Large-Eddy Simulations of Heat Transfer in the Tube Bundle

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Abstract. The tubular heat exchangers are widespread in the oil industry, therefore, the numerical simulation of the flow around a tube bundle is important. In this article, the LES method is used to study heat transfer in a ten-row in-line tube bundle in cross-flow. LES Smagorinsky, LES WALE and LES WM techniques in the numerical simulation were used. The Reynolds number Re was 2400, and the Prandtl number Pr was 7.33. The streamwise spacing-to-diameter ratio of the tube bundle was 1.3, transverse was 2.6. The local heat transfer characteristics of the eighth row are compared with the experimental data. The best agreement with the experimental data was obtained using the LES WALE and LES WM techniques.

1. Introduction

Shell-and-tube heat exchangers are widely used in the oil industry [1]. The cross-flow in a tube bundle has been a classical problem for many decades. There is a large number of experimental [2-4] and theoretical works in this area. [5-8]. The papers last decades are mainly theoretical [9]. Computational fluid dynamics are widely used for numerical studies.

Direct Numerical Simulations (DNS) [10], Large Eddy simulations (LES) [11-14] and Reynolds Averaged Navier–Stokes (RANS) methods using for the numerical simulation flow in a tube bundle. The RANS models can significantly reduce the computational cost required for numerical simulation. The LES model provides more accurate results compared to RANS [15-18] models while requiring less computational cost than DNS. A variety of sub-grid-scale (SGS) models are used in LES simulation. However, SGS models can lead to different results depending on the application [19].

In this paper performed results of the heat transfer of the ten-row in-line tube bundle in cross-flow using LES Smagorinsky, LES WALE and LES WM technique.

2. Details of the numerical simulation

The computational domain of the in-line tube bundle used in this work is shown in figure 1. The inlet flow direction has coincided with the x-axis. The z-axis is parallel to the tubes of the bundle. The computational domain has 10 cylinders in the flow direction. The diameter of the tubes was 0.01 m. The streamwise (x-axis) spacing-to-diameter ratio of the tube bundle was $S_1/D = 1.3$, transverse (y-axis) was $S_2/D = 2.6$. The upstream and downstream length of the tube bundle was $5D$ and $12D$ respectively. The length in the spanwise (z-axis) direction was $1D$.

Details of the mesh of the two cylinders in the tube bundle are shown in figure 2. The number of mesh elements between two cylinders in streamwise direction was 40. The number of mesh elements along the periphery of the cylinders and spanwise directions was 160 and 8 respectively. The
expansion factor in the radial direction was 1.22. The smallest cell in the near-wall region was
\[
\Delta y_{min}/D = 8.1 \cdot 10^{-4},
\]
which similar to the mesh used in paper [20].

At the inlet to the computational domain, constant flow velocity \( u_x = 0.1543 \) m/s normal to the inlet boundary was used for the boundary condition. At the wall of tubes, zero velocity was used for the boundary condition. The temperature of the free-stream was 18.5 °C. Constant temperature 19.5 °C boundary condition was set at the central cylinders.

The calculations were provided with AnsysFluent [21]. The PISO algorithm was used for all calculations. The central differencing scheme was employed to discretize momentum equations. The time step was 0.005 s.

![Figure 1. Computational domain in the xy-plane.](image1)

![Figure 2. Details of the mesh.](image2)

3. Results and discussion
Numerical simulation was performed at the Reynolds number \( \text{Re} = 2400 \). Water was used as the working fluid. The thermophysical properties of water were constant. Prandtl number \( \text{Pr} = 7.33 \). The total calculation time was 16 s. The local value of heat transfer for each tube has averaged over the cylinder surface in spanwise direction and over a period of time \( t = [8; 16, 22] \) s. Figure 3 shows the instantaneous values of the Nusselt number averaged over the surface in spanwise direction of the eighth cylinder in the tube bundle for three different LES techniques.
In Figure 4, the time-averaged local spanwise-averaged Nusselt number of the eighth cylinder for three different LES techniques are compared with the experimental data [2]. LES WALE and LES WM give better agreement with experimental data. LES Smagorinsky give a good prediction of heat transfer in the vortex formation zone at $\phi > 100^\circ$, but overestimates the heat transfer in the front of the cylinder. The maximum heat transfer for LES WALE and LES WM is observed at $\phi$ about 45°, which corresponds to the maximum collision of the fluid flow with the cylinder in the in-line tube bundle. The maximum heat transfer for LES Smagorinsky is observed at $\phi$ about 25° and 70°, while in the zone $\phi$ of about 45° a decrease in heat transfer occurs.

Figure 5 shows the local values of the time-averaged local spanwise-averaged Nusselt number for the remaining cylinders in the tube bundle. The heat transfer around all cylinders the same for LES WALE and LES WM technique. The heat transfer around all the cylinders is the same for the results obtained with the LES Smagorinsky, LES WALE and LES WM at the back of the cylinder and leads to different results in the front of the cylinder.
Figure 5. Time-averaged local spanwise-averaged Nusselt number around 1-7, 9, 10 cylinders.

Figure 6. Variation the time and space average d Nusselt with a row of cylinders.

The Nusselt number averaged over the entire cylinder surface depending on the cylinder row in the tube bundle is shown in figure 6. With an increase in the number of rows (from the second to the ninth
row), an increase in heat transfer occurs for all LES techniques. An increase in heat transfer with an increase in the number of rows is also noted in the work [2]. The deviations of the Nusselt number for the eighth cylinder with experimental data were 28.5%, 7.1%, 2.2% for the LES Smagorinsky, LES WALE and LES WM techniques, respectively.

Instantaneous temperature contours for the time $t = 10$ s are shown in figure 7. For all LES techniques behind the cylinders, unsteady flow and vortex formation are observed. Vortex formation is more pronounced with the LES Smagorinsky technique, which leads to higher heat transfer values (Figure 3).

![Instantaneous temperature contour for $t = 10$ s.](image)

*Figure 7.* Instantaneous temperature contour for $t = 10$ s.
4. Conclusion

In this paper, the results on heat transfer in a ten-row in-line tube bundle using LES Smagorinsky, LES WALE and LES WM techniques were obtained. Local characteristics of heat transfer are compared with experimental data. LES Smagorinsky better predicts heat transfer in the vortex formation zone at $\varphi > 100^\circ$, but overestimates the heat transfer in the front of the cylinder. LES WALE and LES WM techniques are in good agreement with experimental data. The deviations of the Nusselt number of the eighth cylinder with experimental data were 28.5%, 7.1%, 2.2% for LES Smagorinsky, LES WALE and LES WM technology, respectively.

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