Numerical Simulation of Turbulent Sodium Flows in Subchannels of an LMFBR Fuel Subassembly

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

Isothermal and non-isothermal LES (Large Eddy Simulation) has been carried out to fully reproduce the characteristics of the flow field in eccentric annular channels, and rod bundles. 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 for both isothermal and buoyancy driven flows inside annular channels with different eccentricities. The agreement with experiment and DNS/LES results has been found good in both isothermal and buoyancy driven flows in annulus channels. 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, thus reproducing successfully the global pulsation phenomena in tight lattice rod bundles of LMFBRs.

Keywords: LES, Eccentric channel, Advanced Nuclear Systems, Tight Lattice, Global Pulsation

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. 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*

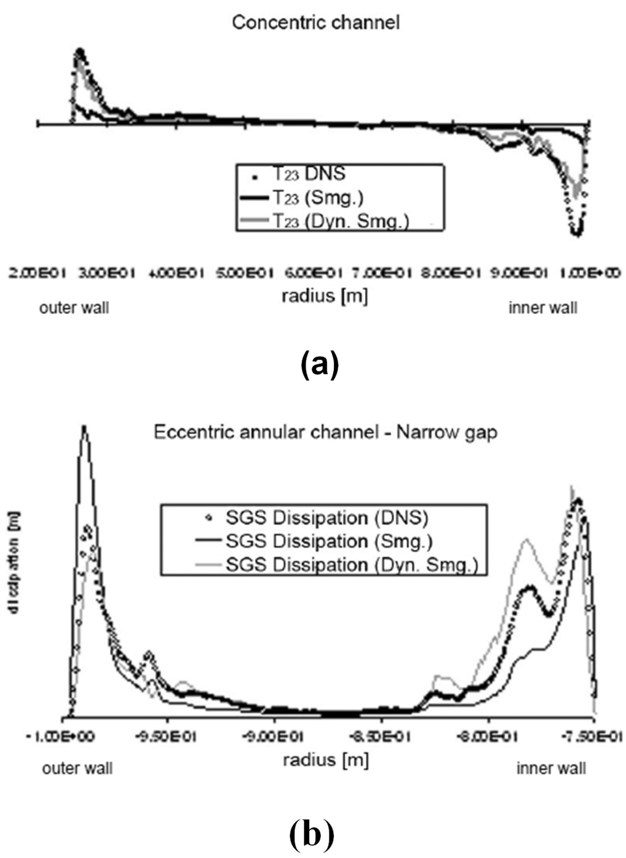

Fig. 1 A priori test for concentric and eccentric channels. Direct comparison for the stresses (a) and comparison for the SGS dissipation (b).

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 coupled with the energy equation 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 time 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 multi-grid preconditioning has also been implemented.

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]. 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 turbulence 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

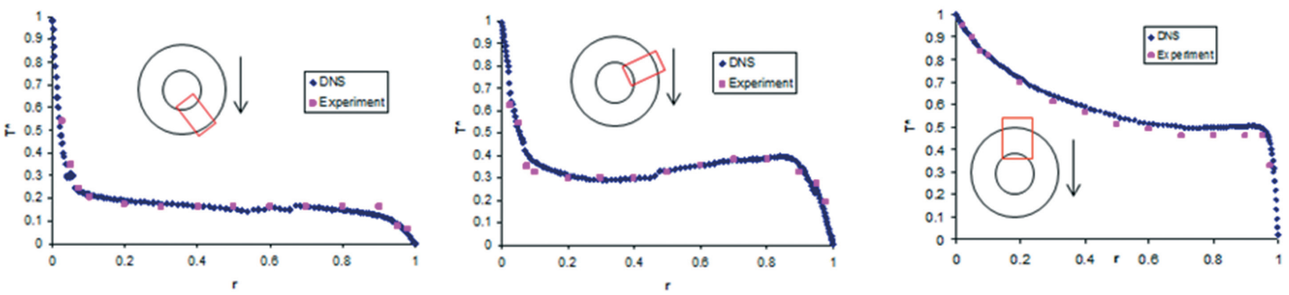

Fig. 2 Radial temperature distributions at different angle positions in the concentric annulus: comparisons of DNS and experiment.

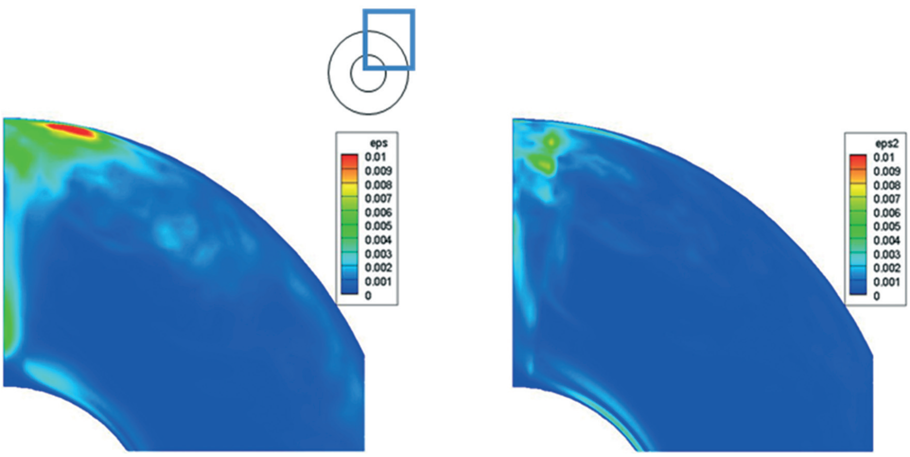

Fig. 3 SGS dissipation: DNS filtered (left) and Dynamic Smagorinsky (right).

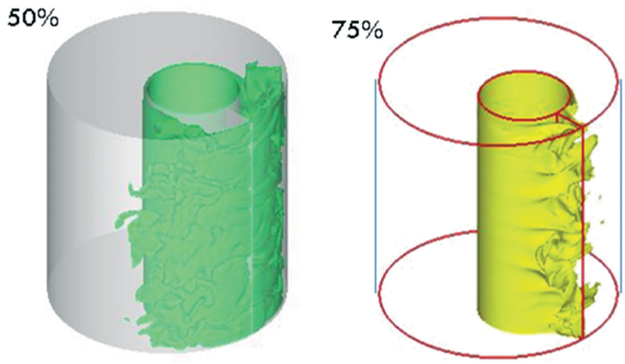

Fig. 4 Normalized temperature ($T^*= (T-T_{out})/(T_{out}-T_{in})$) contours in an eccentric channel: T^*=0.5 (left) and T^*=0.75 (right).

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.

For non-isothermal flows of Pr = 0.71 and Ra = 2,160,000, in a concentric annulus channel with Din/Dout = 0.6, the mesh sizes are chosen to be of the order of the Kolmogorov length scale. A total of 32 million meshes are employed to calculate velocity and temperature distributions inside the annulus. Figure 2 shows comparisons of time-averaged and normalized temperature distributions at different angles to demonstrate good agreement with experiment. In the SGS modeling of the energy equation, filtering introduces a source term which could be approximated by the additional variables to be proportional to the temperature gradient with the turbulent viscosity given by the SGS model and turbulent Prandtl number. Figure 3 compares the time average over 5 time steps (=0.0025s) of the DNS filtered dissipation with the LES with Dynamic Smagorinsky. Total number of meshes in the LES is about one million (1/30 of the DNS case). The agreement is found less satisfactory but still acceptable in the sense that the distributions are similar. This indicates the Smagorinsky model fails if no damping is employed. However the averaged stresses τ_{12} are found remarkably in good agreement between LES and DNS. We have also examined the alignment between the SGS soruce term introduced and the temperature gradient. There we find that the alignment is not particularly good, especially in the plume region where the stresses are more irregular. Figure 4 shows snapshots of temperature contours in the case wheere the narrow gap is on the upper side. It is shown the plume hits the upper wall resulting in high value of variance near the outer wall and stronger temperature fluctuations are generated even near the bottom of the outer wall. Assessment of the SGS modeling is still on-going and more computational results are being examined for eccentric annulus channels.

4. Results for rod bundles of LMFBRs

As a preliminary work we have performed the large eddy simulation of the flow in two-subchannels connected by a narrow gap for an infinite triangular lattice rod bundles, typical of fuel subassembly of sodium-cooled LMFBRs, with periodic boundary conditions in the cross section and in the streamwise direction. Figure 5 (a) streamlines and (b) contour plot for the cross flow velocity are a result of LES for a low Reynolds number turbulent flow (Re=5,500) in a tight lattice rod bundle with P/D=1.05 where P is the pin pitch and D is the rod diameter. The rectangles in (b) represent the regions where coherent structures can be clearly identified. The values are normalized by the 0.1 times the bulk velocity in the axial direction. The vector plot of the horizontal flow components 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]). The cross velocity has a sinusoidal behavior (Fig. 6) that is consistent with the principal mode of turbulence. This oscillatory behavior is called global flow pulsation and has been successfully reproduced by LES.

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 x 10^6	8	8
Case B	0.5	0.5	–	26600	768-300-768	2π	0.18 x 10^9	52	128
Case C	0.5	0.5	–	27100	512-300-512	2π	7.8 x 10^7	24	128
Case D	0.95	0.5	–	8700	256-64-128	2π	2 x 10^6	8	8
Case E	–	–	1.05	6800	(12ξ) 72-42-256	4π	0.9 x 10^7	16	32
Case F	–	–	1.05	20200	(12ξ) 152-99-512	4π	9.2 x10^7	24	128

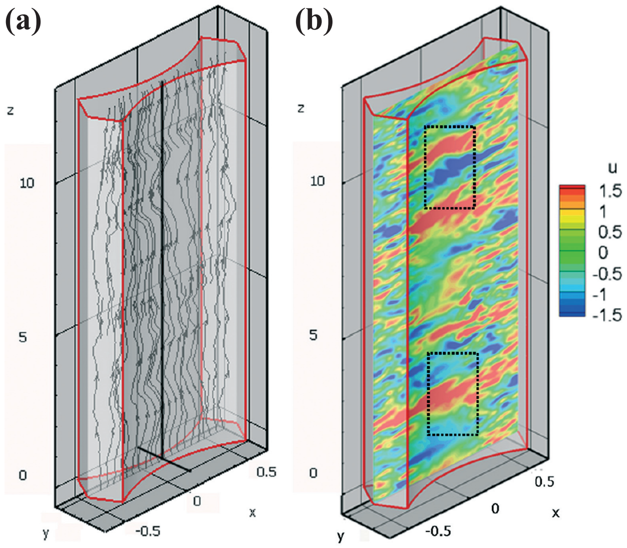

Fig. 5 (a) Streamlines (b) Contour plot for the instantaneous cross flow velocity in an infinite triangular lattice rod bundle P/D=1.05, Re=5,500.

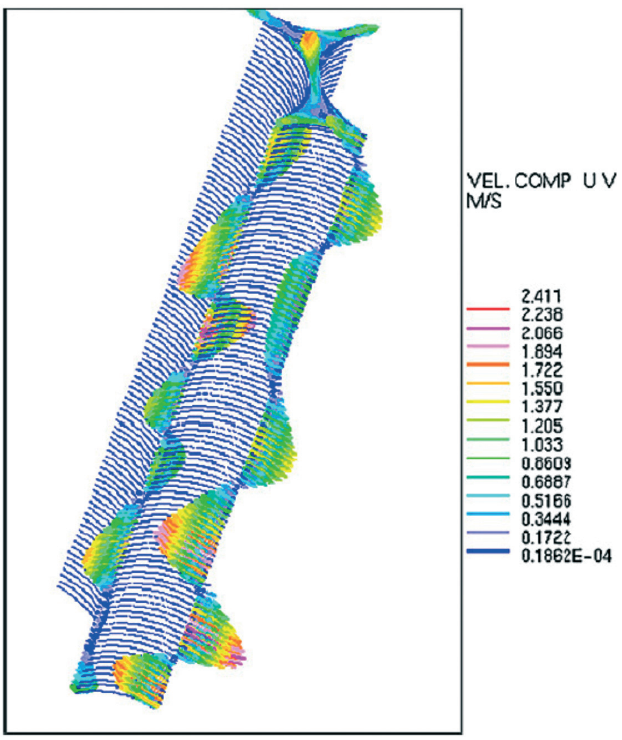

Fig. 6 Flow oscillation between subchannels and cross flow velocity components.

5. Conclusions

A LES code has been developed on the boundary fitted coordinates, with multi-block domain decomposition and a Dynamic SGS model for the isothermal and non-isothermal flows in complex geometries, suitable for the simulation of fuel bundles and annular channels. When applied to rod bundles, 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 tight lattice rod-bundles.

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高速増殖炉燃料集合体サブチャネル内ナトリウム冷却材の乱流シミュレーション

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 を用いた二重円環流路内流路おいて浮力が卓越する自然循環支配の流れ場に対する SGS モデルの検討と、DNS との比較においてモデルの妥当性を評価するとともに偏心二重円環流路内に生じる複雑な流れ場の解析の報告である。高速増殖炉の稠密格子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二重円環流路内乱流の解析結果に基づき、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、燃料集合体内の燃料と燃料との間の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示すグローバルパルセーション現象を同定することができた。

キーワード: LES, 偏心二重円環流路, 新型原子炉, 稠密格子, グローバルパルセーション