INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI
SHORT ABSTRACT OF THESIS

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Thesis Title: Development of a Novel Computational Framework for Non-Newtonian Flows with Applications to Hemodynamics

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SHORT ABSTRACT

This thesis is devoted to the development of a novel finite volume flow solver for incompressible non-Newtonian fluid flows and it application to hemodynamics. The study of flow of blood through blood vessels with constrictions and/or expansions using simulations necessitate the use of unstructured meshes owing to the complex geometries involved where one also has to account for the non-linear dependence of viscosity on strain rate. Towards this objective, we present a new framework referred to as the hybrid staggered/non-staggered framework for incompressible flows. We incorporate both power-law and five-parameter Carreau family of models in the framework, the latter with a view to simulate blood flows. This framework combines ideas from staggered and collocated finite volume approaches and solves for the normal velocities at the faces and for the pressure at the cell centers. Consequently, one obtains a unique framework that inherits the advantages of both frameworks and results in a flow solver that satisfies the discrete incompressibility constraint at all times (without any special treatment) which is easily implemented even on unstructured meshes. The latter advantage stems from the collocated-like treatment of the convective and viscous fluxes although the momentum equation is solved for the normal velocity at the cell faces. Consequently, a critical aspect of this framework is an accurate and efficient strategy to reconstruct the cell-center velocities from the scalar face-normal velocity. We show that a simple vector interpolation based on Green-Gauss theorem is first order accurate for centroidal velocities on unstructured meshes and leads to non-physical solutions. The root cause of spurious numerical solutions is identified to be the inconsistent viscous fluxes and we show that merely refining the mesh does not mitigate this error. This pertinent problem is resolved by proposing an iterative defect correction strategy which allows the velocities and gradients to be reconstructed to second and first order accuracy respectively. We numerically demonstrate that the use of this strategy is essential to ensure accurate numerical solutions of non-Newtonian flows using the proposed hybrid staggered/non-staggered framework. The framework is shown to be nominally second order accurate both in space and time on arbitrary polygonal meshes and also conserves both mass and momentum discretely on any mesh topology. The numerical framework is thoroughly validated using a number of canonical test problems involving steady and unsteady flows to highlight its versatility and applicability on unstructured grids. This framework is applied to understand the hemodynamics in stenoses and aneurysms with a view to relate flow parameters with clinical parameters and to gain insight into the role of non-Newtonian behaviour on the flow dynamics. Investigations are performed for steady and unsteady flows in idealised double stenoses and aneurysm geometries for physiological Reynolds numbers assuming the flow to be in a laminar regime and the walls to be rigid. Different models of the Carreau family are found to predict the peak wall shear stress (WSS) differently in the case of double stenoses with the Carreau-Yasuda model computing a higher peak WSS in steady flows. It is found that as the constriction ratio increases, the peak WSS increases as well. For the aneurysm geometry, the Newtonian model is seen to predict a higher WSS compared to the non-Newtonian fluid models at the dome region although the shear-thinning power-law fluid exhibits the highest WSS at the neck region. For a given fluid model, increase in aneurysm size was found to lead to increase in WSS at the neck accompanied by a reduction in WSS in the dome. In order to mimic the realistic flow scenarios, unsteady simulations were carried out using pulsatile inlet velocity profiles for both stenoses and aneurysm geometries where the oscillating shear index (OSI) is reported. It is observed that the OSI is relatively quiet low in regions of peak W SS mean at the constricted regions over a period for all the fluid models. A cavity-like flow was observed for the aneurysm geometry at low pulsatility index while for higher pulsatility index showed flow entrainment from parent artery into the aneurysm dome at different instants of a cycle. In both steady and unsteady simulations, it was observed that the change in constriction ratio (for stenoses) and size (for aneurysms) had a greater impact on the flow dynamics for a given non-Newtonian fluid model. The results from these studies provide insights into the flow dynamics and must be regarded as a first step towards development of an indigenous virtual laboratory for computational hemodynamics that can help devise patient-specific treatment strategies in the future when the framework is extended to three-dimensional flows with fluid-structure interaction.