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3D flow analysis on upper plenum of PWR nuclear power station

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ABSTRACT In this paper, a computer code, thermal hydraulic analysis porous medium analysis(THAPMA), has been developed in order to simulate flow characteristics of an upper plenum. In solution method, a modified PISO algorithm is used , which is not only simpler but also more accurate and more rapid than the original PISO algorithm in solving steady and transient state problem. In light of the design of Qinshan PWR nuclear power station of China, the flow phenomena in the upper plenum, have been numerically simulated.

1 INTRODUCTION

In PWR nuclear power station, it is of great importance to ensure the control rods to be driven normally. However, if a design of the upper plenum is not very appropriate, the hydraulic load of coolant will make the guide tube deform, which will affect the driving of the control rod. So if the magnitude of hydraulic load can be gotten, it would be very good for design. In order to obtain the hydraulic load, the flow characteristic of the upper plenum need to be calculated.

In the paper, a code named thermal-hydraulic-analysis-porous-medium-analysis (THAPMA) based on porous medium analysis method, is programmed to simulate the flow characteristics of the upper plenum. The THAPMA code has been proved reliable by several numerical tests. In order to increase the computing efficiency, in the solution, the PISO algorithm is modified to make the convergence more rapid. Using this THAPMA code, we carry out the numerical simulation of the flow phenomena of the upper plenum based on the design condition of Qinshan PWR nuclear power station of china.

2 GOVERNING EQUATIONS AND DISCRETIZATION

In continuum domain, the conservation equations of mass, momentum, and energy possess a common form. If we denote the general dependent variable as Φ, the corresponding conservation equations have the following form in Cartesian coordinate system[1].

$$\frac{\partial}{\partial t}(\rho\Phi)+\frac{\partial}{\partial x}(\rho u\Phi)+\frac{\partial}{\partial y}(\rho v\Phi)+\frac{\partial}{\partial z}(\rho w\Phi)=\frac{\partial}{\partial x}\left(\Gamma_\Phi\frac{\partial\Phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma_\Phi\frac{\partial\Phi}{\partial y}\right)+\frac{\partial}{\partial z}\left(\Gamma_\Phi\frac{\partial\Phi}{\partial z}\right)+S_\Phi \tag{1}$$

Meanings of the symbols in Eq. (1) can be found in Ref. [1], where $\Phi =$ for mass conservation equation, $\Phi = u, v, w$ for momentum equation on x, y, z direction, respectively, and $\Phi = h$ for energy equation.

In porous medium analysis method, the volume porosity(γ_v) and directional surface porosity ($\gamma_x, \gamma_y, \gamma_z$) are suggested to model solid effect on the flow geometry, and distributed resistance (R_x, R_y, R_z) and distributed heat source or sink($\dot{Q}_{rh}$) are to model solid effect on the momentum and energy exchange of flow. With these parameters the flow domain containing solid materials can be considered as quasi-continuum domain. The conservation equations have the following form in Cartesian coordinate system[1].

$$\frac{\partial}{\partial t}(\gamma_v \rho \Phi) + \frac{\partial}{\partial x}(\gamma_x \rho u \Phi) + \frac{\partial}{\partial y}(\gamma_y \rho v \Phi) + \frac{\partial}{\partial z}(\gamma_z \rho w \Phi) = \frac{\partial}{\partial x}\left(\gamma_x \Gamma_\Phi \frac{\partial \Phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(\gamma_y \Gamma_\Phi \frac{\partial \Phi}{\partial y}\right) + \frac{\partial}{\partial z}\left(\gamma_z \Gamma_\Phi \frac{\partial \Phi}{\partial z}\right) + \gamma_v S_\Phi \tag{2}$$

Equation (2) is very general, because it can reduce to a conservation equation for a continuum regime when we make volume porosity and directional surface porosity $\gamma_v, \gamma_x, \gamma_y, \gamma_z = 1$, distributed resistance $R_x, R_y, R_z = 0$, and heat source $\dot{Q}_{rh} = 0$.

The flow equations are discretized with a finite volume method. It is described in detail by Patankar (1980)[2]. In order to avoid oscillatory pressure and velocity fields, a staggered variable arrangement is employed. In the discretized equation, the temporal derivatives are approximated by an implicit first order formula, the diffusion fluxes are discretized by central differencing scheme, the convective fluxes are approximated by two schemes. Of the two schemes, one is first-order upwind scheme, which is used in momemum equation, and another is weighted second upwind and center difference scheme (WSUC), which is implemented in the energy equation. The WSUC is a new scheme possessing accuracy, stability, boundedness and algorithmic simplicity, which is described in detail by reference [3]. In the simulation of upper plenum, because the temperature varying is very small, the energy equation can be negligible because of the small temperature variation.

3 MODIFIED PISO SOLUTION

In the famous COMMIX code[1], two distinct sequences—the semi-implicit and the fully implicit are used. Because of the semi-implicit nature of the formulation, it requires to limit the size of the time step to obtain a stable solution and so it needs a great deal of computer running times. The fully implicit solution sequence named SIMPLEST-ANL, is based on a modification to the SIMPLE/SIMPLER procedures at the Imperial College in England. The SIMPLEST-ANL requires less computer storage than SIMPLER and still has comparable or better computing efficiency. Because the SIMPLEST-ANL is an implicit procedure, it relieves many of the time step size limitations and permits using larger time step sizes. However, an iterative procedure is necessary for the SIMPLEST-ANL. So it spends many computer running time. More recently, Issa and co-workers[4] have proposed the PISO (pressure implicit with splitting of operators) algorithm, which is a non-iterative time-marching procedure and allows larger time step. In Reference [5], the comparison of PISO, SIMPLER and SIMPLEC algorithms for the treatment of the pressure-velocity coupling in steady flow problems is carried out. It is shown that for problems in which the momentum equation is not coupled to a scalar variable the PISO algorithm is superior, but when the scalar variable (such as temperature T) is strongly coupled to the momentum equation the SIMPLER and the SIMPLEC exhibit better behavior. In the PISO algorithm, there is a predictor step and one or more corrector steps. In corrector momentum equations, the coefficients and source terms are calculated using the previous time solution, which is not good for scalar variables that are strongly linked to momentum. From the above statement, we have improved the PISO algorithm combined the characteristics of the SIMPLEST/ANL. In corrector momentum equations, the coefficients and source terms are calculated using the newest solution.

In pressure appearing in the momentum equation is unknown. To convert the indirect specification of pressure to explicit form, the momentum equation can be written as:

$$a_0^{\Phi}\Phi_0 = \sum_{l=1}^{6} a_l^{\Phi}\Phi_l - A^{\Phi}\Delta p + b_0^{\Phi} \qquad (\Phi = u, \mathrm{v}, w) \tag{3}$$

where, b_0^{Φ} doesn't include pressure term.

For convenience in notation, the converged solution at the previous time step is denoted by superscript n, while the solutions at the present time step are denoted by a superscript * at the predictor, * * at the first corrector level, and * * * at the second corrector level.

(a) Predictor step

$$a_0^{\Phi}\Phi_0^{*} = \sum_{l=1}^{6} a_l^{\Phi}\Phi_l^{*} - A^{\Phi}\Delta p^{n} + b_0^{\Phi^n} \qquad (\Phi = u, \mathrm{v}, w) \tag{4}$$

By Eq. (4), the Φ^{*} can be gotten implicitly.

(b) First corrector step

The first corrector equation can be derived by expressing Eq. (5), in which the coefficients and source terms are calculated using the newest solutions excluding the temporal term.

$$a_0^{\Phi}\Phi_0^{**} = \sum_{l=1}^{6} a_l^{\Phi}\Phi_l^{*} - A^{\Phi}\Delta p^{*} + b_0^{\Phi} \tag{5}$$

Eq. (5) can also be expressed as:

$$\Phi_0^{**} = \hat{\Phi}_0 - d^{\Phi}\Delta p^{*} \tag{6}$$

where: $\hat{\Phi}_0 = \dfrac{\sum_{l=1}^{6} a_l^{\Phi}\Phi_l^{*} + b_0^{\Phi}}{a_0^{\Phi}}$, $\quad d^{\Phi} = A^{\Phi}/a_0^{\Phi}$

Substitution of Eq. (6) into the continuity equation leads to the pressure equation, which is the predictor equation for pressure. The predictor pressure p^{*} can be derived implicitly.

In the solution of pressure, when the pressure value at boundary is known, it can enter equation directly. When the velocity value at boundary is known and pressure value is unknown, if let $\hat{\Phi} = \Phi_{bound}$ and $d^{\Phi} = 0$, the pressure at boundary will disappear automatically. So the pressure at boundary is not needed.

Put the predictor pressure p^{*} into Eq. (6), the first corrector velocity Φ_0^{**} can be gotten explicitly.

(c) Second corrector step

$$a_0^\Phi \Phi_0^{***} = \sum_{l=1}^{6} a_l^\Phi \Phi_l^{**} - A^\Phi \Delta p^{**} + b_0^\Phi \qquad (7)$$

Similar to Eq. (5), the coefficients and source terms in Eq. (7) can be calculated using the newest solutions excluding the temporal term.

Using the same way, the first corrector pressure p^{**} and the second corrector velocity Φ_0^{***} can be derived.

4 FLOW ANALYSIS OF UPPER PLENUM

In the design of Qingshan PWR nuclear power station of China, the upper plenum contains 32 check tubes and 37 guide tubes as shown in Fig.1.

In the calculation, governing equations of the flow of the upper plenum are mentioned above in Equation (2). According to the structure and geometrical size of core, the volume porosity and surface permeability can be obtained. The distributed resistance can be calculated by the formulation in Reference [1]. In the light of the design of the upper plenum, coolant enters the bottom of the upper plenum uniformly at a velocity of 1.75 m/s. The exit boundary of the upper plenum is as follows:

$$V_n = \frac{F_{in}}{\sum_i \sum_j \sum_k \alpha_{i,j,k} A_{i,j,k}}$$

where V_n is the normal velocity; F_{in} is volume discharge of entrance, $A_{i,j,k}$ stands for the area of the exit surface cell. For the exit surface cell neighbor with the wall of the upper plenum $\alpha_{i,j,k}$ is 0.5, otherwise $\alpha_{i,j,k}$ is 1.0.

In the calculation, the simple constant turbulent diffusivity model is used. With modified PISO algorithm, solution is carried out. The distributions of velocity and pressure are obtained. Fig. 2 is the velocity distribution on the meridian surface across the axis of exit, where it can be seen that the flow is small in the top-corner of the upper plenum. Fig. 3 is the velocity distribution on the meridian surface normal to the 0-0 line. The two figures indicates that some coolant flow to the exit directly, and some coolant flow to the top of the upper plenum at first, and then get down which makes a pair of edges. From Fig. 4, we can see that the transverse velocities at the neighbor of the exit are larger than those of the bottom and the top cross-section. Fig. 5 is the pressure distribution on the meridian surface across the axis of exit. There is a steep pressure gradient at the neighbor of the exit. The coolant will make large effect on the check tubes and guide tubes at the neighbor of the exit. So the design of the check tubes and guide tubes at these zooms should be paid more attention.

5 CONCLUSION

We develop a computer code, thermal hydraulic analysis porous medium analysis (THAPMA), to simulate the flow characteristics of the upper plenum. In the solution method, a modified PISO algorithm is employed, which is not only simpler but also more accurate and more rapid in convergence than the original PISO algorithm. Moreover, the modified PISO algorithm can effectively solve steady and transient state problem. Besides, with the THAPMA code, the flow phenomena in reactor upper plenum have been numerically simulated in the light of the design condition of Qinshan PWR nuclear power station of China. These simulation results can supply a theoretical basis for the upper plenum design.

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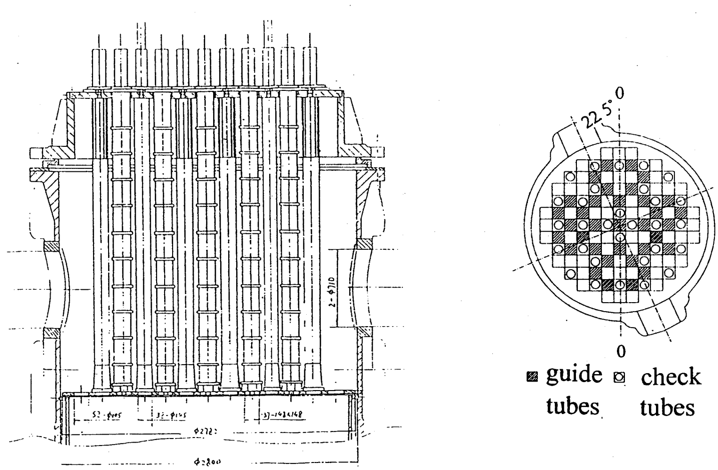


Fig.1. Structure figuer of upper plenum

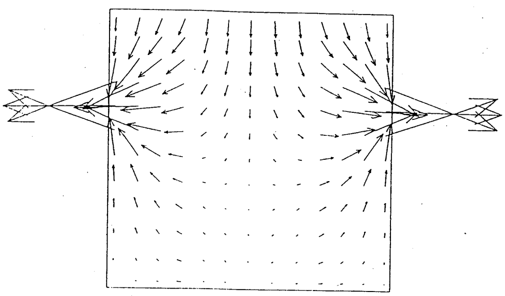


Fig. 2 Velocity distribution on the meridian surface across the axis of exit

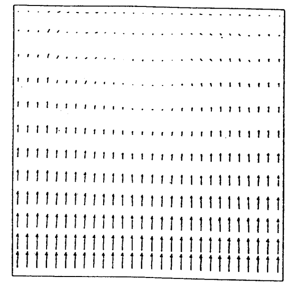
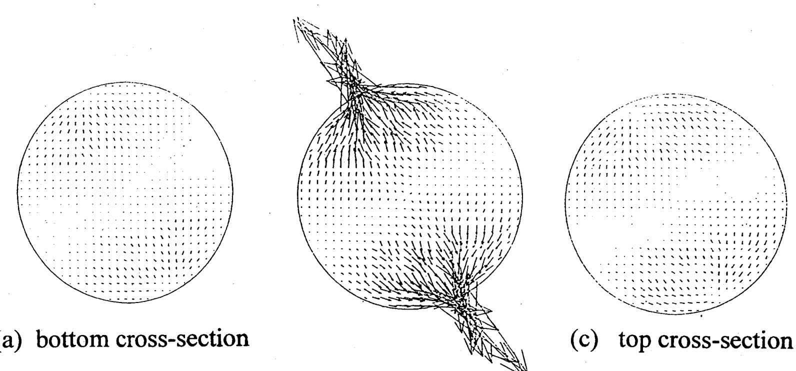


Fig. 3 Velocity distribution on the meridian surface normal to the 0-0 line



(a) bottom cross-section

(b) middle cross-section

(c) top cross-section

Fig. 4 Transverse velocities on the cross-section

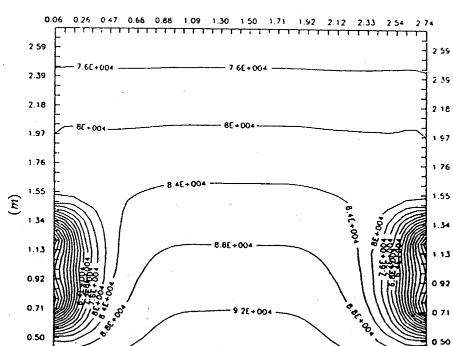


Fig. 5 Pressure distribution on the meridian surface across the axis of exit