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EXPERIMENTAL FLOW ANALYSIS IN FLEXIBLE TUBES WITH VARIABLE THICKNESS

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Abstract. *The present work aims to analyze and compare the fluid dynamic effects on permanent and pulsatile flows, through flexible and rigid tubes with equal internal diameter and different thicknesses in flexible ducts. In addition, also relate the influence of these geometric variants with regard to the flow conditions. To enable these analyses, a mold for making the flexible tubes, as well as the rigid tube model, was designed with the aid of Fusion 360 software (Autodesk, São Rafael, California, USA) and manufactured, through 3D printing. With the aid of a test bench, permanent flows were simulated, at various pump loads, as well as a pulsatile flow analogous to a physiological pulse. Therefore, it is concluded that the results related to pressure and flow in the pulsatile regime are higher in the rigid tube, when compared to the flexible tubes, due to its non-deformable characteristic. However, in the steady state it was found that the average flow and pressure did not show significant differences. Finally, the similarity between the applied pulsatile flow and the human physiological flow was also observed.*

Keywords: *Pulsatile flow, flexible tubes, rigid tubes, experimental analysis, pulsatile flow.*

1. INTRODUCTION

Among the diseases existing in the world, cardiovascular ones are the ones that cause the most death. In Brazil, these comorbidities are responsible for the fourth position in hospital admission and the first cause of death (Figueiredo FSF et al., 2020). Cardiovascular diseases encompass problems related to the functioning of the heart and blood vessels. There are several types of cardiovascular comorbidities, but some are of more concern such as atherosclerosis which causes the accumulation of fatty plaque in blood vessels (Botrel et al., 2000).

Based on this, knowing the behavior of arteries in the human body is of fundamental importance to monitor and seek possible treatments for these vascular diseases. One of the alternatives for the treatment of vascular diseases is Stents, a tube made of metallic material inserted into an artery, which is used to prevent obstruction of these vessels (Lally, C, et al., 2006). According to Grotberg and Jensen (2004), in the occurrence of internal flow in a deformable channel, the interactions between fluid-mechanical and elastic efforts can lead to a range of biologically important phenomena, including non-linear pressure drop relationships, flow rate , wave propagation and the generation of instabilities.

Therefore, there is a search by researchers for new methodologies to analyze the behavior of collapsible tubes, that is, those that suffer elastic or inelastic deformations according to the internal pressure that the fluid flow is causing in the channel wall . Studies with collapsible tubes are developed because these ducts have characteristics similar to those of vessels in the human body. For example, experiments are carried out to simulate a surgical intervention in an artery that has suffered an aneurysm and requires clipping through deformable tubes (Fukushima et al., 2012). In the literature, the behavior of rigid pipes subjected to internal flow is already well described, being one of the bases for the initial theoretical study of fluid mechanics (Fox et al., 2004). However, the study of deformable tubes is more complex and still needs better understanding and research. Several ways to characterize the fluid-structure interaction are reported in

journals, including Modarres-Sadeghi and Païdoussis (2009), who analyzed the behavior of an extensible tube subjected to an internal flow through nonlinear equations.
The present study aims to compare the fluid dynamic interaction behavior between rigid tubes and flexible tubes. Through a device that simulates a pulsatile flow, the pressure and flow differential parameters will be analyzed. It is believed that the results will contribute to a better characterization of the studied objects and be another theoretical-experimental enrichment tool.

2. BIBLIOGRAPHIC REVIEW

For a better understanding of the problem involving the behavior of flexible tubes, when compared to rigid tubes, this topic will be written based on journals that report cases of vascular problems, because these flexible tubes have a similar behavior to vessels, and the relationship of this with fluid dynamic interaction.

Kopel et al. (2001) evaluated the behavior of the elastic properties of the conduction arteries in asymptomatic patients with chronic aortic regurgitation. A control group was introduced into the study to compare properties. High-resolution vascular ultrasound was performed to measure the diameters of the common carotid artery during systole and diastole. Simultaneously with the imaging exam, he measured the common blood pressure for the calculation of arterial distensibility and compliance. According to the author, the echocardiographic assessment in patients with insufficiency revealed a high degree of importance of the disease. He stated that the mean arterial pressure was the same in both groups, but the systolic pressure was higher and the diastolic pressure was lower in the group with insufficiency. He also reported that there was no difference in the diameter of the carotid artery during diastole between the two groups. However, in systole, the diameter of the carotid artery was greater in the group with aortic regurgitation. It concluded that the difference between systolic diameters, diastolic diameters, compliance and distensibility of the arteries were greater in the group with chronic aortic regurgitation. With this, the author was able to measure, through image collection and measurements, the differences in elastic properties between the groups.

Wang and Parker (2004) conducted a study of the main arteries in the human body with a focus on the role played by the left ventricle of the heart. It analyzed the velocity and blood pressure in the 55 main arteries. The analysis observed the wave propagation in the studied vessels. In their work, a table was organized with anatomical and physiological values of blood vessels (arterial length, arterial diameter, thickness and modulus of elasticity of the arteries). He made a relationship between the blood flow velocity and the wave velocity in the artery that enabled data collection. It concluded that the complex wave propagation system of the largest arteries is the factor with one of the greatest relevance for arterial hemodynamics.

Dai et al. (1999) analyzed the effects of external pneumatic compression on the lower legs in the prophylactic treatment of deep vein thrombosis. They examined the distribution of stress within the tissues, the blood flow and the shear force resulting from the procedure of different forms of compression. He used the finite element method (FEA - Finite Element Analysis) to determine the venous collapse as a function of internal pressure and the spatial distribution of external compression. He used the one-dimensional equations that govern the flow in collapsible tubes and the venous collapse ratios obtained by the (FEA) to simulate the blood flow resulting from external compression. Conducted the tests in order to compare symmetrical and asymmetrical circumferential compression and to examine the pressure distribution along the limb. They concluded that asymmetric compression produced greater vessel collapse, greater blood flow velocity and greater shear stress when compared to symmetric compression.

Sorace et al. (2011) selected two groups, one with Chronic Kidney Disease (CKD) and one with people without (CKD), in order to perform non-invasive ultrasound examinations to determine arterial elasticity. The purpose of this analysis was to assess the maturation (dilation and increased resistance of the vessel walls) of the arteriovenous fistula. It assumed the linear elastic medium and determined the modulus of elasticity of the vessel as the ratio between tension (difference between systolic and diastolic pressure) and channel strain. Their preliminary analysis showed that vessels from patients with CKD have a significantly higher modulus of elasticity. He concluded by reporting that measurements of the modulus of elasticity through ultrasound can be another parameter to determine the maturation of the arteriovenous fistula.

Ibrahim (2006) numerically and experimentally investigated the formation of aortic aneurysms. For this, he carried out experiments in latex tubes subjected to hydrostatic pressure and with silicone tubes in the approximate dimensions of the aorta. He analyzed the pressure necessary for the occurrence of bubbles in the walls of the canals, making an analogy with aneurysms, in the tubes and verified how the materials behave. Finally, he validated the experiment by comparing the results with the numerical model developed by the Finite Element Method (FEM).

Y. Ma et al. (2018) developed in their work a relationship between blood pressure and Pulse Wave Velocity (PWV) in human arteries. He reported that non-invasive blood pressure monitoring methods correlating with (PWV), through the Moens-Korteweg (MK) and Hughes equations, already exist and are promising. However, the author states that these equations have gaps for application in human arteries. For this, it presented relationships between blood pressure and (PWV) that do not depend on the equations mentioned above, but that degenerate to the (MK) equation at low blood pressures and which has considerable accuracy when compared to the results of an in vivo experiment using vessels at high pressures. He concluded by stating that for the case of human arteries a simple relationship between blood pressure and PWV, within the blood pressure range, has been validated by literature and experiments in human beings.

Painter (2008) performed studies on the behavior of arterial pulse wave velocity PWV in an elastic tube. He used an expression derived from an equation that relates flow to pressure in a flexible tube considering the fluid as viscous and incompressible. He also used an approximation of a relationship, already known for rigid pipe, between force gradient and flow. As a result, he obtained a prediction that PWV in small arteries will increase when the specific rate of pressure increase decreases over time. He stated that the previously spoken rate decreases with an increase in myocardial ischemia and suggested that an increase in PWV is a predictor for a myocardial infarction. He concluded that PWV increases as the arteries decrease, and this increase may be related to the decrease in myocardial contraction force and not to arterial stiffness.

Sabrina et. al. (2020) produced a hemodynamic study of fluids inside an intracranial aneurysm (AI) with the aid of Computational Fluid Dynamics (CFD). It considered flow analysis in steady and transient conditions to obtain qualitative and quantitative results. It validated a blood analogous fluid through qualitative analysis and the flow behavior, in steady state, was similar to that experimentally visualized in a real aneurysm. In the transient regime, they obtained results in agreement with the previous analysis. Finally, they stated that the use of computational tool (CFD) is a good alternative for the diagnosis and treatment of intracranial aneurysm.

MU et al. (2019) carried out a numerical and experimental study to analyze the effect of pulsatile flow at different frequencies and on the flow resistance in the deformation of a lateral aneurysm. He used a pump to simulate pulsatile flow conditions and developed a method for building a flexible aneurysm using silicone as a material. He used software to simulate the fluid-structure interaction in the lateral aneurysm and compare the results with the experiment. He obtained results that may explain that one of the risk factors for aneurysm rupture is the abnormal flow in that region.

3. METHODOLOGY

3.1 Manufacturing of Models

A mold was designed with the help of Fusion 360 software (Autodesk, São Rafael, California, USA) to manufacture flexible tubes with an internal diameter of 10 mm. This value was selected based on the study by Lorchirachoonkul (2021), which describes as a physiological diameter range for an Internal Jugular Vein (VJI) the range from 9.1 mm to 10.2 mm, since this dimension makes it easier to manufacture flexible ducts.

The mold was manufactured through additive manufacturing in a 3D printer, which is split with an internal volume made of Polylactic Acid (PLA). The mold contains three cylindrical channels where the tubes are placed which, together with the internal volume, enable the fabrication of tubes with wall thicknesses, varying between 1.0 mm, 1.5 mm and 2.0 mm.

In the manufacture of flexible silicone tubes, the following materials were used:

- Silicone rubber and catalyst (Redelease),
- Brush,
- White Lub Release Agent,
- Scale accurate to 0.1 g,
- Split mold,

The manufacturing process began with the application of release agent on the inside of the mold and on the internal volume, in order to facilitate the removal of the tube after the silicone had been cured. Subsequently, an amount of silicone was mixed with the catalyst (30g of silicone with 0.9 g of catalyst) for application in the two parts of the mold, which was then closed to form the ducts.

For the procedure, some care was needed so that, after the tube had been cured, they could be removed without damaging its structure. One of the difficulties encountered was the formation of bubbles when filling the internal parts of the mold. At the time of mixing between the silicone and the catalyst, bubbles formed due to the circular movement. Thus, when pouring the silicone into the mold, the bubbles were concentrated between them.

Therefore, in the drying process of the pipeline, a vacuum formed, due to the presence of these bubbles, causing a structural disapproval of it in the experimental stage, since the defects in question would cause failures when subjected to internal flow pressures. The rigid tube with the same geometric characteristics as the flexible tubes were manufactured in a PLA 3D printer.

3.2 Experimental procedure

The experimental procedure was carried out on a test bench, the result of a study by Santos, W. B. A., (2021), capable of simulating a flow, acquiring and processing data through sensors and microcontrollers integrated into the system. Afterwards, these data were exported to perform the analysis and comparison of the fluid dynamic behavior between the tubes.

The bench consists of the control section, hydraulic test circuit, pump, sensors and data software. The pump used is a Rhondamac brand, model CF-2201[a] with a power supply voltage of 12V, capacity of 3A of direct current, maximum flow rate of up to 4.5 L/min (7.5x10-5 m3/s) and maximum pressure of 110 Psi (758.42 kPa).

The control section consists of an Arduino Uno, a switching power supply, a power circuit and the Rhondamac pump. The role of this section is to control the fluid flow that changes according to the pump's rotation.

The hydraulic circuit is composed of Poly Vinyl Chloride (PVC) hoses, which are responsible for conducting the liquid, a stainless steel water reservoir and the tube to be analyzed.

The sensor section is made up of Freescale model MPX5050DP piezoresistive pressure transducers. The flow sensor used was an Ultini brand, model USNH-HS41TA, located at the exit of the tube analysis section. The pressure sensors receive the reference of the pressure of the ducts through PVC hoses coupled to hydraulic connections in tee format, made of brass material, located at the entrance and exit of the pipes under analysis. It also has an Arduino Nano with the function of receiving the electrical signals sent by the flow sensor. The Arduino Uno, on the other hand, receives the electrical signal from the two pressure sensors.

The TELEMETRIVIEW software is responsible for receiving the data, viewing the parameters and exporting it in an Excel spreadsheet format. In Figure 1 the workbench with its main components is schematic.

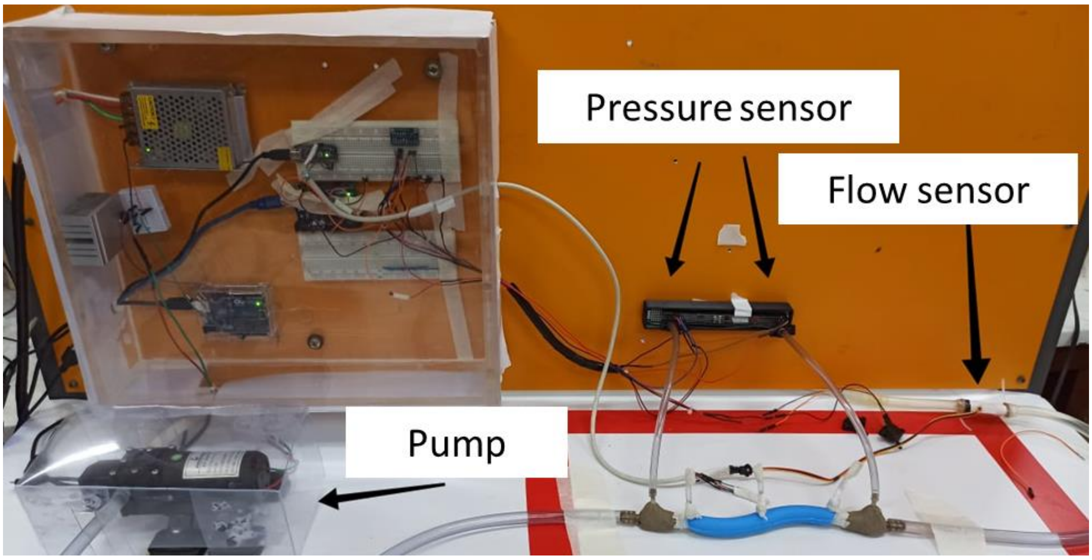

Figure 1. Experimental bench.

The bench experiment consists of supplying a water flow through a silicone tube, with thicknesses of 1.0 mm, 1.5 mm, 2.0 mm and a rigid tube in the steady state and pulsatile regime. For this, a bench was used that allows the pumping of water with a capacity to simulate the two flow regimes. In steady state, tests were performed with pump power at 30%, 35%, 40%, 45%, 50%, 55%, 60%, 65%. The experiment started at 30% pump power, as this is the percentage needed to overcome the flow inertia, and ended with 65% due to a limitation found in the software to perform data acquisitions above this value,

In the pulsatile regime, the flow was defined according to four distinct mathematical functions and boundary conditions analogous to those of a physiological pulse. These same experimental conditions were applied to a rigid tube with dimensional characteristics analogous to the flexible tube.

3.3 Data acquisition and analysis

Telemetreview software translates the signals sent by the Arduino and provides visualization of pressure and flow variation over time. The flow rates of the four tubes were collected in steady and pulsatile conditions. The inlet and outlet pressures in the tubes were also collected. These data were stored and later exported in Excel spreadsheet format.

In Excel, the data is processed and pressure and flow graphs over time are generated. Data were divided into two analysis categories. In the first one, the test results were compared using the pressure and flow graphs between the four tubes in the steady state. In the second, the same comparisons were made, but in the pulsatile regime.

4. RESULTS AND DISCUSSIONS

4.1 Mold

In the mold manufactured by additive manufacturing, 3D printing, a quality as expected was observed, but improvements were needed to make the manufacture of flexible tubes. The internal volume was sanded in order to improve its surface roughness and later a super glue was applied to the entire body of the internal volume. In addition, a structural reinforcement was made, after its rupture in a test, with the application of a wire longitudinally inside it. In Figure 2 we can see the split mold housing, the internal volume with an external diameter of 10 mm and the guide pins.

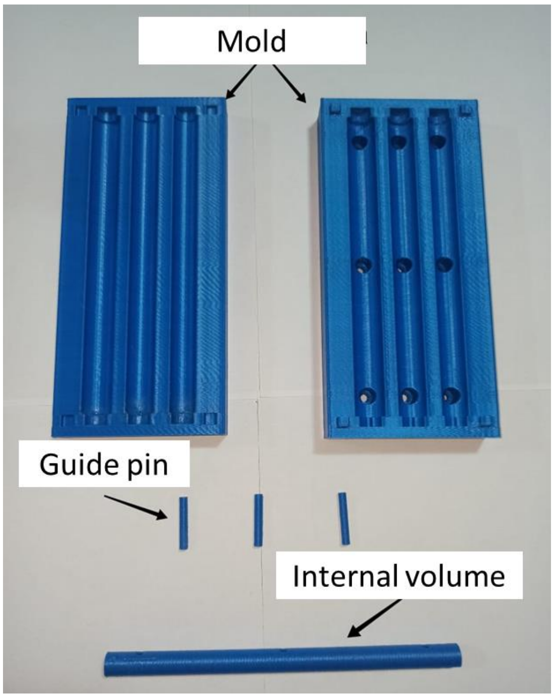

Figure 2. Mold

4.2 Silicone and PLA tubes.

The silicone tubes manufactured through the mold were of the necessary quality, without voids and superficial tears, for the performance of the test on the bench. In the rigid tube, regions with internal filling in PLA deficient were observed, with this, instant superglue was applied to prevent breakage and leaks. In Figure 3 we can see one of the flexible used in the tests.

Figure 3. Silicone flexible tube

4.3 Pulsatile Regimen

The behavior of the pulsatile flow was analyzed through data of the pressure at the inlet (PI) and pressure at the outlet (PO) of the flow, as well as the flow pulse. Graphs were generated as a function of normalized time to frame the pulses of the four tubes in the same period. In Figure 4 we have the result of the pressure pulse measured at the inlet of the flows stopping the flexible and rigid tubes.

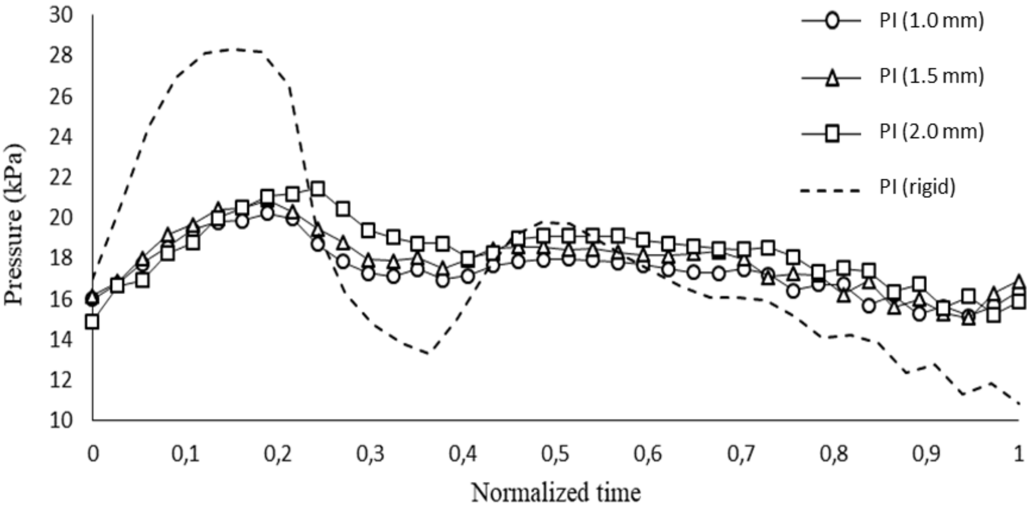

Figure 4. Pressure pulse at the inlet.

We can identify the shape of a physiological pulse in the four tubes characterized by peak systolic pressure and trough diastolic pressure. For the rigid tube a PI peak of 28.3 kPa (212.27 mmHg) was obtained. For the 2.0 mm tube, a PE peak of 21.44 kPa (160.81 mmHg) as well as 20.90 kPa (156.76 mmHg) and 20.22 kPa (151.66 mmHg) is observed for 1.5 mm and 1.0 mm tubes respectively.

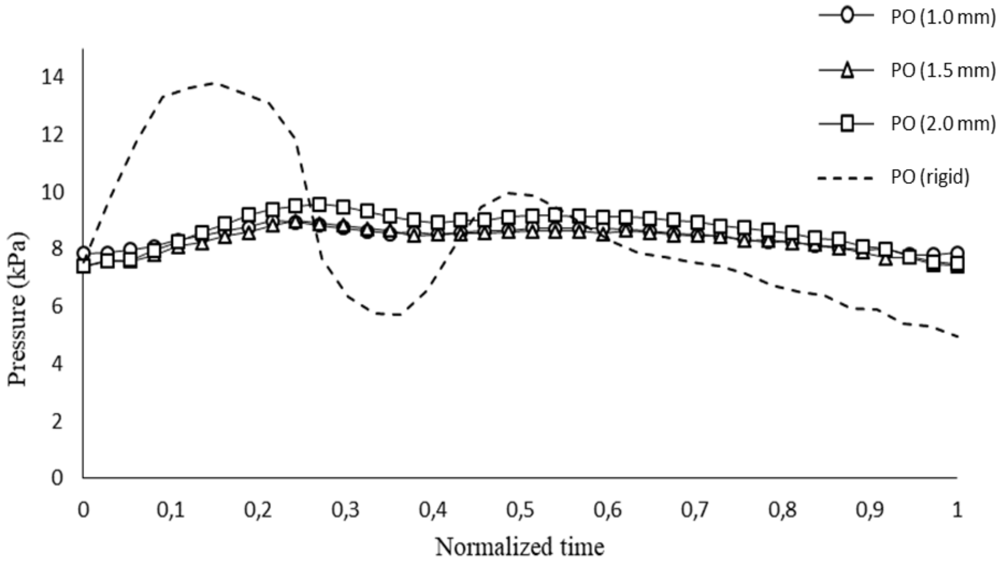

Figure 4. Pressure pulse at the outlet.

At the exit of the rigid tube (outlet), a peak pressure of 13.82 kPa (103.66 mmHg) was reached. Flexible tubes showed a smaller peak, compared to rigid, as well as at the inlet. For the 2.0 mm flexible, a peak outlet pressure of 9.56 kPa (71.7 mmHg) and 8.99 kPa (67.43 mmHg) for the 1.5 mm and 1.0 flexible was observed mm equally.

According to Brandão et al, (2017), the pulses change their shape when they are towards the more peripheral vessels. These vessels are, compared to the central arteries, more rigid, thus making the systolic peaks narrower and higher.

In view of the wave pulses obtained at the input and output, the flow behavior in each tube was analyzed. It can be seen that PE and PO in rigid tube have higher and narrower peaks compared to pulses in flexible tubes. This is due to the non-deformable characteristic of the rigid tube, which does not absorb the energy of the wave pulse. In flexible ones, smaller peaks are observed, due to the deformation characteristic that stores the energy of the pressure pulse in the form of elastic potential energy. In addition, the stored elastic potential energy, when released, causes the wave pulse to remain at higher levels at the end of the pulse, that is, while in the rigid one there is a significant pressure drop, in the flexible ones the values remain at levels close to the peak.

Through the data shown in Table 1, it was also found that despite the systolic and diastolic peaks being different in values, the mean pressure variation of a pulse is very close between the tubes, whether they are flexible or not.

Tabela 1. Mean Pressure Difference

Mean Pressure Difference (kPa)			
	Medium pressure (inlet)	Medium pressure (outlet)	ΔP (Medium)
Rigid	17.76	8.49	9.27
Flexible (1.0 mm)	17.42	8.42	9.00
Flexible (1.5 mm)	17.92	8.31	9.61
Flexible (2.0 mm)	18.30	8.69	9.61

Figure 5 relates the difference between the inlet and outlet pressures in each tube with time. Based on this graph, it was observed from time 0.21 that flexible models have a higher pressure drop than the rigid tube model. This behavior reinforces energy transfer and pressure pulse absorption in flexible larger than in rigid.

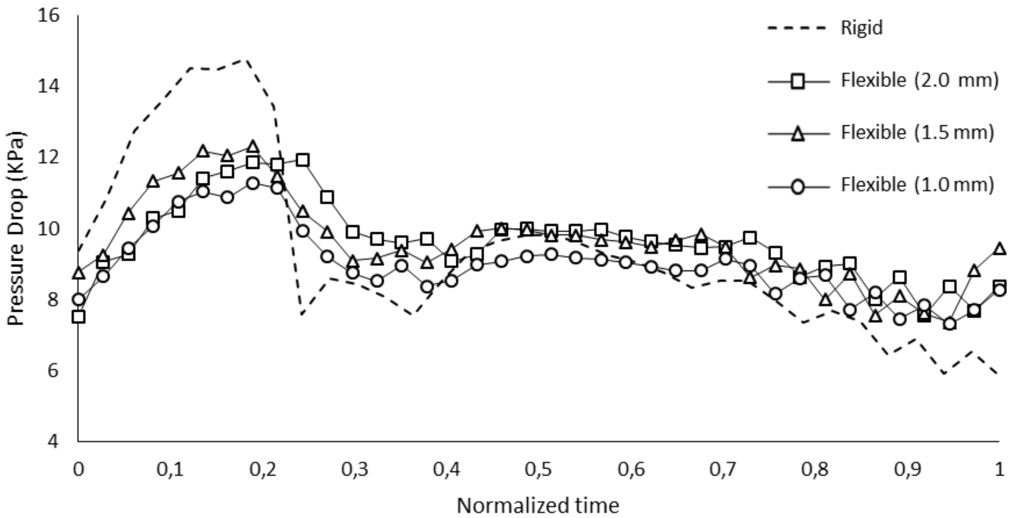

Figure 5. Pressure drop between PI and PO.

Finally, pulsatile flow data in relation to time were generated in all ducts. Figure 6 shows the flow pulses over time.

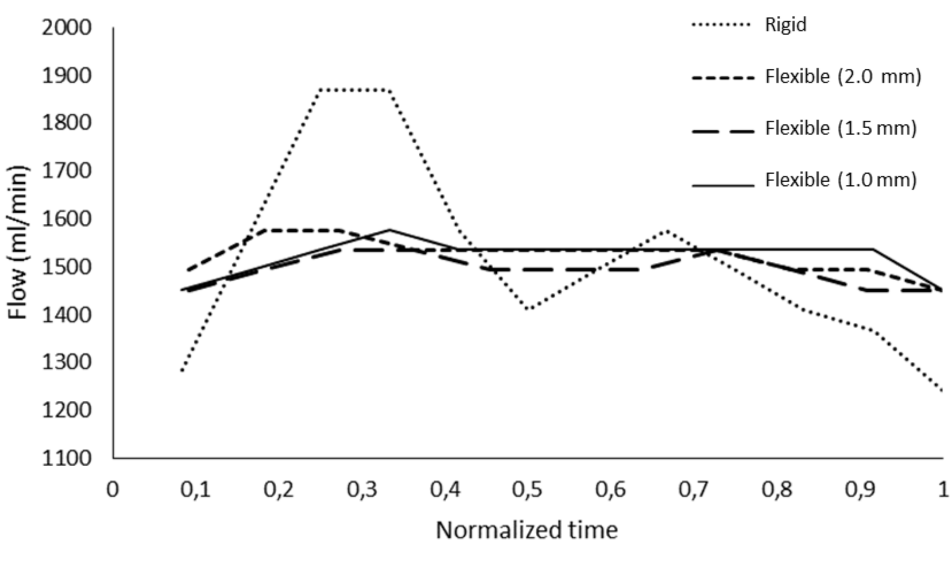

Figure 6. Flow in the pulsatile regime.

Note a behavior similar to that which occurred in the pressure pulse, where the rigid model has a higher flow peak, while in the other flexible tubes the effect of the damping of the flow pulse can be verified due to its expansion and energy storage. It is noticed that the number of points collected through the flow sensor has a smaller amount in the range. Thus, some punctual differences in the flow pulse cannot be observed.

5. CONCLUSIONS

According to the obtained results, it can be concluded that in the pulsatile flow regime the results are in agreement with the literature. In this regime, the pressure and flow pulses of the rigid tube were observed in values greater than those of the flexible tubes because it does not absorb the energy of the flow.

Among the flexible ones, it is concluded that the values of the pressure and flow pulses decrease with the reduction of thickness between the ducts. It is concluded that the series of flexible tubes maintains higher flow and pressure levels due to the transfer of elastic potential energy to the fluid.

6. REFERENCES

Botrel T.E.A., Costa R.D., Costa M.D., Costa A.M.D, 2000. "Doenças cardiovasculares: causas e prevenção". *Rev. Bras. Clín.*, Vol. 26, No. 3, pp. 87-90.

Botti L., Canneyt K., Kaminsky R., Claessens T., Planken R.N., Verdonck P., 2013. "Numerical Evaluation and Experimental Validation of Pressure Drops Across a Patient-Specific Model of Vascular Access for Hemodialysis". *Cardiovascular Engineering and Technology*, Vol. 4, No. 4, pp. 485–499.

Brandão, A. A., Amodeo, C., Alcântara, C., Barbosa, E., Nobre, F., Pinto, F., Vilela-Martin, J. F., Bastos, J. M., Yugar-Toledo, J. C., Mota-Gomes, M. A., Neves, M. F. T., Malachias, M. V. B., Rodrigues, M. C., Junior, O. P., Jardim, P. C. B. V., Cunha, P. G., Póvoa, R., Fonseca, T., Dias, V. P., Barroso, W. S., Oigman, W., 2017. "Posicionamento luso-brasileiro de pressão arterial central". *Arquivos Brasileiros de Cardiologia*, Vol. 108, No. 2, pp. 100–108.

Carvalho, S, 1998. *A numerical simulation of carotid artery flow* (in Portuguese). Master's Thesis, Graduate Program in Applied Mathematics, Federal University of Rio Grande do Sul, Porto Alegre, Brazil.

Dai, G., Kamm, R. D., Gertler, J. P., 1999. "The effects of external compression on venous blood flow and tissue deformation in the lower leg". *Journal of Biomechanical Engineering*, Vol. 121, No. 6, pp. 557–564.

Figueiredo F.S.F., Rodrigues T.F.C.S., Rêgo A.S., Andrade L., Oliveira R.R., Rodavanovic C.A.T., 2020. "Distribuição e autocorrelação espacial das internações por doenças cardiovasculares em adultos no Brasil". *Rev. Gaúcha Enferm.* Vol. 41, e20190314.

Fox, R.W., McDonald, A.T. and Pritchard, P.J., 2004. *Introduction to Fluid Mechanics* (in Portuguese), LTC, Rio de janeiro.

Fukushima, J.C., Paschoalini, A.T., Bazani, M.A., Michelan, N., 2012. "Clipagem Arterial Utilizando Modelo Artificial Construído". In *10ª Conferência Brasileira de Dinâmica, Controle e Aplicações – DINCON 2011*. Águas de Lindóia Brazil.

Grotberg, J.B., Jensen, O.E., 2004. "Biofluid mechanics in flexible tubes". *Annual Review of Fluid Mechanics*, Vol. 36, pp. 121–147.

Ibrahim, L. B., 2006. *Numerical and experimental investigations of aneurysm mechanics in isotropic rubber tubes* (in Portuguese) – Master's Thesis, Graduate Program in Civil Engineering, PUC, Rio de Janeiro, Brazil.

Kopel, L., Tarasoutchi, F., Medeiros, C., Carvalho, R.T., Grinberg, M., Lage, S.G., 2001 "Distensibilidade arterial como possível mecanismo compensatório na insuficiência aórtica crônica". *Arquivos Brasileiros de Cardiologia*, Vol. 77, No. 3, pp. 258–261.

Lally, C., Kelly, D., Prendergast, P., 2006. *Stents*. Wiley Encyclopedia of Biomedical Engineering, M. Akay.

Lorchirachoonkul T., Ti, L. K, Manohara, S., Lye, S.T., Tan, S.A., Shen, L., Kang, D.S., 2012. "Anatomical variations of the internal jugular vein: implications for successful cannulation and risk of carotid artery puncture". *Singapore Med J.* Vol. 53, No.5, pp.325-8.

. Ma Y., Choi .J, Hourlier-Fargette A., Xue Y., Chung H.U., Lee J.Y., Wang X., Xie Z., Kang D., Wang H., et al., 2018. "Relation between blood pressure and pulse wave velocity for human arteries". *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 115, No. 44, pp. 11144–11149.

Modarres-Sadeghi, Y., Païdoussis, M.P., 2009. "Nonlinear dynamics of extensible fluid conveying pipes, supported at both ends". *Journal of Fluids and Structures*, Vol. 25, No. 3, pp. 535–0543.

Mu, L.Z., Li, X.Y., Chi, Q.Z., Yang, S.Q., Zhang, P.D., Ji, C.J.; He, Y., Gao, G., 2019. "Experimental and numerical study of the effect of pulsatile flow on wall displacement oscillation in a flexible lateral aneurysm model". *Acta Mechanica Sinica/Lixue Xuebao*, Vol. 35, No. 5, pp. 1120–1129.

Painter, P. R., 2008. “The velocity of the arterial pulse wave: A viscous-fluid shock wave in an elastic tube”. *Theoretical Biology and Medical Modelling*, Vol. 5, pp. 1–6.

Rangel, J. F., 2021. *Analysis of pulsatile flow in rigid and flexible arteriovenous fistula: In vitro study*. (in Portuguese). Master’s Thesis, Graduate Program in Mechanical Engineering, Federal University of Rio Grande do Norte, Natal, Brazil.

Sabrina, M., Miranda, V., Souza, D. P., 2020. *Numerical study of flow in a real intracranial aneurysm for different Reynolds numbers* (in Portuguese). Master’s Thesis, Graduate Program in Industrial Engineering, CEFET-RJ, Rio de Janeiro, Brazil

Santos, W. B. A., 2021. *Analysis of pulsatile flow in arteriovenous fistula with variation of in vitro and in silico anastomosis angle* (in Portuguese). Master’s Thesis, Graduate Program in Mechanical Engineering, Federal University of Rio Grande do Norte, Natal, Brazil

Sorace, A.G., Robbin, M.L., Abts, C., Lockhart, M.E., Allon, M., Hoyt K., 2011. “Arterial elasticity as a predictor for arteriovenous fistula maturation: Preliminary results”. *IEEE International Ultrasonics Symposium*, IUS, pp. 943–946.

Wang, J.J., Parker, K.H., 2004. “Wave propagation in a model of the arterial circulation”. *Journal of Biomechanics*, Vol. 37, No. 4, pp. 457–470.

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