Chapter 6

Experimental Investigation

The purpose of the experimental investigation is to verify the computational results over a limited range of parameters. Experiments were carried out for steady flow in a simple stenosis model. We did not intend to carry out a complete experimental investigation for all Reynolds number and stenosis geometries. The aim of the experiments was to compare the flow quantities obtained from the measurements with those found from computation based on a typical model with Reynolds number within the physiological range. The agreement between the numerical simulation and the experimental measurements, and with other numerical and experimental evidence, give us confidence in our numerical model.

An interesting feature of the experimental investigation is that we can obtain some information which is very difficult to obtain numerically. For instance, finding the effect of disturbances on the flow quantities is very difficult for the numerical simulation for low Reynolds numbers (less than 1000). In fact, such disturbances in the flow exist at most locations of the arterial system, because it is highly affected by branches and curvature. Complete information on this subject needs a thorough investigation by analysing the full spectrum of velocity fluctuations. This is outside the scope of this thesis, though some knowledge of this nature from the results of simple experimental measurements such as the velocity profile, pressure recovery and shear rate (shear stress) at the wall, help us to be aware of the limitations of the numerical results.

With this as background, we will discuss the experimental methods in this chapter.
The results will be compared with those of the numerical simulation in the next chapter.

6.1 Stenosed Model

The experimental model was constructed from plexiglas. The symmetric constriction followed a cosine curve with a 75 % area reduction. The geometry of the model is shown in Figure 6.1. The stenosed model was machined to an accuracy of $1 \times 10^{-2}$ cm. The cosine contour was selected previously in both theoretical calculations [28], and in experimental measurements [35]. It is one of the simplest representation of an arterial stenosis, as it provides the smooth variation which is found in many physiological cases. The same model is also used in our theoretical calculations.

6.2 Test Facilities

The fundamental facility for our steady state measurements is the water tunnel designed and fabricated entirely in the Department of Mechanical Engineering. It was originally
designed by Aminzadeh [72] for his experimental study of hydraulic performance of the aortic prosthesis using an enlarged valve model and later modified extensively by Akutsu [73] to suit requirement for his investigation of artificial heart valves. The main criterion governing the design was the Reynolds number, which is based on the size of model and the viscosity of the working fluid. Thus, the flowrate is treated as the parameter for reference. The flowrate range in which a steady flow situation can be established is from 10 \text{ cm}^3/\text{sec} to 300 \text{ cm}^3/\text{sec} as governed by the characteristics of the power unit. With water as the working fluid and the model size 5.08 cm in diameter, the Reynolds number range is around 200 to 8,000.

The tunnel is shown schematically in Figure 6.2. It consists of two separate test circuits and three subassemblies: the test chambers; the fluid return system; and the power unit consisting of a pump and a drive motor. The large test section is built of four plexiglas walls 2.44 m long, 1.905 cm thick and wide enough to produce an inside cross-section of 20.32 \times 20.32 \text{ cm}. The relatively long length was purposely chosen to ensure sufficient room for installation of flow distributing and straightening devices, and to permit the positioning of the model with ease. A vent, 10.16 cm in diameter and 30.5 cm high, located on the downstream end of the test section provided for fluid expansion as well as an escape route for the air bubbles. It also serves as an effective check against the over pressurization of the test section, particularly near the model location, irrespective of the pump’s operating condition. There are five access ports to the inside of the section, through each end, via two hatches, and through a porthole, located such that an arm can reach, position and adjust the model anywhere in the tunnel. In addition, several smaller portholes which could take 1.6 cm N-C plugs were drilled and tapped on the top of the plastic “box”. Furthermore, 2.54 cm portholes are also provided on the side face of the “box”. These openings were used to mount the model and convey pressure conducting lines. They were sealed off employing the plugs with “O”-rings when not in
Figure 6.2: Schematic diagrams of Water Tunnel.
use. Two glass plates, 63.5 \times 13.97 \times 1.27 \text{ cm}, recess-mounted in the sides of the test section provided optically flat, homogeneous and thermally stable walls for inspection and photography. A drain positioned at the bottom of the "box" facilitated complete draining and flush cleaning of the tunnel.

The tunnel is provided with an alternate channel of flow consisting of a PVC setting chamber, a plexiglas test section and support blocks. The setting chamber is made from 25.4 \text{ cm} diameter PVC tube with length of 104 \text{ cm}. It is connected to the plexiglass tube test section carrying the stenosed model. The system is constructed in a way which allows for easy changing of the stenosed model, thus providing a wide variety of test model configurations.

In the present study, the inner diameter of the upstream and downstream tubes was selected to be 5.08 \text{ cm} to allow good spatial resolution for measuring velocity profiles. The entrance length of the tube prior to the stenosis is 50 \text{ cm} (10 times the diameter) because of the length limit of the tunnel. The stenosis model with connecting tubes was installed inside the large test-section, described earlier, for velocity measurements using a LDA system and pressure measurement using a pressure transducer. Of critical importance was the transition of the flow from the pump outlet to the test-section. For the large test-section where flow from the pump has to expand from a 7.62 \text{ cm} diameter tube to the 20.32 \times 20.32 \text{ cm} box, the jet like flow has to be diffused and spread evenly across the test cross-section. This was achieved by the following arrangement:

- several sections of honeycombs to straighten the flow through turbulent exchange and laminar damping,

- brass screens of different pore size with or without fiberglass wool in between.

Located between the end of the test-section and the power drive unit is the return section essentially comprising a heat exchanger, PVC pipes and elbows with connecting
flanges, flow control valves and a radiator hose. A copper pipe, 350 cm long with 7.62 cm diameter in conjunction with 244 cm long and 15.24 cm diameter PVC plastic sewer pipe formed an annular single pass heat exchanger. With the coolant supplied by a water main it was possible to maintain the temperature of the working fluid within 0.2°C. PVC elbows and sections of the radiator hose provided relatively easy, anti-corrosion and vibration free connections between the test section and the heat changer.

The power unit consists of a centrifugal pump (Auora type GAPB, 200 gal/min, 7.6 m head, 1750 rpm) driven by a three horsepower variable D.C motor. The pump impeller and housing are of cast brass to guard against possible corrosion. The motor is energized by a three phase grid, the voltage being adjusted through an auto transformer (Variatc model 4711) and rectified by selenium diodes. No further smoothing of D.C. output was required.

Flow rate in the tunnel was monitored using a sharp edge orifice plate mounted upstream of the pump inlet. The plate location was selected so as to make its reading relatively free from upstream and downstream disturbances in the form of elbows, change in section at the pump inlet, pump suction, etc. A filter (10 micron) in a bypass circuit across the pump is used to minimize dirt contamination of the fluid.

6.3 Flow Measurement System - Instrumentation

The physical quantities, such as pressure distribution, the shear stress along the wall and the scale of the separation region, are of fundamental importance for the flow in stenosed arteries. They are known to have some correlation with the occurrence and the growth of the stenoses. Obtaining first hand evidence of these quantities will assist in the understanding the flow field in the presence of stenosis.
6.3.1 Measurement of Velocity

Charting of the velocity field around the stenosis is not a easy task. Recognizing that the flow field is complicated because of separation and the irregular boundary contour, the flow measuring system should:

- be able to monitor stagnant and negative flow; and
- not perturb the local flow, i.e., it should be non-invasive.

Hence, a single component Laser Doppler Anemometer (LDA) was employed for the measurement of the axial velocity component.

LDAs are non-contact optical instruments for the investigation of fluid flow in gases and liquids. Laser anemometry is a technique which utilize scattered light from particles in a fluid element to measure the velocity of that element. This relatively new technique is based on the invention of the gas laser in the early sixties, with its unique property of spatial and temporal coherence. Most current laser anemometers measure either the rate of change of frequency of the scattered light after scattering or the time flight between spatial regions of high intensity in the measuring volume. The former is called Laser Doppler Anemometer (LDA) and the later is called the Laser Transit Time Anemometer (LTA). LDA, being better suited for the real time measurement, was preferred.

A split laser beam from a single laser source is made to cross in the flow field to perform a measuring volume, the region of interference fringe pattern. This is accomplished using a beam splitter and a focusing lens. Fluid particles in the measuring volume at a given instant scatter light in all directions with frequency modulation. As a cross-section through the measuring volume consists of alternate light and dark regions, a particle passing through the fringe system emits light pulses at a frequency dependent upon its velocity. This is referred to as the beat or doppler frequency. The standard laser
anemometer system has a 180 degree direction ambiguity. In other words, it can not distinguish between forward or backward flow. This would be a serious limitation in the present study. In a refined system the problem is overcome by a frequency shift between the split beams using a Bragg cell thus causing asymmetry in the interference fringe pattern.

The use of a laser doppler anemometer for velocity measurement involves careful consideration of the system elements such as:

- optics and optical arrangement;
- seeding of the flow;
- size and type of laser;
- type of signal processor;
- data acquisition and reduction system.

These were considered in conjunction with anticipated characteristics of the flow field:

- near zero and/or negative velocity;
- complex anatomical shape;
- continuous data.

After considerable delibration the following components were selected for the LDA system:

- Ion Laser Technology Ar-Ion laser model 5490 AW 00 with 100 mW output, wavelength $5.30 \times 10^{-9}$;
- OEI LDA Transmitter Optic Module consisting of
- \(LD - 0 - 0102\) Optical adapter,
- \(LD - 0 - 210\) Polarization rotator module,
- \(LD - 0 - 310\) Beam splitter module,
- \(LD - 0 - 420\) Double bragg cell module,
- \(LD - 0 - 610\) Lens module \(f = 310\ mm;\)

- DISA 55 × 34 PM Receiving optics;

- TSI Photomultiplier model 962 with model 965 power supply;

- DISA 55L20 Signal processor consisting of
  - 55L30 Preamplifier,
  - 55L37 Frequency tracker,
  - 55L40 Meter unit.

The laser unit and the optics package employed here is a forward scatter mode. The beam was split into two parallel beams at a distance of 48\(mm\), then focused by a lens \((f = 310\ mm)\). At the intersection of the beams an approximately ellipsoidal sampling volume is produced. The dimensions of the sampling volume were \(1.3 \times 0.3\ mm\) for this investigation. Lax liquid solution was used as feeding particle for the measurement. Using a frequency tracker, the value of the shifted frequency \(f_D\) is measured and hence the velocity component normal to the fringes can be determined by the following relationship

\[
V = \frac{\lambda f_D}{2 \sin(\frac{\theta}{2})},
\]

where \(\lambda\) is the wavelength \((= 5.30 \times 10^{-9}\ m\) for this arrangement), \(\theta\) is the beam intersection angle \((9.13^\circ)\), and \(V\) is the component of velocity in the plane of the beams and perpendicular to the bisector of the included angle \(\theta\).
6.3.2 Traversing Mechanism

In order to measure the velocity at different locations, the LDA system was supported on a platform with three degree of freedom permitting, within limits, any desired spatial positioning of the measuring volume. The traversing gear consists of two subassemblies: base traverse mechanism for rough positioning and a micrometer controlled $X - Y$ translation stage for finer movement in a horizontal plane.

The base traverse mechanism was designed and fabricated entirely in the Department of Mechanical Engineering. It consists of three platforms of which two ride on a pair of hardened steel rods with linear bearings permitting movement in a horizontal plane, while the third rides on a modified mechanical jack permitting vertical movement. The maximum travel distance available is $86.6 \times 23.7 \text{ cm}$ along the horizontal plane and $22.8 \text{ cm}$ in the vertical direction. All platform components are made from heavy aluminum plates with $13 \text{ mm}$ thickness to minimize static deflection and vibration problems.

The fine adjustment horizontal translation stage, supported by the base, was made by A.W. Becker GmbH of Germany. It is free to move $10 \text{ cm}$ in each direction with an accuracy of $0.001 \text{ mm}$. Figure 6.3 shows the LDA system with its traverse mechanism.

6.3.3 Pressure Transducer

Because the pressure (both its absolute value and difference at different locations) is very small (order of $10^{-4} \text{ psi}$), a highly sensitive instrument for its measurement is demanded. This was accomplished using a “Barocel Modular Pressure Transducing System” developed by Datametrics Inc. of Waltham, Massachusetts. The type 550 - 5 Barocel sensor is designed to operate with fluid over the pressure range of $0 - 10 \text{ psi}$. The unit is high precision, stable capacitive voltage divided with a variable element in the form of a thin prestressed steel diaphragm which deflects proportionally to the magnitude of the applied
Figure 6.3: LDA System with a Transversing Gear.
pressure. To isolate the external pressure medium from the sensor diaphragm-capacitance system, the unit uses highly sensitive metallic bellows. The volume between the bellows, isolator and sensor diaphragm is filled with degreased silicon oil which serves both as a pressure transmitting fluid and as a dielectric. The pressure signal from the external liquid medium is transmitted by the bellows to the silicon oil which in turn deflects the diaphragm to produce the required change in capacitance. An A.C. carrier voltage at 10 KHz is applied to the stationary capacitor plates, and a bridge circuit determines an output voltage dependent on the ratio of the capacitance of the diaphragm to each of the stationary plates. The carrier voltage is therefore modulated according to the input pressure. The unit sensitivity is 0.007 N/m² (1.015 × 10⁻⁸ psi) provided the pressure sensor is fully isolated from external sources of vibration and noise. It was imperative to ensure removal of all traces of air pockets from the pressure conducting lines for satisfactory operation. Barocel is accurately calibrated for steady pressure. The calibration plot is shown in Figure 6.4.

### 6.3.4 Flow Meter

Although the built in sharp edged orifice flow meter in the water tunnel monitored the average flow rate, it did not give satisfactory results because the present study focused on relatively small flow rates. A more sensitive sharp edged orifice flow meter thus was carefully designed and installed into the flow system to meet the requirement. Before its final installation, the orifice plate was calibrated according to the standard ASME procedure. Pressure difference across the orifice plate was recorded using a Barocel pressure transducer in conjunction with a Data Metric Manometer model 1018. The calibration plot for the orifice plate is shown in Figure 6.5.
Figure 6.4: Calibration Curve of Pressure Transducer.

Figure 6.5: Calibration Curve of Orifice Flow-meter.
6.4 Test Procedure

The success of any experiment depends, to some extent, on the recognition of the the capacity and limitation of the equipment used. Performance specifications for instruments normally provide this information. However, they must be checked through actual operation. Furthermore, at times, it was necessary to push the equipment to its utmost capability to collect vital data. Hence extensive preliminary tests were carried out before embarking upon an experiment to ensure accuracy (which implies reliability through repeatability) of results.

Figure 6.6 shows schematically the arrangement of instrumentations and data acquisition and processing system used for the steady state measurements of pressure and velocity.

Pressure distribution along the test section was measured using a batocel pressure transducer (Data metrics type 550-5) in conjunction with an electric manometer (Data metric type 1018B). Barocel being a differential pressure transducer, one side is connected to the location of interest through its system of distribution values, while the other side is exposed to an upstream location. Actual pressure tap locations used are shown in Figure 6.1. All air bubbles from pressure conducting lines were carefully removed as they affect the results. This was achieved by opening all the distributing valves to allow the conducting fluid to flow through the pressure conducting line with the tunnel running for about 30 minutes. This also ensured a uniform concentration of water solution throughout the test system. As pressure levels were often very low, especially at low Reynolds number, any change in viscosity or density of the working fluid resulted in a zero shift. To account for this, all measurements were preceded by the monitoring of pressure at no flow condition.

After removing all traces of air bubbles, the distribution valve was opened for the
Figure 6.6: Diagram of Instrumentation, Data Acquisition and Processing System.
measurement of the zero flow pressure at that tap location. Depending on the viscosity of
the solution used, normally a few minutes of setting time was necessary for the pressure
to be stabilized. The pressure was recorded and the valve closed. The procedure was
repeated at all the pressure tap location. Then the tunnel was activated to establish a
desired steady flow rate as given by the orifice meter, and a new pressure signal measured.

Velocity measurements were recorded using the LDA system described previously.
The circular tube with a constriction was placed inside the large square test-section of
the water tunnel with the same simulation fluid surrounding it to minimize the effect
of changes in refractive index between the tunnel material (plexiglas) and the solution.
To further minimize the refraction effect due to the circular cross section of the flow
test section, velocity measurements were conducted in the horizontal plane through the
center of the test section. Only the velocity along the test section was measured in
this experiment. With an appropriate flow rate set, the lase beam was first focused
inside the test tube wall, giving a constant frequency uneffect by the flow field, thus
confirming the setting and the LDA system. Next, the measuring volume was moved
to the interface between the wall and the flow field using the traverse mechanism. It
was possible to indentify the interface accurately by monitoring a sudden change in the
LDA signal. Having established the wall boundary, the measuring volume progressively
scanned the flow field. The signal from the LDA system was filtered prior to data analysis
to eliminate the high frequency noise. The mean velocity value was noted using a digital
voltmeter with an appropriate time constant (DISA type 55D31) and RMS value was
noted using a RMS voltmeter (TSI model 1060) and calculated from the instant velocity
recorded by the IBM personal computer. The average flow rate given by the orifice meter
was also recorded.
6.5 Data Processor

The velocity signal (from the frequency tracker) and pressure signal (from the electronic meter) output were analog, and were converted into digital signals by an Analog to Digital Converter (ADC) before getting to the IBM PC. Since the tracker frequency range was high (= 10 \( KHz \)) in all measurements, the frequency of the signal fluctuations at the measured Reynolds numbers was at least an order of magnitude lower (< 0.5 \( KHz \)), and the frequency of the environmental noise was much higher (> 10^{10} \( MHz \)), this produced no detectable error. The environmental noise had no effects on the signal also because its intensity was much lower than the laser beam (10^{-4} lower in magnitude).

In the calculation of mean and disturbed velocities, time average of 800 data blocks were employed and usually 20 cycles were used to ensure the reliability. The velocity was expressed as

\[
u(x, t) = U(x) + u'(x, t), \tag{6.2}
\]

where \( u \) is the instantaneous velocity, \( U \) is the average velocity, and \( u' \) is the fluctuation. The mean pressure was calculated in a similar way. 10 cycles were enough for the usual case while 20 cycles were used when the low frequency fluctuation was large.