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Thermal entrance region of laminar and turbulent pipe flows subject to nonuniform heating

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The heat transfer properties of fully-developed, axially symmetric pipe flows is generally well understood across a wide range of Reynolds and Prandtl numbers[1]. Recently, nonuniformly heated pipe flows have received attention in the literature[2]. Such conditions are present in e.g. solar thermal receivers.

In this contribution, we discuss the thermal entrance behavior of passive scalars in laminar and turbulent pipe flows. For the laminar part, we developed a novel analytical solution to the extended Graetz problem, which to the authors' knowledge has not yet been solved for nonuniform heating. For the turbulent part, we will present data over a range of Prandtl numbers and up to intermediate Reynolds numbers.

In particular, we show that the mean heat transfer properties (global Nusselt number) does not depend on the distribution of the heat flux over the azimuthal direction. This holds exactly for laminar flow, and we also observe that it holds for turbulent flow, including the thermal entrance region and various Prandtl numbers. For turbulent flows, the Nusselt number is indiscernible from the fully developed state after 5 to 20 diameters, depending on the Prandtl number.

In contrast, for pointwise first-order statistics, the presence of a $k = 1$ mode (half-sided heating) significantly increases the length until a fully developed state is reached. Azimuthal heating modes $k = 0$ and $k = 2$ take approximately the same time to develop. This again holds for both laminar and turbulent pipe flows. However, second order scalar statistics (relevant for e.g. fluctuating thermal stresses) take even longer to fully develop: we observe thermal entrance lengths upwards of 100 diameters for such quantities if the $k = 1$ mode is dominant. This is also apparent from instantaneous snapshots of the scalar field (Figure 1). These results highlight the importance of considering the thermal entrance for nonuniform boundary conditions.

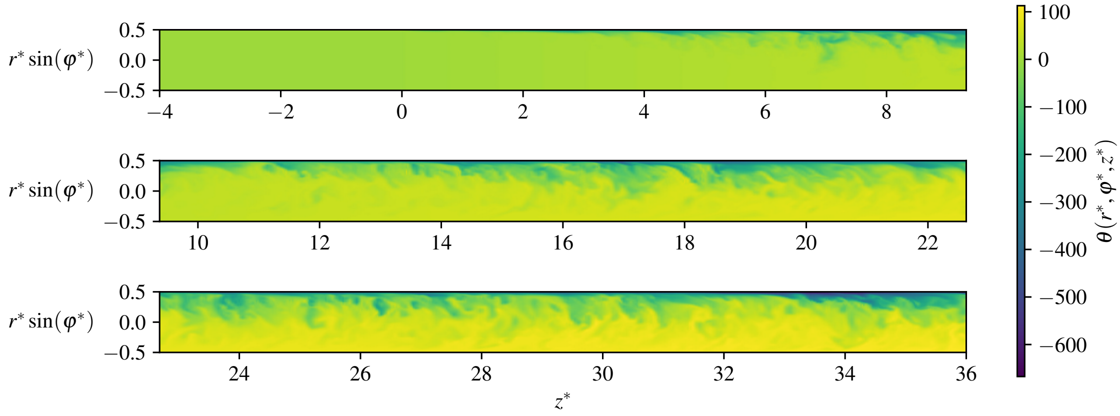

Figure 1: Instantaneous dimensionless temperature θ for a case with constant heat flux on the upper half, adiabatic wall on the lower half of the pipe. Heating commences at $z^* = 4$. $Re_\tau = 180$, $Pr = 0.71$. It is apparent that the temperature fluctuations continue to develop well into the third row of the plot.

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[1] Pirozzoli, *JFM* **965**, A7 (2023)

[2] Straub et al., *IJHFF* **77**, 352–358 (2019)