ABSTRACT

The transverse mixing phenomenon in triangular lattice is analyzed with CFD method. The calculation results were validated against experimental data, and the effects of Reynolds number, Prandtl number and pitch to diameter ratio on the turbulent mixing were analyzed. The effect of Prandtl number on the coherent structure and turbulent mixing is the weakest, then is the Reynolds number. The effect of pitch to diameter ratio on the turbulent mixing factor is the most significant. As the pitch to diameter ratio increase from 1.03, the turbulent mixing factor decreases gradually and the mixing in lattice becomes weaker and weaker.

INTRODUCTION

In nuclear reactor, the lattice with the pitch to diameter ratio less than 1.1 is usually called as tight lattice. In this kind of lattice, the transverse flow between subchannels is much more significant than that in lattice with wider gap\(^1\). In tight lattice, the transverse flow is periodically with the maximum transverse velocity of about 10% of the bulk velocity. This kind of transverse flow could improve the transverse mixing and heat transfer significantly. The experimental and theoretical results revealed that this transverse flow is one kind of large scale, quasi periodic vortex structure\(^1, 2, 4\). This kind of vortex structure is dominated by the turbulent large scale coherent structure, rather by the secondary flow.

In this research, the commercial software FLUENT with the unsteady Reynolds Stress Models was adopted to investigate the turbulent mixing in tight lattice. The calculation results were validated with experimental data, and then the turbulent mixing factor in tight lattice was investigated.

NUMERICAL MODELS

Tight lattice

In the present simulation the focus will be on the experimental setup of Krauss and Meyer\(^1, 2\), which is shown in Fig.1, the choice is motivated by the detailed velocity distribution published by the authors and the extension of the experimental model that allows assuming the flow as fully developed in the interior of the bundle array. The tight lattice with different Reynolds numbers, Prandtl numbers, and pitch to diameter ratios are analyzed. In particular we will refer to the experimental case characterized by the following:

1. Reynolds number of 38754,
2. a hydraulic diameter of 33.5 mm, rod diameter of 140.0 mm,
3. P/D of 1.06,
4. the working fluid (air) has a kinematic viscosity of 1.7807e-5 m\(^2\)/s,
5. the constant heat flux of 0.98 kW/m\(^2\).

Boundary condition

In the streamwise direction, two possible choices are available, the inlet/outlet couple of boundary conditions and periodic boundary conditions. In the present paper, the periodic boundaries were applied because this boundary condition needs shorter channel length and less mesh. This numerical model has widely demonstrated its success in turbulence simulations\(^3\). If the domain length is too big, the calculation needs too much computational resource. However, if the length is too small, it...
could not describe the transverse flow very clearly. In the present case, the domain length has been set as equal to four times of the experimental wavelength (found equal to 150 mm).

As for the boundary conditions in the cross section, an ideal computational model of Krauss and Meyer’ experiment would include the entire cross section of the experiment\cite{1}. However, this would be extremely expensive computationally. The numerical approach adopted in the present case considers the model visualized in Fig.2, the domain is given by two sub-channels connected by a narrow gap. The boundary conditions include three couples of periodic boundaries (Fig. 2). The radial periodic boundaries are set according to the experiments \cite{1}.

![Fig.2 Boundary conditions](image)

**Fig.2 Boundary conditions**

**Code and Numerical scheme**

The calculations presented in this work have been performed with the CFD code FLUENT 6.3. The numerical schemes adopted in the present case are:

1. the discretized equations are solved with a predictor corrector approach adopting the PISO algorithm.
2. temporal discretization is performed through an Implicit Euler scheme.
3. the third order Quadratic Upstream Interpolation of Convective Kinematics scheme (QUICK) has been adopted to guarantee the accuracy.
4. the low Reynolds method is used to deal with the near wall boundary layer and the first near wall mesh has been kept at a value of $y^+<1.0$. The mesh generation in the lattice is similar with that of Merzari and Ninokata\cite{3}, which is shown in Fig.3. A total of 576,000 meshes were generated.

![Fig.3 Mesh generation](image)

**Fig.3 Mesh generation**

The implementation of Unsteady Reynolds Averaged Navier-Stokes simulation (URANS) approach in comparison to DNS and LES needs much coarser grids for the simulation, which consequently leads to larger time stepping resulting in orders of magnitude difference in computing time. URANS also has the potential of predicting large scale flow oscillations \cite{3}. The unsteady Reynolds Stress Model (RSM) was used in the present simulation. Unlike one and two equation models, RSM accounts for the effect of flow history due to terms representing the convection and diffusion of the shear stress tensors. It was verified that this model was successful in resolving the turbulence anisotropy. The Courant number was kept below 0.2.

**VALIDATION WITH EXPERIMENTS**

Fig.4 presents the prediction of streamwise velocity, wall temperature, wall shear stress and turbulent intensity. In Fig.4, the streamwise velocity is normalized with the time averaged bulk velocity $U_b$. The wall temperature and wall shear stress are normalized by the spatial and time averaged wall temperature and wall shear stress, respectively. The turbulent intensity is normalized with the square of shear velocity $u'_r$. 

2 Copyright © 2013 by ASME
Fig. 4 Validation with experimental data

It is shown in Fig. 4 that the present work could simulate the flow oscillation in the narrow gap accurately. The calculated streamwise velocity, wall temperature, wall shear stress and turbulent intensity are consistent with Krauss and Meyer’s experimental data\textsuperscript{1}. The prediction of streamwise velocity and wall temperature is better than that of wall shear stress. The relative discrepancies of streamwise velocity and wall temperature are no more than 5\%, and the relative discrepancy of wall shear stress is also acceptable. The calculated turbulent intensity is also in agreement with experimental results. The maximum discrepancy is next to 10\%. It can be thought that the present work could give acceptable results of the turbulent flow and coherent structure in the tight lattice. Figs. 4b and 4c indicate that the results solved by the steady Reynolds Stress Model are not acceptable. The simulation discrepancy is more than 20\%. That is because the coherent structure in the narrow gap oscillates periodically, while the steady Reynolds Stress Model could not simulate the unsteady oscillation.

EFFECT OF REYNOLDS NUMBER

The effects of Reynolds number, Prandtl number and pitch to diameter ratio on the coherent structure and turbulent mixing are investigated. In this section, the effect of Reynolds number is analyzed. The Reynolds numbers in the calculation are 10000, 20000, 38754, 80000, 120000 and 200000. The other parameters are the same with that in experiments.

Rehme\textsuperscript{5} reviewed the experimental data on natural mixing between subchannels of rod bundles by turbulent interchange. He also developed a correlation of mixing factor. He insisted that the heat transported through the gap per unit length by the effective mixing velocity can be expressed as:

\[ q_{ij} = \rho C_p w_{eff} W (T_i - T_j) \]  

(1)

where \( w_{eff} \) is the effective mean mixing velocity. It should be noted that the time mean value of fluctuating transverse mass flow rate is zero. Therefore, no net mass exchange result. \( W \) is the gap width. \( T_i \) and \( T_j \) are the bulk temperatures of
subchannels \(i\) and \(j\). The heat transported through the gap per unit length can also be written as:

\[
q_{ij} = \rho C_p \bar{w} \bar{Y} \frac{T_i - T_j}{\delta_{ij}}
\]

(2)

where \(\delta_{ij}\) is the mixing distance which is assumes to be the centroid distance between the subchannels \(i\) and \(j\). As a result the mixing factor \(Y\) can be expressed as:

\[
Y = \frac{w_{eff} \vec{\delta}_{ij}}{\bar{\varepsilon}}
\]

(3)

where \(\bar{\varepsilon}\) is a reference eddy viscosity, which can be expressed as:

\[
\bar{\varepsilon} = \frac{\nu}{20} \sqrt{\frac{\lambda}{8}}
\]

(4)

where \(\nu\) is the kinematic viscosity, \(\text{Re}\) the Reynolds number and \(\lambda\) the friction factor.

EFFECT OF PRANDTL NUMBER

Prandtl number is an important dimensionless parameter dominating the flow and heat transfer. In this section, the effect of Prandtl number on the turbulent flow in tight lattice is analyzed by changing heat diffusion coefficient. The working fluid is the same with that shown in the former section. The parameters in these cases are shown by the following:

Case 1: \(U_0, \nu_0, a_0, \text{Re}_0, \text{Pr}_0\)

Case 2: \(U_0, \nu_0, 0.5a_0, \text{Re}_0, 2\text{Pr}_0\)

where the parameters in Case 1 are just equal to the experimental data. \(U_0\) is bulk velocity, \(\nu_0\) is the kinematic viscosity, \(a_0\) is the heat diffusion coefficient, \(\text{Re}_0\) and \(\text{Pr}_0\) denote the Reynolds number and Prandtl number, respectively.

<table>
<thead>
<tr>
<th>Case description</th>
<th>(w_{eff}) (m/s)</th>
<th>(Y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1: (U_0, \nu_0, a_0, \text{Re}_0, \text{Pr}_0)</td>
<td>1.11</td>
<td>133.07</td>
</tr>
<tr>
<td>Case 2: (U_0, \nu_0, 0.5a_0, \text{Re}_0, 2\text{Pr}_0)</td>
<td>1.16</td>
<td>140.42</td>
</tr>
</tbody>
</table>

Table 1 gives the effective mixing velocity and mixing factor in these two cases. It is shown in Table 1 that if the Reynolds numbers are the same, the Prandtl number may also affect on the turbulent mixing although its effect is less than that of the Reynolds number.

EFFECT OF PITCH TO DIAMETER RATIO

Pitch to diameter ratio is also a very important parameter that affects on the large scale coherent structure. In this section, the effects of pitch to diameter ratio on the coherent structure, turbulent mixing and local heat transfer are analyzed. The Reynolds number is the same with the experimental Reynolds number 38754. These pitch to diameter ratios in the calculation are 1.01, 1.02, 1.03, 1.04, 1.06 and 1.12.
Fig. 6 presents the variations of effective mixing velocity and mixing factor with P/D. The effective mixing velocity is normalized with the average streamwise velocity. The normalized effective mixing velocity decreases linearly with the increasing of P/D as it is greater than 1.02. As for P/D=1.01, the effective mixing velocity is very small, about 1.56mm/s, there is nearly no momentum and energy transfer within the subchannels. As the P/D is greater than 1.02, the mixing factor decreases with the increasing of P/D. As for P/D=1.01, the mixing factor is only 0.2, about three orders of magnitude smaller than that in the lattice of P/D=1.02. In this case, the transverse velocity in the gap is next to zero and the streamwise velocity is also very small, but the wall temperature is very big. This operation condition is very dangerous and should be avoided.

CONCLUSIONS

The turbulent mixing in tight lattice was investigated. The effects of the Reynolds number, Prandtl number and pitch to diameter ratio on the turbulent mixing were analyzed. The calculation results are in satisfactory agreement with experimental data. The turbulent mixing might be affected by the Reynolds number, Prandtl number and pitch to diameter ratio. The effect of the Prandtl number on the turbulent mixing is limited than that of the Reynolds number. The effect of pitch to diameter ratio on the turbulent mixing in tight lattice is the most significant.

ACKNOWLEDGMENTS

This work is supported by National Nature Science Foundation of China (No. 51206183)

REFERENCES