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Quasi-direct numerical simulation of a pebble bed configuration, Part-II: Temperature field analysis

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HIGHLIGHTS

- Quasi direct numerical simulations (q-DNSs) of a pebble bed configuration have been performed.
- This q-DNS database may serve as a reference for the validation of different turbulence modeling approaches.
- A wide range of qualitative and quantitative data throughout the computational domain has been generated.
- Results for mean, RMS of temperature and respective turbulent heat fluxes are extensively reported in this paper.

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ABSTRACT

Good prediction of the flow and heat transfer phenomena in the pebble bed core of a high temperature reactor (HTR) is a challenge for available turbulence models, which still require to be validated. While experimental data are generally desirable in this validation process, due to the complex geometric configuration and measurement difficulties, a very limited amount of data is currently available. On the other hand, direct numerical simulation (DNS) is considered an accurate simulation technique, which may serve as an alternative for validating turbulence models. In the framework of the present study, quasi-direct numerical simulation (q-DNS) of a single face cubic centered pebble bed is performed, which will serve as a reference for the validation of different turbulence modeling approaches in order to perform calculations for a randomly arranged pebble bed. These simulations were performed at a Reynolds number of 3088, based on pebble diameter, with a porosity level of 0.42. Results related to flow field (mean, RMS and covariance of velocity) have been presented in Part-I, whereas, in the present article, we focus our attention to the analysis of the temperature field. A wide range of qualitative and quantitative data for the thermal field (mean, RMS and turbulent heat flux) has been generated.

1. Introduction

In addition to experimental techniques, in the last decades direct numerical simulation (DNS) has shown to be a useful tool not only for turbulent research but also more widely for providing detailed and time-accurate information about the fluid behaviour. The very large computation requirements however are still a major constraints to the simulation of complex turbulent flows in realistic geometrical configurations. One such example is the simulation of a high temperature reactors (HTR) core, which consists of around thirty thousand (30,000) spherical pebbles and exhibits a complex flow and heat transfer behavior (Janse van Rensburg and Kleingeld, 2011). The heat transfer around the curved pebble surfaces varies noticeably for both laminar and turbulent flow regimes. The wire-melt experiments in the Arbeitsgemeinschaft Versuchs Reaktor (AVR) in Germany, recently reported by Moormann (2008), have indicated that excessive pebble temperatures could be reached in certain flow conditions. A possible explanation to the unexpectedly high temperatures is the appearance of local hot spots, as a consequence of the complex turbulence phenomena, which could in fact affect the pebble integrity. The variation in the turbulence level while flow accelerates in the narrow gap regions has a drastic influence on the local heat transfer, and moreover, the pressure gradients have a very strong influence on the appearance of boundary layers therefore making the flow regime even more complex to predict (Shams et al., 2012).

While it is not possible to perform DNS of a realistic pebble bed configuration, turbulence modelling approaches (such as LES, URANS and hybrid RANS/LES methods) allow reducing the computational cost and make simulation of such complex turbulent flows feasible. However, prediction capabilities of modelling approaches

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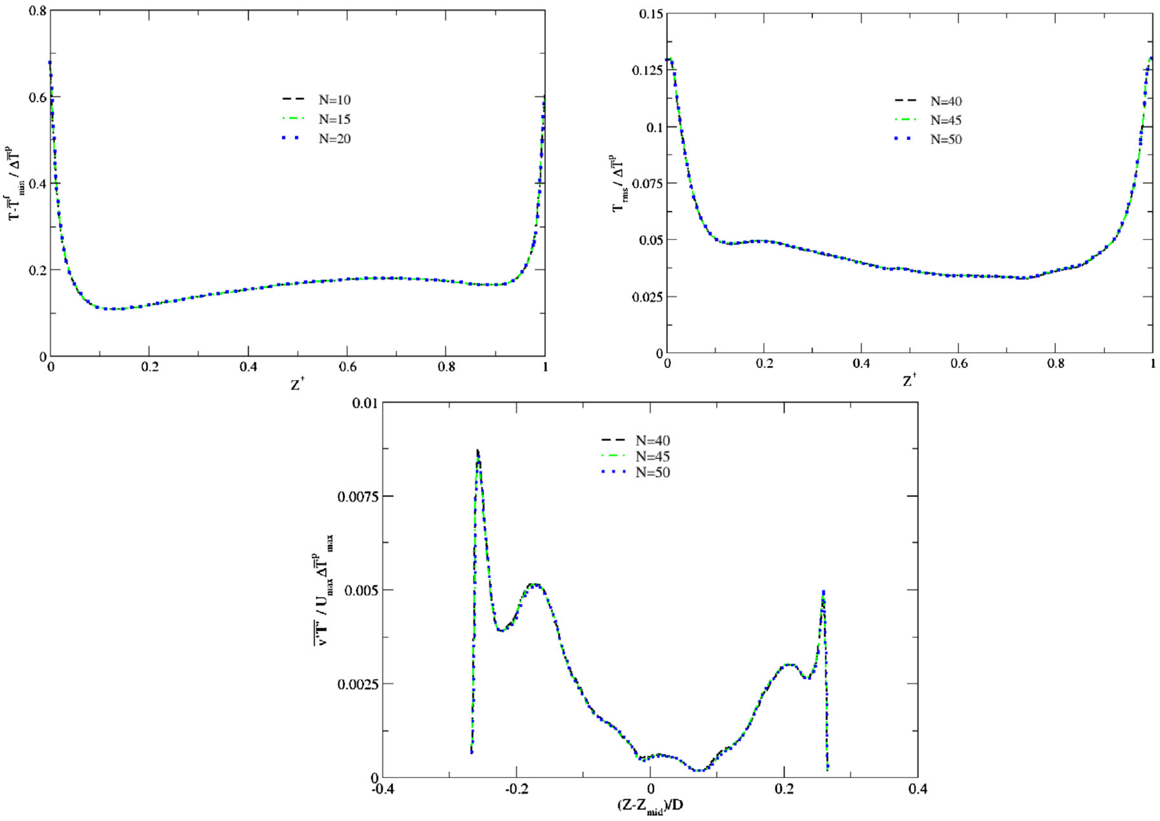

Fig. 1. Evolution of mean temperature for 10, 15 and 20 flow through times (top: left) and RMS of temperature (top: right) and turbulent heat flux of principle velocity component (bottom) for 40, 45 and 50 flow through times, respectively.

for such a complex flow are still questionable. In order to gain confidence in the accuracy of various turbulence models, their validation is a fundamental step and needs to be performed. A small number of experiments have been performed, and due to the geometrical complexities a very limited amount of data is still available (Dominguez et al., 2008; Lee and Lee, 2008, 2010). Recently, a detailed study has been performed by Shams et al. (2012) to optimize the pebble bed configuration in order to perform DNS type calculations. This study provides a very complete picture on to the influence of boundary conditions, computational domain, meshing and all related constraints that should be respected in order to obtain a database of sufficient accuracy, and which can serve for turbulence modeling validation.

Following the guidelines provided by Shams et al. (2012) quasi direct numerical simulation of a single cubic structured pebble bed configuration has been performed. Detailed investigation of flow and temperature fields has been performed and the flow field results were reported in Part-I of this work (Shams et al., submitted for publication). In the present Part-II, results related to the temperature field are presented and discussed in detail. An extensive database for the temperature field is documented in Section 3, and conclusive remarks projected on the existing results are also reported.

2. Case description

In the present study, the flow parameters adopted for the simulations are derived from the PBMR-250MWth design data (Lee and Lee, 2008, 2010). Helium is adopted as a working fluid with a density, viscosity, thermal conductivity and specific heat of 5.36 kg/m^3, 3.69×10^{-5} N s/m^2, 0.3047 W/m K and 5441.6 J/kg K, respectively. Following the domain optimization study of Shams et al. (2012) a scaled mass flow rate of 0.016 kg/s is used, which gives a Reynolds number of 3088 based on the pebble diameter. The imposed inlet temperature is 737 K with a heat flux of 8317 W/m^2. Tri-periodic boundary conditions are imposed for mass flow rate and temperature. For all details regarding the boundary conditions and flow parameters readers are referred to Part-I of this article (Shams et al., submitted for publication).

3. Results and discussion

Following the same approach adopted for the flow field analysis (Shams et al., submitted for publication), particular attention was devoted to ensuring that statistically converged mean and RMS fields where obtained for the fully developed temperature field. The average inlet velocity (i.e. 0.35 m/s) is used to define the flow through times for the computational domain. Fig. 1 (left), shows the evolution of the time averaged (mean) temperature profile along the center of the domain for three different time averaged values, i.e. after 10, 15 and 20 flow through times, and where the temperature field is non-dimensionalized by the minimum predicted fluid temperature (T^f_{min}), i.e. 771 K, and the mean temperature difference ($\Delta\bar{T}^p$) appearing on the pebble surface, i.e. 32 K. The results confirm that the mean temperature is statistically converged, on the other hand, statistical convergence for RMS values required considerably longer integration time. The time averaged RMS of temperature for 40, 45 and 50 flow through times is shown in Fig. 1 (right). A close analysis for statistical convergence gives a maximum difference (in %) between N40–N45, N40–N50 and N45–N50 of 0.3, 0.3 and 0.2, respectively, whereas, the average differences (in %) between N40–N45, N40–N50 and N45–N50 are 0.03, 0.05 and 0.02,indicating that the thermal field has reached sufficient statistical convergence for temperature RMS. Moreover, time averaged