STEPS AS HYDRAULIC ROUGHNESS ELEMENTS IN SEGMENTALLY LINED TUNNELS

by

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DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and has not previously in its entirety or in part been submitted at any university for a degree.

Signature Date

SYNOPSIS

Segmentally lined tunnels are increasingly being built to transfer water from one water scheme to another. The segments that line such tunnels are often in the form of pre-cast concrete sections, which are placed around the perimeter of the tunnel.

As these tunnels are very expensive to construct, it is imperative that their hydraulic capacities can be calculated accurately. Even a slight variation in the design diameter has a significant effect on the cost of the tunnel.

Due to the construction method involved, alternative segments are not always properly aligned. This creates roughness elements in the tunnel commonly known as steps. These steps occur randomly and vary in size. Since the steps lead to increased roughness and thus decrease the hydraulic capacity of the tunnel, it is essential that this effect be allowed for in the design of the tunnel.

A hydraulic model was used to determine the contribution of steps to the hydraulic roughness, according to step size and frequency of steps.

SINOPSIS

Tonnels word al hoe meer gebou om water tussen waterskemas te vervoer. Die voering van sulke tunnels word dikwels saamgestel uit voorafvervaardigde beton panele wat geplaas word om 'n huls langs die omtrek van die tonnel te vorm.

Aangesien hierdie tonnels geweldig duur is om te bou, is dit uiters noodsaaklik dat die hidrouliese kapasiteit van 'n tonnel akkuraat bereken kan word. 'n Klein variasie in die diameter van die tonnel het 'n betekenisvolle effek op die koste daarvan.

Die konstruksiemetode van sulke tonnels veroorsaak dat opeenvolgende panele nie altyd presies oplyn nie. Sulke afwykings in die belyning van die tonnelpanele veroorsaak klein trappies, wat bydra tot die ruheid in die tonnel en sodoende die kapasiteit daarvan laat afneem. Die afwykings varieer in grootte en kom in geen spesifieke patroon voor nie.

'n Modelstudie is uitgevoer om die bydrae wat die afwykings in the belyning van die opeenvolgende ringe tot die hidrouliese weerstand maak, te bepaal.

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WB02	Water Quality Management	4
WH02	Applied Hydrology	4
WH05	River Hydraulics	4
WW01	Water Environmental Science	4
TOTAL:		**36**

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LIST OF SYMBOLS

A	=	cross-sectional area
C	=	Chezy's coefficient
C_d	=	contraction coefficient
d	=	smaller diameter
D	=	diameter
D_c	=	diameter of orifice
f	=	friction factor
Fr	=	Froude number
g	=	gravitational acceleration
h_f	=	head loss due to friction
h_T	=	total head loss
$h_{pipefriction}$	=	head loss due to pipe friction
h_{steps}	=	head loss due to steps
h_w	=	difference in pressure heights
h_v	=	water height above notch
k	=	absolute roughness
K_l	=	local loss coefficient
K_s	=	loss coefficient for step
K_{SC}	=	loss coefficient for sudden contraction
K_{SE}	=	loss coefficient for sudden expansion
L	=	length
l	=	length of segment
n	=	Manning's coefficient
n	=	number of steps per metre
p	=	pressure
P	=	wetted perimeter
Q	=	discharge
R	=	hydraulic radius

R_0	=	eddy radius
Re	=	Reynolds number
S	=	energy grade
S_0	=	bed slope
S_f	=	hydraulic grade line
s	=	step size
v	=	velocity
$\bar{v}$	=	average velocity
v_0	=	shear velocity
V_0	=	velocity at the center of rotation
y	=	distance from pipe surface
ρ	=	density
z	=	elevation
μ	=	viscosity
υ	=	dynamic viscosity
λ	=	dimensionless coefficient
τ	=	shear stress
$\bar{\tau}$	=	average shear stress
α	=	kinetic energy correction factor

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

The Katse Dam in Lesotho was built to provide water to Gauteng. This water has to be transported to South Africa via tunnels through the mountains. During the design of these tunnels various assumptions were made to quantify the roughness of the tunnels. The HDTC (Highlands Delivery Tunnel Consortium) needed to verify these assumptions and the roughness of the tunnels needed to be determined. Two main roughness components were of concern, namely the box-outs and the steps. These components were modelled in two different studies, however this report deals only with the modelling of the steps and the results of tests carried out in one model study.

1.2 OBJECTIVES

This thesis deals with a laboratory study, performed to determine the effect of steps in a segmentally lined tunnel on the hydraulic roughness of the tunnel.

The objective of the thesis is to develop a means to quantify the additional roughness that the steps cause in segmentally lined tunnels. A model study, simulating different step sizes and configurations of the steps, was supplementary to a literature survey of the hydraulic roughness elements.

The HDTC required that the model study be based on a tunnel with a diameter of 3.5 m and segment lengths of 1.4 m. The contribution of the steps as roughness elements was to be determined for flow velocities of 1 m/s to 5 m/s. The effect of the configuration of the consecutive steps, i.e. the frequency of steps also needed to be evaluated. It was envisaged that the results of the study would produce design parameters for future design of segmentally lined tunnels.

CHAPTER TWO

LITERATURE STUDY

2.1 GENERAL

This chapter deals with the theory of water flowing in pipes with regard to the energy losses due to surface irregularities or hydraulic roughness of the pipes. The basic equations are discussed and stream power theory in terms of pipe flow is derived to establish a means to analyse the test data in terms of this power theory. Furthermore, the theory concerning hydraulic modelling is discussed.

2.2 FLUID FLOW CONCEPTS

Generally the flow of fluid is very complex and the mathematical analysis thereof is only possible if certain assumptions and simplifications are made (Massey, 1989). The flow characteristics, such as velocity and pressure and fluid parameters such as density, describe the time-space relationship for the fluid in motion (Featherstone and Nalluri, 1988).

Flow can be described as steady or unsteady. For steady flow, the flow parameters are independent of time.

Flow can also be categorised as uniform or non-uniform flow. A flow is uniform if its characteristics at any given instant remain the same at different points in the direction of flow.

Three fundamental principles form the basis for the mathematical analysis of hydraulic calculations, namely the continuity equation, the energy equation and the momentum equation. These principles are summarised in the following sections.

2.2.1 Continuity equation

The principle of conservation of mass can be stated mathematically as the equation of continuity. The principle states that the mass stays constant with time. Considering steady flow of fluid through a streamtube, the mass entering a control volume equals the mass leaving the controlled volume per unit of time.

$$\int \rho v \partial A = \text{constant} \tag{2.1}$$

$$\text{with} \quad \begin{aligned} \rho &= \text{density of the fluid} \\ v &= \text{velocity of the fluid} \\ \partial A &= \text{cross - sectional area} \end{aligned}$$

For an incompressible fluid this equation reduces to:

$$\int v \partial A = \text{constant} \tag{2.2}$$

If the cross-sectional area decreases, the velocity increases. The discharge is defined as velocity times cross-sectional area and for two different cross-sections of a conduit it can be stated:

$$\mathrm{Q} = v_1 \mathrm{A}_1 = v_2 \mathrm{A}_2 \tag{2.3}$$

where Q = discharge

(Massey, 1989)

2.2.2 Energy equation

If an elemental streamtube in motion along a streamline is considered, Bernoulli's theorem states that the total energy at all points along a steady streamline of an ideal, incompressible fluid flow is constant. Bernoulli's equation, also referred to as the energy equation, can be written as follows:

$$z + \frac{p}{\rho g} + \frac{v^2}{2g} = \text{constant} \tag{2.4}$$

where p = pressure

The first term is referred to as the gravity head (elevation), the second as the pressure head and the third term as the velocity head.

If this equation is modified for real fluid flows, energy losses due to frictional forces and real velocity distribution, need to be taken into account (Featherstone & Nalluri, 1988).

$$z_1 + \frac{p_1}{\rho g} + \frac{\alpha_1 v_1^2}{2g} = z_2 + \frac{p_2}{\rho g} + \frac{\alpha_2 v_2^2}{2g} + \text{Losses} \tag{2.5}$$

where z = elevation

α = kinetic energy correction factor

2.2.3 Momentum Equation

The momentum equation states that the net force on a control volume between two points equals the rate of change of moment.

$$p_1 A_1 + p_1(A_2 - A_1) - p_2 A_2 = \rho Q(v_2 - v_1) \tag{2.6}$$

where A = cross-sectional area

This equation is used for sudden expansions or sudden contractions (see Figure 2.1) where separation from the boundary is experienced. Turbulent eddies form in these regions, which lead to energy losses.

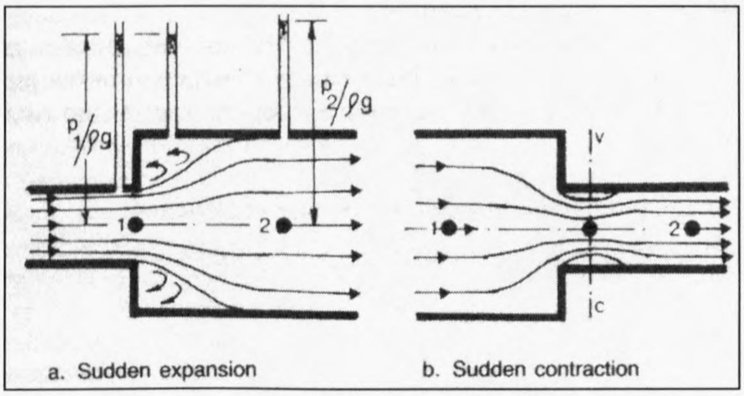

Figure 2.1: Energy losses in sudden transitions (Featherstone & Nalluri, 1988).

2.3 TYPES OF FLOW

Fluid flow may be classified as either laminar of turbulent. Although it was Hagen (1797-1884) who noticed that the type of flow in a pipe changed depending on the velocity and viscosity of the fluid, the experiments of Osborne Reynolds in the early 1880's demonstrate the two different types of flow clearly.

2.3.1 Laminar flow

In laminar flow, fluid particles flow in smooth layers with one layer gliding smoothly over the adjacent layer. The viscous shear stresses dominate in laminar flow and the velocity distribution is governed by Newton's law of viscosity (Featherstone & Nalluri, 1988).

2.3.2 Turbulent flow

In turbulent flow, the paths of the individual particles occur in three dimensions. Turbulent flow occurs most commonly in engineering practice. The individual particles follow random paths, with only a net average velocity in the direction of flow.

The Reynolds number (Re) is a dimensionless number that represents the ratio of inertial forces to the viscous forces and which identifies the type of flow. For pipe flow the Reynolds number is written as:

$$\mathrm{Re} = \frac{vD}{\upsilon} \tag{2.7}$$

For Re less than 2000 the flow is laminar and for Re more than 2000 flow is either transitional or turbulent.

2.4 ENERGY LOSSES FROM TURBULENT FLOW IN PIPES

Flow in pipes is usually turbulent and very complex. The flow conditions in the prototype and the model, studied for this report, are also turbulent. The following section discusses the different energy losses for turbulent flow in pipes under uniform full flow conditions. These losses can be categorised as friction losses and minor losses.

2.4.1 Friction losses

The different flow equations used to determine the friction losses in pipes are only applicable for uniform flow conditions. There were many experimenters who devoted their attention to friction losses in the middle nineteenth century. The formulas they produced are largely empirical.

The well-known Darcy-Weisbach formula gives the head loss due to friction as follows:

$$h_f = \frac{\lambda L v^2}{2gD} \qquad (2.8)$$

where
$\lambda = 4f$ = dimensionless coefficient
f = friction factor
L = length over which h_f occurs
g = acceleration due to gravity
D = diameter

Colebrook and White (1939) found that adding the functions for smooth and rough turbulent boundary conditions (known as the Kármán-Prandtl equations) resulted in a function, which fitted flow data on commercial pipes.

$$\frac{1}{\sqrt{\lambda}} = -2\log\left(\frac{k}{3.7D} + \frac{2.51}{\mathrm{Re}\sqrt{\lambda}}\right) \qquad (2.9)$$

where k = absolute roughness
Re = Reynolds number

Since the Colebrook-White equation does not yield λ (or f) directly, Moody (1944) plotted the relationship of λ to Re number as the Moody diagram (see Figure 2.2). Many formulae have been proposed to give λ (or f) directly for the entire range of k/D and Re. Haaland produced the following formula (Massey, 1989):

$$\frac{1}{\sqrt{f}} = -3.6\log\left(\frac{6.9}{\text{Re}} + \left(\frac{k}{D}\right)^{1.11}\right) \tag{2.10}$$

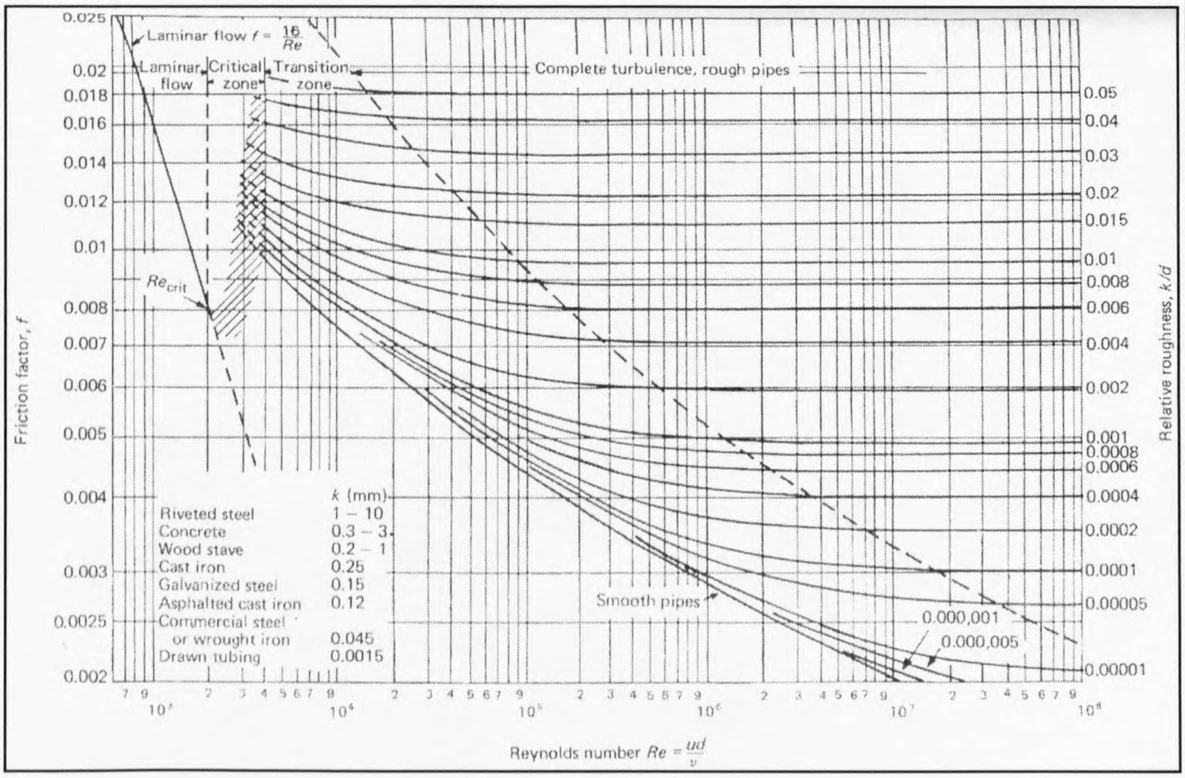

Figure 2.2: Moody diagram (Massey,1989)

Combining the Darcy-Weisbach and Colebrook-White equations produces an expression for the average velocity:

$$v = -2\sqrt{2gDS_f}\,\log\left(\frac{k}{3.7D} + \frac{2.51\upsilon}{D\sqrt{2gDS_f}}\right) \tag{2.11}$$

where S_f = hydraulic grade line

υ = dynamic viscosity

Morris (1955 and 1959) expresses *f* as a function of many variables, namely, *Re*, *Fr*, *We*, *Ma*, the radial height of the roughness, longitudinal spacing, peripheral spacing and the diameter of the pipe.

Manning and Chezy also derived equations to consider when evaluating friction losses. Although these formulas were originally derived for steady uniform open channel flow, they can also be applied for pipe flow.

Chezy deduced the Chezy equation from the results of experiments of open channel flows in 1769 (Massey, 1989).

$$v = C\sqrt{RS_0}$$

$$\text{where} \quad \begin{aligned} C &= \text{Chezy's coefficient} \\ R &= \text{hydraulic radius} \\ S_0 &= \text{bed slope} \end{aligned}$$

For pipe flow the Chezy equation can be written as:

$$v = C\sqrt{\frac{D}{4}S_f} \tag{2.12}$$

$$\text{with} \quad C = 18\log\left(\frac{12 * \frac{D}{4}}{k + \frac{3.3\upsilon}{\sqrt{g\frac{D}{4}S_f}}}\right)$$

The studies on pipes show that the friction factor, f, depends on the Re number and the relative roughness of the pipe (k/D). C depends very little on Re, while k/R influences the value of C more significantly. Although open channels vary widely in shape, experience has shown that the shape of the cross-section has little effect on the flow if the shear stress, τ_0, does not vary much round the wetted perimeter, P (Massey, 1989).

Many attempts to correlate data to predict C have been made. Robert Manning (1816-1897) derived a simple expression that is widely used. He expressed C as:

$$C = \frac{R^{\frac{1}{6}}}{n} \tag{2.13}$$

Manning's n is a dimensional value (s/m$^{(1/3)}$) with no direct physical relationship between n and the physical boundary dimensions. Manning's formula can be written as follows:

$$v = \frac{R^{\frac{2}{3}} S_0^{\frac{1}{2}}}{n} \tag{2.14}$$

where
v = average velocity
n = Manning's coefficient
R = hydraulic radius
S_0 = bed slope (= energy slope for uniform steady flow)

Darcy-Weisbach's friction factor, f and Manning's n are related by:

$$n = R^{\frac{1}{6}} \sqrt{\frac{f}{2g}} \tag{2.15}$$

The abovementioned three equations (Darcy-Weisbach, Chezy and Manning) are identical in their basic form. Manning's n has no physical meaning and is only applicable for rough turbulent flow. On the other hand, the coefficients of the Darcy-Weisbach and Chezy equations can be described in terms of the absolute roughness, k, of the pipe, as well as fluid viscosity.

2.4.2 Local losses

Apart from the friction losses in pipes, there are some transitional losses that can be identified. The losses due to junctions, bends, valves and other changes in the cross-sectional area, such as sudden contractions or expansions can be classified as local losses.

These losses are usually expressed as a multiple of the velocity head:

$$\text{Head loss} = K_l \frac{v^2}{2g} \tag{2.16}$$

where K_l = local loss coefficient

This formula was used to express local energy losses due to the steps along the inner surface. The local loss coefficient due to a step, K_s, was analysed.

2.4.3 Combined losses

In Bernoulli's energy equation the terms for the losses due to different impacts are added up to give the total head loss. The losses due to friction of the pipe wall and losses due to transitions in the cross-sectional area and losses due to protrusions (like steps) can be added up to calculate the total head loss over a pipe section.

Morris (1955 and 1959) concluded that different roughness effects could be added linearly, i.e. friction factors due to different roughness effects may be added together to produce the overall friction factor for the surface.

2.5 FLOW RESISTANCE

2.5.1 Introduction

The equations discussed in the previous paragraphs deal with uniform flow in pipes flowing full. All of these equations are empirical and aim to quantify the friction due to the roughness of the pipe wall. The head losses due to transitions or other protrusions are quantified with empirical coefficients.

In an attempt to quantify the losses with a mathematical analysis, the power theory is discussed. The power theory was derived for open channel flow (Rooseboom, 1980; Rooseboom, 1992). The following section derives the same theory for pipe flow.

2.5.2 Shear stress and velocity distribution

Flow in pipes is usually turbulent and therefore highly complex. Although flow is usually laminar in new tunnels, rough turbulent flow prevail in the older tunnels. An analysis of turbulent flow requires boundary-layer theory. The dissipation of energy by fluid friction results in a fall in piezometric head in the direction of flow. If the pipe is uniform (cross-section and roughness) and the flow is fully developed, this pressure gradient is uniform.

Consider steady flow of water between two cross-sections of a pipe. As there is no acceleration of the disc element, the forces acting on the element have to be in equilibrium. The shear forces on the perimeter of the disc element are equal to the forces due to the energy slope. Hence, consider a portion of the disc element, a pie element (see Figure 2.3).

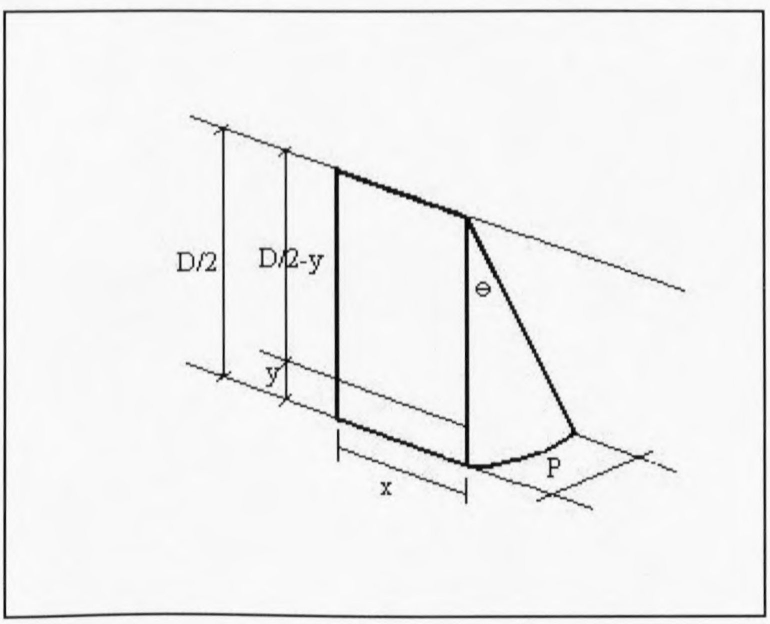

Figure 2.3: Pie element of fluid flow in a pipe

Consider a pie element under steady flow conditions. The shear force acting on the lower or outer plane of the element is as follows (refer to Figure 2.3):

$$\tau(\Delta x \times p) = \tau \times \Delta x \times \theta(\frac{D}{2} - y) \tag{2.17}$$

The opposing force due to the energy slope can be written as:

$$\rho g(volume)\sin S = \rho g \Delta x \frac{\theta}{2}\left(\frac{D}{2} - y\right)^2 \sin S \tag{2.18}$$

Assuming that the pressure difference across the pipe is small and for $\sin S \approx S$, then

$$\tau = \frac{\rho g S}{2}\left(\frac{D}{2} - y\right) \tag{2.19}$$

From this equation it can be seen that shear stress is linear with $\tau = 0$ at $y = \frac{D}{2}$ (center of the pipe) and $\tau_{\max} = \frac{\rho g S D}{4}$ at the surface of the pipe.

2.5.2.1 Laminar flow

In laminar flow the shear stress is due to the viscous action and can be described by the Newtonian equation

$$\tau = \mu \frac{dv}{dy} \tag{2.20}$$

From equation 2.19 and 2.20 the velocity at a distance y from the pipe surface is found to be:

$$v = \frac{\rho g S}{4\mu}\left(Dy - y^2\right) \tag{2.21}$$

The average velocity can be derived by integration

$$\bar{v} = \frac{\rho g S D^2}{24\mu} \tag{2.22}$$

2.5.2.2 Turbulent flow

While viscous forces dominate in laminar flow, the inertia forces dominate in turbulent flow. In turbulent flow small fluid particles move in all directions and there is a continuous interchange of momentum between the particles. The shear stresses are due to eddying motions, whereby portions of fluid temporarily move as units.

From continuity, the angular velocity of an eddy must equal the velocity gradient existing at the center of the eddy. If an eddy (with radius R) is considered, the average shear stress for the eddy element can be derived as:

$$\bar{\tau} = \frac{\rho}{2\pi} R^2 \left(\frac{dv}{dy}\right)^2 \tag{2.23}$$

From equation 2.19 and 2.23 follows:

$$\frac{\rho g S}{2}\left(\frac{D}{2} - y\right) = \frac{\rho}{2\pi} R^2 \left(\frac{dv}{dy}\right)^2$$

$$\frac{dv}{dy} = \frac{\sqrt{\pi g S\left(\frac{D}{2} - y\right)}}{R} \tag{2.24}$$

To find R as a function of y, a small element, which moves momentarily as a unit must be envisaged. The angular velocity of a small element at a distance y from the surface of the pipe is $\frac{dv}{dy}$ and the translatory velocity is $y\frac{dv}{dy}$. The translatory velocity is common to all the elements in the pipe section and equals a constant, V_0 (Rooseboom, 1980).

$$V_0 = y\frac{dv}{dy} = \frac{y\sqrt{\pi g S\left(\frac{D}{2} - y\right)}}{R}$$

If $y \rightarrow 0$ then $\frac{D}{2} - y = \frac{D}{2}$ and $y = R_0$

$$V_0 = \frac{R_0\sqrt{\pi g S\frac{D}{2}}}{R_0} = \sqrt{\pi g S\frac{D}{2}}$$

$$\frac{\rho g S}{2}\left(\frac{D}{2} - y\right) = \frac{\rho}{2\pi}R^2\left(\frac{\sqrt{\pi g S\frac{D}{2}}}{y}\right)^2$$

$$y^2\left(\frac{D}{2} - y\right) = R^2\frac{D}{2}$$

$$R = y\sqrt{\frac{D - 2y}{D}}$$

Now the velocity distribution can be written as:

$$\frac{dv}{dy} = \frac{\sqrt{\pi g S\left(\frac{D}{2} - y\right)}}{y\sqrt{\frac{D-2y}{D}}}$$

$$= \frac{\sqrt{\pi g S}\sqrt{\frac{D-2y}{2}}\sqrt{\frac{D}{D-2y}}}{y}$$

$$= \frac{\sqrt{\pi g S \frac{D}{2}}}{y}$$

By integration from y_0 to y the velocity distribution is:

$$v = \sqrt{\pi g S \frac{D}{2}} \ln \frac{y}{y_0} \tag{2.25}$$

For the average velocity:

$$\bar{v} = \frac{\int_{y_0}^{\frac{D}{2}} v dy}{\frac{D}{2} - y_0}$$

$$= \frac{\int_{y_0}^{\frac{D}{2}} \left(\sqrt{\pi g S \frac{D}{2}} \ln \frac{y}{y_0} \right) dy}{\frac{D}{2} - y_0}$$

$$= \frac{\sqrt{\pi g S \frac{D}{2}} \int_{y_0}^{\frac{D}{2}} \left(\ln \frac{y}{y_0} \right) dy}{\frac{D}{2} - y_0}$$

$$= \frac{\sqrt{\pi g S \frac{D}{2}} \int_{y_0}^{\frac{D}{2}} (\ln y - \ln y_0) dy}{\frac{D}{2} - y_0}$$

$$= \frac{\sqrt{\pi g S \frac{D}{2}} \left([y \ln y - y]_{y_0}^{\frac{D}{2}} - [y \ln y_0]_{y_0}^{\frac{D}{2}} \right)}{\frac{D}{2} - y_0}$$

$$= \frac{\sqrt{\pi g S \frac{D}{2}} \left(\left(\frac{D}{2} \ln \frac{D}{2} - \frac{D}{2} - y_0 \ln y_0 + y_0 \right) - \left(\frac{D}{2} - y_0 \right) \ln y_0 \right)}{\frac{D}{2} - y_0}$$

$$= \frac{\sqrt{\pi g S \frac{D}{2}} \left(\frac{D}{2} \ln \frac{D}{2 y_0} - \left(\frac{D}{2} - y_0 \right) \right)}{\frac{D}{2} - y_0}$$

For $\frac{D}{2} \approx \frac{D}{2} - y_0$ follows:

$$\bar{v} = \frac{\sqrt{\pi g S \frac{D}{2}\left(\frac{D}{2}\right)\left(\ln \frac{D}{2y_0} - 1\right)}}{\frac{D}{2}}$$
$$= \sqrt{\pi g S \frac{D}{2}\left(\ln \frac{D}{2y_0} - \ln e\right)}$$
$$= \sqrt{\pi g S \frac{D}{2}\left(\ln \frac{D}{2y_0 e}\right)}$$

With $y_0 = \frac{R_0}{14.8}$ follows (Rooseboom, 1980):

$$\begin{aligned} \bar{v} &= \sqrt{\pi g S \frac{D}{2}\left(\ln \frac{14.8D}{2R_0 e}\right)} \\ &= 5.77\sqrt{gS\frac{D}{4}}\log\frac{5.45D}{2R_0} \end{aligned} \tag{2.26}$$

This equation can be compared with the Chezy equation:

$$\begin{aligned} \bar{v} &= 18\sqrt{S\frac{D}{4}}\log\left(\frac{12}{k} * \frac{D}{4}\right) \\ &= 5.75\sqrt{gS\frac{D}{4}}\log\left(\frac{12}{30y_0} * \frac{D}{4}\right) \\ &= 5.75\sqrt{gS\frac{D}{4}}\log\left(\frac{12 * 14.8}{30 * R_0} * \frac{D}{4}\right) \\ &= 5.75\sqrt{gS\frac{D}{4}}\log\frac{5.92D}{4R_0} \end{aligned} \tag{2.27}$$

For the above form of the Chezy equation, the last term, $\frac{3.3\upsilon}{\sqrt{gRS}}$, is ignored, if it is assumed that the flow will be rough turbulent (Rooseboom, 1980). In this analysis of the power theory applied to pipe flow, it was assumed that shear stress distribution on the wetted perimeter was constant. The shear stress increases linearly from the center of the pipe to the pipe surface (Massey, 1989; Featherstone and Nalluri, 1988).

2.6 HYDRAULIC MODELLING

2.6.1 Introduction

Hydraulic models are often used to quantify coefficients and unknown parameters that are not accurately described in the literature. The design of tunnels entails that the losses in the system be quantified, to optimize the required tunnel diameter for conveying the water. The friction losses due to wall roughness can be estimated from the existing literature. The losses caused by the steps in the tunnel could not be quantified, since the coefficients are not clearly defined in the literature. Thus a model study was required to simulate the impact of steps as hydraulic roughness elements.

The local losses caused by the steps could then be quantified to determine head loss coefficients. In order to model this properly, model laws needed to be satisfied.

2.6.2 Model laws

If accurate data are to be obtained from a model study, there must be a dynamic similitude between the model and the prototype. This requires that there should be a geometric and kinematic similitude. For strict dynamic similitude the Mach, Reynolds, Froude, and Weber numbers for the prototype and model must be the same. This is generally impossible to achieve simultaneously, except for a full-scale model. In many model studies only two of these need to be of the same magnitude. (Streeter & Wylie, 1975)

In modelling, the prevailing forces need to be identified before deciding on the model law that needs to be satisfied.

2.6.2.1 Froude Law

The Froude number represents the ratio of the inertia force to the gravity forces (Massey, 1989). The Froude number, Fr, becomes the governing parameter in flows with a free surface since gravitational forces are predominant. Stilling basins, weirs and open channels are examples of hydraulic structures where the Froude law is predominant. (Featherstone & Nalluri, 1988).

If the length relationship is given by:

$$n_l = \frac{l_p}{l_m}$$

where the suffix 'p' denoting prototype and the suffix 'm' denoting model

Then the Froude law is:

$$\frac{Fr_p}{Fr_m} = 1$$

$$\frac{v_p}{\sqrt{g_p l_p}} = \frac{v_m}{\sqrt{g_m l_m}}$$

$$\frac{v_p}{v_m} = \sqrt{\frac{g_p l_p}{g_m l_m}}$$

$$n_v = \sqrt{n_g n_l}$$

The gravitational acceleration, g, is usually the same for the model and the prototype. The velocity relationship prevails:

$$n_v = \sqrt{n_l}$$

The relationships for the Froude law are summarized as follows:

Length: $n_l = \frac{l_p}{l_m}$

Area: $n_A = n_l^2$

Velocities: $n_v = \sqrt{n_l}$

Time: $n_t = \sqrt{n_l}$

Discharge: $n_Q = n_v n_A = n_l^{5/2}$

2.6.2.2 Reynolds Law

The Reynolds number, Re, represents the ratio of inertia forces to viscous force (Massey, 1989). Reynolds modelling is adopted for studies of flows without a free surface, such as pipe flow (Featherstone & Nalluri, 1988). In steady pipe flow, viscous and inertial forces are the only ones of consequence; hence the same Reynolds number for prototype and model provides dynamic similitude (Streeter & Wylie, 1975).

$$\frac{\mathrm{Re}_p}{\mathrm{Re}_m} = 1$$

$$\frac{v_p l_p}{\upsilon_p} = \frac{v_m l_m}{\upsilon_m}$$

$$n_v = \frac{v_p}{v_m} = \frac{l_m \upsilon_p}{l_p \upsilon_m}$$

Should the same fluid be used in the model as for the prototype, i.e. $\upsilon_m = \upsilon_p$, the equation reduces to:

$$n_v = \frac{1}{n_l}$$

The relationships for the Reynolds law is summarized as follows:

Length: $n_l = \dfrac{l_p}{l_m}$

Area: $n_A = n_l^2$

Velocity: $n_v = \dfrac{1}{n_l}$

Time: $n_t = n_l^2$

Discharge: $n_Q = n_l$

2.6.2.3 Other laws

Some of the other model laws relate to parameters like the Weber number and the Cauchy number. The Weber number represents the ratio of inertia forces to surface tension forces. This applies when the flow depth becomes small. The Cauchy number represents the ratio of inertia forces to compression forces. This applies if pressure surges in the model are of consequence. For this model study neither of these are applicable and therefore these are not discussed in further detail.

CHAPTER THREE

MODEL CONFIGURATION

3.1 PROTOTYPE VERSUS MODEL

3.1.1 Prototype

The steps that were modelled in this study occurred in a tunnel with a diameter of 3.5 m. The length of the ring segments, i.e. the minimum distance between steps, is 1.4 m. The construction of the tunnel comprised that pre-cast sections and a keystone section be placed to shape the perimeter of the lining of the tunnel (see Figure 3.1). While the tunnel boring took place, these pre-cast sections were placed.

Figure 3.1: Lining of the tunnel (pre-cast sections and keystone section)

Due to the construction method and a permissible margin of error, the consecutive ring segments do not align properly. Consequently, roughness elements, commonly known as steps, are created between the consecutive segments.

Figure 3.2 shows a typical step in the tunnel lining. The typical offset in the field is smaller than 10 mm (Pitt and Ackers, 1982). For the tunnels built in Lesotho, some step sizes measured approximately 50 mm. Although flow velocities in tunnels rarely exceed 3 m/s (Pitt and Ackers, 1982), it was envisaged that the flow velocity in this tunnel varies from 1 m/s to 5 m/s.

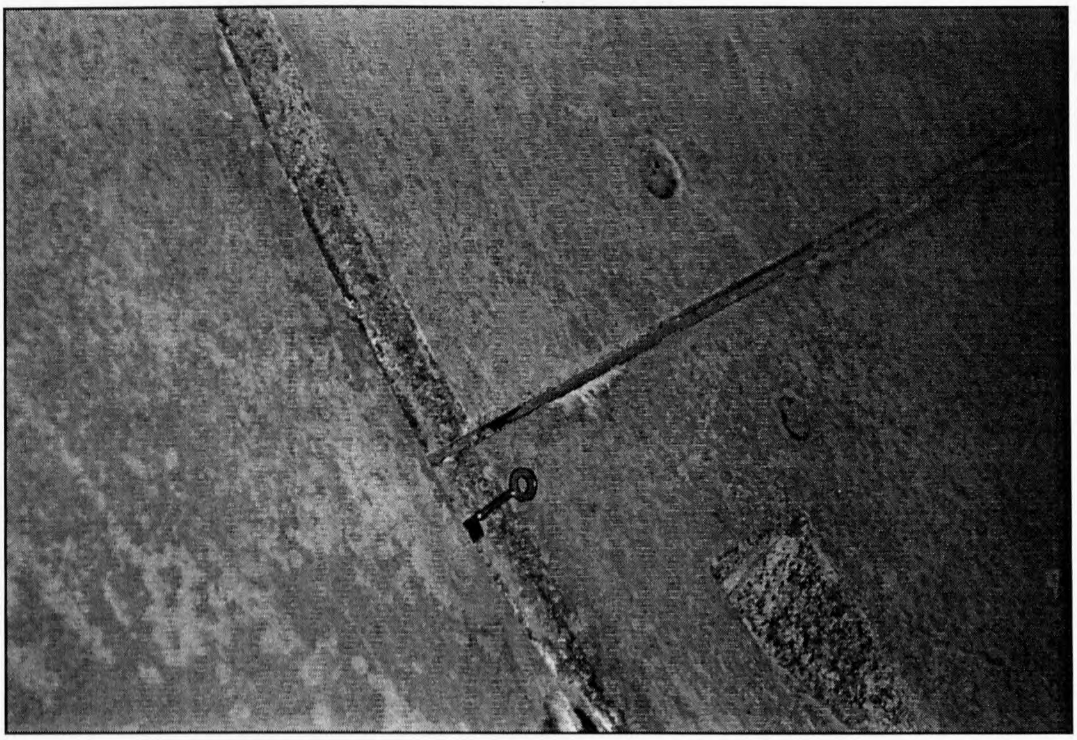

Figure 3.2: Typical step in the lining of the tunnel

3.1.2 Model parameters

The hydraulic model in this study was used to evaluate the contribution of the steps, with respect to step size and the frequency of steps, as a hydraulic roughness element. There are certain limitations to the scaling of hydraulic models. The physical dimensions of the model and the available space, as well as the maximum discharge capacity of the laboratory should be considered. These factors limit the model size on the upper side, while dynamic similitude usually limits the model on the lower side. Should the model become too small, viscous effects might result in incorrect results. It is good practice to ensure that the Reynolds number in the model is large enough to simulate the friction factors of the prototype.

The scale of the model was fixed on 1:19.337. In deciding on the model scale, various aspects needed to be considered:

- availability of PVC pipe (size and class)
- minimum wall thickness of model segments to ensure that rings do not deform when assembling the model (approximately 10 mm)
- costs of the model set-up
- available space in the Hydraulics Laboratory of the University of Stellenbosch.
- pump capacity in the laboratory
- measurements to be taken during model tests
- demolishing and reassembling the model to test different configurations
- maximum anticipated pressure gradient over the length of the model

Since gravitational flow prevails in the model, the model was built according to the Froude law (see section 2.6.2.1). Assuming geometrical similitude, the following relationships were obtained:

Length (horizontal and vertical direction): $n_l (= n_x = n_y) = \dfrac{l_p}{l_m} = 19.337$

Velocity: $n_v = \dfrac{v_p}{v_m} = \sqrt{n_l} = 4.379$

Discharge: $n_Q = n_l^{5/2} = 1644.3$

Reynolds number: $n_{\mathrm{Re}} = \dfrac{\mathrm{Re}_p}{\mathrm{Re}_m} = 85.0$

where the suffix 'p' refers to the prototype and the suffix 'm' refers to the model

The Reynolds numbers for the prototype is in the rough turbulent zone, while the Reynolds numbers for the model is smaller (see Table 3.1) and in the transitional zone.

The prototype and corresponding model parameters are summarised in Table 3.1.

Table 3.1: Prototype and model parameters

PARAMETER	PROTOTYPE	MODEL
Internal diameter	3500 mm	181 mm
Length of segment	1400 mm	72.5 mm
Step size	19.3 mm	1 mm
Step size	58 mm	3 mm
Velocity range	1 m/s to 5 m/s	0.227 m/s to 1.137 m/s
Discharge range	9.6 m^3/s to 48.1 m^3/s	5.8 l/s to 29.3 l/s
Reynolds number	3 500 000 to 17 500 000	41 000 to 206 000

Metal strips were used as spacers with the segments of the model to create the steps. These strips were exactly 1 mm and 3 mm thick. Therefore, the different steps sizes for the model were selected as 1 mm and 3 mm.

3.2 LABORATORY LAYOUT

All the tests were conducted in the hydraulics laboratory of the Department of Civil Engineering at the University of Stellenbosch. While conducting model tests, water is often pumped directly from a basin to the model. Due to a varying water level in such a basin, the discharge to the model would not be constant. Thus, it is essential to use constant height supply basins to insure a constant discharge for a specific model test. This laboratory is equipped with constant height basins. One of these basins is shown in figure 3.3.

Figure 3.3: Constant height basins

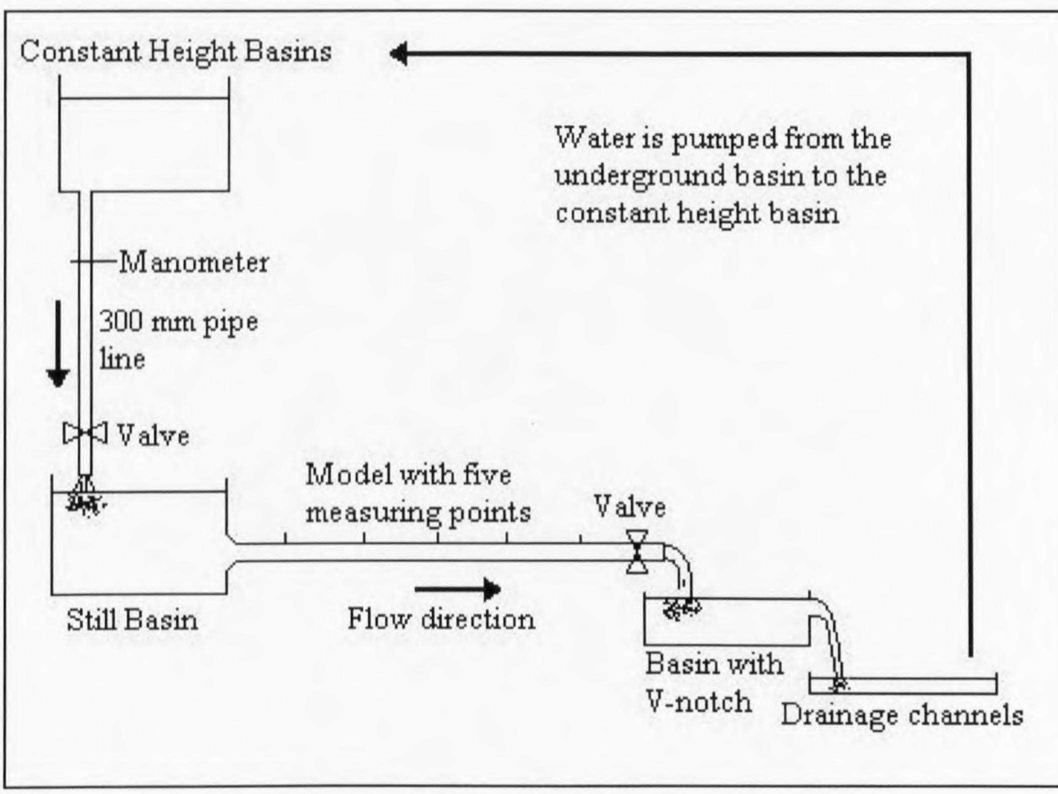

Figure 3.4: Schematic layout of the laboratory

The paragraphs below explain the layout of the laboratory around the model and Figure 3.4 shows a schematic layout.

A pipeline with a diameter of 300 millimetres conveys the water from the constant height basins to the model. In this pipeline, discharge is measured by means of a manometer and controlled by a valve at the end of the line. The pipeline leads into a stilling basin upstream of the model. This basin, shown in Figure 3.5, is approximately 1.01 m deep, has a length of 3.8 m and a width of 1.9 m. It was used to simulate different pressure heights in the model. From this basin, the flow is conveyed to the model.

Figure 3.5: Stilling basin upstream of the model

Figures 3.6 shows a photograph of the model from downstream. The PVC pipe that forms the model is supported by a framework made of angle iron and wood. This structure can be seen between the valve in the foreground and the stilling basin in the background.

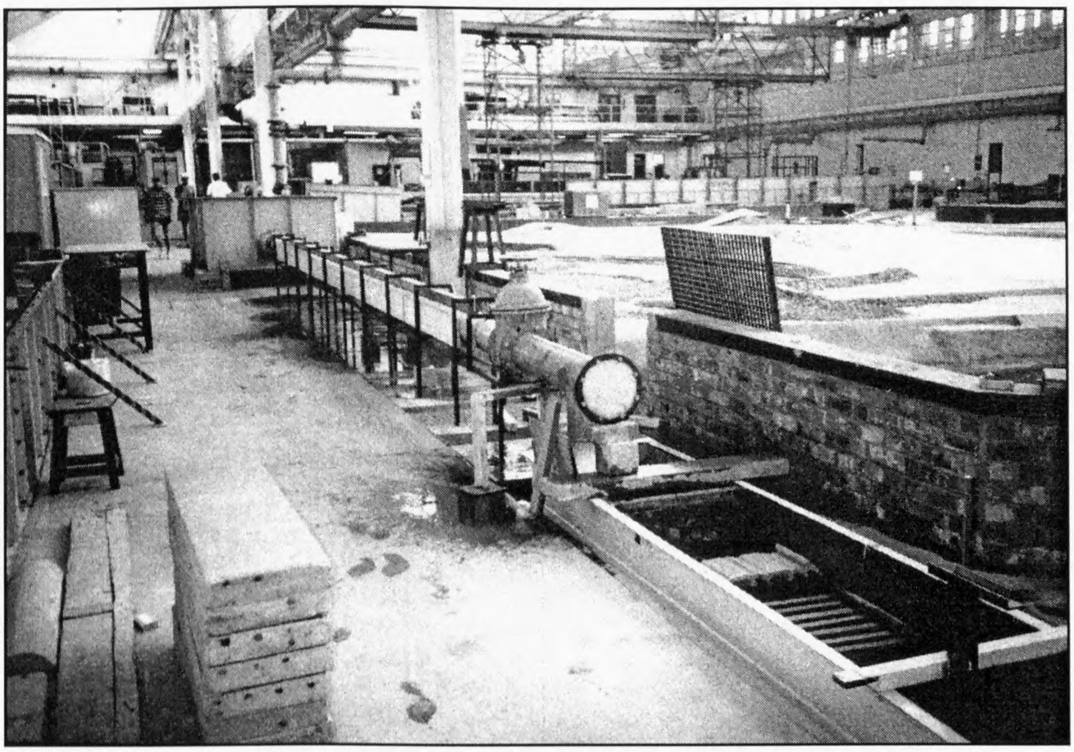

Figure 3.6: Photograph of the model from downstream

A valve at the end of the model ensured that positive pressure conditions could be simulated. The water discharges into a third basin on the downstream side of the model. The outlet of this basin is a V-notch. Hereby the discharge could be measured again and compared to the discharge measured by the manometer in the upstream pipeline.

The water returns to an underground basin via drainage channels from where it is pumped back to the constant height basin. In this manner, the water can be circulated through the model at a constant rate.

3.3 MODEL LAYOUT

The model consists of a PVC pipe cut into segments of equal size and glued together. A framework made of angle iron and wood supports the model. At the bottom and top, wooden beams were used to hold the segments in position. The sides of the segments were supported by plywood. These beams and the plywood were bolted to the angle iron framework.

The model was constructed in the following manner. Starting from the upstream side the different segments were glued together one by one with a silicon sealant. While gluing the segments together, any excess silicon was removed to ensure a clean step perpendicular to the flow direction.

Depending on the model set-up, which needed to be tested, metal strips were put underneath or on top of the segments to create the steps within the model. These metal strips were the exact thickness of the required step size (1 mm or 3 mm). For ease of construction, the steps were displaced vertically. Assuming that the shear stresses are uniformly distributed on the inside perimeter of the pipe, lateral displacement of the segments would not amend the test results.

The construction of the model was divided into four sections, a section being the distance between two measuring points. After a section of segments was glued together and supported at the bottom and the sides, the top beam was bolted into place, to support the segments from all sides. Support in the longitudinal direction was provided by a mechanism at the downstream valve. After completing the length of the model and bolting the downstream valve into place, a force in the upstream direction was applied. The downstream valve was connected to the model as well as the framework. By means of bolts and clamps, the valve was squeezed in the upstream direction, thus applying a force in the longitudinal direction and holding the segments in position. This also minimised leakages from the model.

3.4 PROBLEMS EXPERIENCED IN FIRST SETUPS

Initially a smooth PVC pipe was tested. These tests were carried out to establish if the testing and measuring of the hydraulic gradient were correct. However, certain problems occurred due to the position of the model in the laboratory.

3.4.1 Set-up without a stilling basin

At first the model was connected directly to the 300 mm pipe which connects to the constant height basin. The valve upstream of the model created a low-pressure zone upstream of the model. This led to pressure surges in the model and a lot of air bubbles within the model. Due the surges, the levels at the points where the hydraulic gradients were to be measured did not stabilize rapidly and the presence of the air bubbles made measuring even more difficult.

Closing of the valve downstream of the model, created more problems. The valve needed to be closed to create additional pressure in the model, but closing it altered the flow measured by the manometer. Thus, a test to simulate a specific flow rate could not be conducted since opening or closing any of the two valves isolating the model affected the flow rate.

One could argue that the upstream valve could be ignored and the downstream valve could be used to control the flow through the model. Hereby the pressure of the constant height basins would be imposed on the model. Due to the physical layout of the laboratory, this was impractical. The constant height basins are more or less six metres above the floor of the laboratory and the model would not have been able to handle such a high pressure after having been cut into segments and reassembled.

3.4.2 Set-up with opening of supply pipe below the water level

The initial set-up was changed to a set-up with a stilling basin upstream of the model, to prevent surges within the model. The outlet of the supply pipe was placed below the water level to make the stilling basin more efficient. However, when the level in the stilling basin was increased, by closing the downstream valve, the flow through the supply pipe was slightly altered. This increase in water level and the corresponding decrease in flow rate made it virtually impossible to conduct a specific test.

This problem was overcame by releasing the water to atmospheric pressure, above the water level in the stilling basin. Eventually the layout as shown in Figure 3.4 was used. A floating raft in the stilling basin calmed the surface and flow directors at the inlet to the model ensured steady, uniform flow in the model.

CHAPTER FOUR

LABORATORY TESTS

4.1 THEORY FOR MODELLING OF THE LOSSES

With steady flow in a uniform pipe the shear stress, τ_0, is constant over the length of the pipe. This resistance results in a constant head loss per unit length. This constant loss per unit length is referred to as the energy grade line (see Figure 4.1).

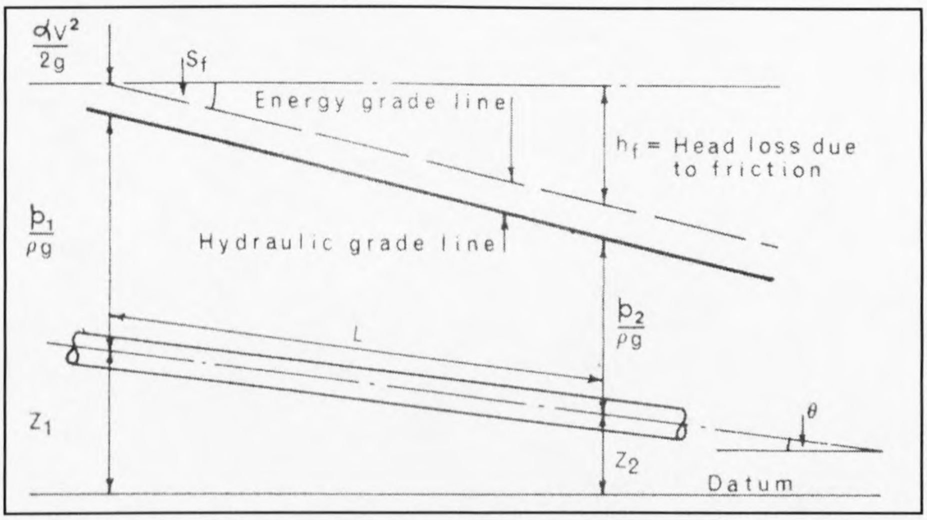

Figure 4.1: Pressure head and energy gradients in full, uniform flow (Featherstone & Nalluri, 1988)

For a uniform pipe, the average velocity over the length of the pipe is assumed to be the same. Thus, the velocity head over the length of the pipe remains constant. The hydraulic grade line (pressure slope) and the energy slope are therefore, parallel. From Figure 4.1 it can be seem that by measuring the piezometric pressure difference between two points the hydraulic grade line and head loss due to friction between these points can be defined.

To evaluate the losses due to the steps in the model, the basic roughness of the model without steps needed to be measured. The friction coefficient can be calculated with the Darcy-Weisbach equation and a relative roughness for the model can be calculated in terms of the Moody diagram.

According to Morris (1955 and 1959), the combined head loss due to the different roughness elements may be added together to produce the overall friction factor. In terms of the model study this implies that the head loss due to the steps can be calculated by subtraction of all the losses due to other elements than the steps.

For a specific model test the discharge through the model, and therefore the average velocity in the model is measured. The average energy slope is measured, by measuring pressure head along the length of the model. From the energy slope the total head loss for a specific test can be calculated. This in turn can that be divided into head loss due to friction and the remainder gives the head loss due to the steps. The total head loss, h_T, is equal to the head loss due to pipe friction, $h_{(\text{pipe friction})}$, plus the head loss due to the steps, $h_{(\text{steps})}$ (see equation 4.1). Thus, by subtracting the head loss calculated for the model without steps from the total head loss for any configuration with steps, the head loss due to the steps can be calculated.

$$h_T = h_{(\text{pipe friction})} + h_{\text{steps}} \tag{4.1}$$

4.2 MODEL TESTS PERFORMED

To check whether the model reproduced the friction factor correctly, the smooth PVC pipe (not yet cut into segments) was tested first. Different model configurations with different numbers of steps per metre were tested thereafter. These step configurations (set-ups) are shown in Figure 4.2.

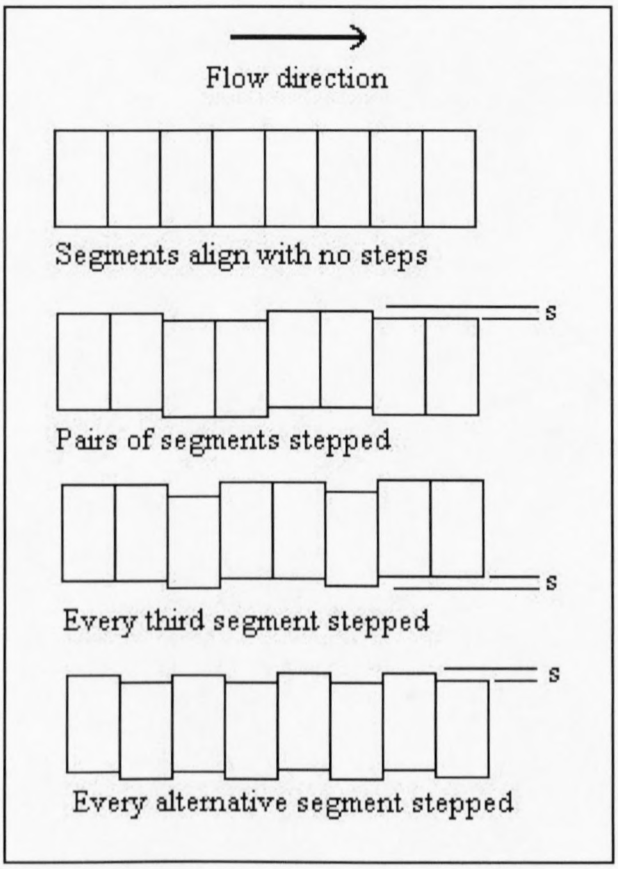

Figure 4.2: Step configurations

Eight different set-ups of the model were tested. The model set-ups are tabulated below:

Table 4.1: Model set-ups tested

TEST NAME (Appendix A)	STEP SIZE (mm)	CONFIGURATION (Steps/m)	DESCIPTION
A1 to A5	Smooth pipe		No segments
B1 to B5	0	0	Segments aligned with no steps
F1 to F5	1	6.9	Pairs of segments stepped
G1 to G5	1	9.3	Every third segment stepped
H1 to H5	1	13.8	Every alternative segment stepped
C1 to C5	3	6.9	Pairs of segments stepped
D1 to D5	3	9.3	Every third segment stepped
E1 to E5	3	13.8	Every alternative segment stepped

For each of the abovementioned set-ups the model was tested for five different flow velocities to represent an extensive range of Re numbers. These velocities and the associated discharges through the model are summarised in Table 4.2. Since the discharge through the model could not be controlled precisely with the gate valve, the exact discharge through the model was measured for each test.

Table 4.2: Different velocities tested

PROTOTYPE VELOCITY (m/s)	MODEL VELOCITY (m/s)	MODEL DISCHARGE (l/s)
1	0.227	5.85
2	0.455	11.71
3	0.682	17.56
4	0.910	23.41
5	1.137	29.27

4.3 FLOW MEASUREMENT

4.3.1 Manometer

In the pipeline that supplies water to the model, a manometer (Figure 4.3) is used to measure discharge. A pressure differential is created along the flow path by a sudden constriction in the pipeline. This constriction is an orifice plate with a diameter of 213 millimetres. A water manometer measures the pressure difference, between the upstream and downstream sides of the orifice.

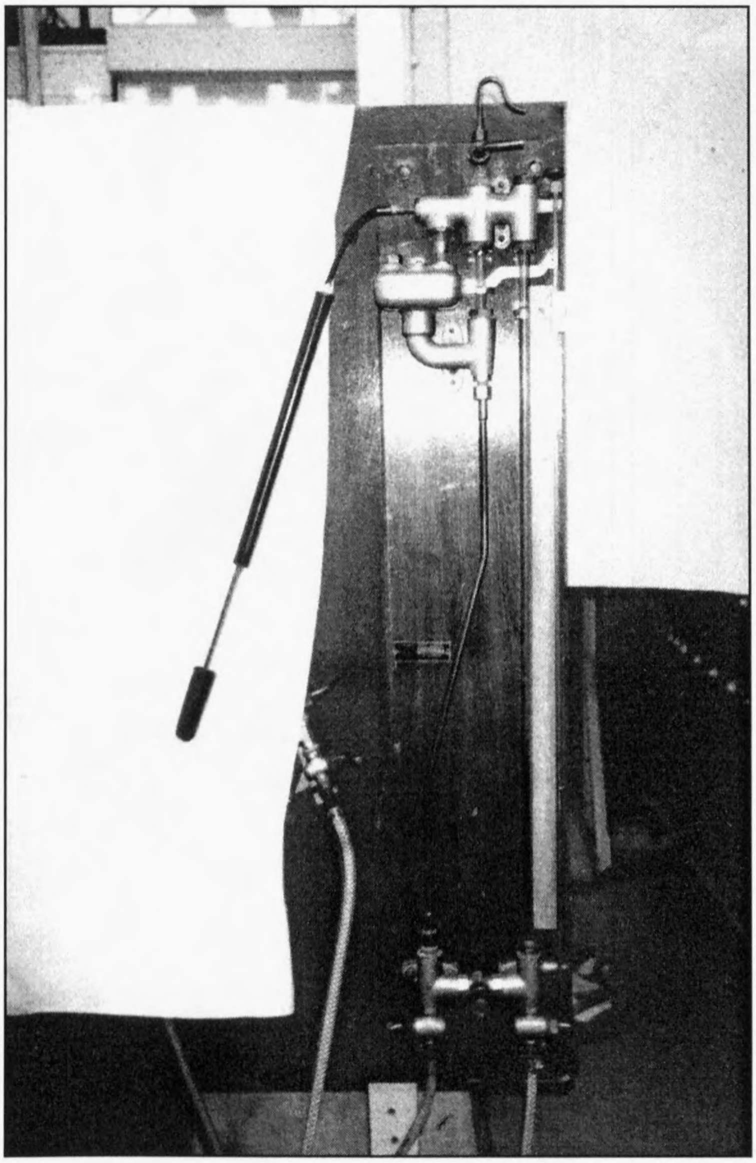

Figure 4.3: Photograph of the water manometer

Using equation 4.2 the discharge through the orifice can be determined.

$$Q = \frac{C_d \sqrt{2g}\, \frac{\pi}{4} D_c^2}{\left(1 - \left(\frac{D_c}{D}\right)^4\right)^{\frac{1}{2}}} h_w^{\frac{1}{2}} \tag{4.2}$$

D = diameter of the pipeline
= 300 mm

D_c = diameter of the orifice
= 213 mm

C_d = contraction coefficient
= 0.6

h_w = difference in pressure heights in metre water

According to The British Standard Code C_d can be between 0.60 and 0.63. A value of 0.60 was found applicable. Figure 4.4 shows the relationship between the discharge through the orifice versus the water head.

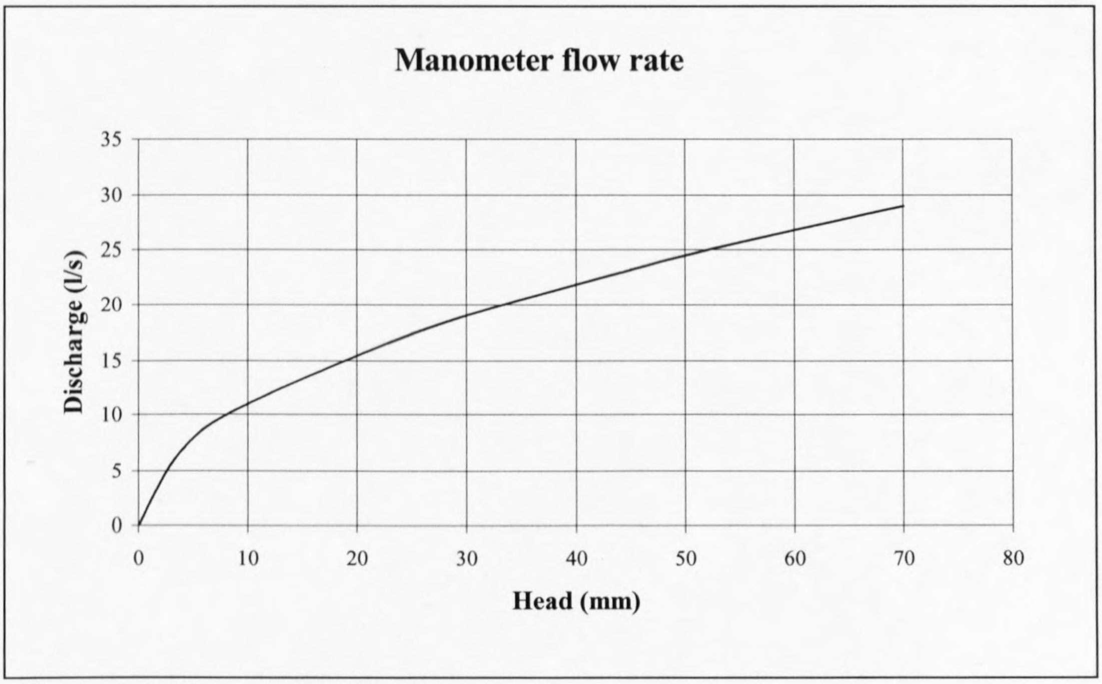

Figure 4.4: Manometer calibration

4.3.2 V-notch

A V-notch (Figure 4.5) was used to determine the discharge at the downstream side of the model. By measuring the height of the water level above the lower end of the notch the discharge through the notch can be determined. Equation 4.3 shows the relationship between the height of the water level and the discharge.

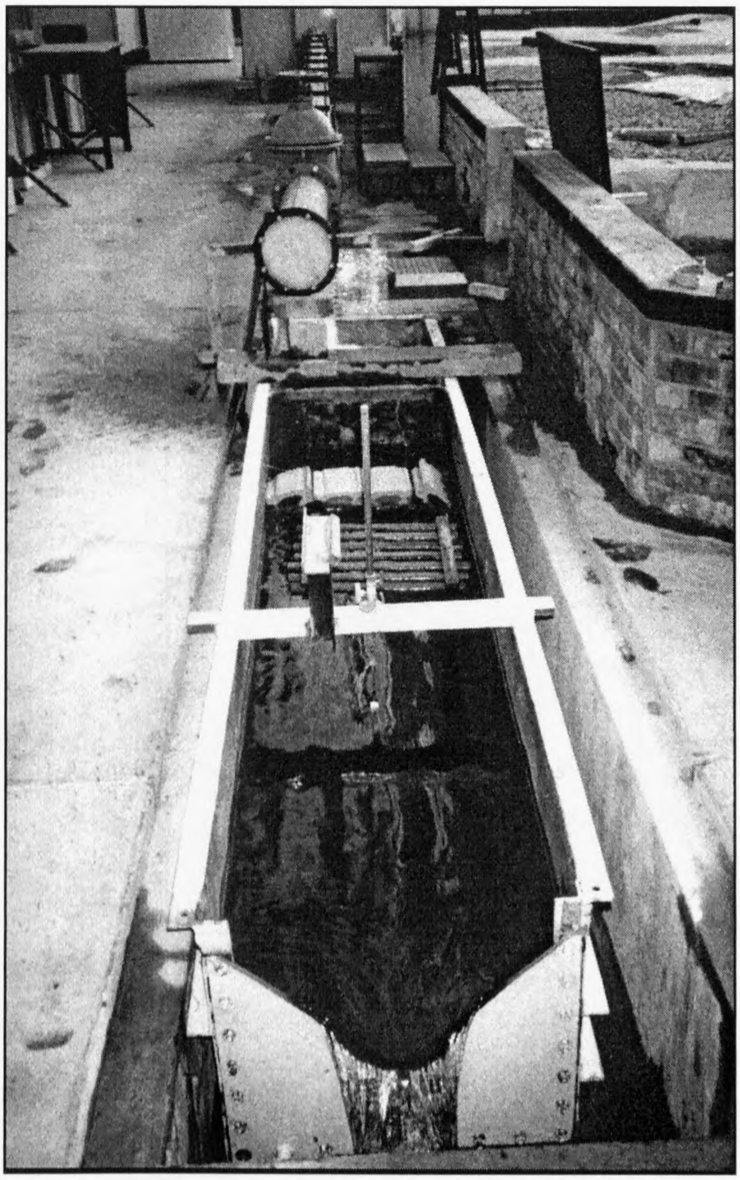

Figure 4.5: V-notch weir (foreground)

$$Q = \frac{8}{15} C_d \sqrt{2g} \tan\frac{\theta}{2} h_v^{2.5} \tag{4.3}$$

θ = angle of the V-notch

= 90°

C_d = contraction coefficient

= 0.585

h_v = water height above lower end of the notch

According to The British Standards C_d equals 0.585 for water heights of ± 0.16 m. Considering that heights between 0.110 and 0.220 metres were used in this study, this value was found appropriate. Figure 4.6 shows the discharge over the V-notch versus the water height.

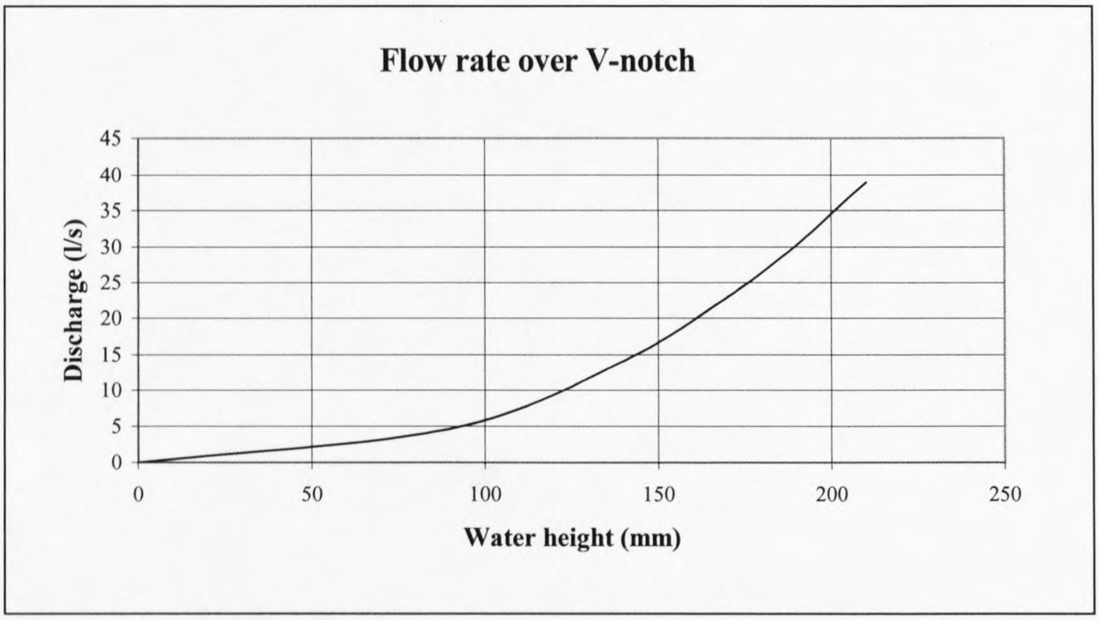

Figure 4.6: V-notch calibration

4.4 PIEZOMETRIC PRESSURE MEASUREMENT

For each model test the piezometric pressure heights were measured at five different points along the length of the model. At each point a 6 mm hole was drilled through the top of the PVC pipe segment. A PVC connection piece was welded onto the pipe segment above the hole. A transparent tube (6 mm diameter) connected each of the holes to a transparent cup. The water levels (piezometric pressure heights) in these cups were measured to an accuracy of 0.2 mm (see Figure 4.7). At each of these points, five different height recordings were taken to ensure that the pressure heads had stabilised. The results were recorded on a test sheet.

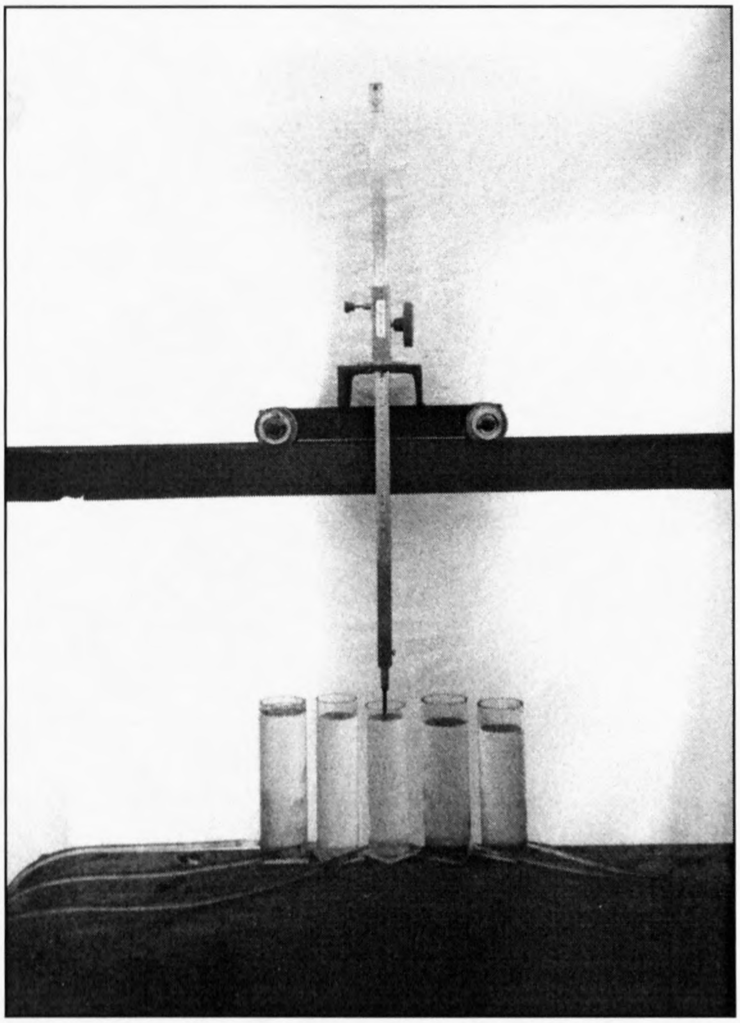

Figure 4.7: Transparent cylinders to measure piezometric pressure heights

The pressure heads represented the pressure slope. To ensure that entry losses and exit losses were not included, the first and last measuring points were positioned approximately one metre (± five times the pipe diameter) away from the model's upstream and downstream ends, respectively. A converging distance piece, equipped with flow directors, ensured sufficient boundary layer formation in the upstream section of the pipe. Thus, the pressure heights measured at the first measuring point align with the gradient lines (see Appendix A).

Appendix A contains the test results, showing the monometer and V-notch flow measurements and the piezometric pressure measurements for the different tests.

CHAPTER FIVE

MODEL TEST RESULTS AND APPLICATION

5.1 HYDRAULIC GRADE LINE

The measurements for a specific model test were recorded on a test sheet (see Appendix A). The average piezometric heights were plotted over the distance of the model for a specific test. This provided a linear relationship, the hydraulic grade line. The value of this pressure slope (see graphs on test sheets in Appendix A) for the individual tests was determined by linear regression. The results of all the tests are summarised in Appendix B.

5.2 FRICTION FACTOR

The friction factor for the model configuration without any steps and the model configuration with 0 mm steps were analysed with the Darcy-Weisbach equation (equation 2.8). An absolute roughness value for the two set-ups was calculated with the Colebrook-White equation and the equation produced by Haaland (equation 2.10). From these calculated values, relative roughness value for the set-up with no steps can be estimated as k/D=0.0005, and for the set-up with 0 mm steps, the absolute roughness value can be estimated as k/D=0.00075 (see Figure 5.1). The grooves between the segments, and the silicon sealant used to seal them, added approximately 50% to the absolute roughness of the model.

Based on the Moody diagram, the friction factors versus the Reynolds numbers for the tests are shown in Figure 5.1. The Reynolds numbers indicate that the flow conditions were not rough turbulent, but in the transition zone. The relative roughness lines for the Moody diagram were added to evaluate the trend of the friction factors. The tests for the different set-ups follow the same trend as the relative roughness values, k/D, on the right-hand side of the graph (rough turbulent zone). Thus, for higher Reynolds numbers, each set-up will correspond to a constant friction factor. Too low Reynolds numbers in the transition zone, resulted in the tests on the left-hand side not to follow the trend of the absolute roughness lines.

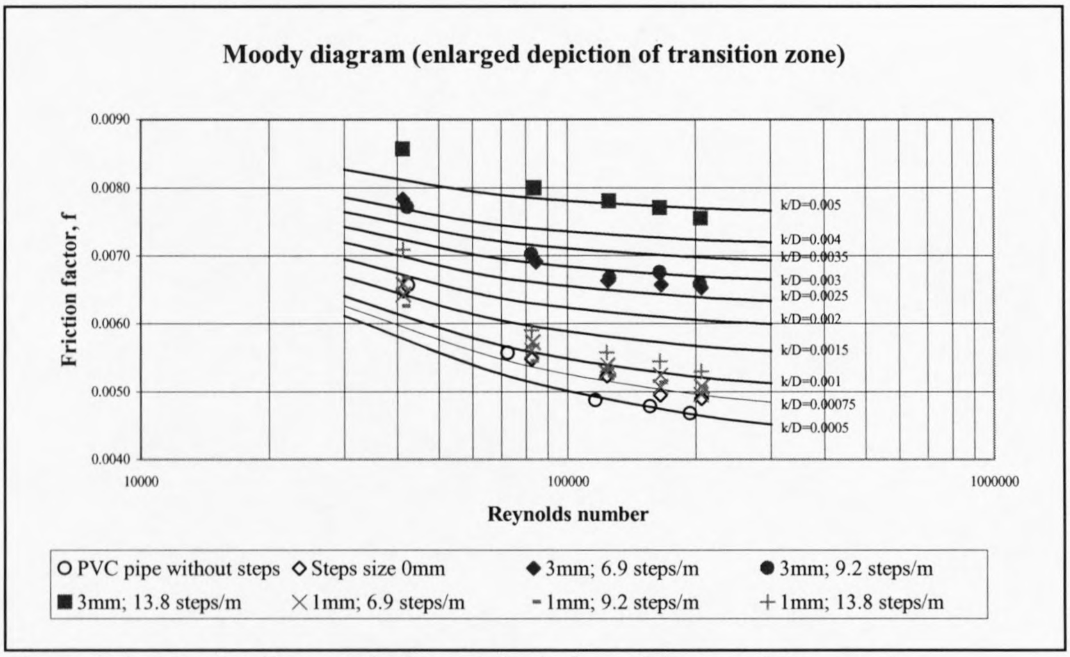

Figure 5.1: Moody diagram (enlarged depiction of the transition zone)

Pitt and Ackers studied the hydraulic roughness of fifteen segmentally lined tunnels in the UK. The following correlation was found between the measured geometry for the segment alignment and the roughness deduced from the hydraulic tests done in the tunnels (Pitt and Ackers, 1982):

$$k_s = 0.3 + 60\left(\left|\bar{s}\right|\right)^2 / l \tag{5.1}$$

with k_s = absolute roughness (mm)

l = segment length (mm)

$\left|\bar{s}\right|$ = absolute average step size (mm)

Figure 5.2 shows Equation 5.1 and the model data. The roughness, calculated with the Colebrook-White equation, for the different model configurations was plotted.

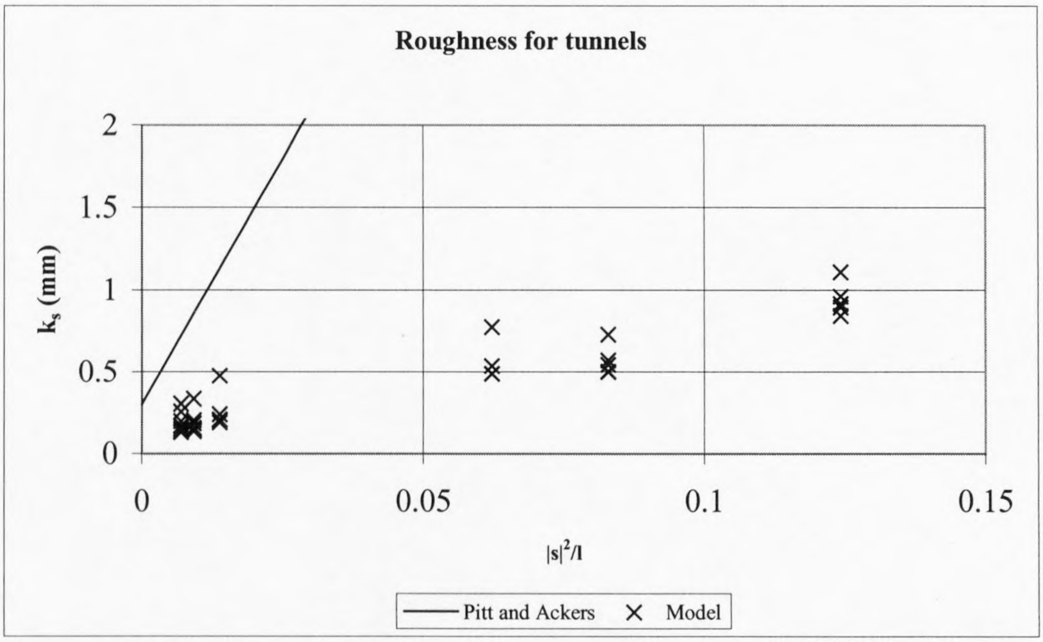

Figure 5.2: Roughness for tunnels (Pitt and Ackers, 1982)

The roughness of the model is less than predicted by equation 5.1 and the data tend towards a linear relationship.

5.3 K_s-VALUES FOR STEPS AS LOCAL LOSSES

The head losses due to the steps were analysed in terms of a local loss coefficient per step, K_s. Referring to equation 4.1, the K_s-values were calculated as follows:

$$S_{f(total)} = S_{f(pipe)} + n * (\text{head loss per step})$$
$$S_{f(total)} = S_{f(pipe)} + nK_s \frac{v^2}{2g} \tag{5.2}$$

with n = number of steps per metre

The friction slope due to the surface roughness, $S_{f(pipe)}$, was calculated by assuming the relative roughness, k/D = 0.00075 (see previous paragraph). The alternative steps in the longitudinal direction were evaluated as individual elements contributing to the head loss.

The resulting K_s-values are shown in Figure 5.3.

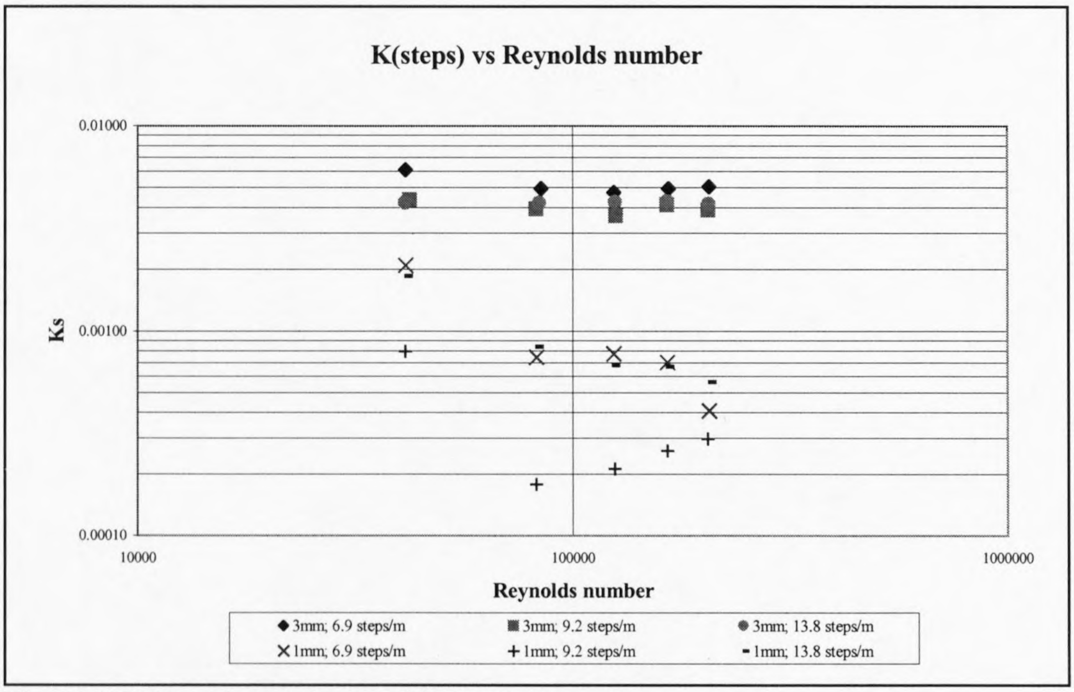

Figure 5.3: K_s-values vs Reynolds number

The K_s-values in Figure 5.3 tend to follow the same pattern between friction factor, Re and k/D found by Nikuradse (Figure 5.4) in the transition zone. The K_s-values firstly decrease and then increase with an increase in Reynolds number for the 3 mm set-ups. The 1 mm set-ups however do not show this trend.

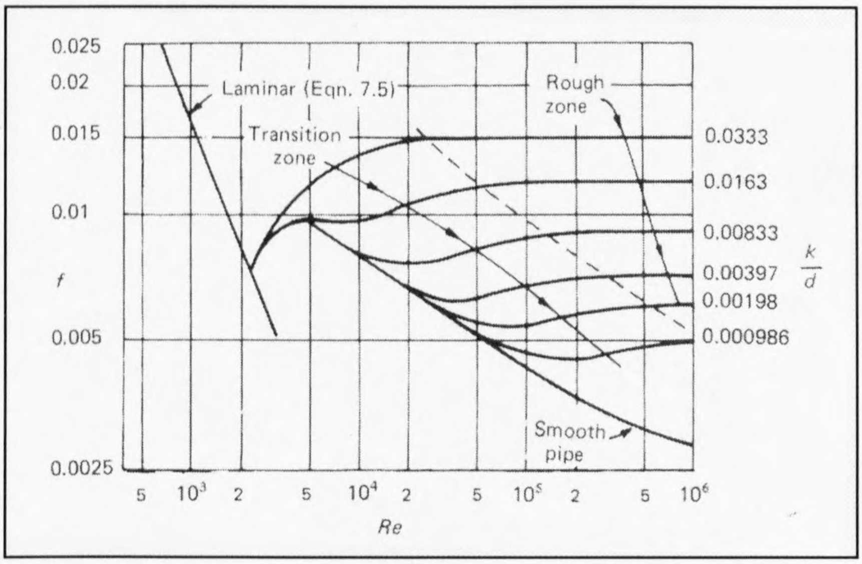

Figure 5.4: Nikuradse's sand roughened pipes (Massey, 1989).

To express the K_s-values as a function of the step sizes, at least three data points are required. A constant value of K_s is expected in the turbulent zone, whereas the tests were performed for Re numbers in the transition zone. The Re numbers for the prototype are in the turbulent zone and most probably constant K_s-values will be valid for each step size.

The K_s-value for the 3 mm steps is approximately constant at a value of 0.0044 (see Figure 5.3). For the 1 mm steps, a value of 0.0007 can be used. These values were selected conservatively after calculating the average K_s-values from the data sets and considering Figure 5.3. Assuming that the value of K_s is zero for a step size of zero millimetres, the following data points were used:

Table 5.1: K_s-values for various step sizes

STEP SIZE (mm)	s/D	K_s	NOTE
0	0	0.0	
1	0.00552	0.0007	See Figure 5.2
3	0.01657	0.0044	See Figure 5.2

With the data in table 5.1 the following relationship was derived:

$$K_s = 12.558\left(\frac{s}{D}\right)^2 + 0.057\left(\frac{s}{D}\right) \tag{5.3}$$

with s = step size
D = diameter

Equation 5.3 is an empirical formula for this model study and it needs to be tested for a wider range of step sizes and bigger Re numbers.

Losses introduced by sudden contractions or sudden expansions are also based on the velocity head. The loss coefficient for both a sudden expansion and sudden contraction is given in terms of the diameters (White, 1986):

$$K_{SE} = \left(1 - \frac{d^2}{D^2}\right)^2 \tag{5.4}$$

$$K_{SC} \approx 0.42\left(1 - \frac{d^2}{D^2}\right) \tag{5.5}$$

where K_{SE} = loss coefficient for sudden expansion

K_{SC} = loss coefficient for sudden contraction

D = diameter

d = smaller diameter

Consider a step as a combination of a sudden contraction and a sudden expansion. By taking the smaller diameter as the model diameter minus the step size, the following can be calculated:

Table 5.2: Loss coefficient for sudden expansions and contractions

STEP SIZE	*d/D*	K_{SE}	K_{SC}	*K(weighted)*	K_s
1 mm	0.994	0.0001	0.0046	0.0024	0.0007
3 mm	0.983	0.0011	0.0138	0.0074	0.0044

The loss coefficients calculated in Table 5.2 for the different step sizes, do not compare with the loss coefficient for steps as obtained from the model study. The steps are very small, resulting in high values for $\frac{d}{D}$ and the steps are neither sudden expansions, nor sudden contractions.

5.4 CHEZY'S COEFFICIENT FOR STEPS

The Chezy coefficient depends little on Re, while the influence of k/D on the value is more significant. With the velocity and total friction slope known for the each test, the Chezy coefficient, C, was calculated for each test with the Chezy formula. Using equation 2.12, the absolute roughness, k, was calculated. Figure 5.5 shows the absolute roughness values which were calculated versus Re for the different tests.

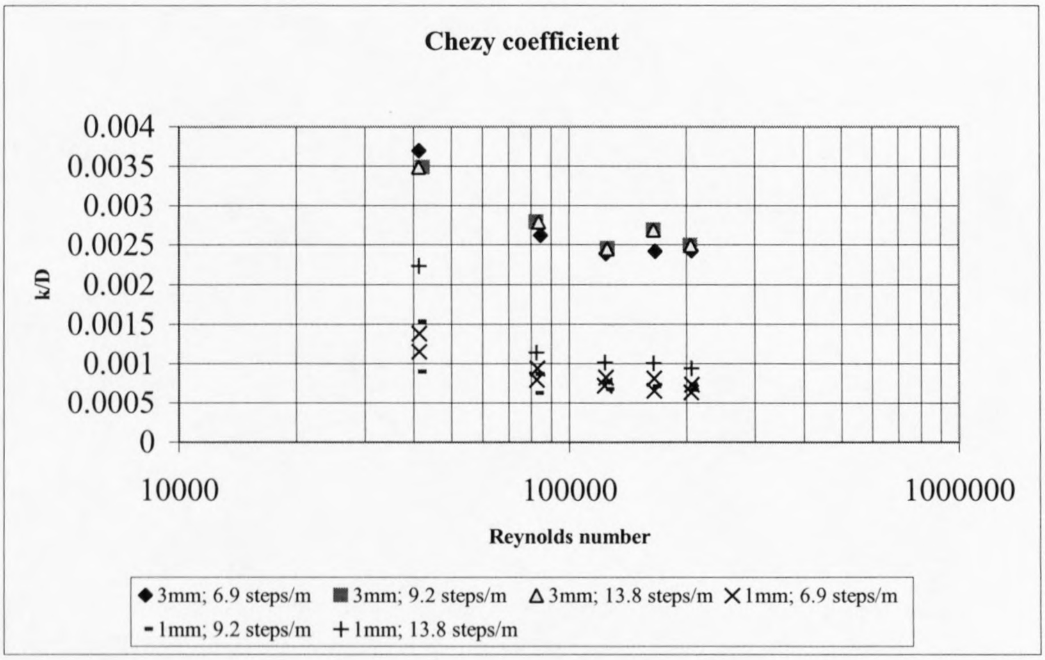

Figure 5.5: k/D vs Reynolds number

From Figure 5.5 and considering average k/D-values calculated with the test data, constant k/D values were assumed for the different step sizes (see Table 5.3). Ignoring the tests done at the lower Reynolds number, k/D was assumed constant with an increase in Reynolds number. The longitudinal spacing of the steps was not important.

Table 5.3: k/D-values for various step sizes

STEP SIZE (mm)	s/D	k/D	NOTE
0	0	0.00062	Average value for 0 mm configuration
1	0.00552	0.00090	See Figure 5.4
3	0.01657	0.00250	See Figure 5.4

From these data points (Table 5.3) the following exponential relationship was derived:

$$\frac{k}{D} = 0.0006e^{85\frac{s}{D}} \tag{5.6}$$

with s = step size
D = diameter

If the step size is known, the value of k can be calculated by using equation 5.6. Then the Chezy equation (equation 2.12) gives the relationship between the hydraulic grade line and the average velocity for the conduit.

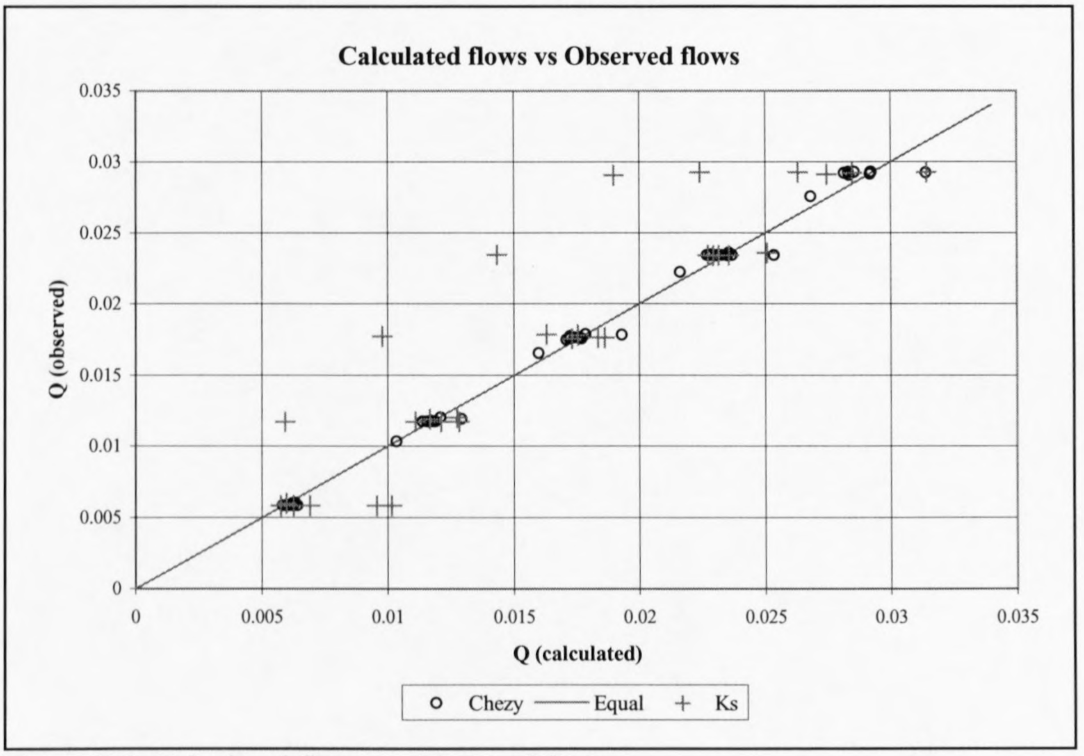

Figure 5.6: Calculated flows vs Observed flows

Figure 5.6 shows that the flows calculated with the equation derived for relative roughness (equation 5.6) in terms of the Chezy equation, produced more accurate flows than those calculated with the equation for steps as roughness element in term of local losses (equation 5.3).

5.5 POWER THEORY FOR STEPS

In essence the power theory states that power made available by an element, equals the power applied to maintain the motion of the element, plus the power deficit per unit volume (see equation 5.7). The relationship for the average velocity for pipe flow was derived in section 2.5.

Total power applied = power applied to overcome friction + power applied at steps (ΔP)

$$\int_0^L \int_0^A \rho g S_{f(total)} vdAdl = \int_0^L \int_0^A \rho g S_{f(pipe)} vdAdl + \Delta P$$
$$\rho g S_{f(total)} QL = \rho g S_{f(pipe)} QL + \int_0^{n*s*d_s} \int_0^A \rho g S_{f(steps)} vdAdl \tag{5.7}$$

with d_s a dimensionless step coefficient, indicating the length over which the step affects the velocity distribution.

From equation 5.7 the power applied at the steps can be written as:

$$\text{Power applied at steps} = \int_0^{n*d_s*s} \int_0^A \rho g S_{f(steps)} vdAdl$$
$$\Delta P = \rho g S_{f(steps)} v \left(\frac{\pi D^2}{4} \right) n * d_s * s \tag{5.8}$$

From equation 2.26 and assuming that $s = 2R_0$ the velocity is:

$$v = 5.77 \sqrt{g S_{f(steps)} \frac{D}{4}} \log \left(\frac{5.45D}{s} \right)$$

The friction slope due to the steps can also be:

$$S_{f(steps)} = \frac{\Delta H}{n * d_s * s}$$

d_s is the portion or effective length over which power is applied at a step, divided by the step size. Consider that an the effective length would be proportional to a the step size, resulting in a constant value for d_s. Thus, assuming that the coefficient, d_s will be constant for different step sizes and configurations the following is obtained from equation 5.8:

$$\Delta P = \rho g\left(\frac{\Delta H}{n * d_s * s}\right) 5.77\sqrt{g\left(\frac{\Delta H}{n * d_s * s}\right)\left(\frac{D}{4}\right)}\left(\log\left(\frac{5.45D}{s}\right)\right)\left(\frac{\pi D^2}{4}\right) n * d_s * s$$

$$d_s = \frac{\Delta H}{n * s}\left[\frac{\rho g \Delta H * 5.77\sqrt{g\frac{D}{4}}\left(\log\left(\frac{5.45D}{s}\right)\right)\left(\frac{\pi D^2}{4}\right)}{\Delta P}\right]^2$$

where ΔP is calculated with equation 5.7

The resulting d_s-values are shown in figure 5.7:

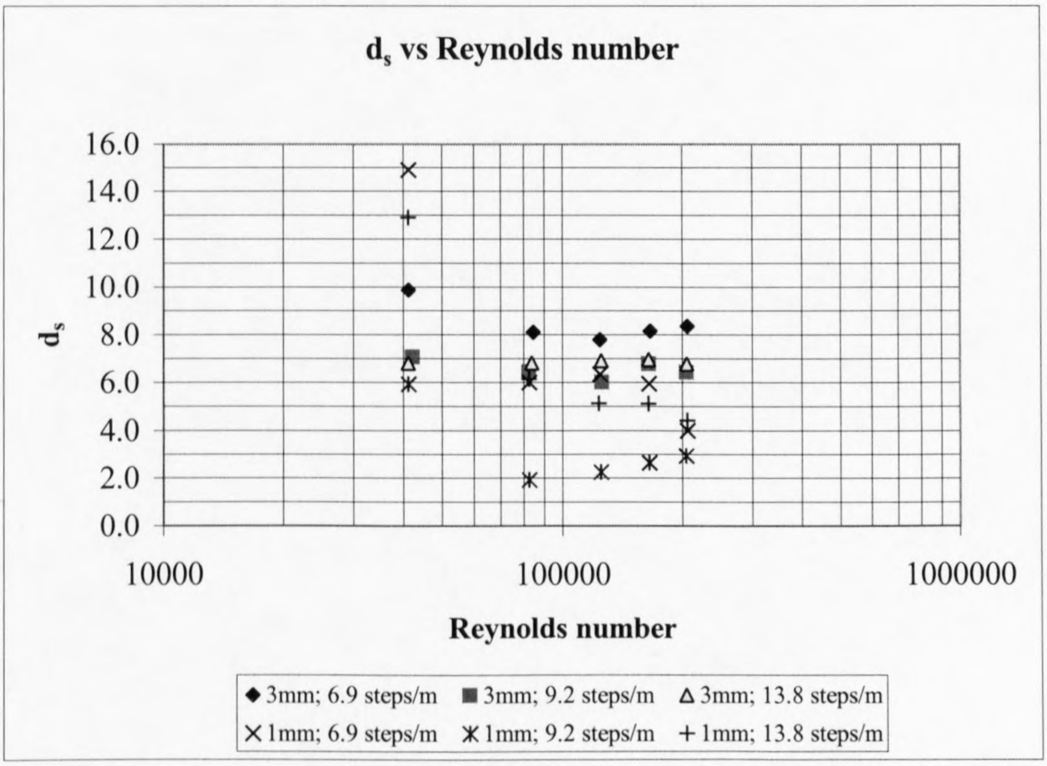

Figure 5.7: d_s-values vs Reynolds number

A constant d_s-value, for the tests with different step sizes and model configurations, was expected. Figure 5.7 shows that the d_s-value for the 3 mm step size varies between 6 and 8. The d_s-value for the 1 mm step size and configuration with 6.9 steps per metre is also of this magnitude, but the tests for the other 1 mm configurations resulted in lower d_s-values. These unsatisfactory results might be due to scale effects, low Reynolds numbers or the fact that tests were conducted in the transition zone and not the turbulent zone. Future tests, at a bigger scale and Reynolds numbers in the turbulent zone, might confirm a constant value for d_s.

5.6 DESIGN APPLICATION

The hydraulic capacity of a segmentally lined tunnel, with steps contributing to the roughness of the tunnel, can be calculated by using the same equations for the prototype, as those derived for the model in the previous sections.

Referring to section 5.3, a K_s-value can be allocated to the different step sizes by using equation 5.3. With the step size and diameter of the tunnel, the K_s-value can be calculated. If the number of steps per unit length of the tunnel is known, equation 5.2 gives the relationship between the average velocity and $S_{f(total)}$. For a range of step sizes equation 5.2 can be written as:

$$h_{total} = h_{f(tunnel)} + n_1 K_{s1}\frac{v^2}{2g} + n_2 K_{s2}\frac{v^2}{2g} + ... + n_x K_{sx}\frac{v^2}{2g}$$

with n_x = the number of steps (size x) over the length of the tunnel

The above calculations can be checked with the Chezy equation (section 5.4). The average step size over the length of the tunnel and the tunnel diameter can be used to calculate k with equation 5.6. Substituting this k-value in equation 2.12 gives the relationship between the velocity and S_f.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

1. CONCLUSIONS

The model study was successfully completed. The piezometric pressure measurements for the different tests resulted in well-defined hydraulic grade lines calculated with linear regression.

The average velocity measurements and the hydraulic grade lines were used to evaluate the roughness of the model and the contribution of steps as roughness elements.

Tests, representing two different step sizes in the prototype, and three different configurations in terms of the frequency of the steps, were performed.

Losses at steps were analysed as local losses with a K_s-value representing a specific step size. The tests for this model study are in the transition zone. Tests with higher Re numbers would confirm the constant K_s-values. The K_s-value is expressed mathematically in terms of the step size. However, the relationship should be confirmed with tests on more step sizes (not only two) and higher Re numbers.

The data was also analysed in terms of the Chezy equation. This resulted in an exponential relationship between k/D and s/D. The longitudinal spacing of the steps was not important.

The velocity distribution was previously only derived for open channel flow. As part of the thesis the velocity distribution and the power theory was derived for pipe flow. This was done to provide a method in which the power applied at each step, could be calculated mathematically in terms of the step size. The results from the application of this derived theory were not satisfactory.

6.2 RECOMMENDATIONS

The tests conducted in this model study were done at a scale of 1:19.337. The smallest step size in the model was 1 mm. To eliminate the possibility of scale effects, it is recommended that future tests be done at a bigger scale.

Although the Re numbers for the prototype are in the smooth turbulent zone, those for the model study were in the transition zone. Nevertheless, the K_s-value can be assumed to be constant for a specific step size, from the patterns in the Moody diagram. It is recommended that future tests of the same step sizes be done at higher Re numbers to ensure flow conditions in the turbulent zone and not in the transition zone. This should confirm that constant K_s-values apply in the rough turbulent zone.

Expressing the data in terms of Chezy equation yields an exponential relationship between s/D and k/D. This was derived with the values for two different step sizes and the normal pipe friction factor was assumed to represent a 0 mm step size. It is recommended that this relationship be confirmed with tests with other values of s/D.

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APPENDIX A

TEST RESULTS

TEST A1

SET-UP

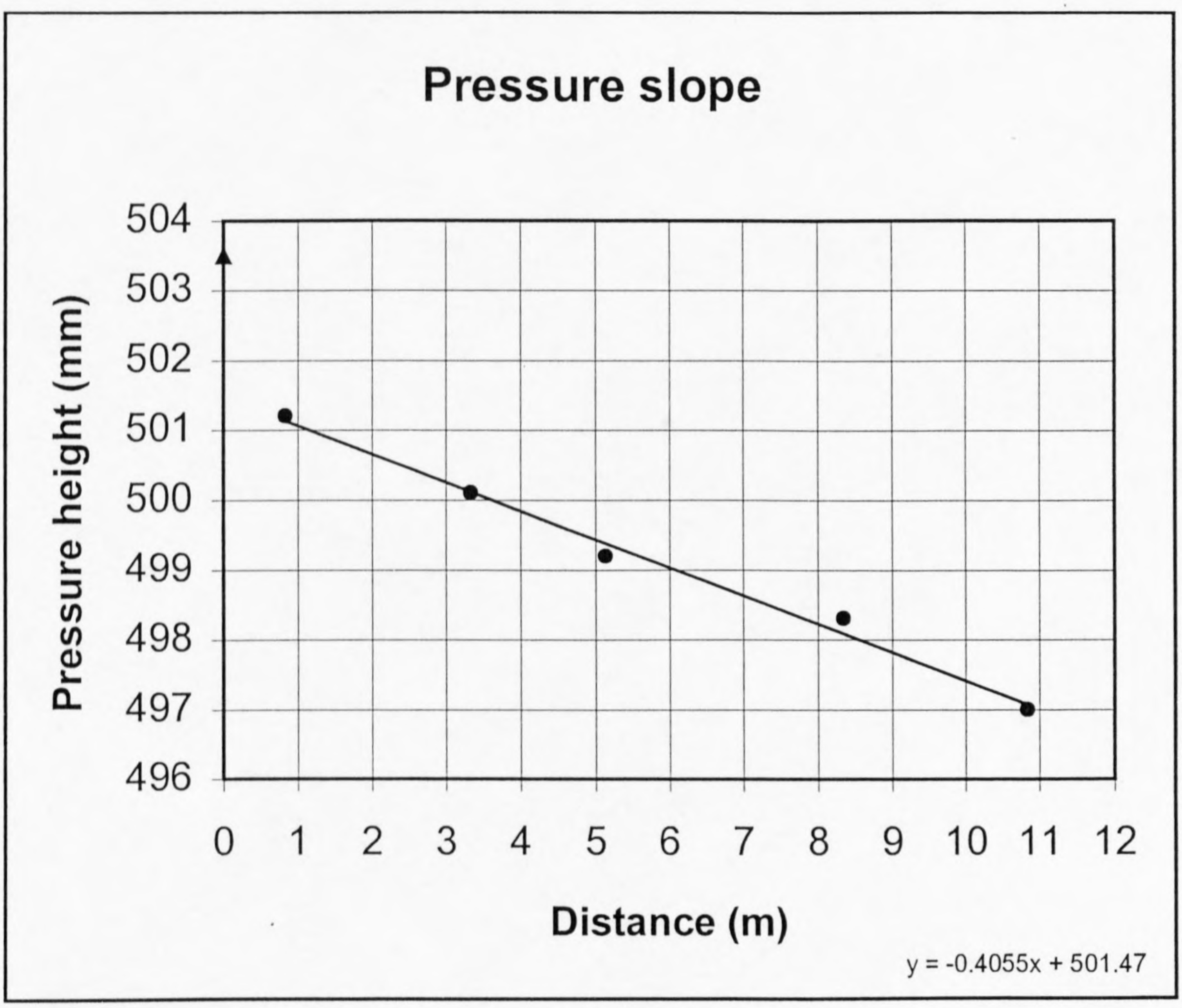
Step size (mm)	Smooth
Steps/m	0

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	3	6.01
V-notch	113.7	6.02
Difference (%)		0.3%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.836	3.332	5.134	8.342	10.842
Pressure heights (mm)		501.2	500.1	499.2	498.3	497.0
		501.2	500.1	499.2	498.3	497.0
		501.2	500.1	499.2	498.3	497.0
		501.2	500.1	499.2	498.3	497.0
		501.2	500.1	499.2	498.3	497.0
Average height (mm	503.5	501.2	500.1	499.2	498.3	497.0



Average velocity = 0.234 (m/s)
Pressure slope = 0.4055 (mm/m)

TEST A2

SET-UP

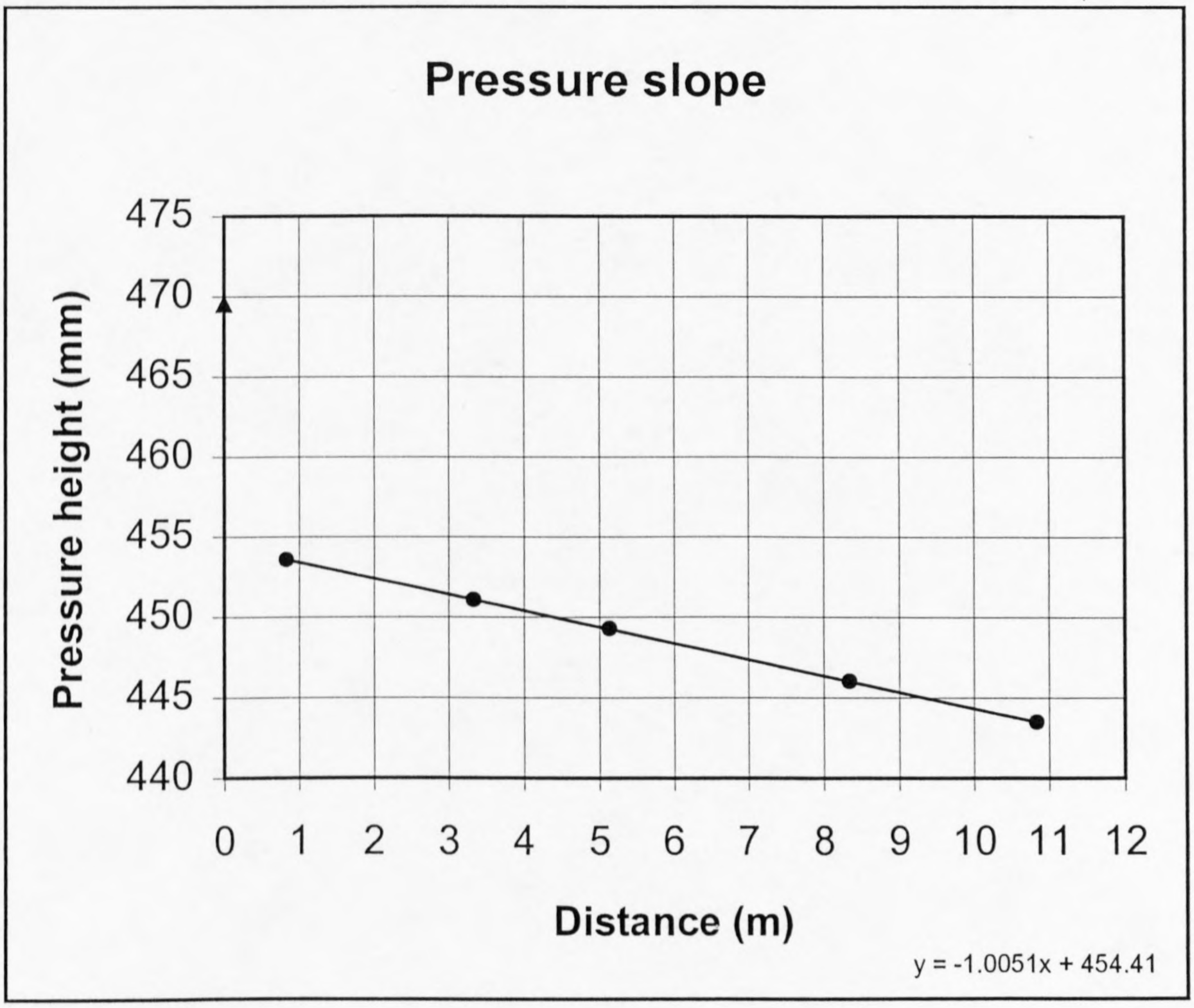
Step size (mm)	Smooth
Steps/m	0

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	10	10.97
V-notch	140.9	10.30
Difference (%)		-6.5%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.836	3.332	5.134	8.342	10.842
Pressure heights (mm)		453.5	451.0	449.2	446.0	443.5
		453.5	451.0	449.3	446.1	443.5
		453.6	451.0	449.3	446.0	443.5
		453.6	451.1	449.3	446.0	443.5
		453.6	451.1	449.3	446.0	443.5
Average height (mm	469.5	453.6	451.0	449.3	446.0	443.5



Average velocity = 0.400 (m/s)
Pressure slope = 1.0051 (mm/m)

TEST A3

SET-UP

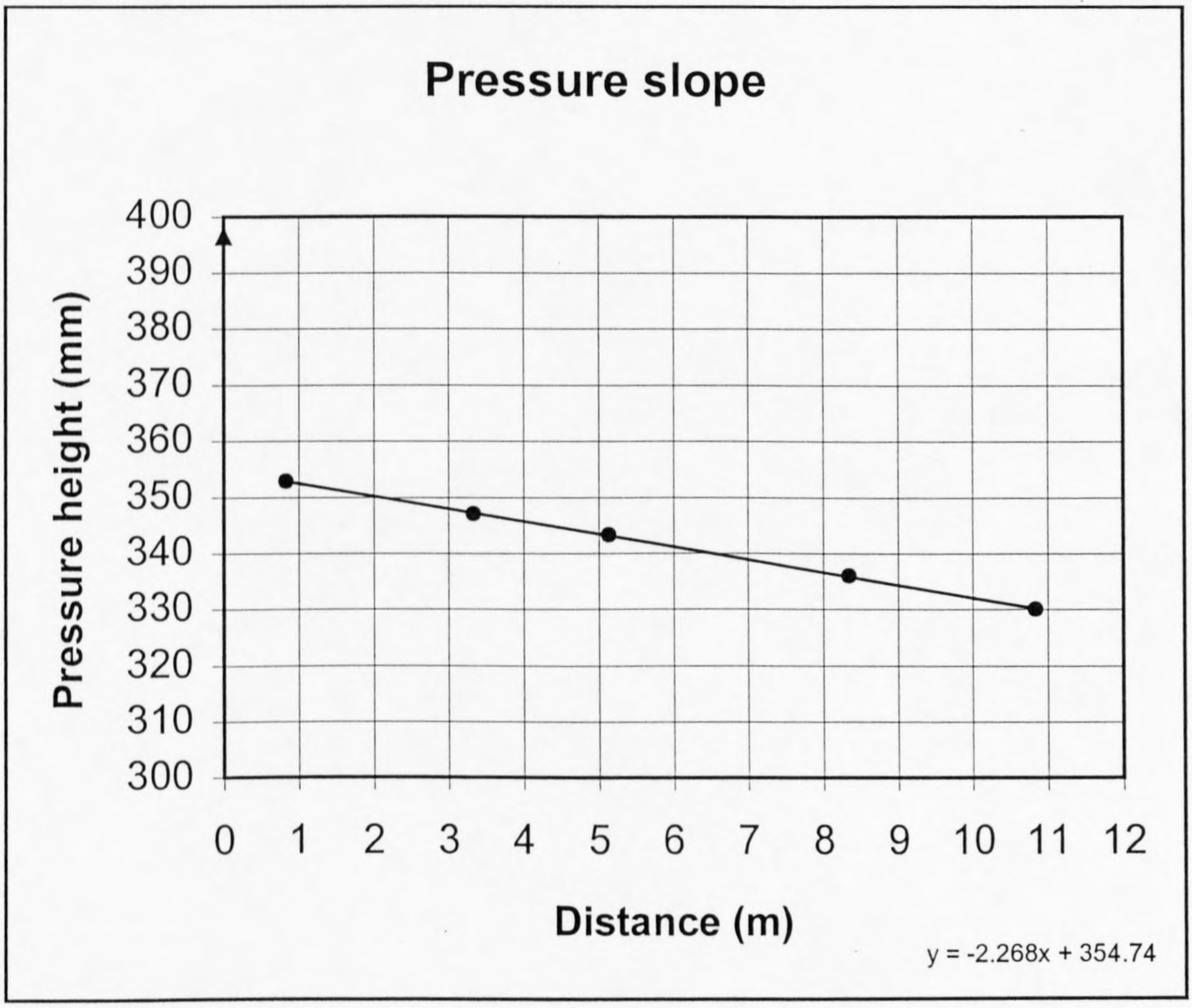
Step size (mm)	Smooth
Steps/m	0

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	26	17.69
V-notch	170.3	16.54
Difference (%)		-6.9%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.836	3.332	5.134	8.342	10.842
Pressure heights (mm)		352.9	347.0	343.2	336.1	330.1
		353.0	347.2	343.2	336.0	330.1
		352.8	347.0	343.2	335.9	329.9
		352.7	347.0	343.2	336.0	330.0
		352.8	347.0	343.2	336.0	329.9
Average height (mm	396.5	352.8	347.0	343.2	336.0	330.0



Average velocity = 0.643 (m/s)
Pressure slope = 2.268 (mm/m)

TEST A4

SET-UP

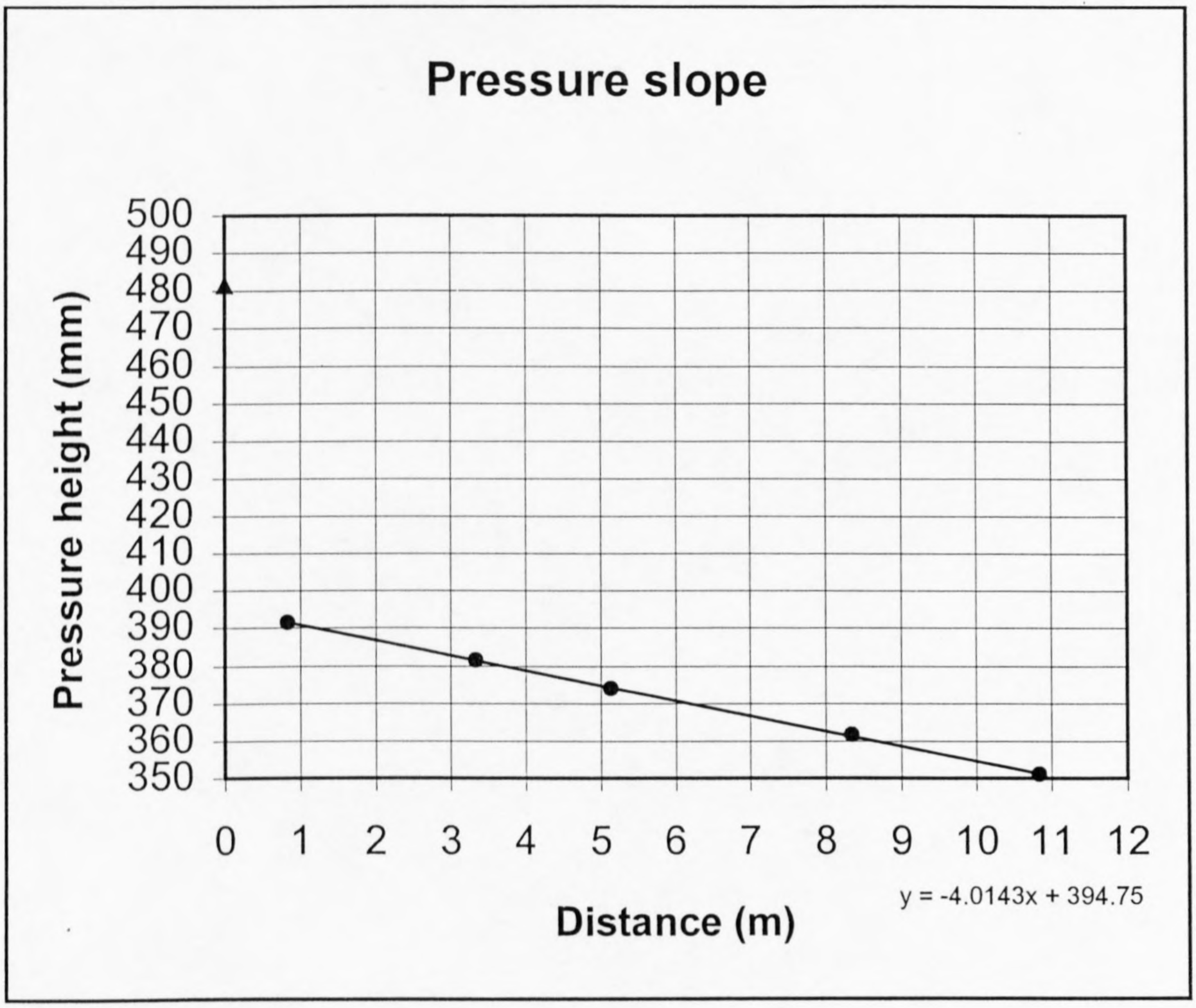
Step size (mm)	Smooth
Steps/m	0

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	45.5	23.40
V-notch	191.6	22.21
Difference (%)		-5.4%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.836	3.332	5.134	8.342	10.842
Pressure heights (mm)		391.3	381.7	374.0	361.7	351.0
		391.5	381.3	373.9	361.8	351.0
		391.4	381.3	373.8	361.7	350.9
		391.4	381.4	373.9	361.6	351.1
		391.4	381.4	373.8	361.7	351.0
Average height (mm	481.5	391.4	381.4	373.9	361.7	351.0



Average velocity = 0.863 (m/s)

Pressure slope = 4.014 (mm/m)

TEST A5

SET-UP

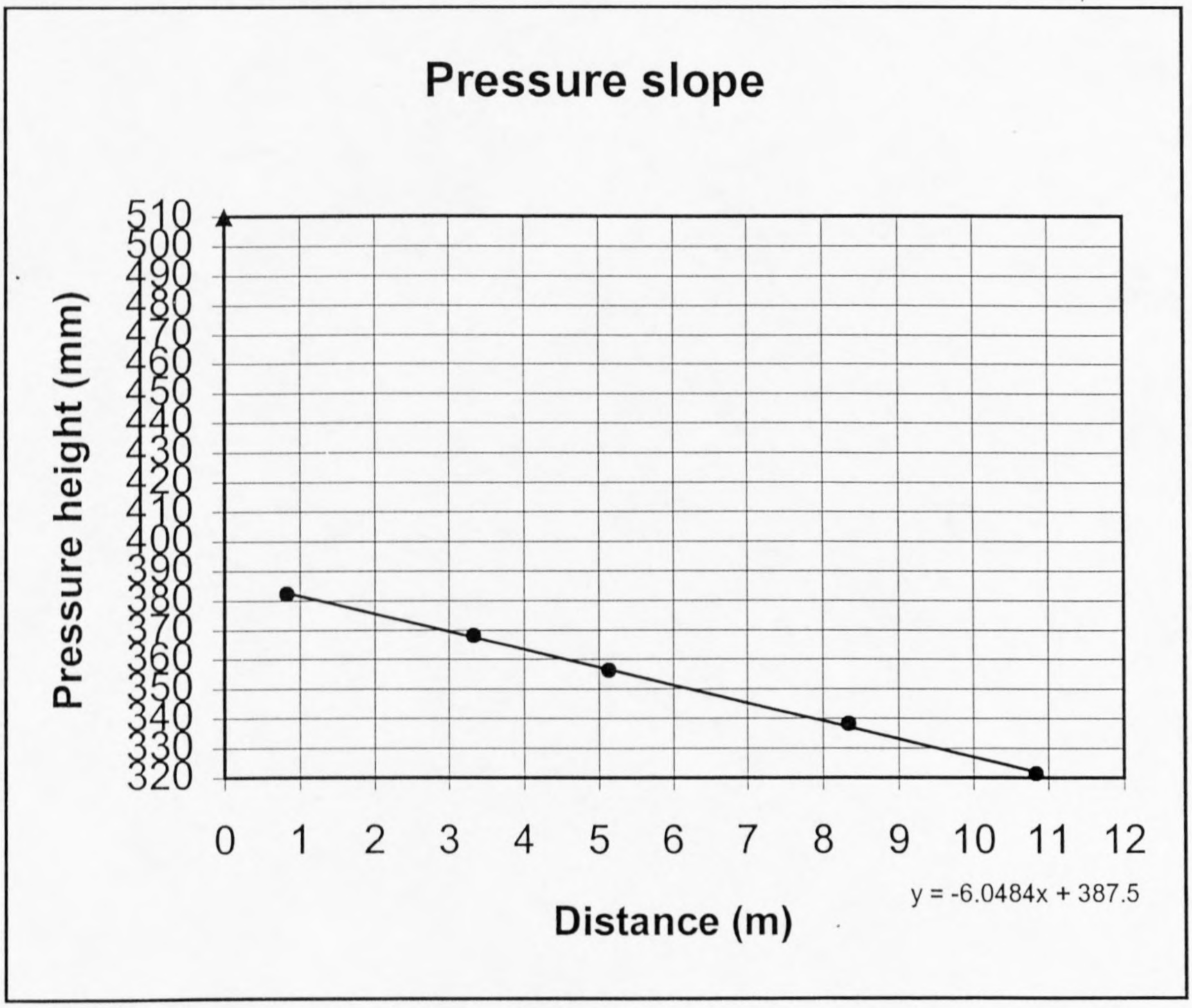
Step size (mm)	Smooth
Steps/m	0

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	70.5	29.13
V-notch	208.9	27.56
Difference (%)		-5.7%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.836	3.332	5.134	8.342	10.842
Pressure heights (mm)		382.0	368.0	356.1	338.2	321.4
		382.0	367.8	356.1	338.1	321.2
		382.0	367.9	356.1	338.0	321.0
		382.0	367.8	356.1	337.8	321.1
		382.0	367.8	356.1	338.0	321.3
Average height (mm	509.5	382.0	367.9	356.1	338.0	321.2



Average velocity = 1.071 (m/s)
Pressure slope = 6.048 (mm/m)

TEST B1

SET-UP

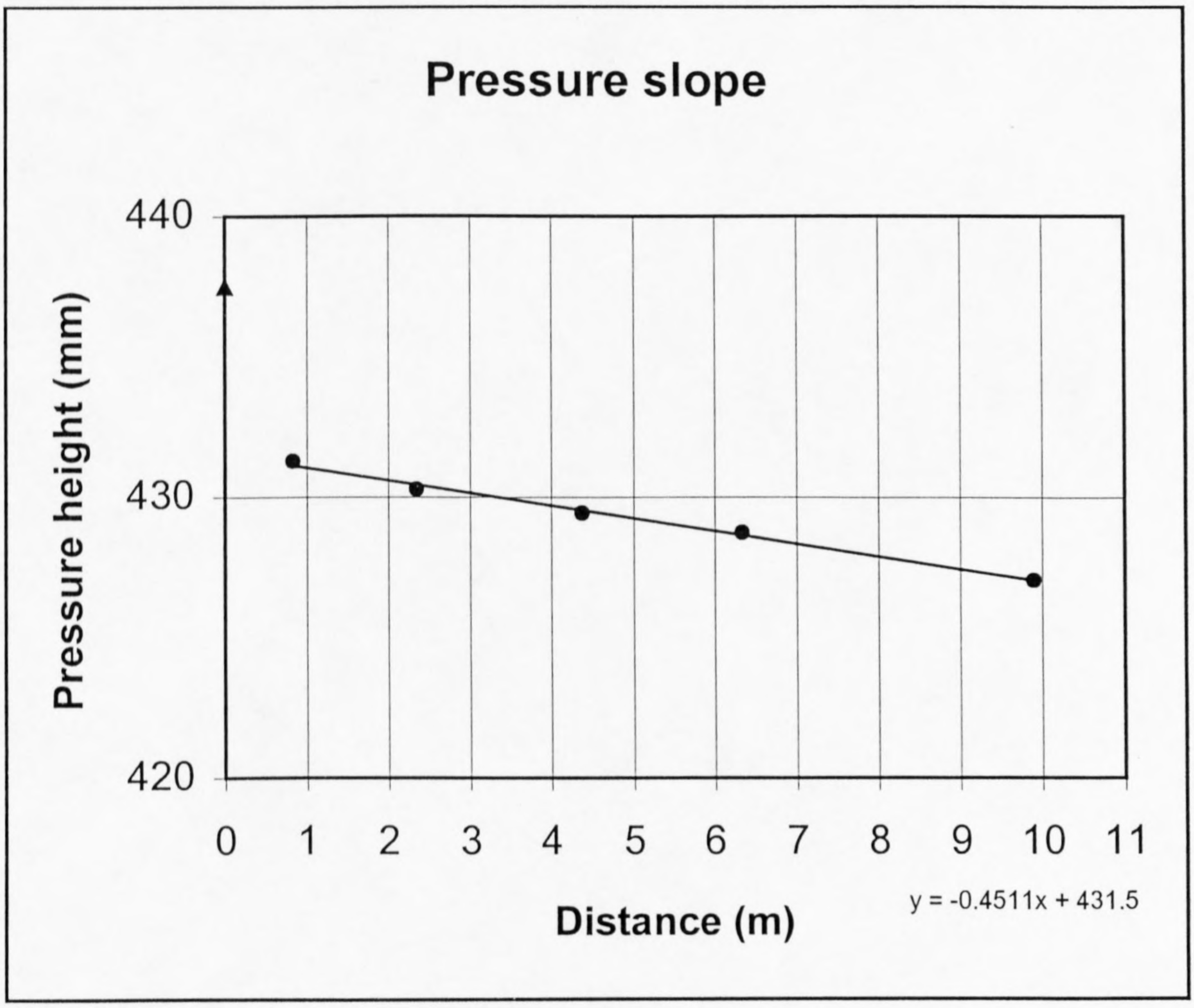
Step size (mm)	0
Steps/m	

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	3.0	6.01
V-notch	116.8	6.44
Difference (%)		6.8%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.83	2.35	4.377	6.335	9.899
Pressure heights (mm)		431.3	430.5	429.5	428.8	427.0
		431.3	430.3	429.4	428.8	427.1
		431.3	430.3	429.4	428.8	427.1
		431.2	430.1	429.4	428.7	427.0
		431.3	430.2	429.4	428.6	427.0
Average height (mm	437.5	431.3	430.3	429.4	428.7	427.0



Average velocity = 0.250 (m/s)
Pressure slope = 0.4511 (mm/m)

TEST B2

SET-UP

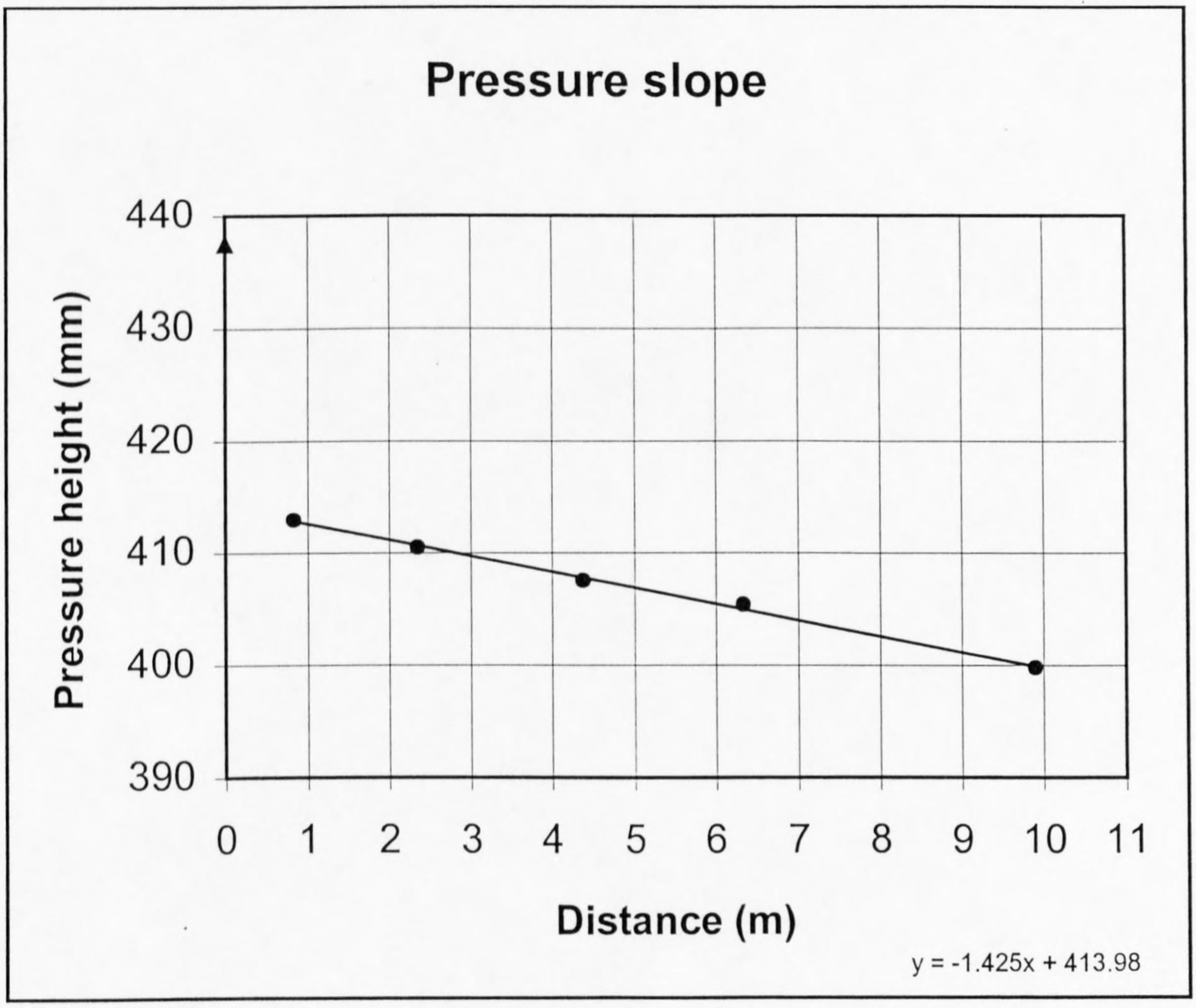
Step size (mm)	0
Steps/m	

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	11.5	11.76
V-notch	151.8	12.41
Difference (%)		5.2%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.83	2.35	4.377	6.335	9.899
Pressure heights (mm)		413.0	410.5	407.5	405.2	399.7
		412.9	410.5	407.5	405.5	399.8
		412.9	410.5	407.5	405.3	399.8
		412.9	410.3	407.5	405.4	399.7
		413.0	410.5	407.5	405.4	399.8
Average height (mm	437.5	412.9	410.5	407.5	405.4	399.8



Average velocity = 0.482 (m/s)
Pressure slope = 1.425 (mm/m)

TEST B3

SET-UP

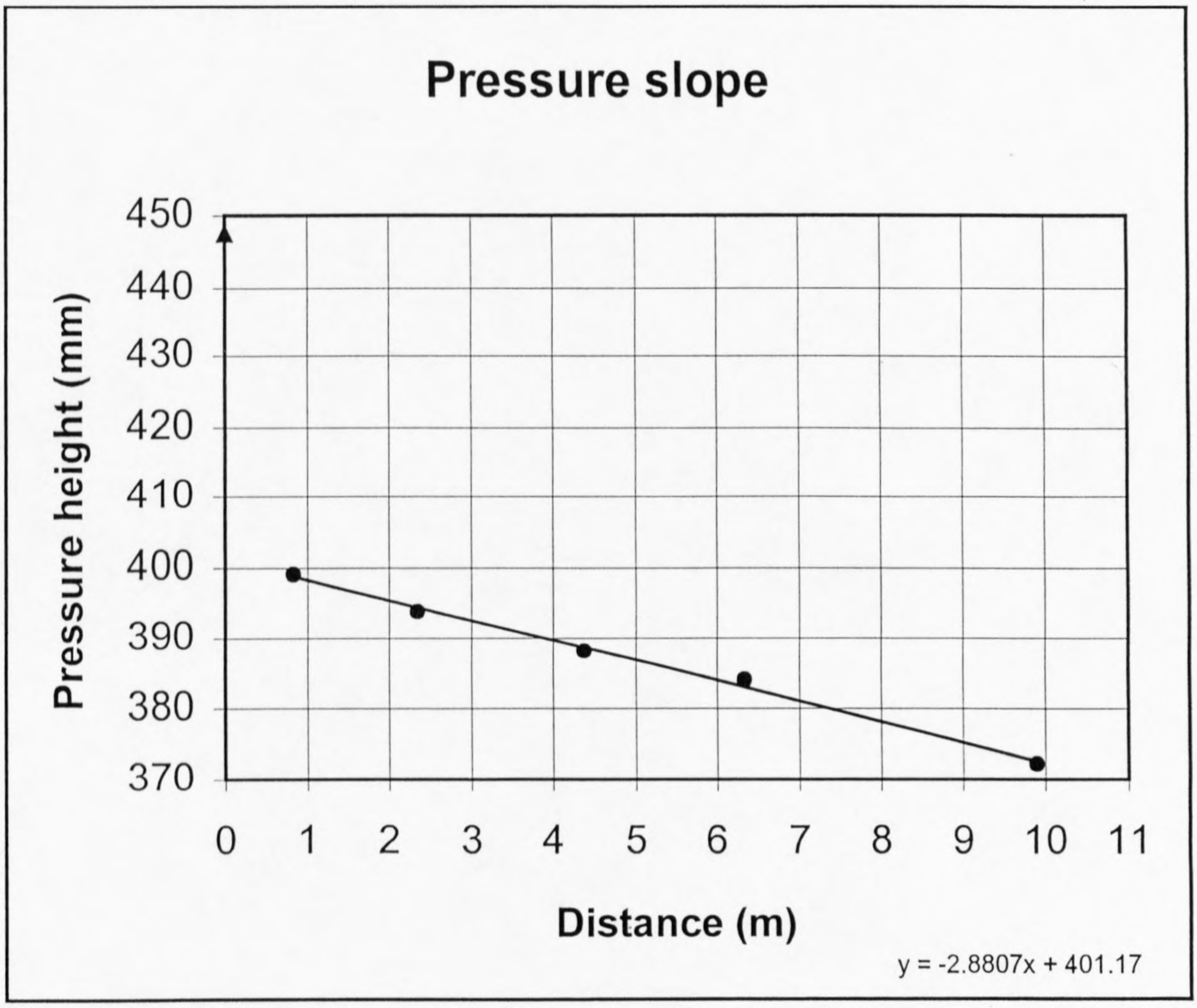
Step size (mm)	0
Steps/m	

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	26.0	17.69
V-notch	175.7	17.88
Difference (%)		1.1%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.83	2.35	4.377	6.335	9.899
Pressure heights (mm)		399.1	393.5	387.8	383.5	371.5
		398.8	393.7	388.0	384.0	372.4
		399.1	394.0	388.2	384.1	372.6
		399.1	394.1	388.1	384.2	372.5
		399.4	394.1	388.2	384.0	372.5
Average height (mm	447.5	399.1	393.9	388.1	384.0	372.3



Average velocity = 0.695 (m/s)
Pressure slope = 2.8807 (mm/m)

TEST B4

SET-UP

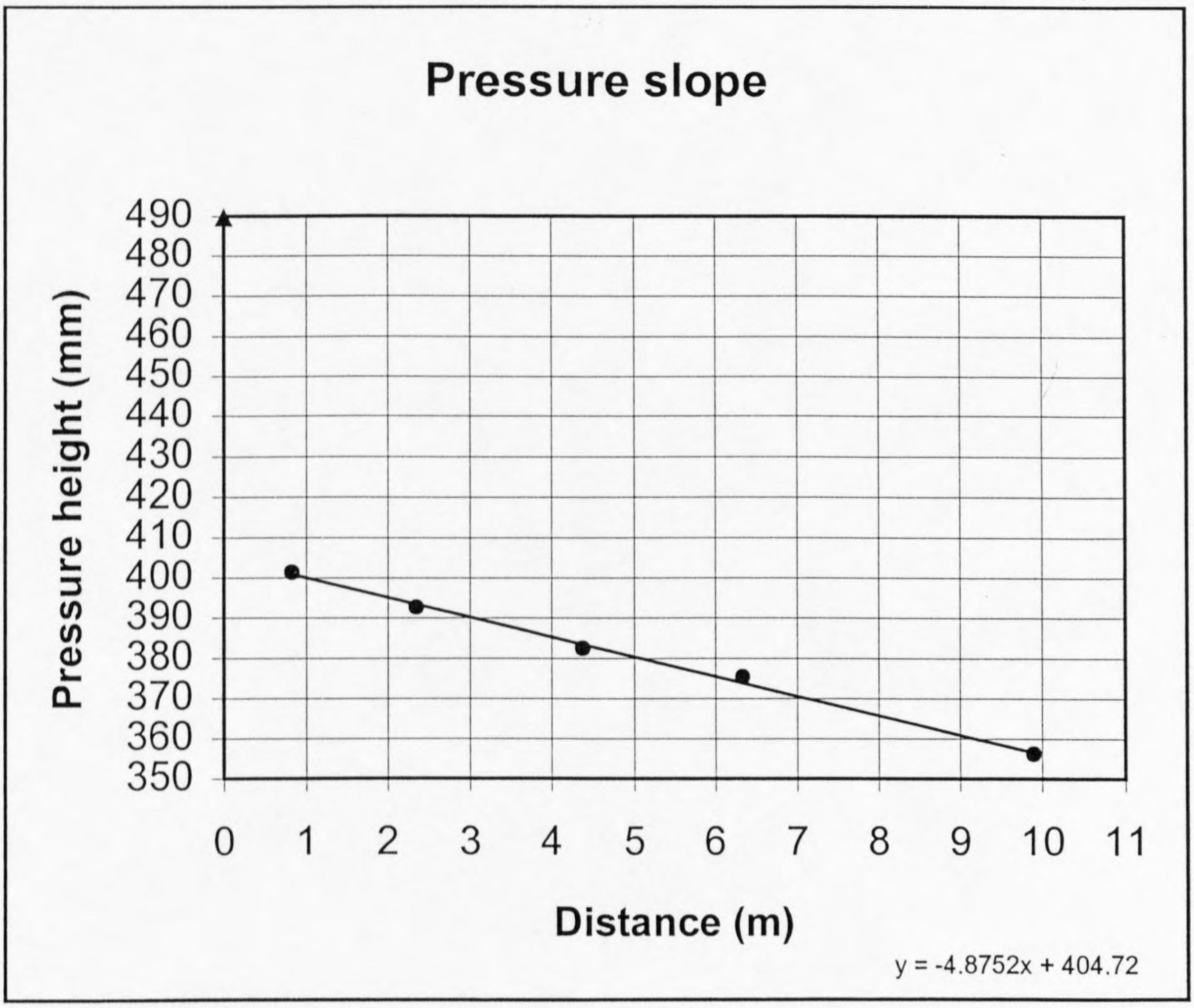
Step size (mm)	0
Steps/m	

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	45.5	23.40
V-notch	195.7	23.41
Difference (%)		0.1%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.83	2.35	4.377	6.335	9.899
Pressure heights (mm)		402.4	393.1	383.2	375.9	356.0
		401.1	392.7	382.0	375.1	355.7
		400.7	392.3	381.9	375.2	356.3
		401.7	392.6	382.9	375.8	356.5
		400.5	392.2	381.9	374.5	355.9
Average height (mm	489.5	401.3	392.6	382.4	375.3	356.1



Average velocity = 0.910 (m/s)
Pressure slope = 4.8752 (mm/m)

TEST B5

SET-UP

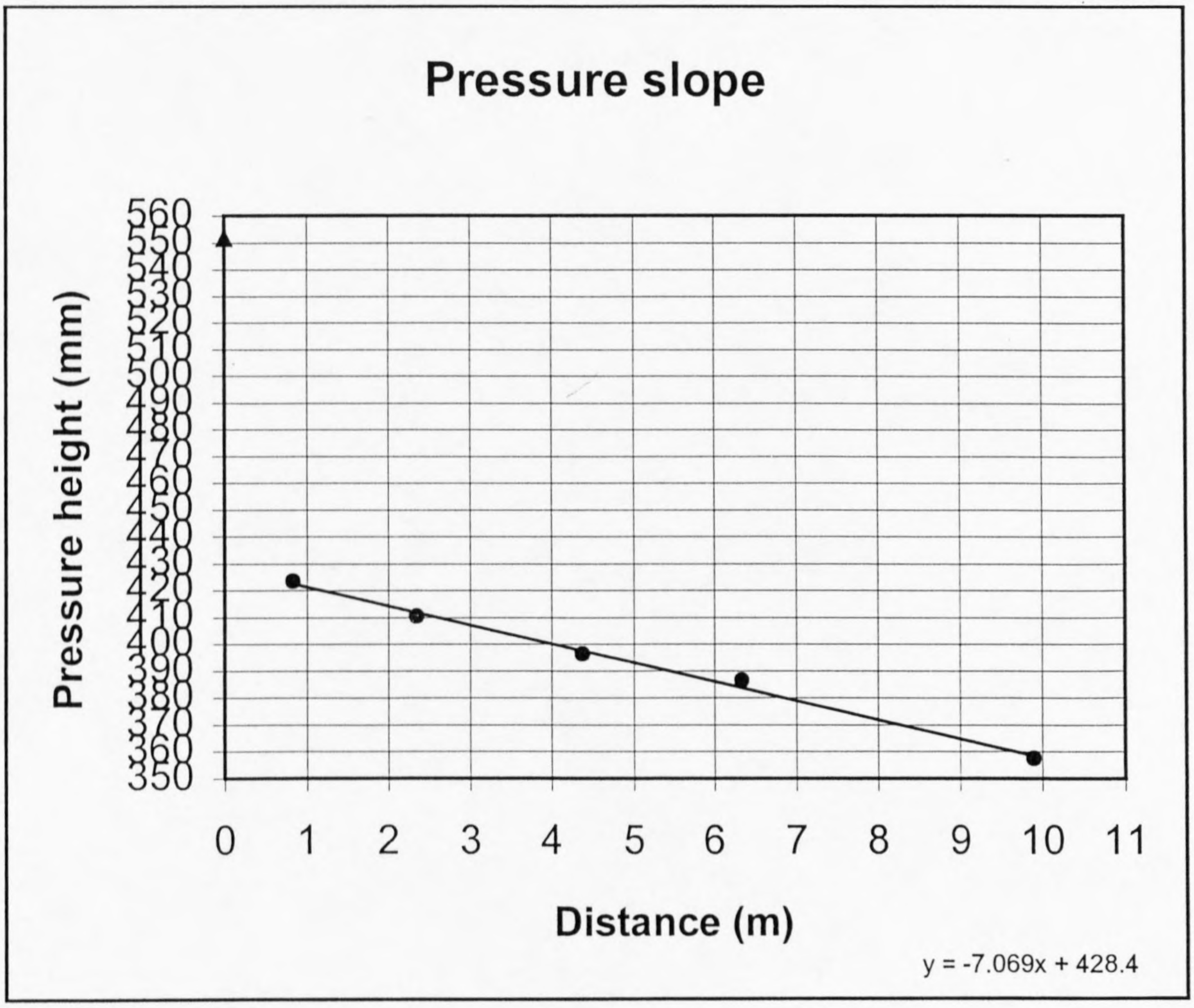
Step size (mm)	0
Steps/m	

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	69.5	28.92
V-notch	212.6	28.80
Difference (%)		-0.4%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.83	2.35	4.377	6.335	9.899
Pressure heights (mm)		423.5	410.0	396.1	386.3	357.3
		423.3	410.2	395.9	386.3	357.5
		423.6	410.5	396.3	386.3	357.8
		423.5	410.6	396.1	386.1	357.6
		423.5	410.6	396.3	386.3	357.7
Average height (mm	551.5	423.5	410.4	396.1	386.3	357.6



Average velocity = 1.119 (m/s)
Pressure slope = 7.069 (mm/m)

TEST C1

SET-UP

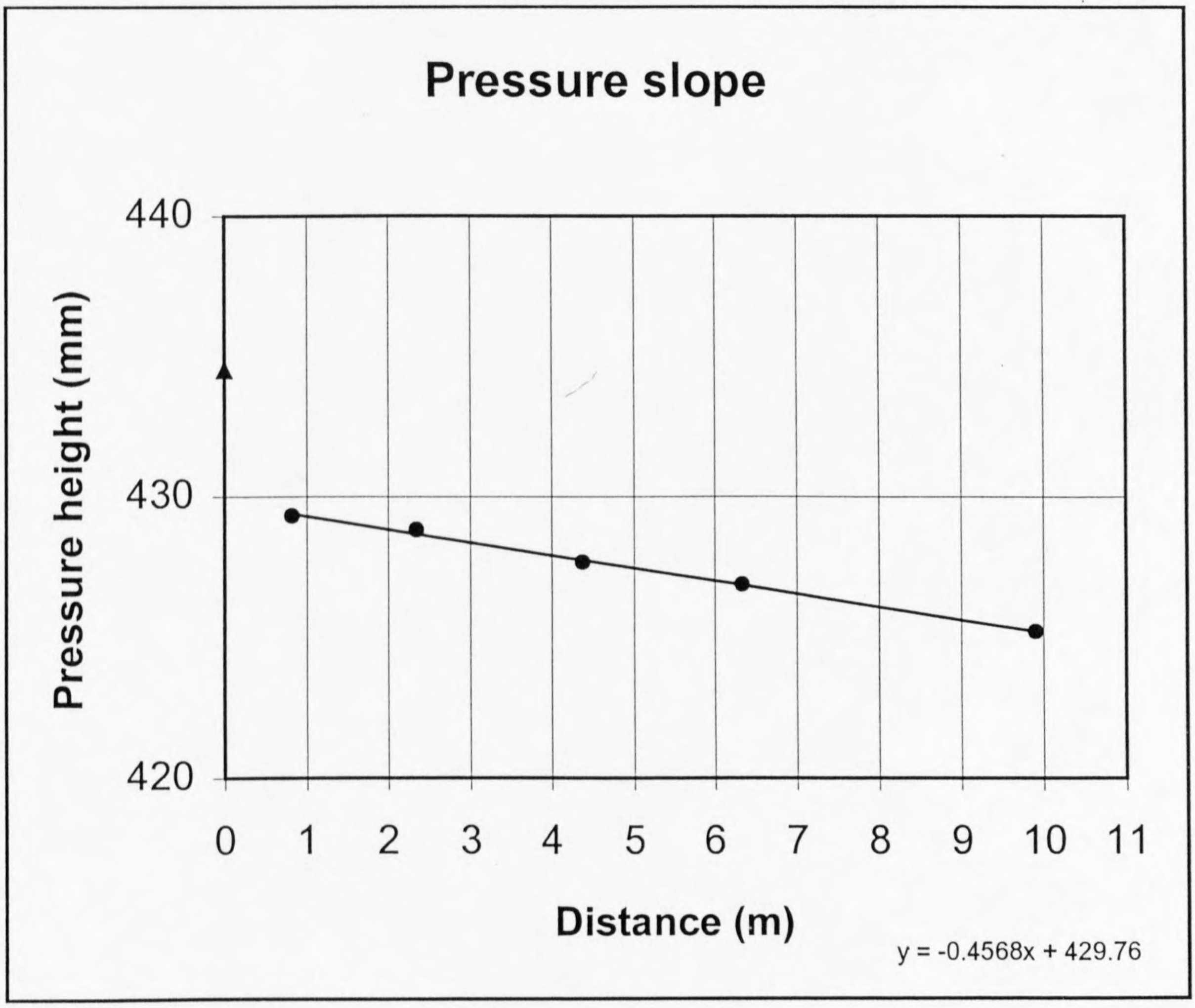
Step size (mm)	3
Steps/m	6.9

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	2.5	5.48
V-notch	112.4	5.85
Difference (%)		6.3%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.825	2.35	4.379	6.338	9.903
Pressure heights (mm)		429.4	429.0	427.8	426.9	425.3
		429.3	428.9	427.7	426.9	425.3
		429.2	428.8	427.7	427.0	425.2
		429.3	428.7	427.5	426.8	425.1
		429.4	428.7	427.7	426.8	425.3
Average height (mm	434.5	429.3	428.8	427.7	426.9	425.2



Average velocity = 0.227 (m/s)
Pressure slope = 0.4568 (mm/m)

TEST C2

SET-UP

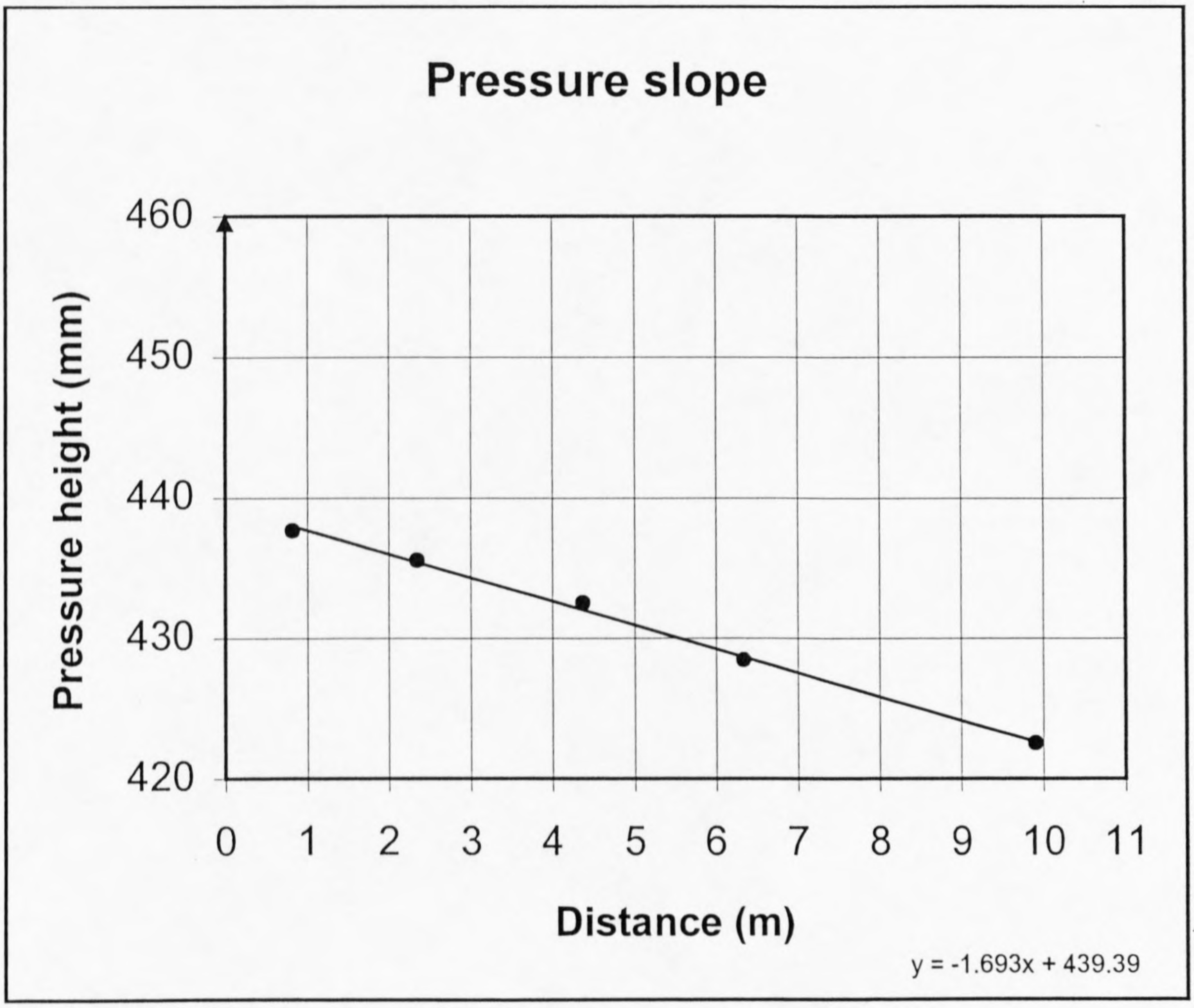
Step size (mm)	3
Steps/m	6.9

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	11.0	11.50
V-notch	149.8	12.00
Difference (%)		4.1%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.825	2.35	4.379	6.338	9.903
Pressure heights (mm)		437.4	435.6	432.4	428.3	422.4
		437.7	435.4	432.5	428.4	422.5
		437.7	435.6	432.5	428.5	422.5
		437.7	435.6	432.5	428.4	422.7
		437.8	435.5	432.5	428.5	422.6
Average height (mm	459.5	437.7	435.5	432.5	428.4	422.5



Average velocity = 0.466 (m/s)
Pressure slope = 1.693 (mm/m)

TEST C3

SET-UP

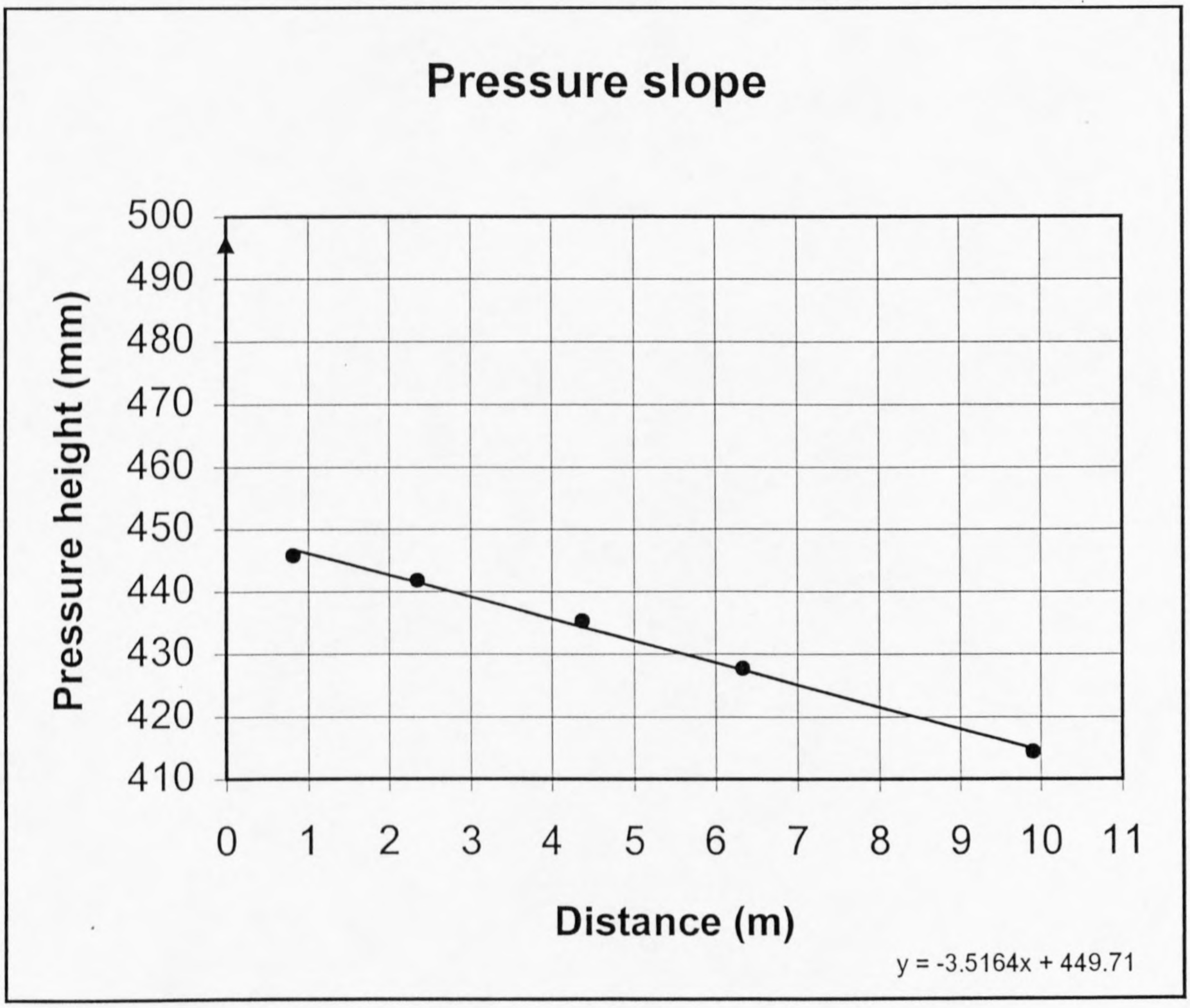
Step size (mm)	3
Steps/m	6.9

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	25.5	17.52
V-notch	174.8	17.65
Difference (%)		0.8%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.825	2.35	4.379	6.338	9.903
Pressure heights (mm)		445.8	441.7	435.3	427.8	414.4
		445.8	441.9	435.3	427.7	414.3
		446.0	441.9	435.5	427.6	414.2
		445.7	442.0	435.3	427.7	414.4
		445.9	441.6	435.1	427.2	414.4
Average height (mm	495.5	445.8	441.8	435.3	427.6	414.3



Average velocity = 0.686 (m/s)
Pressure slope = 3.5164 (mm/m)

TEST C4

SET-UP

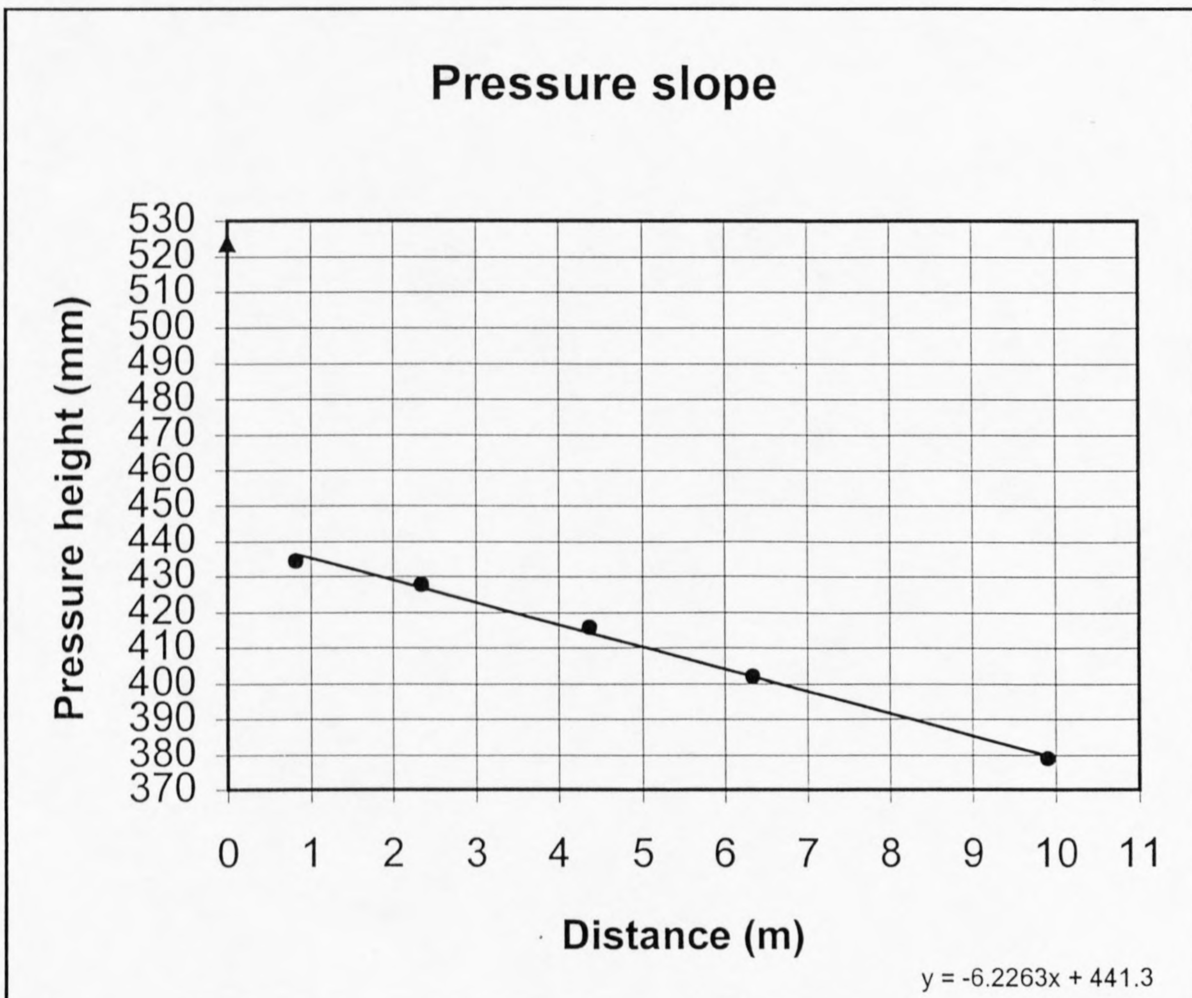
Step size (mm)	3
Steps/m	6.9

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	45.0	23.27
V-notch	196.3	23.59
Difference (%)		1.4%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.825	2.35	4.379	6.338	9.903
Pressure heights (mm)		434.2	427.4	415.5	401.6	378.1
		433.9	427.2	415.0	401.5	378.6
		434.2	427.9	415.9	401.9	378.9
		434.5	428.1	416.1	402.3	379.0
		434.4	427.9	416.2	402.2	379.2
Average height (mm	523.5	434.2	427.7	415.7	401.9	378.8



Average velocity = 0.917 (m/s)
Pressure slope = 6.2263 (mm/m)

TEST C5

SET-UP

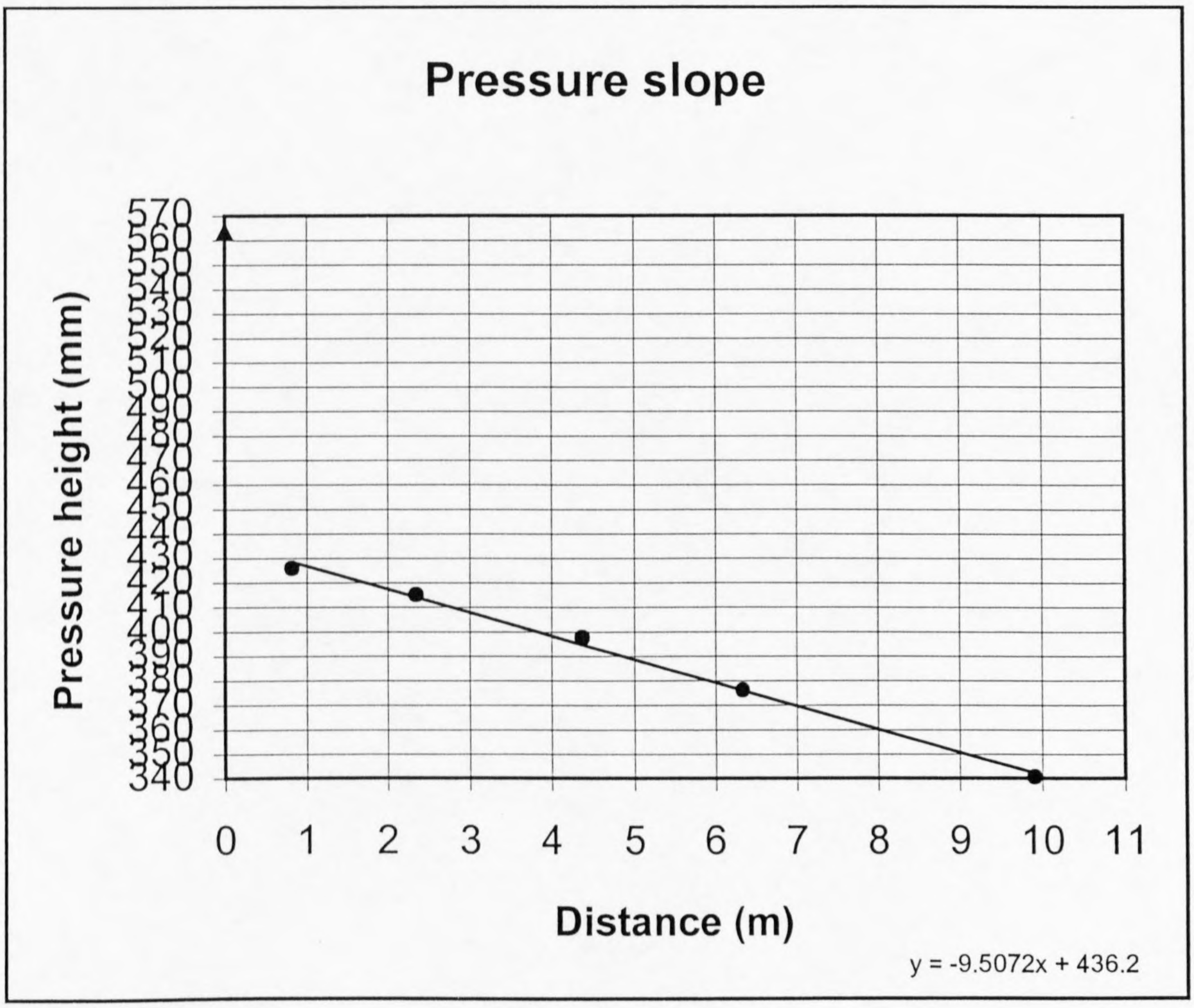
Step size (mm)	3
Steps/m	6.9

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	71.5	29.33
V-notch	213.9	29.24
Difference (%)		-0.3%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.825	2.35	4.379	6.338	9.903
Pressure heights (mm)		425.9	414.8	397.2	375.9	340.4
		425.4	414.6	397.4	375.7	340.4
		425.8	415.1	397.9	376.3	340.7
		425.6	415.0	397.4	376.3	340.8
		425.6	414.9	397.4	376.5	340.8
Average height (mm	563.5	425.7	414.9	397.5	376.1	340.6



Average velocity = 1.136 (m/s)
Pressure slope = 9.5072 (mm/m)

TEST D1

SET-UP

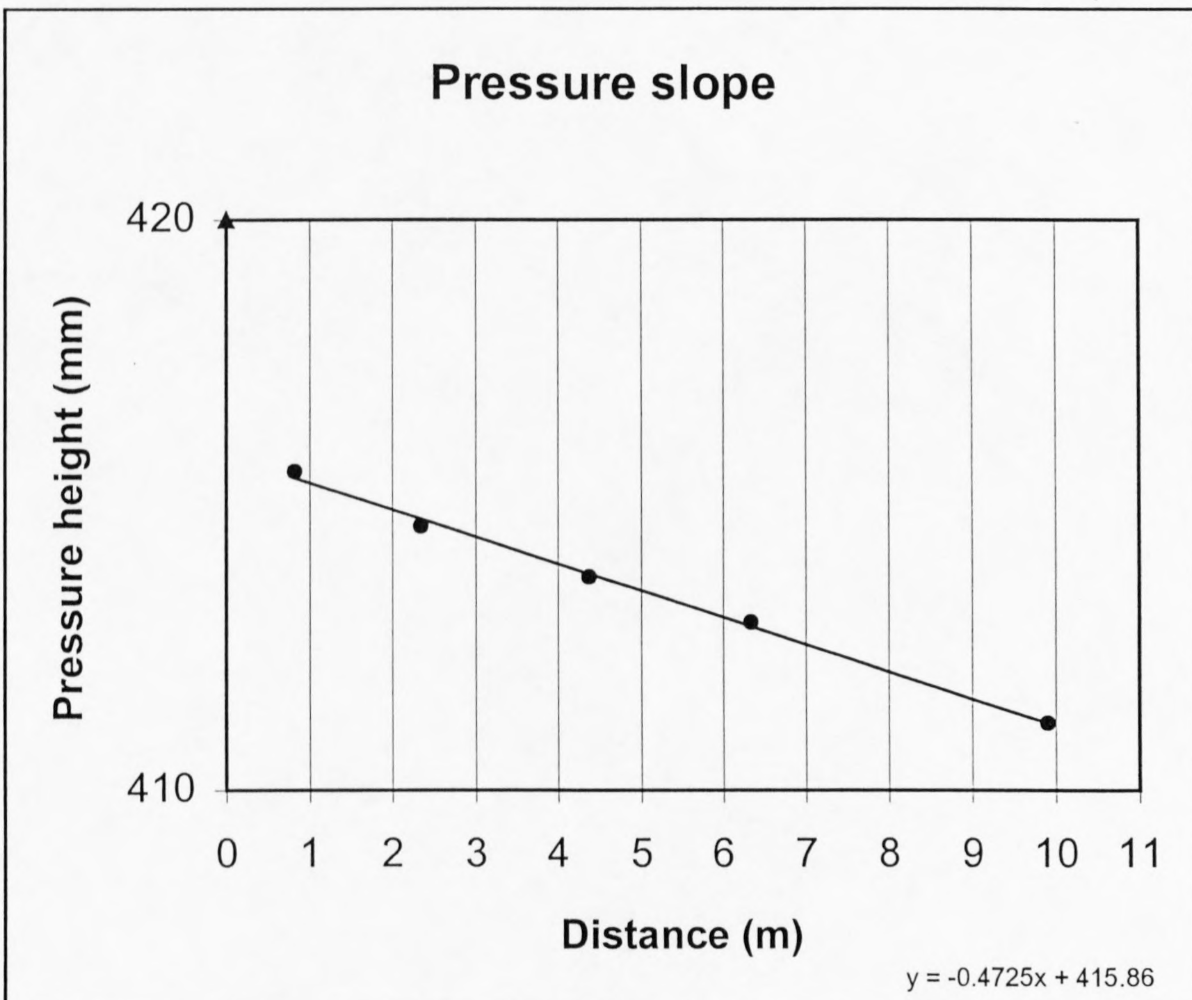
Step size (mm)	3
Steps/m	9.2

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	3.0	6.01
V-notch	113.5	6.00
Difference (%)		-0.2%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.828	2.35	4.375	6.336	9.901
Pressure heights (mm)		415.7	414.6	413.9	412.9	411.3
		415.6	414.6	413.8	412.9	411.2
		415.5	414.6	413.7	413.0	411.2
		415.6	414.7	413.6	413.0	411.0
		415.5	414.6	413.7	412.9	411.2
Average height (mm	420	415.6	414.6	413.7	412.9	411.2



Average velocity = 0.233 (m/s)
Pressure slope = 0.4725 (mm/m)

TEST D2

SET-UP

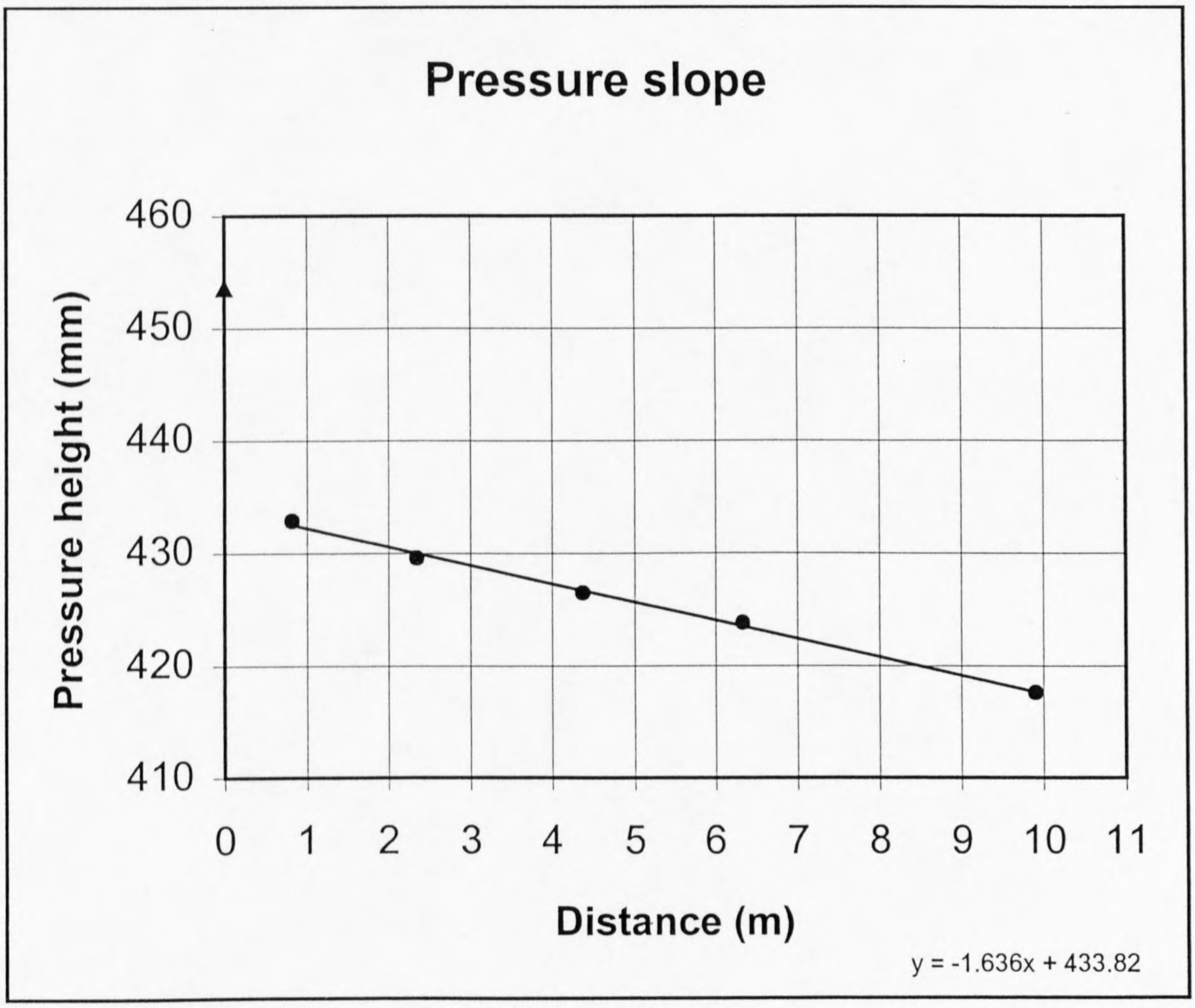
Step size (mm)	3
Steps/m	9.2

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	11.0	11.50
V-notch	148.3	11.70
Difference (%)		1.7%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.828	2.35	4.375	6.336	9.901
Pressure heights (mm)		432.7	429.5	426.7	423.8	417.7
		432.8	429.7	426.5	423.9	417.5
		432.7	429.5	426.4	423.7	417.5
		432.9	429.5	426.3	423.8	417.5
		432.9	429.5	426.5	423.7	417.6
Average height (mm	453.5	432.8	429.5	426.5	423.8	417.6



Average velocity = 0.455 (m/s)
Pressure slope = 1.636 (mm/m)

TEST D3

SET-UP

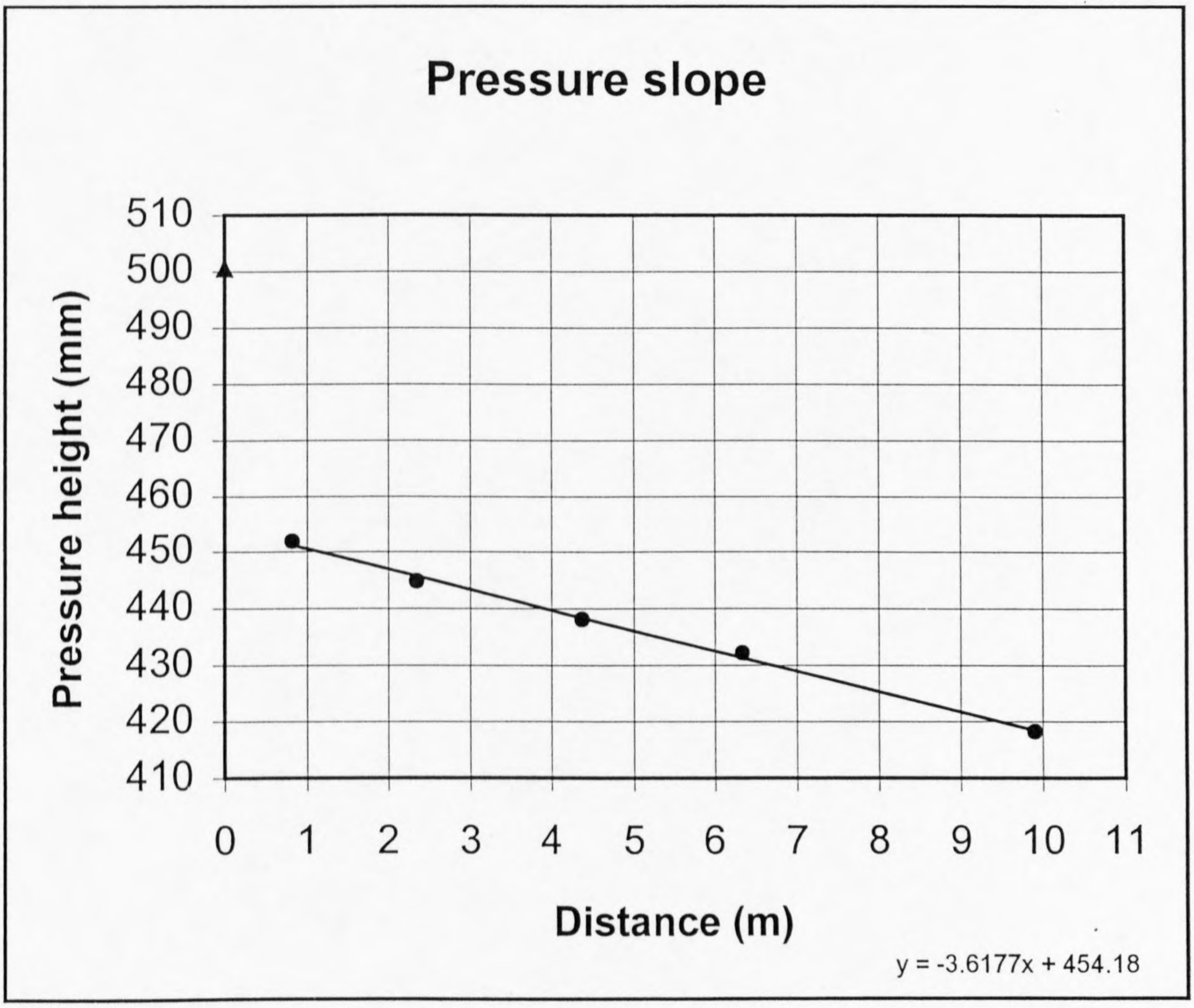
Step size (mm)	3
Steps/m	9.2

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	25.5	17.52
V-notch	175.6	17.86
Difference (%)		1.9%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.828	2.35	4.375	6.336	9.901
Pressure heights (mm)		452.0	444.8	438.2	432.1	418.4
		451.8	444.8	438.2	432.1	418.1
		451.8	444.8	438.0	432.2	418.2
		451.8	444.6	437.9	432.0	417.9
		451.7	444.7	437.9	432.2	418.0
Average height (mm	500.5	451.8	444.7	438.0	432.1	418.1



Average velocity = 0.694 (m/s)
Pressure slope = 3.6177 (mm/m)

TEST D4

SET-UP

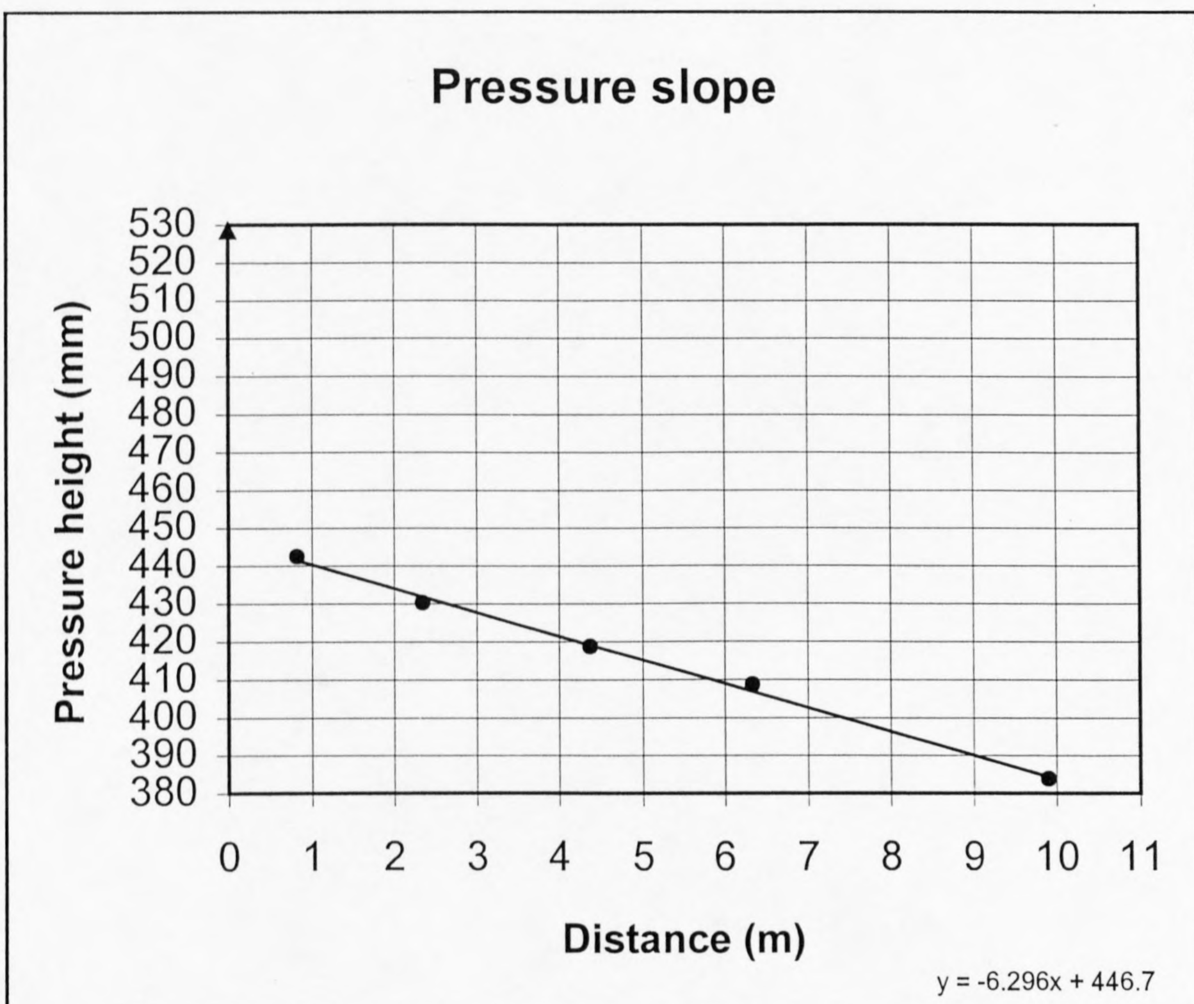
Step size (mm)	3
Steps/m	9.2

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	45.5	23.40
V-notch	195.7	23.41
Difference (%)		0.1%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.828	2.35	4.375	6.336	9.901
Pressure heights (mm)		442.2	430.0	418.5	408.5	383.7
		442.7	430.3	418.6	408.4	383.3
		442.4	430.0	418.7	408.6	383.9
		442.7	430.3	418.9	408.7	384.0
		442.5	430.3	418.9	408.6	383.9
Average height (mm	528.5	442.5	430.2	418.7	408.6	383.8



Average velocity = 0.910 (m/s)
Pressure slope = 6.296 (mm/m)

TEST D5

SET-UP

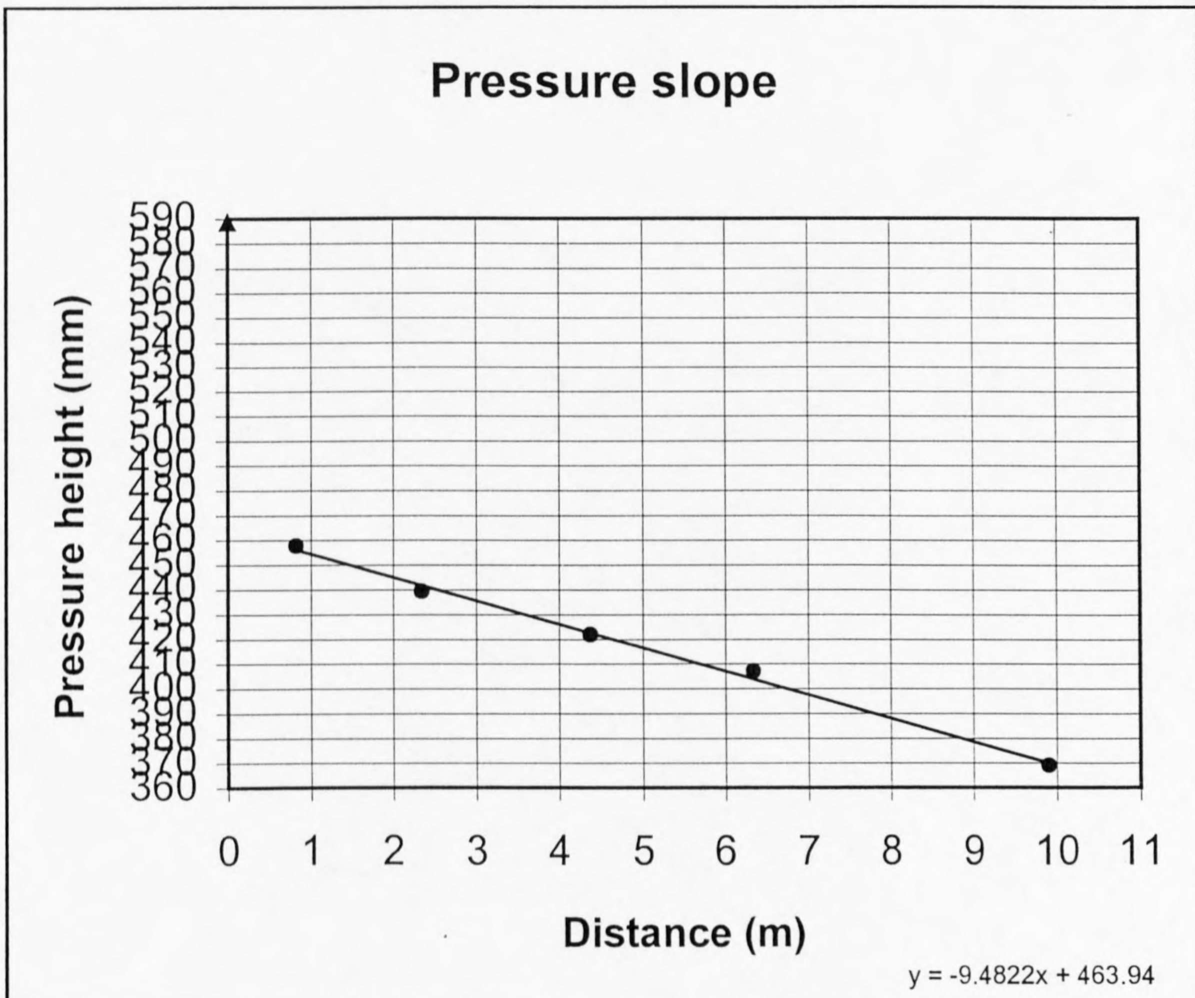
Step size (mm)	3
Steps/m	9.2

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	70.0	29.02
V-notch	213.5	29.11
Difference (%)		0.3%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.828	2.35	4.375	6.336	9.901
Pressure heights (mm)		457.8	439.5	422.0	407.1	369.4
		457.9	439.4	422.0	407.4	369.3
		457.6	439.0	421.5	406.8	368.6
		457.2	438.9	421.4	406.7	368.5
		456.9	438.7	421.5	406.7	368.8
Average height (mm	588.5	457.5	439.1	421.7	406.9	368.9



Average velocity = 1.131 (m/s)
Pressure slope = 9.4822 (mm/m)

TEST E1

SET-UP

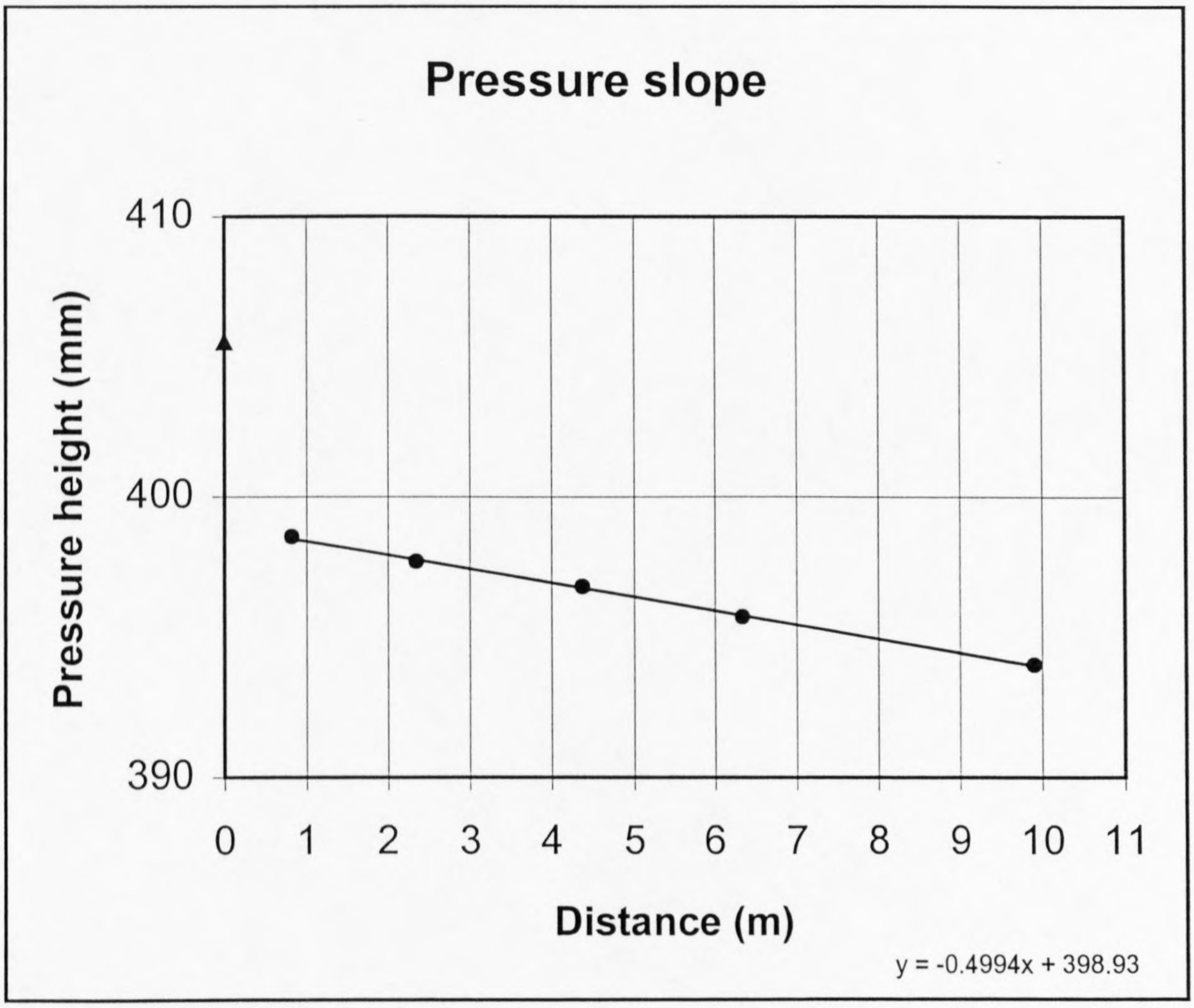
Step size (mm)	3
Steps/m	13.8

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	2.8	5.80
V-notch	112.4	5.85
Difference (%)		0.8%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.826	2.35	4.379	6.339	9.901
Pressure heights (mm)		398.6	397.8	396.9	395.8	394.1
		398.6	397.8	396.8	395.8	394.1
		398.6	397.7	396.8	395.7	393.8
		398.6	397.5	396.7	395.5	394.1
		398.5	397.6	396.7	395.7	394.0
Average height (mm	405.5	398.6	397.7	396.8	395.7	394.0



Average velocity = 0.227 (m/s)
Pressure slope = 0.4994 (mm/m)

TEST E2

SET-UP

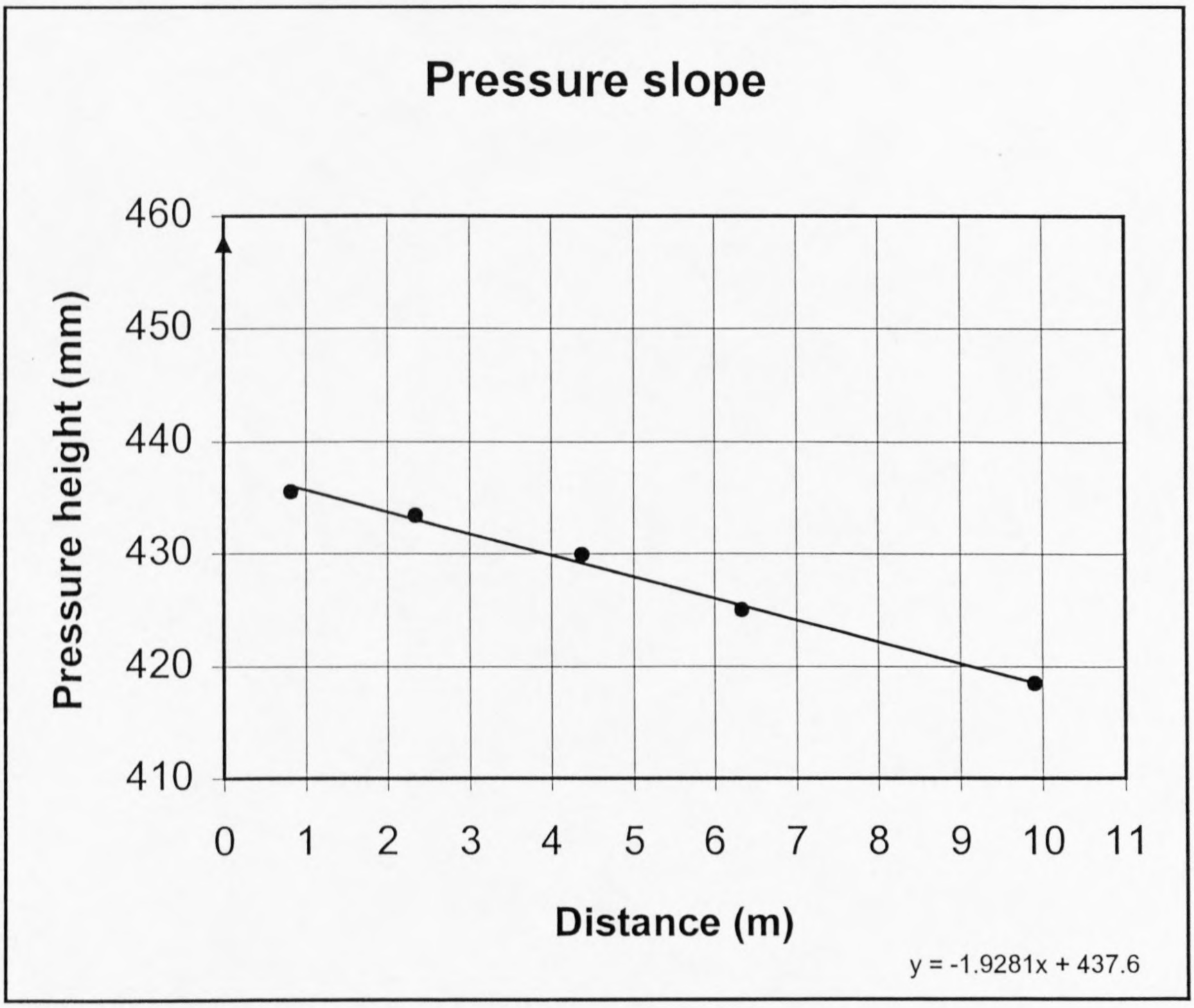
Step size (mm)	3
Steps/m	13.8

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	11.0	11.50
V-notch	149.3	11.90
Difference (%)		3.3%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.826	2.35	4.379	6.339	9.901
Pressure heights (mm)		435.4	433.0	429.8	424.5	418.2
		435.1	433.5	429.7	425.1	418.3
		435.5	433.4	429.9	425.0	418.4
		435.5	433.6	430.0	425.1	418.5
		435.7	433.5	430.1	425.0	418.7
Average height (mm	457.5	435.4	433.4	429.9	424.9	418.4



Average velocity = 0.462 (m/s)
Pressure slope = 1.9281 (mm/m)

TEST E3

SET-UP

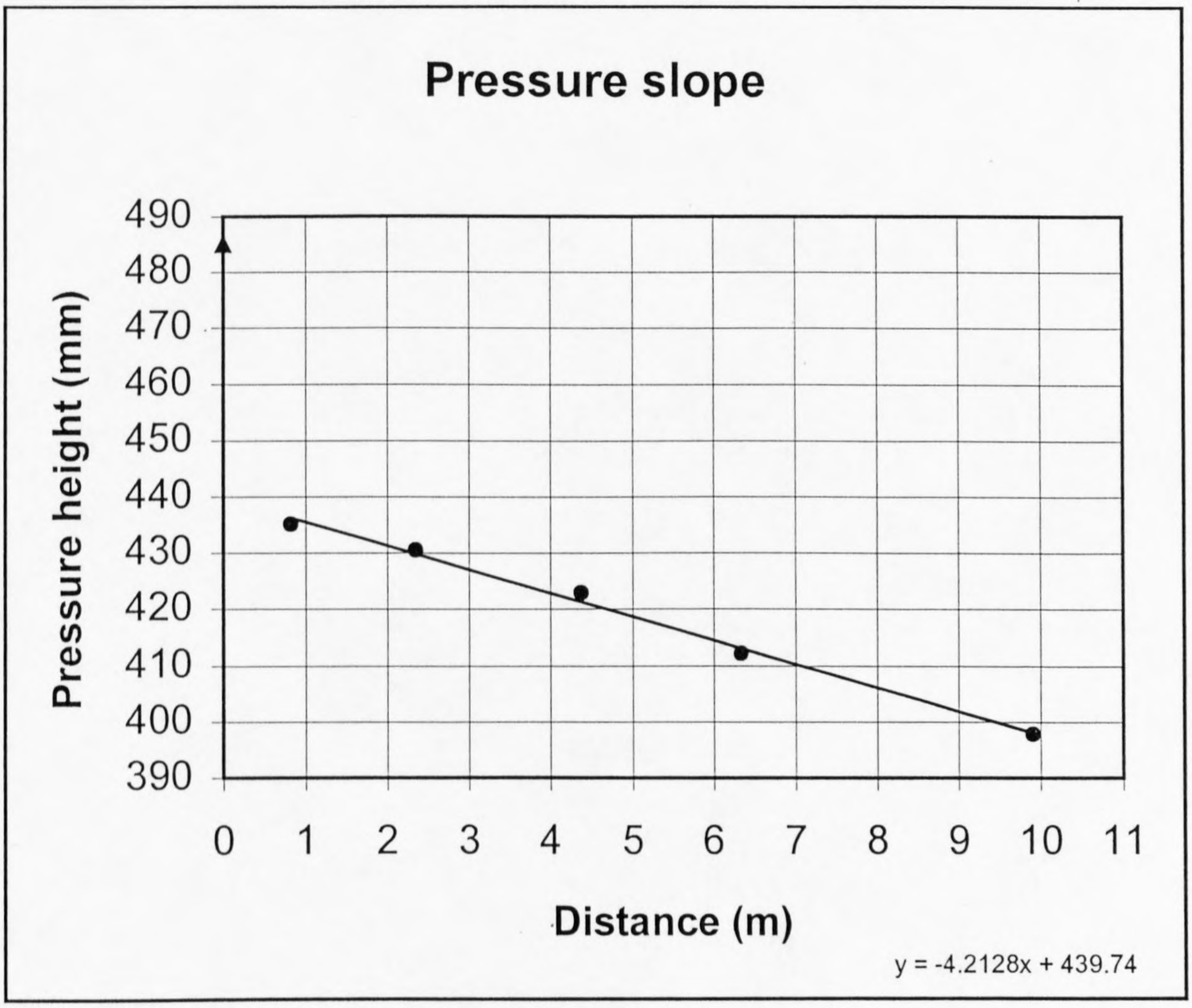
Step size (mm)	3
Steps/m	13.8

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	25.5	17.52
V-notch	175.4	17.81
Difference (%)		1.6%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.826	2.35	4.379	6.339	9.901
Pressure heights (mm)		435.0	430.5	422.8	411.9	397.8
		435.1	430.3	422.9	412.2	397.8
		435.2	430.5	422.9	412.3	397.9
		435.1	430.6	423.1	412.2	397.7
		435.1	430.3	423.0	412.1	397.9
Average height (mm	485	435.1	430.4	422.9	412.1	397.8



Average velocity = 0.692 (m/s)
Pressure slope = 4.2128 (mm/m)

TEST E4

SET-UP

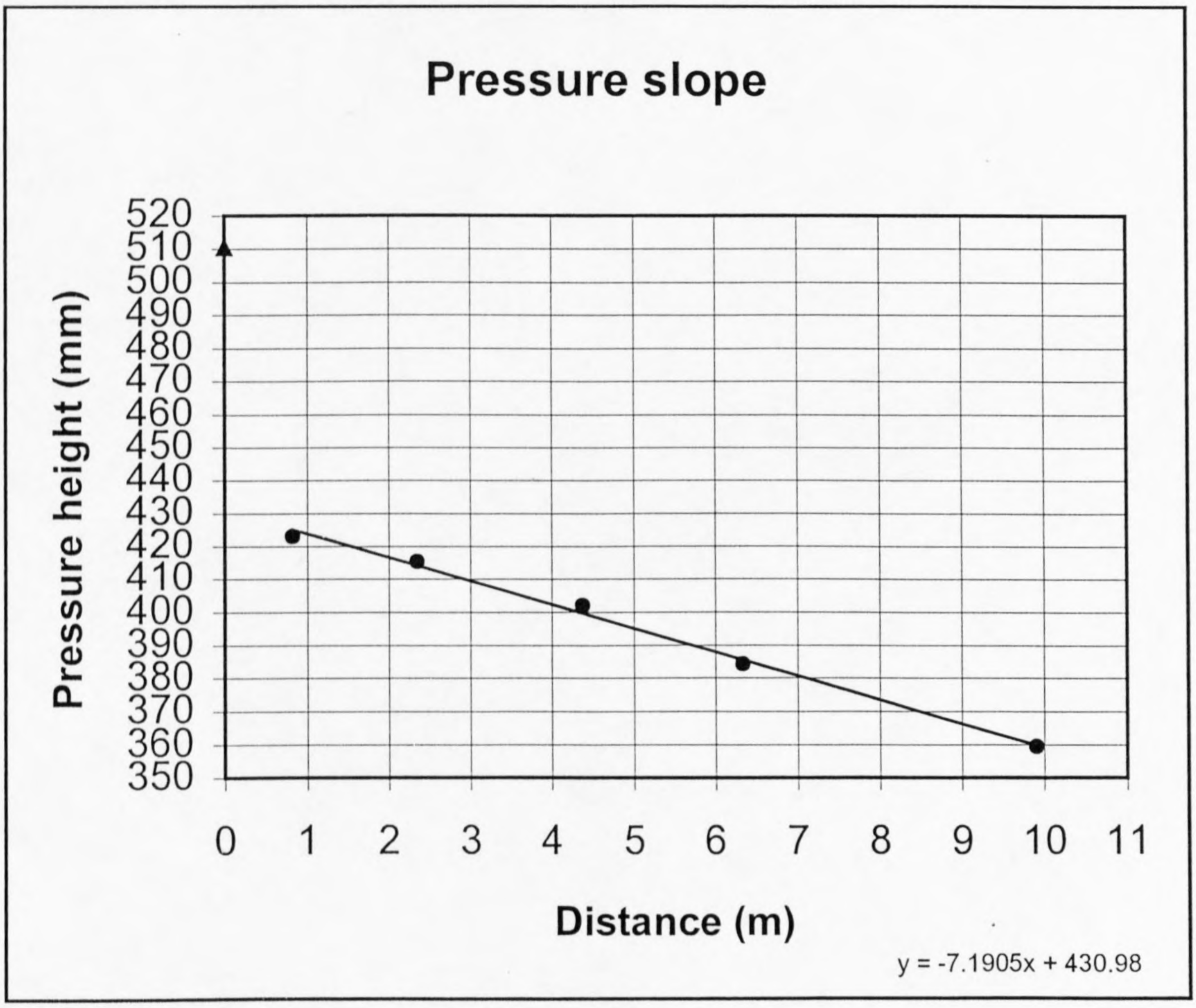
Step size (mm)	3
Steps/m	13.8

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	45.0	23.27
V-notch	195.7	23.41
Difference (%)		0.6%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.826	2.35	4.379	6.339	9.901
Pressure heights (mm)		423.3	415.6	402.5	384.7	359.7
		423.1	415.5	401.9	384.0	359.5
		422.9	415.3	401.5	383.5	358.6
		422.5	415.0	401.5	383.9	360.0
		423.2	415.5	402.3	384.3	359.3
Average height (mm	510.5	423.0	415.4	401.9	384.1	359.4



Average velocity = 0.910 (m/s)
Pressure slope = 7.1905 (mm/m)

TEST E5

SET-UP

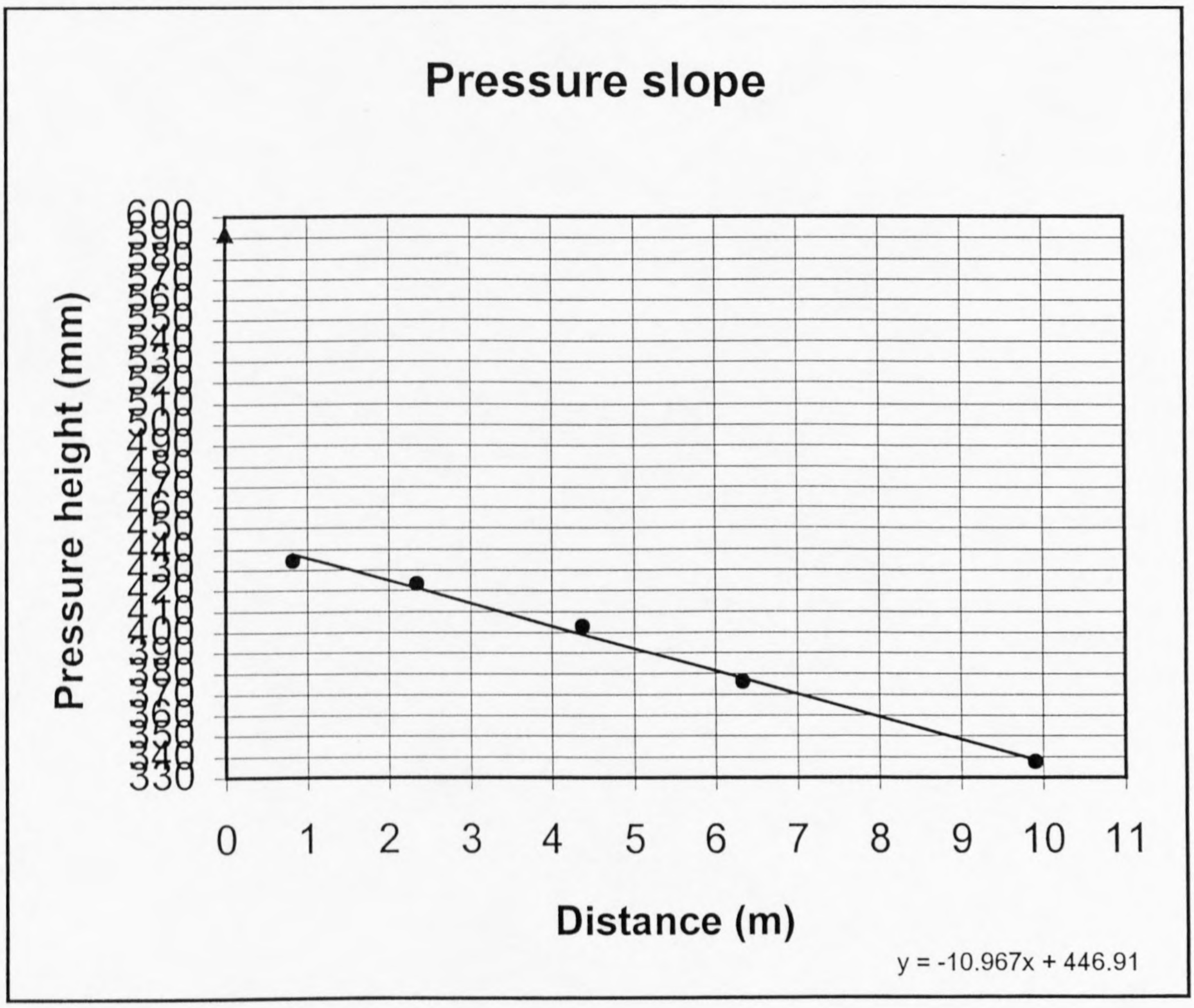
Step size (mm)	3
Steps/m	13.8

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	71.5	29.33
V-notch	213.8	29.21
Difference (%)		-0.4%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.826	2.35	4.379	6.339	9.901
Pressure heights (mm)		434.7	423.3	403.2	376.0	337.4
		434.2	423.2	402.6	375.6	337.5
		434.2	423.2	402.7	375.9	337.3
		434.4	423.2	402.9	375.9	337.3
		434.4	423.1	402.7	375.6	337.6
Average height (mm	591.5	434.4	423.2	402.8	375.8	337.4



Average velocity = 1.135 (m/s)
Pressure slope = 10.967 (mm/m)

TEST F1

SET-UP

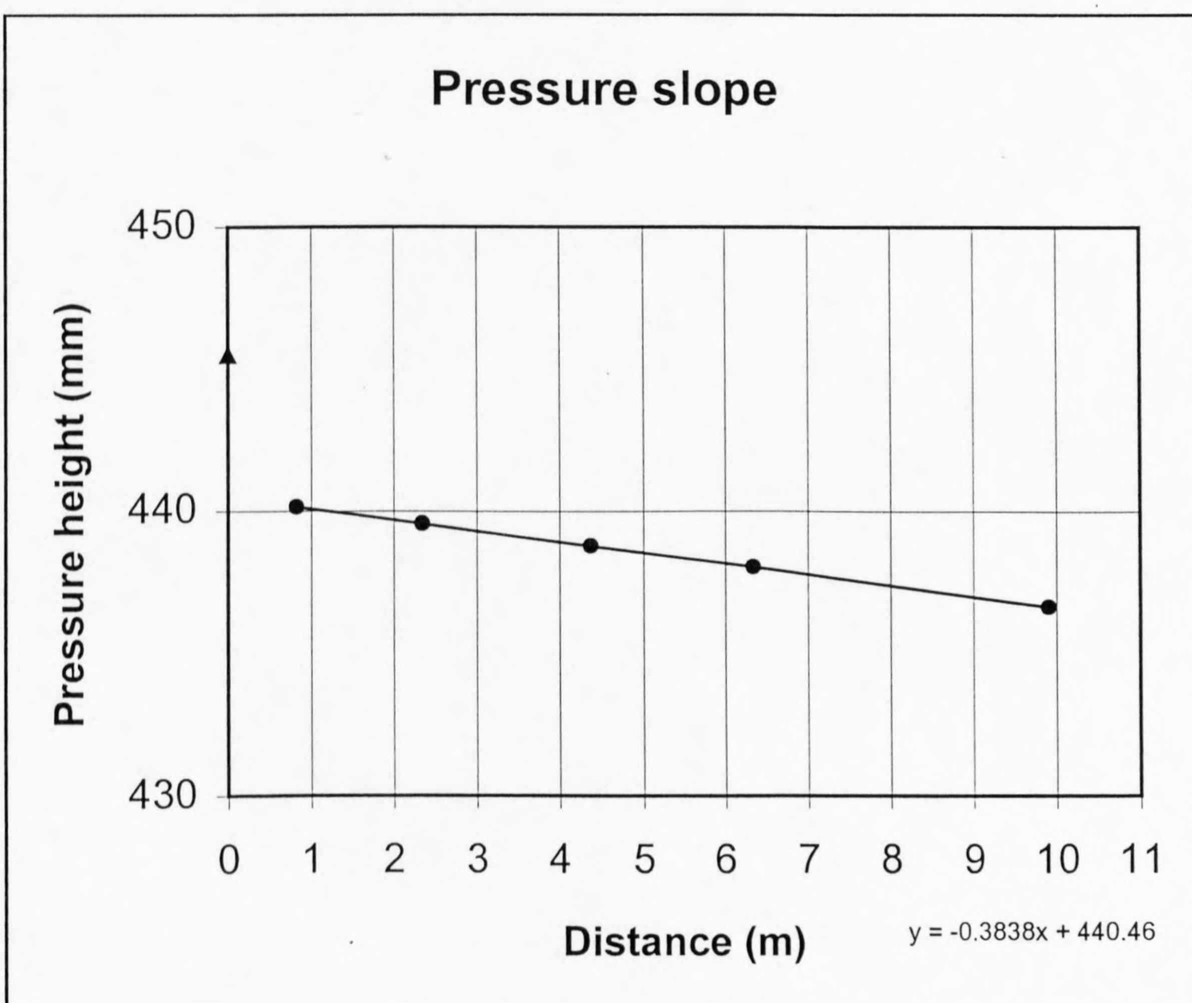
Step size (mm)	1
Steps/m	6.9

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	3.0	6.01
V-notch	112.4	5.85
Difference (%)		-2.6%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.828	2.35	4.377	6.338	9.904
Pressure heights (mm)		440.0	439.3	438.6	437.8	436.6
		440.0	439.6	438.6	438.0	436.4
		440.1	439.5	438.9	438.1	436.7
		440.3	439.7	438.8	438.2	436.8
		440.3	439.7	439.0	438.0	436.8
Average height (mm	445.5	440.1	439.6	438.8	438.0	436.7



Average velocity = 0.227 (m/s)
Pressure slope = 0.3838 (mm/m)

TEST F2

SET-UP

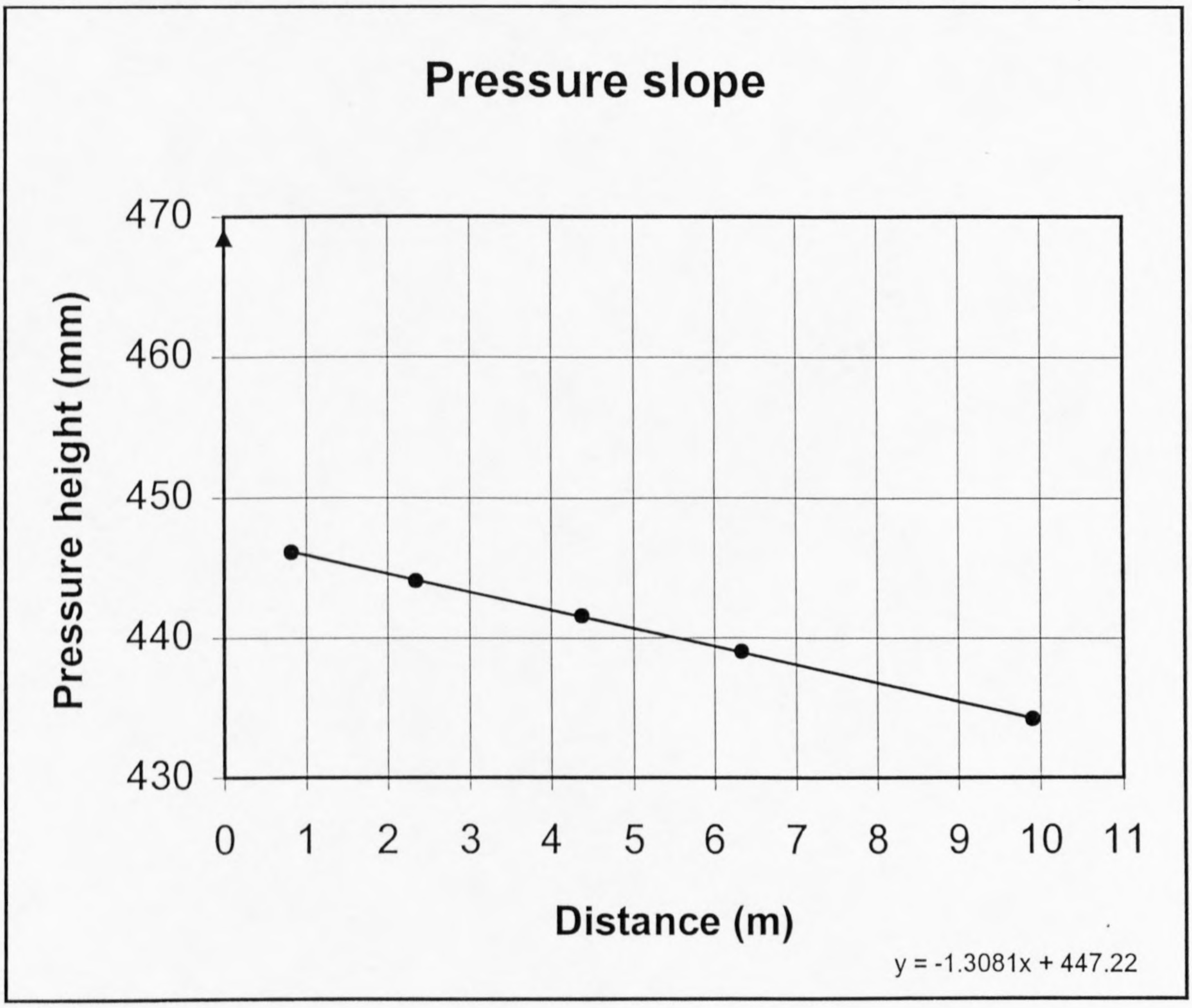
Step size (mm)	1
Steps/m	6.9

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	11.0	11.50
V-notch	148.3	11.70
Difference (%)		1.7%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.828	2.35	4.377	6.338	9.904
Pressure heights (mm)		445.8	443.9	441.4	438.8	434.0
		446.1	443.9	441.5	438.8	434.2
		446.1	444.1	441.6	439.1	434.2
		446.2	444.3	441.6	439.1	434.2
		446.3	444.3	441.8	439.2	434.4
Average height (mm	468.5	446.1	444.1	441.6	439.0	434.2



Average velocity = 0.455 (m/s)
Pressure slope = 1.3081 (mm/m)

TEST F3

SET-UP

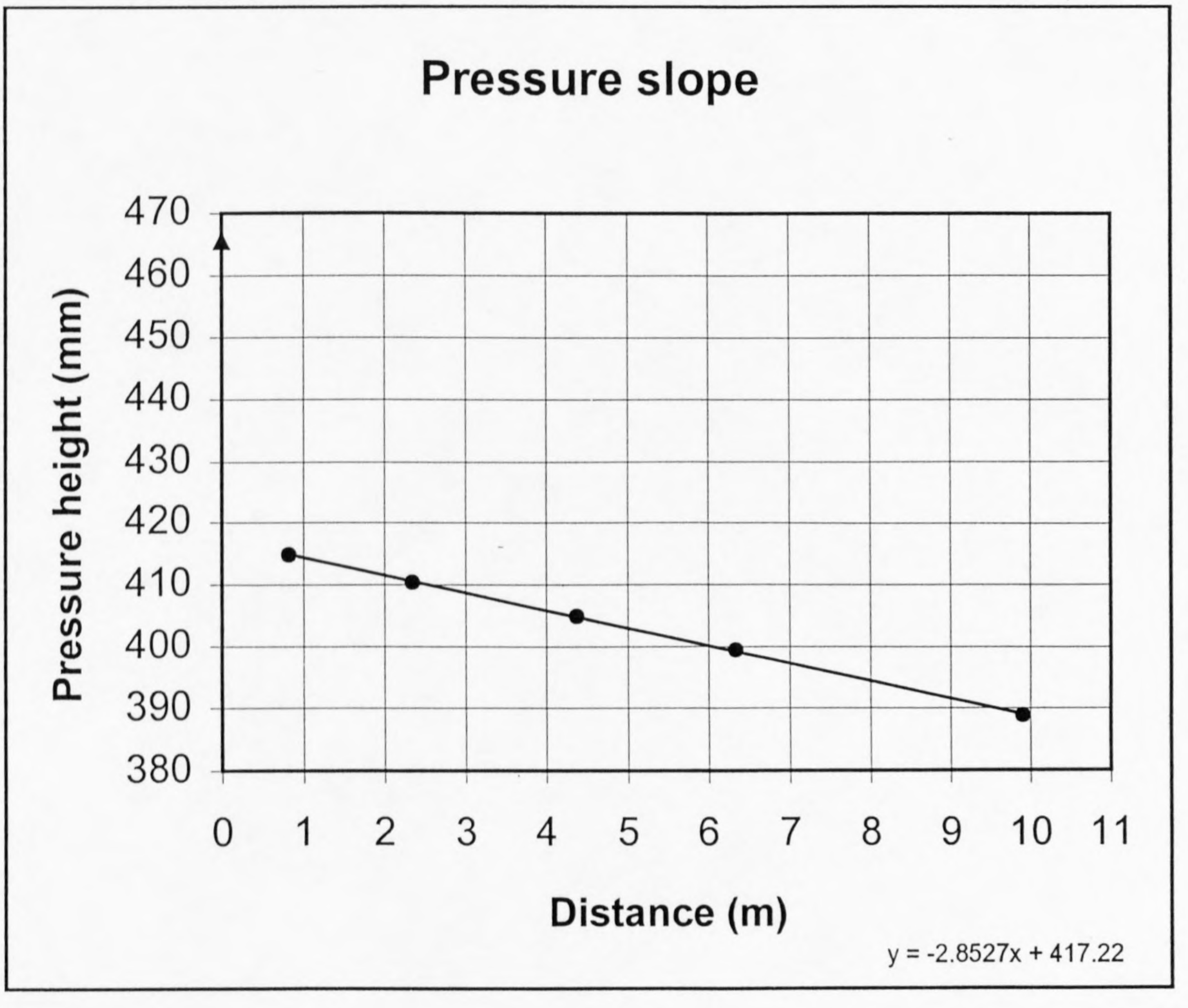
Step size (mm)	1
Steps/m	6.9

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	25.5	17.52
V-notch	174.7	17.63
Difference (%)		0.6%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.828	2.35	4.377	6.338	9.904
Pressure heights (mm)		414.7	410.3	404.7	399.2	388.8
		414.9	410.2	405.0	399.4	388.9
		415.0	410.4	405.0	399.4	388.4
		414.6	410.4	404.8	399.5	388.7
		414.7	410.5	405.0	399.6	389.0
Average height (mm	465.5	414.8	410.4	404.9	399.4	388.8



Average velocity = 0.685 (m/s)

Pressure slope = 2.8527 (mm/m)

TEST F4

SET-UP

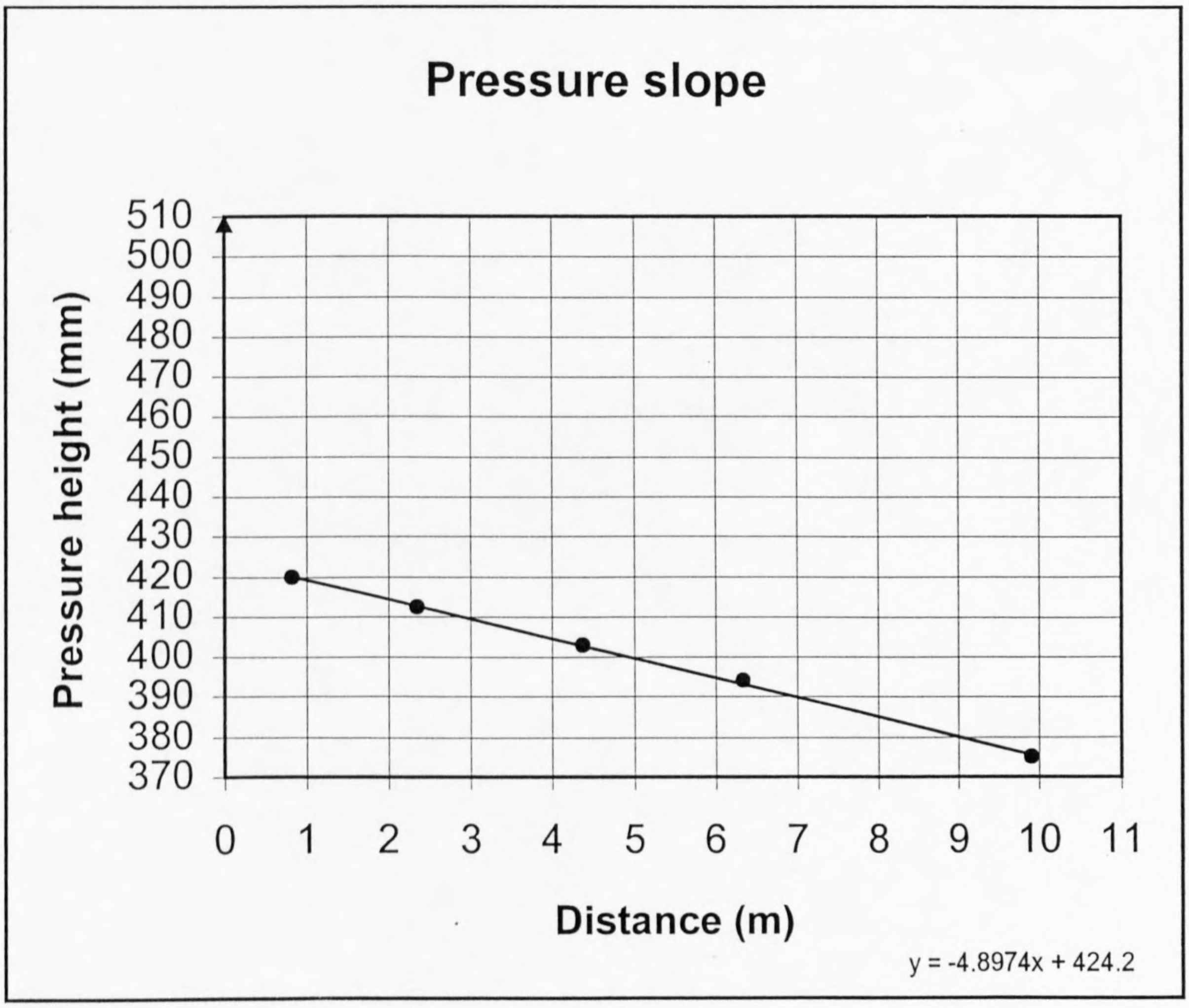
Step size (mm)	1
Steps/m	6.9

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	46.0	23.53
V-notch	195.7	23.41
Difference (%)		-0.5%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.828	2.35	4.377	6.338	9.904
Pressure heights (mm)		420.4	412.1	402.9	393.7	375.6
		420.0	412.6	403.1	394.2	375.4
		419.7	412.6	403.2	394.2	375.1
		420.0	412.4	402.8	394.0	374.4
		419.5	412.3	402.9	394.0	375.2
Average height (mm	508	419.9	412.4	403.0	394.0	375.1



Average velocity = 0.910 (m/s)
Pressure slope = 4.8974 (mm/m)

TEST F5

SET-UP

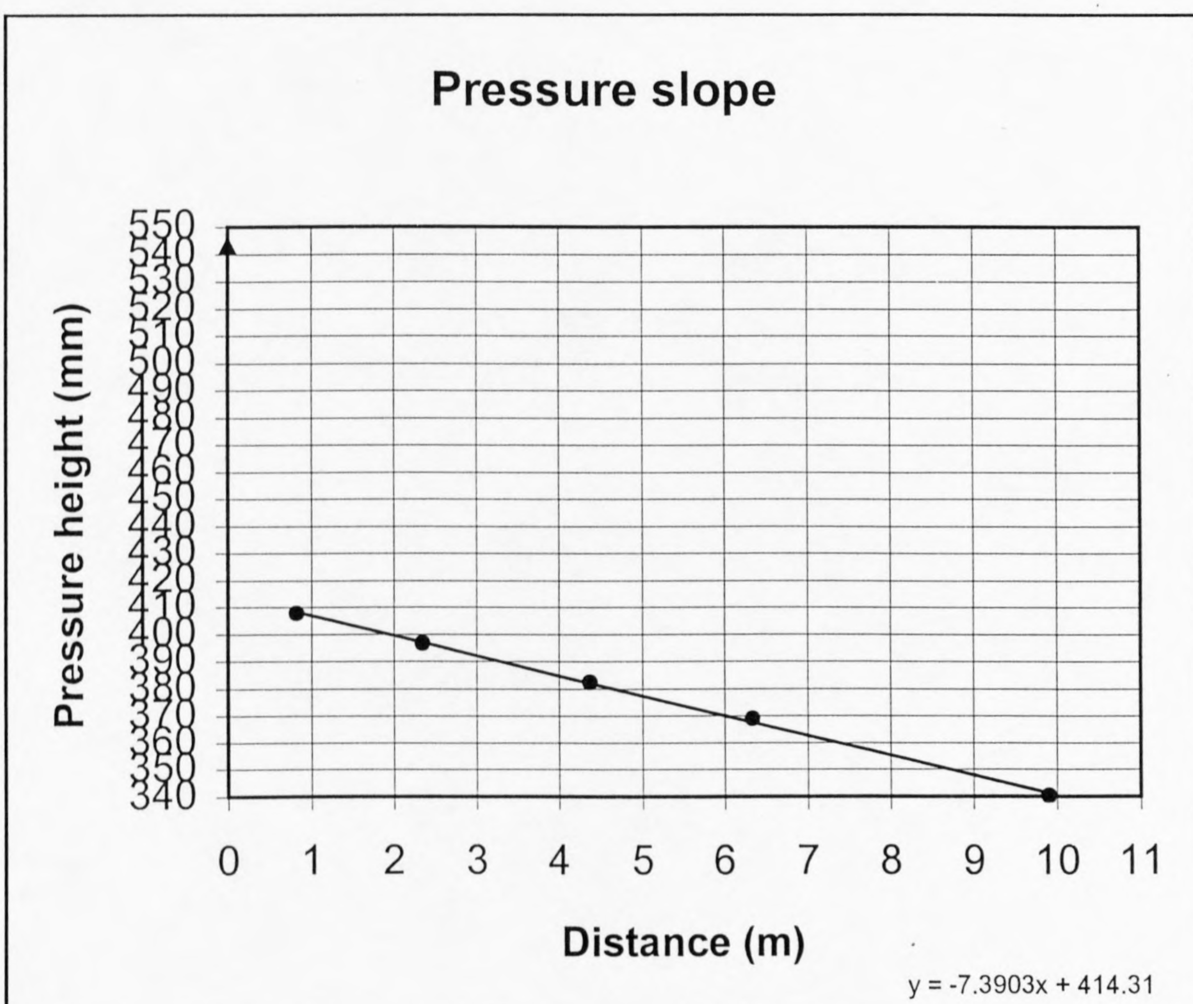
Step size (mm)	1
Steps/m	6.9

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	71.5	29.33
V-notch	213.9	29.24
Difference (%)		-0.3%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.828	2.35	4.377	6.338	9.904
Pressure heights (mm)		408.0	397.0	382.6	369.0	340.2
		407.9	396.9	382.4	369.2	340.2
		407.4	396.2	382.2	368.5	340.1
		407.1	396.4	382.2	368.8	340.2
		407.8	396.8	382.4	368.9	340.1
Average height (mm	543	407.6	396.7	382.4	368.9	340.2



Average velocity = 1.136 (m/s)
Pressure slope = 7.3903 (mm/m)

TEST G1

SET-UP

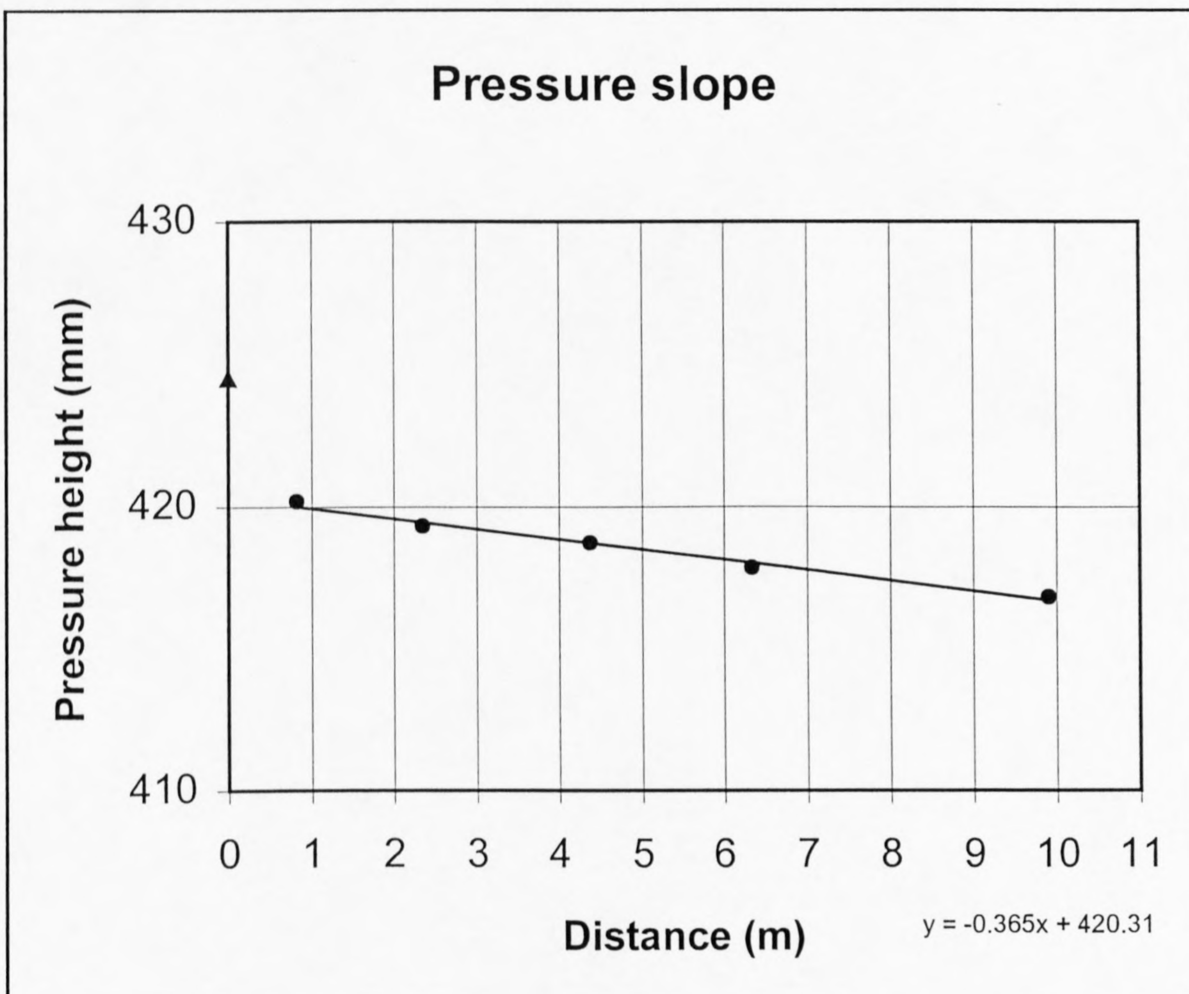
Step size (mm)	1
Steps/m	9.2

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	2.9	5.91
V-notch	112.4	5.85
Difference (%)		-0.9%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.826	2.349	4.378	6.338	9.902
Pressure heights (mm)		420.3	419.2	418.8	417.8	416.9
		420.2	419.3	418.8	417.8	416.8
		420.2	419.2	418.7	417.7	416.8
		420.0	419.5	418.6	417.9	416.7
		420.2	419.4	418.7	417.9	416.9
Average height (mm	424.5	420.2	419.3	418.7	417.8	416.8



Average velocity = 0.227 (m/s)

Pressure slope = 0.365 (mm/m)

TEST G2

SET-UP

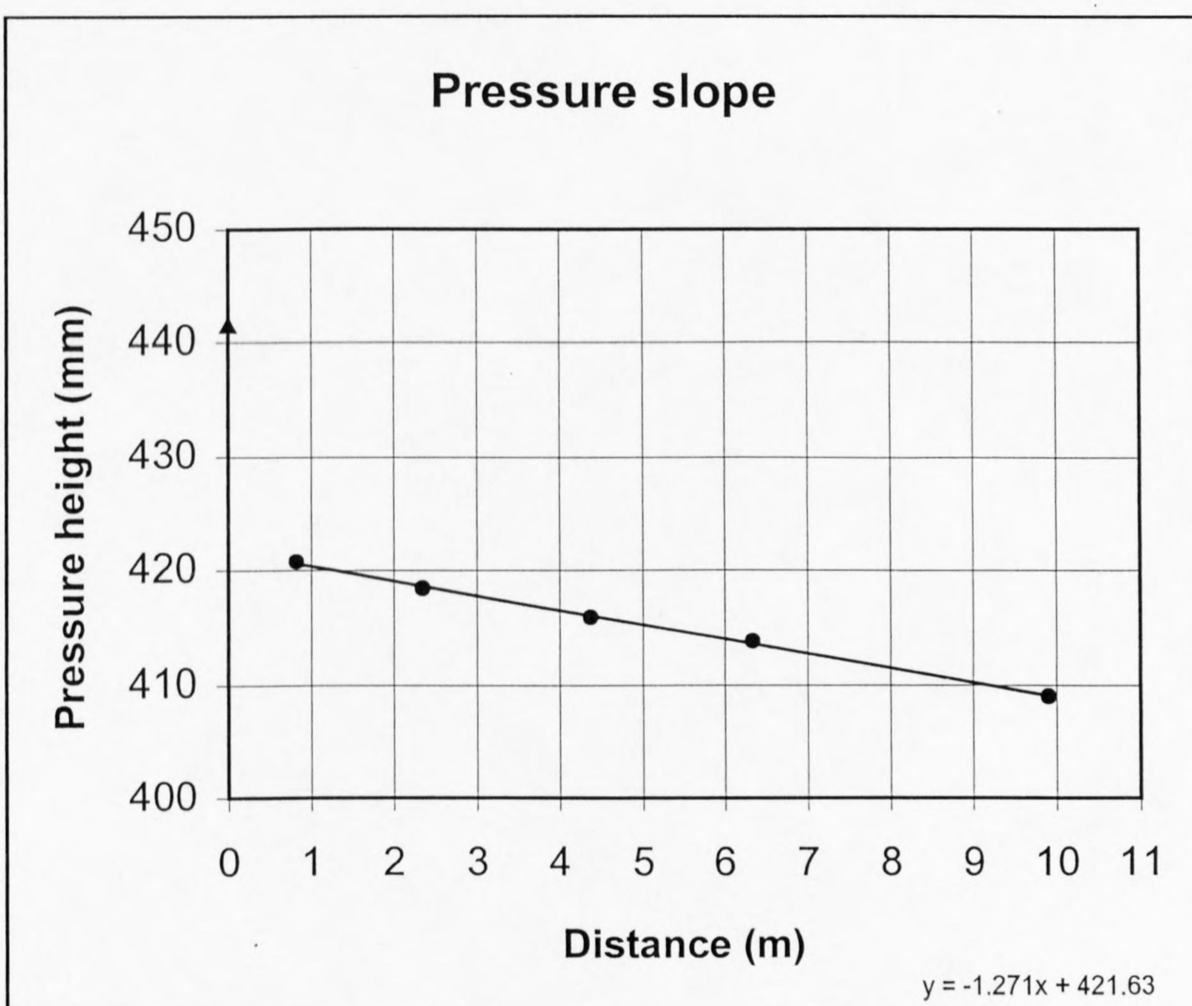
Step size (mm)	1
Steps/m	9.2

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	11.0	11.50
V-notch	148.3	11.70
Difference (%)		1.7%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.826	2.349	4.378	6.338	9.902
Pressure heights (mm)		420.8	418.5	416.0	413.8	409.1
		420.9	418.6	416.0	413.8	409.2
		420.8	418.3	416.0	413.8	409.0
		420.7	418.5	415.9	413.9	408.8
		420.5	418.4	415.7	413.7	408.9
Average height (mm	441.5	420.7	418.5	415.9	413.8	409.0



Average velocity = 0.455 (m/s)
Pressure slope = 1.271 (mm/m)

TEST G3

SET-UP

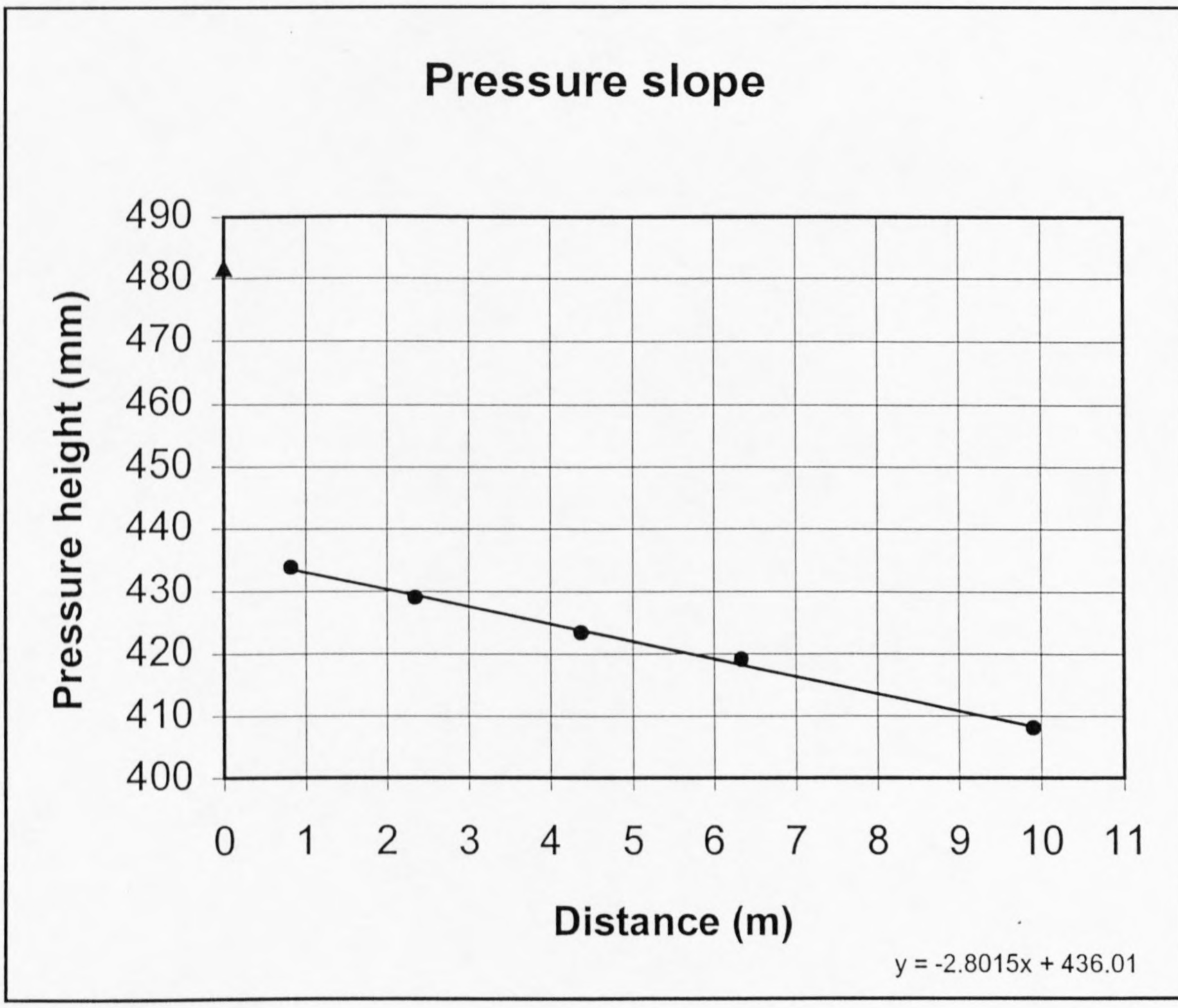
Step size (mm)	1
Steps/m	9.2

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	25.0	17.34
V-notch	175.1	17.73
Difference (%)		2.2%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.826	2.349	4.378	6.338	9.902
Pressure heights (mm)		434.2	429.2	423.4	419.3	408.2
		434.1	429.0	423.4	419.2	408.2
		434.0	429.0	423.4	419.0	408.1
		433.9	428.8	423.3	418.9	407.8
		433.8	428.8	423.3	419.0	407.7
Average height (mm	481.5	434.0	429.0	423.4	419.1	408.0



Average velocity = 0.689 (m/s)
Pressure slope = 2.8015 (mm/m)

TEST G4

SET-UP

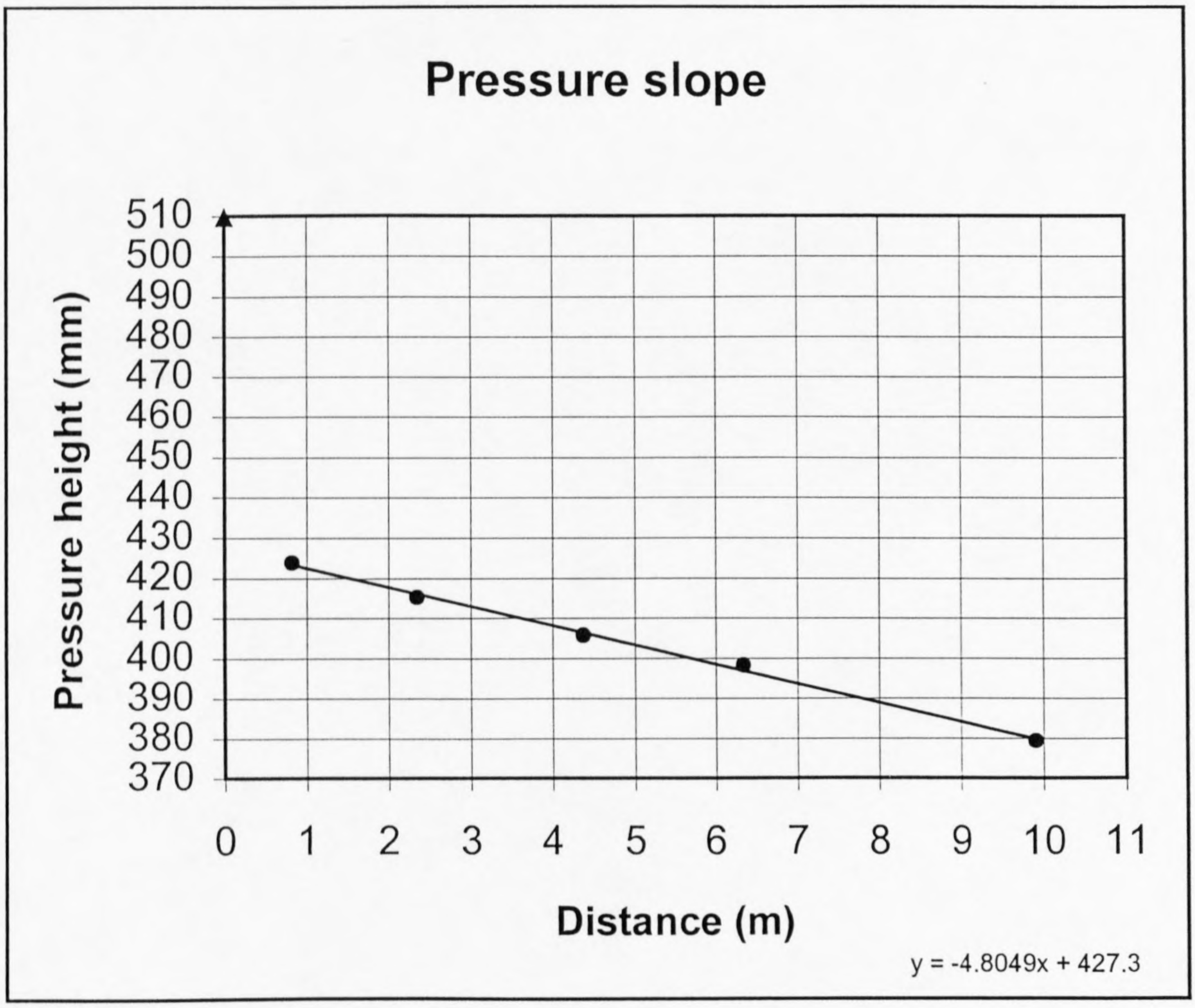
Step size (mm)	1
Steps/m	9.2

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	45.0	23.27
V-notch	195.8	23.44
Difference (%)		0.7%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.826	2.349	4.378	6.338	9.902
Pressure heights (mm)		424.4	415.7	405.7	398.4	379.0
		423.9	415.2	405.3	398.5	379.9
		423.4	414.8	406.4	398.8	379.5
		424.2	415.5	405.7	397.9	378.8
		423.4	414.5	405.3	397.7	379.0
Average height (mm	509.5	423.9	415.1	405.7	398.3	379.2



Average velocity = 0.911 (m/s)
Pressure slope = 4.8049 (mm/m)

TEST G5

SET-UP

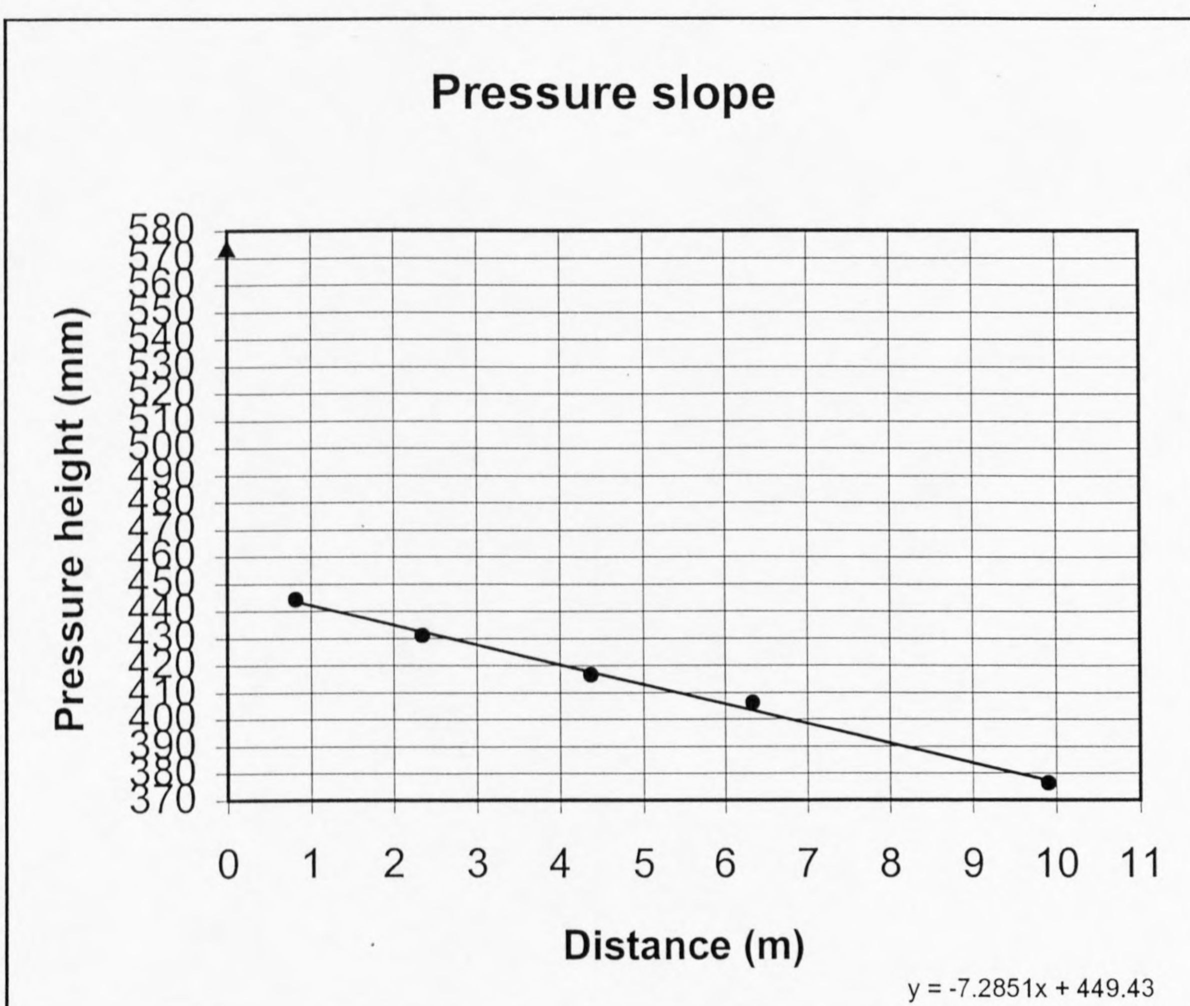
Step size (mm)	1
Steps/m	9.2

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	69.5	28.92
V-notch	213.3	29.04
Difference (%)		0.4%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.826	2.349	4.378	6.338	9.902
Pressure heights (mm)		443.8	430.7	416.3	405.7	376.4
		444.2	431.0	416.0	406.1	376.0
		444.0	430.8	416.8	406.3	376.6
		444.2	431.2	417.0	406.2	376.1
		444.1	430.9	416.7	406.0	375.9
Average height (mm	573.5	444.1	430.9	416.6	406.1	376.2



Average velocity = 1.128 (m/s)
Pressure slope = 7.2851 (mm/m)

TEST H1

SET-UP

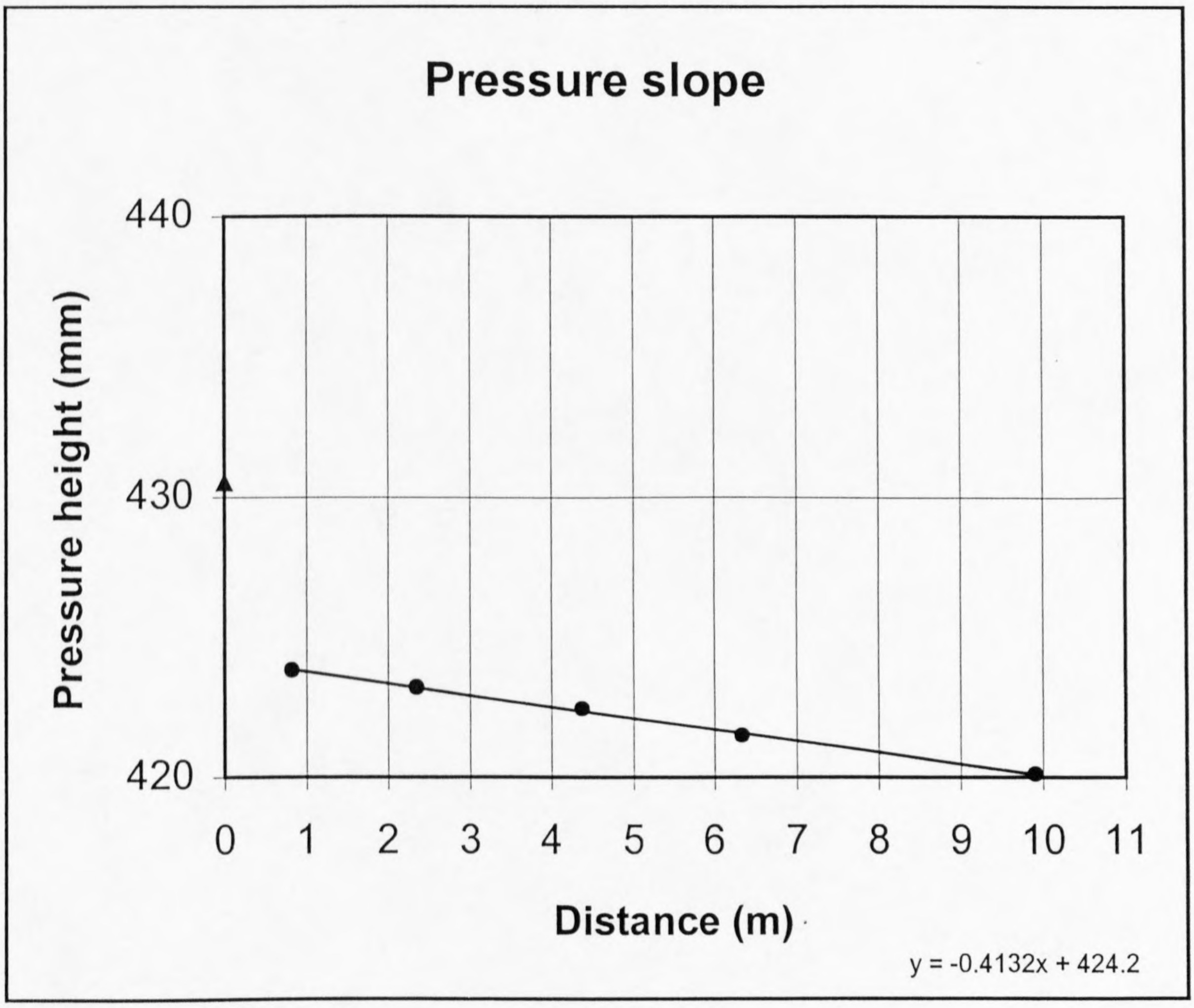
Step size (mm)	1
Steps/m	13.8

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	3.0	6.01
V-notch	112.4	5.85
Difference (%)		-2.6%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.828	2.35	4.38	6.34	9.907
Pressure heights (mm)		423.9	423.2	422.5	421.3	420.1
		423.8	423.3	422.4	421.6	420.0
		423.7	423.2	422.4	421.5	420.1
		423.9	423.2	422.5	421.5	420.2
		423.8	423.3	422.6	421.5	420.2
Average height (mm	430.5	423.8	423.2	422.5	421.5	420.1



Average velocity = 0.227 (m/s)
Pressure slope = 0.4132 (mm/m)

TEST H2

SET-UP

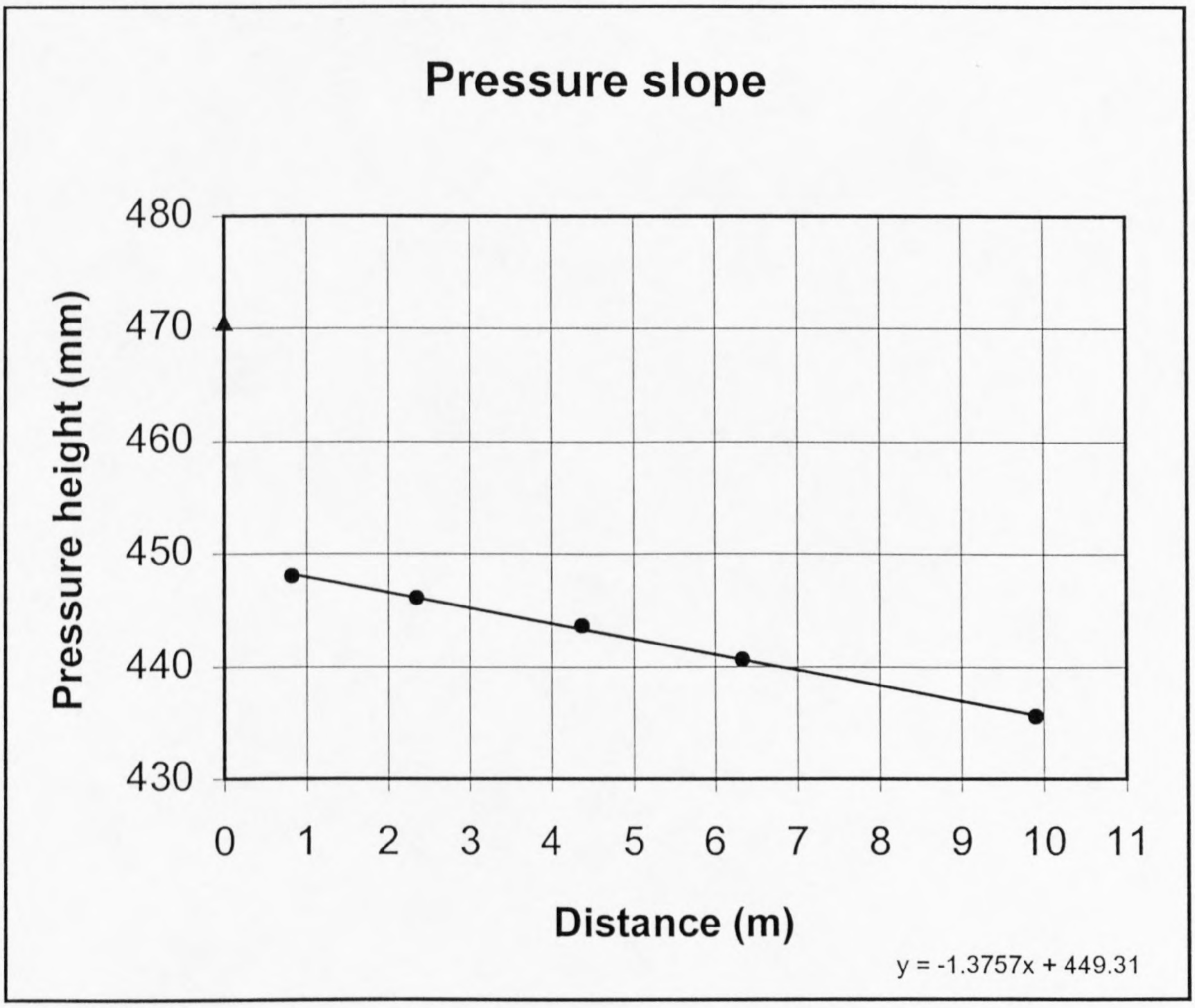
Step size (mm)	1
Steps/m	13.8

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	11.5	11.76
V-notch	148.3	11.70
Difference (%)		-0.5%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.828	2.35	4.38	6.34	9.907
Pressure heights (mm)		448.0	446.1	443.7	440.7	435.6
		448.0	446.0	443.6	440.6	435.4
		448.0	446.1	443.4	440.6	435.5
		448.1	446.0	443.6	440.5	435.7
		448.0	446.0	443.6	440.7	435.6
Average height (mm	470.5	448.0	446.0	443.6	440.6	435.6



Average velocity = 0.455 (m/s)
Pressure slope = 1.3757 (mm/m)

TEST H3

SET-UP

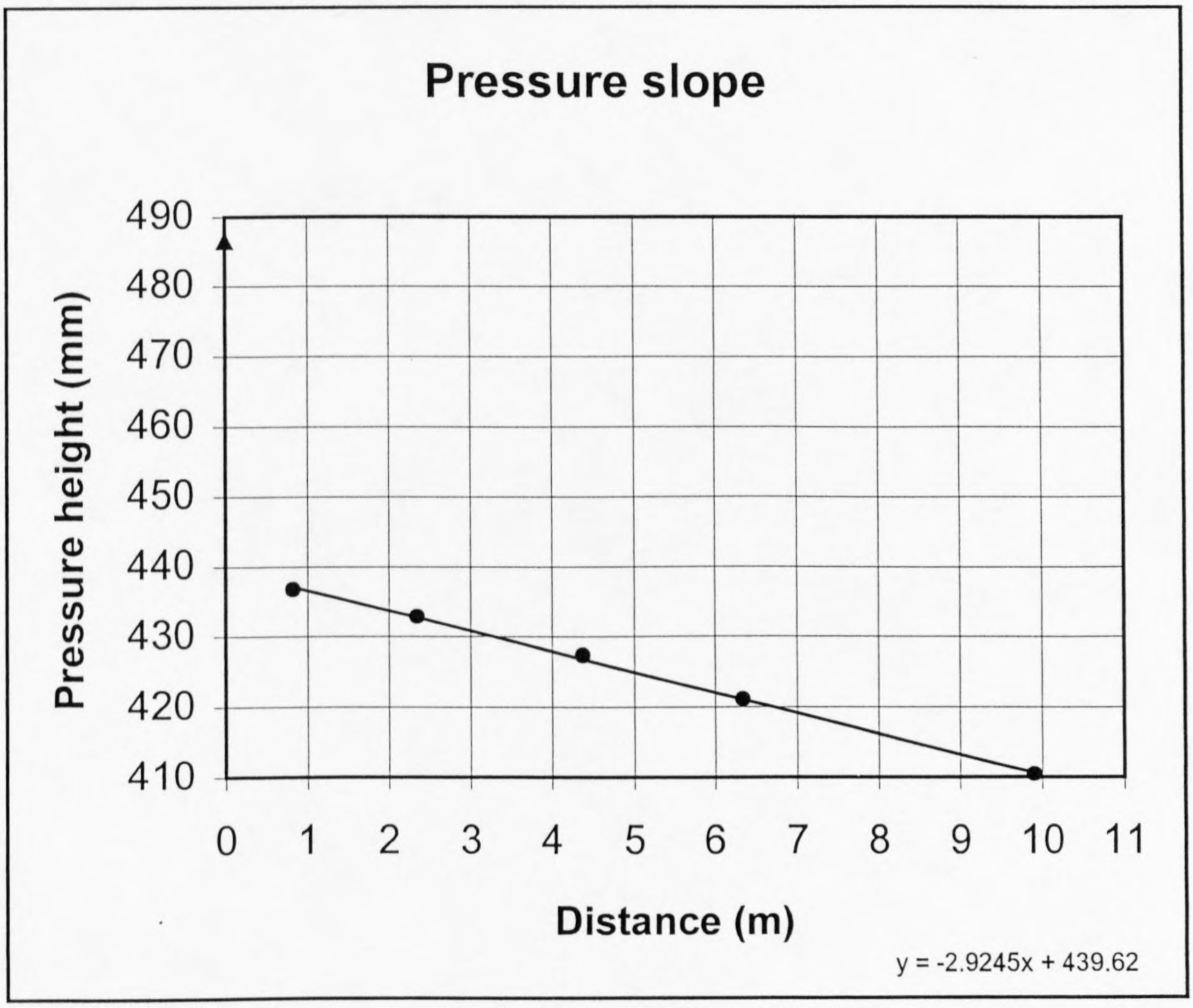
Step size (mm)	1
Steps/m	13.8

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	26.0	17.69
V-notch	174.4	17.55
Difference (%)		-0.8%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.828	2.35	4.38	6.34	9.907
Pressure heights (mm)		436.7	432.8	427.5	421.1	410.6
		436.9	432.8	427.5	421.1	410.4
		436.8	432.9	427.2	420.9	410.4
		436.7	433.0	427.4	421.1	410.3
		436.7	432.9	427.2	421.1	410.4
Average height (mm	486.5	436.8	432.9	427.4	421.1	410.4



Average velocity = 0.682 (m/s)
Pressure slope = 2.9245 (mm/m)

TEST H4

SET-UP

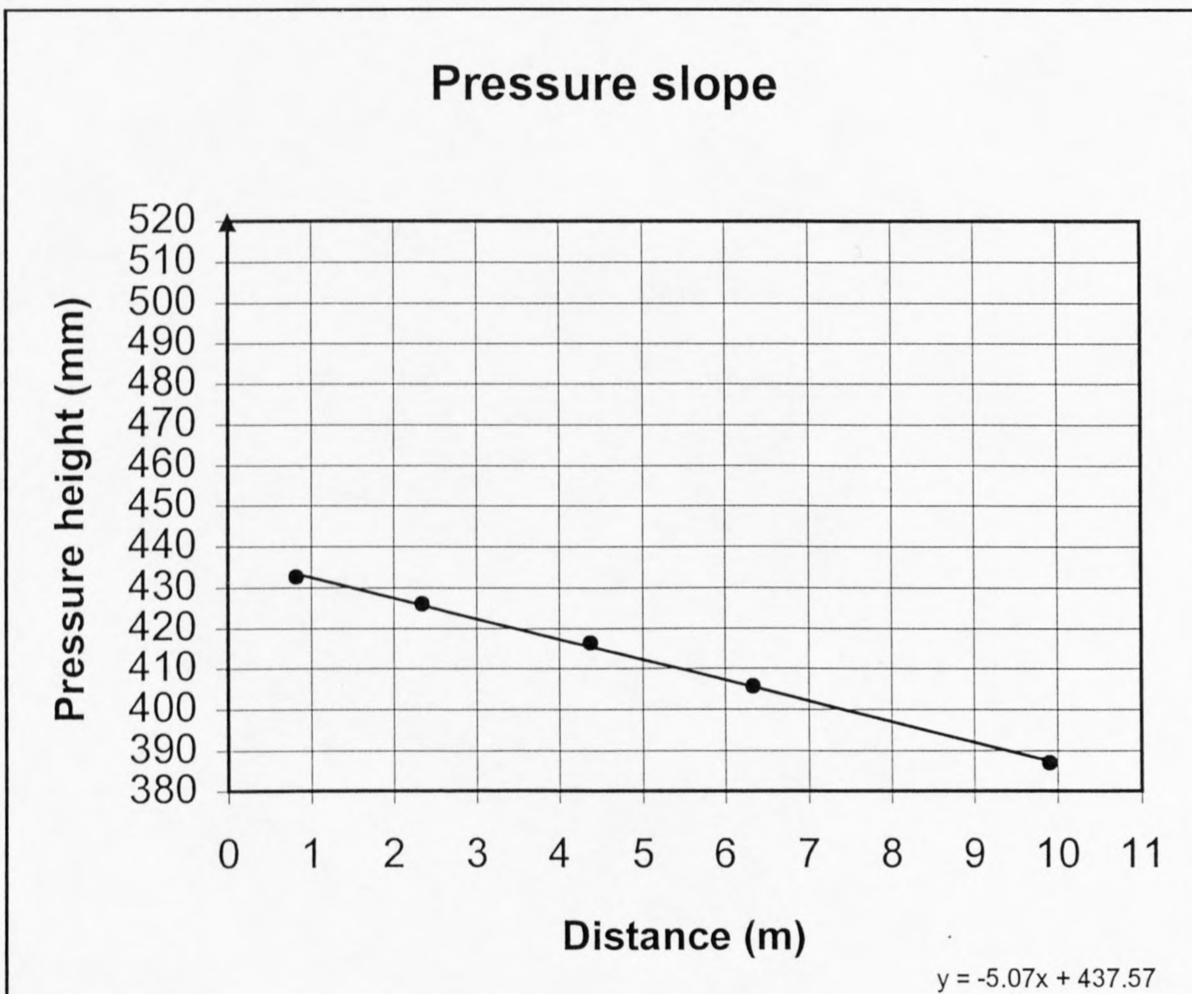
Step size (mm)	1
Steps/m	13.8

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	45.5	23.40
V-notch	195.6	23.38
Difference (%)		-0.1%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.828	2.35	4.38	6.34	9.907
Pressure heights (mm)		432.5	425.9	416.3	405.4	387.1
		432.8	426.5	416.9	405.7	386.6
		432.4	425.7	415.8	404.9	386.5
		432.2	426.0	416.3	406.1	386.8
		432.4	425.8	416.4	405.5	387.2
Average height (mm	519.5	432.5	426.0	416.3	405.5	386.8



Average velocity = 0.908 (m/s)
Pressure slope = 5.07 (mm/m)

TEST H5

SET-UP

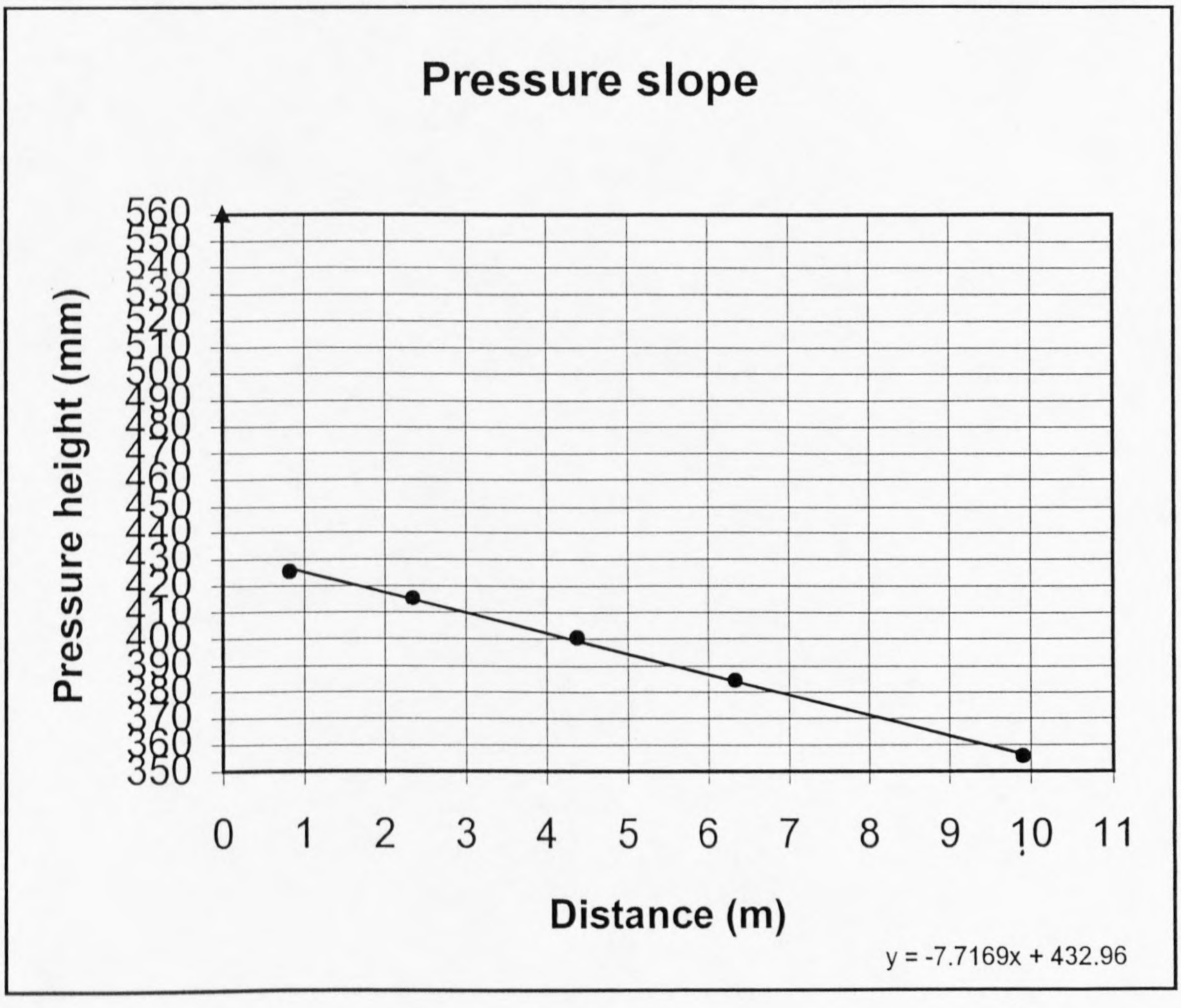
Step size (mm)	1
Steps/m	13.8

FLOW MEASUREMENT

	h (mm)	Q (l/s)
Manometer	72.0	29.43
V-notch	213.9	29.24
Difference (%)		-0.7%

MEASURED DATA

Reference point	Basin	1	2	3	4	5
Distance (m)	0	0.828	2.35	4.38	6.34	9.907
Pressure heights (mm)		425.3	415.4	400.7	384.7	356.7
		425.9	415.7	400.8	384.6	355.8
		425.3	415.5	400.3	384.6	355.7
		425.2	415.3	400.1	384.1	355.0
		424.6	414.8	400.1	383.8	355.5
Average height (mm	560	425.3	415.3	400.4	384.4	355.7



Average velocity = 1.136 (m/s)
Pressure slope = 7.7169 (mm/m)

APPENDIX B

SUMMARY OF TEST RESULTS

SUMMARY OF RESULTS

TEST NAME	REGRESSION SLOPE (m/m)	VELOCITY (m/s)	STEP SIZE (mm)	NUMBER OF STEPS PER METRE	NOTE
A1	0.0004055	0.234			Smooth pipe with no segments
A2	0.0010051	0.400			Smooth pipe with no segments
A3	0.0022680	0.643			Smooth pipe with no segments
A4	0.0040143	0.863			Smooth pipe with no segments
A5	0.0060484	1.071			Smooth pipe with no segments
B1	0.0003782	0.227	0		Segments aligned for pipe friction measurement
B2	0.0012779	0.455	0		Segments aligned for pipe friction measurement
B3	0.0027472	0.682	0		Segments aligned for pipe friction measurement
B4	0.0046206	0.910	0		Segments aligned for pipe friction measurement
B5	0.0071341	1.137	0		Segments aligned for pipe friction measurement
C1	0.0004568	0.227	3	6.9	
C2	0.0016930	0.466	3	6.9	
C3	0.0035164	0.686	3	6.9	
C4	0.0062263	0.917	3	6.9	
C5	0.0095072	1.137	3	6.9	
D1	0.0004725	0.233	3	9.2	
D2	0.0016360	0.455	3	9.2	
D3	0.0036177	0.694	3	9.2	
D4	0.0062960	0.910	3	9.2	
D5	0.0094822	1.131	3	9.2	
E1	0.0004994	0.227	3	13.8	
E2	0.0019281	0.463	3	13.8	
E3	0.0042128	0.692	3	13.8	
E4	0.0071905	0.910	3	13.8	
E5	0.0109666	1.135	3	13.8	
F1	0.0003838	0.227	1	6.9	
F2	0.0013081	0.455	1	6.9	
F3	0.0028527	0.685	1	6.9	

TEST NAME	REGRESSION SLOPE (m/m)	VELOCITY (m/s)	STEP SIZE (mm)	NUMBER OF STEPS PER METRE	NOTE
F4	0.0048974	0.910	1	6.9	
F5	0.0073903	1.137	1	6.9	
F1B	0.0003750	0.227	1	6.9	
F2B	0.0013495	0.457	1	6.9	
F3B	0.0027519	0.679	1	6.9	
F4B	0.0047366	0.910	1	6.9	
F5B	0.0071864	1.134	1	6.9	
G1	0.0003650	0.227	1	9.2	
G2	0.0012710	0.455	1	9.2	
G3	0.0028015	0.689	1	9.2	
G4	0.0048049	0.911	1	9.2	
G5	0.0072851	1.129	1	9.2	
G1B	0.0003891	0.227	1	9.2	
G2B	0.0013223	0.455	1	9.2	
G3B	0.0027923	0.682	1	9.2	
G4B	0.0047932	0.910	1	9.2	
G5B	0.0072700	1.137	1	9.2	
H1	0.0004132	0.227	1	13.8	
H2	0.0013757	0.455	1	13.8	
H3	0.0029245	0.682	1	13.8	
H4	0.0050700	0.909	1	13.8	
H5	0.0077169	1.137	1	13.8	