STUDY OF THE STEADY FLOW IN AN ARTERIAL BLOOD FILTER USING PIV

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Abstract..*Particle image velocimetry is a well-established technique for obtaining quantitative velocity information over extended regions of a flow with high accuracy. Dye injection is a quite simple technique and can give a qualitative idea about the flow structure. The objective of this work is to study the flow in an arterial blood filter. A test circuit was developed and both techniques (particle image velocimetry and dye injection) were used to analyze the flow structures. Dye injection was done using water as working fluid while a solution of water and glycerin was used in the tests using the particle image velocimetry technique. Velocities profiles were analyzed and the results show a good agreement between both techniques.*

Keywords. *Blood filter, PIV, Visualization, Flow*

1. Introduction

Extracorporeal circulation (CEC) has become a common clinical practice. In this technique the blood is pumped by a pump, an oxygenator plays the role of the lungs while a filter is used to filter the blood before its reinfusion into the patient's arterial system. Arterial line filters are now routinely used in cardiac surgery in order to decrease the microemboli load to the patient (Mueller at all, 1999). Its efficacy in removing different kinds of microemboli has been well documented but there are some troubles associated with the use of an arterial blood filter like the pressure gradient across the filter, destruction of red blood cells and platelet changes (Bergdahl and Bjork, 1980).

Most blood conducting devices have exhibited some degree of thrombus formation. One of the main concerns when designing cardiovascular devices, like blood pumps, membrane oxygenators and blood filters, is to ensure the elimination or minimization of thrombus formation. Activation of the blood, which in turns leads to thrombosis, can be caused by a number of adverse flow characteristics including turbulence, recirculation, stasis and high shear stresses (Mussivand et all, 1999). In terms of flow visualization, high shear stresses can be regarded as one of the cause of red blood cell damage while stagnation and standing vortexes can be regarded as causes of thrombus formation (Yamane et all., 1998).

The experimental technique of particle image velocimetry (PIV) has proven to be a valuable method for quantitative, two-dimensional flow structure evaluation (Quenot at all., 1998). PIV has been used in the studies of flow in artificial heart valves (Browne et al, 2000) and can also be applied to the flow analysis in blood pumps and arterial blood filters.

Flow visualization is an important experimental tool to obtain a visible flow pattern and study the velocity in artificial devices (Aron at all, 1997). Techniques used are an oil film method, a tuft method, a tracer method and dye injection (Sakuma et all, 1995). In this study a dye injection method utilizing a Web camera was applied to visualize the flow in an arterial blood filter. Axial and radial velocities components were measured using a commercial particle image velocimetry system. The results were combined and an analysis of the flow in an arterial blood filter was performed.

2. Materials and Methods

2.1. The blood filter

The filter studied is used in open heart surgeries. The filter is project to be used in adult patients and can be operated with a maximum flow rate of 6 liters per minute. The body filter is made using acrylic and polyester is used in the filtering element. The filter inlet and outlet connectors have a diameter of 9,5 mm and are made of acrylic. The filtering element has a porosity of 40 µm. A bypass line can be used in situations where the filtering element pores are closed and another line is used to eliminate the air trapped by the filter. A schematic view of the filter, its elements and how it works is shown in figure 1. In figure 1, unfiltered blood is indicated by blue arrows while red arrows indicate filtered blood

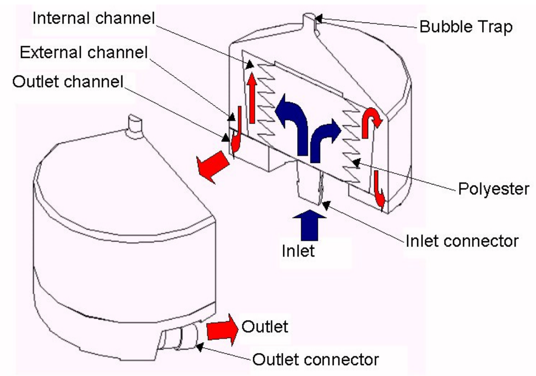

Figure 1. Schematic view of the filter

Blood flowing in an ascendent way pass through the inlet connector, located at the bottom of the filter. The blood flow is divided axially at the inner part of the filtering element while the blood flows through the polyester. The filtered blood reaches the internal channel and still has an ascendent movement. The blood changes direction at the top of the internal channel reaching the external channel and describing a counterclockwise helical movement in direction of the outlet channel. The collected blood flows in direction of the outlet collector leaving the filter.

2.2. The flow circuit

A test bench was assembled in order to reproduce the flow condition observed during a cardiopulmonary bypass. Figure 2 depicts schematically the test circuit.

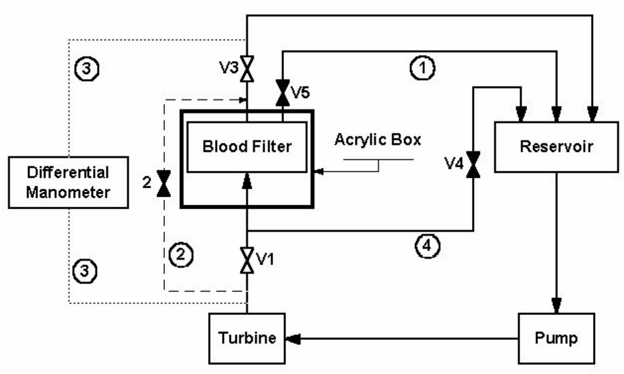

Figure 2 – Schematic view of the test circuit

Working fluid was pumped through the turbine and blood filter returning to the circuit reservoir. Line 1 represents the bubble trap and was used during the circuit filling up. During the PIV measurements many particles, necessary due to the PIV working principle, were captured by the filtering element and Lines 2 and 4 were used together to clean the filter using a retrograde flow. Pressure drop across the filter was monitored by a differential manometer, indicated by the lines 3. Flow rate was monitored by a turbine flow meter and the pump rotating speed was controlled changing the excitation voltage of a brushless motor. All elements were connected using PVC flexible tubes. A prismatic acrylic box was used as optical window to minimize optical distortions. During the PIV measurements and flow visualization tests the filter was placed inside this prismatic box filled with water. The flow rate used in the PIV tests was 4.5 liters per minute which is an accordance with the values used during a cardiopulmonary bypass. The flow was seeded with Al_2O_3 particles with a mean measured diameter of 48 μm. Water was used as working fluid during the visualization tests using dye injection and the flow rate was estimated using Reynolds similitude between water and the water-glycerin solution.

2.3. Particle Image Velocimetry

A commercial PIV system was used to measure the axial and radial velocity components. The system consists of a double cavity Nd-Yag laser (Newwave solo PIV II-30), a CCD camera (80C60 Hisense PIV/PLIF), a processor and a computer. The laser produces pulses of short duration (5 ns), in a frequency of 30 Hz, with a diameter of 2,5 mm, energy of 30 mJ per pulse, a wavelength of 532 nm. The laser passes through a set of lenses. This set consists in a spherical len with a focal length of 1000 mm which controls the plane thickness (about 3 mm) and a cylindrical len with a focal length of 300 mm used to create the laser plane. The CCD camera has a resolution of 1280 x 1024 pixels, and operate in a frequency of 7,0 Hz in the double frame mode. The camera was focused normal to the illuminated planes. The images were collected and stored in the computer. For each plane, 20 successive images were collected, which yield 10 instantaneous velocity fields after processing. These fields were combined resulting in a mean field velocity. The images were treated with a cross correlation scheme using an interrogation area of 32 x 32 pixels and an overlay of 50%. A commercial software (Flowmap) was used to acquire data and to control the laser, CCD and processor. PIV measurements were performed at four different planes labeled N, S, E and O. The coordinate system adopted in the measurements is located at the lower left corner of the acquired PIV image. The system is oriented in such a way that x axis is directed radially and y axis axially. Figure 3 shows the measurement planes and the coordinate system used during the PIV measurements.

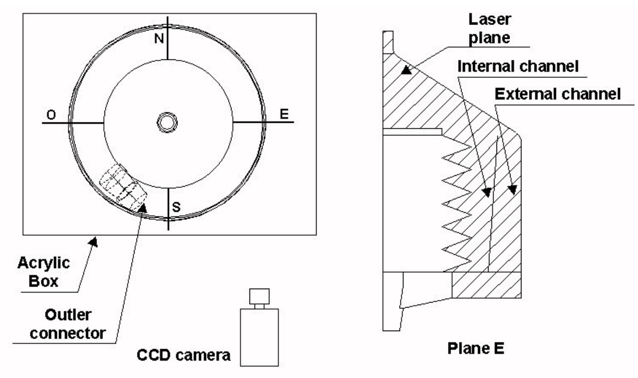

Figure 3 – Coordinate systems and measurements planes

The working fluid was a combination of 40%, in mass, of glycerin with 60% of water. This working fluid was chosen because it matches the blood transport properties. At 25°C, the blood analog fluid has a density of 1.09 g/cm^3 and absolute viscosity of 3.18 mPa.s. One problem associated with this working fluid when using a optical measurement technique is the refraction index. The measured refraction index of the solution was 1.383 which is lower than 1.49, the refractive index of the filter wall. This difference implies in a displacement of the plane of light due the refraction of the light. All measurements were done in planes along the center line of the filter, as shown in figure 3. The laser was placed above the filter in such a way that the laser plane could intercept the filter along the center line of the filter eliminating the plane refraction.

The measurements performed give, for every point located in the measurement plane, the mean value of the velocity components. The mean velocities can be evaluated using the following equations

$$\overline{U} = \frac{1}{N}\sum_{1}^{N} \tilde{u}_n \qquad (1)$$

and

$$\overline{V} = \frac{1}{N}\sum_{1}^{N} \tilde{v}_n \ . \qquad (2)$$

where $\tilde{u}_n$ e $\tilde{v}_n$ are the u and v values at every image pair processed and N is the number of image pairs acquired.

2.4. Flow visualization

Flow visualization was done using the same test bench described before. Dye was injected, using a needle, through eight orifices made at the upper part of the filter. Four orifices are located over the internal channel and the others over the external channel. The subscript *e* refers to points located over the external channel while the subscript *i* identifies orifices located over the internal channel. At each internal orifice the dye was injected at three different levels while at the external orifices dye injection was performed at four different levels. Figure 5 shows the injection points and levels. It must be pointed out that the nomenclature used to label the measurement planes was adopted to the injection points. Visualization was performed using a WEB camera placed normal to the filter wall in the region where the needle was placed.

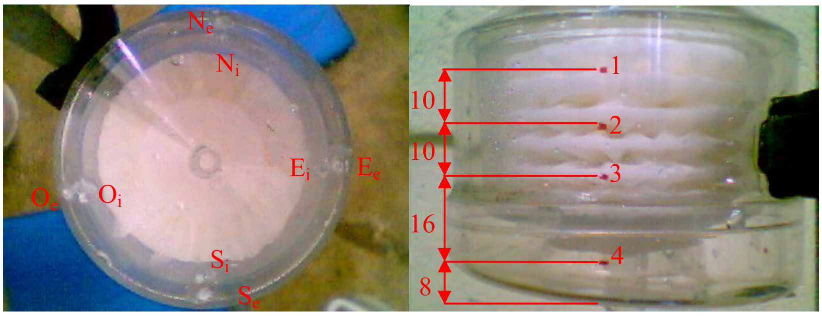

Figure 5 – Injection points and levels

Water, at 25°C, was used as working fluid and Reynolds similitude was used to evaluate the its flow rate. The characteristic length used in the Reynolds number evaluation was the diameter of the inlet connector.

$$Re_{\mathrm{water}} = Re_{\mathrm{sol}.40\%} \tag{3}$$

and so

$$\frac{\rho_{\mathrm{water}} \mathrm{V}_{\mathrm{water}} \mathrm{D}_{\mathrm{filter}}}{\mu_{\mathrm{water}}} = \frac{\rho_{\mathrm{sol}.40\%} \mathrm{V}_{\mathrm{sol}.40\%} \mathrm{D}_{\mathrm{filter}}}{\mu_{\mathrm{sol}.40\%}} . \tag{4}$$

Water flow rate can be expressed in terms of water-glycerin flow rate and kinematics viscosity as

$$\mathrm{Q}_{\mathrm{water}} = \frac{\nu_{\mathrm{water}}}{\nu_{\mathrm{sol}.40\%}} \mathrm{Q}_{\mathrm{sol}.40\%} = \frac{0{,}857}{2{,}898} 4{,}5 = 1{,}33 \tag{5}$$

The flow rate used was 1,33 l/min. The similitude asserts that the flow pattern observed using water is the same of that using the solution of water and glycerin.

3. Results and Discussion

3.1. Flow visualization

Figure 6 shows the flow visualization in the internal channel in planes O, N, E and S, respectively.

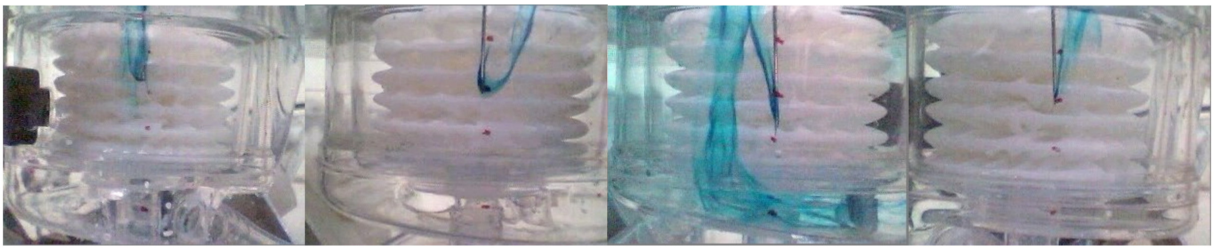

Figure 6 – Flow visualization in the internal channel

In all planes the flow has an ascendent behavior with the axial velocity component greater than the tangential component because the dye displacement is greater in the vertical sense. Figure 7 shows the flow visualization in the external channel.

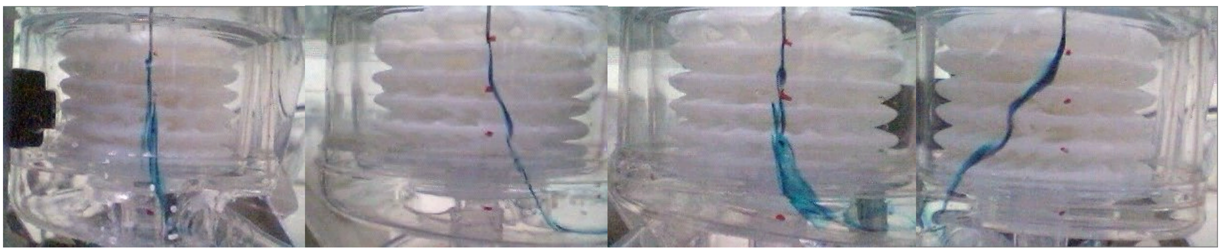

Figure 7 – Flow visualization in the external channel, in planes O, N, E and S, respectively.

In this case the flow has a descend counterclockwise pattern in planes O, N and E. In plane S the dye flows in a clockwise sense due to the outlet channel proximity. The tangential component increases as the dye reaches the outlet channel. In all images in figures 6 and 7 the dye has no tendency to disperse indicating a flow with small velocity components.

3.2. PIV measurements

Figure 8 shows the velocity vectors and the axial component in the four planes. A positive value represents ascendent flow, Y positive, while negative indicates descendent flow, Y negative. As shown by the visualization using dye at the internal channel the flow presents a ascendent pattern. The maximum axial velocity was 0.13 m/s in plane E near the top of the internal channel. In the others planes the velocity has a value near of 0.08 m/s in the same region indicating an uniform flow in this planes. At the external channel the flow has a descendent pattern as indicated by the signal of the velocity component. The maximum value, in modulus, observed is –0.189 m/s in the plane O and it happens due to the outlet connector proximity which induces an acceleration to the flow. In the planes N and S the maximum, presents the same value of –0.163 m/s. The plane E is the most distant form the outlet connector and this is the reason for such a small value of –0.09 m/s. The velocity vectors profiles in all images show that the velocity is maximum in the central part of the channel and decreases near the wall. In plane S, in the outlet channel is possible to see a parabolic profile while in the plane O a recirculating pattern can be observed.

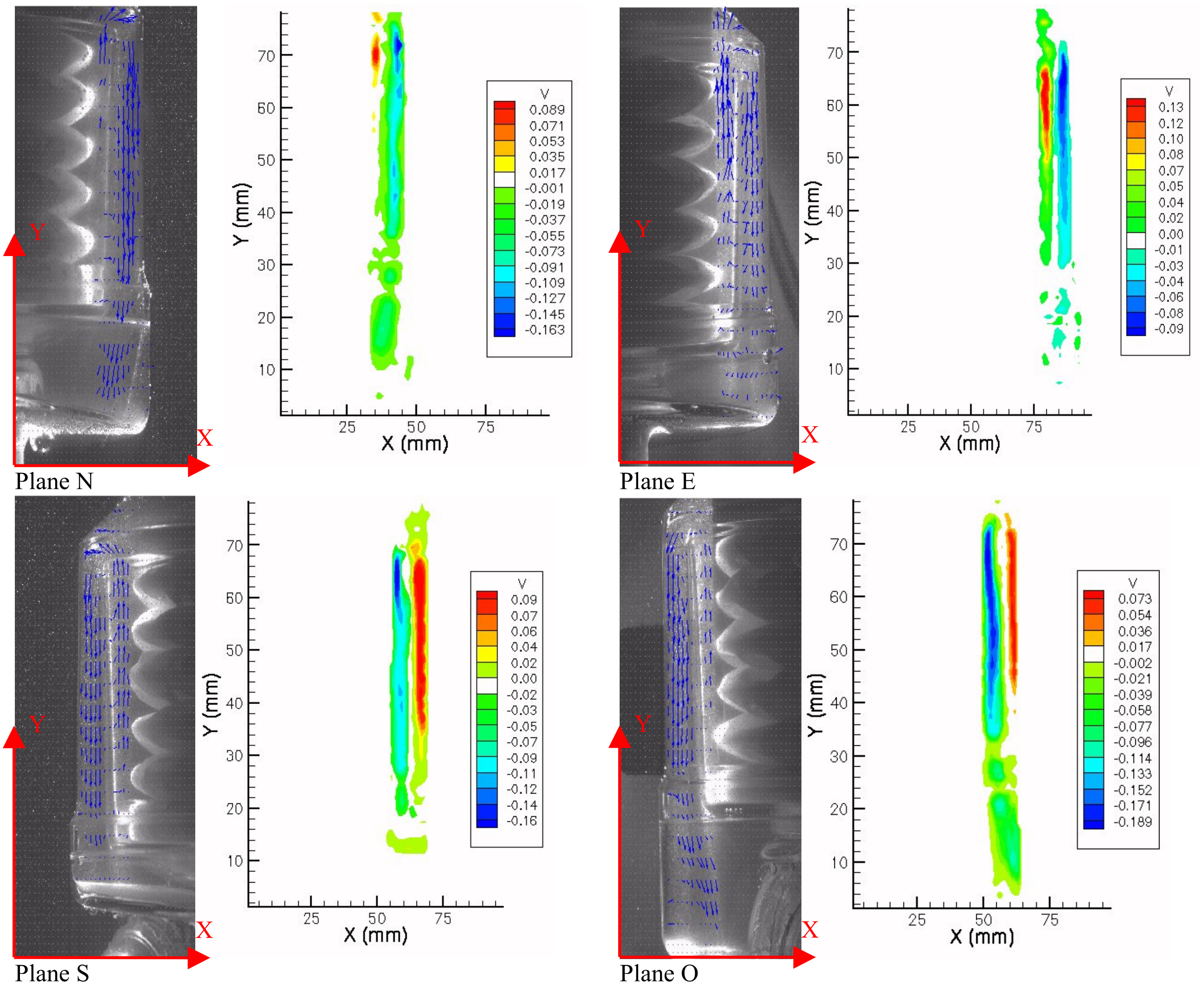

Figure 8 – Axial velocity in m/s

Velocity vectors and the radial component in the four planes are show in figure 9. In planes N and E a positive value represents radially external flow, X positive, while negative indicates radially internal flow, X negative. In planes S and O the velocity signal has the opposite meaning. The visualization study using dye was not able to give any information about the radial component. The maximum radial velocity was 0.133 m/s in plane N, and 0.14 m/s (absolute value) in plane S, both near the top of the internal channel. This behavior was observed in planes E and O but with a lower velocity value of 0.07 m/s. In the outlet channel the radial component is small and in this region the flow is predominated by the tangential component as shown by the visualization study. The low velocity values with a maximum value of 0.14 m/s explain the dye behavior during the visualization tests.

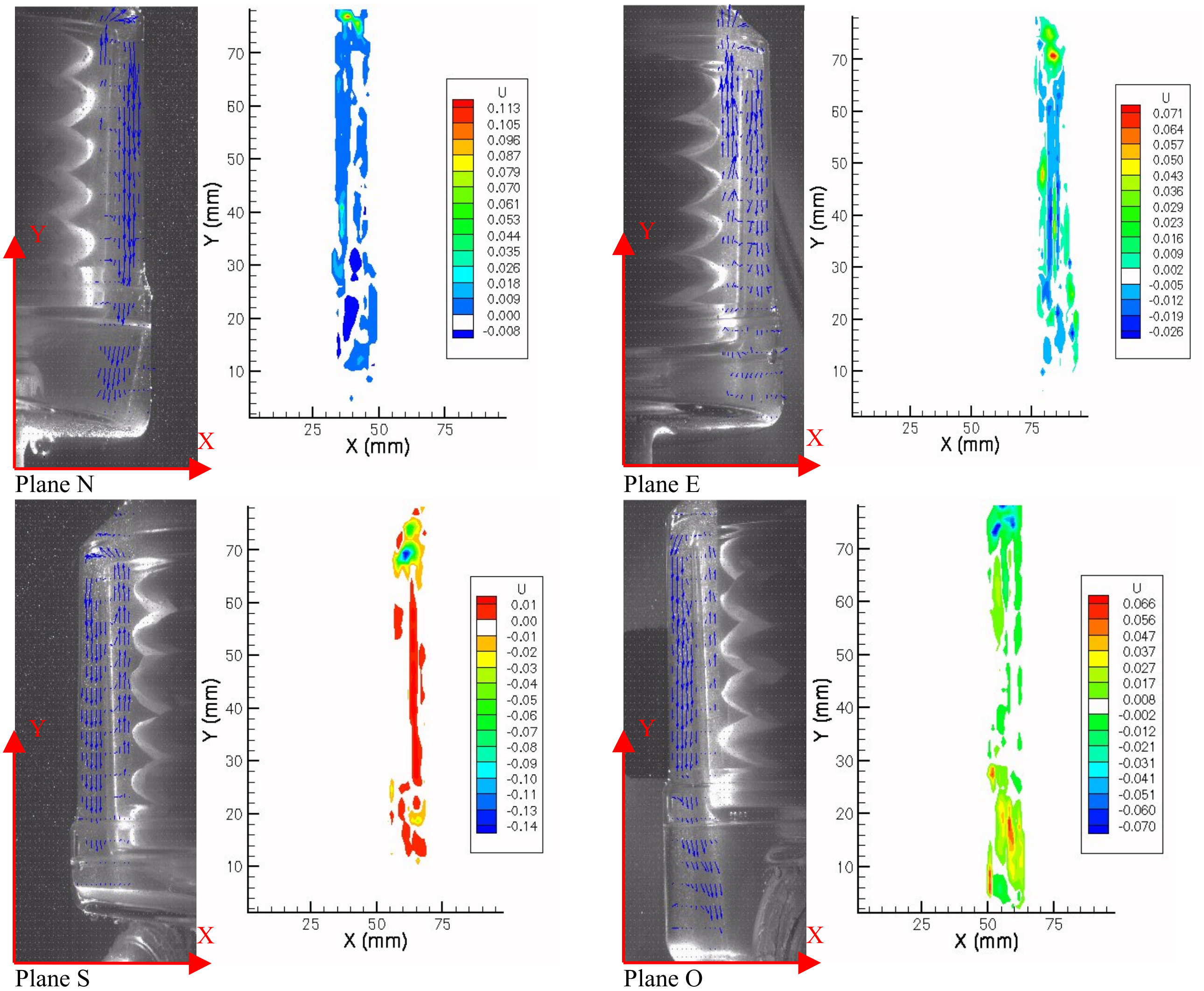

Figure 9 – Radial velocity in m/s

4. Conclusions

In this work a commercial PIV system was used to study the flow inside an arterial blood filter. A test bench was developed in order to allow the use of the PIV system and a working fluid with viscosity and density similar those of blood was used. Velocities profiles were measured at four planes and results show an uniform pattern flow in the four planes. The flow was visualized using the dye injection technique and the results are in good agreement with the PIV measurements.

5. Acknowledgement

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