23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

DESIGN, OPTIMIZATION, MANUFACTURING, AND CHARACTERIZATION OF AN VENTRICLE ASSIST PUMP

Luís Fernando Nogueira de Sá
Escola Politécnica, University of São Paulo, São Paulo, Brazil
luis.sa@usp.br

Juan S. Romero
Federal University of Espirito Santo, Espirito Santo, Brazil
juan.saenz@ufes.br

Oswaldo Horikawa
Escola Politécnica, University of São Paulo, São Paulo, Brazil
ohorikaw@usp.br

Emílio Carlos Nelli Silva
Escola Politécnica, University of São Paulo, São Paulo, Brazil
ecnsilva@usp.br

Abstract. *Flow machines are very important to medical industry, being widely used on various processes, in special, the auxiliary cardiac devices. Thus, performance improvements are relevant factors and can be achieved by using optimization methods, such as topology optimization. This work aims to develop a method to design a radial flow machine rotors that works on laminar flow, based on Topology Optimization Method (TOM). The design of a rotor involves firstly modelling the fluid flow by using Navier-Stokes equations on a rotary referential and using the Finite Element Method for solving these differential equations. This modelling is performed by using FEniCS, an OpenSource platform for finite element problem solving. To determine the material distribution on domain, a porous flow model based on Darcy equation is employed, by using a local permeability that permits a transition between fluid and solid. In the optimization problem formulation, a multi-objective function is defined, aiming to minimize the pressure loss, vorticity and power. The optimization problem is implemented by using DOLFIN-adjoint platform and the PyIpopt optimizer. Optimized topologies of flow machine rotors are obtained by using this method. Their performance is analyzed by evaluating velocity and pressure distributions inside rotor. Prototypes of these rotors are built by using a 3D printer and an experimental characterization is performed by measuring fluid flow and pressure head.*

Keywords: *flow machine design, topology optimization, ventricle assist pump, rotor design*

1. INTRODUCTION

Radial Flow Machines are widely spread over the industry, being used in several applications with different scales. They can be not only big sized machines, such as the turbines used by Thermoelectric and hydroelectric industries for energy generation, but also small sized pumps used in medical applications, such as auxiliary blood pumps (Neethu et al., 2010).

The ventricular auxiliary devices (VAD) are considered temporary solutions and cannot completely replace the human hearth (Rose et. al, 2001; Slaughter et al., 2013). Thus, VADs are usually implanted in patients that can wait for a heart transplant, functioning as a bridge between the diagnosis and the operation. However, the study of commercial pump Heart Ware presented by Aaronson et al. (2012), shows that these pumps are becoming more effective and for patients with advanced heart failure they can provide an extended life expectancy of one year, which is comparable to patients that receive the heart transplantation. Thus, the performance and reliability of these devices are of fundamental importance, and small performance gains can provide big benefits for the patient life.

By using the topology optimization method to design the pump, we can achieve performance gains. A topology optimization applied to flow machines is done in the work of Romero and Silva (2014), where the pump fluid flow is modeled as Navier-Stokes flow with the addition of a rotary reference system, arising the effects of Centrifugal and Coriolis force. In their work diverse configurations are designed through optimization for the pump rotor, exploring the influence of the initial domain and the effects of changes in the boundary conditions. As a result, non-intuitive geometries are obtained.

This work aims to develop an optimized rotor to be used in ventricular assist pumps. This paper is organized as follows. In Section 2, the Navier-Stokes equations are introduced. In Section 3, the finite element formulation is presented. In Section 4, topology optimization is discussed and the optimization problem is proposed. In Section 5 the software environment implementation is provided. Section 6 shows the experimental methodology. Numerical results are discussed in Section 7. In Section 8 the experimental results are presented and concluding remarks are provided in Section 9.

2. MODELING RADIAL FLOW MACHINE

2.1 Navier-Stokes equations for incompressible fluids

In this work it will be considered for the modelling only Newtonian flows, low Reynolds numbers, and a steady state analysis. Thus, the incompressible Navier-Stokes is given by (Romero and Silva, 2014):

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla p + \mu \nabla \cdot (\nabla \mathbf{u} + \nabla \mathbf{u}^{\mathrm{T}}) + \rho \boldsymbol{f} \tag{1}$$

where, $\boldsymbol{u}$ is the velocity field, p is the pressure field, μ is the fluid viscosity and ρ is the fluid density.

The incompressibility imposed on mass conservation yields the continuity equation

$$\nabla \cdot \boldsymbol{u} = \mathbf{0} \tag{2}$$

2.2 Rotating reference system

Inertial forces appear due to rotary motion, thus, the coriolis and centrifugal terms must be added to the Navier-Stokes equations. Also, a resistive force due to the porosity is introduced, giving (Romero et Silva, 2014):

$$\rho \nabla \mathbf{u_r} \cdot \mathbf{u_r} = -\nabla p + \mu \nabla \cdot (\nabla \mathbf{u} + \nabla \mathbf{u}^{\mathrm{T}}) + \rho \boldsymbol{f} - \boldsymbol{f_{co}} + \boldsymbol{f_{ce}} + \boldsymbol{f_r} \tag{3}$$

where $\boldsymbol{f_r}$ is Darcy's resistance for viscous fluid, which is given by $\boldsymbol{f_r} = -K(\alpha)\boldsymbol{u_r}$, $\boldsymbol{f_{co}}$ is the Coriolis force, given by $\boldsymbol{f_{co}} = -2\rho\, \boldsymbol{\Omega} \times \boldsymbol{u_r}$ and $\boldsymbol{f_{ce}}$ is the centrifugal force, given by $\boldsymbol{f_{ce}} = -\rho\boldsymbol{\Omega} \times \boldsymbol{\Omega} \times \boldsymbol{r}$.

Finally for a domain $\boldsymbol{\Omega}$, the porosity is introduced into the Navier-Stokes steady state equation as a source term $K(\alpha)$ giving rise to the Brinkman model with a convection term (Romero et Silva, 2014), where K is the porosity field, thus:

$$\rho \nabla \mathbf{u} \cdot \mathbf{u} = \nabla \cdot \mathbf{T} + \rho \boldsymbol{f} - 2\rho\, \boldsymbol{\Omega} \times \mathbf{u} - \rho\boldsymbol{\Omega} \times \boldsymbol{\Omega} \times \boldsymbol{r} - K(\alpha)\mathbf{u} \tag{4}$$

3. FINITE ELEMENT FORMULATION

In this work, the Navier-Stokes equations in a rotating reference system is solved by using the weighted residuals procedure of Galerkin's method applied to the partial differential equations to obtain the weak formulation. Thus, by using triangular elements and the interpolation shown in Fig. 1, the problem can be expressed by Eq. 5 (Reddy and Gartling, 2010):

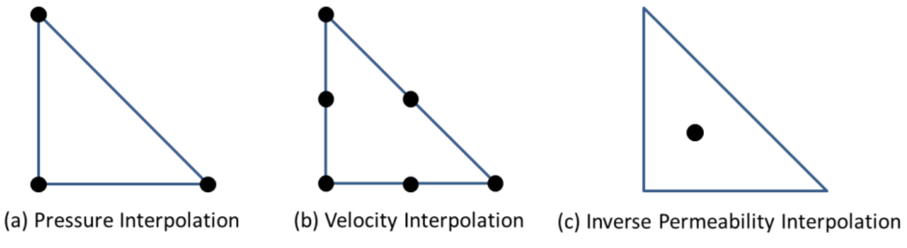

Figure 1. Velocity, pressure and inverse permeability interpolation.

$$\begin{bmatrix} \mathbf{C(u)+K} & -\mathbf{Q} \\ -\mathbf{Q}^{\mathrm{T}} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{u} \\ \mathbf{p} \end{bmatrix} = \begin{bmatrix} \mathbf{f} \\ \mathbf{0} \end{bmatrix} \tag{5}$$

This non-linear system is solved with Newton Method.

4. OPTIMIZATION APPLIED TO FLOW MACHINES

4.1 Material Model

In order to determine the path to be followed by the fluid flow and to define a design variable to perform a topology optimization, a porous domain is introduced by Borrvall and Petersson (2003). This is done by introducing the absorption term *K* that controls the material distribution in the domain, given by:

$$K(x) = K_{max} + (K_{min} - K_{max})\alpha_i \frac{1+q}{\alpha_i + q} \tag{8}$$

where q is a parameter that controls the linearity of the interpolation.

The absorption coefficient κ can be considered as a interpolation to the material flux on the domain, which represents the transition of material between low porosity (solid, κ = 1) and high porosity (fluid, κ = 0) regions. This coefficient is a function of α, a pseudo-density field which is the optimization problem design variable.

4.2 Energy Dissipation

Energy loss minimization is very important for a number of applications, specially applications with energy source restrictions, such as portable and small size applications such as cardiac pumps, a better performance from the flow channels. Thus, in this work minimizing the energy dissipation is one of the objective functions, it is equivalent to minimize the average pressure drop (Borrvall and Petersson, 2003), and is given by:

$$\boldsymbol{\Phi} = \int_{\Omega} \left[\frac{1}{2}\mu\,(\nabla\mathbf{u} + \nabla\mathbf{u}^T):(\nabla\mathbf{u} + \nabla\mathbf{u}^T) + k(x)\boldsymbol{u}^2\right] d\Omega \tag{9}$$

where **u** is the relative velocity field.

4.3 Vorticity

Vorticity represents the shear stress in the fluid and a high vorticity can damage particles flowing in the current, causing a loss of material integrity, mixing the fluid. It can be prejudicial to sensitive fluids such as blood, causing hemolysis. The functional form for vorticity is given by (Romero and Silva, 2014):

$$\mathrm{J}(\mathbf{u}) = \int_{\Omega} |\nabla \times \mathbf{u}|^2\, d\Omega \tag{10}$$

where **u** is the relative velocity field.

4.4 Power of a pump

For a pump, it is important to minimize the transmitted torque to the fluid. The power on a pump can be expressed by the dot product of the rotational velocity and the applied torque,

$$\dot{W} = \Omega \cdot \mathrm{T}_{ext} \tag{11}$$

In this work the angular velocity is considered to be constant, so the power functional can be simplified to minimize the torque. Also, For flow machine analysis it is convenient to choose a fixed control volume enclosing the rotor for analysis of torque reactions. The body force contribution may be neglected due to symmetry. Thus, considering that the mass flow in the inlet domain is normal to the boundary, the total torque for steady flow will be equal to the integral of the boundary outlet flow (Romero and Silva, 2014):

$$\boldsymbol{T}_{ext} = \int_{\Omega} \nabla \cdot [\rho(\boldsymbol{r} \times \boldsymbol{u}_a) \otimes \boldsymbol{u}_a]\, d\Omega = \int_{\Gamma} \rho(\boldsymbol{r} \times \boldsymbol{u}_a)\boldsymbol{u} \cdot \boldsymbol{n}\, d\Gamma \tag{12}$$

where **u** is the relative velocity and $\boldsymbol{u}_a = \boldsymbol{u} + \Omega \times \boldsymbol{r}$ is the absolute velocity.

Thus,

$$\boldsymbol{T}_{ext} = \int_{\Gamma_s} \rho(\boldsymbol{r} \times \boldsymbol{u})\boldsymbol{u} \cdot \boldsymbol{n}\, d\Gamma + \int_{\Gamma_s} \rho(\boldsymbol{r} \times \Omega \times \boldsymbol{r})\boldsymbol{u} \cdot \boldsymbol{n}\, d\Gamma$$
$$= \boldsymbol{T}_r + \boldsymbol{T}_t = T_r \boldsymbol{e}_3 + T_t \boldsymbol{e}_3 \quad (13)$$

4.5 Multi-Objective Function

In this work a multi-objective functional is defined by using the energy dissipation, vorticity and power. The functional then becomes:

$$\boldsymbol{\psi} = \omega_e \log \boldsymbol{\Phi} + \omega_v \log J \pm \omega_t \log T_e \quad (14)$$

where $\boldsymbol{\psi}$ is the multi-objective function, $\boldsymbol{\Phi}$ is the viscous dissipation term, J is the vorticity term and T_e is the power term. ω_e, ω_v and ω_t are the weighting coefficients associated with energy dissipation, vorticity and torque respectively. They allow the influence of each term on the final functional, also it is considered that $\omega_e + \omega_v + \omega_t = 1.0$.

4.6 Sensitivity Analysis

The sensitivity analysis consists of gradient evaluation of the objective functions in order to provide information about the function and the constraints to guide the optimization. In this work the adjoint method is used to calculate the sensitivities. The adjoint method creates a problem given by the derivation of the governing equation in weak form, and allow obtaining the functional gradient by using the derivatives with respect to the output variables.

5. NUMERICAL IMPLEMENTATION

5.1 Optimization Algorithm

The optimization procedure is iterative and consists of the following steps: (a) Solving Rotating Navier-Stokes equations with a given initial value for design variables; (b) Calculate adjoint equations; (c) Calculate sensitivities; (d) Update the design variable; (e) Verify the stopping criteria. These steps are shown in Fig. 2.

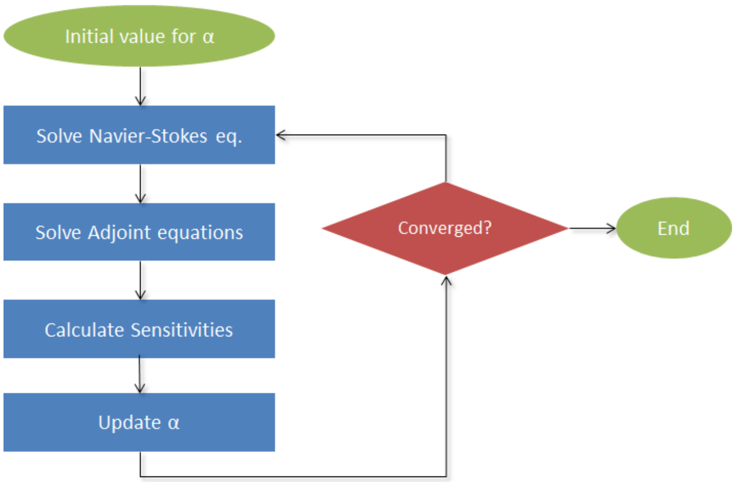

Figure 2. Optimization procedure.

5.2 Solving the Optimization Problem

In this work the topology optimization problem is implemented by using the *FEniCS* system, which is a software framework to solve partial differential equations by using the finite element method (FEM). Thus, the implementation is done by inserting the problem in a language very similar to math syntax of the problem weak formulation. The sequence of steps to solve the optimization involves firstly defining an initial material distribution and the boundary conditions, then the FEniCS routines are called to solve the FEM system returning the solution vector [u1 u2 p]. With this, the functional is evaluated and the DOLFIN-adjoint (Funke et al., 2012) is called and performs the adjoint problem derivation, in order to calculate the sensitivity of the functional with respect to the design variable. Next, this information is passed to the optimizer IPOpt, that computes the next material distribution over the domain. The process is repeated until the functional value converges, in which case the optimum solution is reached.

6. EXPERIMENTAL METHODOLOGY

6.1 Pump Prototype Design

The pump dimensions are based on ventricular assist pumps, so it is a small scale pump. The electrical motor is brushless, composed of silicon steel rings with a coil and a ring of magnets coupled to the rotor. The pole change is done by using a controller and three hall sensors distributed 60 degrees apart of each other. The controller controls the pump rotation by limiting the pole change velocity. The rotor and the carcass are built by using a 3D printer (Stratasys – Objet 350) with the materials VeroWhitePlus and VeroClear. The pump assemble is shown in Fig. 3.

Figure 3. Pump assemble.

6.2 Experimental Setup

In order to test the built prototype an experiment is performed. The experiment aims to measure the pressure head and the mass flow given by the pump. Thus, the experiment consists of a water tank, a flow sensor and a manometer coupled to the pump. The pump rotation speed is controlled by a commercial controller that uses a DC source. The flow sensor and the hall sensor outputs are read by using an oscilloscope. The scheme representing this assemble is shown in Figure 4.

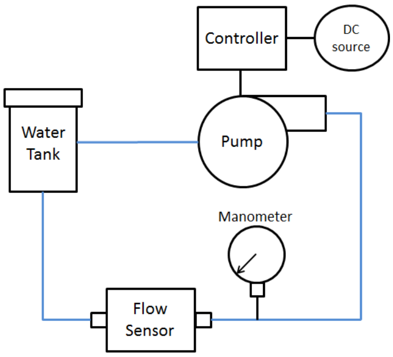

Figure 4. Experimental site scheme.

7. NUMERICAL RESULTS

7.1 Domain definition

The topology optimization method is used by considering only the flow field between blades, without considering the volute influence. Even though the fluid in a real flow machine is three-dimensional, for the case of radial centrifugal impellers, the axial velocity component can be neglected in comparison to the radial and tangential components, hence the flow path can be approximated as a two-dimensional problem (Romero and Silva, 2014).

The rotor is modelled as a half-circumference, given that the rotor has a radial symmetry, with the blade geometry being repeated in a radial pattern. The problem is solved by using arbitrary dimensions, having an inner radius of 0.4 and an outer radius of 1.0. The angular velocity used is 1000 rpm. Also, the values for kmax and kmin form Eq. 8 are 10,000 and 0 respectively.

The boundary conditions are velocity of 1.0 in the inlet, pressure equals to 0 in the outlet and null velocity on the wall, as shown in Fig. 5.

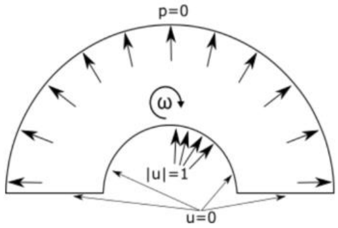

Figure 5. Design domain and boundary conditions.

7.2 Straight Blade Initial Guess

Given the domain shown in Fig. 5, it is possible to choose different initial conditions for the optimization process. Thus, in this section an initial domain distribution of a straight blade is used, as shown in Fig. 6, where the orange part represents fluid domain (α_i = 1) and the blue part represents the solid domain (α_i = 0).

Figure 6. (a) Straight blade initial guess; (b) Straight blade rotor.

The topology optimization results considering this initial guess and Eq. 14 with different values for the weight factor are shown in Fig. 7. Table 1 shows the functional values (Eq. 9, 10 and 13) for each result.

Table 1 shows that the functional values vary in accord to the objective function, thus, the second line, where the energy dissipation is the only objective, has a better energy dissipation value than the original domain (first line). In addition, it is possible to notice, that the multi-objective function presents a Pareto behavior, where one functional is minimized in detriment of another. For example, comparing the third line, where the vorticity functional is considered in parallel to the energy dissipation, to the second line (only energy dissipation objective) it has a lower value for the vorticity function however it presents a higher value for the energy dissipation.

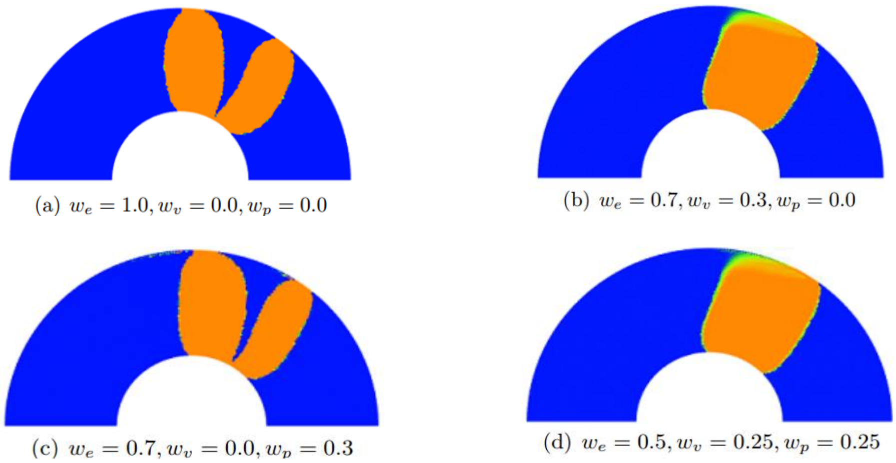

Figure 7. Topology optimization results by considering a straight blade as initial guess.

Table 1. Functional values results by considering a straight blade as initial guess.

	we	wv	wp	Volume	Energy Dissipation	Vorticity	Torque
Straight Blade	-	-	-	0.329	6.926	60.814	33.605
Fig. 7 (a)	1.0	-	-	0.329	6.188	65.339	33.079
Fig. 7 (b)	0.7	0.3	-	0.329	11.518	54.508	33.095
Fig. 7 (c)	0.7	-	0.3	0.329	6.396	67.171	32.737
Fig. 7 (d)	0.5	0.25	0.25	0.329	13.412	51.124	31.231

8. EXPERIMENTAL RESULTS

8.1 Built Rotors

The topology optimization results can be interpreted and re-scaled to the ventricular pump dimensions, and then the rotor can be designed in a CAD software and exported to be printed with a 3D printer. This process is illustrated in Fig. 8.

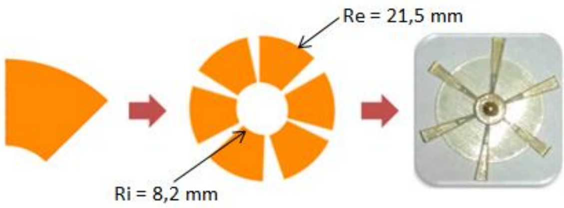

Figure 8. Post-processing process for the straight blade.

In this work, only straight blade and the topology prioritizing the energy dissipation has been built. Figure 9 shows the built rotors.

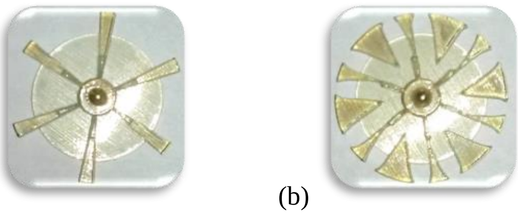

Figure 9. Built rotors: (a) Straight blade; (b) Topology results for energy dissipation objective.

8.2 Experimental Characterization

The experimental characterization is done by measuring the pump pressure head and the mass flow at the outlet, thus, the comparison is done only for these two quantities. Thus, a curve comparing the straight blade rotor and the optimized is built, by having the mass flow in the x axis and the pressure head in the y axis. The curve considering the pump in different operation points is shown in Fig. 10.

The angular velocity imposed to obtain the optimized results has magnitude of 1000.0 rpm, for this case, it is represented by the region around 2.5 l/min. Thus, from Fig. 10, it is possible to notice that the optimized rotor has a slightly higher pressure around this point, as expected given the results of the Tab. 1.

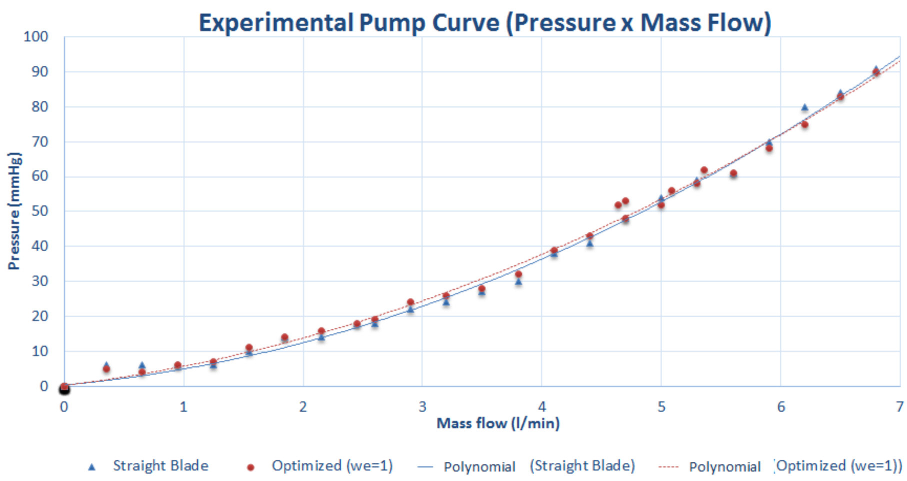

Figure 10. Pump experimental curve for straight blade and optimized rotor.

9. CONCLUDING REMARKS

In this work, a novel method for designing radial flow machine rotor based on TOM has been developed. The topology optimization is applied to design 2D rotors aiming to minimize the energy dissipation, the vorticity and the power consumption. The results are interpreted and a prototype is built by using a 3D printer.

The numerical results show that it is possible to obtain a non-intuitive layout satisfying all design criteria. The optimization shows that the double channel configuration which is quite similar to the blade splitter concept is a quite efficient design for radial flow machine rotors. In addition, prototypes could be successfully built by using 3D printer technology and the optimized rotor built showed a slightly higher pressure than the original rotor.

In future work we intend to improve the model by considering non-newtonian model, 3D problems and fluid-structure interaction in order to better represent the reality.

10. ACKNOWLEDGEMENTS

The fourth author thanks the financial support of CNPq (National Council for Research and Development) under grants 304121/2013-4.

11. REFERENCES

Aaronson, K. D. et al.,2012. “Use of an intrapericardial, continuous-flow, centrifugal pump in patients awaiting heart transplantation”. *Circulation*, v. 125, n. 25, p. 3191-3200, 2012.

Borrvall, T. and Petersson, J.,2003. “Topology optimization of fluids in Stokes flow”. *International Journal for Numerical Methods in Fluids*, v. 41, n. 1, p. 77-107, jan. 2003.

Funke, S.W. et al.,2012. “The automation of PDE-constrained optimisation and its applications”. 2012.

Neethu, S., Shinoy, k. and Shajilal, A.S., 2010. “Novel design, optimization and realization of axial flux motor for implantable blood pump”. *2010 Joint International Conference on Power Electronics, Drives and Energy Systems & 2010 Power India*, Ieee, p. 1-6.

Reddy, J.N. and Gartling, D.K., 2010. “The Finite Element Method in heat Transfer and Fluid Dynamics”. *CCRC Press 2010*.

Romero, J.S. and Silva, E.C.N., 2014. “A topology optimization approach applied to laminar flow machine rotor design”. *Comput. Methods Appl. Mech. Engrg*, v. 279, p. 268-300, 2014.

Rose, E.; et al., 2001. “Long-Term Use of a Left Ventricular Assist Device”. *The New England Journal of Medicine*, v. 345, n. 20, p. 1435-1443, 2001.

Slaughter, M.S. et al. “HeartWare ventricular assist system for bridge to transplant: combined results of the bridge to transplant and continued access protocol trial”. *The Journal of Heart Lung Transplant*, v. 32, n.7, p. 675–683, 2013.

12. RESPONSIBILITY NOTICE