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Highly-resolved LES of turbulent convective flow along a PWR rod bundle

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ABSTRACT

A detailed numerical analysis of the turbulent convective flow along the heated rods of an idealized Pressurized Water Reactor (PWR) sub-channel is investigated using the CFD code TransAT. The flow is pretty much similar to circular pipe flow. Turbulent effects are predicted using highly-resolved Large-Eddy Simulation (LES) with a grid resolution of up to 6 million cells, resolving the viscous-affected layer. The sub-grid scale (SGS) viscosity produced by the model is indeed found to be of marginal effect for the grid and Reynolds number employed. Only first-order turbulence statistics are presented here. The results are discussed in detail, in particular key features specific to rod bundles, including low-Re effects in the narrow gap zone and the strong secondary flow motion, which is shown to exceed the turbulence counterpart (through the shear stress) near the wall. The secondary-flow motion induced by the mean flow is shown to be responsible for a large portion of the wall-to-flow heat transfer. The comparison of the LES results with existing DNS of pipe flow shows a very good agreement as to first-order statistics; higher-order statistics (including energy budgets) of the fluctuating fields have not been explored. A data basis has been generated for turbulence model comparison. Like in turbulent pipe flow, a physical explanation for the observed differences can be routed in the transverse curvature effects of the bundle geometry.

1. Introduction

The onset of nucleate boiling on solid wall occurs when the temperature of the wall slightly exceeds saturation [1]. The small vapor bubbles form and stay attached to the solid wall. Past the point of net vapor generation, the bubbles detach and remain trapped within a layer relatively close to the wall, beyond which – towards the core flow – they condense. Under turbulent conditions, the flow will be further affected by large and small eddies, affecting in turn the rate of wall-to-core-flow heat transfer and thus phase change, both near the wall (boiling) and far in the core flow (condensation). The first objective of this exercise is to assess the performance of the ITM/CFD code TransAT [2] in predicting the turbulent convective flow upward along the heated rods of a PWR sub-channel. The key predicted quantity is the length at which the rod surface temperature reaches nucleation temperature, approximated here as the saturation temperature. For simplicity, we refer to it as the distance to the onset of nucleate boiling (X_{ONB}). Predicting this quantity correctly requires accurate prediction of turbulent flow, since the wall temperature is strongly dependent on the flow structures, its unsteadiness and the rate of turbulent-stresses anisotropy. The problem is inspired by the PSBT (short for PWR Sub-channel and Bundle Tests) single sub-channel benchmark. The onset of nucleate boiling on the nuclear rod surface is one of many other complex mechanisms that pose challenges to the modellers [4]. Without listing all the features associated with turbulent flow in narrow gaps of sub-channels, it is perhaps useful to evoke the most important ones which the authors believe as key issues in modelling using mainstream CFD. The reader may refer to the review paper of Rehme [5] compiling early research findings on the subject, who has also noted the flow along a rod bundle is pretty much similar to circular pipe flow. Early experiments [6] revealed the existence of macroscopic pulsating flow structures (not necessarily turbulence) in the regions adjacent to the gaps, with strong implications on the mixing between adjacent sub-channels. This phenomenon was proved later on by Meyer [7]. Other important features were identified experimentally as marked characteristics of flow along rod bundles [8,9], including secondary flow motion and large-scale turbulent motions enhancing heat extraction from the heated wall.

Clearly, there are incentives to resort to 3D CFD for the prediction of the detailed fluid flow and temperature distribution in rod

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bundles for safety issues and operational reliability of the fuel elements. Sub channel analysis ignores the fine structures of velocity and temperature distributions in the flow passages, and can thus not account for mixing effects caused by the presence of spacers or other geometrical disturbances. Large-scale turbulent motion and larger periodic pulsating structures responsible for mixing between sub-channels are out of reach of steady state approaches resorting to statistical averaged models [10]. Further, secondary flow motion could be predicted using anisotropic models (to a limited degree though) or full Reynolds stress models only. While the velocity magnitude associated with secondary flow moving within the elementary cells of the sub-channels maybe small (of the order of 10%) compared to the axial one, its implication on heat transfer is important, in particular near the wall, which appeals for the use of wall-resolved strategies. LES of turbulent flow along rod bundles are indeed rare in the literature, with the exception of the Japanese group [11–13] who produced several interesting contributions to the subject. Other contributions to the subject include the work of Merzari et al. [14] and Ninokata et al. [15].

We present the results of a LES and highly-resolved LES of turbulent convective flow upward along the heated rods of an idealized PWR sub-channel. The selected test-case is inspired by the PSBT single sub-channel benchmark [3], in terms of radial dimensions in particular, albeit the deliverables are different from the actual PSBT case. The focus here is on detailed flow profiles and temperature at the wall rather than on global parameters as required in the benchmark. The operating conditions selected here are made on purpose different from PSBT, namely the power, which has been adjusted according to the reduced length (1m instead of 3.65 m). The second objective is to provide a rich data basis to help assess the predictive performance of practical turbulence models to predict mean and RMS profiles, stresses and turbulent fluxes, wall temperature at which saturation conditions are reached.

2. Modelling

This work used the CFD code TransAT© developed at ASCOMP, which is a multi-scale, multi-physics, conservative finite-volume solver for single- and multi-fluid Navier-Stokes equations. The grid arrangement is collocated, and the solver is pressure based (Projection Type), corrected via density for compressible flows. Turbulent flows can be treated in two ways: RANS statistical models and Scale Resolving Approaches like LES and its DES and V-LES variants. LES is built within a dedicated version, with specific routines for pressure coupling, boundary conditions, diffusive fluxes and near-wall stress integration. A 2nd order implicit scheme is used for time marching. The solvers employed for pressure-velocity coupling include: GMRES, GMG & AMG, from the PETSc solver library. In LES the motion of the super-grid turbulent eddies is directly captured, whereas the effect of the smaller scale eddies is modeled or represented statistically by means of simple models, very much the same way as in Reynolds-averaged models (RANS); i.e. the usual practice is to model the sub-grid stress tensor by an eddy viscosity model. The code TransAT proved very efficient for LES and DNS problems [16].

2.1. Highly-resolved LES

A full DNS of this flow is difficult if one takes as reference published DNS of turbulent channel flow performed in Cartesian grids. The reasons are obvious: (i) the high Reynolds number typical to PWR's would require grids of hundreds (up to the billion) of million cells, in particular because the near-wall resolution is key in this context, and (ii), the complex bounding geometry implies use of non-Cartesian grids, which add numerical diffusion to the discretization scheme, unless use is made of the Immersed Boundary Technique [12]. The resort to LES [17] is thus a pragmatic and defendable choice, but the meshing level or concentration may be an issue and has to be clarified first. Indeed, while a coarse mesh would not allow predicting a large portion of the structures, a very fine mesh could return results that are close to DNS in that the non-resolved eddy viscosity is marginally important; this is the essence of the so-called 'Highly-resolved LES', which applies as a simple definition to problems in which the ratio of eddy to molecular viscosity does not exceed 1.5–2, in comparison with conventional LES where this ratio should fall in the range 5–10. Other measures have been introduced, including comparing the subgrid-scale eddy viscosity to the resolved turbulence.

2.2. The filtered LES equations

In LES the motion of the super-grid turbulent eddies is directly captured whereas the effect of the smaller scale eddies is modeled or represented statistically by means of simple zero-equation models, very much the same way as in Reynolds-averaged models (RANS); i.e. the usual practice is to model the sub-grid stress tensor by an eddy viscosity model. In terms of computational cost, LES lies between RANS and DNS and is motivated by the limitations of each of these approaches. Since the large-scale unsteady motions are represented explicitly, LES is more accurate and reliable than RANS.

LES involves the use of a spatial filtering operation $\overline{F}(x,t) = \int_{-\infty}^{\infty} F(\boldsymbol{x}',t)G(\boldsymbol{x}-\boldsymbol{x}')d\boldsymbol{x}'$, where the fluctuation of any variable $F(\boldsymbol{x},t)$ from its filtered value is denoted by $f' = \overline{\mathrm{F}} - \mathrm{F}$. Filter function $G(\boldsymbol{x}-\boldsymbol{x}')$ is invariant in time and space, and is localized, and obeys the properties: $G(\boldsymbol{x}) = G(-\boldsymbol{x})$, and $\int_{-\infty}^{\infty} G(\boldsymbol{x})dx = 1$. Applying the filtering operation to the instantaneous Navier-Stokes equations under incompressible flow conditions leads to the system of filtered transport equations for turbulent convective flow (the equations are well known and are not repeated here), which involve the so-called SGS stress tensor and turbulent heat flux defined as:

$$\tau_{ij} \equiv \overline{\rho}(\overline{u_i u_j} - \overline{u_i}\,\overline{u_j}); \quad q_j'' \equiv \overline{\rho}(\overline{T u_j} - \overline{T}\,\overline{u_j}) \tag{1}$$

Only the deviatory part of the SGS stress tensor is to be modeled using a statistical approach similar to RANS. This way, turbulent scales larger than the grid size are directly solved, whereas the effects of SGS scales are modeled.

2.3. SGS modeling

LES is based on the concept of filtering the flow field by means of a convolution product. The specific super-grid part of the flow with its turbulent fluctuating content is directly predicted whereas the sub-grid scale (SGS) part is modeled, assuming that these scales are more homogeneous and universal in behavior. For turbulent flows featuring a clear inertial subrange the modeling of the SGS terms in the statistical sense could thus safely borrow ideas from the RANS context, in particular use of the zero-equation model to mimic the momentum diffusive effects on the resolved field. Use is generally made of the Eddy Viscosity Concept, linking linearly the SGS eddy viscosity and thermal diffusivity to the gradients of the filtered velocity and temperature, respectively:

$$\begin{aligned} &\tau_{ij} = -2\mu_{sgs}\overline{S_{ij}} + \frac{1}{3}\delta_{ij}\tau_{ll}; \quad \mu_{sgs} = (Cs\Delta)^2\overline{\rho}|\overline{S}|^2 \\ &q_j'' = -\alpha_\theta \frac{\partial \overline{T}}{\partial x_j}; \quad \alpha_\theta = \frac{\mu_{sgs}}{\mathrm{Pr}_t} \end{aligned} \tag{2}$$

The closure for the eddy viscosity above follows in general the Smagorinsky kernel model, linking the eddy viscosity to the square of a length scale and a time scale (the inverse of the second