International Journal of Industrial Engineering and Management (IJIEM), Vol.3 No 2, 2012, pp. 99-104
Available online at www.iim.ftn.uns.ac.rs/ijiem_journal.php
ISSN 2217-2661

UDK: 616.1:004

Software Technologies for the Analysis of Blood Flow in the Human Body

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Received (06 April 2012); Revised (17 May 2012); Accepted (06 June 2012)

Abstract

This paper presents an overview on software technologies used in study of blood flow in the human body. Basic equations of fluid flow are presented and the basis for creating an independent software package PAK-F for the calculation of viscous fluid flow. The carotid artery bifurcation fluid flow simulations are compared by software PAK-F and COMSOL Multiphysics in the case study. Geometry of the carotid artery bifurcation is obtained through the analysis of images from CT scanner. Finite element model is created on real 3d geometry model. Presented numerical results show that developed software PAK-F corresponds well with results from COMSOL Multiphysics.

Key words: *bifurcation, blood flow, fem, wall shear stress*

1. INTRODUCTION

Biomechanics is a relatively new scientific area that has emerged from several scientific areas such as medicine, engineering, computational science. Expansion of the computer sciences brings biomechanics to a new level higher than the level of about 20 years ago. Software programs for the management of biomechanical characteristics have evolved along with computers. In recent years there are more software programs that are based on calculations of blood flow in arteries, air flow in the lungs and stress conditions in human skeletal system. Good management of these technologies may lead to research improvement but also to cutting costs of research, increasing the field of application, etc.

Atherosclerosis is one of the most widespread diseases that affecting blood vessels in the human body. The studies presented in [1-5] shows that very responsible are hemodynamic factors such as low or reversed wall shear stress. Computational fluid dynamics (CFD) is an area of fluid dynamics that can be applied to study the hemodynamic factors in human body.

The software package COMSOL Multiphysics (www.comsol.com) is one of the newer software that deals with coupled multiphysical problems. It contains many modules for study of fluid flow from module for laminar flow, turbulent flow, module for fluid flow through porous media and fluid-structure interaction. The nature of this software package enables easy handling and using the interface.

The software package PAK-F [6] was developed at the Laboratory for Engineering Software, Faculty of Engineering, Kragujevac. It consists of modules for steady and transient incompressible fluid flow with heat transfer. It is based on finite element method and on the fundamental equations of viscous fluid flow. The reason for development of domestic software in addition to other relevant software is based on cost effectiveness and the possibility of upgrading the software in terms of solving biomechanical problems. To create an analysis file for software PAK-F, it is necessary to create a model in any pre-processors such as GID, FEMAP, CATIA etc. After fluid flow analysis results are printed in a form that can be post-processed in other software such as FEMAP, GiD, Paraview, IDEAS, PAK-G, etc.

This paper is structured as follows: basic equations of incompressible fluid flow and the development of software PAK-F are given in the sections 2 and 3. In the section 4 – the case study, the blood flow through carotid artery bifurcation is presented which has intention to investigate capabilities and performances of software package PAK-F comparing them with

COMSOL Multiphysics. Section 5 gives conclusions and directions for improvement of managing software in the sense of needs of research and software performances.

The main goal of this paper is to confirm that software PAK-F is qualitative tool for scientific research with capabilities that corresponds to the well known software packages such is COMSOL Multiphysics.

2. BASIC EQUATIONS OF INCOMPRESSIBLE FLUID FLOW

Basic differential equations that governing the flow of an incompressible fluid [7-9] are the Navier-Stokes equations given by expressions:

$$\rho\left(\frac{\partial \mathrm{v}_i}{\partial t}+\mathrm{v}_{i,j}\mathrm{v}_j\right)+p_{,i}-\mu \mathrm{v}_{i,jj}-\mathrm{f}_i^V=0 \tag{1}$$

$$\mathrm{v}_{i,i}=\mathrm{v}_{1,1}+\mathrm{v}_{2,2}+\mathrm{v}_{3,3}=0 \tag{2}$$

Equation (1) represents the second Newton's law applied to the mass of fluid in control volume and (2) represents the continuity equation of fluid flow. In previous equations ρ is the fluid density, v is velocity of fluid, p is pressure of fluid, μ is dynamic viscosity and f_i^V is volume forces. Using Galerkin method, with appropriate interpolation functions:

$$\mathrm{v}_i=\mathrm{h}_I\mathrm{V}_i^I \qquad I=1,2,\dots,N \tag{3}$$

$$p=\hat{\mathrm{h}}_I\mathrm{P}_I \qquad I=1,2,\dots,M \tag{4}$$

and integration by volume of finite element, a matrix form of equations (1) and (2) is obtained such as:

$$\mathbf{M}\dot{\mathbf{V}}+\mathbf{K}_{vv}\mathbf{V}+\mathbf{K}_{vp}\mathbf{P}=\mathbf{F}_v \tag{5}$$

$$\mathbf{K}_{vp}^T\mathbf{V}=0 \tag{6}$$

Components of this matrix and vectors are:

$$\bar{\mathbf{M}}_{IJ}=\rho\int_V \mathrm{h}_I\mathrm{h}_J dV \tag{7}$$

$$\left(\bar{\mathbf{K}}_{\mathrm{vv}}\right)_{\mathrm{IJ}}=\int_{\mathrm{V}} h_{\mathrm{I}}v_{\mathrm{j}}h_{\mathrm{J,j}}\mathrm{dV}+\int_{\mathrm{V}}\mu h_{\mathrm{I,j}}h_{\mathrm{J,j}}\mathrm{dV} \tag{8}$$

$$\left(\mathbf{K}_{\mathrm{vpi}}\right)_{\mathrm{IJ}}=-\int_{\mathrm{V}} h_{\mathrm{I,i}}\hat{h}_{\mathrm{J}}\mathrm{dV} \tag{9}$$

$$\left(\mathbf{F}_{\mathrm{vi}}\right)_{\mathrm{I}}=\int_{\mathrm{V}} h_{\mathrm{I}}f_{\mathrm{i}}^{\mathrm{V}}\mathrm{dV}+\int_{\mathrm{S}} h_{\mathrm{I}}\left(-\mathrm{p}\delta_{\mathrm{ij}}+\mu v_{\mathrm{i,j}}\right)n_{\mathrm{j}}\mathrm{dS} \tag{10}$$

By grouping equations (5) and (6), system of differential equations is presented as:

$$\begin{bmatrix}\mathbf{M} & 0\\ 0 & 0\end{bmatrix}\begin{bmatrix}\dot{\mathbf{V}}\\ \dot{\mathbf{P}}\end{bmatrix}+\begin{bmatrix}\mathbf{K}_{vv} & \mathbf{K}_{vp}\\ \mathbf{K}_{vp}^T & 0\end{bmatrix}\begin{bmatrix}\mathbf{V}\\ \mathbf{P}\end{bmatrix}=\begin{bmatrix}\mathbf{F}_v\\ 0\end{bmatrix} \tag{11}$$

which can be written in the following form:

$$\hat{\mathbf{M}}\dot{\mathbf{U}}+\hat{\mathbf{K}}\mathbf{U}=\mathbf{F} \tag{12}$$

The system of equations (12) is a symmetrical system of nonlinear differential equations of first order by unknown values in nodes $\mathbf{V}$ and $\mathbf{P}$. The matrix $\mathbf{K}_{vv}$ (8) is nonlinear, since it depends on velocity. Wall shear stress is a hemodynamic factor which have great importance to study the problem of blood flow. In this case wall shear stress is calculated based on equation:

$$\boldsymbol{\tau}_W=-\mu\left.\frac{\partial \mathbf{u}_t}{\partial \mathbf{n}}\right|_{wall} \tag{13}$$

where $\boldsymbol{\tau}_W$ is wall shear stress, $\mathbf{u}_t$ is tangential velocity and $\mathbf{n}$ is the direction of a unit vector normal to the wall at the moment.

3. DEVELOPMENT OF SOFTWARE PAK-F

The software package PAK-F consists of modules for steady and transient incompressible fluid flow with heat transfer. It is developed on finite element method and it corresponds to the fundamental equations of viscous fluid flow. Programming language FORTRAN which is especially suited for numeric computation and scientific computing was used in order to develop basic subroutines of PAK-F. The global algorithm that describes software PAK-F is shown in Fig. 1.

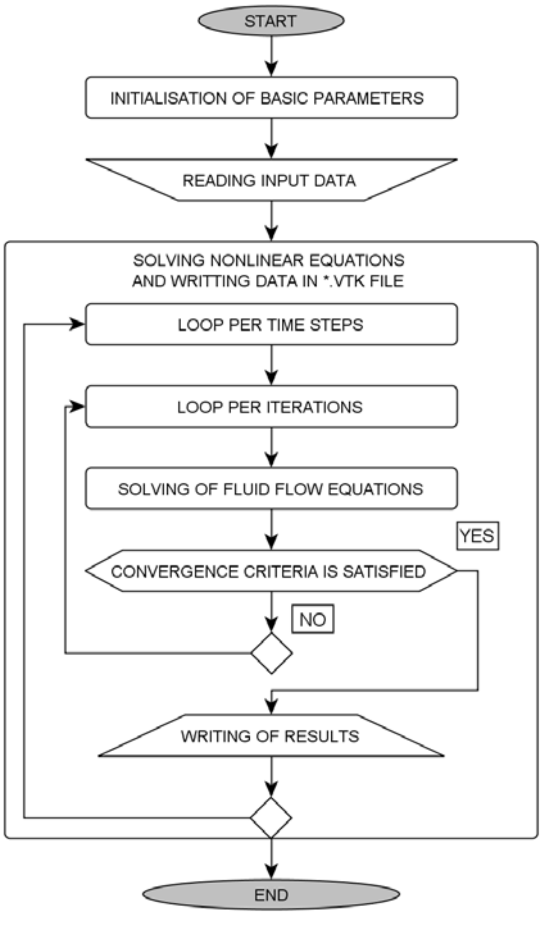

Figure 1. Global algorithm of software PAK-F

At the beginning of the program basic parameters related to fluid flow and load inputs is initialized. The program contains the main loop with time steps. Within this loop there is loop by iterations. Solving nonlinear equations of fluid flow (12) is performed iteratively. The size of unbalanced loads is determined in every iteration and it corresponds to the increments of speed and pressure. This procedure continues until convergence criteria are not satisfied or until corresponding increments of displacements and pressures are not become enough small. After this, PAK-F presents the obtained results that can be post processed in several file formats such as FEMAP neutral file, IDEAS graphics file, VTK Paraview format.

4. CASE STUDY: COMPARATION OF SOFTVARE PACKAGES USED FOR SIMULATING BLOOD FLOW

Simulation of blood flow through the carotid artery in human body was carried out on a realistic three-dimensional geometry.

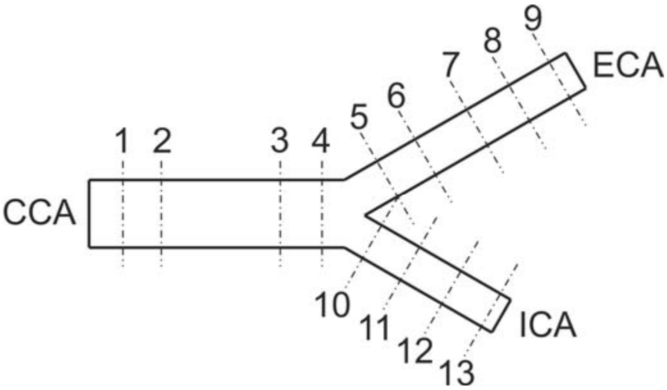

Figure 2. Schematic model of carotid artery bifurcation

The geometry of the artery is obtained by images from CT scanner using STL and CAD programs. A schematic model of the carotid bifurcation is shown in Fig. 2. The division of the geometric model is built by typical cross sections shown in Fig. 2.

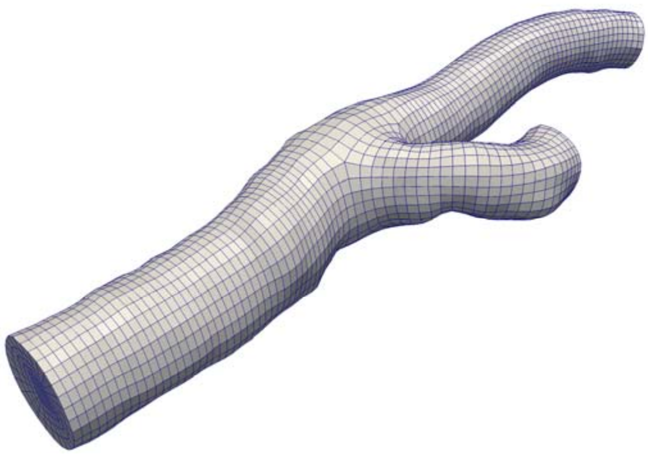

Figure 3. FEM model of carotid artery bifurcation

Mesh of finite elements was created by parametric modeling software and in proper format exported for simulating in softwares PAK-F and COMSOL Multiphysics. Finite element model contains 18706 elements with 20720 nodes (Fig. 3).

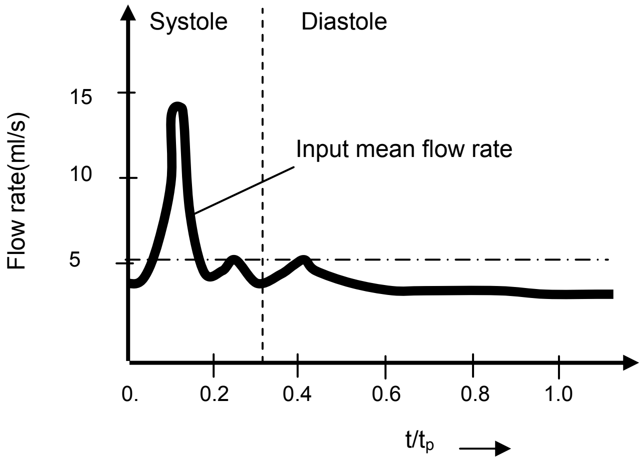

Figure 4. Input flow waveform for one pulse cycle

Time function that was used is a standard phase of systole and diastole of one cardiac cycle in human body (Fig.4).

The boundary conditions for the calculation model are:

- inlet velocity profile is parabolic 3d inlet like a fluid flow through a circular tube,
- on the walls of the artery fluid velocity is set to zero (no-slip condition) and
- on the output side of artery surface forces are set to zero.

4.1. Results of simulation in software PAK-F

The calculation was performed in 30 steps (10 by 0.02s and 20 by 0.03s which gives in total 0.8s). According to the literature [10-13] following input data is used: the average flow velocity in the inlet $v_{mean} = 16.9\left[cm/s\right]$, density of blood is $\rho = 1050\left[kg/m^3\right]$ and coefficient of dynamic viscosity is $\mu = 0.003675\left[Pa \cdot s\right]$. Results obtained by PAK-F are printed in *. vtk file as described in [14]. Figs. from 5 to 10 shows the results of velocity field and wall shear stress.

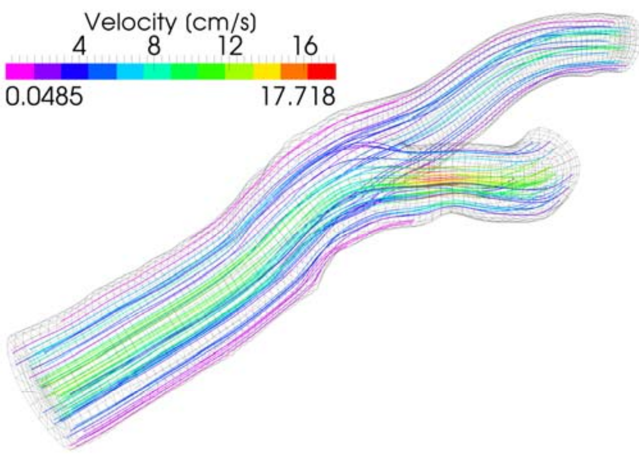

Figure 5. Velocity field in step 01 obtained by PAK-F

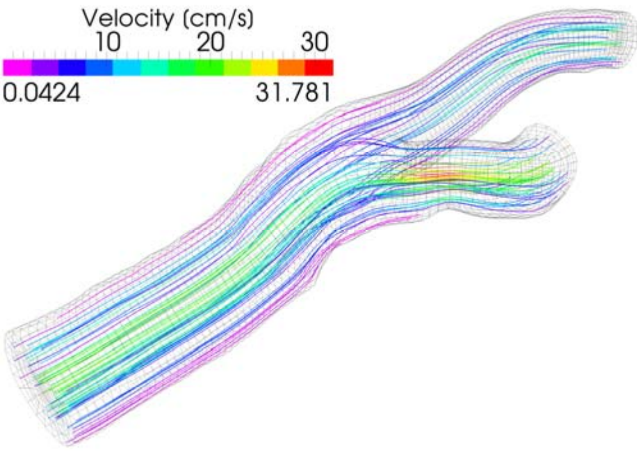

Figure 6. Velocity field in step 03 obtained by PAK-F

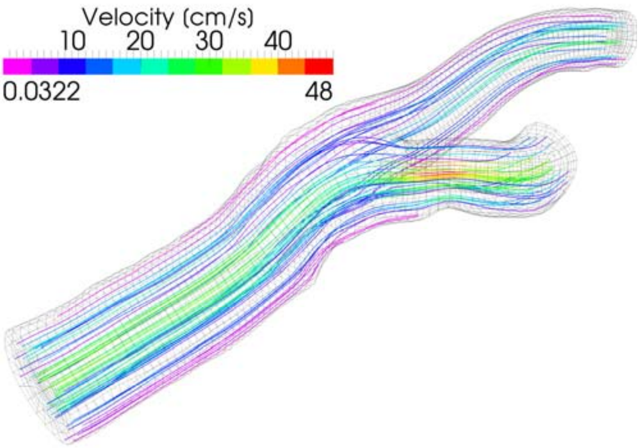

Figure 7. Velocity field in step 05 obtained by PAK-F

Fluid velocity is changed depending on the region that is being observed on carotid artery bifurcation. On the internal carotid artery (ICA) it can be seen where there is a narrowing of blood vessels it leads to increased blood flow velocity.

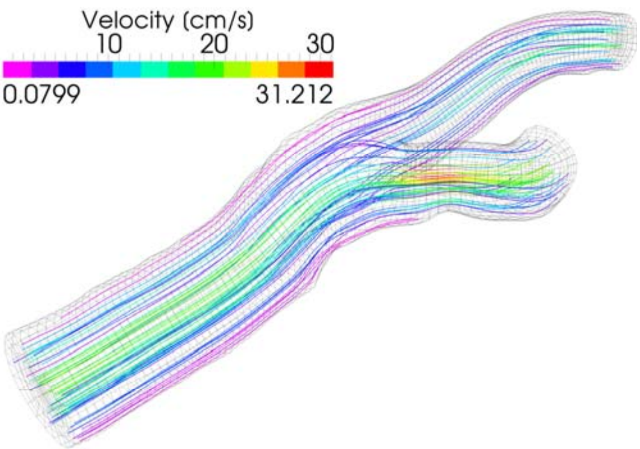

Figure 8. Velocity field in step 07 obtained by PAK-F

On the external carotid artery (ECA) where cross section is bigger and flow velocity is smaller there is low values of wall shear stress (fig. 9 and fig. 10). In these areas where wall shear stresses have small values there is possibility for the occurrence of atherosclerosis.

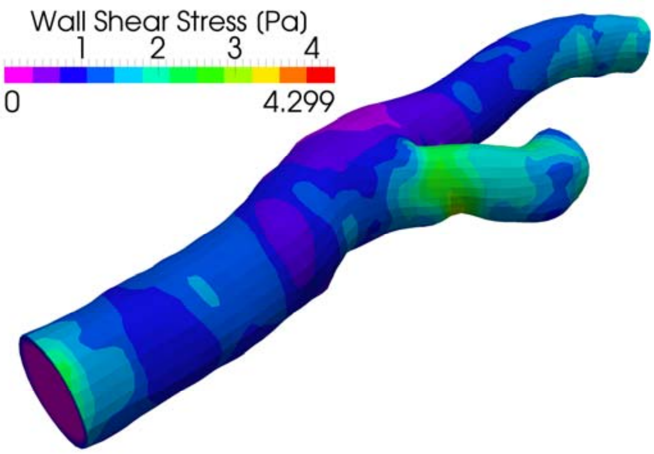

Figure 9. Wall shear stress in step 05 obtained by PAK-F

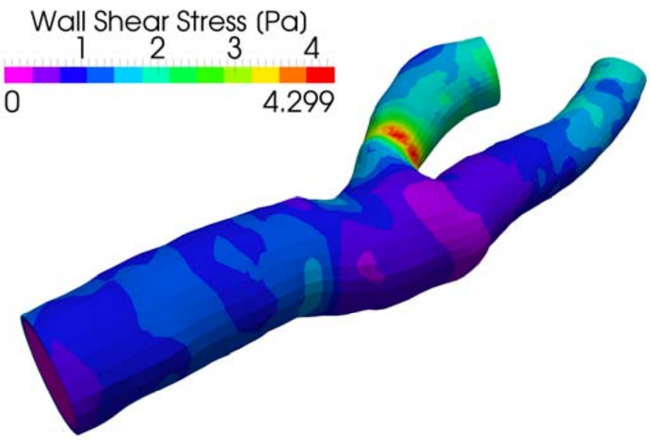

Figure 10. Wall shear stress in step 05 obtained by PAK-F

Fig. 9 and 10 shows wall shear stress in step 05 of cardiac cycle. In this step there is maximum value of wall shear stress at peak systolic flow.

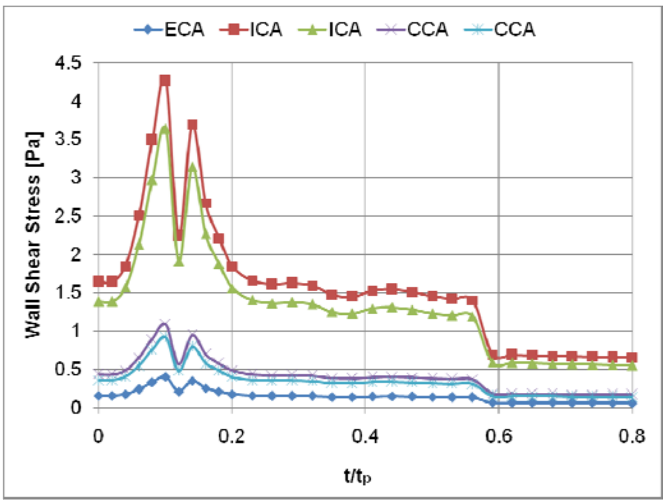

Figure 11. Comparison of WSS in the CCA, ICA and ECA during one time cycle obtained by PAK-F

On Fig. 11 the change of wall shear stress during a cycle is showed. Constriction problems of blood vessel can be successfully solved by installing the stents where there is a possibility of total congestion of blood vessels. After placing the stent, blood vessel lumen and cross section is increased. Then same analysis can be done by following procedure to gain insights into improving the functioning of blood vessels of the patient.

4.2. **Results of simulation in software Comsol Multiphysics**

The same simulation of blood flow through the carotid bifurcation was performed in COMSOL Multiphysics software V.4.2. Finite element model used for simulation in software PAK-F is used also here with same initial values and material properties.

Results obtained after calculation in software COMSOL Multiphysics are shown in the following figures. In order to gain a better insight into blood flow, the results of velocity field is shown on the model through several sections.

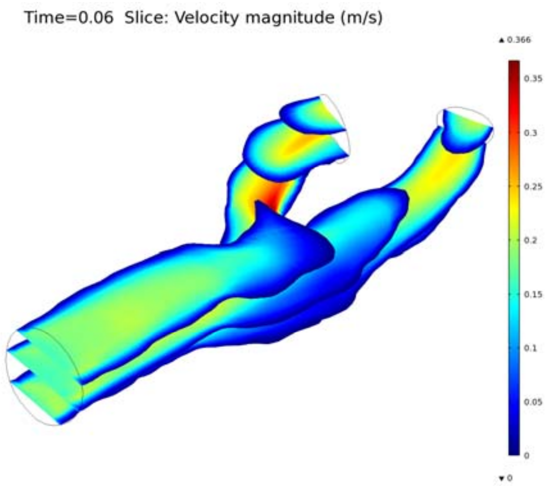

Figure 12. Velocity field in step 03 obtained by COMSOL Multiphysics

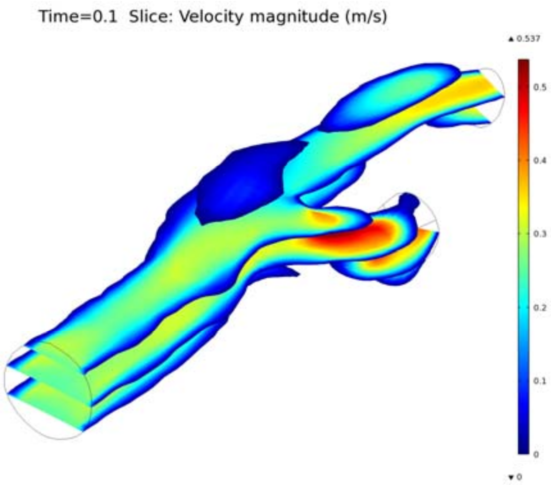

Figure 13. Velocity field in step 05 obtained by COMSOL Multiphysics

Blood flow velocity in step 03, 05 and 07 are shown in Figs. from 12 to 14. On Figs. from 15 to 16 results of wall shear stress in step 05 is obtained.

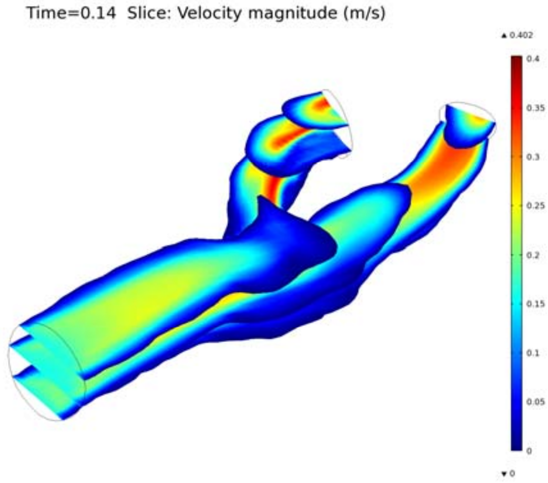

Figure 14. Velocity field in step 07 obtained by COMSOL Multiphysics

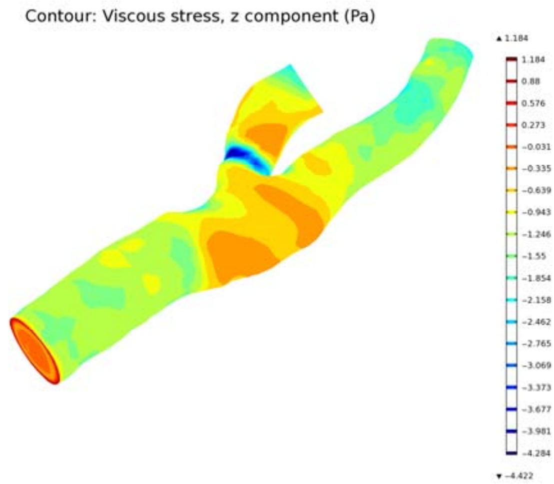

Figure 15. Wall shear stress in step 05 obtained by COMSOL Multiphysics

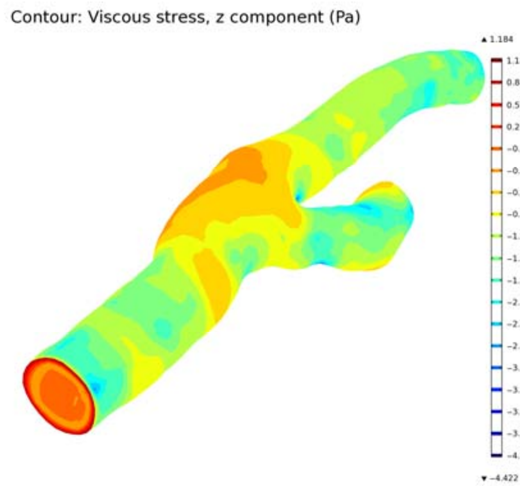

Figure 16. Wall shear stress in step 05 obtained by COMSOL Multiphysics

5. CONCLUSION

Provided case study illustrates the application of PAK-F in the study of hemodynamic characteristics of carotid artery bifurcation. It can be seen that numerical results obtained by software PAK-F correspond well with results from software COMSOL Multiphysics. This is very important issue because it indicates that developed software – PAK-F is very precise software tool which can give inputs to cardiologysts. Thanks to the obtained results, cardilogysts are set in the role of decision makers. They have clear view about insight of the blood flow through carotid artery bifurcation, so they can suggest surgical intervention or not. That is the first part of this papers contribution. The other part of contribution corresponds to the fact that new software tool PAK–F is tested and its performances are measured. Software PAK-F is able to solve the problems of laminar viscous incompressible fluid flow.

The combination of PAK-F with certain programs for pre-processing and post-processing gets a powerful tool that can be further upgraded in other areas such as soil mechanics, mechanics of solids, fracture mechanics, SPH, etc. The future research is going to be oriented to the upgrade of software that will give a platform for coronary arteries and heart malfunctioning simulation as well as air flow simulation that exists in human lungs. The nature of PAK-F set some limitations such as impossibility of solving turbulent fluid flow. Other limitations are related to the problems of analyzing compressible fluid flow which cannot be solved in this version of PAK-F.

Compared to the COMSOL Multiphysics, it can be concluded that PAK-F is enough user friendly according to the possibilities and ergonomics of the software. Diagrams and results are clear and can be exported to other software packages such as FEMAP, GiD, Paraview, IDEAS, PAK-G which make PAK-F very flexible and suited for the scientific research.

6. ACKNOWLEDGEMENT

The part of this research is supported by Ministry of Education and Science, Republic of Serbia, Grants TR32036, III41007 and OI175082.

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Softverske tehnologije za analizu protoka krvi u ljudskom telu

Aleksandar Nikolić, Milan Blagojević, Miroslav Živković, Aleksandar Aleksić i Slobodan Savić

Rezime

Ovaj rad predstavlja pregled softverskih tehnologija koje se koriste u izučavanju protoka krvi u ljudskom telu. Predstavljene su osnovne jednačine protoka fluida, kao i osnova za kreiranje nezavisnog softverskog paketa PAK-F za računanje protoka viskoznog fluida. Simulacije bifurkacije protoka fluida kroz vratnu aortu su upoređene uz pomoć softvera PAK-F i COMSOL Multiphysics u studiji slučaja. Geometrija bifurkacije vratne aorte dobijena je pomoću analize slika sa CT skenera. Model konačnih elemenata je stvoren na osnovu stvarnog 3D geometrijskog modela. Predstavljeni numerički rezultati pokazuju da se razvijeni softver PAK-F dobro poklapa sa rezultatima dobijenim pomoću COMSOL Multiphysics softvera.

Ključne reči: *bifurkacija, protok krvi, MKE, zidni napon smicanja*