Effect of Reynolds number and bundle geometry on the turbulent flow in tight lattice bundle

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Abstract

The flow structure in tight lattice is still of great interest to nuclear industry. The accurate prediction of flow parameter in subchannels of tight lattice is likable. Unsteady Reynolds Averaged Navier Stokes (URANS) is a promising approach to achieve this goal. The implementation of URANS（Unsteady Reynolds Averaged Navier Stokes）approach will be validated by comparing computational results with the experimental data of Krauss (1998). In this paper, the turbulent flow with different Reynolds number(5000~215000) and different P/D(1.005~1.2) are simulated with CFD code CFX12.The effects of the Reynolds number and the bundle geometry(P/D) on wall shear stress, turbulent kinetic energy, turbulent mixing and large scale coherent structure in tight lattice are analyzed in details.

It is hoped that the present work will contribute to the understanding of these important flow phenomena and facilitate the prediction and design of rod bundles.

Keywords: Tight rod bundle, Flow structure, URANS

1 Introduction

Tight lattice fuel assemblies have been proposed for advanced reactors. The fuel utilization will be enhanced with decreasing the pitch-to-diameter P/D, i.e., less coolant volume fraction in the core which results in less moderation assures harder neutron energy spectrum and leads to higher conversion of ^{238}U to ^{239}Pu (Oldekop et al.,1982,Uchikawa,2005,Cheng et al.,2008).

Early experimental observations on turbulent flow in rod bundle had been carried out in the early sixties. As the development of the measurement techniques, more experiments were presented in the late nineties (Rehme, 1973, Trupp and Azad, 1975, Trippe and Weinberg, 1979, Seale,1979, , Rehme,1987, Krauss and Meyer, 1998). The experiments show that the turbulent flow in a rod bundle has completely different characteristics than the turbulent flow in a pipe. The high mixing in the gap region was observed. Once it was explained by the secondary flow, but the later experiments prove that secondary flow is not the major factor for high mixing. The so called flow pulsation phenomenon was responsible for this high mixing. Vortices are transported in the longitudinal quasi-periodically with this oscillating flow. The interactions between the transported vortices result in a gain in the momentum transfer and increase in the mixing. These flow oscillations depend highly on the configuration of subchannels and Reynolds number. The phenomenon presents a Reynolds threshold below which no actual oscillation is observed (Meyer and Rehme,1994). It was found that the pulsation frequency in a rod–wall gap decreases measurably as the gap size decreases in the range $1.015 \leqslant W/D \leqslant 1.250$ (Baratto et al.,2006). Although a complete understanding of these oscillations has still not to be achieved. Flow instability was mostly accepted as the origin of these oscillations.

Up to now numerical investigations have used various approaches, such Reynolds averaged Navier-Stokes (RANS), unsteady RANS (URANS), LES and DNS to study rod bundle flows (Baglietto and Ninokata, 2003, Chang and Tavoularis, 2005, Chang and Tavoularis, 2007, Merzari et al.,2006， Ninokata et al.,2009).The works show that RANS with isotropic turbulence models will miss the anisotropy in the rod bundle. Although the anisotropic turbulence models are capable of reproducing the turbulence-driven secondary flows in subchannels, the secondary flow is less dominant in the case of tightly packed geometries. The Unsteady Reynolds-Averaged Navier-Stokes (URANS) approach captures the flow oscillation in the tight lattice rod bundle so that the accuracy in the prediction of averaged statistics is achieved since the wavelength of the oscillations was grossly over-predicted. Among all these approaches, DNS is the most preferred one because the global flow pulsation phenomena are still unknown or not clearly understood. LES has reproduced almost identical results with DNS for the turbulent flows in the rod bundle. Given the computational cost of the DNS and LES, URANS is a general practical approach capable of challenging arbitrary fuel rod-bundle design.

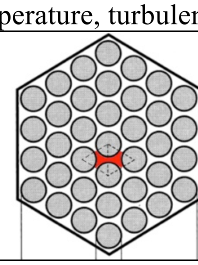
This paper focuses on the simulation of the turbulent flow inside different subchannels with RANS and URANS. The effect of the turbulence model on these simulations is investigated systemically. The features of the coherent structure in tight lattice with different P/D and different Reynolds number are studied in detail.

2 Numerical procedure

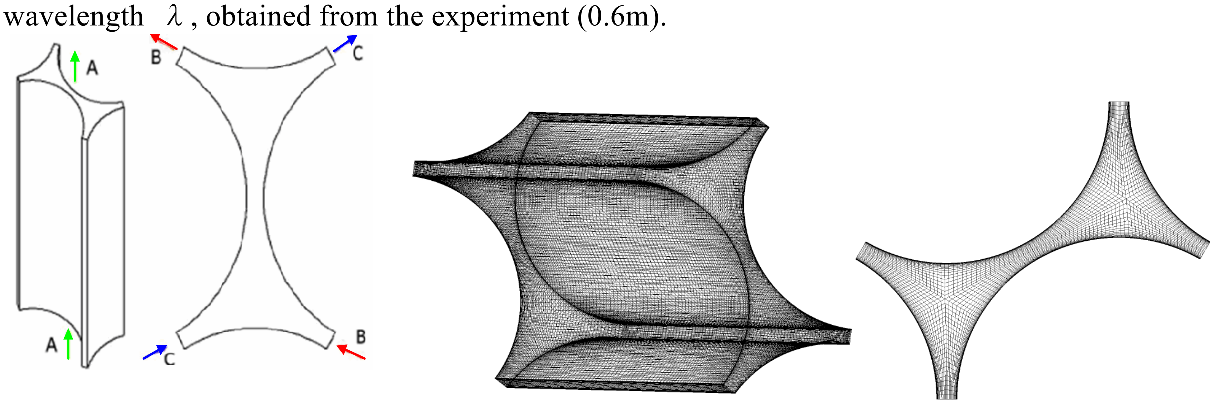
In the present work, numerical results will be validated by experiments of Krauss and Meyer. Detailed information of experimental and numerical setup are shown in Table 1 (Krauss and Meyer,1998).

Krauss and Meyers' experiment were conducted in a rod bundle of 37 parallel rods (O.D.140 mm) arranged in a triangular array built in a hexagonal symmetric horizontal channel. The total length of the working section is L=11.50 m. The measurements of wall shear stress, axial velocity and turbulent intensity in tight lattice are performed in the experiment. The Reynolds Stress Model will be applied to RANS&URANS simulation

Table 1: Experimental and numerical setup in the present study

Parameter\case	Krauss and Meyer (1998)
Array configuration	triangular array
Working fluid	air
Rod length m	6.9
Rod diameter mm	140
Pitch-to-diameter ratio	P/D=1.06
Fluid bulk velocity m/s	20.63
Fluid bulk temperature ^{o}C	47
Hydraulic diameter mm	33.5
Reynolds number	38754
Heat Flux kW/m^2	isothermal
CFD approach	RANS & URANS
Turbulent Model	SSG
Measured data used in this paper	stream wise velocity, wall shear stress, wall temperature, turbulent intensity
Cross section picture	

The computational domain consists of two sub-channels connected by a narrow gap. The boundary conditions include three couples of periodic boundaries (Figure 1) and non-slip walls. In the present case the computational length has been chosen to be equal to four times the average streamwise wavelength λ, obtained from the experiment (0.6m).



(a) Triangular array (b) Mesh structure

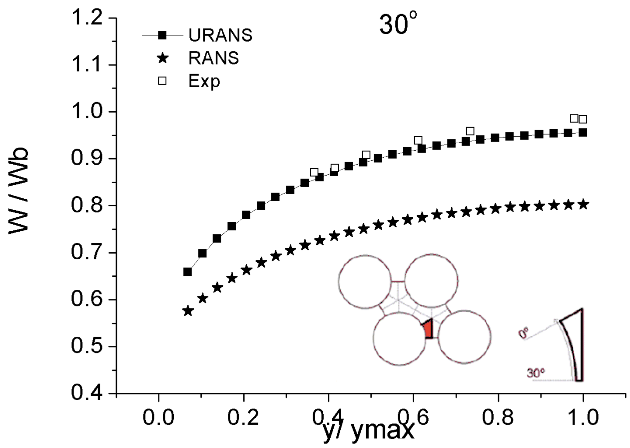
Fig1: Computational domain and Mesh for URANS

The mesh presented in Fig 1 has been used, for a total of more than 600,000 meshes. In any case, the time step size has been ensured to satisfy:

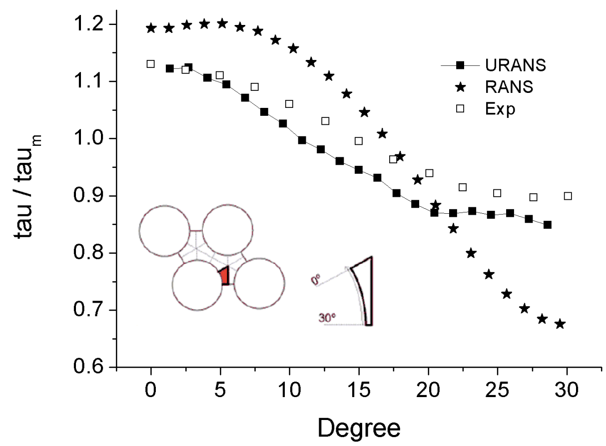
$$\Delta t << \frac{1}{f}$$

Where f is the smallest dominant frequency that can be observed a posteriori as the simulation develops. Δt has been chosen equal to 10^{-4} s.

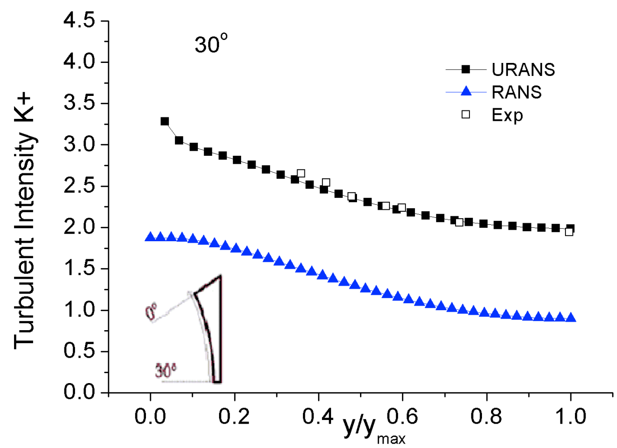
3 Results and Discussion



a) Stream wise velocity distribution (ϕ=30°)



b) Wall shear stress distribution



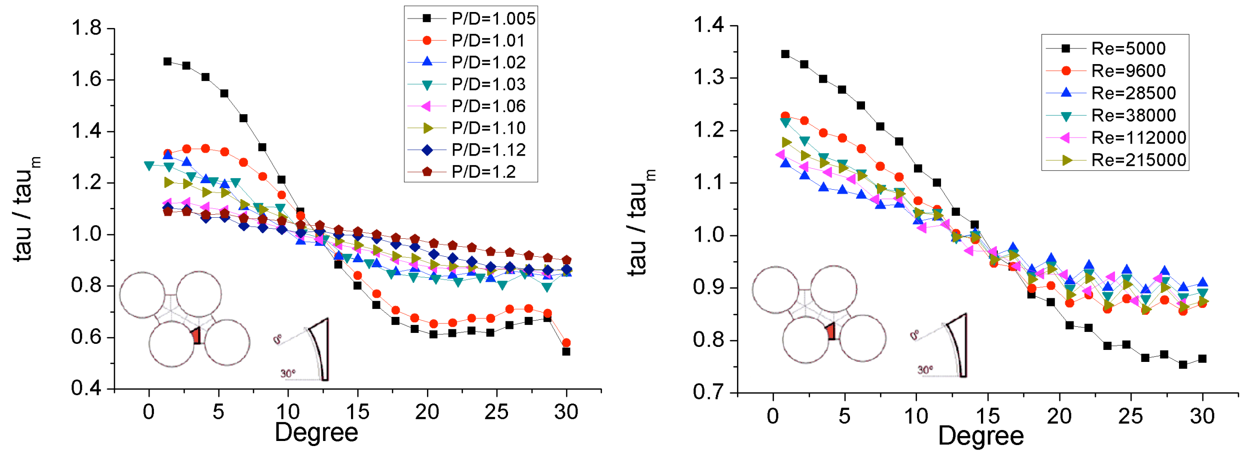
c) Turbulent intensity distribution

Fig 2 Comparison between experiment，URANS and RANS

Fig 2 show the comparison between experimental data and simulation results from URANS and RANS. The URANS simulation significantly improved the accuracy so that it is credible for prediction of the turbulent flow in tight lattice.

In order to investigate the effect of Reynolds number and P/D on turbulent flow in tight lattice, flow behavior with Reynolds number ranging from 5000 to 215000 and P/D ranging from 1.001 to 1.2 is simulated in triangular array.

3.1 Wall shear stress



a) b)

Fig 3 Effect of P/D and Re on wall shear stress

The homogeneity of the wall shear stress increases with the increase of P/D (Fig3a).The maximum wall shear stress appear in the widest flow region, while the maximum wall shear stress has obvious drift in DNS simulation(Baglietto, Ninokata,2006). The URANS simulations miss this monotonic trend which is also found in experiment and still not fully understand. The homogeneity of the wall shear stress is poor for low Reynolds number (Fig3b).The wall shear stress in not sensitive to the Re for high Reynolds number.

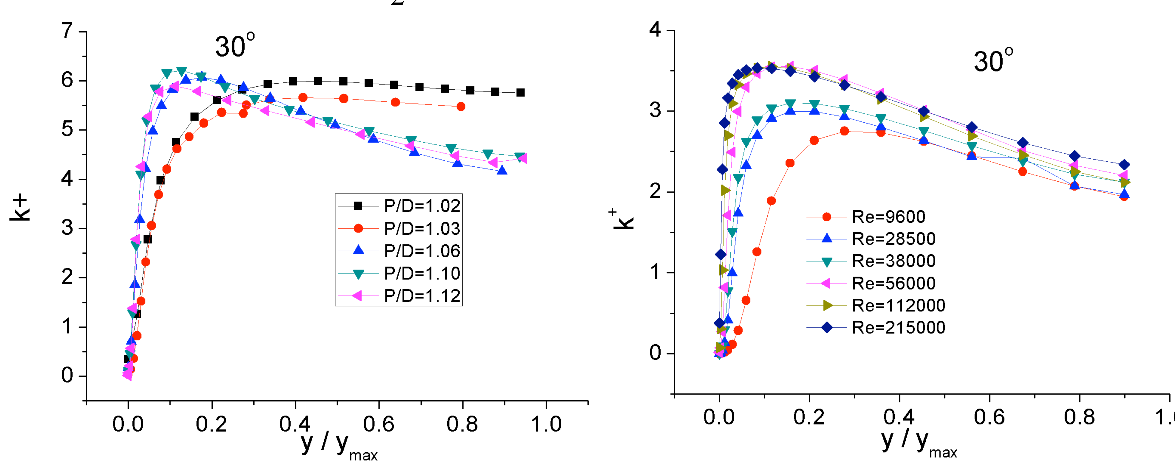
3.2 Turbulent kinetic energy

The definition of the relative kinetic energy of none coherent structure is

$$knc^{+} = \frac{1}{2}(u^2 + v^2 + w^2)/u_\tau{}^2$$

where u, v, w are axial, radial and azimuthal fluctuation velocity, respectively. u_τ is shear velocity. The resolved velocity fluctuation is identified as coherent, and the solutions of the Reynolds stress equations are identified as non-coherent. The kinetic energy of the coherent velocity fluctuation is obtained by time averaging the sum of the squares of the resolved velocity component fluctuations as:

$$kc^{+} = \frac{1}{2}(\overline{(\mathrm{U_x} - \overline{U_x})^2} + \overline{(\mathrm{U_y} - \overline{\mathrm{U_y}})^2} + \overline{(\mathrm{U_z} - \overline{\mathrm{U_z}})^2})/u_\tau{}^2$$



a) b)

Fig 4 Effect of P/D and Re on turbulent kinetic energy (ϕ=30°)

Where U_x, U_y, U_z is the transient axial, radial and azimuthal velocity. The total time-averaged turbulent kinetic energy per unit mass is determined as the sum of the above terms

$$k^+ = kc^+ + knc^+$$

Figure 4 show the effect of P/D and Re on turbulent kinetic energy at 30° azimuthal angle. With the decrease of P/D, the effect of the coherent structures becomes more significant, which leads to greater contribution to the kinetic energy far away from the wall (Fig4a). The change law of k^+ with the increase of Re is similar to that of knc^+ (Fig4b). k^+ become larger and closer to the wall when Re become larger. Furthermore, it is not sensitive to Re when Re reach some critical value. It hints some characteristics of the coherent structure.

3.3 Turbulent mixing

For the present geometry, let us denote the two subchannels adjacent to the gap as 1 and 2, and assume that the bulk temperatures in the two subchannels are Tb1 and Tb2, respectively. Following Rehme (1992), the convective heat transfer rate between these subchannels can be expressed as

$$Q = \rho C_p w_{eff} \delta_{12} L (T_{b1} - T_{b2})$$

Where w_{eff} is an effective mixing velocity across the gap. It can be expressed in terms of an eddy viscosity υ_T ,a mixing distance δ_{12} between the two subchannels, and an empirical mixing factor Y, which accounts for the subchannel shape, as

$$w_{eff} = Y \frac{\upsilon_T}{\delta_{12}}$$

Further utilizing the empirical relationship (Rehme, 1992)

$$\upsilon_T = 0.0177 \upsilon \mathrm{Re} \sqrt{f_t}$$

Where υ is the kinematic viscosity of the fluid, $f_t = 0.18 \mathrm{Re}^{-0.2}$ is the friction factor for smooth circular tubes, and specifying δ_{12} by geometrical reasoning. Moller（1992）suggest to specify δ_{12} as the distance between the center of two subchannels($\frac{\sqrt{3}}{3}P$) for tight lattice. Y need to be determined from available empirical information. Rehme (1992) propose the empirical relationship as follow:

$$Y_R = \frac{C}{\delta / D}$$

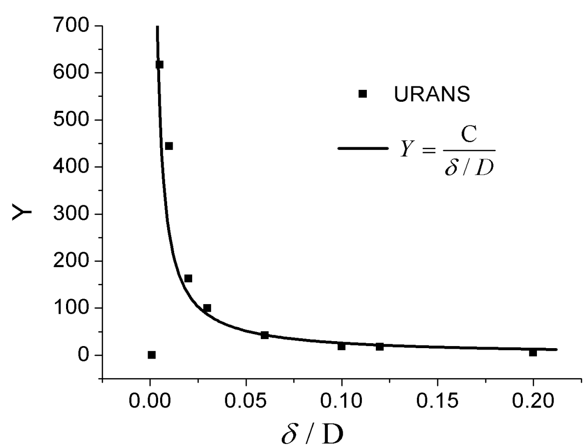


Fig 5 Effect of P/D on mixing factor

The empirical relationship predict the increase of Y with the decrease of δ/D. This paper get C=2.58 through Least square method. But the relationship means infinite mixing with zero gaps, which is in contradiction to the common knowledge. Fig 5 shows the effect of P/D on mixing factor. When P/D>1.001, the numerical results agree well with the relationship. Apparently the relationship miss the disappearance of the mixing with P/D=1.001.No relationship is capable of predicting that the mixing is ignorable when P/D reaches some critical value.

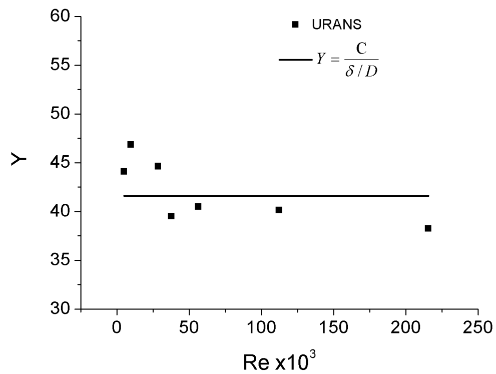


Fig 6 Effect of Re on mixing factor

Fig 6 shows the effect of P/D on mixing factor. Y is 41.61 from the relationship. The numerical results are within the error of 11.2%.

3.4 coherent structures

The flow oscillation is caused by the coherent structure, as proposed by Jeong and Hussain (1995). The parameter Q is introduced to identify this coherent structure and is defined as the second invariant of the velocity gradient tensor:

$$Q = -\frac{1}{2}\frac{\partial U_i}{\partial x_j}\frac{\partial U_j}{\partial x_i} = -\frac{1}{2}\left(S_{ij}S_{ij} + \Omega_{ij}\Omega_{ij}\right)$$

where the strain rate tensor and rotation rate tensor are defined as

$$S_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right), \text{ and } \quad \Omega_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} - \frac{\partial U_j}{\partial x_i}\right),$$

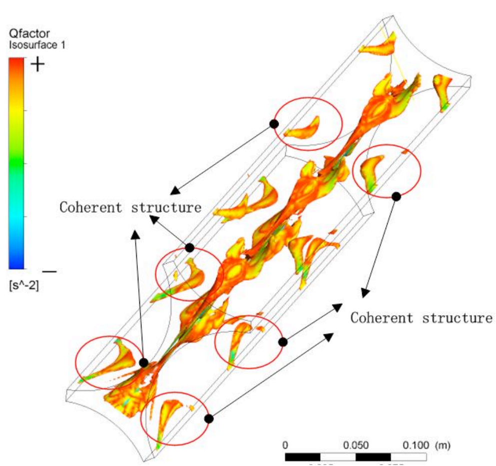


Fig 7: Coherent structure identified by the Q_m

respectively. Positive values of Q indicate regions where vorticity overcomes strain. The present study fails to identify the coherent structure by Q. Therefore, a modified Q_m was introduce as

$$Q_m = -\frac{1}{2}\left(C_q S_{ij} S_{ij} + \Omega_{ij}\Omega_{ij}\right)$$

Where $C_q<1$ is an empirical factor which reduce the weight of strain effect. By selecting $C_q=0.55$(Chang and Tavoularis,2007) and $Q_m=1$, it becomes possible to identify the surface of the coherent structure. Figure7 show the coherent structure identified in the tight lattice. It is observed that the coherent structure appears in pairs on either side of the gap.

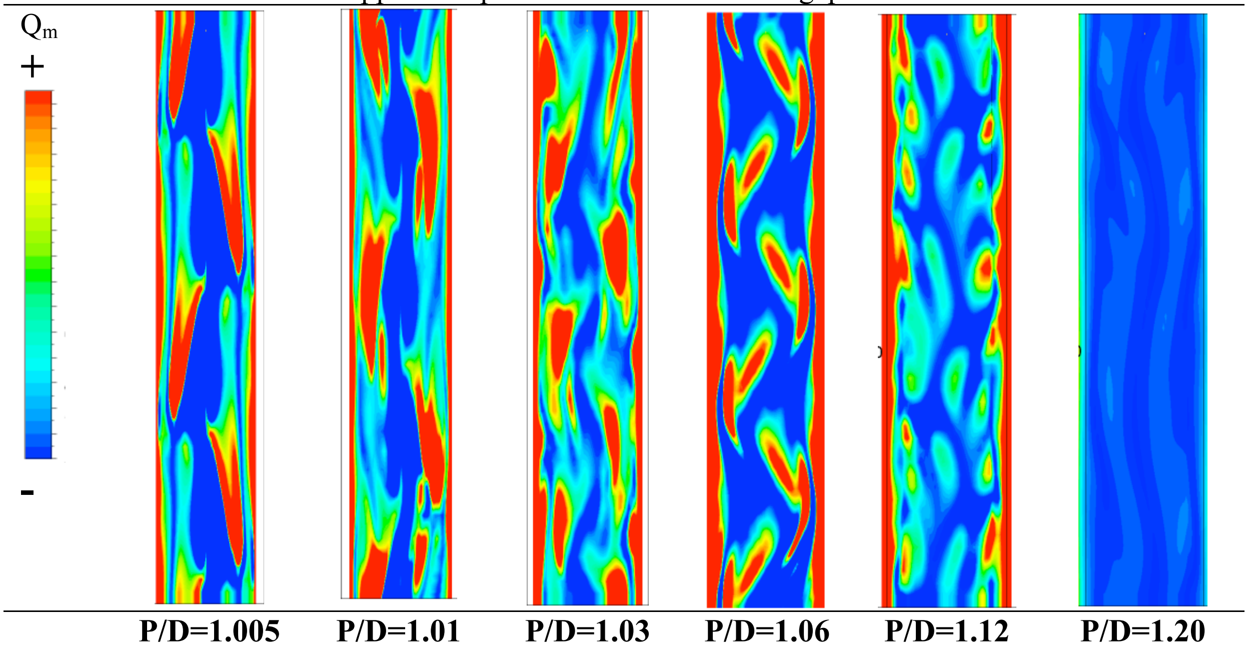


Fig 8: Q_m contour on plane YOZ for different P/D

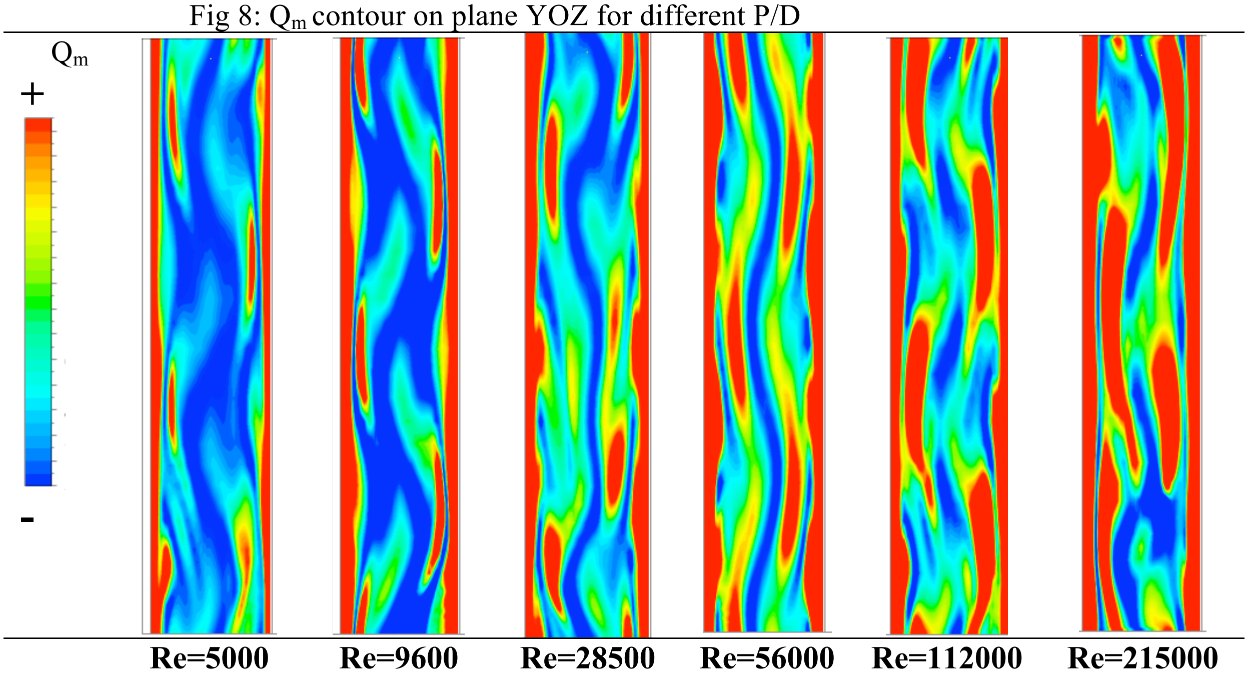


Fig 9: Q_m contour on plane YOZ for different Reynolds number

The contour of Q_m on plane YOZ with different P/D values is shown in Figure 8. With the increase in P/D, the scale and the configuration of the coherent structure become smaller and more irregular. The coherent structure is not obvious at P/D=1.2.

The contour of Q_m on plane YOZ with different Reynolds numbers is shown in Figure 9. It is observed that the scale of the coherent structure appears in pairs and increases with the increase in Reynolds number. The coherent structure exists even with low Reynolds number (5000). It was pointed out that there exists threshold value of Reynolds number, below which no oscillation occurs.(Lexmond et al.,2005) This phenomenon is also validated in this numerical study.

4 Conclusions

The validity of the methodology is based on the experimental data of Krauss and Meyer (1998).With the Reynolds number range from 5000 to 215000 and P/D range from 1.001 to 1.2, the effect of the Reynolds number and the bundle geometry on the flow oscillation are investigated in this study.

In very tight lattice(P/D<1.1),the effect of P/D on the wall shear stress and turbulent kinetic energy is significant due to the dramatic variation of the amplitude and the frequency of the flow oscillation in the gap region.

This paper verifies the inverse ratio between mixing factor Y and geometric factor δ/D before δ/D below critical value.

For the fixed geometry (P/D),the flow parameter .i.e, stream wise velocity ,wall shears stress, turbulent kinetic energy is not sensitive to the Re when Re is higher than some value(9600 in this paper).

The scale of the coherent structure increase when the Reynolds number increase or the P/D decrease. There exists a critical P/D for specified Reynolds number, blow which the coherent structure disappear.

5 References

Baglietto, E., Ninokata, H., 2003. Turbulence models evaluation for heat transfer simulation in tight lattice fuel bundles. In: Proceedings of the 10th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-10), Seoul, Korea.

Baratto, F., Bailey, S.C.C., Tavoularis, S., 2006. Measurements of Frequencies and Spatial Correlations of Coherent Structures in Rod Bundle Flows. Nucl. Eng. Des, 236, 1830-1837.

Chang, D., Tavoularis, S., 2005. Unsteady numerical simulations of turbulence and coherent structures in axial flow near a narrow gap. ASME J. Fluids Eng, 127 (3),458–466.

Chang, D., Tavoularis S., 2007. Numerical simulation of turbulent flow in a 37-rod bundle Nucl. Eng. Des, 237, 575-590.

Cheng, X., Liu, X.J., Yang, Y.H., 2008. A Mixed Core for Supercritical Water-Cooled Reactors, Nucl. Eng.Tech, 40(1), 1-10

Jeong, J., Hussain, F., 1995. On the Identification of a Vortex. J. Fluid Mech, 285, 69–94.

Krauss, T., 1996. Experimentelle Untersuchung des turbulenten Wärme- und Impulstransports in einem beheizten Stabbündel. Dissertation Univ. Karlsruhe, also FZKA 5799, Forschungszentrum Karls-ruhe, Germany.

Krauss, T., Meyer, T., 1998. Experimental investigation of turbulent transport of momentum and energy in a heated rod bundle. Nucl. Eng. Des. 180,185–206.

Lexmond, A.S., Mudde, R.F., Van der Haagen, T.H.J.J., 2005. Visualization of the vortex street and characterization of the cross flow in the gap between two subchannels. In: Proceedings of the 11th Nureth, Avignon, France.

Mantlik, F., Heina, J., Chervenka J., 1976. Results of local measurements of hydraulic characteristic in triangular pin bundle. UJV-3778-R, Rzez, Czech Republic.

Merzari, E., Ninokata, H., Baglietto, E., 2006 Large Eddy Simulation of the Vortex Street between Rectangular channels. NTHAS 5, Jeju Island, Korea.

Meyer, L., Rehme, K., 1994. Large-Scale Turbulence Phenomena in Compound Rectangular Channels, Exp Therm. Fluid Sci., 8, 286-304.

Ninokata,H., Merzari, E., Khakim A., 2009. Analysis of low Reynolds number turbulent flow phenomena in nuclear fuel pin subassemblies of tight lattice configuration. Nucl. Eng.Des 239(5), 855-866

Oldekop, W., Berger, H.D., Zeggel, W., 1982. General features of advanced pressurized water reactors with improved fuel utilization. Nucl. Tech 59, 212-227.

Rehme, K., 1973. Simple method of predicting friction factors of turbulent flow in non-circular channels. Int. J. Heat Mass Tran.,16, 933.

Rehme, K., 1987. The structure of turbulent flow through rod bundles. Nucl. Eng. Des. 99, 141. Seale, W.J., 1979. Turbulent diffusion of heat between connected flow passages. Nucl. Eng. Des. 54, 183.

Rehme K, The structure of turbulence in rod bundles and the implications on natural mixing between the subchannels.International Journal of Heat and Mass Transfer,1992, 35(2): 567–581.

Moller S.V, Single-phase turbulent mixing in rod bundles. Experimental Thermal and Fluid Science,1992, 5:26–33.

Trippe, G., Weinberg, D., 1979. Non-isotropic eddy viscosities in turbulent flow through rod bundles. In: Kakac, S., Spalding, D.B.(Eds.), Turbulent Forced Convection in Channels and Bundles, vol.1. Hemisphere Publishing Corporation, Washington,505

Trupp, A.C., Azad, R.S., 1975. The structure of turbulent flow in triangular array rod bundles. Nucl. Eng. Des. 32, 47.

Uchikawa, S., et al., 2005. Investigations on innovative water reactor for flexible fuel cycle (LFWR).Proceedings of GLOBAL, Tsukuba, Japan, 358.