Simulation study of turbulent mixing characteristics of tight lattice with triangular arrangement under blockage condition

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Abstract. The study of turbulent mixing in the gaps of fluid sub-channels in the tight lattice under blockage conditions is of great significance to the prediction of the thermal-hydraulic behavior of fuel assemblies under accident conditions. The CFD method was used to simulate the fluid flow phenomenon in the blockage condition in the tight lattice, and the velocity field and the turbulent mixing coefficient distribution in the section and downstream of the blockage under different blockage conditions were further compared and analyzed. The analysis results show that the blockage mainly affects the flow field of the sub-channel where it is located and the adjacent sub-channels. The turbulent mixing coefficient in these channels will increase significantly; when the sub-channel blockage rate is small, the turbulent mixing coefficient downstream of the blockage will be reduced; the short length will make the flow field near the top of blockage segment more complicated. The obtained changes of transverse and axial turbulent mixing coefficients under different blockage conditions can provide a reference for the parameter setting of the sub-channel analysis program.

1. Introduction

The compact cell assembly can increase the conversion rate of $^{238}$U and thus increase the fuel utilization rate. At present, the cores of new high-efficiency power reactors designed in many countries adopt a tight arrangement of fuel elements. However, this arrangement will make the rod spacing and rod diameter ratio (P/D) of the fuel rods smaller, so it is more prone to blockage accidents than traditional rod bundles. The morphology of the playground downstream of the blockage will change significantly due to the influence of the blockage; at the same time, the heat and mass transfer characteristics will also change. Therefore, it is necessary to carry out research on the flow conditions of the tight cell assembly blockage conditions.

In view of the fluid flow and heat transfer properties of the compact cell assembly, domestic and foreign scholars have carried out a large number of experiments and simulation studies. ROWE [1] studied the axial velocity and turbulence intensity in the sub-channel of the rod bundle, and concluded that one of the important parameters affecting the flow characteristics in the sub-channel is the pitch ratio. Hooper [2] and Rehme [3] found that there is a strong momentum energy exchange in the rod gap of the tight lattice element. Meyer et al. [4-5] used a high-speed camera to photograph the large-scale vortex structure of water flowing in the slit for the first time. The numerical research results of Baglietto [6] show that the turbulence model that accurately simulates the anisotropy of turbulence can truly
reproduce the flow in the compact cell bundle. Yu Yiqi [7] conducted a numerical study on the turbulent flow of air in the channel of closely arranged triangular cells, and found that the SSG Reynolds stress model has a good simulation of the flow, and it also shows that the simulation of turbulent anisotropy in the tight lattice is very important. Ye Xin Owen [8] used the flow field tracing method to capture the visual information of the transient flow between the rod walls in the tight lattice in the range of Re=2000–40000, and the results showed that when Re≥5000, large-scale pulsating flow occurred. Wen Yan’s [9] simulation found that the periodic vortex structure causes strong periodic flow oscillations between the two sub-channels, which is the main reason why the turbulence of the tight lattice sub-channels is strengthened. Hao Sijia [10] carried out a numerical simulation on the fluid flow phenomenon in the blockage condition of the tight lattice arranged in a 5×5 square, and obtained the change law of the transverse and axial turbulent mixing coefficient under the blockage condition of the square tight lattice.

At present, the research on the tight lattice flow mainly focuses on the optical rod flow field, and there are few studies on the flow of this type under blockage conditions. Therefore, this paper uses the CFD method to study the effect of sub-channel blockage on the flow field and turbulent mixing coefficient.

2. Geometric model and meshing

2.1. Geometric model
The complete channel section is used as the model for 3D CFD flow calculation. The model parameters are as follows: the rod outer diameter is 15mm, the rod spacing is 16.4mm, the channel length is 43.42mm, the rod bundle is arranged in a triangle, and the total model height is 800mm. The model parameter selection is based on the size range in the literature [11-12], which belongs to the tight lattice size range. The model is divided into three parts, from top to bottom, it is blockage downstream, blockage section, and blockage upstream. A total of three working conditions are selected for comparison. The first set of blockage conditions is that different numbers of sub-channels in the blockage section are blocked. This condition establishes three blockage models: single-channel blockage, connected dual-channel blockage, and unconnected dual-channel blockage. The three blockage lengths are all 5cm. The second group is a single-channel blockage condition with different blockage rates. The blockage rates of the three blockage models are 100%, 50%, 33.3%, and the three blockage lengths are all 5cm. The third group is a single channel with different blocking lengths. The three blockage models are in order: the length of the blockage section is 5cm, the length of the blockage section is 3cm, and the length of the blockage section is 1cm. The origin of the coordinate system of each group of working conditions is selected at the center of the entrance section, and the flow direction is the positive direction of the y-axis. The schematic diagram of the channel geometry model and the blockage model are shown in Figure 1.
The cross-sectional schematic diagram of the analysis area is shown in Figure 2. The hexagonal tight lattice element is divided into 60 sub-channel gaps (G1-G60) in order to analyze the mixing characteristics of the blockage downstream sub-channels. The center line L1 of the hexagon of the cross-section of the blockage section is selected to analyze the velocity distribution at the blockage downstream of different heights and perform grid independence analysis.

2.2. Meshing and irrelevance analysis
A hexahedral structured grid is used for division. In order to ensure grid independence, four grid models have been established. The number of grids of these four grid models is shown in Table 1. According to the literature [13-15], this turbulence model adopts the SSG Reynolds stress model. This model considers the anisotropy of fluid turbulent flow, streamline curvature, sudden stress changes and the influence of secondary flow. Therefore, the fluid flow of the compact grid can be better simulated. The inlet is set as a velocity inlet, and the outlet is set as a pressure outlet. The pressure-velocity coupling calculation adopts the SIMPLEC algorithm, the momentum equation adopts the second-order central difference discretization, the wall adopts the non-slip condition and the $y^+$ value at the wall is less than 5. The grid division diagram is shown in Figure 3.
Table 1. Parameter of main grid

| Scheme | 1  | 2  | 3  | 4  |
|--------|----|----|----|----|
| Number of grids/ten thousand | 54 | 90 | 148 | 286 |

Fig 3. Calculation section meshing

Fig 4. Grid sensitivity analysis

(a) Reynolds stress  
(b) Speed

The main parameters for selecting 1Dₜ downstream of the blockage (Dₜ is the hydraulic diameter) are shown in Figure 4. Figure 4a shows the G45 position Reynolds stress (uu) comparison after the abscissa is dimensionless, and Figure 4b shows the speed comparison of L1. The forecast trends of the four schemes are relatively consistent, but the calculation results of schemes 1 and 2 have larger errors compared with the calculation results of schemes 3 and 4. Scheme 4 sets a large number of grids, and the calculation result is more accurate but takes a long time. The accuracy of scheme 3 and scheme 4 is in good agreement, and the quantitative deviation is small. Considering the calculation accuracy and calculation time comprehensively, scheme 3 is selected for simulation calculation.

3. Analysis method and comparison of results

3.1. Processing method and verification

The main object of this paper is the turbulent mixing coefficient. The speed conditions studied are in the transition zone and the turbulent zone, and the inlet Reynolds number Re=2000, 5000, 10000, 20000, 30000. Calculate the turbulent mixing coefficient β [16-17] with reference to the method widely used in
the definition of the sub-channel analysis program, as shown in equation (1). The relationship between average velocity pulsation and Reynolds stress is calculated by equations (2) and (3).

\[
\beta = \frac{|\bar{e}|}{V_m} \quad (1)
\]

\[
|\bar{e}| = \frac{\sqrt{\overline{\varepsilon^2}}}{\sqrt{\pi}} \quad (2)
\]

\[
\overline{\varepsilon} = \overline{uu} \cos^2 \alpha + \overline{ww} \sin^2 \alpha \quad (3)
\]

Where: $|\bar{e}|$ is the sub-channel gap velocity pulsation; $V_m$ is the average mainstream velocity of the adjacent sub-channel fluid; $\overline{\varepsilon}$ is the average Reynolds stress; $\overline{uu}$ and $\overline{ww}$ are the average Reynolds stress at the x-axis and y-axis directions, respectively; $\alpha$ is the angle between the normal direction of the sub-channel gap and the x-axis. Since the sub-channels are arranged in a triangle, the value of the sub-channel $\alpha$ is 30° or 90° according to different positions; $\overline{uu}$, $\overline{vv}$, $\overline{ww}$ are respectively Reynolds stress along x, y, z.

### 3.2. Comparison of different sub-channel blockage and mixing degree

The blockage of different numbers of sub-channels is controlled as an independent variable, the blockage rate is 100%, and three sub-channel blockage conditions are compared: single channel is completely blocked, connected dual channels are completely blocked and unconnected dual channels are completely blocked.

The results of the working condition velocity field in two states of transitional flow (Re=5000) and turbulent flow (Re=20000) are selected for analysis. Figure 5 shows the velocity cloud diagram of different hydraulic diameters ($D_h$) downstream of the blockage zone of a single channel and the velocity line diagram of L1 position under two working conditions. In the figure, the detected axial position is selected according to the distance from the blocked section, and measured by an integer multiple of $D_h$. $1 D_h$ is the length of 1 times the hydraulic diameter from the outlet plane of the blocked section. From the perspective of the influence range, the main influence range of the blockage section is the adjacent sub-channels around the blockage. From the fact that the lateral velocity flows in the opposite direction near the downstream of the blockage, it can be seen that the fluid in the blockage and adjacent sub-channels will flow to the blocked sub-channel downstream. There is a backflow area 2 $D_h$ downstream of the blockage position. The lateral velocity will gradually increase to a maximum value and then gradually decrease within 4 $D_h$, and the lateral velocity will recover faster within about 10 $D_h$.

Comparing the velocity diagrams shows that when the Reynolds number changes, the velocity change trends at different hydraulic diameters are similar. At $1 D_h$, under the two different Reynolds number conditions, the speed showed a trend of first remaining unchanged and then rising to the maximum value and then decreasing. At 4 $D_h$, the speed under the two working conditions also showed a trend of first increasing to a certain amplitude, then decreasing and then increasing to the maximum value and then decreasing. At 12 $D_h$, the speed of the two working conditions showed a trend of first rising to an amplitude, then slowly decreasing, then increasing to the maximum value and then decreasing. The change of the Reynolds number will not have a significant impact on the downstream flow field distribution of the blockage. But the change of Reynolds number will affect the fluid velocity at the same position. When the Reynolds number is high, the speed of the fluid downstream of the blockage increases. At the same time, the presence of blockages will also lead to a decrease in the local Reynolds number closer to the downstream.
Fig 5. Fluid velocity distribution

Compare the turbulent mixing coefficients of the sub-channel gaps at different heights downstream of the single channel blockage in Fig. 6, and the detected sub-channel gap positions are all marked in the figure. In the transition zone and the turbulent zone, the change of Reynolds number has little effect on the downstream mixing coefficient distribution, which is similar to the results compared in the previous article; the Reynolds number mainly affects the mixing coefficient of the fluid under normal working conditions. Qualitatively, the turbulent mixing coefficient of the sub-channel gap (G45) where the blockage is located will increase within 4 Dh downstream. This is due to the macroscopic vortex structure in this range, which enhances the turbulent mixing here. After that, the turbulent mixing coefficient will decrease rapidly within about 18 Dh, and then slowly approach the normal working condition. For the adjacent sub-channel gap (G51) where the blockage is located, the turbulent mixing coefficient is somewhat different from the normal operating conditions. The turbulent mixing coefficient will show an upward trend within 5 Dh, will show a downward trend within 5 Dh to 10 Dh, and the change trend will tend to normal working conditions within the range of 10 Dh to 40 Dh. For the remaining sub-channel gaps (G16, G21), the turbulent mixing coefficient will drop to close to normal operating conditions within 3 Dh. From a quantitative point of view, the maximum turbulent mixing coefficient of the sub-channel gap where the blockage is located will increase to about twice the normal turbulent mixing coefficient, and the maximum turbulent mixing coefficient of its adjacent sub-channels will increase to within 1.26 times of the normal operating conditions. The sub-channel increase will be even lower.
Since the change of the Reynolds number in the transition zone and the turbulent zone has little effect on the distribution of turbulent mixing coefficient, the analysis is carried out under the Re=5000 working condition. The turbulent mixing coefficient of the gaps between the connected dual-channel at different heights of the blockage downstream and the unconnected dual-channel is compared, and the results are shown in Fig. 7. Qualitatively, the turbulent mixing coefficient in the gap of the sub-channel where the blockage is located will increase within 5 $D_h$ downstream of the blockage. The turbulent mixing coefficient of the gap (G51) between adjacent sub-channels shows different distributions due to the different sub-channel gaps within a certain range downstream of the blockage, but there will be a maximum value on the whole and then slowly decrease to normal operating conditions. The sub-channel (G21) shows a slow downward trend within 10 $D_h$ and the decline is not large, and tends to normal operating conditions within 10 $D_h$ to 40 $D_h$. Compared with the connected dual-channel blockage condition, the turbulent mixing coefficient of the sub-channel (G45) of the unconnected dual-channel blockage condition increases within 7 $D_h$ and then drops to the normal condition. The two sub-channels (G16, G51) of the unconnected dual-channel blockage condition are close to the same in the range of 3 $D_h$ to 40 $D_h$.

Quantitatively, for the sub-channel (G45), the turbulent mixing coefficient of the sub-channel gap where the blockage of the connected dual-channel blockage is located will increase to 1.6 times the normal turbulent mixing coefficient; the turbulent mixing coefficient in the gap between the sub-channels where the blockage is located in the unconnected dual-channel will increase to 1.18 times the normal turbulent mixing coefficient. The maximum, minimum and variation range of the turbulent mixing coefficient of the sub-channel (G16) are similar under the two blocking conditions. Comparing the two blocking conditions, the variation range of the turbulent mixing coefficient of the sub-channel (G21) is also similar.
In summary, downstream of the blockage, the blockage mainly affects the turbulent mixing coefficient of the blockage and its adjacent subchannels. The turbulent mixing coefficient of the sub-channel gap where the blockage is located will increase to 1 to 2 times the turbulent mixing coefficient of the normal working condition downstream of the blockage, and this increase will decrease with the increase of the Reynolds number. When the connected dual-channels are blocked or the unconnected dual channels are blocked, the form of the blocked downstream flow field is more complicated.

3.3. Comparison of mixing degree of different blocking rates

The blocking rate of different sub-channels is controlled as an independent variable. The selected blocking sub-channels are all single channels, and three sub-channel blocking conditions are compared, namely, single channel 100% blockage, single channel 50% blockage, and single channel 33.3% blockage.

Select the transition flow (Re=5000) and turbulent flow (Re=20000) to analyze the results of the speed field under working conditions. In the transition zone and the turbulent zone, the change of Reynolds number will not have a significant impact on the flow field distribution law of the blockage downstream, so the analysis is carried out under the Re=5000 working condition. Figure 8 is a cloud diagram of the axial velocity at different hydraulic diameters downstream of the plugging with three blockage rates under single channel blockage conditions. From the perspective of the lateral influence range, the main influence range of the blockage section is also concentrated on the blockage and its adjacent sub-channels, but as the blockage rate decreases, the degree and scope of the blockage's influence on the flow field will decrease. From the perspective of the longitudinal influence range, as the blocking rate continues to decrease, the distance for the downstream flow field to recover to normal operating conditions will become shorter.

![Cloud image of fluid velocity at different plugging rates](image)

(a)100% blockage (b)50% blockage (c)33.3% blockage

**Fig 8.** Cloud image of fluid velocity at different plugging rates
When Re=5000, the turbulent mixing coefficients of the sub-channel gaps at different heights downstream of the plugging rate of 50% and 33.3% are compared in Fig. 9, and the positions of the detected sub-channel gaps are all marked in the figure. The calculation result of the 100% blockage rate is shown in Figure 6a.

For the 50% blockage rate: qualitatively, the turbulent mixing coefficient of the blockage in the sub-channel gap (G45) will increase sharply, and the overall trend will increase first and then decrease. The turbulent mixing coefficients of the sub-channel gaps (G21, G51) show a trend of decreasing first and then remaining unchanged. In the range of 20 D_h to 40 D_h, the turbulent mixing coefficients of the two sub-channel gaps have similar changing trends. The turbulent mixing coefficient of the sub-channel gap (G16) drops to close to normal operating conditions within about 5 D_h downstream of the blockage. The reason why the turbulent mixing coefficient of G45 has a sharp rise is that there are vortex structures near G45, and the reason why the other sub-channels do not have large-scale vortex structures nearby. From a quantitative point of view, the turbulent mixing coefficient of the adjacent sub-channels of the blockage will increase to about 1.3 times of the normal working condition at the maximum, and the increase rate of the remaining sub-channels will be lower.

For the case of 33.3% blockage rate: the turbulent mixing coefficient of the sub-channel gap (G45) near the blockage is obviously different from that of the other sub-channel gaps, and can be increased to about 1.2 times the normal working condition at most. The turbulent mixing coefficient of G45 decreases rapidly after 2 D_h downstream of the blockage. Due to the influence of the vortex structure, it generally increases first and then decreases. A similar phenomenon occurs when the blockage rate is 50%, which shows that the turbulent mixing coefficient of the nearby sub-channel gaps with vortex structures will fluctuate, and this fluctuation is manifested as the turbulent mixing coefficient first increases and then decreases. At the same time, the turbulent mixing coefficient near the blocked sub-channel gap needs a longer distance than the remaining sub-channel gap to return to normal operating conditions. Due to the small blockage rate of 33.3%, the turbulent mixing coefficients of the sub-channel gaps except for the sub-channels near the blockage have a small difference in quantity, but there are also blockages in the adjacent sub-channel gaps. The turbulent mixing coefficient is about 5 D_h. The phenomenon of rapid descent within the sub-channels, while the turbulent mixing coefficients of the remaining sub-channels also have no obvious change.

![Fig 9. Cross-mixing coefficients at different downstream locations of single channel with different plugging rates](image)

In summary, in the downstream of the blockage, a small sub-channel blockage rate will reduce the disturbance of the flow field caused by the blockage and reduce the maximum value of the downstream turbulent mixing coefficient, and has a tendency to promote the turbulent mixing coefficient to return to normal operating conditions.
3.4. Comparison of the degree of mixing of different blockage lengths

Controlling different blockage lengths as independent variables, the selected blockage sub-channels are all single channels, and three blockage lengths are compared: single channel 5cm blockage, single channel 3cm blockage and single channel 1cm blockage.

Select the transition flow (Re=5000) and turbulent flow (Re=20000) to analyze the results of the speed field under working conditions. The change of Reynolds number will not have a significant impact on the flow field distribution law downstream of the blockage. The comparison of the turbulent mixing coefficients downstream of the blockage of different sub-channels is shown in Figure 10. Under the condition of Re=20000, the length of the blockage section is 1cm, and the turbulent mixing coefficients of G45 and G51 are compared. G45 is the sub-channel where the blockage is located, and the turbulent mixing coefficients at different hydraulic diameters downstream of the blockage are all greater than the turbulent mixing coefficients of G51 at the same height. G51 is the adjacent sub-channel where the blockage is located. The turbulent mixing coefficient of G45 shows a steep downward trend, while the turbulent mixing coefficient of G51 decreases more gently. The length of the plugging section is 3cm. The turbulent mixing coefficients of G45 and G51 are compared. At different hydraulic diameters downstream of the blockage, the turbulent mixing coefficient of G45 is greater than that of G51. Comparing the length of the blockage as an independent variable, when the blockage section is 1cm, within 20 $D_h$, the turbulent mixing coefficient of G51 shows an approximately linear decline, and the turbulent mixing coefficient of G45 shows a rapid decline trend; when the plugging section is 3cm, within 20 $D_h$, the turbulent mixing coefficient of G51 shows a slow decline, and G45 shows a rapid decline. When the fluid is in a turbulent flow zone with strong turbulent, the shorter the length of the blockage will result in more complicated fluid flow near the blockage downstream of the blockage. This may be due to the fact that the fluid in the blockage section needs a certain length after the flow channel suddenly shrinks. Gradually stable, if the length of the blockage is short, the fluid that is not stable will enter the downstream of the blockage after abrupt expansion, which intensifies the complexity of the flow downstream of the blockage.

![Fig 10. Comparison of turbulent cross-mixing coefficients downstream of blockage at different sub-channel locations](image)

Comparing the turbulent mixing coefficients of G45 and G51 when Re=20000 under the three blockage lengths, as shown in Figure 10. For G45, as the length of the blockage increases, the maximum value of the downstream turbulent mixing coefficient will also increase. When the Reynolds number is small, the speeds at which the turbulent mixing coefficients of the three blockage lengths return to normal operating conditions are basically the same. When the Reynolds number is higher, the turbulent mixing coefficient of the low blockage length condition has a more obvious downward trend, which is caused by the more disorderly structure of the low blockage length vortex when the turbulence is higher. For G45 and G51, the changing trends of the turbulent mixing coefficients of the three blockage lengths are similar, but the maximum value and the change range are different. The difference in the length of the blockage has a greater impact on the turbulent mixing coefficient at a short distance downstream of the blockage, but it does not affect the recovery speed of the turbulent mixing coefficient in general.
Fig 11. Comparison of turbulent mixing coefficients in downstream blockage with different blockage lengths

In summary, when the length of the blockage is too short and the vortex scale in the blockage is larger than the length of the blockage, the structure of the vortex downstream of the blockage will be more complicated, resulting in a significant increase in the turbulent mixing coefficient of the fluid or fluctuations; when the blockage length is sufficient to contain the blockage. When the vortex structure in the segment is blocked, the vortex structure downstream will be relatively stable. Different blockage lengths have a greater impact on the turbulent mixing coefficient of the fluid at a position closer to the downstream of the blockage, and then the turbulent mixing coefficient will return to normal operating conditions at a similar speed.

4. Conclusion
In this paper, the CFD numerical simulation method is used to study the blockage conditions of the hexagonal tight lattice elements, and the distribution of turbulent mixing coefficients at different positions in the channel under different blockage conditions is obtained. The analysis shows that the large-scale vortex structure existing in the blockage section and its downstream is the main reason for the complexity of the turbulent mixing coefficient downstream of the blockage section. Qualitatively, the blockage has a major influence on the turbulent mixing coefficient of fluids at different locations, and the blockage sub-channel and its adjacent sub-channels will be significantly different from the normal operating conditions. For the remaining sub-channels, blockage has little effect on the turbulent mixing coefficient. From a quantitative point of view, the turbulent mixing coefficient downstream of the blockage sub-channel will increase to within 2 times of the normal working condition, and it will drop rapidly within 20 Dh, and then gradually return to the normal working condition; the turbulent mixing coefficient downstream of the remaining sub-channels will increase to within 1.5 times of normal operating conditions, and then gradually return to normal operating conditions. For different sub-channel blockage rates, a small sub-channel blockage rate will reduce the disturbance of the downstream flow field caused by the blockage and reduce the maximum value of the downstream turbulent mixing coefficient. For different blockage length conditions, if the blockage length is too short, it will have a greater impact on the turbulent mixing of fluids near the downstream. The correlation result of the turbulent mixing coefficient downstream of the blockage can provide a reference for the parameter setting of the sub-channel analysis program.

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