Volume 4, Supplement 1, 2002

ACTA OF BIOENGINEERING AND BIOMECHANICS

BIOMECHANICS OF SPORT • MEDICAL BIOMECHANICS • ENGINEERING BIOMECHANICS •

PROCEEDINGS OF THE 13TH CONFERENCE
OF EUROPEAN SOCIETY OF BIOMECHANICS

OFICYNA WYDAWNICZA POLITECHNIKI WROCŁAWSKIEJ

Flow Visualisation and Flow Measurement with Particle Image Velocimetry (PIV) in the Chamber of a New Left Ventricular Assist Device (DLR-Heart).

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Objective

Optimization of the pump chamber geometry is one of the main issues in the design process of a new VAD-system. By avoidance of turbulent flow and no-flow phenomenon, energy loss and the risk of thrombembolism can be reduced significantly. It is especially important to recognise and eliminate areas of reverse flow and of high shear stress. In this study, flow visualisation with a birefringent fluid was compared with velocity measurements (Particle Image Velocimeter, PIV). This comparison led to an improvement in the geometry of the pump chamber and the kinematics of the pump membrane.

The DLR-Heart

The DLR-Heart is designed to assist the left ventricle. It is connected to the left heart chamber and blood supply and pumps blood back to the aorta using high pressure, in co-ordination with the heart. The DLR heart works on pumping principle of simultaneous suction and forward pumping with the help of two chambers that lie on top of each other. This arrangement makes it possible for the unit to intake blood and pump it out simultaneously as one chamber is compressed and the other concurrently released. For compression, a very thin pusher plate is used (Fig. 2). The two chambers lie very close together so that only when one chamber is compressed can the other fully open. This allows for an extremely flat construction. The chambers are designed in an arch form to place the propulsion unit directly under the arch to minimize system largeness.

Fig. 1 The DLR-Heart, a Left Ventricular Assist Device

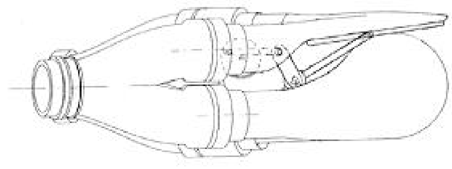

Fig. 2 Artificial heart chambers with pusher plate

Two normal heart valve prostheses are attached to the entrance to the pressure tubes. A so-called sail valve is attached to the exit reducing the risk of hemolyse and thromboses when the unit is used as a support for the left ventricle. Y-form connectors are used for the in-take and out-flow of the support unit to the heart and from the unit to the aorta

The unit is driven by an electric motor. The continuously running motor produces a sinus curve (1) of the pusher plate through an eccentric drive lever r_1 and r_2.

$$s(t) = r_3 \cdot \sin\left[\frac{r_1}{r_2}\Delta t_s v\right] \qquad (1)$$

Methods

The first VAD-chamber was designed (CAD) based on physiologic and engineering aspects using Pro Engineer software (PTC), which allows the design of volume based models. Molds were created from the CAD–Data. The molds were the basis for the production of models using technical and medical silicon.

First, symmetrical tubes with equal entrance and exit diameters were created. The diameter at the middle of the tube was approximately twice as large as that at the entrance and exit. The models were made of technical silicon (RT 601, Wacker Chemie). The models were drawn with design software and then a negative mold was created from aluminium. Wax was poured into this mold creating a positive core tube. A separator paste is painted over the core and then silicon is applied while the core is rotated by an electric motor. The

silicon is applied in layers creating a consistent wall of ca. 0.6 mm. The tube compliance is 10%. of the cross section (Fig. 3).

Experimental set-up

For the experiments a specially designed simulator for physiological flow and resistance was used. To investigate the flow within the chamber, the VAD and its kinematics was reproduced in Plexiglas making the flow visible, so that PIV velocity measurements could be done.

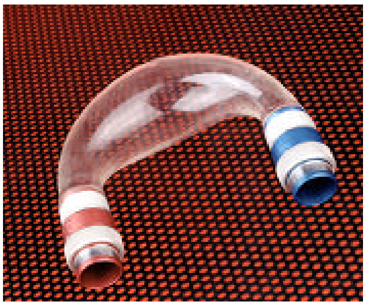

Fig. 3 Artificial, silicon heart chamber with adapters

For the flow visualisation studies a birefringent Vanadium Pentoxid solution (VaO2) was used. For the PIV measurements a DMSO solution (Dimethylsulfoxid-Seperan) was used. Both fluids show a density of 1050 kg/m^3 and have non-Newtonian flow behaviour (Fig. 4).

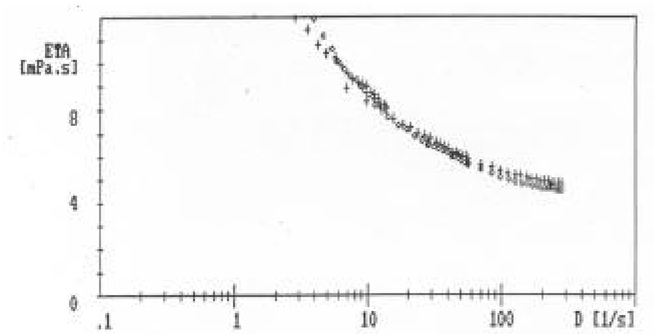

Fig. 4 Viscosity of human blood and DMSO

* Blood H% = 46 at 37°

\+ DMSO-H_20-AP45+AP302 at T = 21°

Experimental studies

Experimental studies were performed with colour flow visualization using a high-speed-camera (Fig. 5) as well as PIV (Fig. 6), using a fluid with bloodlike non-Newtonian characteristics. The measurements were carried out at 65, 90 and 120 beats per minute and at pressures of 12 mmHg and 18 mmHg. The flow volume and pressure was measured at the intake and pressure side of the VAD. During the measurements the motor rotation rate was kept constant so that a sinus curve movement of the pressure plate was created. In the first experiments a tube with a pressure plate that compressed with a tilting motion was studied. From this experiment a new kinematic was developed in which the pusher plate was placed in a rotatable position by two thrust pads and fit optimally into the tube form. This led to a quasi-translation motion in the compression of the tube.

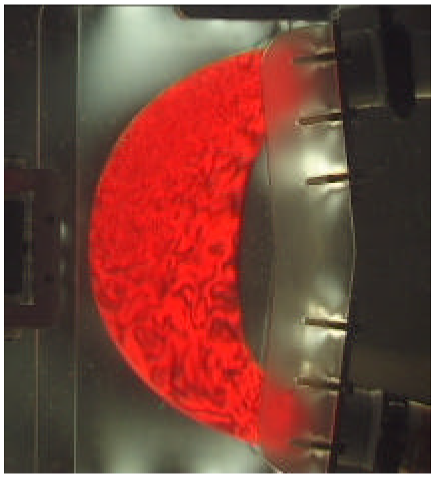

Fig. 5 Flow visualisation with a birefringent fluid

Additionally, geometry of the silicon chambers was changed to obtain better flow conditions. The diameter at the entrance was enlarged by ca. 17% over the exit. The maximum diameter was moved from the middle towards the exit. The opening angle of the entire arch was enlarged.

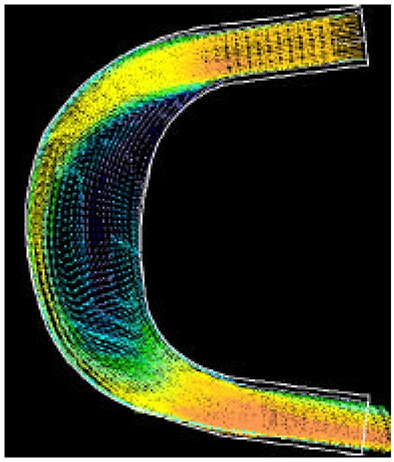

Fig. 6 Flow field, measured with PIV

Results

A separation zone is created by the curve of the arch which is intensified by the tilting motion of the pressure plate. Particles may remain in the this zone for several pump cycles before they are washed out. Because of this the pressure plate kinematic was altered. Instead of the tilting motion of the pressure plate, a purely translation motion was created. This requires increased system performance, however creates an better exit volume and improved flow profiles. The change in the geometry of the pressure tube led to a further, notable improvement: differing diameters at the entrance and exit with the maximum diameter towards the outlet led to markedly better velocity distribution. The reverse flow zone at the inner side of the arch was minimized.