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Augmented Heat Transport of Mono-Sized Sphere-Packed Pipe for Force Free Helical Reactor

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1. Introduction

The sphere-packed pipe (SPP) consists of metal spheres inside a pipe which has been proposed as a heat transfer booster for the high Prandtl (Pr) number fluid [1-3]. One of the potential applications of SPP is using it at the first wall of Force Free Helical Reactor (FFHR) [1-4]. The first wall of FFHR is expected to be exposed to a high thermal load of about 1 MW/m^2, which will be removed by a high temperature molten salt "Flibe" flow. "Flibe," a mixture of LiF and BeF$_2$, has advantages of high heat capacity and reduced magnetohydrodynamic (MHD) pressure drop due to low electric conductivity [3]. In the design of the FFHR blanket a heat transfer coefficient above 20,000 W/m^{2}K is required to remove the high heat flux [2].

This computational fluid dynamics (CFD) analysis aims to evaluate the flow structures and heat transfer characteristics in SPP resorting to ANSYS CFX 12.1.

2. Methods and Results

2.1 Numerical Simulation

A 600 mm SPP with internal diameter D of 56mm filled with 64 mono-sized spheres of diameter d of 27.6 mm is considered to assess flow characteristics (Fig. 1). The porosity is 0.508. Unstructured meshes are applied to discretize the CFD domain. The working fluid enters with a constant velocity U_o and uniform temperature T_o at the inlet whereas the outlet boundary condition was taken to be a constant pressure $p = 0$ for simplicity. No slip boundary condition was assumed at the wall as well as on the spheres surfaces. It is assumed that the fluid flow in SPP is incompressible. Fully developed flow is expected of the CFD domain.

For $D/d > 1.4$ and the Reynolds number $Re_d > 120$ (Re_d is defined based on the sphere size) the flow in SPP is in the turbulent regime [5]. The shear stress transport (SST) k–ω models are used for turbulence simulation. In order to validate the CFD model Re and thermal boundary condition were chosen to match Re of the available experimental data [3].

A residual root-mean-square (RMS) target value of 10^{-5} (10^{-8} for the energy equation) was defined for the CFD simulations to ensure complete convergence. The dimensionless wall distance y^+ for the near wall cells is in the reasonable range. The temperature-dependent thermophysical properties of the working fluid taken from the IAPWS-IF97 water data are implemented in ANSYS CFX 12.1.

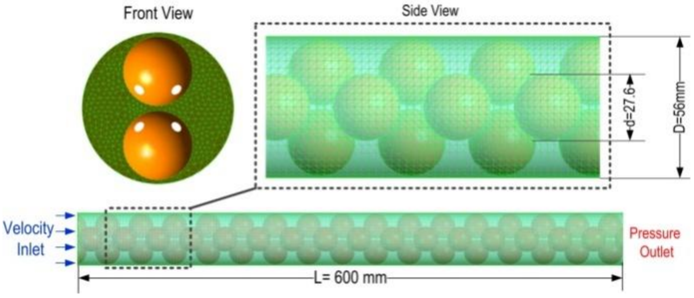


Fig. 1. CFD domain and corresponding boundary conditions and meshes.

2.2 CFD Results

Pressure drop measured between the bottom and top of SPP is normalized by the length of SPP. The CFD prediction is compared against the Seto et al. [3] test data and the Ergun [6] correlation in Fig. 2. Observe that the CFX results coincide with Seto et al.'s test data [3] and Watanabe [7]. Ergun's correlation overestimates the CFX predictions for the pressure drop.

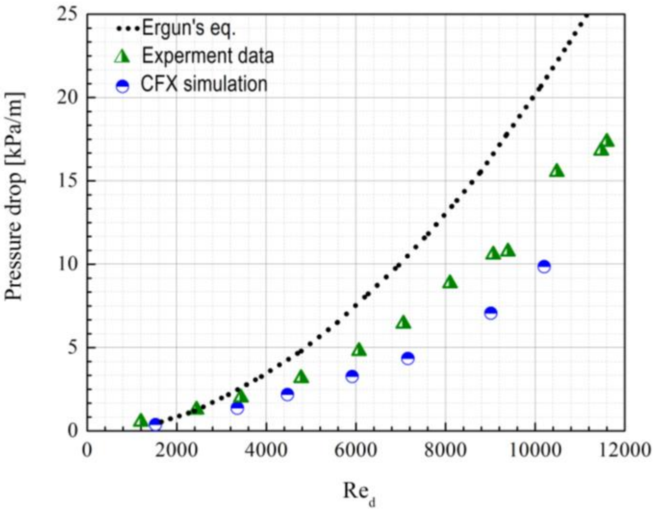


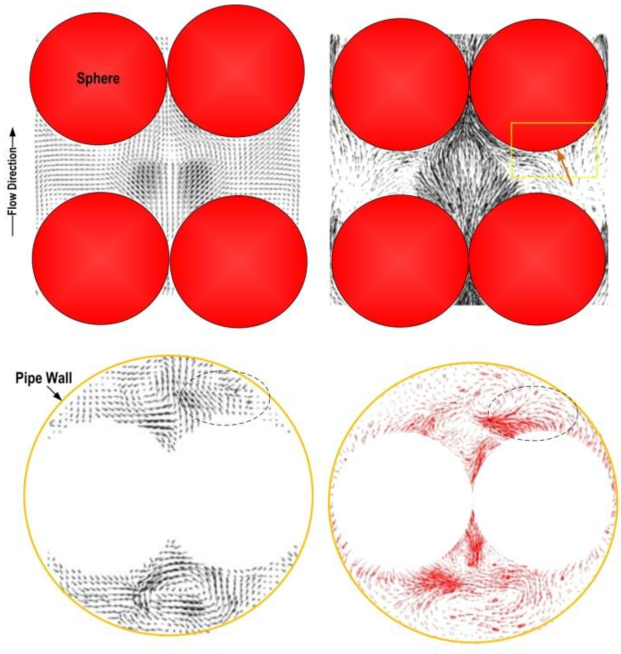
Fig. 2. Normalized pressure drop along the SPP.

This inconsistency may attribute to the differences in the packing structure in Ergun's and the CFD model. However, the CFD and experimental data of Seto et al. [3] show a strong correlation, with the CFD marginally underpredicting the pressure drop. Moreover, the flow near the pipe wall noticeably affects the pressure drop characteristics under the high-particle *Re* conditions [3].

The FFHR blanket, including SPP cooling system, is practically exposed to a high magnetic field, which causes a MHD pressure drop [2, 3]. The reduction in the MHD pressure drop is one of the prime concerns for the design of the FFHR blanket, including the SPP cooling system. The MHD pressure drop is highly correlated to the coolant velocity. Moreover, the electrolysis of Flibe may occur under the high flow rate conditions [3]. Considering the above explanation the SPP cooling system with a low flow rate might be more appropriate with regard to reducing the MHD effect and electrolysis FFHR blanket.

Figure 3 compares the flow field for the experiment and the CFX simulation at Re_d = 4900. The stagnation points are clearly shown on the sphere surface which may lead to a hot spot.

Figure 4 illustrates the heat transfer coefficient *h* compared against the heat transfer characteristics in the straight pipe with the same internal diameter calculated by the Gnielinski [8] correlation for a fully developed turbulent flow. Note that the heat transfer performance of the SPPs is on average about eight times greater than that of the straight pipe. This implies that the SPP is appropriate heat transfer promoter in reducing the MHD pressure drop and the electrolysis effect.



Experiment [3]　Ansys CFX 12.1

Fig. 3. Flow field for ANSYS CFX simulation compared with experiment [3] (Re_d = 4900).

3. Conclusions

The heat transfer performance of the SPPs is on average eight times greater than that of the straight pipe. A modified correlation is required which considers the SPP packing structure and wall effect to determine the accurate pressure drop.

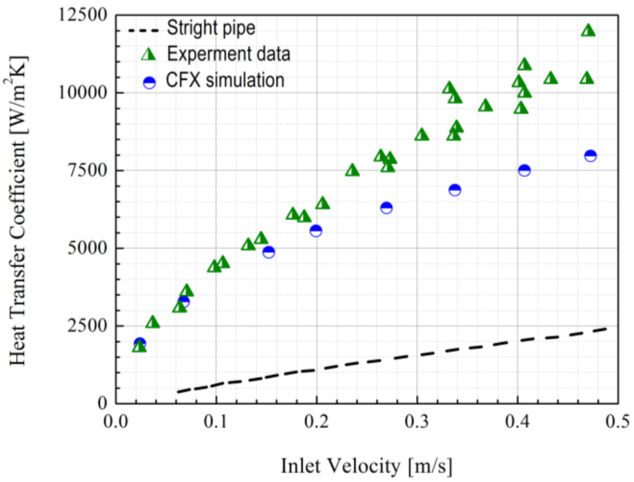


Fig. 4. Effect of the flow velocity on the heat transfer coefficients.

Acknowledgments

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