Heat transfer in a turbulent channel flow with super-hydrophobic or liquid-infused surfaces on one wall

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The thermal performance of super-hydrophobic and liquid infused surfaces (SHS and LIS, respectively) in turbulent flows is investigated using direct numerical simulations. These surfaces consist of a micro-texture (typically ridges or posts) with cavities filled with a secondary fluid which generates a slippery interface with the primary fluid (typically water). The heterogeneous solid-fluid and fluid-fluid interface created by the cavities and the secondary fluid leads to an average slip at the crest plane, which reduces the mean shear (thus, the drag) in the overlying flow. Experimental and numerical studies have corroborated this potential for drag reduction and the underlying mechanism. Despite the progress made in understanding the mechanism leading to drag reduction, less is known on the heat transfer process over SHS and LIS. The present paper aims at filling this gap by discussing direct numerical simulations results of turbulent flow and heat transfer over SHS and LIS.

Simulations are performed for a channel with a textured wall and a second fluid inside the cavities. The texture consists of either transversal or longitudinal bars with various pitch-to-height ratios. We use the immersed boundary method (Orlandi & Leonardi, 2006) to model the texture in the simulations. A secondary fluid is present in the cavities between the bars, with one viscosity ratio with the primary fluid mimicking super-hydrophobic surfaces, and another one representing liquid-infused surfaces. Two conditions are investigated for the interface between the fluids: (i) a rigid, flat interface at the crest plane, representing the asymptotic case of infinite surface tension; and (ii) deformable interface with finite surface tension (the Weber number is $We = 40$, which approximately corresponds to a Capillary number $Ca \sim 10^{-3}$). In the second case ($Ca \sim 10^{-3}$), the dynamics of the interface is fully coupled to fluid governing equations with the level-set method (García Cartagena et al., 2018).

The simulations for $We = 0$ corroborate the drag-reducing capabilities of LIS and SHS observed in the literature. For longitudinal ridges, the drag can be decreased respect to the smooth wall up to 15 – 20% for LIS and SHS, with increasing drag reduction magnitude for increasing pitch between the bars. However, the surface heat flux is reduced respect to the smooth wall for both LIS and SHS. Transversal bars, which are found to increase drag, have better performance in this regard compared to the longitudinal ones, with a marginal decrease in the heat transfer. The rigid interface damps the velocity fluctuations close to the crest plane, thus reducing the vertical turbulent heat transport. However, the heterogeneity at the crest plane, with no-slip and slippery regions, induces dispersive fluxes which mitigate this damping effect, in particular for transverse square bars. The (non-dimensional) heat transfer to drag ratio $q/\tau$ is found to be larger than one (which is the value for a smooth wall) for longitudinal bars, meaning that heat is transferred more efficiently despite the surface flux reduction. The texture orientation seems to have a primary effect on the heat transfer efficiency, with transversal bars presenting $q/\tau < 1$. The present results suggest a continuous transition from longitudinal SHS/LIS, $q/\tau > 1$, to smooth wall $q/\tau = 1$ and to transverse textures or classic rough surfaces, $q/\tau < 1$ (Leonardi et al., 2015).

In the case of $We = 40$, the interface deformation allows the generation of wall-normal velocity fluctuations at the crest plane. This generally tends to increase the drag of the surface. More momentum is transferred and dissipated inside cavities by the Reynolds stress generated by the dynamics of the interface, which is detrimental for drag reduction (Arenas et al., 2019). Nevertheless, the heat transfer performance is enhanced for most of the geometries compared to the $We = 0$ case thanks to the non-zero turbulent heat transport at the crest plane. Some configurations also present an increase in heat flux relative to the baseline smooth wall. In particular, super-hydrophobic longitudinal bars are found to reduce drag and enhance heat flux at the same time. In general, the heat transfer efficiency is positively affected for $We \neq 0$.

REFERENCES