Rheology-based wall function approach for wall-bounded turbulent non-Newtonian flows

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Abstract: Despite significant efforts, modeling fully developed turbulent flow for non-Newtonian (Herschel-Bulkley) fluids in pipes has always been a challenge. The available semi-empirical, theoretical, and numerical models are either inconsistent with the experimental data or limited to a class of non-Newtonian fluids called power-law, which, when compared with Herschel-Bulkley (HB) fluids, do not require yield stress to flow. Among available CFD approaches, researchers are more inclined towards RANS modeling, which provides a balance between cost and accuracy, over other methods such as DNS or LES. One such approach[1] for RANS modeling incorporates a rheology-based wall function for HB fluids based on the Prandtl mixing length hypothesis in the RANS solver. In the current study, we validate this approach by simulating wall shear stress and velocity profiles against the experimental data, for a range of flows varying from Reynolds numbers of 3,000 (laminar) to 120,000 (turbulent), using a single-phase fluid with HB characteristics. Measurements were taken upstream and downstream of a 90-degree pipe bend, and simulations were performed using both k-ε and RSM models for turbulence closure, with the wall function implemented as a specified shear boundary condition. We demonstrated that this approach significantly improved predictions of wall shear stress and velocity profiles compared to the standard wall function of Launder and Spalding[2], achieving high levels of statistical correlation (R2 = 0.97 from 0.91) and low errors (RMSE: from 0.12 to 0.02 and ME: from 0.32 to 0.03). The no-slip condition dictates that the fluid velocity at the pipe wall is zero, resulting in a high velocity-gradient in the immediate vicinity of the wall. This also leads to the domination of viscous forces near the wall, resulting in laminar conditions. Incorporating fluid rheology through the use of the wall function provides an input for generating accurate velocity profiles of the flow at different distances from the wall, essential for modeling fully developed turbulent flow for non-Newtonian fluids in pipes. We anticipate that this approach could serve as a promising alternative to expensive and time-consuming experimental procedures, especially for turbulent flows in pipe systems. The implications of this research extend beyond, with applications spanning industries such as mining, chemical processing, and petroleum for the transport of materials, as well as in sanitation systems for the transportation of domestic waste slurry through pipes.

Keywords: Non-Newtonian fluids, Herschel-Bulkley, turbulence, Computational fluid dynamics, wall-bounded flows

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[1] Mehta et. al, *Water.*, **10**, 124 (2018).

[2] Launder and Spalding, *Comput. Methods Appl. Mech. Eng.*, **3**, 269-289 (1974).