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Advances in Engineering Software 39 (2008) 407–415
ADVANCES IN ENGINEERING SOFTWARE
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Unstructured grid and unstructured grid porous methods for numerical analysis of TACR moderator calandria

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Received 15 May 2006; received in revised form 4 March 2007; accepted 13 March 2007
Available online 25 May 2007

Abstract

In the design of the Thorium-based Advanced CANDU Reactor (TACR), the moderator system is used to remove the moderator heat in normal operations and to remove the residual heat in accidents. The numerical methods to analyze the heat transfer in the moderator calandria are required. In this paper, the moderator calandria is analyzed by using two types of numerical methods, an unstructured grid method and an unstructured grid porous method. Both methods use collocated unstructured grids and a new average filter method to eliminate the non-physical checkerboard pressure. The unstructured grid porous method introduces the porous method to consider the large tube bundles in the calandria. It is concluded that both methods are effective to analyze the thermal performance in the TACR calandria. Four different designs of the calandria are analyzed and are compared.

Keywords: Unstructured grid; Porous method; Thorium; CANDU; Moderator calandria

1. Introduction

The Thorium-based Advanced CANDU Reactor (TACR) is designed based on the CANDU heavy water reactor, especially the NG CANDU heavy water reactor, which was called the Thorium-based Advanced Nuclear Energy System (TANES) in the preliminary work [1]. Similar to other CANDU reactors, the TACR has a large moderator calandria. The cross section of a typical moderator calandria is shown in Fig. 1. The vessel is cylindrical, with large square-arranged tube bundles inside. The moderator flows into the calandria through the inlet nozzle, goes through the tube bundles and then flows out of the calandria from the outlet nozzle.

In designs of the TACR, the moderator calandria with the heavy water inside play roles not only as a part of the moderator system, but also as a residual heat removal system during the loss-of-coolant accident in which the normal and the emergency core cooling systems are both lost simultaneously. All tubes in the calandria contain double layers, an internal pressure tube (PT) and an external calandria tube (CT). While in accidents, the PT and the CT may contact with each other and the heat inside the PT transfers into the moderator. The moderator temperature distribution in the normal condition is important for the prediction of the location of the contact between the PT and the CT. For this reason and in order to achieve a better design of the moderator system, an accurate analysis on parameter distributions in the calandria and a study of the corresponding numerical methods are required.

Several numerical analyses have been carried out to simulate the thermal performance in the moderator calandria of the CANDU reactors. The difficulties primarily lie in the description of the complex geometry of the tube bundles. The moderator system of the CANDU6 was simulated by Fath and Hussein [2] based on a two-dimensional incompressible laminar model. The circular pressure tubes were assumed equivalently to be square in order to use coarse square grids, stepped grids were used to consider the circular boundary of the calandria and the turbu-

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doi:10.1016/j.advengsoft.2007.03.007

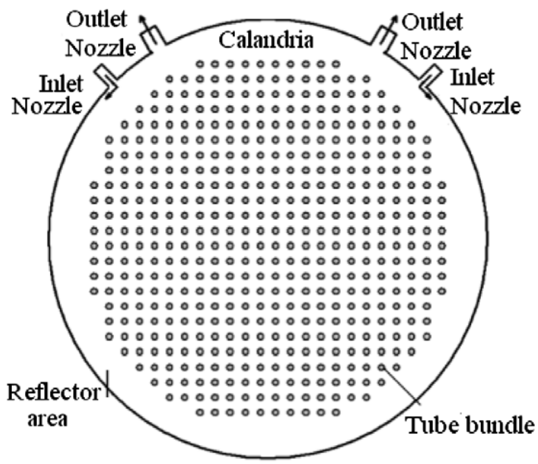

Fig. 1. Typical moderator calandria.

lence effect was neglected. Yoon et al. [3] investigated the temperature distribution in the CANDU6 calandria by experiments and also by numerical calculations with CFX4.3. In their numerical method, an incompressible model and the standard k–ε turbulence model were used. The cylindrical coordinate was employed to satisfy the calandria boundary and the porous media approach was employed to consider the effect of the PT bundles. It was difficult to get exact porous parameters such as the volume-porosity, the surface-permeability, the distributed resistance and the distributed heat source, because the grids were cylindrical arranged and the bundles were arranged in square lattices. Thus, the average and uniform porous parameters were used approximately. AECL developed a code MODTURC-CLAS to calculate CANDU moderator system [4]. The CANDU9 was investigated two-dimensionally by this code and the numerical results are compared with the experimental results. The porous media method with the approximate average porous parameters was also used to simulate the flow and heat transfer in the cross section of the moderator calandria.

In recent years, with the development of computer techniques, more and more elaborate numerical methods are introduced into the simulations of various engineering problems. In order to describe the flow and heat transfer in complex geometries especially in rod bundles, the porous media approach [5], the body-fitted curvilinear coordinate, the structured grid with composite techniques and various unstructured grid methods have been more and more proposed.

In this paper, the two-dimensional flow and heat transfer in the moderator calandria of the CANDU reactors in the normal condition are investigated numerically, using two types of numerical methods, the unstructured grid method and the unstructured grid porous method. Both methods use the collocated grids and a new average filter method (AFM) to eliminate the non-physical checkerboard pressure. In the unstructured grid porous method, the porous media approach with exact porous parameters is used to treat the tube bundles and the unstructured grids are utilized to give accurate boundary conditions. Four different designs of the locations of the inlet nozzle and the outlet nozzle of the moderator calandria are calculated using the unstructured grid method, and the results are compared to get the proper choices for certain design purposes.

2. Governing equations

The moderator calandria is located horizontally. The bulk flow of the moderator in the calandria is almost within the cross section, so that two-dimensional incompressible governing equations based on the conservation laws of mass, momentum and energy, the boussinesq approximation to consider the buoyancy of the mixed convection and the standard k–ε turbulence model are used.

The conservation equations are

$$
\begin{aligned}
&\frac{\partial}{\partial x}(\rho u)+\frac{\partial}{\partial y}(\rho v)=0\\
&\rho\frac{\partial}{\partial x}(uu)+\rho\frac{\partial}{\partial y}(vu)=-\frac{\partial p}{\partial x}+(\mu+\mu_t)\frac{\partial}{\partial x}\left(2\frac{\partial u}{\partial x}\right)\\
&\qquad+(\mu+\mu_t)\frac{\partial}{\partial y}\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)\\
&\rho\frac{\partial}{\partial x}(uv)+\rho\frac{\partial}{\partial y}(vv)=-\frac{\partial p}{\partial y}+\rho g\beta(T-T_0)\\
&\qquad+(\mu+\mu_t)\frac{\partial}{\partial x}\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)+(\mu+\mu_t)\frac{\partial}{\partial y}\left(2\frac{\partial v}{\partial y}\right)\\
&\rho\frac{\partial}{\partial x}(uh)+\rho\frac{\partial}{\partial y}(vh)=(\lambda+\lambda_t)\frac{\partial}{\partial x}\left(\frac{\partial T}{\partial x}\right)+(\lambda+\lambda_t)\frac{\partial}{\partial y}\left(\frac{\partial T}{\partial y}\right)+q_h
\end{aligned}
\tag{1}
$$

where u and v are the velocities of the directions x and y; p is the pressure; ρ is the density; μ is the viscosity; β is the thermal expansion coefficient; T is the temperature and T_0 is the reference temperature; h is the enthalpy; q_h is the heat source; λ is the thermal conductivity; the subscript t represents the turbulence.

k and ε equations are

$$
\begin{aligned}
&\rho\frac{\partial uk}{\partial x}+\rho\frac{\partial vk}{\partial y}=P_k-\rho\varepsilon+\frac{\partial}{\partial x}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x}\right]\\
&\qquad+\frac{\partial}{\partial y}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial y}\right]\\
&\rho\frac{\partial u\varepsilon}{\partial x}+\rho\frac{\partial v\varepsilon}{\partial y}=(c_{1\varepsilon}P_k-c_{2\varepsilon}\rho\varepsilon)\frac{\varepsilon}{k}+\frac{\partial}{\partial x}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x}\right]\\
&\qquad+\frac{\partial}{\partial y}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial y}\right]\\
&P_k=\mu_t\left[2\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2+2\left(\frac{\partial v}{\partial y}\right)^2\right]
\end{aligned}
\tag{2}
$$

where $c_\mu=0.09$, $c_{1\varepsilon}=1.44$, $c_{2\varepsilon}=1.92$, $\sigma_T=1.0$, $\sigma_k=1.0$, $\sigma_\varepsilon=1.3$.

As in Fig. 1, the moderator calandria is symmetrical along the central line, so half part of the calandria is considered.

Boundary conditions are

(1) Inlet condition:

$$u = u_{\text{in}}, \quad v = v_{\text{in}}, \quad h = h_{\text{in}}$$
$$k_{\text{in}} = 0.005\left[\frac{1}{2}(u_{\text{in}}^2 + v_{\text{in}}^2)\right] \tag{3}$$
$$\varepsilon_{\text{in}} = C_\mu^{3/4} k_{\text{in}}^{3/2}/(0.07L_{\text{in}})$$

where L_{in} is the reference length of the inlet.

(2) Outlet condition:

$$\partial\phi/\partial n = 0, \quad \phi = u, v, h, k, \varepsilon \tag{4}$$

(3) The no-slide condition is employed for the velocity at the wall $u = v = 0$, and the standard wall functions are also implemented to give the values of the velocity, the enthalpy and the turbulent parameters near to the wall.

(4) Symmetric axis condition:

$$u = 0, \quad \partial\phi/\partial x = 0, \quad \phi = v, h, k, \varepsilon \tag{5}$$

(5) The SIMPLE solver is used. The typical pressure condition for the collocated grids is adopted:

$$\partial p/\partial n = 0. \tag{6}$$

(6) There is CO_2 between the PT and the CT to insulate the heat transfer in the normal condition, so the adiabatic boundary condition is used at the wall of the tube bundles.

The moderator system is designed not only to moderate, but also to remove the moderator heat, which is 5% of the reactor power. It is considered into the heat source of the energy conservation equation.

3. Unstructured grid method

3.1. Discretization

The unstructured grid method is used to calculate the moderator system. The governing equations (1) and (2) above are in the Cartesian coordinate and they should be discretized into the unstructured grids by the finite volume method (FVM). The unstructured grids are polygons and the number of edges of the grid is not limited in theory, but only the triangular and the quadrilateral grids are considered in this paper with a novel local curvilinear coordinate theory. In Fig. 2, the local curvilinear coordinate (ξ, η) is defined at the point b on one of the edges of the cell P.

P is the current cell and B is the neighboring cell. The two elementary vectors of this coordinate are

$$\vec{r}_\xi = x_\xi \boldsymbol{i} + y_\xi \boldsymbol{j}, \quad \vec{r}_\eta = x_\eta \boldsymbol{i} + y_\eta \boldsymbol{j} \tag{7}$$

where $\boldsymbol{i}$ and $\boldsymbol{j}$ are the elementary vectors of the Cartesian coordinate; $x_\xi = \partial x/\partial\xi$, $y_\xi = \partial y/\partial\xi$ and so on.

The Jacobian can be derived as

$$J = \vec{\boldsymbol{A}} \cdot \vec{r}_\xi/\Delta\eta = \nabla\xi \cdot \vec{r}_\xi \tag{8}$$

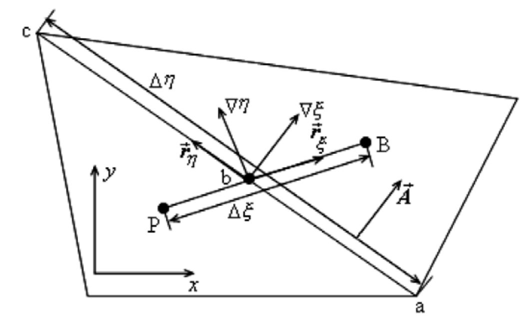

Fig. 2. Geometry of unstructured grid.

where $\vec{\boldsymbol{A}} = A_x\boldsymbol{i} + A_y\boldsymbol{j} = \Delta\eta\nabla\xi$ is the area vector and

$$A_x = y_c - y_a = \Delta\eta y_\eta = \Delta\eta J\xi_x$$
$$A_y = -(x_c - x_a) = -\Delta\eta x_\eta = \Delta\eta J\xi_y \tag{9}$$

The area of the quadrilateral $aBcP$ is defined as

$$\Omega_{aBcP} = [(\Delta\xi\vec{r}_\xi)\cdot\nabla\xi]\Delta\eta/2 = J\Delta\xi\Delta\eta/2 \tag{10}$$

According to the Gauss theorem, the following equation can be derived out:

$$\int_\Omega \frac{\partial\phi}{\partial x}\,\mathrm{d}\Omega = \sum\phi A_x = \sum\Delta\eta J\xi_x\phi$$
$$\int_\Omega \frac{\partial\phi}{\partial y}\,\mathrm{d}\Omega = \sum\phi A_y = \sum\Delta\eta J\xi_y\phi \tag{11}$$

where $\sum$ is the sum of all the edges of the cell P.

Therefore, the flux term can be expressed as

$$\int_\Omega\left[\frac{\partial}{\partial x}(\rho u\phi) + \frac{\partial}{\partial y}(\rho v\phi)\right]\mathrm{d}\Omega$$
$$= \sum(\Delta\eta JU\rho\phi)_b = \sum\left[\frac{(\Delta\eta J\rho U)_b}{2}(\phi_B + \phi_P)\right] \tag{12}$$

where $U = \xi_x u + \xi_y v$ is the component of the contravariant velocity of the local curvilinear coordinate. The diffusion term can be represented as

$$\int_\Omega\left[\frac{\partial}{\partial x}\left(\Gamma_\phi\frac{\partial\phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(\Gamma_\phi\frac{\partial\phi}{\partial y}\right)\right]\mathrm{d}\Omega$$
$$= \sum\left[\left(\frac{\Delta\eta}{\Delta\xi}Jg_{11}\Gamma_\phi\right)_b(\phi_B - \phi_P)\right]$$
$$+ \sum\left[(Jg_{12}\Gamma_\phi)_b(\phi_c - \phi_a)\right] \tag{13}$$

where $g_{12} = \xi_x\eta_x + \xi_y\eta_y$.

The discretized form of the conservative equation is

$$A_{P,\phi}\phi_P = \sum A_{B,\phi}\phi_B + Q_{P,\phi} \tag{14}$$

where $A_{B,\phi} = D_b - \frac{1}{2}F_b$, $A_{P,\phi} = \sum(A_{B,\phi} + F_{b,\phi})$

The flux term and the diffusion term are

$$F_b = (\Delta\eta J\rho U)_b, \quad D_b = (\Delta\eta/\Delta\xi Jg_{11}\Gamma_\phi)_b \tag{15}$$

The hybrid scheme is used for the flux term:

$$A_{B,\phi} = \max(-F_b, D_b - F_b/2, 0) \tag{16}$$

The source term is

$$Q_\phi = \int_\Omega S_\phi \, d\Omega + \sum[(Jg_{12}\Gamma_\phi)_b(\phi_c - \phi_a)] \tag{17}$$

A SIMPLE solver is derived in the collocated unstructured grid system, which is similar to the SIMPLE solver used in the Cartesian coordinate [6]. The general minimum residual (GMRES) arithmetic is used to solve the discretized linear equations.

3.2. Average filter method

A typical collocated arrangement of variables [7] is employed. It means all the parameters are defined at the same location, the center of the cell. However, to the SIMPLE solver, this arrangement will bring the problem of the checkerboard pressure, which is generated when solving the pressure equation [8,9]. Traditionally, the staggered grid system is used to solve this problem, but it is very complicated to the unstructured grids. Generally, the momentum interpolation method [10,11] is used in the collocated unstructured grid system, but it is also not convenient. The complete pressure correction algorithm [12] is achieved from the derivation of the SIMPLE process in the Cartesian coordinate and is more convenient than other methods.

The average filter method (AFM), which is much simpler and effective to eliminate the checkerboard pressure in the unstructured grids, is developed in this paper. If grids used in calculations are fine enough, there will be no physical pressure wave of one grid size and the local pressure is smooth, but the numerical pressure wave will still be generated in the numerical process. A simple way to eliminate this numerical wave is to use a numerical filter when solving the pressure equation. This filter should be simple because of the complicated relations between the unstructured grids, and in this method the local cell should be relative only to its neighboring cells, in order to avoid eliminating the real physical pressure wave and to do no response to the real pressure distribution.

The simplest way is to use the average value of the adjacent cells to smooth the pressure and filter the wave of one grid size.

(1) After solving the pressure equation, the pressure is revised as

$$\tilde{p}_P^* = p_P^n + \alpha_p p_P' \tag{18}$$

where $\tilde{p}^*$ is the temporary revised pressure.

(2) The average pressure of the neighboring cells is used to revise the pressure:

$$p_P^* = (1-\beta)\tilde{p}_P^* + \frac{\beta}{n}\sum \tilde{p}_B^* \tag{19}$$

where p^* is the revised pressure; n is the number of the neighboring cells; β is a filter factor, which can be adjusted in calculation.

In fact, AFM introduces the $1-\delta$ pressure difference as in other methods but is convenient to be used.

4. Results of the unstructured grid method

4.1. Verification of the unstructured grid method

Two benchmark examples are performed to verify the reliability of the unstructured grid method and AFM.

The first benchmark example is the problem of the lid driven square cavity. The unstructured grids are used and the calculated streamline distributions of different *Re* numbers are shown in Fig. 3. The results are compared with the cases in [13] and are proved to be accordant.

The second benchmark example is the problem of the natural convection in a square cavity to verify the reliability of this method to simulate the heat transfer and the natural convection problems. The streamline and the temperature distributions of different *Ra* numbers are shown in Fig. 4. The results are compared with the cases in [14] and are proved to be in agreement.

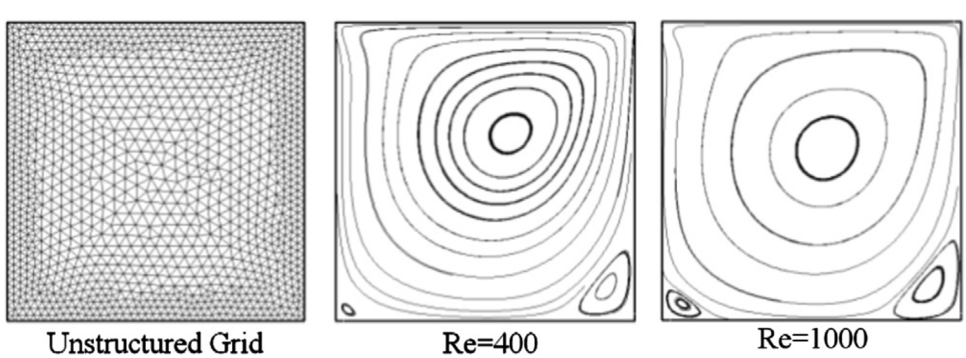

Fig. 3. Grids and results of lid driven square cavity.

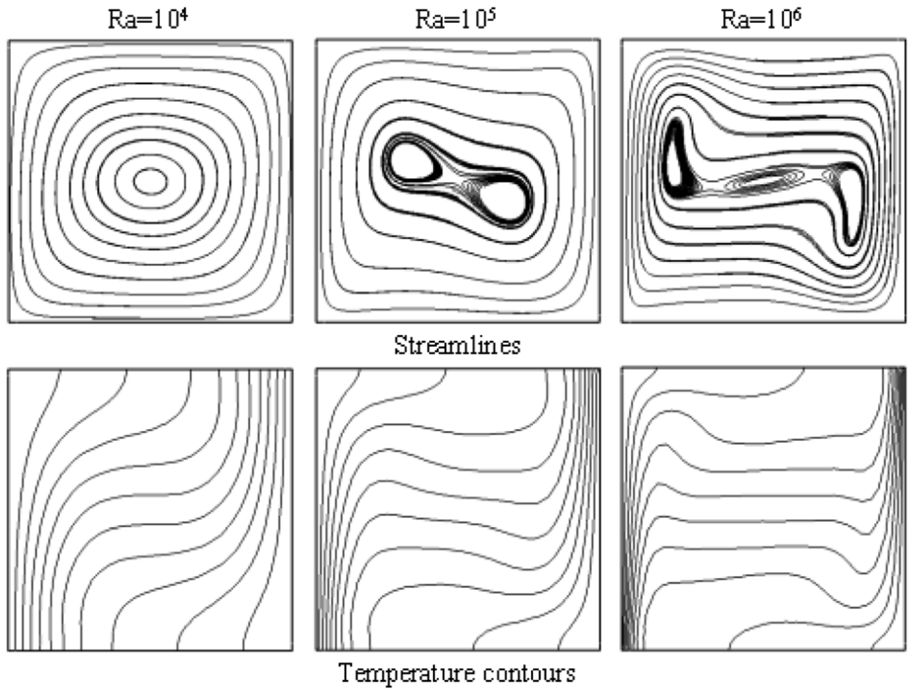

Fig. 4. Results of natural convection square cavity.

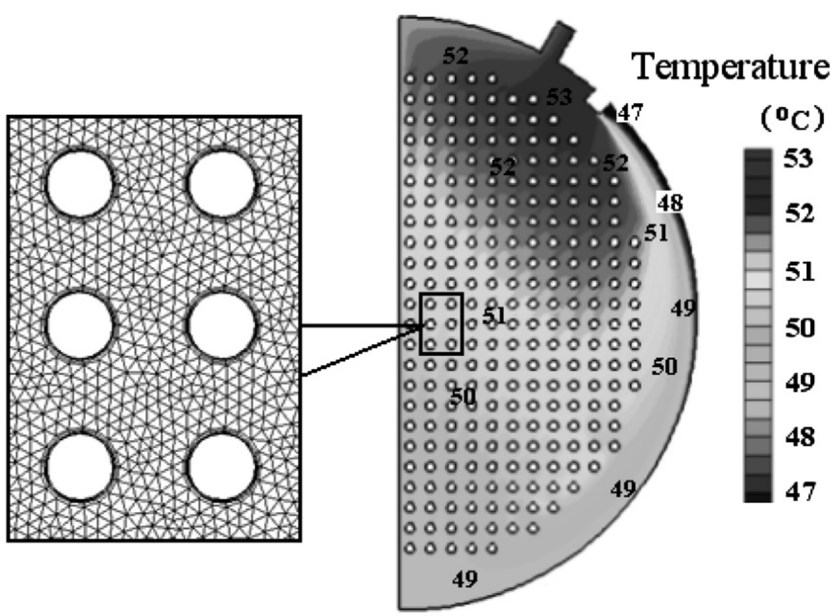

Fig. 5. Grids and temperature distributions.

It can be seen that the unstructured grid method and AFM are effective methods to predict the flows and heat transfer.

The flow and heat transfer in the CANDU9 moderator calandria are simulated by the unstructured grid method. AFM is used to eliminate the pressure wave. The models and the boundary conditions were described above. The unstructured grids for CANDU9 moderator calandria and the result of the temperature distribution are shown in Fig. 5.

The result is compared with the experimental results of the CANDU9 Moderator Test Facility of [4]. The temperature distributions of the present calculation and the experimental data are in agreement. It can be concluded that the unstructured grid method can be used to analyze the moderator calandria of the CANDU reactors effectively and correctly.

4.2. Discussions for TACR

The moderator system of the TACR is expected to use the passive natural circulation, so optimized designs on the structure of the moderator calandria is important. One of the choices is to optimize the locations of the inlet nozzle and outlet nozzle.

In the design of the TACR, 580 tubes are located in the moderator calandria. For convenience, an equivalent simplified TACR calandria is assumed: The calandria diameter is 1 m, the tube diameter is 0.1 m, the tube pitch is 0.14 m, the heat power is 500 MW and the inlet temperature is 46.85 °C.

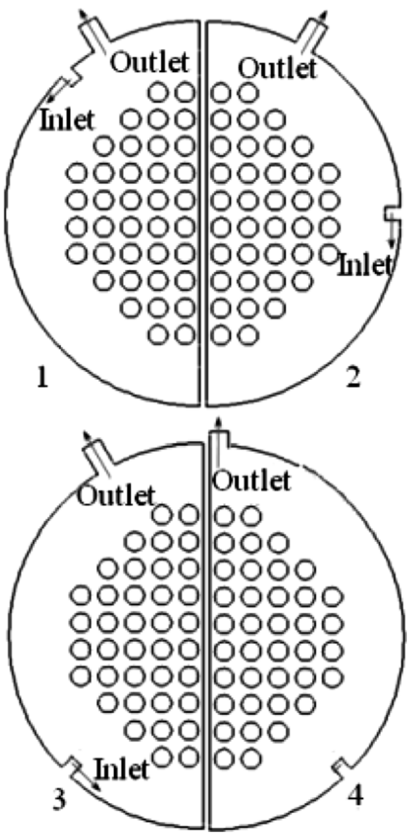

Fig. 6. Different designs of the locations of the inlet and outlet nozzles.

Four designs of the different locations of the inlet and outlet nozzles are shown in Fig. 6.

Fig. 7 shows the streamline and the velocity distributions of the design 1. The moderator flows into the calandria from the inlet nozzle, flows downward along the calandria wall, turns upward through the tube bundles and then flows out of the calandria. The location of the inlet nozzle of the first design ensures the moderator to flow throughout the calandria and remove the moderator heat out sufficiently.

Fig. 7 also shows the pressure and the temperature distributions of the design 1. It can be seen that the AFM is effective to smooth the checkerboard pressure. The highest temperature is between the bundle region and the outlet.

Fig. 8 shows the streamline and the temperature distributions of the design 2, the design 3 and the design 4.

It is discovered that when the inlet nozzle is moved down, the highest temperature will improve. In the design 3, a large part of the moderator flows upward from the reflection region rather than through the bundle region, which cause a rise of the highest temperature. The mass flux in the bundle region of the design 1 is large, so the highest temperature is low. Therefore, from the point of view of the lower highest temperature in the calandria, the design 1 is the best choice.

In the design 3, there is a stagnated area at the top region, where the velocity is very small, so the local temperature is high. The design 4 can be considered as an improvement of the design 3. The location of the outlet nozzle is on the top to remove the stagnated area and to make the temperature there drop. The distances of the inlet nozzle and the outlet nozzle of the design 1 and the design 2 are both small, which are adverse to ensure the natural circulation in the moderator system. In these two designs, the velocity in the lower part of the calandria is small, so it is difficult to ensure the flow go though the bundles in natural

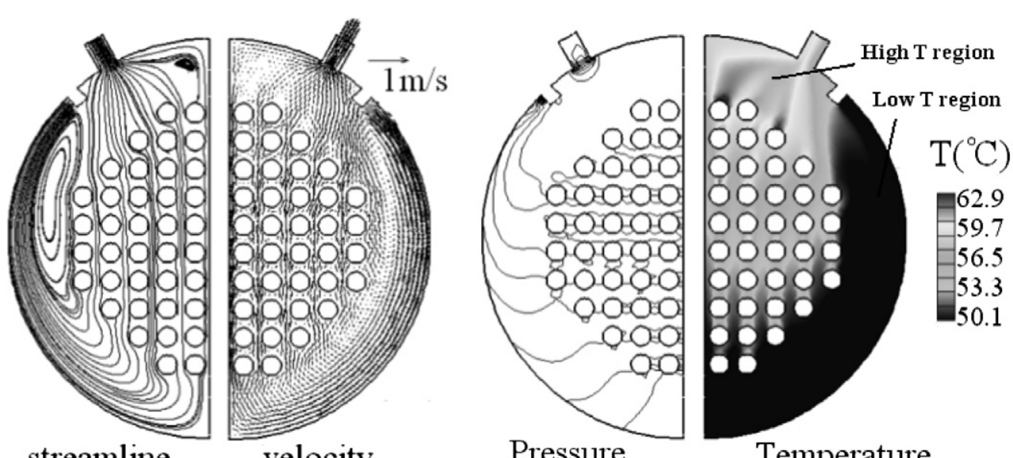

Fig. 7. Results of design 1.

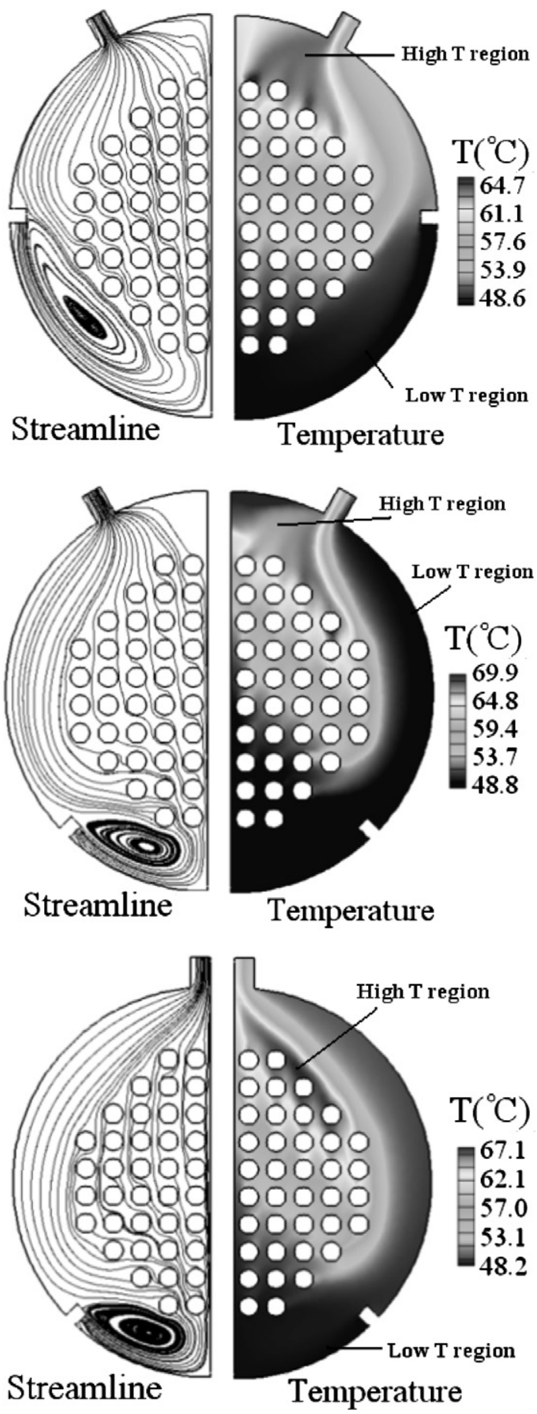

Fig. 8. Results of design 2, design 3 and design 4.

circulations. Accordingly, from the point of view of the passive design, the design 4 is considered as the best choice.

5. Unstructured grid porous method

5.1. Grid distribution

The unstructured grid method can be used to analyze the flow and heat transfer in the CANDU moderator calandria carefully and exactly, but much computing time is necessary because the number of the grids is large and the coefficient matrix of the discretized linear equation is complicated to be solved. In order to find an effective and quicker way, the unstructured grid porous method is developed. The unstructured grid porous method uses the porous media method [5,15] in the unstructured grid system, which can provide not only the exact boundary conditions for the inlet, the outlet and the calandria wall, but also the exact local porous parameters rather than the approximate uniform parameters used in other studies.

In the CANDU reactor calandria, the boundary of the vessel is cylindrical, and the inlet nozzle and the outlet nozzle are located on the circle boundary. If the porous media method in the Cartesian coordinate is used, stepped grid should be used at the boundary. It is too coarse to get an exact solution because the bulk flow is mainly along the radial direction rather than the axial direction of the calandria. In order to give an exact boundary condition, the body-fitted grid should be used. The cylindrical coordinate is one of the choices, but the way to describe the inlet and outlet boundaries is rough. The cylindrical coordinate also gets into trouble because of the square arrangement of the tube bundles. When the porous media method is used, the perimeter and the transverse area of the tubes in each grid should be made sure. But it is difficult because they are different in different grids. Therefore, exact porous parameters are hard to be decided, which is replaced by average and uniform porous parameters approximately in other studies.

The unstructured grids is employed in the unstructured grid porous method, while they are body-fitted at the boundaries of the inlet, the outlet and the calandria wall, and are square-arranged in the bundle region according to the arrangement of tubes. Fig. 9 shows the unstructured girds used in the analysis of the moderator calandria, where the left one is the grid distribution and the right one is a comparison of the grids and the locations of the tubes. Each tube is divided into four parts by four square-arranged grids

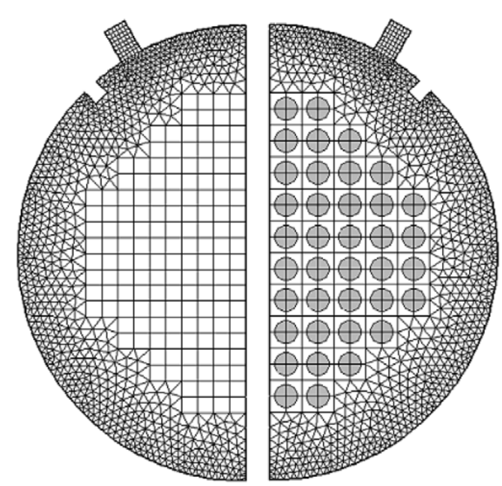

Fig. 9. Grids used in the unstructured grid porous method.

and this kind of division is regular and uniform, so exact porous parameters are easy to be given.

5.2. SIMPLE solver of the unstructured grid porous method

The SIMPLE process in the collocated grids for the unstructured grid porous method is derived.

The conservation equations are discretized by the FVM as

$$\sum[\gamma_b(\Delta\eta JU\rho\phi)_b = \gamma_v\int_\Omega S_\phi \mathrm{d}\Omega + \sum\left\{\gamma_b\left[\Delta\eta J\Gamma_\phi\left(g_{11}\frac{\partial\phi}{\partial\xi}+g_{12}\frac{\partial\phi}{\partial\eta}\right)\right]_b\right\} \quad (20)$$

where γ_b is the surface-permeability on the cell edge b, γ_v is the volume-porosity of the current cell, and the distributed resistance and the distributed heat source are imported into the source term S_ϕ.

The flux term and the diffusion term can be defined as

$$F_b = \gamma_b(\Delta\eta J\rho U)_b, \quad D_b = \gamma_b\left(\frac{\Delta\eta}{\Delta\xi}Jg_{11}\Gamma_\phi\right)_b \quad (21)$$

Then the discretized equation can be written as

$$\begin{aligned} &A_{P,\phi}\phi_P = \sum A_{B,\phi}\phi_B + Q_{P,\phi} \\ &A_{B,\phi} = D_b - \frac{1}{2}F_b, \quad A_{P,\phi} = \sum A_{B,\phi} \\ &Q_\phi = \gamma_v\int_\Omega S_\phi \mathrm{d}\Omega + \sum[\gamma_b(Jg_{12}\Gamma_\phi)_b(\phi_c - \phi_a)] \end{aligned} \quad (22)$$

The momentum equation can be obtained as

$$\begin{aligned} &A_{P,u}u_P = \sum A_{B,u}u_B - \gamma_v\sum[(\Delta\eta J\xi_x)_b p_b] + Q_{P,u} \\ &A_{P,v}v_P = \sum A_{B,v}v_B - \gamma_v\sum[(\Delta\eta J\xi_y)_b p_b] + Q_{P,v} \end{aligned} \quad (23)$$

The revised velocities u_P^{**} and v_P^{**} satisfy:

$$\begin{aligned} &\rho_P^* u_P^{**} = \rho_P^n u_P^* - \frac{\gamma_v\rho_P^n}{A_{P,u}^n}\sum[(\Delta\eta J\xi_x)_b p_b'] \\ &\rho_P^* v_P^{**} = \rho_P^n v_P^* - \frac{\gamma_v\rho_P^n}{A_{P,v}^n}\sum[(\Delta\eta J\xi_y)_b p_b'] \end{aligned} \quad (24)$$

The velocities at the cell edge can be derived as

$$\begin{aligned} &\rho_b^* u_b^{**} = \rho_b^n u_b^* - \frac{(\gamma_v)_b\rho_b^n}{A_{b,u}^n}(\Delta\eta J\xi_x)_b(p_B' - p_P') \\ &\rho_b^* v_b^{**} = \rho_b^n v_b^* - \frac{(\gamma_v)_b\rho_b^n}{A_{b,v}^n}(\Delta\eta J\xi_y)_b(p_B' - p_P') \end{aligned} \quad (25)$$

where $(\gamma_v)_b = [(\gamma_v)_P + (\gamma_v)_B]/2$ is the average volume-porosity at the cell edge.

The contravariant velocity is

$$\rho_b^* U_b^{**} = \rho_b^n U_b^* - C_b^n(p_B' - p_P') \quad (26)$$

$$C_b^n = [(\xi_x^2)_b/A_{b,u}^n + (\xi_y^2)_b/A_{b,v}^n](\gamma_v)_b(\Delta\eta J)_b\rho_b^n \quad (27)$$

The contravariant velocity is introduced into the mass conservation equation:

$$\sum[\gamma_b(\Delta\eta J)_b\rho_b^* U_b^{**}] = 0 \quad (28)$$

The pressure equation can be written as

$$\begin{aligned} &A_{P,p}^n p_P' = \sum A_{B,p}^n p_B' + Q_p^n \\ &A_{B,p}^n = \gamma_b(\Delta\eta J)_b C_b^n, \quad A_{P,p}^n = \sum A_{B,p}^n \\ &Q_p^n = -\sum\gamma_b(\Delta\eta J)_b\rho_b^* U_b^* \end{aligned} \quad (29)$$

This procedure is different from the normal SIMPLE solver, especially in the fact that the average volume-porosity is introduced. The AFM is also utilized in this process.

The models used in the unstructured grid porous method are the same as those of the unstructured grid method, including the mass, the momentum and the energy conservation equations, the boussinesq approximation, the standard k–ε turbulent model and the standard wall functions.

5.3. Results and discussion

The streamline and velocity distributions calculated using the unstructured grid porous method are shown in Fig. 10, while the pressure distribution and temperature distribution are also shown in Fig. 10.

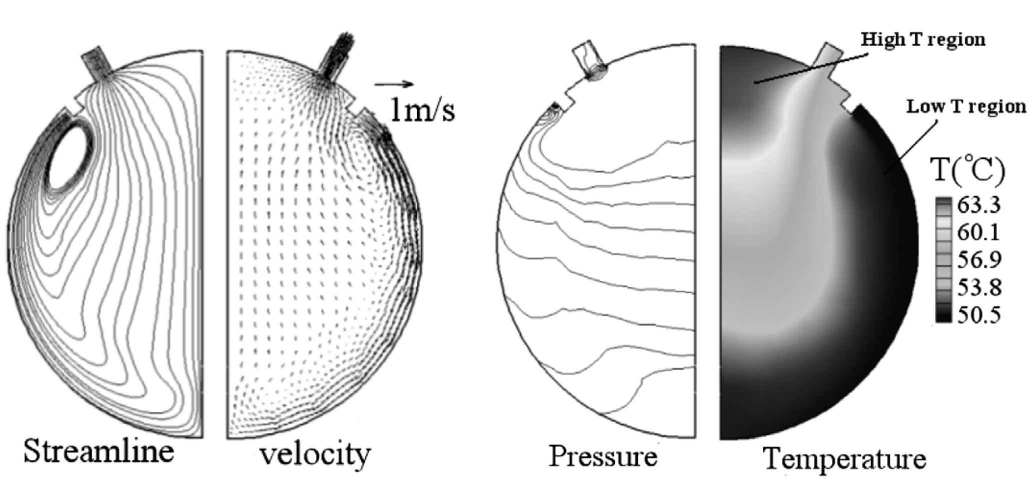

Fig. 10. Results of design 1 by using the unstructured grid porous method.

These results are compared with the results of the unstructured grid method in Fig. 7. It should be mentioned that the velocity of the porous method is an average of the equivalent continuous fluid. The pressure distribution proves the effectiveness of AFM to eliminate the pressure wave. The temperature distribution of the unstructured grid porous method is similar with the results of the unstructured grid method. The results of the unstructured grid porous method are more uniform compared with the results of the unstructured grid method. The computing time of the unstructured grid porous method is less than a quarter of the unstructured grid method because of the small number of the grids.

6. Conclusion

The unstructured grid method and the unstructured grid porous method are developed to simulate the flow and heat transfer in the moderator calandria of the TACR and other CANDU reactors.

The unstructured grid method is a refined and effective method to analyze the moderator calandria of the TACR. The results of the unstructured grid porous method are more uniform and approximate compared with the unstructured grid method because the porous parameters are decided by some experience equations. Nevertheless, the unstructured grid porous method is an effective method to analyze the TACR calandria, which will save much computing time and can be utilized as a qualitative method.

AFM is developed and is proved to be effective to eliminate the numerical checkerboard pressure to get the real smooth pressure distribution, not only in the unstructured grid method but also in the unstructured grid porous method.

Several designs with different locations of the inlet nozzle and outlet nozzle are compared. From the point of view of lower highest temperature in the moderator calandria, the inlet nozzle should be located high, as the design 1. From the point of view of the passive design, the distance of the inlet nozzle and the outlet nozzle should be larger, as the design 4.

Acknowledgements

This work is undertaken as a part of the Joint Research and Development Program funded by Atomic Energy of Canada Limited (AECL) and Tsinghua University of China under the ‘‘Advanced Thorium Reactor Study Agreement’’.

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