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IN VITRO STEADY FLOW VELOCITY AND SHEAR STRESS MEASUREMENTS IN THE VICINITY OF A JELLYFISH VALVE

Ali A. Sakhaeimanesh and Yos S Morsi
Modelling and Diagnostics Group
School of Mechanical and Manufacturing Engineering
Swinburne University of Technology, Hawthorn, Victoria
Australia

Geoff D. Tansley
School of Engineering
Flinders University of South Australia, Adelaide
Australia

Simon Yu
School of Mechanical and Production Engineering
Nanyang Technological University, Singapore 2263

ABSTRACT

Elevated turbulent shear stresses resulting from disturbed flow through prosthetic heart valves can cause damage to red blood cells and platelets. The purpose of this study is to examine the turbulent shear stresses occurring downstream of a newly designed valve, namely the Jellyfish valve, under steady and pulsatile flow conditions. The results reported here are only for steady flow cases of 15 and 26 l/min. The diagnostic Laser Doppler Anemometry (LDA) technique is used to determine the fluid flow and the shear stress parameters at different locations downstream of the valve. The results indicated that for flow below 26 l/min the shear stresses are in the range of 0-94 N/m^2 and for 15 l/min the maximum shear stress has a value of 43 N/m^2.

Furthermore it was observed that the circulation region is mainly located between the face of the valve and 15 mm downstream of it. Such a finding is of significance to thrombus formation.

INTRODUCTION

One of the key areas in artificial heart research is the design and construction of suitable valves. Mechanical valves such as the Björk-Shiley have been traditionally used in conjunction with artificial hearts. Recently however these valves are found to cause a ring thrombus at the interface between the valve ring and the blood pump. They are also expensive and can introduce water hammer (Imachi et al 1988).

Although the clinical success of a given valve design is based on many factors, one being the fluid flow phenomena, particularly in vitro velocity profiles and shear stresses (Yoganathan et al, 1979). High shear stress levels in the main arteries are thought to have an adverse effect on erythrocytes (Sallam et al, 1983, Nevaril et al, 1968), activate platelets (Williams, 1973, Stein et al, 1984) and contribute to thrombus formation (Stein et al, 1974). Both the magnitude and the duration of the shear stresses influence the onset and severity of the damage to the constituents of blood (Roony, 1970 and Leverett et al, 1972). According to Giersiepen (1988), the critical shear stress range for lethal erythrocyte and thromobocyte damage is 200 to 400 N/m^2 for an exposure time of 1 to 10 msec, which is the estimated time for a blood cell to pass through a heart prosthesis. Despite the importance of this fluid mechanics data, few studies are found in the open literature. Among these, on the investigation of shear stresses, Yoganathan et al (1979) reported on the studies of Björk-Shiley, and on Caged-ball valves. Later Tillman et al (1984) used flush mounted shear stress probes to examine three different types of mechanical valves. The author reported a peak stress value of 120-140 N/m^2 at the large orifice of a Björk-Shiley valve, 12-15 N/m^2 at the large orifice of a Lillehei-Kaster valve and 85 N/m^2 at the valve ring of a Starr-Edwards valve. Einav et al (1988a) evaluated the shear stress distributions along the cusps of polymeric tri-leaflet valves and reported a maximum shear stress value of 170 N/m^2. In the flow stagnation zones which are more prone to thrombus formation than the areas of high shear stresses some research has been done such as the work by Petscheck and Weiss, (1970), Kingsley et al, (1967) and Hanle et al (1988).

In this study a particular design of valve, developed by Imachi, known as the Jellyfish valve, is being examined by the authors at Swinburne University of Technology. The Jellyfish valve is unique in design; incorporating a thin flexible membranous occluder made of polyurethane attached centrally to a rigid frame made of solution-cast coated with polyurethane. The potential advantages that this valve could offer are: minimal flow disturbance, hence relatively low shear stresses and pressure gradients, limited occluder inertia and therefore reduced regurgitant flow and reduced cost which is an important factor since the cost of the valves is a significant proportion of the cost of VAD's (Imachi et al 1989). Other studies have also been reported by the authors and co-workers (Larson and Morsi 1993 and Vinh et al, 1995).

EXPERIMENTAL APPARATUS

Figure 1 shows our mock circulatory system for steady flow, which consists of a reservoir tank, a gate, an electromagnetic square wave flowmeter (model SFW-5, Zepada instrument, Seattle), two liquid filled columns for measuring the pressure gradients and a 21 mm ID valve seat made of glass coupled with a 20 mm ID long quartz tube with a refractive index of 1.54. The valve chamber was placed in an index matching enclosure filled with water. The blood analogue fluid used here consisted of a 0.9% saline solution in water. Hollow glass spheres with an average diameter of 40 microns were used as the LDA seeding particles. The flow rates used in this investigation ensured mean velocities of 0.8 m/s and 1.4 m/s.

The four-beam, two-colour (488 nm and 514.5 nm) 5 Watt Argon-Ion laser was coupled to a two-component fibre optic probe (LDA). This facilitated access to the measurement station. The length of the probe had a beam separation of 38 mm and a focal length of 250 mm. This ensured two overlapping, orthogonal ellipsoid shaped measurement volumes of 0.1173 x 0.1169 x 1.536 mm. Two of the beams were shifted by 40 MHz to enable negative velocity measurement. A LDA data reduction software package called Floware acquired and stored the signal processor outputs and converted them to velocity values. The signal processor used was a burst spectrum analyser (BSA) which can be used at very low values of signal to noise ratio. Data acquisition was used in continuous mode with 3000 samples, and stop mode was validated on 3000 samples. Data was processed using the residence time weighting technique; all measured moments are weighted by the measured residence times of the individual scattering particles.

DISCUSSION AND RESULTS

Under steady-flow conditions, the Jellyfish membrane was seen to open into an asymmetric four-lobed configuration. Due to the difficulty associated with the control volume access, more measurements were not possible in the region close to the valve. Velocity and shear stress profiles taken at different locations along the tubes are shown in figures 2 to 5. As indicated earlier, a long tube was installed before the valve to ensure that flow at the inlet is uniform and developed with appropriate shear stress distribution.

At 0.5 D downstream the turbulent shear stresses were found to be in the range of 1 - 43 N/m^2 for a flow of 15 l/min, and 0 - 94 N/m^2 for a flow of 26 l/min respectively. These values are below the threshold values for in-bulk haemolysis (around 500 Pa) and for haemolysis at prosthetic surfaces (around 150 Pa). Both these values occurred 3-5 mm from the inside tube wall in the areas of jetting - flow was not axisymmetrical. As shown in the velocity profiles a flow reversal was evident at approximately 11 mm downstream of the valve. This indicates a region of recirculation and stagnation around the hub of the valve in the wake of the hub and between the folds of the membrane. Haemostasis (stagnation of blood) is known to promote thrombus formation and a shear rate value of below 7/second is considered critical. The flow reversal gradually decayed and was totally dissipated at around 75 mm downstream of the valve. Furthermore, jetting was evident onto the wall just distal to the valve - this will elevate wall shear stresses and is potentially detrimental because of blood lysis in a prosthetic aortic section, or because of endothelial erosion in a natural aorta.

Pressure drops across the valve were 7, 12.2 and 23.1 for flowrates of 10, 15 and 26 l/min respectively.

At the present time a comprehensive experimental programme is being carried out, where pulsatile velocity and shear stresses at different locations is being assessed using LDA, this data will lead to a better insight into shear stresses which are elevated by accelerative fluid motion.

CONCLUSION

LDA has been used to determine the fluid flow and turbulence parameters downstream of an artificial heart valve. It was found that the magnitudes of shear stresses were of the order of 1-43 N/m^2 at a flow rate of 15 l/min which is sub-critical for haemolytic damage and of the order of 0-94 N/m^2 at the flow rate of 26 l/min which is near the threshold value. Velocity profiles downstream of the valve showed strong reversed flow indicating a region of recirculation and a stagnation zone around the hub of the valve which can be more prone to thrombus formation.

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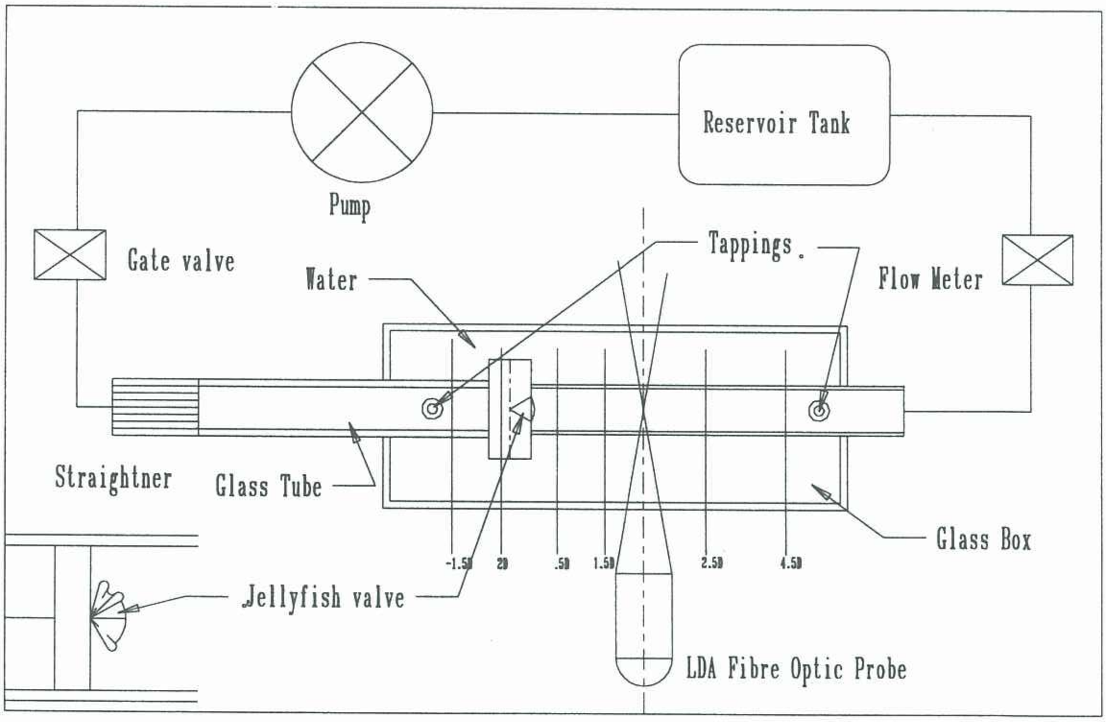

Figure 1: Experimental apparatus

Fig. 2: Turbulent shear stress, Flow rate: 15 l/min

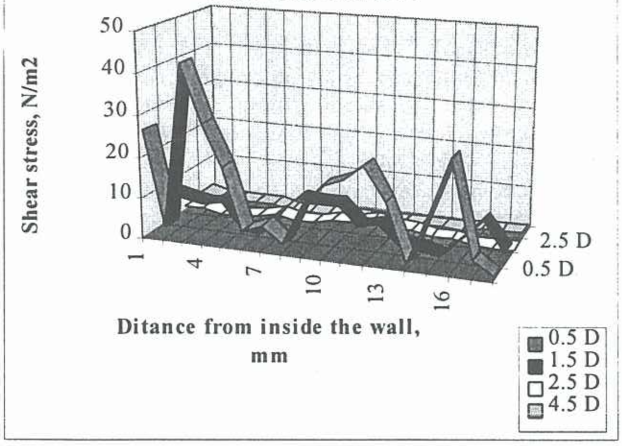

Fig. 3: Axial velocity profiles, Flow rate: 15 l/min

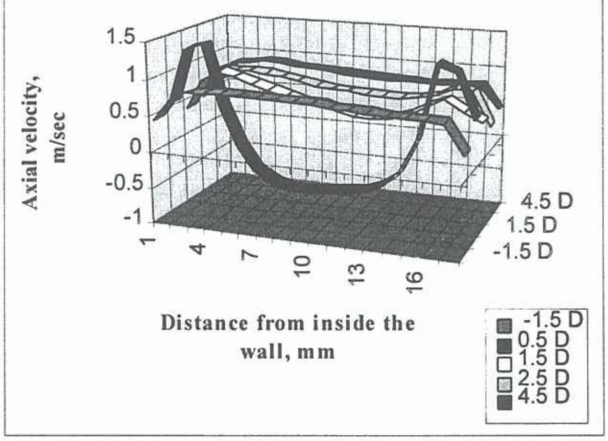

Fig. 4: Turbulent Shear stresses, Flow rate: 26 l/min

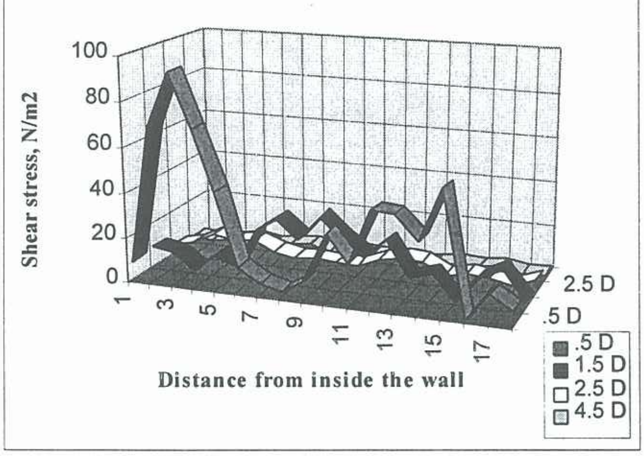

Fig. 5: Axial velocity profiles, Flow rate: 26 l/min