Large Eddy Simulation of the Flows in Annular Channels and Rod Bundles

Project Representative
Hisashi Ninokata Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology

Authors
Elia Merzari Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology
Hisashi Ninokata Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology

LES (Large Eddy Simulation) has been used to fully reproduce the characteristics of the flow field in eccentric annular channels, rectangular channels and rod bundles, to verify and characterize the presence of large-scale coherent structures and to examine their behavior at different Reynolds numbers. The numerical approach is based upon boundary fitted coordinates and a fractional step algorithm; a dynamic Sub Grid Scale (SGS) model suited for this numerical environment has been implemented and tested. The agreement with previous experimental and DNS results has been found good overall for the streamwise velocity, shear stress and the rms of the velocity components. The instantaneous flow field presented large scale coherent structures in the streamwise direction at low Reynolds numbers, while these are absent or less dominant at higher Reynolds. POD (Proper Orthogonal Decomposition) of the flow field on both experimental and computational data has provided a basis on which the code validation is made.

Keywords: LES, POD, Eccentric channel, Advanced Nuclear Systems, Tight Lattice

1. Introduction

In this work extensive calculations have been carried out for the eccentric annulus channel flows as a simplified geometry in connection to the turbulent flows in tight lattice nuclear fuel pin subassemblies. As a first step the LES results have been verified *a priori* and *a posteriori* in annular channels against DNS data and experimental data to ensure the consistency of the formulation. Then LES has been extensively applied to several eccentric annular channel configurations and confirmed the presence of large-scale coherent structures near the narrow gap. There, the influences of the anisotropic turbulence structure and eddy migration behaviors in the non-uniform flow channels have been investigated in detail. Through the use of statistical tool (POD: Proper Orthogonal Decomposition) it has been validated that even the internal structure of turbulence reflects experimental findings. As a last step the methodology has been extended to rod-bundles, where the same oscillations have been observed.

2. Methodology

In previous research several DNS computations have been performed for the concentric and eccentric channels. The data collected has been used to evaluate different SGS model in order to develop an effective LES methodology in boundary fitted coordinates. Several other models have been tested, among which the dynamic mixed model, the self-similarity model and another variant of the dynamic model [3]. Figure 1 shows an example of *a priori* test. The dynamic model and its variant performed fairly well from the point of view of *a priori* and *a posteriori* tests. They may be considered the ideal choice for the simulation of the flow in annular channels and rod-bundles.

The algorithm used to solve the Navier-Stokes equations is based on the Fractional Step Algorithm on a partially non-staggered grid [4]. The equations have been discrtized through a second order consistent scheme [5] and tme advancement has been carried out through an Adams-Bashfort scheme. The Poisson equation for the pressure gauge has been solved with either:

1. An FFT solver (since perioidc boundary conditions have been employed in the streamwise direction) for eccentric channels; or
2. A multiblock solver [6] for the rod bundles.

The multiblock solver uses non-overlapping domain decompositions. The domain is divided into a set of non overlapping structured grids. The algorithms employed by the solver are the Conjugatete Gradient Squared CGS and Bi-Conjugate Gradient [7]. A two-level preconditioning (block-level and upper level) has been adopted [8]. Alternatively, for large scale calculations a geometric multigrid preconditioning has also been implemented.

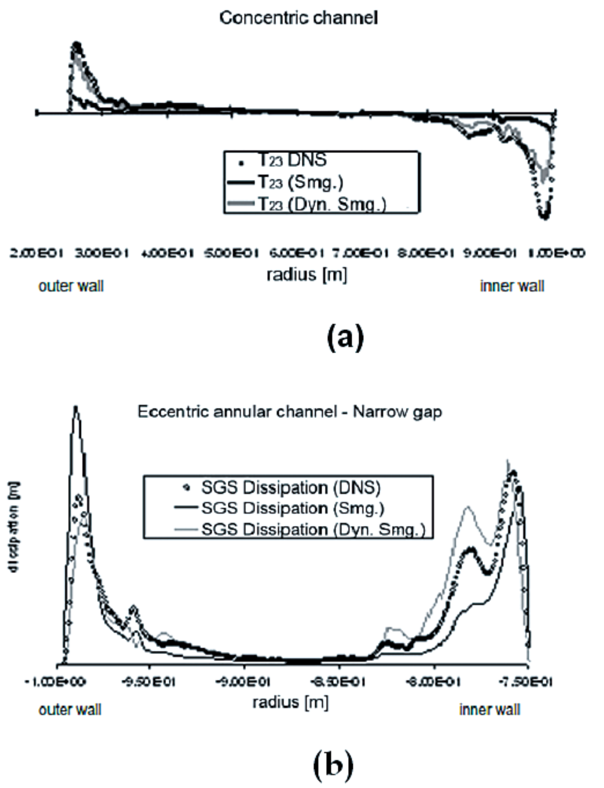

Fig. 1 A priori test for concentric and eccentric channels. Direct comparison for the stresses (a) and comparison for the SGS dissipation (b).

3. Results for eccentric channels

An extensive LES computational campaign has been performed for the eccentric channel at various Reynolds numbers and the eccentricity to investigate the characteristics of the flow in eccentric channels. Some of the cases run are reported in Table 1 for different values of the geometric parameters D_h (hydraulic diameter), $\alpha = D_{in} / D_{out}$ and $e = d/(D_{out} - D_{in})$ where D_{in} and D_{out} are the inner and outer diameters and d is the distance between the axis of the two cylinders. The computation of some of the cases took a considerable amount of time since all scales of turbulence above the inertial range need to be simulated, the DNS case used to validate the LES model a priori required almost 0.2 billion meshes.

The results of the simulations A, C and D have been validated for available DNS and experimental data [9, 10, 11].

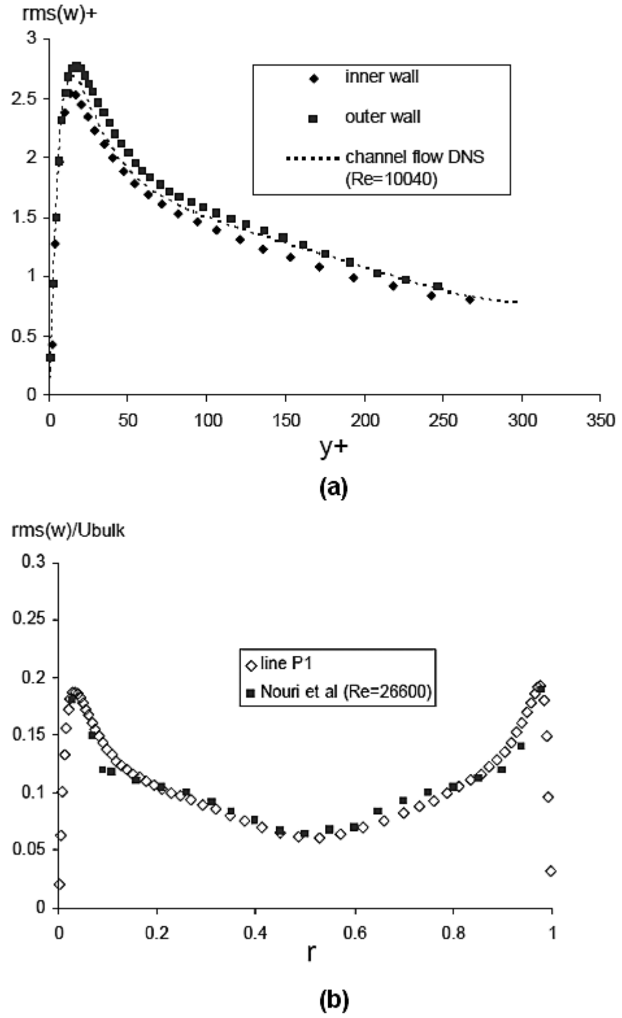

Fig. 2 Rms of the streamwise velocity case D. Profile in wall units (a) and profile normalized by bulk velocity (b). r is the relative distance from the outer wall. Both profiles are taken in the wide gap of the eccentric channel.

Figure 2 shows a comparison of stream-wise velocity rms among experiment, case D (LES) and DNS data. Important aspects of the flow field in concentric and eccentric annuli have been confirmed and reproduced through the present methodology [12]. In particular, the effect of transverse curvature on the inner wall, as well as the effect of eccentricity on the wall shear stress, has been successfully simulated.

From previous works it appears that the transition to tur-

Table 1 LES and DNS cases.

	e	α	p/D	Re	Grid N_ξ-N_η-N_ζ	L/D	Meshes	Time [wks]	CPUs
Case A	0.5	0.5	–	3200	256–64–256	4π	4×10^6	8	8
Case B	0.5	0.5	–	26600	768–300–768	2π	0.18×10^9	52	128
Case C	0.5	0.5	–	27100	512–300–512	2π	7.8×10^7	24	128
Case D	0.95	0.5	–	8700	256–64–128	2π	2×10^6	8	8
Case E	–	–	1.05	6800	(12ξ) 72–42–256	4π	0.9×10^7	16	32
Case F	–	–	1.05	20200	(12ξ) 152–99–512	4π	9.2×10^7	24	128

bulence in geometry such as the eccentric annuli [12] is accompanied by the formation of a street of counter-rotating vortices in the region near the narrow gap. These coherent structures persist at low Reynolds numbers but they progressively become less dominant, at least for an eccentricity equal to 0.5, as the Reynolds number increases.

Contemporarily, in the narrow gap the local profile of the streamwise velocity evolves from a purely laminar solution to a solution characterized by the presence of turbulence production near walls. The shear stress in the narrow gap region evolves from an almost laminar condition for a Reynolds number equal to 3,200 to an increasingly turbulent solution [12].

At low Reynolds number and eccentricity equal to 0.5 the relative dominance of the coherent structures is associated with a strong anisotropy in the narrow gap (turbulence has a local two-component pattern), while at higher Reynolds numbers a nearly isotropic condition is recovered far from the walls. At higher eccentricity (e = 0.95) the coherent structures are absent in the narrow gap region, accounting for a strong viscous damping effect in the case of almost touching channels.

When Reynolds averaging is performing over the flow field, secondary vortices are observed in the cross section. In Fig. 3, an example is shown for case A. The shape of the secondary flows depends on the value of the eccentricity e and the parameter α [12].

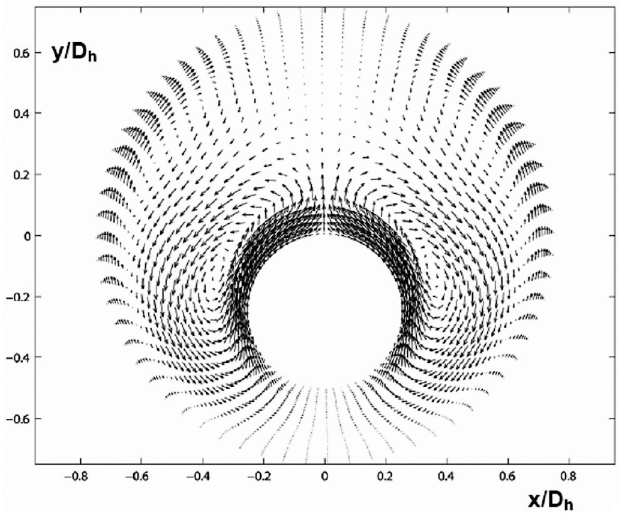

Fig. 3 Secondary Flows for a case A.

4. Proper Orthogonal Decomposition

A POD (Proper Orthogonal Decomposition) study [13] of the fields obtained in this study has been performed to obtain additional insight in the physics of flow in eccentric channels. The power of the POD lies in the fact that the decomposition $\vec{\sigma}_i(\vec{x})$ of the flow field in the POD eigen-functions:

$$\vec{u}'(\vec{x}) = \sum_i a_i \vec{\sigma}_i(\vec{x})$$

where a_i are real coefficients, converges optimally fast in L_2; i.e. a truncation of n modes in the POD decomposition is the optimal possible truncation for the same number of modes. Each mode is characterized by its energy content, the rank of the modes based on their energy content will be called "quantum number" in the following. Detailed description of the procedure used can be found in Sirovich [14].

The POD has been carried out for case A at e = 0.5 with 2000 snapshots. The first 6 modes contain 20% of the total turbulent kinetic energy. In particular the first four modes are representative of a traveling wave of the type $\vec{u} = \vec{u}_0 \sin 2\pi[(x/\lambda) - (t/T)]$, which can in fact be splitted into two terms that differ in the axial direction x by a phase shift of $\pi/2$. Moreover two wavelengths appear to be present. In fact the use of periodic boundary conditions and a finite computational length in the streamwise direction imply a discretized wavenumber spectrum and subsequently the impossibility for the computation to reproduce exactly the correct wavenumber spectrum which is inherently continuous (unless the domain is extremely long, in the sense discussed in [15]).

The most energetic mode of the POD is shown in Fig. 4c and Fig. 4d. It is characterized by a vortex centered in the middle of the gap. Similar modes have been found for a two rectangular channels connected by a narrow gap [15] as shown in Fig. 4b taken from [15]. Interestingly it is present both in experimental data [16] as shown in Fig. 4a and in computations (Fig 4b). It appears that the oscillatory behavior in the narrow gap is dominated by the waves shown in Fig. 4d which seem a quasi-universal pattern present in flows containing a narrow gap. Thus, Simulations show a remarkable success in reproducing the inherent structure of turbulence giving us additional confidence in the validity of the present approach.

5. Results for rod bundles

As a preliminary work we have performed the large eddy simulation of the flow in two-subchannels connected by a narrow gap (Fig. 5a) with periodic boundary conditions in the cross section and in the streamwise direction. Figure 5a displays a snapshot of the transverse velocity field in the cross section with a detail of the central gap. The vector plot shows a vortex positioned near the gap driving the cross flow between the two subchannels, thus mimicking the same phenomenon described previously for eccentric channels and other related geometries ([2]). This is even more evident if the instantaneous cross velocity profile is observed for case D (Fig. 6). The cross velocity has a sinusoidal behavior that is consistent with the principal mode of turbulence shown in Fig. 4.

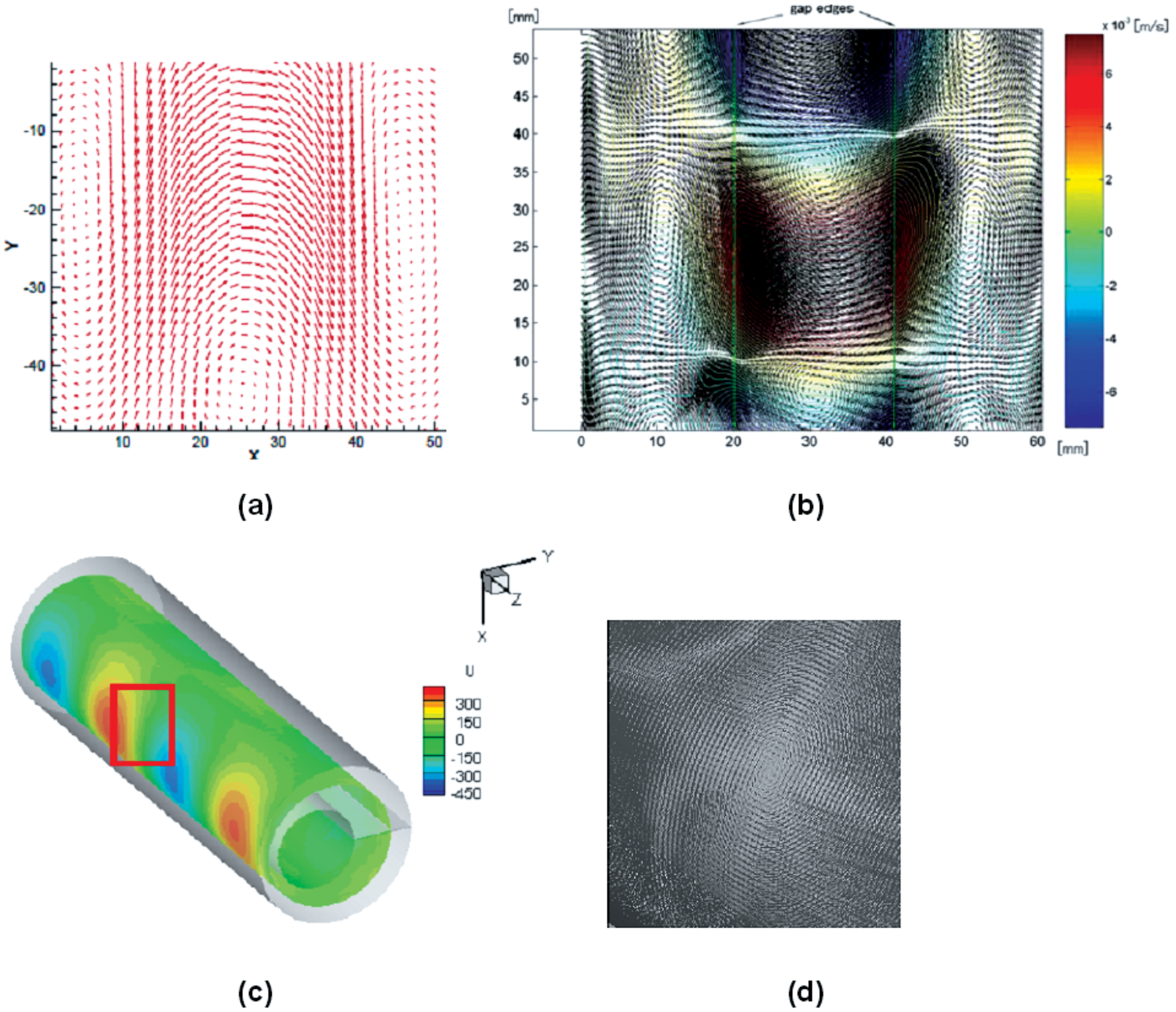

Fig. 4 Most unstable eigenmode (a) POD performed on experimental data on two rectangular channels connected by a narrow gap [16]; (b) POD performed on computational data on two rectangular channels connected by a narrow gap [15]; (c) POD performed on computational data on an eccentric channel (case A); and (d) detail and vector plot of the same mode of Figure 4c.

6. Conclusions

A LES code has been developed on the boundary fitted coordinates, with multi-block domain decomposition and a Dynamic SGS model for the flows in complex geometries, suitable for the simulation of fuel bundles and annular channels. The code has reproduced successfully the turbulent flow features, i.e., presence of secondary flows and the global flow pulsations common to both in annular channels and in rod-bundles. The comparison between Proper Orthogonal Decomposition conducted on experimental data and computational data has also given us confidence that the present methodology is able to reproduce the inner structure of turbulence in geometry containing a narrow gap.

7. References

[1] S.A. Jordan, "A Large Eddy simulation methodology in generalized curvilinear coordinates", *Journal of Computational Physics*, **Vol.148**, pp.322–340 (1999).

[2] S.A. Jordan, "Dynamic Subgrid-Scale Modeling for Large-Eddy Simulations in Complex Topologies", *Journal of Fluids Engineering*, **Vol.123**, 3, pp.619–627 (2001).

[3] E. Merzari and H. Ninokata, "Test of LES SGS models for the flow in annular channels", Proceedings of ICAPP 2007, Nice, France, 13–18 May, 2007.

[4] Y. Zang; R.L. Street, J.R. Koseff, "A non-staggered grid, fractional step method for time-dependent incompressible Navier-Stokes equations in curvilinear coordinates", *Journal of Computational Physics*, **Vol.114**, p.1 (1994).

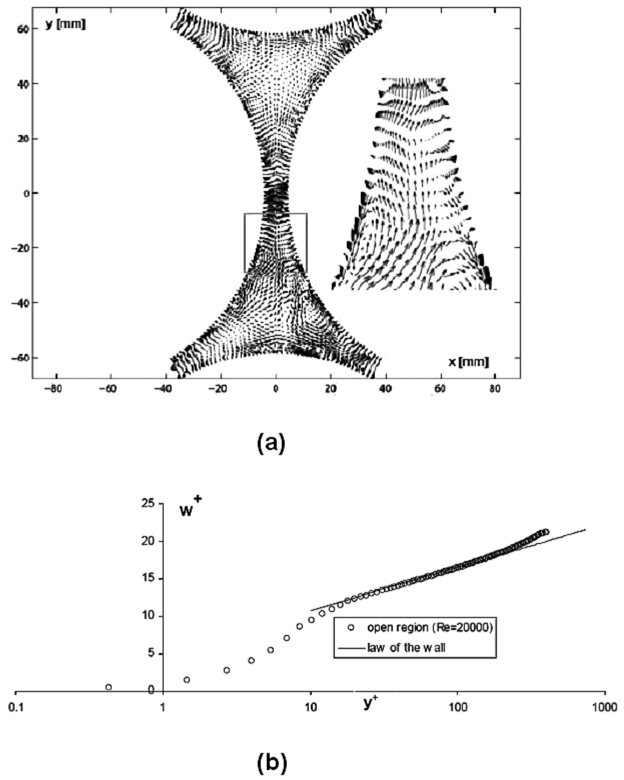

Fig. 5 (a) Snapshot of the velocity field in the cross section. Case F, (only 1/9 of the vectors are shown). (b) Streamwise velocity profile in wall units compared to the wall of the wall in the open region (maximum distance from the narrow gap).

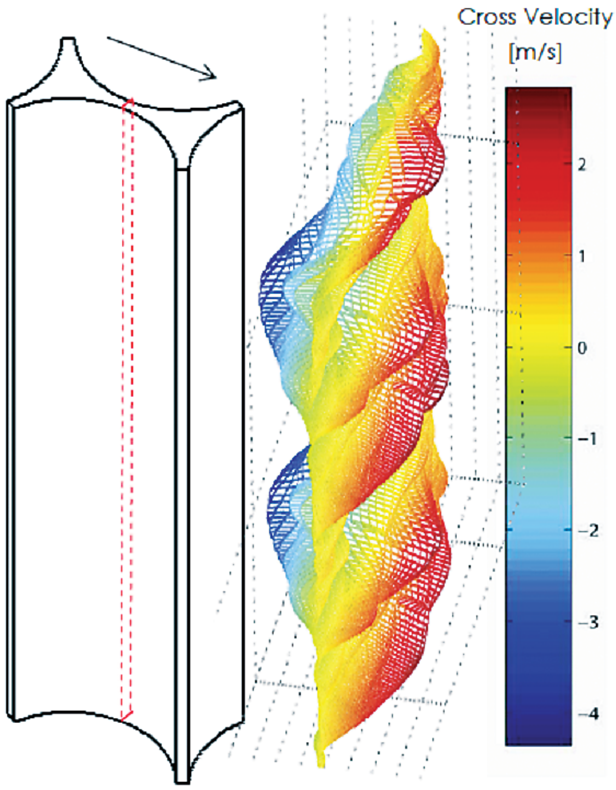

Fig. 6 Snapshot of the cross velocity.

[5] T. Suzuki and N. Kawamura, "Consistency of Finite - Difference Scheme in Direct Simulation of Turbulence", *Trans. JSME*, **Vol.60**, pp.578 (1994). (in Japanese)

[6] T.F. Chan and T.P. Mathew, "Domain Decomposition Algorithms", *Acta Numerica*, pp.61–143 (1994).

[7] D.R. Fokkema, G.L. Sleijpen, and H.A .Van der Vorst, "Generalized Conjugate Gradient Square", *Journal of Computational and Applied Mathematics* (1996).

[8] S.H. Lee, P. Jenny, and H.A. Tchelepi, "A finite-volume method with hexahedral multiblock grids for modeling flows in porus media", *Computational Geo-sciencies*, **Vol.6**, pp.353–379 (2002).

[9] N.V. Nikitin, "Direct Numerical Simulation of turbulent flows in eccentric pipes", *Computational Mathematics and Mathematical Physics*, **Vol.46**, pp.509–526 (2006).

[10] J.M. Nouri, H. Umur, and J.H. Whitelaw, "Flow of Newtonian and non-Newtonian fluids in concentric and eccentric annuli", *Journal of Fluid Mechanics*, **vol.253**, pp.617–64 (1993).

[11] S.Y. Chung, G.H. Rhee, and H. Sung, "Direct numerical simulation of turbulent concentric annular pipe flow Part 1: Flow field", *International Journal of Heat and Fluid Flow*, **vol.23**, pp.426–440 (2002).

[12] E. Merzari and H. Ninokata, "Anisotropy and Coherent Structures for the flow in Annular Channels", *Flow, Turbulence and Combustion*, DOI: 10.1007/s10494-008-9170-2 (in press).

[13] G. Berkooz, P. Holmes, J.L., and Lumley, The proper orthogonal decomposition in the analisys of turbulent flow, *Annual Reviews of Fluid Mechanics*, **25**, pp.539–575 (1993).

[14] L. Sirovich, Turbulence, and the dynamics of coherent structures, Part I: Coherent structures, *Quarterly of Applied mathematics*, **XLV**, pp.561–571 (1987).

[15] E. Merzari, H. Ninokata, and E. Baglietto, "Numerical Simulation of the Flow in Tight-Lattice Fuel Bundles", *Nuclear Engineering and Design*, **238**, pp.1703–1719 (2008).

[16] E. Merzari, H. Ninokta, A. Mahmood, and M. Rohde, "Proper Orthogonal Decomposition of The Flow in Geometries Containing a Narrow Gap", *Theoretical and Computational Fluids Dynamics* (accepted with revision).

LESによる二重円環流路および燃料集合体内の乱流計算

(Large Eddy Simulation of the Flows in Annular Channels and Rod Bundles)

プロジェクト責任者
二ノ方　寿　　東京工業大学　原子炉工学研究所

著者
Elia Merzari　東京工業大学　原子炉工学研究所
二ノ方　寿　　東京工業大学　原子炉工学研究所

本研究の目的は、流路チャンネルが複雑で実験計測上取得困難な詳細な流速分布、乱流特性などを高い信頼性の裏づけをもった直接乱流シミュレーション(DNS)および大渦シミュレーション(LES)によって提供し、現象の解明を実施するとともに現象の機構論的なモデル化を行って高速増殖炉などの集合体設計および原子炉安全性評価に必要な乱流熱流動データベースの構築に資するとともに工学的な応用に有効に活用することである。

複雑形状流路の典型である高速炉または低減速型軽水炉炉心における稠密格子配列型燃料集合体サブチャンネル内の乱流構造のRe数依存性や配列格子のピッチ対燃料直径比に対する依存性は現象論的に極めて複雑である。その現象解明を行うには計算科学的手法が唯一の手段と考えられる。稠密格子燃料集合体内サブチャネル内の乱流は、燃料要素間隔が狭いために壁の影響を強く受け、非等方性が強い。一般的に燃料集合体内の乱流は、P/Dの減少およびRe数が低くなると燃料間隙部近傍でその非均質性が増すとともに、局所的な乱流－層流遷移領域を含み、流れそのものが不安定となることが予測される。

本稿は、境界適合型座標系上のLESを用い、偏心二重円環流路内流路おける十分に発達した乱流と燃料集合体内流路における乱流挙動との類似性に着目して実施した解析結果に基づき、主流方向流れの時間平均流速分布、せん断応力、各揺らぎ成分のＲＭＳなどについて、これまでに得られている直接乱流シミュレーション結果および実験データと比較して十分な精度で一致していることの確認を行うとともに、流路形状の非一様性から生じる二次流れによって輸送される乱流渦の動的な挙動と主流方向における大局的な流れとの相互作用、これらの流路形状とRe数依存性の解明に関する報告である。とくに低Re数条件下では、狭隘ギャップ部における層流と乱流の遷移現象、軸方向スパンに見た大局的な乱流場におけるコヒーレントな振動モードを同定することができた。また、高Re数領域に至っては、等方的な乱流場へ移行し、こうした局所的な乱流－層流遷移現象および大局的な振動現象が消滅することを明らかにした。また、膨大な三次元時間依存の乱流計算結果の図形処理のみでは埋もれてしまう可能性がある物理情報の抽出に、POD(Proper Orthogonal Decomposition)を適用して複雑な乱流構造の動的な挙動を客観的に示すことにより、流動様式間の遷移、局所および大局の流れの振動モード発現のメカニズムを説明した。

キーワード：LES, POD, 偏心二重円環流路, 新型原子炉, 稠密格子