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The research on coherent structure in 7-rod bundle lattice

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ABSTRACT

The generation and development of coherent structure in 7-rod bundle lattice are researched by Unsteady Reynolds-Averaged Navier-Stokes (URANS) method with the Reynolds Stress Model (RSM). The influence of the coherent structure on the flow resistance and heat transfer coefficient is also analyzed. It is revealed that the coherent structure is helpful to improve the performance of lattice. Decreasing the pitch-to-diameter (*P/D*) or properly changing the shape of rod can contribute to the generation of coherent structure. The flow redistribution caused by corner channel has great influence to the coherent structure.

1. Introduction

The sub-channel analytic method has been proverbially employed in the coherent structure numerical simulation (Mayer and Házi, 2006; Horváth and Dressel, 2012). It was assumed that the lattice is infinite in this method, such as reactor and steam generator, in which the influence of wall channel to center channel can be ignored. However, there are lots of little lattice in engineering application, such as heat exchanger. The flow and heat transfer characteristics of corner channel will be greatly affected by wall channel in little lattice. The entire-channel should be modeled if the coherent structure is simulated in little lattice.

The classic little lattices in experimental researches included rectangular channel containing a cylindrical rod (Guellouz and Tavoularis, 2000), 3-rod bundle with triangular arrangement (Silin and Juanicó, 2006), rectangular channel with 4 rods (Rehme, 1978) and 7-rod bundle with triangular arrangement (Cheng and Yu, 2009). In these experiments, the number and arrangement of rods were related to the focuses of studies, for instance, the rectangular channel containing a cylindrical rod had an advantage of recording the transverse flow in gap region and rectangular channel with 4 rods was helpful to study flow and heat transfer characteristics in wall channels. The influence between center channel and wall channel was specially paid attention in this work, so the 7-rod bundle lattice with triangular arrangement was chosen as the research object.

In the numerical researches, there were few cases to simulate the entire bundle for the limitations of computational source and algorithm structure. In the new century, the development of computer science and the optimization of algorithm structure make it possible of simulating the entire bundle. This method has been applied to study the influences of helical wire-wrapped fuel pin and spacer (Gajapathy et al., 2009; Podila et al., 2014). In the flow direction, the periodic boundary conditions were employed to shorten the length of computational domain. It was proved that the coherent structure could be simulated under this setting, however, the Strouhal number would be overestimated and the turbulent momentum would be underestimated (Chang and Tavoularis, 2012). In order to remove the error introduced by periodic boundary conditions and reveal the evolution process of coherent structure, the entire channel in which the coherent structure could achieve stabilization was simulated. The generation, development and stabilization processes of coherent structure were totally presented in this work.

2. Computational procedures

2.1. Geometry

The 7-rod bundle with triangular arrangement was chosen which contains the center channel, the wall channel and the corner channel in this work. Thus the influences of the different channels on the coherent structure could be studied. The computational domain was divided into two segments in flow direction, the entrance segment and the heated segment, as shown in Fig. 1a. The entrance segment could remove the influence of entrancement

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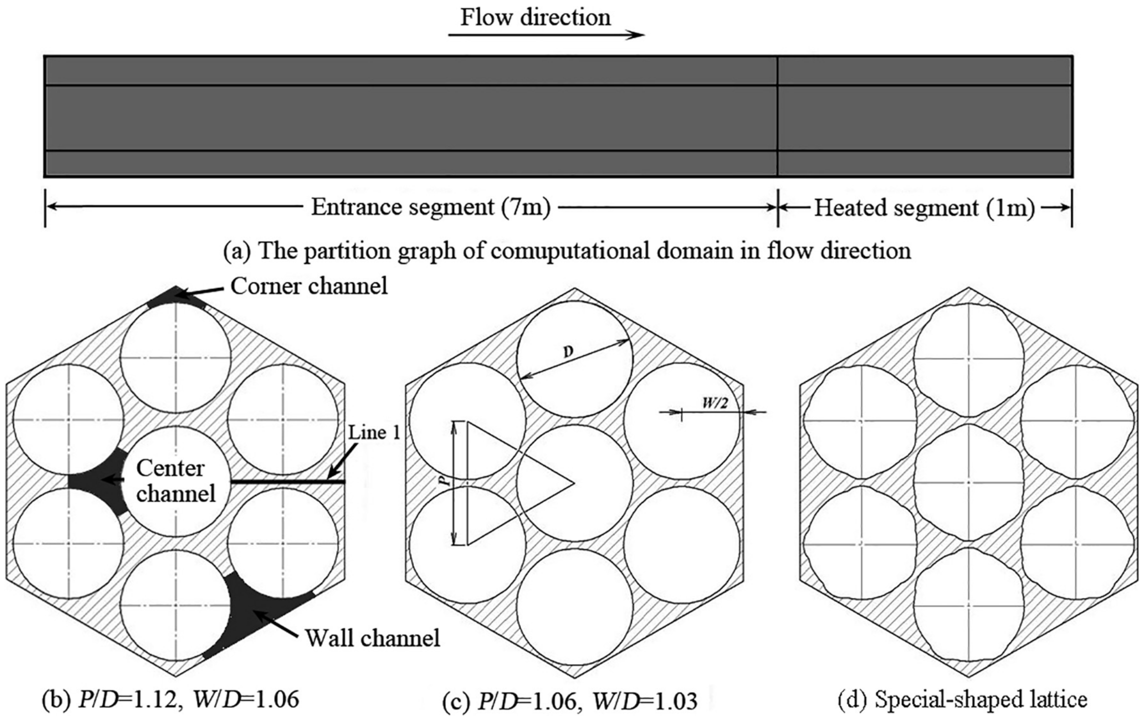

Fig. 1. The schematic diagram of 7-rod bundle computational domain.

to the fluid flow in heated segment. The flow and heat transfer characteristics in heated segment were mainly studied as the performance of lattice. For the turbulent flow in circular tube, 25–40 times hydraulic diameter lengths were required form the entrancement to the flow was fully developed (Todereas and Kazimi, 1990). However, it was revealed that the development of coherent structure was lagging behind the main flow, which means the length of coherent structure developing to stabilization is greater than the length of main flow developing to stabilization (Chang and Tavoularis, 2012). Ensuring the flow and coherent structure reach the fully developed status in heated segment, the length entrance segment is specified as 7 m, which is longer than the 4.6 m length specified in Krauss and Meyer's (1998) experiment. Three types of 7-rod bundle lattice were studied, which included two traditional lattices and one special-shaped lattice (Xiao et al., 2013).

Fig. 1b–d show the cross sections of three 7-rod bundle lattices, the pitch-to-diameter (P/D) and wall-to-diameter (W/D) ratios of former two lattices are $P/D = 1.12$, $W/D = 1.06$ and $P/D = 1.06$, $W/D = 1.03$, respectively. In the special-shaped lattice, the center rod was uniformly arranged six local thickening walls. The outer-ring rods were arranged five local thickening walls distributed in the gap regions of rod-rod and rod-wall. The thickening parameter was decided by the vertex height (e). Table 1 enumerates the detailed geometry and flow parameters in numerical simulations. The hydraulic diameter (D_{ht}) in the table is the total hydraulic diameter considering all of the channels. The Reynolds number (Re_t) is computed by the total hydraulic diameter. The heat flux is same with the experiment setting (Krauss and Meyer, 1998).

2.2. Mesh

After analyzing the geometric construction characters, the mesh was generated based on structured grid method. The minimum geometry element and the topological structure were shown in Fig. 2. It can be found that one sixth bundle is split as the minimum geometry element. The parameters of mesh were setting in flow, wall circumferential and wall vertical directions. The y^+ of the first layer grid could be ensured<1 for there was no complex structures on the wall.

The lattice with $P/D = 1.12$, $W/D = 1.06$ was specified as the analysis object in order to test the grid independence. The flow condition was $Re_t = 64590$. Three different detail levels mesh were generated, shown in Fig. 3. Three meshes had same sizes in the flow direction, which about 0.071D. This size was smaller than that in Chang and Tavoularis's (2012) numerical simulations. In the wall circumferential direction, the maximum sizes of grid were 0.046D, 0.036D and 0.030D, respectively. In the wall vertical direction, the maximum sizes of grid were 0.079D, 0.058D and 0.048D, respectively. The total hexahedron grid numbers of three meshes were 8550818, 11209278 and 15287738, respectively.

Fig. 4 shows the results of the grid independence test. The distribution curves of velocity and temperature on the outlet plane were derived along the line 1 (shown in Fig. 1b). It must be declared that the result simulated by refined mesh could not replace the experimental data. But it was accepted that the mesh was finer, the result was more precise. The reason for that was the truncation error was reduced. It could be found that both the

Table 1
Geometry and flow parameters of 7-rod bundles.

P/D	W/D	e/D	D/mm	Re_t	D_{ht}/mm	$U_b/(m \cdot s^{-1})$	$q_w(kw/m^2)$
1.12	1.06	0	140	15000–85000	57.97	5.12–29.01	1.39
1.06	1.03	0	140	15000–85000	42.80	3.78–21.42	0.98
1.12	1.06	0.03	140	15000–85000	54.23	4.04–22.90	1.39