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Conjugate heat transfer in turbulent liquid metal flows in pipes

Jonathan Neuhauser[*], Jonathan Schmitt[*], Davide Gatti[*], Luca Marocco[†], Bettina Frohnapfel[*]

Liquid metals are a promising working fluid for concentrated solar power plants (CSPs) due to their high thermal diffusivity and melting point, allowing for elevated process temperatures and thus higher efficiency. The design of such plants require accurate modeling of the heat transfer and distribution of thermal loads, but established correlations for heat transfer in turbulent flows are not well-suited for low-Pr fluids such as liquid metals. Azimuthally inhomogeneous heat flux, as usually encountered in CSPs, adds further complexity as models are not calibrated for this case.

So far, numerical studies assessed the influence of thermal boundary conditions on the fluid domain [1]. Therefore, We present a high-fidelity numerical database for conjugate heat transfer (CHT) in turbulent liquid metal flows over a range of Re numbers, a setup for which recent experimental work is available[2]. The data has been acquired using the spectral element code NekRS[3]. The simulations are conducted as Thermal direct numerical simulation (DNS), i.e. the temperature fields are fully-resolved to eliminate the need for thermal subgrid modeling. The DNS data is exploited to appraise various RANS models for the turbulent heat transfer in low-Pr fluids, which we re-implemented and validated in the open-source code OpenFOAM. Conjugate heat transfer adds three dimensionless parameters to Re and Pr: the ratio of thermal conductivities $G_2 = \lambda_s/\lambda_f$, the thermal activity ratio $K = \sqrt{\rho_f c_{p,f} \lambda_f} / \sqrt{\rho_s c_{p,s} \lambda_s}$ and the ratio of diameters D/d.

Figures 1a) and b) show the covariance of dimensionless temperature $\langle \theta' \theta' \rangle^+$ in wall units for $\mathrm{Pr} = 0.025$ and $\mathrm{Pr} = 0.71$ (Air) over a range of K for $Re_b = U_b d/\nu = 5300$ alongside the curves for the limiting cases[2] of constant heat flux (IF) and mixed boundary condition (MBC) applied to the fluid domain. The value of K clearly governs the RMS of the temperature fluctuations near and within the wall, with higher values of K corresponding to higher temperature RMS. In general, temperature fluctuations penetrate the wall much more for the case of $\mathrm{Pr} = 0.025$ compared to $\mathrm{Pr} = 0.71$, which is also prominently visible in the instantaneous snapshot of the temperature fluctuations (Figure 1c). As expected, the characteristic scales of temperature fluctuations are much larger for low-Pr.

Until the conference, we plan to extend this dataset for cases of inhomogeneous heating and higher Re, allowing for direct comparison with the available experimental data[1]. We will also assess the suitability of established turbulent heat flux models for the present case and possibly extend those models towards CHT.

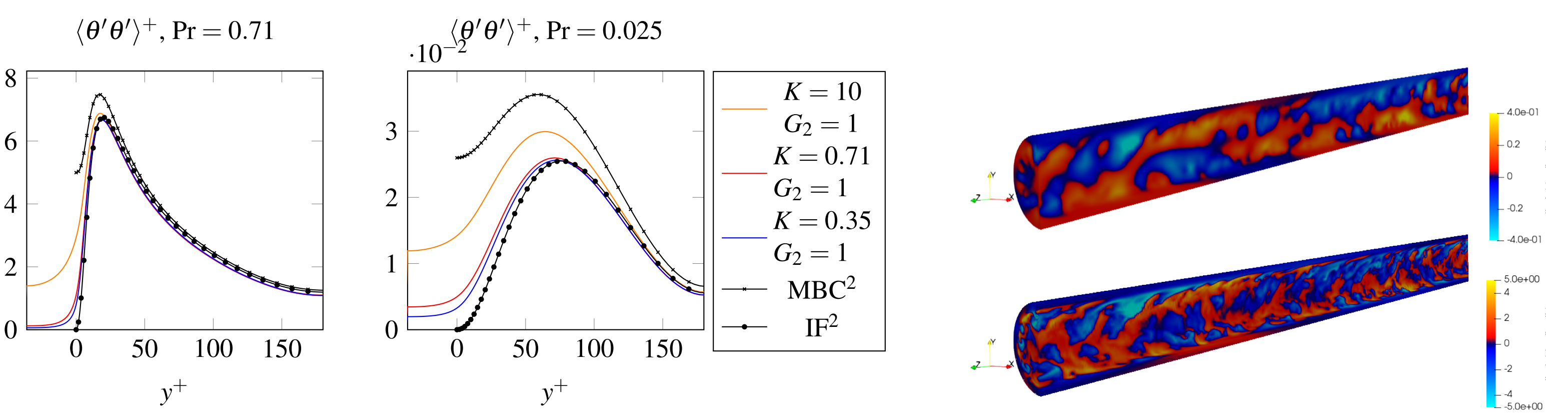

Figure 1: a) and b) Temperature cross-correlation for $\mathrm{Pr} = 0.71$ and $\mathrm{Pr} = 0.025$ for different values of K, c): Snapshots of instantaneous fluctuations for $K = G_2 = 1$ (top: $\mathrm{Pr} = 0.025$, bottom: $\mathrm{Pr} = 0.71$). $D/d = 1.1$.

[*]Institute of Fluid Mechanics, Karlsruhe Institute of Technology, Kaiserstraße 10, 76131 Karlsruhe, Germany
[†]Department of Energy, Politecnico di Milano, via Lambruschini 4, Milan 20156, Italy

[1]Straub et al., *International Journal of Heat and Mass transfer*, **144** (2019).
[2]Laube et al., *International Journal of Heat and Mass transfer*, **221** (2024).
[3]Fischer et al., *Parallel Computing*, **114** (2022).