanced wall function, SST, SST k-omega models were employed for turbulence modeling. Numerical simulation was carried out in the range of Reynolds numbers from 1000 to 10200. The obtained data on heat transfer were compared with the known empirical equation. The best agreement with experimental data over the entire studied range of the Reynolds number was obtained for the RNG k-epsilon model with enhanced wall function. The average deviation from experimental data was 6.3%.

1. Introduction

The flow in tube bundles and in the flow around a single-cylinder is a classical problem. Tube bundles are the main element of tubular heat exchangers. Tubular heat exchangers are used in the fuel and energy complex, in the petrochemical industry in power equipment, etc. There is a huge amount of work has been devoted to the flow in tube bundles. Extensive experimental studies have been carried out by Zukauskas [1]. Zukauskas presents empirical heat transfer equations to predict heat transfer in tube bundles of various configurations and a wide range of Reynolds and Prandtl numbers. With the development of experimental techniques, works with the analysis of flow characteristics in tube bundles began to appear [2,3]. A detailed study of both flow characteristics and heat transfer became easier with the development of numerical methods. The Direct Numerical Simulations (DES) [4], Large Eddy simulations (LES) [5] provide reasonably accurate data on flow characteristics and heat transfer in tube bundles. However, DES and LES are computationally expensive. The Reynolds Averaged Navier – Stokes (RANS) [6-8] methods are less accurate, but they do not require large computational costs. Various RANS turbulence models are used both for simulation flow characteristics and predicting heat transfer in tube bundles. The accuracy of RANS turbulence models in predicting flow and heat transfer characteristics in tube bundles depends on the flow regime and the tube bundle configuration. In engineering applications, the flow in tube bundles is in a wider range of Reynolds numbers. Also, in practice, there is a large number of configurations of tube bundles [9]. Therefore, there is no universal RANS turbulence model.

This article investigates heat transfer in a close in-line tube bundle with various RANS turbulence models. Reynolds numbers are in the range from 1000 to 10200. In the previous articles of the authors, heat transfer in an in-line and staggered tube bundle was investigated in the range of Reynolds numbers from 3020 to 6040 [10, 11]. In these studies [10-11], only the heat transfer of the central

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cylinder in the tube bundle was investigated. However, the heat transfer of a tube bundle depends on the number of tube rows [1]. This article will analyze the effect of a number of tube bundle tubes on heat transfer.

2. Details of the numerical simulation

The physical formulation of the model is presented in (figure 1). The geometry of the computational domain was a rectangular channel with a seven-row tube bundle. The geometric parameters of the model are presented in table 1. The flow in the tube bundle is assumed to be two-dimensional. Gravity is ignored. The fluid flow is incompressible. The velocity at the inlet to the tube bundle was calculated as a function of the Reynolds number. The Reynolds number was calculated from the tube diameter and gap velocity. The degree of turbulence at the inlet corresponded to 0.1%. The temperature of the tubes was equal to 301 K. The temperature of the liquid flow at the inlet corresponded to 300 K. Water was chosen as the working fluid. The heat capacity of the water was 4176.3 J/kg ·K, the dynamic viscosity $8.5 \cdot 10^{-4}$ Pa · s, the thermal conductivity 0.612 W/m · °K, the density 996.5 kg/m^3.

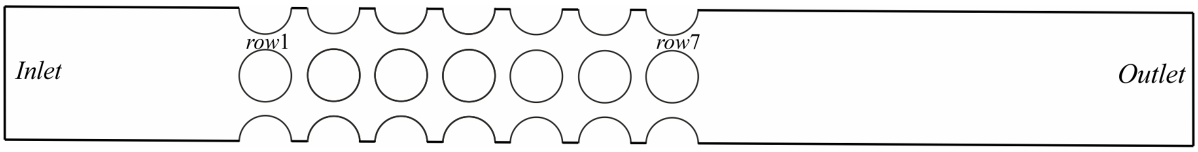

Figure 1. Physical model.

Table 1. Geometrical parameters of physical model.

Geometrical parameters	Value
Length of the inlet section, mm	50
Length of the outlet section, mm	100
Diameter of the cylinder *D*, mm	10
Distance between the tubes centers in longitudinal direction, mm	13
Distance between the tubes centers in transverse direction, mm	13

The fluid flow in the tube bundle was calculated based on RANS turbulence models. For research purposes, three RANS turbulence models were employed. The RANS models tested in this study are: RNG k-ε model with enhanced wall function (RNG k-ε EWF), transition shear stress transport model (SST), SST k-ω model (SST k-ω). The commercial product AnsysFluent was employed for numerical simulation. The SIMPLE algorithm with a steady solver was used in the numerical simulation. Five different grids were constructed to mesh validation. The table 2 shows the number of layers in the near-wall zone of the tubes N_l; mesh size in the tube bundle y/D; the minimum mesh size of the first layer on the tube walls r_{min}/D; expansion coefficient of the grid in the radial direction from the tube wall e_f. With an increase in the number of grid elements from M2 to M5, the Nusselt number is almost unchanged (figure 2). Therefore, the M2 mesh with 96,899 elements was chosen for further modeling.

Table 2. Parameters of mesh by code.

Mesh code	r_{min}/D	y/D	e_f	N_l	Element number
M1	$1.7 \cdot 10^{-3}$	$2.7 \cdot 10^{-2}$			50,293
M2	$1.2 \cdot 10^{-3}$	$1.9 \cdot 10^{-2}$			96,899
M3	$8.3 \cdot 10^{-4}$	$1.3 \cdot 10^{-2}$	1.3	10	192,435
M4	$5.8 \cdot 10^{-4}$	$9.3 \cdot 10^{-3}$			155,349
M5	$4.1 \cdot 10^{-4}$	$6.6 \cdot 10^{-3}$			308,447

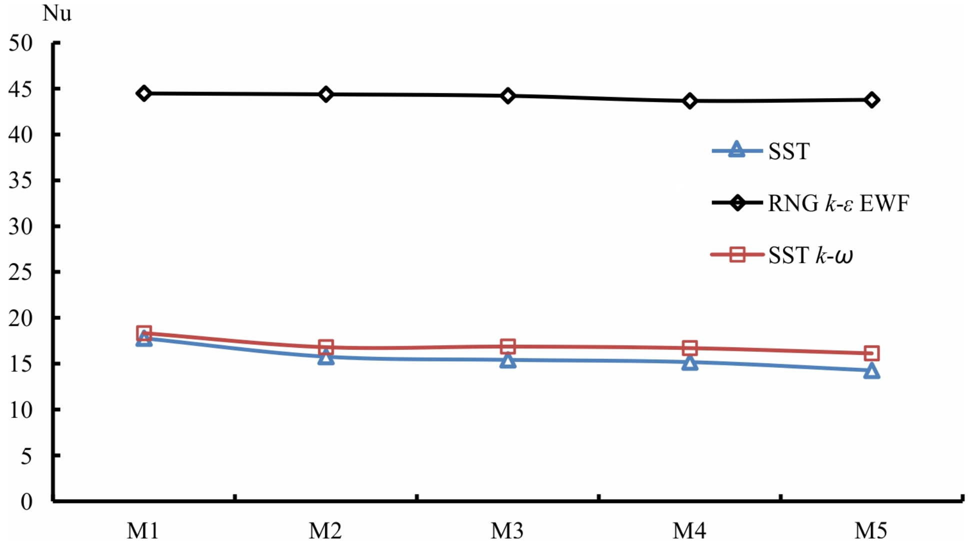

Figure 2. Grid independence test. Nusselt number of the six row at Re number 1000.

3. Results and discussion

Numerical modeling was carried out in the range of the Reynolds number from 1000 to 10200 with a step of 400. The obtained value of the Nusselt number was compared with the well-known empirical equation (1) presented in [1]

$$\mathrm{Nu} = 0.26\,\mathrm{Re}^{0.63}\,\mathrm{Pr}^{0.36}\,. \tag{1}$$

Figure 3 compares the numerical simulation data with the experimental data of Zukauskas calculated by equation (1). The best agreement with the experimental data was obtained using the RNG k-ε EWF model. The deviation of Nu values from equation (1) on average was about 6.3%. The maximum deviation of 17.3% was when the Re = 1400. When the SST model was employed, the mean deviation with equation (1) was 18.2%, the maximum deviation was 58.5% at Re = 1000. For the SST model, the solution was not stable at Re below 3400. With an increase in the Reynolds number SST the model better predicts heat transfer in the tube bundle; at Re = 10200, the deviation from equation (1) was 3.2%. When the SST k-ω model was employed, the average deviation with equation (1) was 19.1%, maximum 55.9% at Re = 1000.

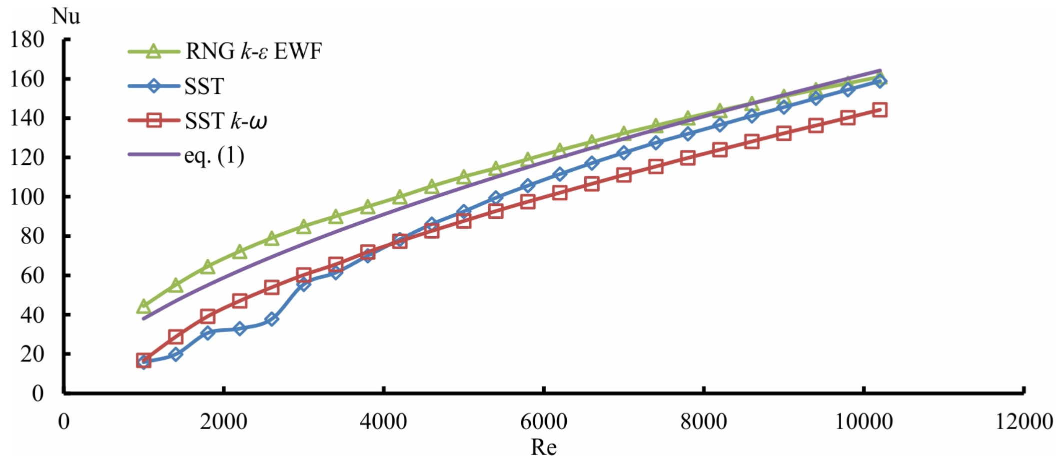

Figure 3. Variation Nusselt number of the six row with Reynolds number.

Figures 4-6 show the rate of heat transfer along the rows of a tube bundle with increasing Reynolds number for different turbulence models. As can be seen from figures 4-6, with an increase in the Reynolds number, the heat transfer increases for all rows of the bundle tubes, which indicates the adequacy of the numerical simulation. The dependence of the tube row on heat transfer is shown in figure 7. The effect of the tube row on heat transfer is different depending on the Reynolds number and the turbulence model. When the RNG k-ε EWF was employed, the heat transfer of the second row was always higher than the first row. With a further increase in the rows numbers (until seventh row), the heat transfer is almost unchanged. The heat transfer of the seventh row in the tube bundle is higher than the other rows, which is more significant with an increase in the Reynolds number. The increase in heat transfer in the second row is associated with an increase in the turbulence of the flow in the tube bundle. These data are consistent with the observations of Zukauskas [1]. The increase in heat transfer of the seventh row can be explained by the occurrence of vortex formation in the leeward side of the seventh cylinder. For the SST and SST k-ω models, similar results were obtained only for the maximum Reynolds numbers. As was found earlier at Reynolds numbers of 10200, the SST and SST k-ω models are in better agreement with the experimental data [1].

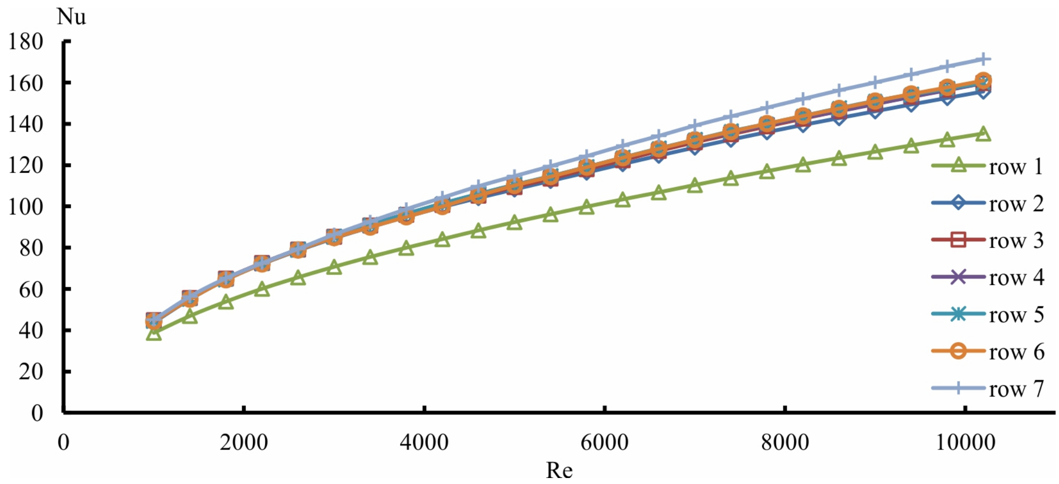

Figure 4. Variation Nusselt number with Reynolds number for RNG k-ε EWF model.

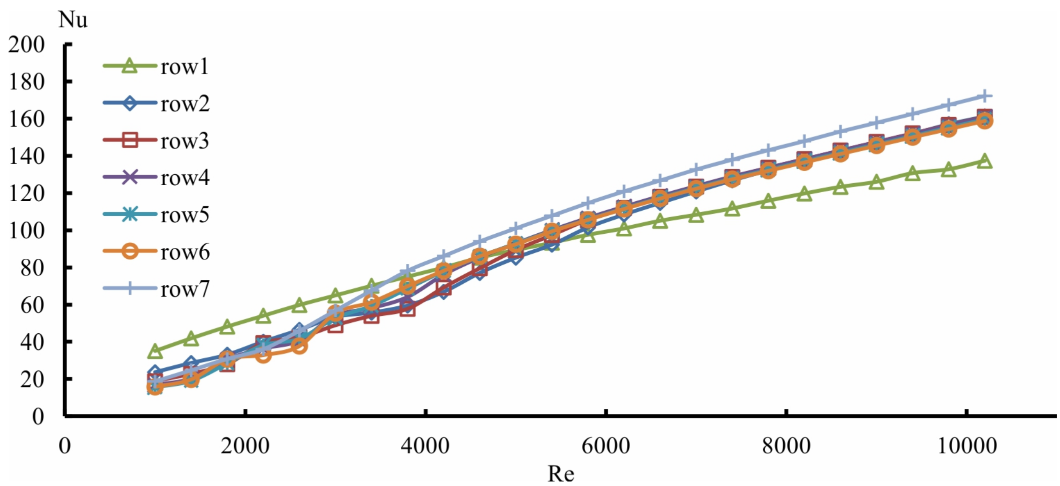

Figure 5. Variation Nusselt number with Reynolds number for SST model.

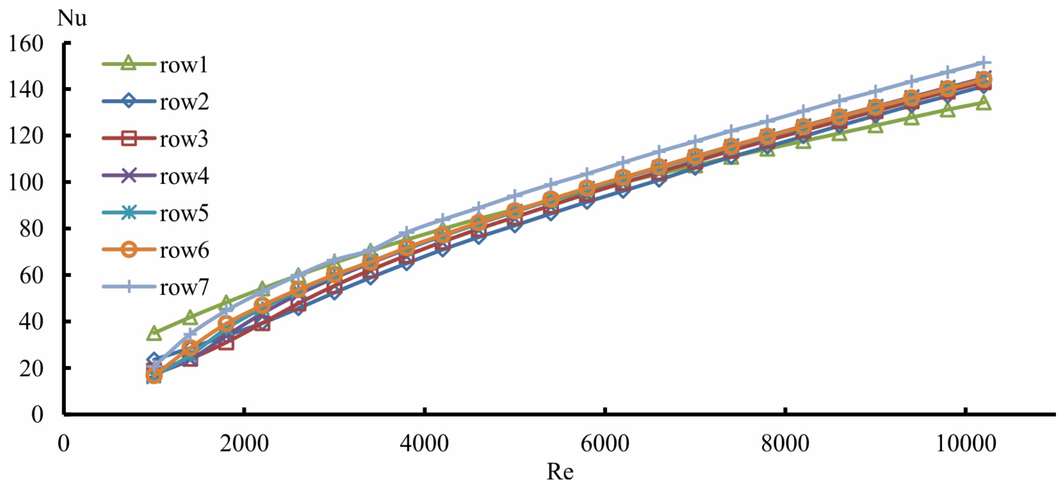

Figure 6. Variation Nusselt number with Reynolds number for SST k-ω model.

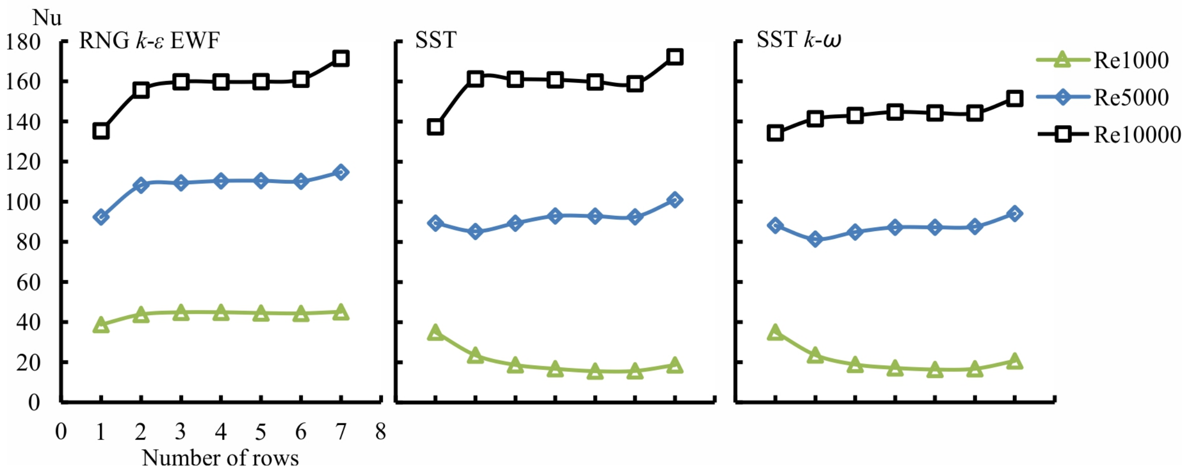

Figure 7. Variation Nusselt number with number of rows.

4. Conclusion

Heat transfer in a seven-row in-line bundle was studied numerically. Three different RANS models were used in the numerical simulations. Good agreement with experimental data was obtained for the RNG k-ε EWF model. The average deviation of the Nusselt number was 6.3% for the SST and SST k-ω models 18.2% and 19.1%. As the Reynolds number increases, the accuracy of the SST and SST k-ω models increases. At the maximum investigated Reynolds number of 10200, the deviation of the Nusselt number for the SST and SST k-models was 3.2% and 12.1%.

Acknowledgments

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