CHAPTER III
EXPERIMENTAL

3.1 Material

- Acrylic Rod
- Deionized water
- Color Dye

3.2 Equipment

- CNC Lathe
- Centrifugal Pump
- Reservoir Tank
- Cooling System
- Flow Meter
- Thermo Couple
- Pressure Transducer
- High Speed Camera

3.3 Methodology

Continuing the work of Villien (2001) and Yong Shao (2006), experiments were performed using a closed, recirculating water loop. The loop is shown in Figure 3.1.

The reservoir was operated under room temperature and atmospheric pressure. The centrifugal pump was used to circulate the fluid through the loop. The flow was adjusted with a rotameter and a manually-operated control valve. A thermocouple was used to measure the coolant temperature before it entered the test section. The test section was an acrylic pipe connected via fittings to the rest of the loop. The internal surface of the pipe was machined to a scalloped contour surface.

The differential pressure transmitter was installed in order to indicate the pressure drop. A drain was introduced after the test section for taking samples. Having passed through the test section, the flow was recirculated through the cooler in which the water was cooled and then returned to the reservoir.

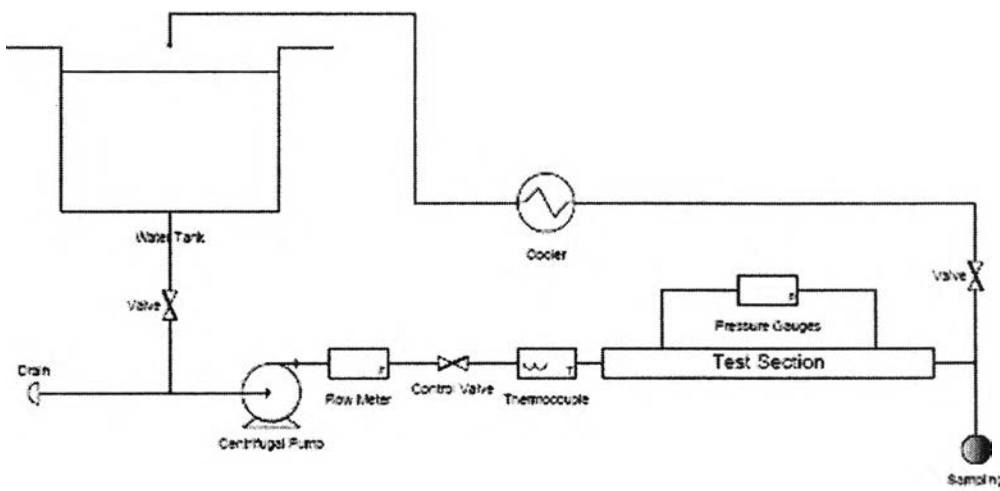

Figure 3.1 Scalloping test loop

The experiments are divided into 3 sections. The first section is validation of FULENT CFD model in which flow visualization and pressure measurement were performed with various Reynolds number. The second section is to investigate the effect of scallop's surface area on pressure drop. The last section is to investigate the effect of scallop's distribution on pressure drop. All the experiment used the same test section but slightly modification.

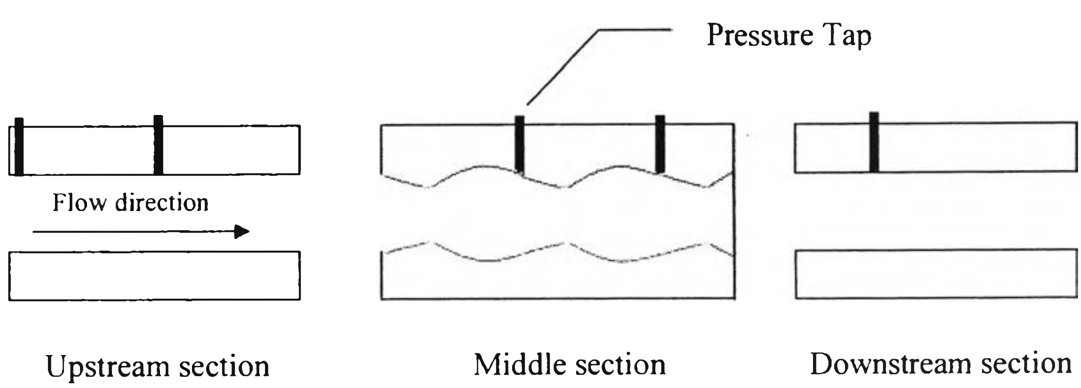

Figure 3.2 Scallop test section

The test section consists of three sections as shown in Figure 3.2. The upstream section is a 91.75 cm straight stainless steel pipe with 2.926 cm and smooth internal surface. This pipe is used to ensure a fully developed pattern of flow at the inlet. The scalloped surface is contained in the middle section of the test section which consists of many individual acrylic scallop profile pieces. In this section, the number and location of the scallop can be changed according to the experiment performed. The downstream section is a 91.75 cm stainless steel pipe used to minimize the turbulence caused by the 90 degree elbow. The internal diameter of these three sections is the same in order to keep flow velocity constant along the test section. The hydraulic diameter is specified for the middle section. Pressure taps are put along the test section for measuring pressure and dye injection.

The middle section made from a 208 cm-long acrylic tube with 5.08 cm outer diameter and 2.93 cm inner diameter. The internal surface of the pipe was machined to a 2-D scalloped surface. The plaster scallops, shown in figure 3.3, were used as a model for the scallop contour. The scallop length calculated from the stable wave length Reynolds number, 23000, (Blumberg et al., 1974) at the flow rate of 9 GPM is 2.728 cm. The depth, determined using the same aspect ratio as the scallop model in figure 7, is 0.415 cm.

Figure 3.3 Plaster scallop contour (K.A. Burrill, 1998)

3.3.1 Test Section Design

Since the sequence and location of scallops are changed frequently, the test section should be flexible and easy to be modified. The test section consists of three major sections described below.

3.3.1.1 Upstream Section

This section is needed to make the flow fully developed so that hydrodynamics of the flow is exactly known. The diameter of the pipe is 2.926 cm. The length of the pipe required for fully-developed flow can be calculated from the equation below.

For turbulence flow:

$$\frac{Le}{d} \approx 4.4\,\mathrm{Re}_d^{1/6}$$

The Reynolds number is 24688

The pipe diameter is 0.02926 m

The average Reynolds number, calculated from the flow rate of 9 GPM which is the half of the maximum flow rate of the pump, is 24688 and the calculated length for this section is 69.47 cm.

Stainless steel is used as a material of construction because of its durability and corrosion resistance. Pressure taps will be put on the inlet and middle of the pipe to measure the pressure drop along this section.

3.3.1.2 Middle Section

In this part, the scallop contour will be machined in the internal surface of the pipe. The scallop sized is determined according to the stable wavelength Reynolds number, 23000, which will give a flute stability (Curl, 1974). The calculated length of the scallop is 2.728 cm.

3.3.1.2.1 Coordinate Preparation

The plaster scallop in figure 3.3 is a reference model for this work. The plaster scallop model is put on graph paper and its coordinates noted for regression. A fifth order polynomial regression is used. Figure 3.4 shows the scallop profile before regression while the regression one is shown in Figure 3.5.

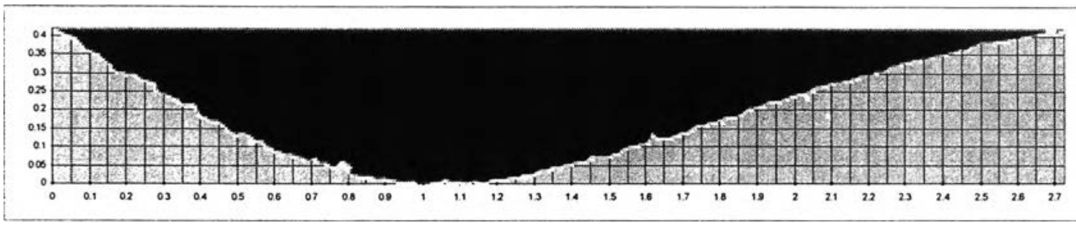

Figure 3.4 Scallop profile before regression (cm)

Even though regression smoothes the profile, it creates a discrepancy between heights in the Y direction at the two ends of the profile. Some points around the end of the scallop profile need to be adjusted.

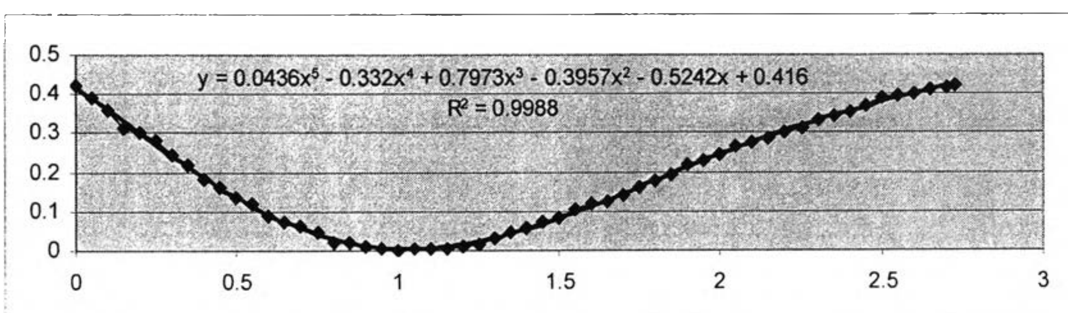

Figure 3.5 Scallop profile after regression (cm)

Table 3.1 shows the scallop profile coordinates used in this work. The first point in the regression is adjusted to the original value, 0.4197 cm. The last two points, 0.4215 cm and 0.4279 cm, are also adjusted to the original values, which are 0.4175 cm and 0.4197 cm respectively. Then the smooth and realistic scallop profile can be obtained.

3.3.1.2.1 Design and Drawing

The drawing is made using AUTOCAD. The adjusted coordinates are used to create the scallop contour. Poly line function is good enough to make a smooth of contour through every coordinate point as shown in Figure 3.6.

Table 3.1 Scallop profile coordinate (cm)

Length	Height	Regression
0	0.4197	0.4160
0.05	0.3925	0.3889
0.1	0.3575	0.3604
0.15	0.3125	0.3310
0.2	0.3025	0.3012
0.25	0.28	0.2714
0.3	0.2425	0.2421
0.35	0.22	0.2135
0.4	0.1825	0.1860
0.45	0.1625	0.1598
0.5	0.135	0.1353
0.55	0.1175	0.1125
0.6	0.09	0.0916
0.65	0.0725	0.0728
0.7	0.0625	0.0563
0.75	0.045	0.0419
0.8	0.0225	0.0299
0.85	0.02	0.0202
0.9	0.01	0.0129
0.95	0.005	0.0078
1	0	0.0050
1.05	0.005	0.0044
1.1	0.005	0.0059
1.15	0.005	0.0095
1.2	0.0125	0.0149
1.25	0.0175	0.0222
1.3	0.0325	0.0311
1.35	0.045	0.0416

Length	Height	Regression
1.4	0.0575	0.0534
1.45	0.0725	0.0665
1.5	0.0825	0.0806
1.55	0.1025	0.0956
1.6	0.1175	0.1114
1.65	0.1275	0.1278
1.7	0.1425	0.1446
1.75	0.1625	0.1617
1.8	0.175	0.1789
1.85	0.1925	0.1961
1.9	0.2175	0.2131
1.95	0.23	0.2300
2	0.2425	0.2464
2.05	0.2675	0.2624
2.1	0.275	0.2778
2.15	0.2875	0.2927
2.2	0.3	0.3069
2.25	0.315	0.3205
2.3	0.335	0.3334
2.35	0.345	0.3456
2.4	0.3525	0.3573
2.45	0.3675	0.3685
2.5	0.39	0.3792
2.55	0.395	0.3898
2.6	0.4025	0.4002
2.65 .	0.4125	0.4107
2.7	0.4175	0.4215
2.7282	0.4197	0.4279

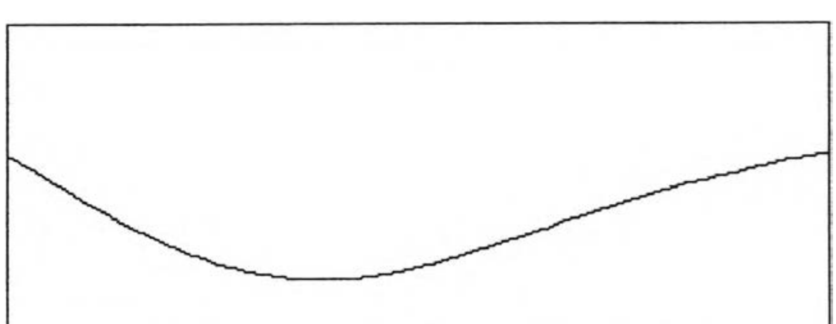

Figure 3.6 Smooth scallop contour

To maximize the flexibility in changing scallop numbers and location, each scallop profile is machined in the internal surface of an individual piece of acrylic. These scallop pieces of acrylic, or even blank pieces without scallops, can be put together. The arrangement and modification are very easy and flexible. The 2D drawing of this acrylic piece is shown in figure 3.7. Figure 3.8 illustrates the 3D model.

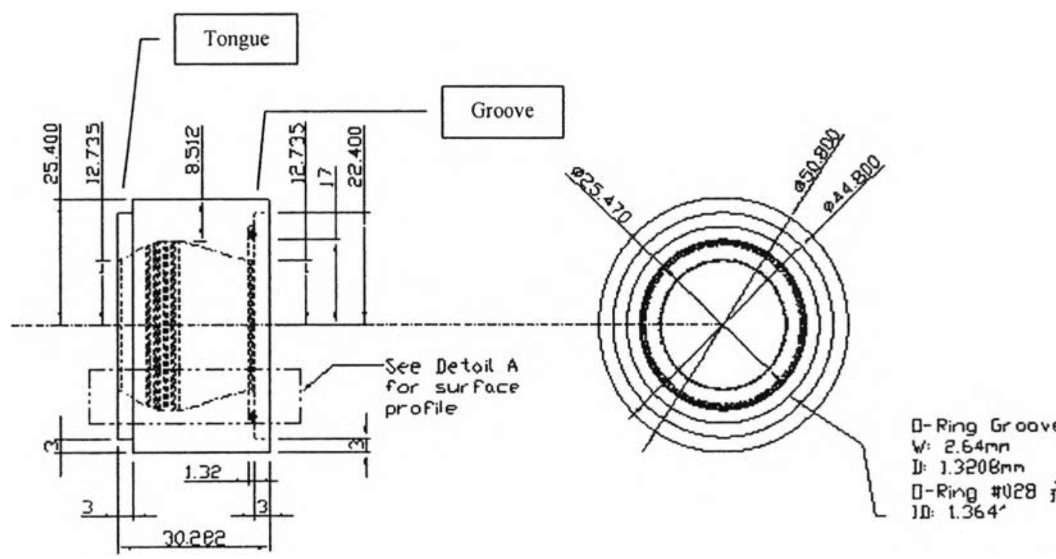

Figure 3.7 2D drawing of scallop piece

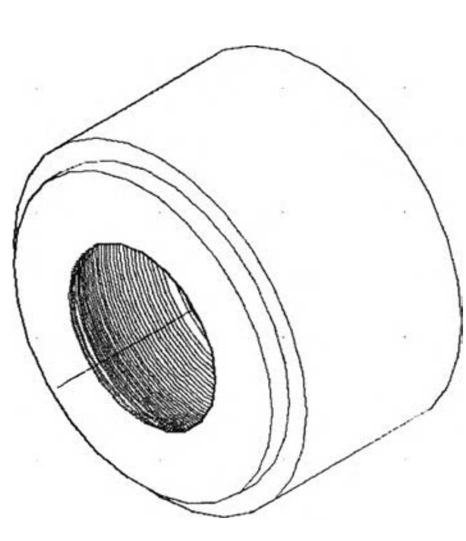

Figure 3.8 3D layout of scallop piece

The surface profile plays an important role in determining the pressure drop. If there is a mismatch at the interface between two scallops, a bump will be created and cause an error in the experimental results. To ensure that the acrylic pieces match each other perfectly, a spigot and recess are machined into every piece. An O-ring is used to prevent leaking.

The acrylic connectors that connect the upstream section and the downstream section to the middle section are also designed. Drawings of these connectors are shown in Figure 3.9 and 3.10 respectively.

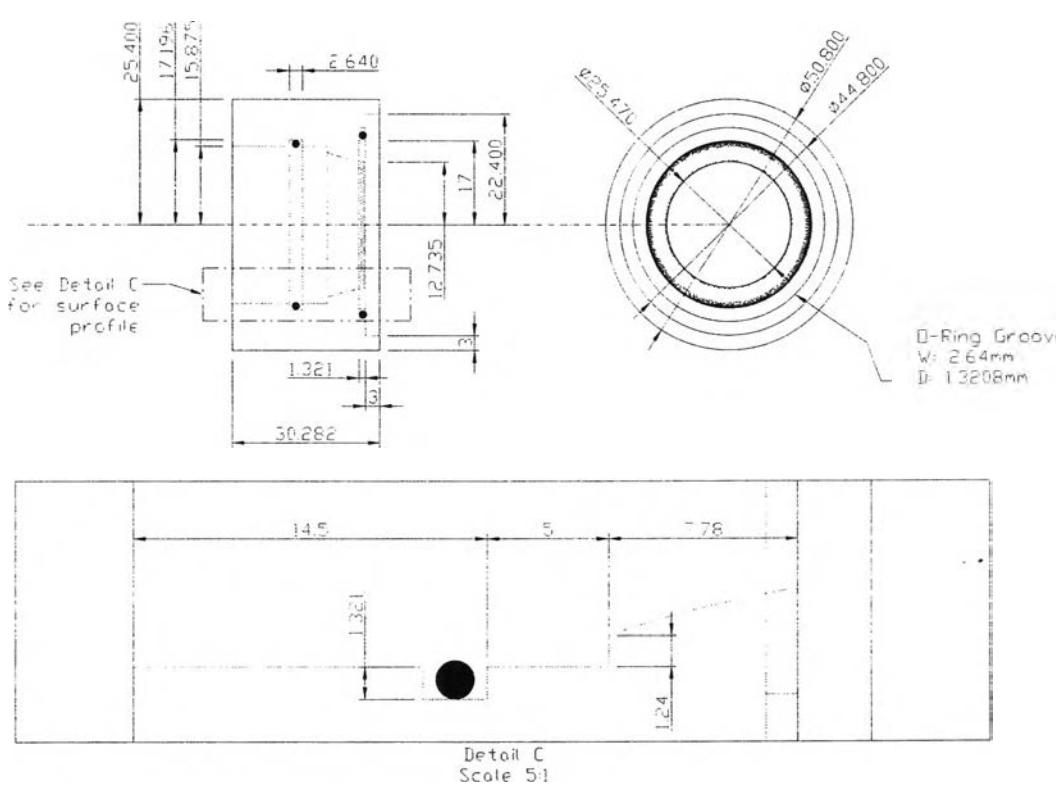

Figure 3.9 Connector between the upstream section and the middle section

Figure 3.11 illustrates how these two connectors join every part of the test section together. Two steel plates are screwed together with long bolts to damp the sections together. The test section is connected to the rest of the loop with compression couplings.

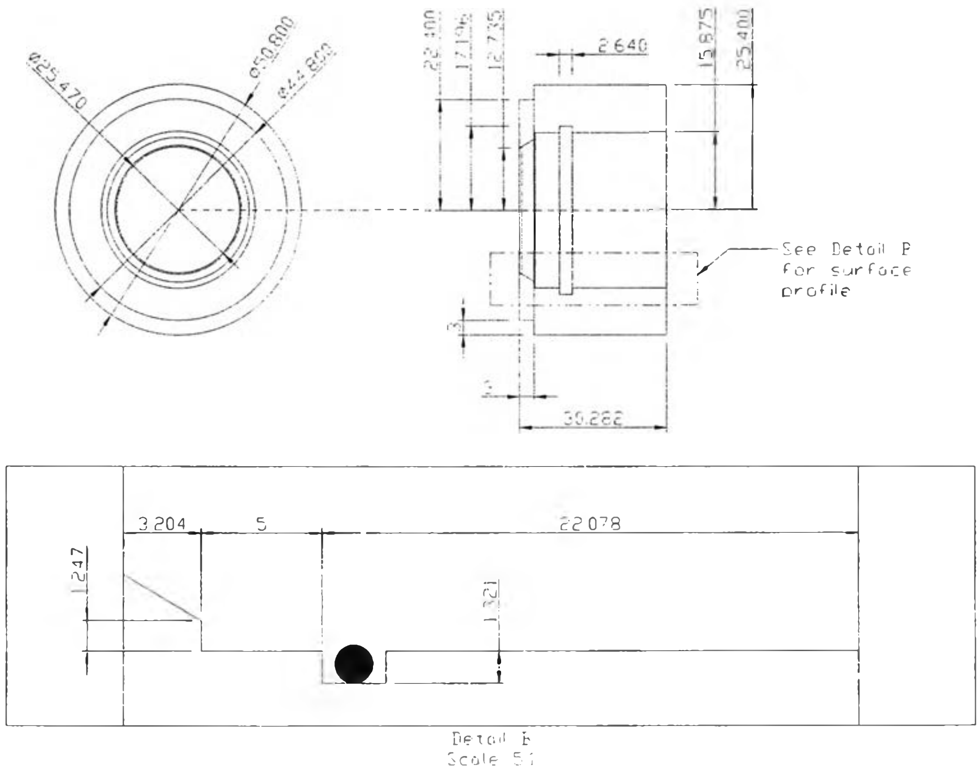

Figure 3.10 Connector between the middle section and the downstream section

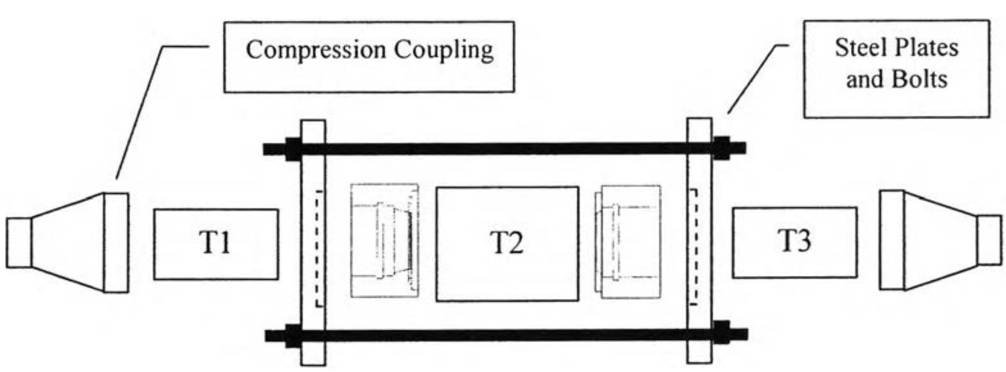

Figure 3.11 Configuration of the test section

If non-scallop internal surface of the pipe is required in the middle section, three more types of connector are needed. These three connectors consist of male connector, female connector and flat surface connector, shown in Figures 3.12, 3.13 and 3.14 respectively. The dimensions are the same as the previous connectors, in Figure 3.9 and 3.10, except for the diameter of flat surface section. Figure 3.15 illustrates how these three connectors create a flat surface section between two scallop pieces.

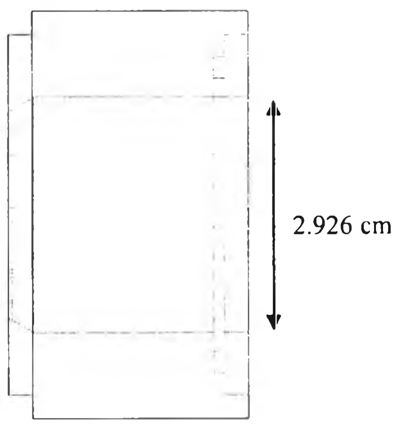

Figure 3.12 Male connector

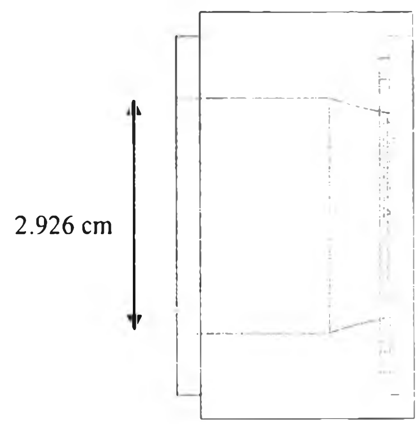

Figure 3.13 Female connector

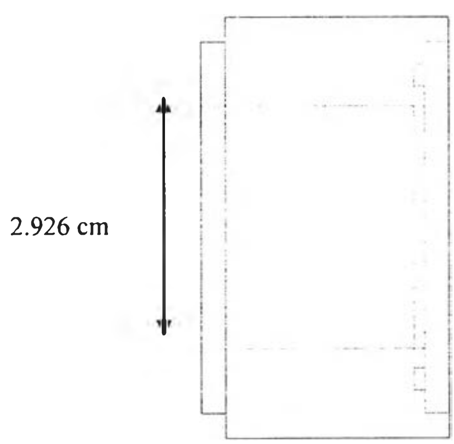

Figure 3.14 Flat surface connector

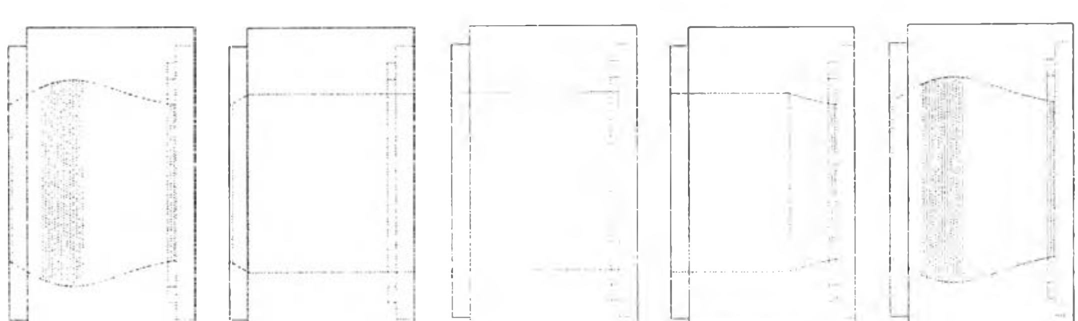

Figure 3.15 Fabrication of flat surface section

A pressure taps are drilled on only some scallop pieces to determine the pressure drop at the location of interest. The number of pressure taps is minimized in order to disturb the flow hydrodynamic as little as possible. The tap is at the average diameter of the whole test section, which is 2.926 cm. The position of the pressure tap is shown in Figure 3.16.

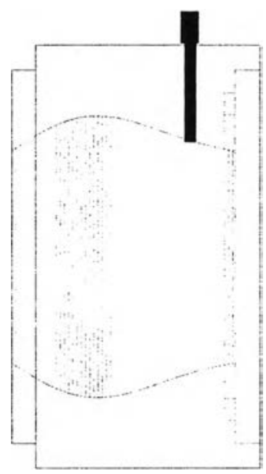

Figure 3.16 Pressure tap used to measure the static pressure

3.3.1.2.1 Machining

Because the internal surface profile is crucial, a high-precision machining process is required to get the best result.

There are six types of acrylic piece to be machined and each type has 4-5 cuts. The operation is divided into two parts. The first part is the preparation process, in which everything is prepared. The second part is the production process.

Preparation Process

First, 2-inch outside-diameter acrylic rods are bored to have 2.461 cm inside diameter. Then the outer surface is turned to a true circle, which increases the precision of the machining. After that, the rods are cut into pieces. The length of each piece is 3.028 cm. Figure 3.17 shows the prepared acrylic pieces.

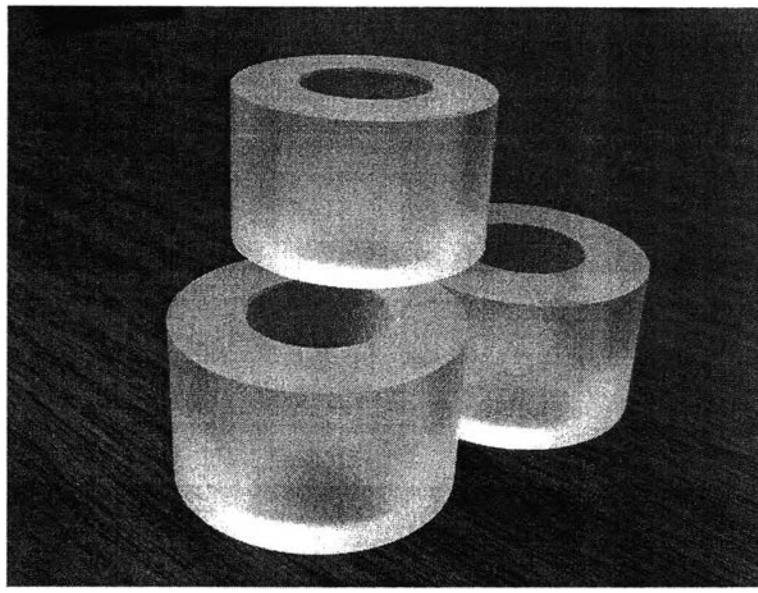

Figure 3.17 Prepared acrylic pieces

There are five cutting tools which cover all types of cut in this work. Each tool is made specific to each type of cut. The tools must be aligned properly to a reference point in order to get a high-precision cut. All the tools are shown in the Figure 3.18.

Figure 3.18 Cutting tools

A CNC lathe, shown in Figure 3.19, is used in this work due to the complex scallop profile and the need for repeated high-precision cuts. To cut with this machine, the program of each cut has to be written and entered into the computer.

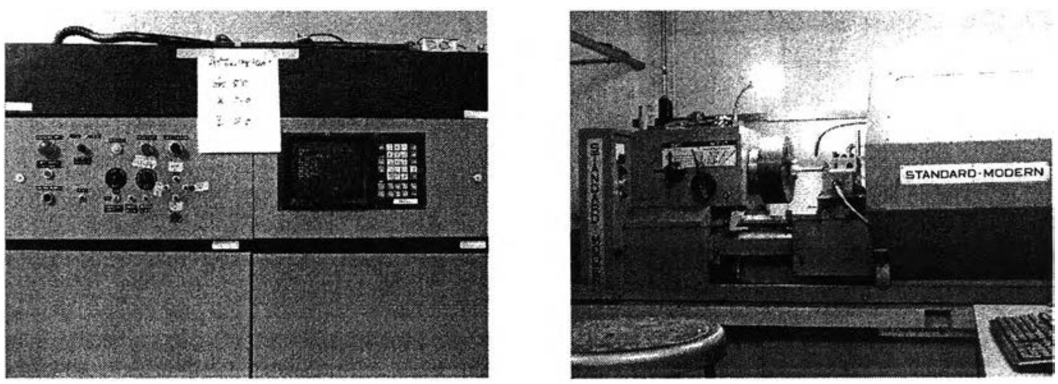

Figure 3.19 CNC lathe

Machining Process

Because the number of pieces to be cut is around 80, a good system of production significantly reduces the machining time. To decrease the machining time, the cutting tool will be change only after every acrylic piece is cut for that specific type of cut provided by the tool.

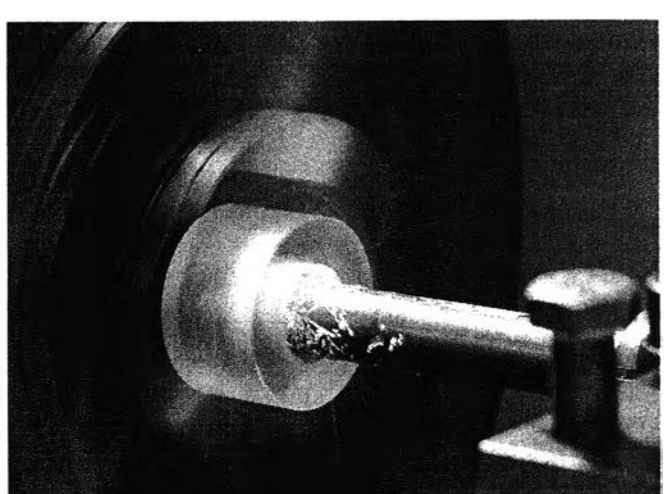

Figure 3.20 The acrylic pieces while machined.

The prepared sample must be loaded into the jaw carefully. The parallel, the pieces of iron with high accuracy parallel surface, should be used to ensure the proper loading. In Figure 3.20, an acrylic piece is machined to the internal scallop profile. Some acrylic pieces which have already been machined are shown in Figure 3.21.

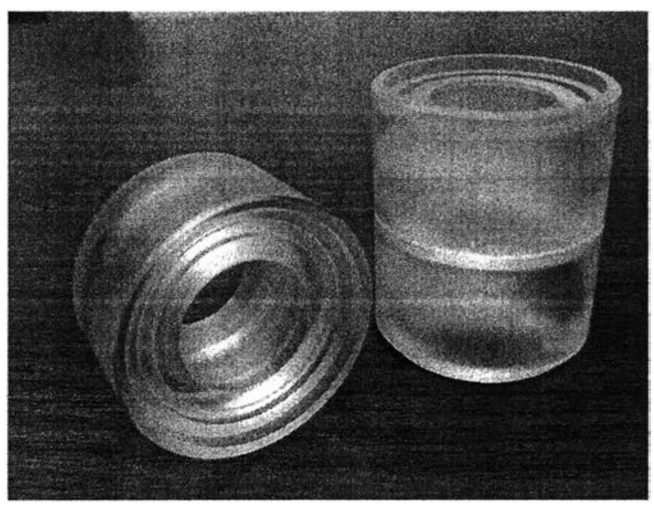

Figure 3.21 Finished acrylic pieces

3.3.1.3 Downstream Section

This section is 91.75 cm stainless steel pipe used to minimize the turbulence effect of the 90 degree elbow placed after the downstream section shown in Figure 3.22. The pressure tap is put on the pipe for a full scale experiment which required a long measured length.

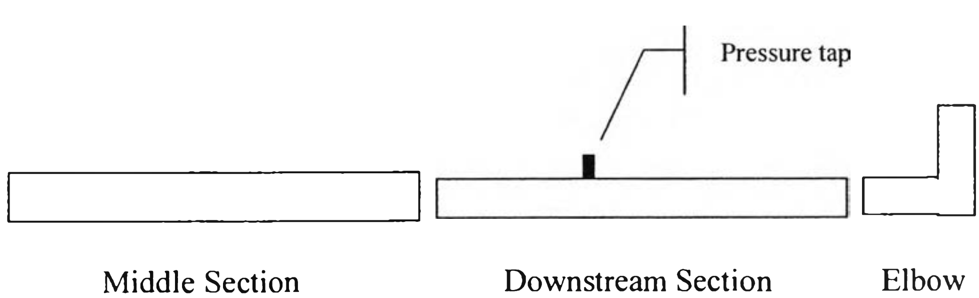

Figure 3.22 Downstream section

3.3.1.2.1 Assembling

Every acrylic pieces are put together. The sequence of acrylic pieces depend on the purpose of experiment. The complete test section and scalloping loop are shown in Figure 3.23 and 3.24 respectively.

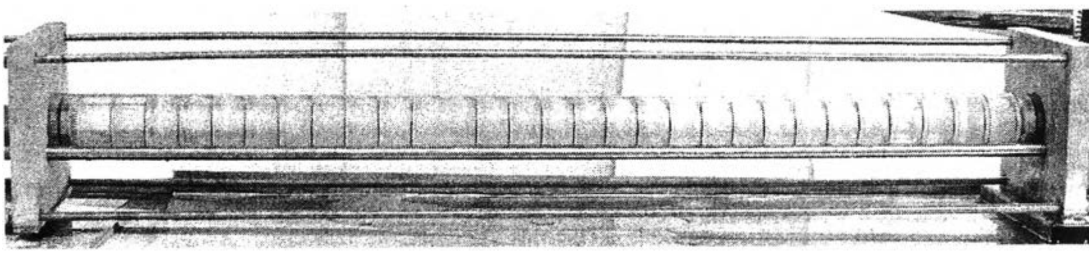

Figure 3.23 complete test section

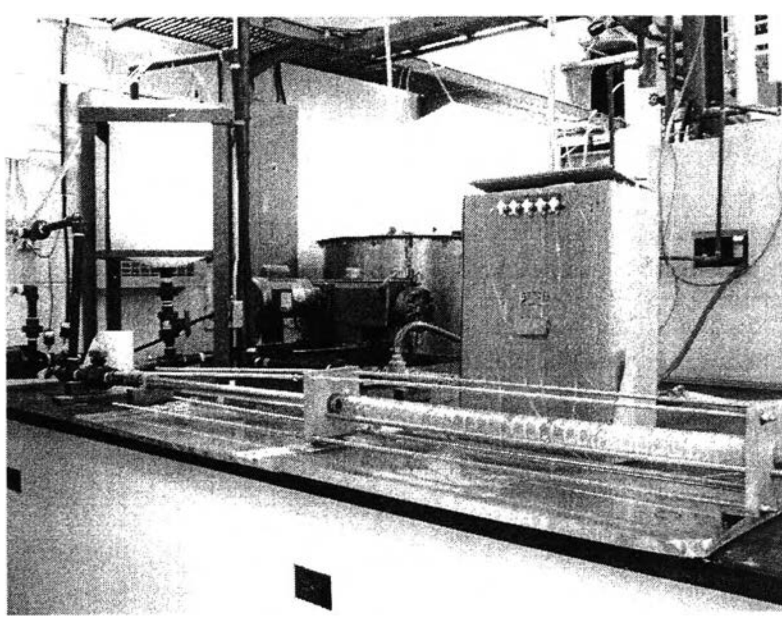

Figure 3.24 Scalloping loop

3.3.2 Validation of FLUENT CFD Model

In order to validate FLUENT model, two experiments have been conducted. Flow visualization experiment obtains qualitative results while pressure measurement obtains quantitative results.

3.3.2.1 Flow Visualization

Bubble technique, which use bubbles as a tracer to track the flow, is applied to this experiment. Bubbles were generated in the reservoir tank by agitation. The bubble size is kept small to minimize the buoyancy effect. The scalloped pieces around the interested area are polished to clear to maximize the visibility as shown in Figure 3.25.

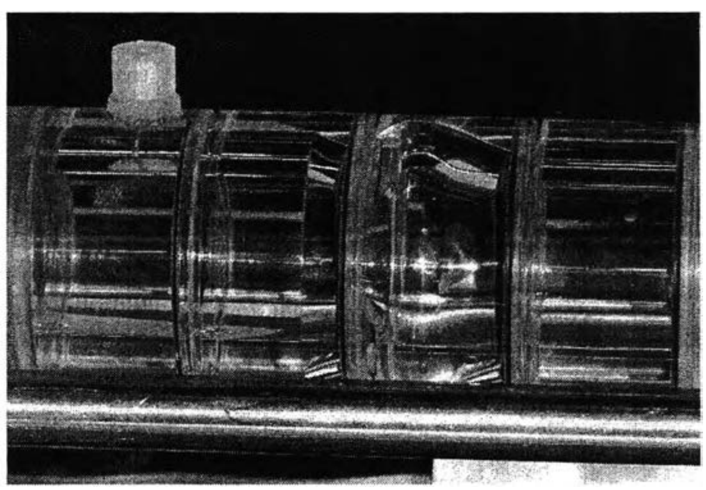

Figure 3.25 Polished scallop pieces

The movement of the bubble is caught by high speed camera at 12 GPM. The stream line of flow is obtained by taking a picture of bubble with low shutter speed. The dye injection technique is also used to compare the result with bubble technique.

3.3.2.1 Pressure Measurement

In order to validate CFD simulation, the static pressure was measured along the test section with one and two scallops as shown in Figure 3.26 and 3.27 respectively.

Figure 3.26 Test section with one scallop

Figure 3.27 Test section with two scallops

Pressure taps were put densely around the scallop area due to a high fluctuation in the pressure. Figure 3.28 illustrate the pressure taps around the scallop area while Figure 3.29 shows the position and distribution of taps.

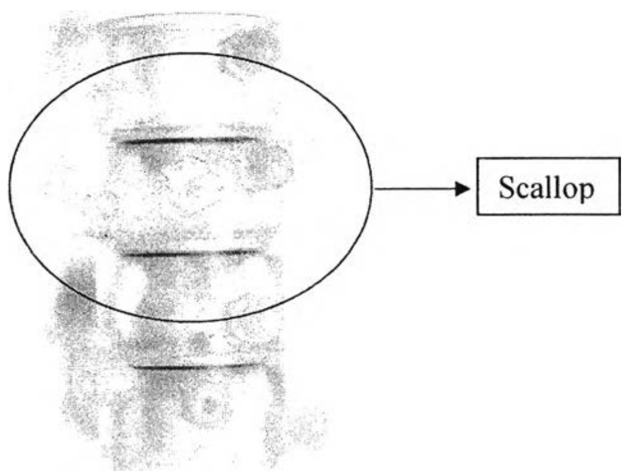

Figure 3.28 Pressure taps around the scallop area

Relative static pressure compare to the end of the test section is measured. Flow rate used are 6, 9, 12, 15 and 18 GPM. High sensitive pressure transducer is used to look up for the static pressure with high accuracy.

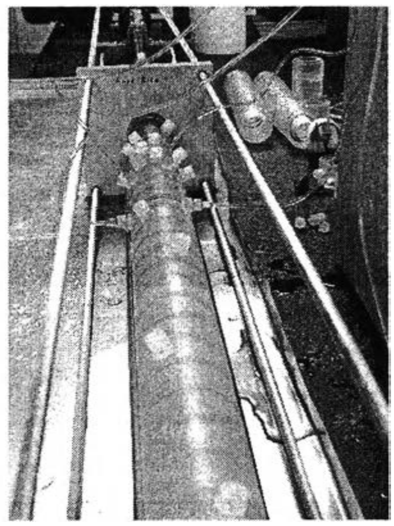

Figure 3.29 Position and distribution of the pressure taps

3.3.3 Effect of Scallop's Surface Area on Pressure Drop

The experiments were conducted in both forward and backward flow. The number of scallop was varied while the pressure drop of the system was measured. The volumetric flow rate was also varied from 6 GPM to 18 GPM. The test matrix is shown in table 3.2.

Table 3.2 Scallop's surface area test matrix for both forward and backward flow

Number of scallop	Flow Rate (GPM)				
	6	9	12	15	18
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					

3.3.4 Effect of Scallop's Distribution on Pressure Drop

In order to investigate the distribution effect, the position and numbers of scallops were varied while the pressure drop of the system was measured. The arrangements of the scallops are divided into 10 set shown in Figure 3.30. The volumetric flow rates used in this experiment were 9 GPM and 12 GPM. The test matrix is shown in table 3.3.

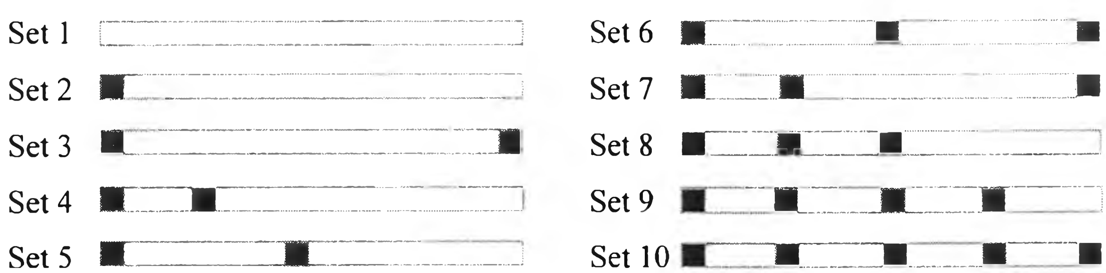

Figure 3.30 The arrangements of scallops

Table 3.3 Scallop's distribution test matrix

Arrangement	Flow Rate (GPM)	
	9	12
Set 1		
Set 2		
Set 3		
Set 4		
Set 5		

Arrangement	Flow Rate (GPM)	
	9	12
Set 6		
Set 7		
Set 8		
Set 9		
Set 10		