Pipes - gliding on air?

Turbulent pipe flow – drag reduction by superhydrophobic surfaces

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In Short

- The transport of water in pipes demands huge amounts of energy worldwide.
- Reason of the energy demand is the wall shear stress at the inner wall of the pipe which results from the no-slip boundary condition and the viscosity of water.
- A reduction of wall shear stress can be obtained by a thin layer of air at the inner pipe wall. Therefore, a surface structure is necessary to keep the air on the surface when submerged under water. Due to the lower dynamic viscosity of air in comparison to that of water, a reduction of wall shear stress can be obtained.
- In this work the potential of drag reduction by a surface structure of long holes in streamwise direction in fully developed turbulent pipe flow is investigated using direct numerical simulation at a friction Reynolds number of $Re_\tau = 180$. Furthermore, the differences of wall bounded turbulent flow in pipes and channels, both with structured surfaces, are evaluated.

The transport of water through ordinary pipes demands huge amounts of energy worldwide. Origin is the no-slip condition at the inner pipe walls and the viscosity of water. This leads to wall shear stress at the inner wall of the pipe. In case of fully developed flow, the wall shear stress is directly related to pressure drop and the required energy for transport. Inspired by the water fern *Salvinia molesta* an air layer can be kept by superhydrophobic structured surfaces (SHS) when submerged under water (Figure 1). The application of such a surface to the inner wall of pipes can lead to the reduction of the wall shear stress due to the lower dynamic viscosity of air in comparison to that of water. From this follows a reduction of energy demand, lower emissions of greenhouse gases, and lower installed power of wind turbines/photovoltaic plants.

In this work the potential of drag reduction by SHS is investigated by direct numerical simulation (DNS) of fully developed turbulent pipe flow. The spatially resolved SHS is modelled with slip (air-water interface) and no-slip (wall-water interface) boundary conditions, widely used in literature [1] [2]. In comparison to fully developed channel flow, literature about pipe flow with spatially resolves SHS are rare. In [3] grooves in streamwise direction were investigated with structure sizes in circumferential direction of $L^+ = 21$ to 83.8 for different surface ratios A_s/A (slip/total surface) at the friction Reynolds number $Re_\tau = 320$. They find an increase in drag reduction with rising L^+ and with A_s/A. A comparison of drag reduction by streamwise grooves in a fully developed channel and pipe flow at $Re_\tau = 180$ were conducted by [4]. They find higher drag reductions in pipe flow. Differences of the Reynolds-stress-tensor between pipe and channel have also been reported by [5] for an ordinary no-slip boundary condition at the wall.

***Figure 1:** Water drop on Salvina molesta.*

Our recent investigations with fully developed turbulent channel flow have shown, that drag reduction strongly depend on geometry and size of the surface structures L^+ (Figure 2). Grooves in streamwise direction deliver the highest drag reduction followed by pillars, holes, and grooves in spanwise direction. For grooves in streamwise direction it is expected that this surface structure is not able to retain the air in practice. Due to the tangential stress on the air-water interface, an air flow in streamwise direction will be induced leading to a permanent air loss. To prevent this, a surface structure with long holes have been suggested and investigated in turbulent channel flow. Depending on the aspect ratio AR (length in streamwise direction / width in spanwise direction), drag reduction near to that of grooves in streamwise direction can be reached.

The anisotropic surface structure of long holes seems to be an appropriate choice for pipes due to the fixed main flow direction. To our knowledge, long holes have not been investigated in turbulent pipe flow, so far. In addition, a comparison of the effect of pillars in channel and pipe flow on drag reduction

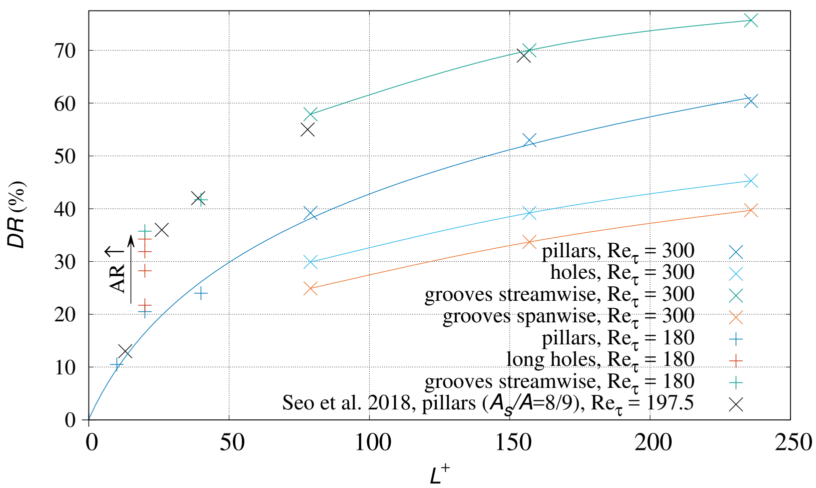

Figure 2: *Drag reduction DR plotted versus structure size L^+ in wall units for different surface structure geometries. Own data is generated with a surface ratio of $A_s/A = 3/4$. Simulations at $Re_\tau = 300$ were conducted with OpenFOAM, for $Re_\tau = 180$ the code nek5000 was used. For the data of [1] $A_s/A = 8/9$ and $Re_\tau = 180$ hold.*

is missing. From this, the objective of this proposal follows.

The main goals of this investigation are

- characterisation of fully developed turbulent pipe flow with SHS surface structures of different geometries (long holes with different aspect ratios, pillars) at a friction Reynolds number of $Re_\tau = 180$,
- determination of slip length at the inner wall of the investigated surface structures for use with RANS models,
- comparison of pipe and channel flow with respect to drag reduction, velocity profile, Reynolds-stress-tensor and further quantities to gain a deeper physical understanding to inner turbulent flows with SHS.

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More Information

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