# Multiscale simulation of blood flow in the Ventricular Assist Device

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Abstract

The aim of this paper is to propose a model that describes the flow of blood in the Ventricular Assist Device (VAD), which is used in case of severe heart illnesses when the natural heart supplies the body with an insufficient volume of blood. Any damage or improper functioning of the VAD can result in the patient's death. This implies the constant need to improve the design of VADs and artificial valves which are crucial parts of the device. Thus, a lot of efforts are spent on simulations of blood flow through the VAD. FE method is usually used. Regarding the rheological model, an effort is made to introduce as realistic as possible description of the blood viscosity. The particular objective of the present work is accounting for the blood's multiphase structure in modelling. The blood is considered as a two phase liquid, which consists mainly of deformable red blood cells and plasma, exhibiting thixotropic properties. The proposed solution is based on the multiscale model consisting of three calculations levels. Computational fluid dynamics (CFD) simulations were performed to determine relevant model parameters. Cellular automata and lattice Boltzmann method concentrate on describing the red blood cells behaviour. The theoretical bases of the model, as well as results of simulations of blood flow through the VAD, are presented in the paper.

*Keywords: multiscale simulation, blood flow, lattice Boltzmann, thixotropic fluid*

## 1. Introduction

Computer simulation can provide help to design of medical devices. Based on previous research [1,3,4] it is possible to describe blood flow as fluid flow inside device. Modelling can help locate sites at risk of generating hemolysis or thrombus formation. These two processes are essential for design of VAD. Blood consists of a suspension of cells, mainly erythrocytes in Newtonian medium, plasma. Components of blood can be damaged due to stress in many cases. One of main cause is the magnitude and duration of stress loading experienced by the cells. Obvious is, if longer red cells are under shear stress then their structure will be more exposed to failure. This breakdown or destruction causes release of haemoglobin into plasma what highly limit the blood's ability to effectively transport oxygen. Formation of blood clot due to diseases or low shear stress is another important process. To define areas of potential risk it is necessary to define stagnation zone where velocity value is close to zero.

Advantage of using of simulation is possibility to omit expensive experiments as well as it is possible to propose alternative virtual prototypes. However, numerical simulations are highly complicated because the flow is unsteady and have thixotropic character.

## 2. Multiscale simulation

Prediction of the main flow parameters, such as flow lines, shear rates and shear stresses, turbulences etc. provide limited range of information. Conventional models of blood flow discussed in [5] have limited applications, because flow of blood has such issues as the interaction between phases, changes in thermodynamics, turbulences or simultaneous occurrence of events involving different scales. Proposed multiscale model expand possibility of investigated parameters without rapid increase of needed computational forces.

As macro scale model computational fluid dynamics (CFD) are willingly used. This method can predict the pressure flow, hydraulic efficiencies, flow geometry and stress level. However it is still a big challenge to model two phases flow in this method. This disadvantage strictly limits possibility of using CFD in case of blood flow.

To obtain more information about dynamics of micro structural changes, it is necessary to use supportive method which can describe, with satisfactory accuracy, changes on this level. Lattice Boltzmann method (LBM) is able to do it [2]. The computational environment was developed with OpenLB library. In order to simulate this method, it is necessary to define a representative volume element (RVE), which provides calculations space. It is possible to use an arbitrary material model of blood. The parameters which define blood properties are the geometry, hematocrit and degree of agglomeration. The created model is adopted as an approximation to the ellipsoid shape of single cells.

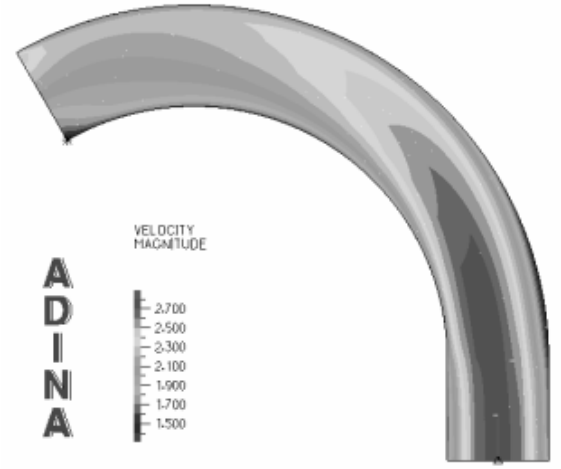


Figure 1: Result of simulation, the velocity field.

## 3. Results

The results present possibility of model in case of a simple test. This test is created by the shape of the curved tunnel with velocity gradient greater than that involved by actual narrowing of blood vessels caused by atherosclerosis. In order to verify the results obtained in the various sub-programs, it is needed to ensure identical conditions for each space. The Casson model of blood rheology was considered. Such parameters of the flow as the shape of the computing space and blood properties are of primary consideration. Fig. 1 shows the velocity distribution obtained in the program ADINA. The test was performed for the uneven distribution of hematocrit in the blood concentration in the axis of the domain.

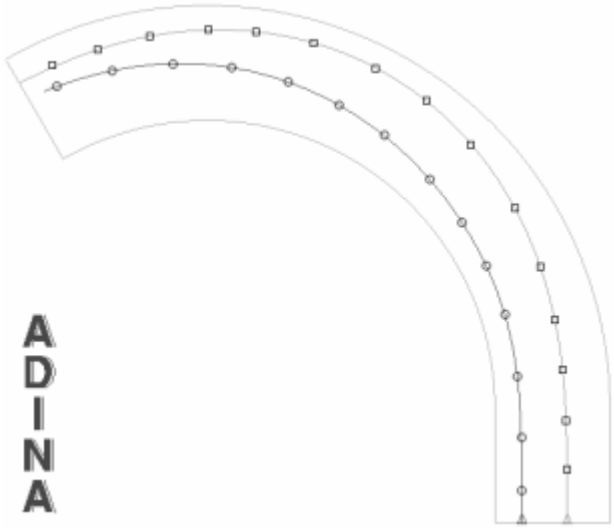


Figure 2: The flow of RVE for different initial positions.

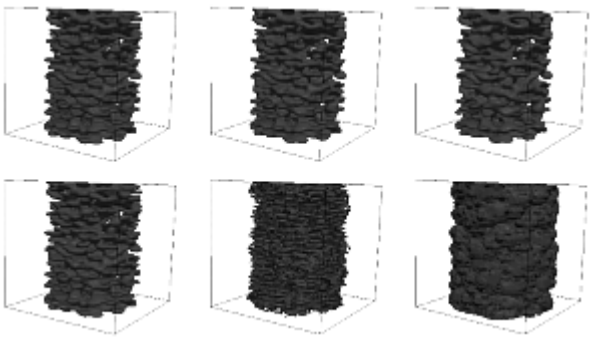

Figure 3: The distribution of red blood cells from the top without taking into account the shear rate (top square, down circular line of trace RVE).

In order to simulate the LBM method, it is necessary to define a representative volume element (RVE), which provides space calculations. Fig. 2 shows the path of movement defined by the volume after completion of all steps for the simulation of the test case. Fig. 3 shows the changes in RVE structure. In the case of circular line of trace in Fig. 2, cell aggregation is the main process, which occurs in blood. This proves that the process of connecting the components is actually observed. The dynamics of the process is small and critical changes occur after multiple steps of calculation. For square line of trace in Fig. 2, behaviour of the system is noticeably different than previously described. Considering the second step, it is seen that the shape of cells has changed and created discs with a diameter similar to the diameter of red blood cells. In the third step, the shape changes again, acquiring a spherical form. Changing the shape does not adequately reflect the physical phenomenon, due to some imperfections of the model. Molecules are not limited, because the shape of the front depends only slightly on the shape of the initial distribution.

## 4. Summary

The aim of this study was to develop a multi-scale model used to describe the phenomena occurring during multiphase flow of the incompressible fluid with the thixotropic effect. The proposed model behaves in a manner consistent with the expectations. Under low shear rate the red blood cells have a tendency to aggregate. As a result of the transition zone with larger gradient of velocity, agglomerated particles undergo fragmentation. What is even more important, the model allows accounting for the effect of shear history on the microstructure. The apparent degree of aggregation and changes in hematocrit depend on the shear rate. The presented results document the possibility of modelling such phenomena as changes in viscosity during shear-induced changes of flow. Depending on the degree of aggregation and on shear rate, hematocrit changes and these changes have an impact on the nature of the flow.

Simple rheological models are used in the work, allowing for the approximate description of the flow of blood. In order to improve performance, it is necessary to include in these models the feedback from the LBM solution to the FE model. The degree of agglomeration of blood cells will become a variable in the viscosity model.

Presented model can be expanded by other sub-models witch can provide information about strain distributions at the surface of VAD or flexible wall motion.

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