PRESSURE MEASUREMENTS FOR STEADY STATE INSPIRATORY FLOW IN A MODEL OF THE CENTRAL AIRWAYS

by

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ABSTRACT

Differential pressure measurements were made using a pressure transducer between different cross sections along a life-sized model of the human central respiratory tract. A viscous fluid was used to raise the pressure drops to measurable levels. The Reynolds numbers varied between 389 and 1730 for the trachea. Pressure drops across cross sections below the first bifurcation were found to be non-uniform due to secondary flows.

The pressure drop along the trachea was found to be in good agreement with Langhaar's theory for entry flow in a tube and data for sinusoidal flow found by Thomas Hennessey. The pressure drops below the first and second bifurcations were found to be proportional to $\rho U_o^{1.25}$ and $\rho U_o^{1.15}$ respectively.

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List of Symbols

b	constant
c	constant
d	diameter
ℓ	length
ΔP	differential pressure
Q	flow rate
r	radius
Re	Reynolds number $U_o\ d/\nu$
t	time
U_o	mean velocity
u	axial velocity
$\dot{V}$	volume flow rate
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density

I. Introduction

The study of human respiration is a difficult fluid mechanical problem. The force that drives the flow of air into and out of the lungs is a pressure gradient along the airways of the lung from the oxygen-blood interface of the alveoli to the atmosphere. For inspiration to occur this pressure gradient must be negative, that is the pressure at the alveoli must be less than atmospheric. For expiration to occur the pressure gradient must be positive. This pressure gradient is expended in accelerating the flow along the airways and in overcoming frictional resistance.

In flowing from the atmosphere to the alveoli air must pass through the mouth or nasal passages, the larynx, the trachea, and 23 generations of bronchi. The size of these airways ranges from the 19 mm. I.D. of the trachea to less than 0.5 mm. I.D. for the last three generations. According to Weibel (1) these bronchi are essentially in the form of a bifurcating network, that is each bronchi of generation x divides into 2 smaller bronchi of generation x + 1.

Flow in the upper airways during inspiration is usually turbulent because the Reynolds number exceeds 2000 and because the mouth, the nasal passages and the larynx introduce disturbances in the flow. The flow in the smaller bronchi becomes laminar as the Reynolds number becomes small. The velocity decreases due to the increase in total cross sectional area of the tubes. Bifurcations and bends produce secondary flows of a helical nature.

These complications make it difficult to attempt an analytic investigation of the pressure drop in the lungs. The pressure drop is important because it determines the airway resistance to flow. This airway resistance is defined as the overall pressure drop from the atmosphere to the alveoli divided by the flow rate. The resistance is a very important factor in certain respiratory diseases such as bronchitis, asthma and emphysema. Asthma (an allergic reaction) constricts the bronchioles through mucus secretion, thereby increasing resistance. In emphysema the airway tissues are degeneratively weakened and collapse at high velocities only during expiration, due to the pressure drop in the accelerating flow. This collapse greatly increases the resistance.

For an accurate diagnosis of respiratory diseases it is important to determine in which part of the airways and during what part of the breathing cycle the increase in resistance takes place. Present techniques permit only measurements of the overall airway resistance in patients. A good understanding of the fluid mechanics of the airways is therefore necessary to correctly interpret the clinical data.

II. Previous Work

The initial analysis of airway resistance was done by Rohrer (2) in 1915. He developed the following equation from simple consideration of simple fluid mechanics and *in vivo* data,

$$\Delta P = K_1 \dot{V} + K_2 \dot{V}^2$$

where ΔP is the total pressure drop from mouth to the alveoli, $\dot{V}$ is the volume flow rate, and K_1 and K_2 are coefficients which are functions of lung volume. This equation is still being used by physicians.

Rohrer assumed that the first term, $K_1 \dot{V}^2$, was due to laminar flow while the second term, $K_2 \dot{V}^2$, was due to turbulence in the flow. From this interpretation K_1 should be proportional to μ and K_2 to ρ. However, Jaeger and Matthys (3) found that K_1/μ and K_2/μ were not constant when different gases were used.

Schroter and Sudlow (5) and Shreck and Mockros (4) made experimental measurements of the velocity distribution in air flowing at a steady rate through a large glass model of a bifurcating network. Their results showed the velocity distributions were highly asymmetric below the first bifurcation. Also they found higher velocities existed along the inner edge of the daughter tubes. Below the second bifurcation the profiles become more symetric but were still not parabolic.

Pedley, Schroter, and Sudlow (6,7) used these results and developed a theoretical method by which the pressure drop due to viscous dissipation across a bifurcation could be computed, for steady flows. Their result was expressed as:

$$\Delta P = \frac{C}{4\sqrt{2}} \left[Re \left(\frac{d}{\ell}\right)\right]^{1/2} \left[\frac{8Q\mu\ell}{\pi r^4}\right]$$

where the second quantity in brackets is the corresponding Poiseuille pressure drop. The method becomes of course invalid when the quantity $\frac{C}{4\sqrt{2}} \left[Re \left(\frac{d}{\ell}\right)\right]^{1/2}$ becomes less than unity.

Hennessey (8) investigated experimentally the pressure drop in a life size glass model of the trachea and first two generations of bronchi for sinusoidal flow. He amplified the pressure drops by using a viscous fluid instead of air.

His results showed that in the trachea the pressure drop obeyed approximately the theory developed by Langhaar (9) for steady flow at the entrance of a tube and that helical secondary flows were present causing azimuthal pressure variations.

It is important to know whether the flow in the airways is quasi-steady, that is, behave at each instant of time as if it were steady. Only if the flow is quasi-steady are the results of steady flow experiments and theories directly applicable to the lungs.

The present experiment was carried out in order to compare the pressure drops for steady flows with the corresponding ones obtained at the peak of an oscillatory flow and resolve the preceding question.

III. Considerations of the Fluid Mechanics

The flow of a viscous fluid through a tube results in the formation of a boundary layer against the wall due to the action of shear forces between the fluid and the wall. Figure 1 illustrates flow in the trachea and the first bifurcation. The boundary layer increases in the direction of flow, with the result that the fluid in the central, or inviscid, core must accelerate to maintain continuity. This acceleration results in a pressure drop along the tube due to the Bernouilli effect.

The boundary layer is thin at high flow rates. For a flow rate of 500 ml/sec, the boundary layer fills only a small fraction of the volume of the first two generations. For a low flow rate of 50 ml/sec the boundary layer fills the tube completely prior to the first bifurcation.

The distance downstream that it takes for the boundary layer to fill a tube is defined as the entrance length.

The bifurcations disrupt the boundary layer growth somewhat. The boundary layer on the outside edge of the tube continues past the bifurcation and maintains normal growth. However, the inner edge of the bifurcation causes a new boundary layer to form and begin growing. This gives a slight increase in the cross sectional area of the inviscid core, and therefore a small increase in pressure. Another result of the bifurcation is that the peak velocity of a cross section below a bifurcation will occur closer to the inner edge.

In order to make comparisons between flow in the human airways and those in the model, two major parameters must remain the same. They are the aspect ratio $\frac{\ell}{d}$, and the Reynolds number, Re. The Reynolds number is the ratio of inertial forces to viscous forces. Table 1 presents values of these parameters for normal respiration of air. If a different fluid than air is used in the experiment scaling laws must be used to transform the experimental data into their physiologic equivalent.

IV. Experimental Apparatus

Apparatus Constructed by Hennessey

The test section (Figure 2) is a life-size model of the trachea and the first two generations of bronchi. The trachea consists of a 19 mm. I.D. glass tube which branches into two daughter tubes of 13.6 mm. I.D. Each of these daughter tubes in turn branches into two smaller tubes of 10 mm. I.D. The smallest tubes empty into the fluid reservoir (see Figure 3).

Pressure taps were machined into the glass at chosen sites. The edges of the tap holes were smoothed to prevent disruption of the flow. Rigid tubing was used to conduct the taps to the manifold of a differential pressure transducer (Pace model No. CP-49-2 psi). A system of plastic valves was used to control the selection of pressure taps for comparison.

The test section was mounted in a divided tank. The rear division of the tank acted as a reservoir to hold approximately 5 gallons of fluid. The other division of the tank was left empty to facilitate observation of the flow in the test section.

The entrance to the test section was connected to an expander tube. This tube served to model the mouth and to damp any irregularities introduced into the flow by the pump. The expander was 3 inches in diameter with a neck to 19 mm. at the attachment of the test section. The transition from expander to test section was smoothed by aluminum ferrules, used to prevent turbulence in the flow. The expander was connected by a length of 1 1/2 inch copper to a piston pump.

The test fluid consisted of a mixture of 72% glycerine and 28% distilled water. This fluid was chosen because the actual pressure drop in air was too small to measure directly. For example the actual pressure drop in the _in vivo_ trachea is on the order of 0.04 centimeters of water, while the smallest pressure drop in the model trachea using the test fluid was 0.75 centimeters of water.

Present Apparatus

The above apparatus was retained with modifications to permit the use of steady flow pumps.

The valving system required extensive modification to prevent leaks. As before, plastic medical stopcocks were used for the valves. Luer-Lock medical connectors were used to attach the valves to the transducer manifold. The valves were connected to the tap lines by tubing connectors. This system allowed the valves to be tightened to prevent leaks or to be totally replaced after continued use had destroyed their seals.

The piston pump was replaced with a Moyno 3L3 helical stator pump. This pump works on a principle similar to an Archimede's screw, but maintains positive displacement. The pressure fluctuations in the output flow are small. The pump maintains a linear increase in flow rate with drive shaft R.P.M. A small generator was connected to the center of the pump drive shaft to act as a simple tachometer. The flow rates for different pump speeds were measured and the generator output calibrated to these values.

The pump's input and output leads were connected to the expander tube and the reservoir respectively by 1/2 inch I.D. thick-walled Tygon tubing. The tubing was used because it was strong enough to prevent collapse due to cavitation and yet was compliant enough to damp out any pressure fluctuations in the flow.

A D.C. motor was used to power the pump. The armature and field voltages were controlled by power supplies, allowing a variable speed ratio of 9:1.

A new method of calibrating the transducer was devised to check the suspicion that signal drift was occurring. A two tube manometer was built with wire sighting levels at 1 centimeter distances for accuracy. The two tubes were connected to the transducer manifold through a double set of valves. These valves allowed the manometer to be disconnected when not in use to eliminate pressure fluctuations caused by the column vibrating. The calibration was checked before every run. Figure 4 shows a representative calibration curve.

The output of the differential pressure transducer was recorded on a Plotamatic 715m X-Y recorder. The transducer output was connected to the X axis while a time base ran the Y axis. A simple bias circuit consisting of a 1.5 volt battery and a variable resistor was used to zero the transducer output for zero differential pressure.

A Saybolt Universal Viscometer was used to measure the kinematic viscosity of the fluid before and after each run. The specific gravity was measured by a Fisher Hydrometer at the same time.

V. Experimental Procedures

The initial step in taking a set of data was to mix the fluid in the reservoir thoroughly by running the pump. The kinematic viscosity, temperature, and specific gravity of the mixed fluid was measured. Then the calibration manometer was connected to the manifold and filled with fluid from the reservoir. The manometer valves were opened, thereby pressurizing the manifold to a head of 1 meter of water. Each tap was opened and any bubbles in that section of the manifold and the tap line were flushed into the reservoir. Also the transducer vents were opened to expell any bubbles there.

When the lines were free of bubbles the transducer output was connected to the recorder. Calibration of the transducer was achieved by setting the manometer at zero differential pressure, then raising the water level to plus 10 centimeters of water, then lowering it to minus 10 centimeters of water, and then resetting to zero while recording the output of the transducer. The resulting value of volts per centimeter of fluid had to be divided by the specific gravity of the fluid to convert the result to volts per centimeter of water. Then the manometer was removed.

The zero pressure line was then recorded by opening taps 1 and 2 while the pump was stopped and setting the bias circuit to give a net voltage of zero. This allowed the pressure difference due to the height differential between the test section and transducer to be zeroed out. At each speed this procedure of biasing for zero pressure had to be carried out. This procedure also showed any shifts in the zero line that might have occurred. These shifts were also less than 1% of the trachea pressure drop.

Then the pump was set to the desired speed. The required taps were opened two at a time and the transducer output recorded. All of the desired pressure drops were recorded before the pump was set to the next speed.

After the entire speed range had been recorded, the pump was stopped. The temperature, kinematic viscosity, and specific gravity were checked again. The average values of the initial and final viscosity and specific gravity were used in the data reduction.

VI. Results and Discussion

A complete set of data for a given run consists of differential pressure measurements between the following taps (see Figure 2): 1s-2s, 2s-3s, 3s-4s, 3b-4b, 3b-5b, 3s-3b, 4s-4b, 5s-5b, 1s-4s, and 1s-4b. The letters s and b represent the location of the taps on the tubes, either on the side (s) or bottom (b). A representative set of pressure measurements is given in Figure 5.

Even with semi-compliant tubing being used to damp out pressure fluctuations, taps 1 and 2 show rapid fluctuations of about 7% of the pressure drop in the trachea. A mean value of these fluctuations was marked and the pressure drop measured from there.

The values of temperature, viscosity, and specific gravity changed over the course of a run. Table 2 gives a summary of the initial and final values of each quantity for each run. Also shown are the minimum and maximum Reynolds numbers reached in the trachea.

The values of the pressure drops between the different taps were normalized with respect to $1/2\ \rho U_o^2$. The normalized pressure drops were plotted against Reynolds number to eliminate any dependence on viscosity. (see Figures 6 through 9). The values of $1/2\ \rho U_o^2$ and Reynolds number in the smaller tube were used for normalizing and plotting the pressure drop across a bifurcation. The values of Reynolds number and $1/2\ \rho U_o^2$ in the trachea were used to normalize and plot the pressure drop for the entire test section (taps 1s-4s and 1s-4b).

Pressure Drop Along the Trachea

The normalized pressure drop between taps 1s-2s along the trachea is shown in Figure 6. The normalized pressure drop decreases as $Re^{-.70}$. This means that ΔP is proportional to $U_o^{1.30}$.

Langhaar (9) and Shapiro et. al. (10) investigated the pressure drop in the entrance length of a pipe for steady flow. Their results show the pressure drop is greater than the corresponding Poiseuille pressure drop for a similar pipe. Here the pressure drop is a result of the acceleration of the core as the boundary layer develops. The predicted pressure drop using Langhaar's theory is shown in Figure 6. The steady flow theory seems to underestimate the actual pressure drop.

Hennessey's experimental data points for sinusoidal flow are also shown in Figure 6. His values slightly exceed those from steady-state measurements. In general the difference between the two is about 2 to 3% of the steady-state flow values.

Pressure Drop Across the First Bifurcation

Figure 7 presents the normalized pressure drop for taps 2s-3s across the first bifurcation. The normalized pressure drop decreases as $Re^{-0.75}$ which means ΔP is proportional to $U_o^{1.25}$. The dependence of the normalized pressure drop upon Reynolds number is expressed as:

$$\frac{\Delta P}{1/2\ \rho U_o^2} = 10^b \ Re^{-0.75}$$

where b = 1.81.

This result differs appreciably from the predictions of Pedley et. al. based on the assumption that the boundary layer remains thin. On using the same normalization their prediction is:

$$\frac{\Delta P}{1/2\ \rho U_o^2} = 8\sqrt{\frac{\ell}{r}}\ C\ Re^{-0.5}$$

This curve is also plotted in Figure 7 for the appropriate length to diameter ratio ℓ/d. Pedley et. al. found a considerable variation in C, ranging from 1.11 to 2.44, but they recommend a weighted value of 1.85. However, a value of C = 0.74 fits our experimental values much more closely.

Figure 7 also shows Hennessey's experimental data for the first bifurcation. The normalized pressure drop is proportional to $Re^{-0.7}$ which means ΔP is proportional to $U_o^{1.3}$. Again slight differences between the two curves exist, ranging from 3% of the steady-state values at low Re to 10% at high Re.

Pressure Drop Across Second Bifurcation

The normalized pressure drops for taps 3b-4b (across the second bifurcation) are shown in Figure 8. The normalized pressure drop decreases as $Re^{-0.85}$, which means that ΔP is proportional to $U_o^{1.15}$. The results may be presented as:

$$\frac{\Delta P}{1/2\ \rho U_o^2} = 10^b\ Re^{-0.85}$$

where b equals 2.04.

In this case Pedley's theory does not agree at all with the present experimental observations. Pedley's theory predicts that the normalized pressure drop will be proportional to $Re^{-0.5}$ (see previous section). The differences between the experimental points for steady flow and Pedley's theory make any comparison meaningless.

Hennessey's data points are represented in Figure 8 also. His normalized pressure drop was proportional to $Re^{-.6}$ which means ΔP is proportional to $U_o^{1.4}$. In this case the two sets of data differ substantially.

Accumulative Pressure Drop

The normalized pressure drop for the entire test section (taps 1s-4s) is shown in Figure 9. The normalized pressure drop decreases as $Re^{-.75}$ which means ΔP is proportional to $U_o^{1.25}$.

Since Pedley's theory cannot be used to predict the pressure drop across more than one bifurcation, the data is compared only with Hennessey's results. The agreement between the two curves is extremely good. The variation between the two is only 5% of the steady-state values.

Azimuthal Pressure Drop

The experimental data of azimuthal pressure drops (taps 3s-3b, 4s-4b, and 5s-5b) are inconclusive. Taps 3s-3b and 4s-4b showed traces that were below the resolution of the transducer. However taps 5s-5b showed a pressure drop that was proportional to U_o^2 and varied from .145 centimeter of water at the lowest Reynolds number (184) to 1.25 centimeters at the highest Reynolds number (822).

VII. Conclusion and Recommondations for Further Work

Two main results emerge from this experiment. First the pressure drop along the different sections is proportional to U_o^n. The values of the exponent n fall between the limits of 1.5 corresponding to very thin boundary layers and 1 corresponding to fully developed Poseuille flow. As expected the exponent decreases from 1.30 for the trachea to 1.15 for the region across the second bifurcation where the boundary layer is thickest. Secondly, the good overall agreement between the data obtained for steady flow and those for oscillatory flow obtained by Hennessey upholds the assumption that flow in the lungs is quasi-steady at normal breathing frequencies.

In further studies the range or Reynolds numbers should be extended to 10^4 or above in order to penetrate well into the turbulent regime and to cover the complete physiological range. This extension can be accomplished easily by lowering the test fluid viscosity and using a more sensitive transducer than the one which was used. Expiratory flows should be also considered, as Hennessey's data has shown that the pressure drops were consistently higher than for inspiratory flows.

References

1. Weibel, F.R., Morphometrics of the lung. In: Handbook of Physiology, Sect. 3, Respiration, Vol. I, Chap. 7, Washington, D.C., Am Physiol. Soc.

2. Rohrer, F., Arch. Ges. Physiol. 162: 225, 1915.

3. Jaeger, M.J. and Matthys, H., "The Patterns of Flow in the Upper Human Airways", J. Appl. Physiol. 6, 113-127, 1968.

4. Schreck, R.M. and Mockros, L.F., "Fluid Dynamics in the Upper Pulmonary Airways", AIAA Preprint 70-788, 1970.

5. Schroter, R.C. and Sudlow, M.F., "Flow Patterns in Models of the Human Bronchial Airways", Resp. Physiol. 7, 341-355, 1969.

6. Pedley, J.T., Schroter, R.C. and Sudlow, M.F., "Energy Losses and Pressure Drop in Models of Human Airways", Resp. Physiol 9, 371-386, 1970.

7. Pedley, J.T., Schroter, R.C. and Sudlow, M.F., "Predictions of Pressure Drop and Variation of Resistance Within the Human Bronchial Airways", Resp. Physiol. 9, 387-405, 1970.

8. Hennessey, Thomas V., Pressure Measurements in a Model of the Upper Respiratory Tract for Sinusoidal Flow, Masters Thesis, Dept. of Mechanical Engineering, M.I.T., Cambridge, Mass., 1971.

9. Langhaar, H.L., "Steady Flow in the Transition Length of a Straight Tube", J. Appl. Mech. 9, A55-58, 1942.

10. Shapiro, A.H., Siegal, R., and Kline, S.J., "Friction Factor in the Laminar Entry Region of a Smooth Tube", Proceedings of 2nd Nat'l Congress of Appl. Mech., 733-741, 1954.

PARAMETERS OF RESPIRATORY FLOW

AIR (SEA LEVEL)

Generation	Aspect ratio L/d	Reynolds No: $U_0 d/\nu$		
		Flow rate in liter/sec		
		0.5	1	2
0 (trachea)	6.65	2280	4560	9120
1	3.24	1570	3140	6280
2	3.23	1085	2170	4340
3	3.26	810	1620	3240
4	3.29	365	730	1460
5	3.36	280	560	1100
10	3.50	25	50	100

TABLE 1

PROPERTY VARIATIONS

#	Date of Run	Re (trachea) Low	High	Viscosity (centi-stokes) Initial	Final	Specific Gravity Initial	Final	Temperature °F Initial	Final
1	Oct. 12	394	935	17.5	16.78	1.186	1.1845	78	79
2	Oct. 28	410	1060	16.95	16.6	1.1845	1.183	77	79
3	Nov. 10	389	1730	19.4	16.8	1.877	1.1842	77	90

TABLE 2

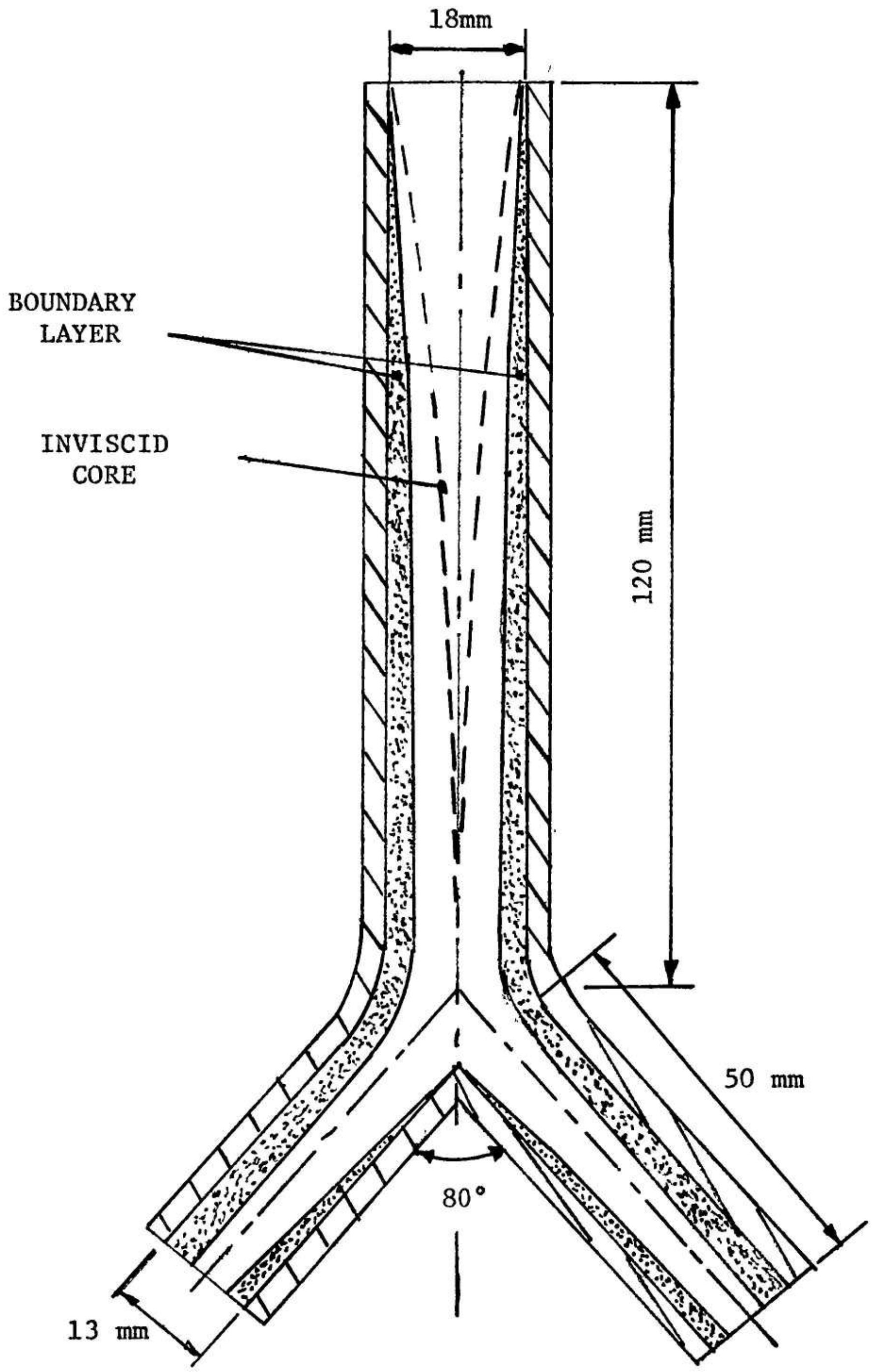

Figure 1. Diagram of Boundary Layer Growth

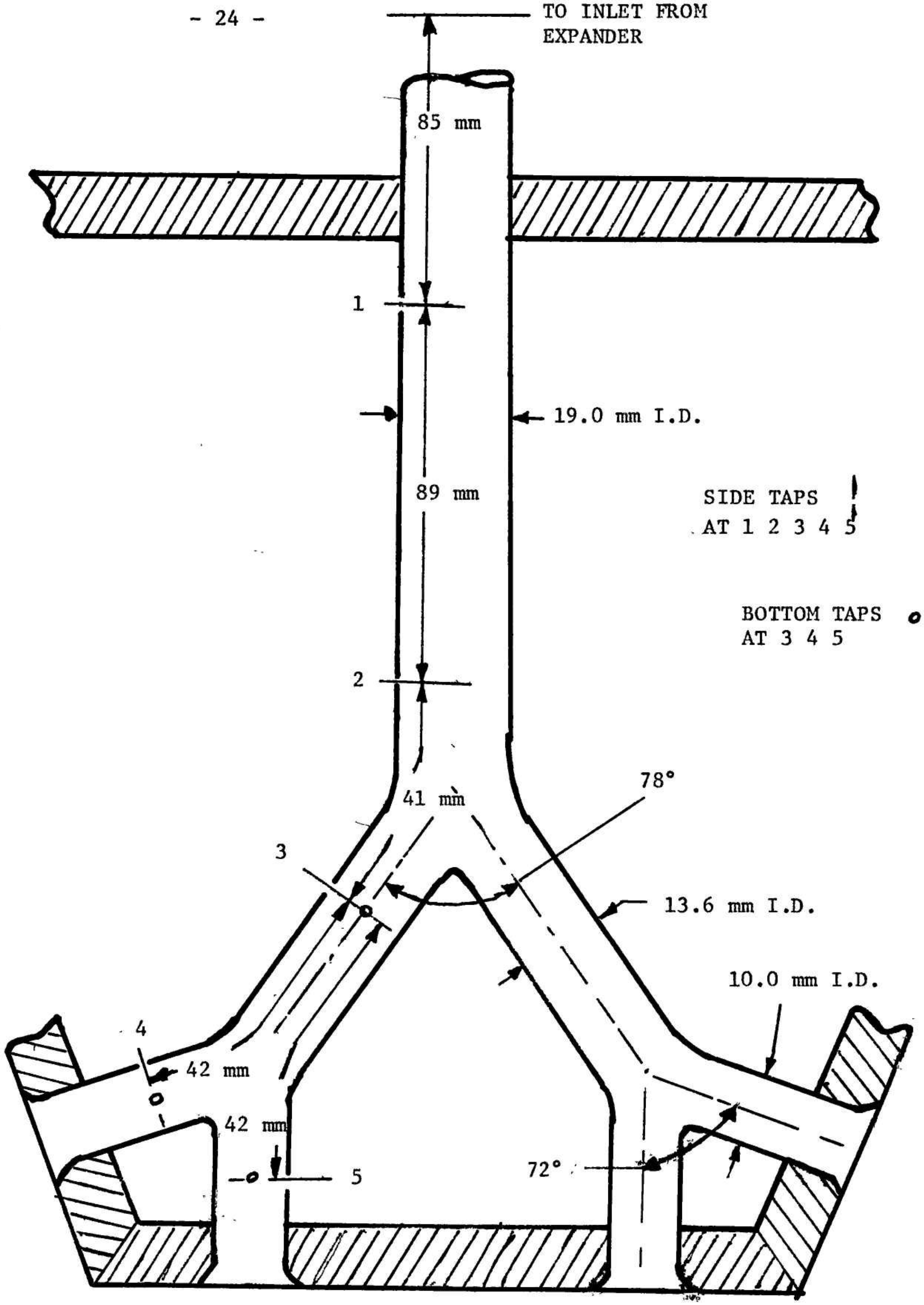

Figure 2. Diagram of Test Section

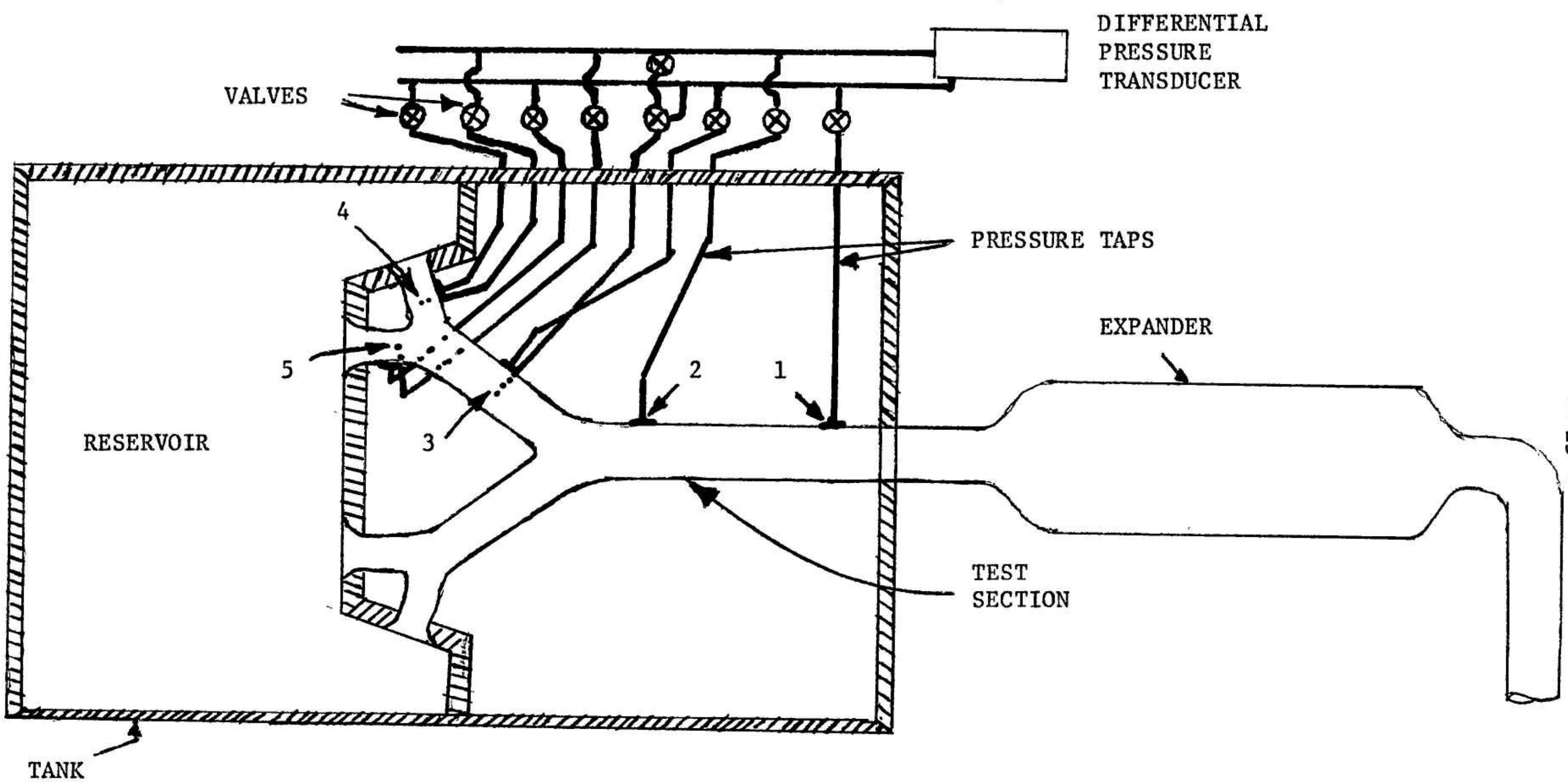

Figure 3. Schematic Diagram of Test Apparatus

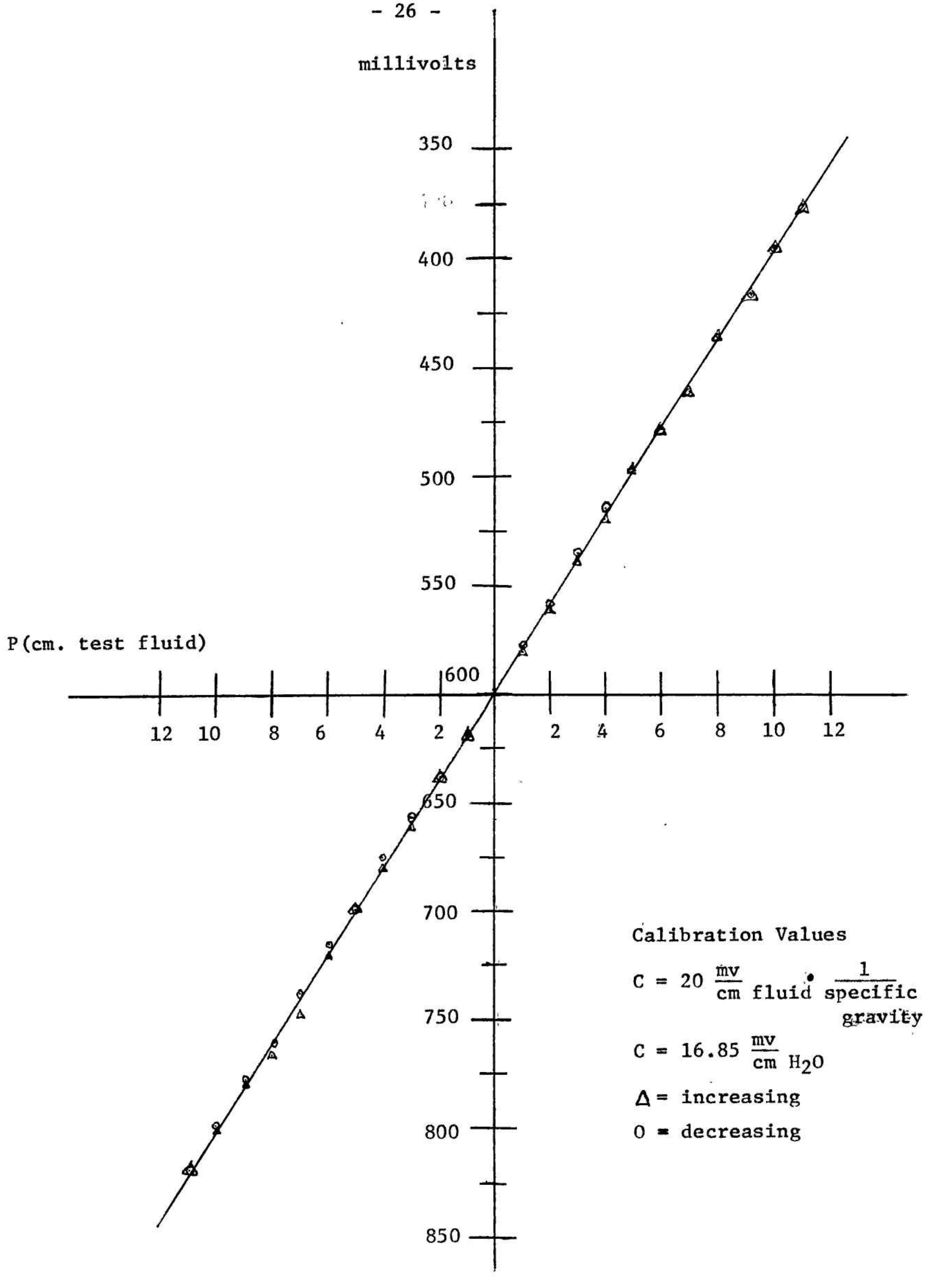

Figure 4. Transducer Calibration Curve

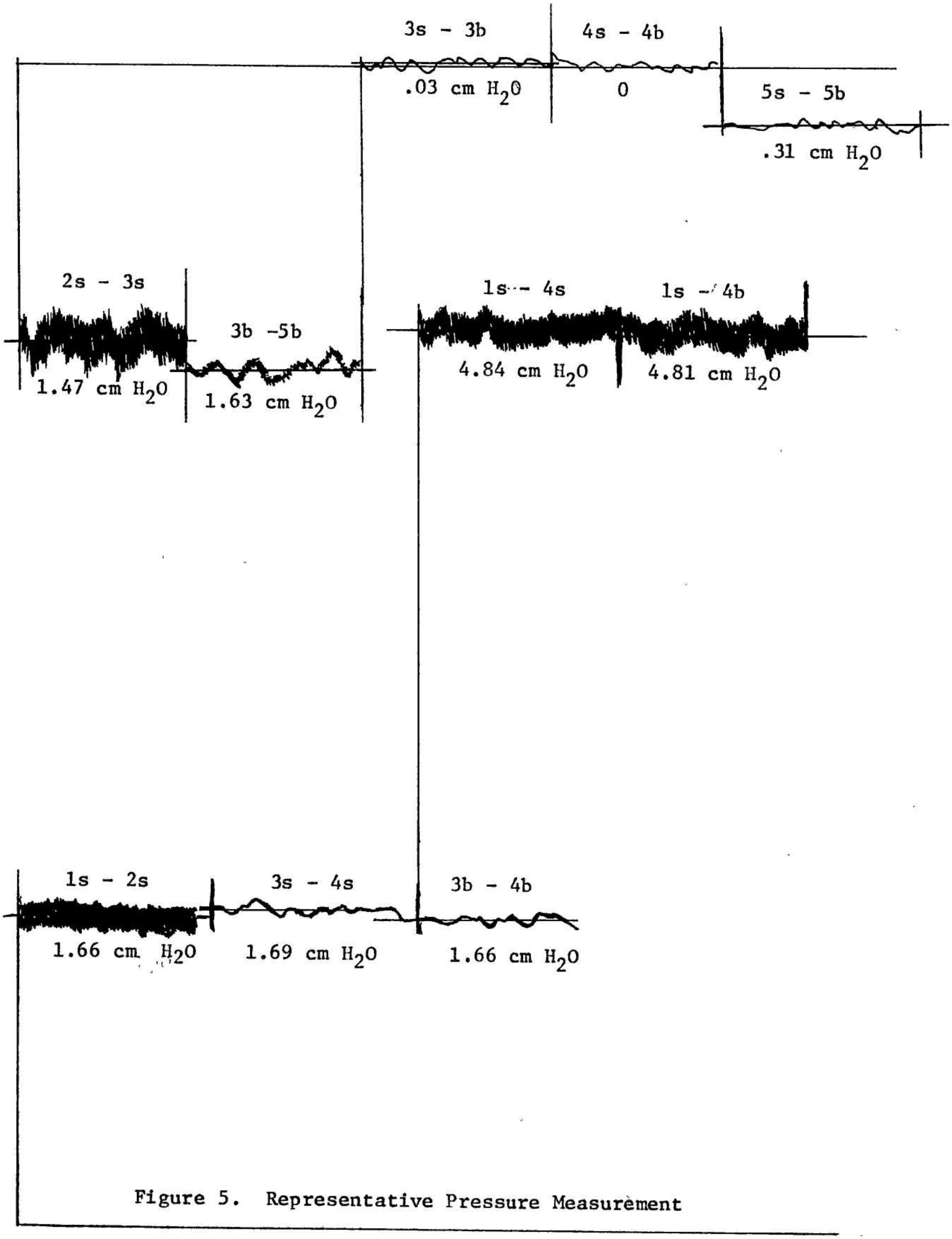

Figure 5. Representative Pressure Measurement

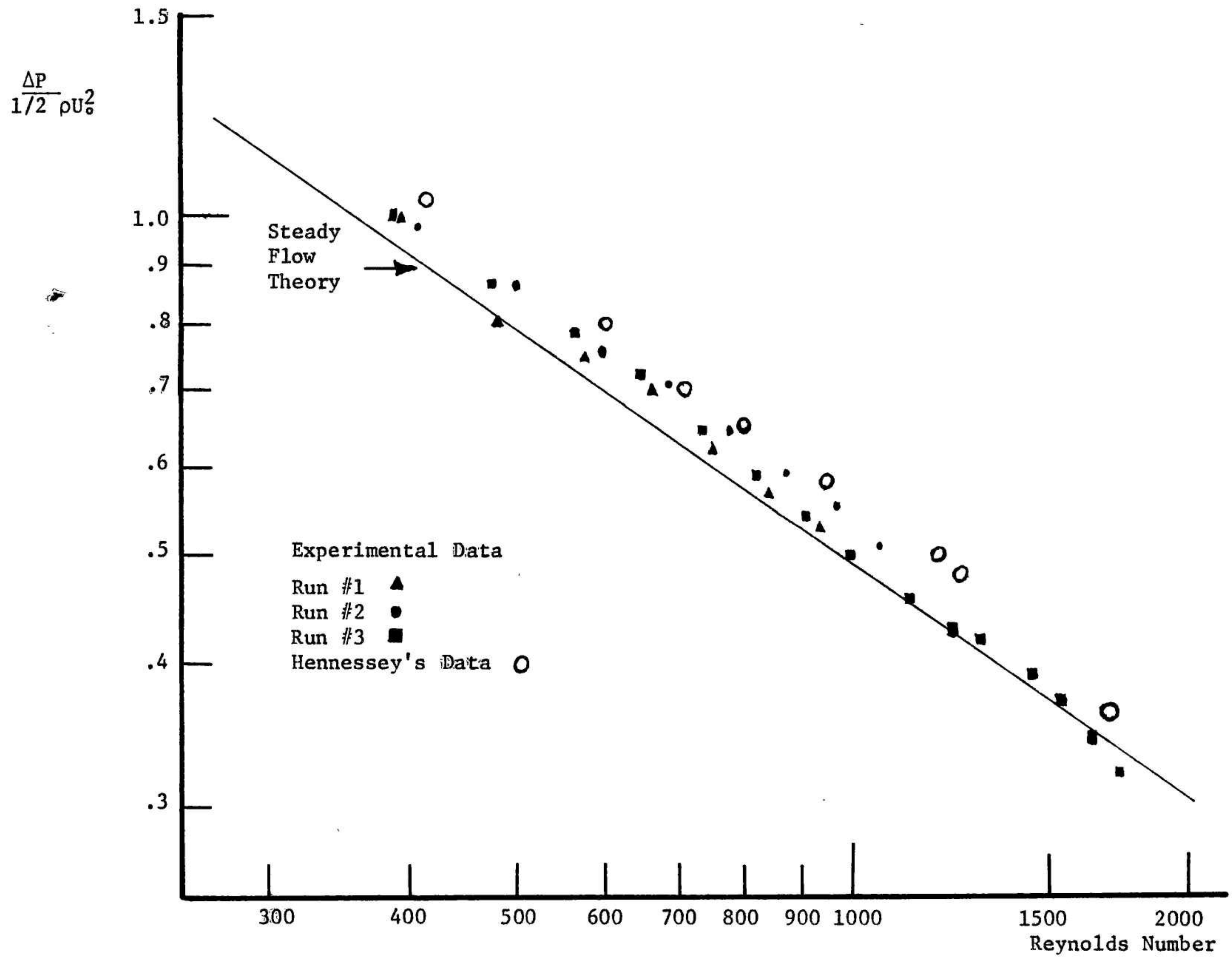

Figure 6. Normalized Pressure Drop for Sections 1s - 2s

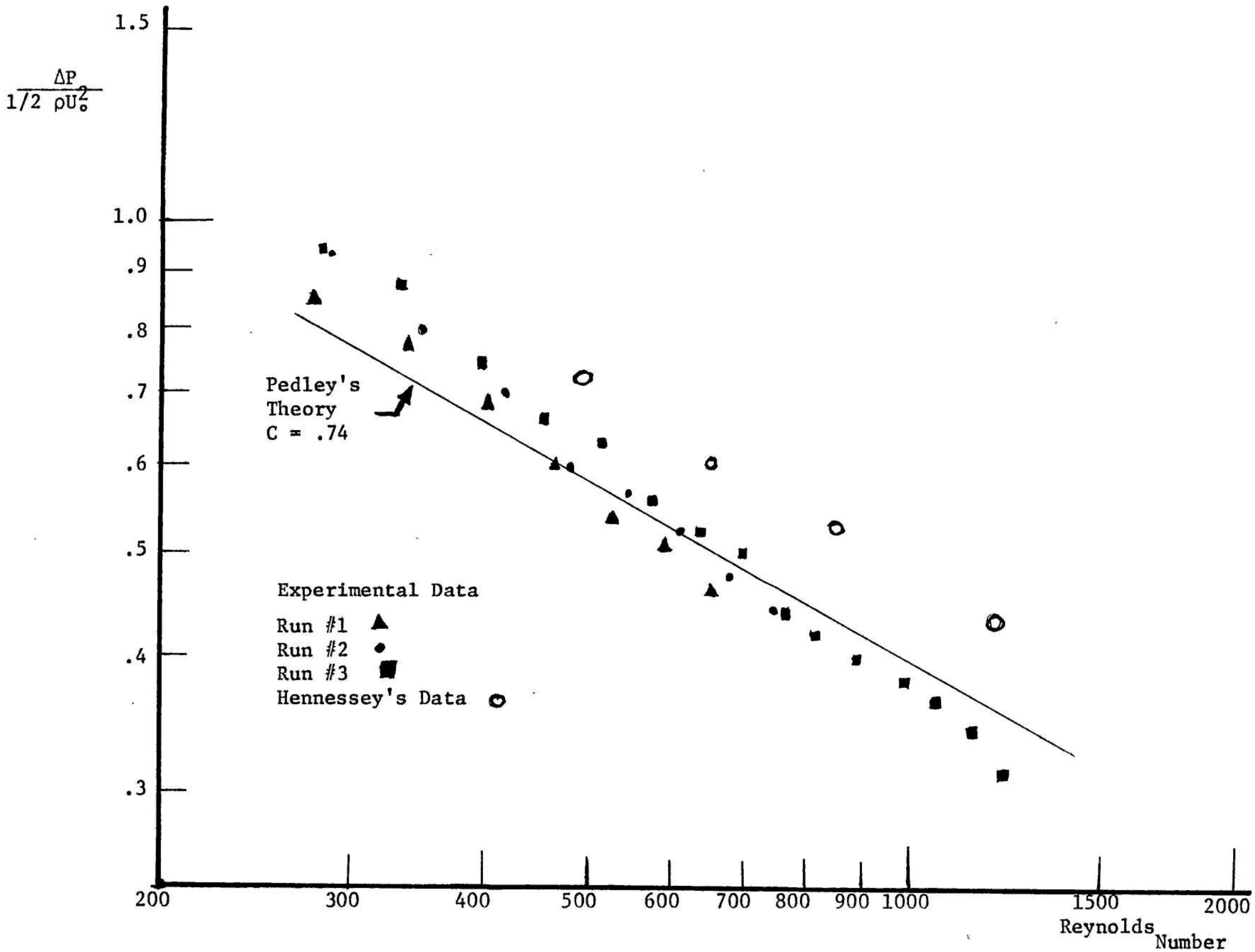

Figure 7. Normalized Pressure Drop for Sections 2s -3s

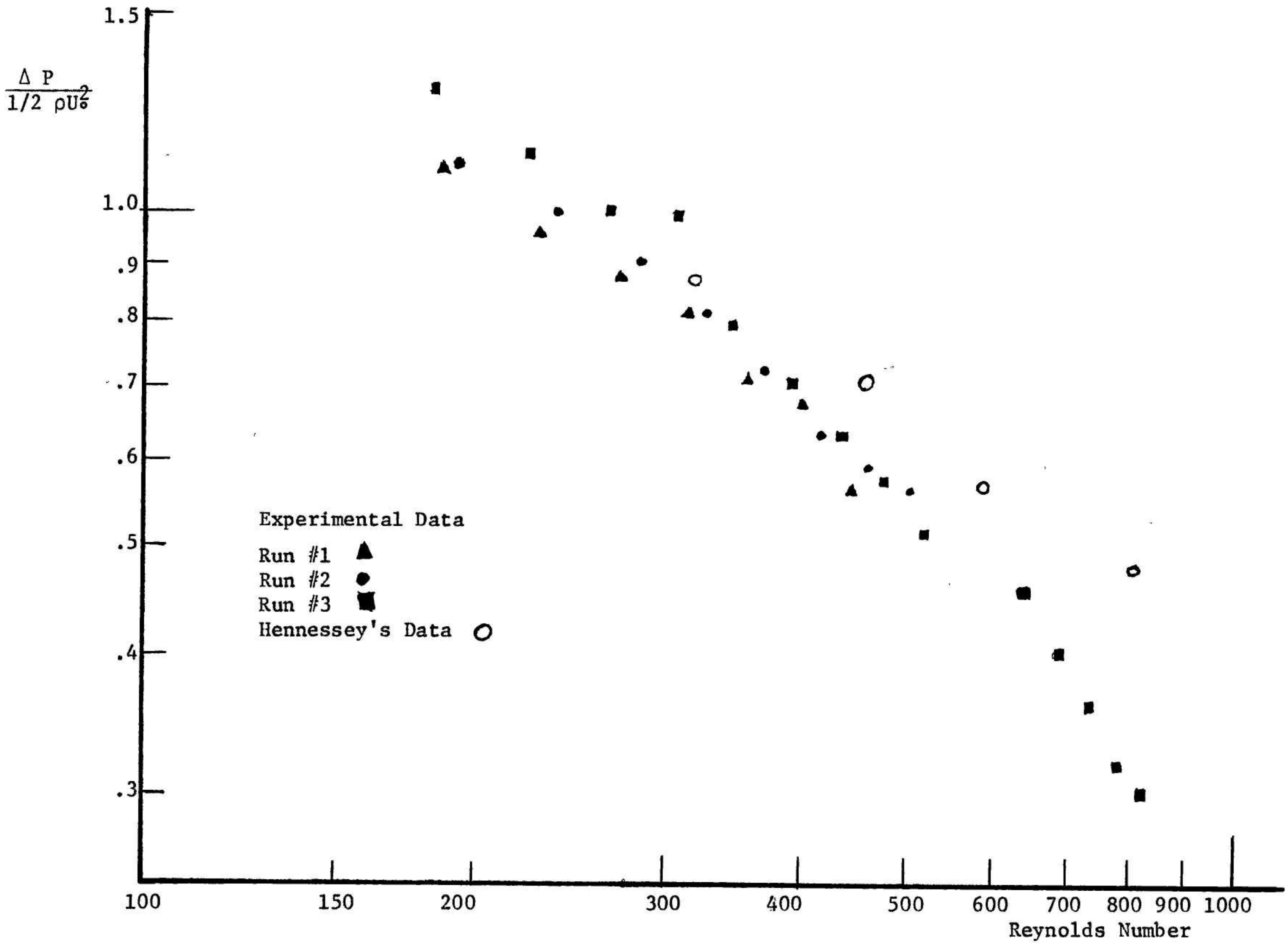

Figure 8. Normalized Pressure Drop for Section 3b -4b

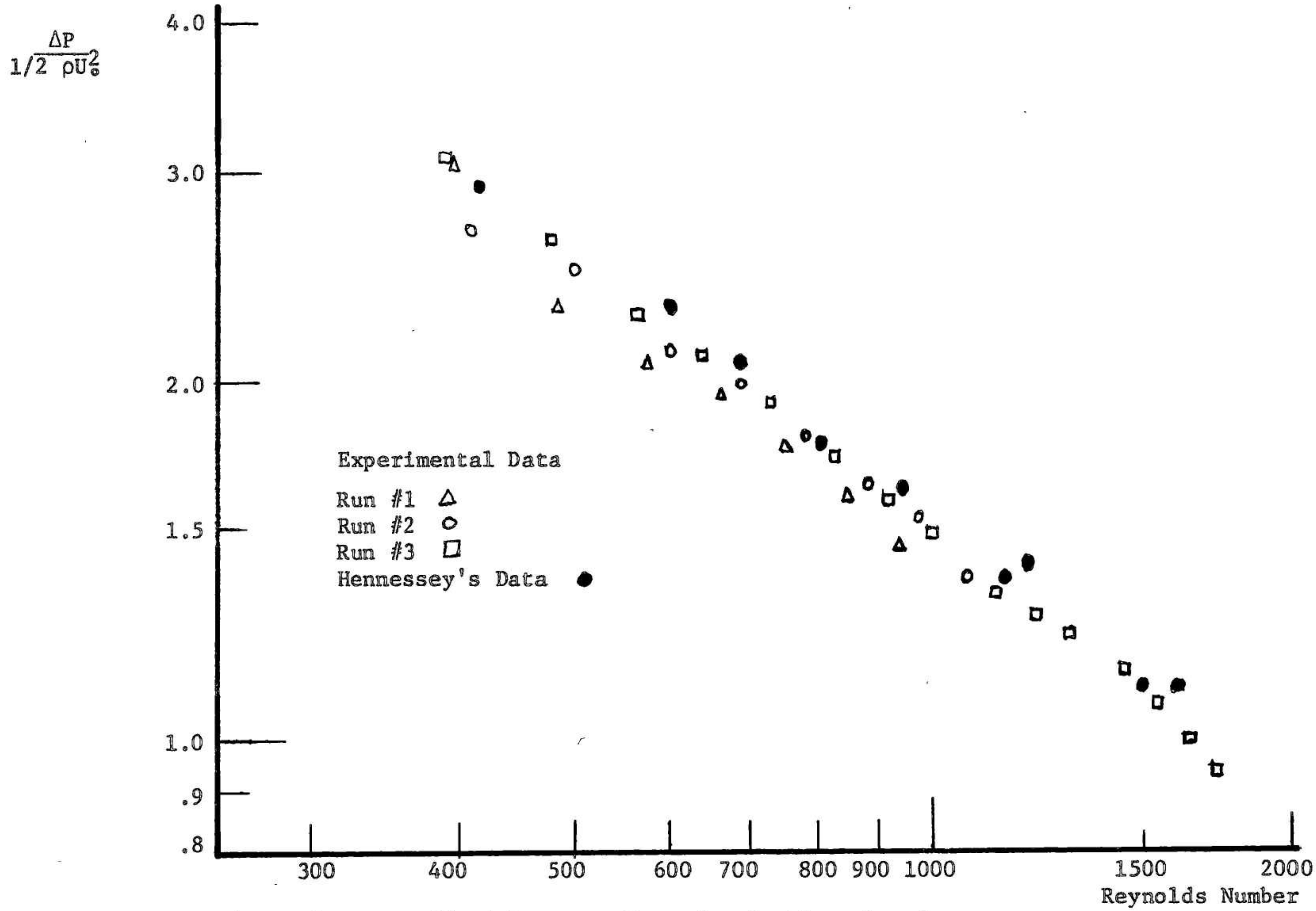

Figure 9. Normalized Pressure Drop for Sections 1s -4s