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Modelling and analysis of the blood flow using multiphase approach

According to the World Health Organization statistics, cardiovascular diseases are the leading cause of premature death worldwide. Therefore, understanding the fundamental mechanisms and phenomena occurring in the cardiovascular system may be helpful for the early detection and diagnosis of developing pathological changes in blood vessels. Often, pharmacological treatment can be used instead of complicated and expensive surgical procedures in the case of lesions detected at an early stage of their development. In recent years, numerical modelling of fluid mechanics has found wide application in many engineering fields and can also be successfully used to simulate flows in living organisms. Computer models can be used to carry out virtual experiments that will give answers regarding the description of the phenomenon and the flow conditions in the human body. Numerical modelling is also used to construct medical devices, such as artificial hearts and valve implants. An accurate image of the velocity and pressure fields obtained during the flow simulation can help, for example, in identifying areas at risk of pathological changes (plaque build-up) and cardiovascular disease.

The goal of the thesis is to show the feasibility and usefulness of the multiphase approach for blood flow modelling. The proposed model validation is performed using both literature reports and experimental data.

Multiphase approach. The research aimed to investigate the possibility of using Computational Fluid Dynamics to simulate multiphase blood flow in blood vessels and microchannels. Numerical analysis of blood flow in the aorta, right coronary artery, and microchannels with hyperbolic constriction of various sizes was performed. Blood was treated as a nonhomogeneous mixture consisting of three main components. Modelling the blood flow as a multiphase medium allows distinguishing the primary blood components in the model: erythrocytes, leukocytes, and plasma.

Blood flow in aorta. The three-phase Euler-Euler model was used to simulate blood flow in the aorta. In this approach, each modelled phase is treated as an interpenetrating continuum. A pulsating artery condition has been implemented to reproduce the pulsatile nature of blood flow. The Windkessel model was used to consider the influence of the entire circulatory system on the selected section of the vessel.

Blood flow in coronary artery. A numerical model of coronary blood flow was constructed using the Euler-Euler two-phase approach to map the interactions between plasma and red blood cells accurately. The interaction between the two main components is significant in vessels with smaller diameters, where the tendency of erythrocytes to migrate towards the core of the vessel is visible, the so-called Fåhræus-Lindqvist effect. The nature of the particle flow is influenced by the granular temperature, which represents the energy of the particles chaotic movement. The built-in granular temperature equation has been modified using the User Defined Functions.

Blood flow in microchannels. The numerical model of blood flow on a microscale simulated the flow of dextran, a substitute for plasma and erythrocytes. The hyperbolic narrowing of the microchannels on forming a Cell-Free Layer was investigated. The model uses the Euler-Euler approach and the Euler-Lagrange hybrid multiphase modelling. The simulation results were validated using the results of an in vitro experiment. The simulations were performed using the commercial ANSYS Fluent software (ANSYS Inc., USA).

Methodology choice. The thesis aimed to propose and summarize an appropriate methodology for the simulation of blood flow in vessels of various scales. The analysis of the presented results was used to prepare a guidelines for constructing numerical models of blood flow in vessels of various scales. The parameters and settings of the solver have been summarized, allowing to build a model capable of reproducing the fundamental nature of blood flow. Both the guidelines and the the user-defined function (UDF) source codes are provided for other researchers to use in the future research.

Keywords: cardiovascular biofluid mechanics, hemodynamics, CFD, blood flow, red blood cells, aorta, coronary artery, microchannel, multiphase, Euler-Euler model, Euler-Lagrange model