Two-fluid models: A computational platform to analyze coupled thermal and shear effects in dense suspension flows

Pranay P. Nagrani[1], Federico Municchi[2], Amy M. Marconnet[1]*, Ivan C. Christov[1†]

[1] *School of Mechanical Engineering, Purdue University, West Lafayette, Indiana 47907, USA*

[2] *Faculty of Engineering and School of Mathematical Sciences, University of Nottingham, University Park, Nottingham NG7 2RD, UK*

Flows of dense suspensions are important to a number of terrestrial and extraterrestrial technologies including life support systems and cooling of electronic devices. Here, we develop a two-fluid model (TFM) to simulate the particle migration phenomenon in non-Brownian dense suspense flows. The TFM is implemented as solver in the open-source computational framework of OpenFOAM®. We incorporate stress heterogeneity of dense suspension under shear based on the established phenomenological models of viscosity and normal stress. We incorporate thermal transport in the dense suspensions by developing a novel closure relation for inter-phase heat transfer coefficient in the TFM. The closure relation is calibrated successfully against a prior experiment on flow in a concentric Couette cell from the literature. We demonstrate how a thermo-rheological flux term can be deduced from the TFM, in addition to shear-induced flux, to understand the coupling of shear and thermal gradients in the system on particle migration. The interplay between heat transfer and shear migration was studied computationally by imposing shear in the system via rotation of the inner cylinder of Couette cell for two different thermal boundary conditions: $\Delta T < 0$ and $\Delta T > 0$, where $\Delta T = (T_{\text{in}} - T_{out})$ is the temperature difference across the gap, while T_{in} and T_{out} are temperatures at the inner and outer walls of the Couette cell. A novel effect was found for $\Delta T > 0$: that the shear- and thermal-induced migration fluxes act in opposite direction to cancel the net particle migration. Meanwhile, for $\Delta T < 0$, the fluxes act in the same direction to aid the particle migration. Next, we studied the particle migration phenomenon in an eccentric Couette cell system. We observed that, for $\Delta T > 0$, the Nusselt number Nu increases with eccentricity owing to secondary flow in the system. Meanwhile, for $\Delta T < 0$, there exists a maximum for Nu, after which it decreases due to enhanced particle migration and large flow re-circulation zones. Finally, we employed the proposed computational TFM framework to analyze electronics cooling by forced convection for microchannel cooling. We used a suspensions of high thermal conductivity (Boron Nitride) particles in an example 3M™ Fluorinert™ FC-43 cooling fluid. Three-dimensional simulations were run to quantify the temperature distributions under uniform heating (5 W) and under hot-spot heating (2 W/cm^2) conditions at the lower wall of the microchannels. A 100 K junction level temperature improvement (enhanced thermal spreading) was seen for hot-spot heating and 10 K was observed for uniform heating, demonstrating the enhanced cooling capabilities of dense particulate suspensions of high-conductivity particles, over a clear FC-43 fluid.

*marconnet@purdue.edu

†christov@purdue.edu