Non-uniform heating effects in turbulent pipe flows

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Abstract:
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 non-uniform 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]. These boundary conditions cannot capture the effect of the heat exchange between the flow and the surrounding solid. Hence, we present data on conjugate heat transfer (CHT) in turbulent pipe flow, including azimuthally inhomogeneous heating over a range of Re numbers, a setup for which recent experimental work is available [2]. The thermal development region is also considered in the dataset (for lower Reynolds numbers), see also Figure 1 for an overview of the configuration. The data has been acquired and cross-validated using two separate numerical codes. The presented results are obtained from a second-order finite differences code based on [3], while the spectral element code NekRS was used for cross-validation.

Our database shows that the mean heat transfer for given Pr and Re number depends mainly on the ratio of thermal conductivities $G_2 = \lambda_\mathrm{s}/\lambda_\mathrm{f}$ (see Figure 2). Furthermore, we show that the mean heat transfer (Nusselt number) only depends on the mean heat flux, but not its distribution around the circumference. This result is exactly true for laminar flow, but also holds well for turbulent flow, conjugate heat transfer and the thermal inlet region.

We investigate how conjugate heat transfer and inhomgeneous heating affects higher order turbulent statistics such as the temperature covariance. Based on the energy spectra of temperature, we explore how the concept of the turbulent convection velocity [4] can be applied to the temperature field, including the solid domain. Both information are required for an estimate of the thermal stresses induced by temperature fluctuations.

Until the conference, we plan to extend this dataset to cases of higher Re, allowing for direct comparison with the available experimental data [2].

References

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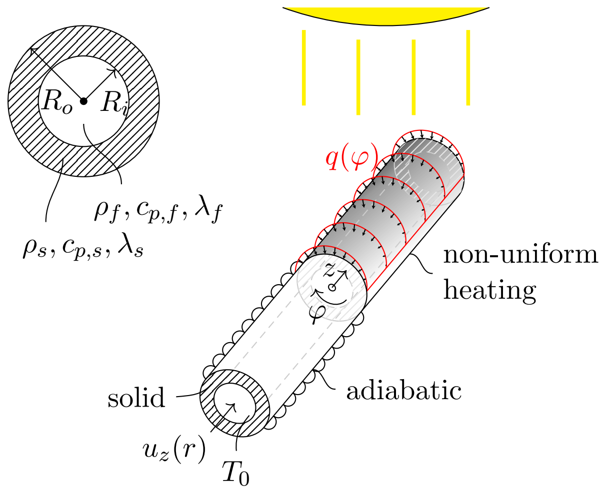

Figure 1: Sketch of the considered configuration. The fluid enters into the pipe at a constant temperature, and is heated starting at $z = 0$; the heat flux is independent of z, but varies with φ. The thermally fully-developed state is present sufficiently far away from $z = 0$.

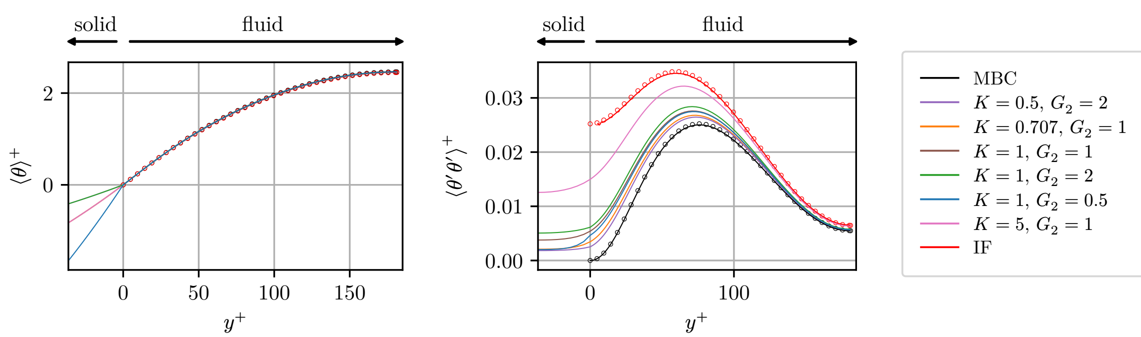

Figure 2: Fully developed temperature statistics for q = const., $Re_\tau = 180$, $Pr = 0.025$. The mean temperature depends on $G_2 = \lambda_s/\lambda_f$ while the temperature covariance is goverened by the thermal activity ratio $K = \sqrt{\rho_f c_{p,f}\lambda_f}/\sqrt{\rho_s c_{p,s}\lambda_s}$. The limiting cases (mixed boundary condition MBC and constant heat flux IF on the fluid) are given for reference.

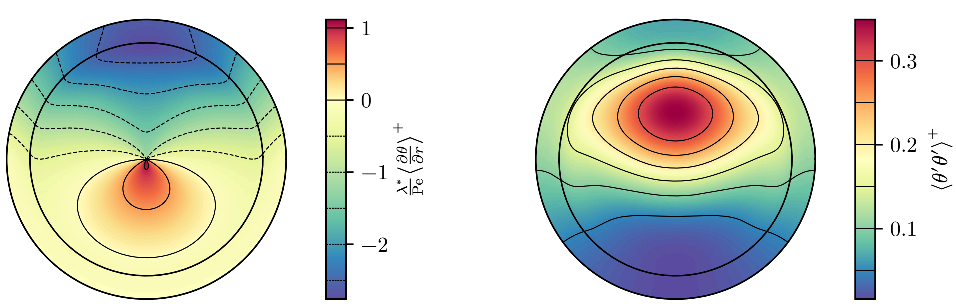

Figure 3: Radial heat flux and temperature covariance for a non-uniformly heated pipe. Half-sinusoidal heating (as in Fig. 1). $Re_\tau = 180$, $G_2 = 1$, $K = 5$, $Pr = 0.025$. Non-uniform heating increases the absolute level of temperature variance significantly, and a high value of K leads to temperature variances penetrating deeper into the pipe.