MASTER

An experimental facility to simulate the unsteady flow in piston pumps due to valve closure

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Abstract

A set-up was built to study the unsteady flow in piston pumps due to valve closure. In this set-up a valve closes under influence of a downward flow. The interaction of the pressure wave with the system and the influence of changes of the set-up on the pressure wave were studied.

A program that was written to simulate the pressure wave propagation in the set-up was only able to describe the first pressure rise reasonably. The results of the measurements show that the pressure build-up in the set-up can be described with pressure waves travelling through the system and reflecting at boundaries. The long term developement of the pressure wave can not be described accurately.

If the system is contains a very elastic element compared to the rigid steel delivery pipe (as in the case of the presence of an air chamber) the pressure build-up and the time dependence can also be described with a quasi-static theory in which the fluid is considered rigid.

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Contents

1 Introduction

The interest in unsteady flow, resulting from the closing of valves, in reciprocating piston pumps (fig. 1.1) stems from the idea that the unsteady flow may be the cause of the ecessive pump rod forces that are measured in these pumps.

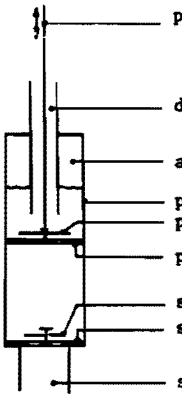

figure 1.1 piston pump

Pump rod forces due to hydrodynamic effects in piston pumps have already been studied by Verheij[9]. The importance of pump rod forces is motivated by the problem of pump rod failure that frequently occurs in piston pumps.

Another point of interest is the influence of the piping system on the pressure wave generated by the closing of the valve and the effect of an airchamber on the wave.

In order to study these unsteady flow phenomena a simple set-up, that makes use of a number of existing facilities, was designed and built.

Furthermore introductory experiments were carried out to determine the properties of the set-up and to study the effect of some modifications on the propagation of pressure waves. The available theory, see e.g. Wylie and Streeter[1], was translated in a computer program to simulate the pressure wave propagation, and the results were compared with the measurements.

Because of the introductory character of the measurements the subjects of gas release and cavitation were omitted.

In chapter two the theory that describes the propagation of pressure waves in rigid pipes is presented. It is also shown how the resulting equations are adapted for numerical purposes. Two simplified equations are introduced that allow a direct interpretation of the phenomena that occur at boundaries. Finally a quasi-static description of surge tanks and airchambers is given.

Chapter three describes the set-up in detail. The experimental procedure is described and a description of the measurement equipment is given.

In chapter four the experiments that were performed are described and the results are presented.

Conclusions and suggestions are given in chapter five.

2 Theory

2.1 Introduction

The theory that describes pressure transients following valve closure in rigid pipes is known as waterhammer theory. This theory is teated in many books such as Wylie and Streeter[1], Parmakian[2], Chaudry[3] and Fox[4]. In the theory presented in this chapter parts of these books are used. The main difference is in the use of the pressure p instead of the pressure head H. In paragraph 2.2 the continuity equation and momentum equation are developed for unsteady flow. Paragraph 2.3 gives a possible solution of these equations with the help of the method of characteristics. This method is used in an attempt to find a numerical solution of the unsteady flow in the specific configurations of chapter 3. Because the equations that are found are not very accessible for direct interpretation two simplified equations are derived. The simplified equations lead to the one-dimensional wave equation which allows for a more direct interpretation.

2.2 Waterhammer theory

First the equation of motion is developed similar to the treatment of Wylie and Streeter. This is basically a one dimensional treatment.

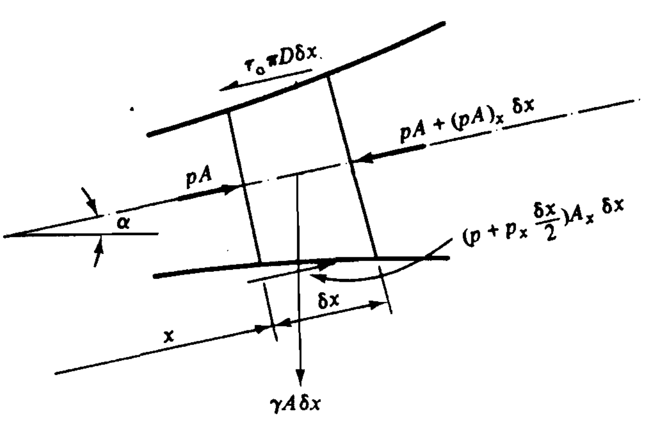

figure 2.1 fluid element with forces[1]

Figure 2.1 shows a fluid element between walls with the forces acting on it. The +x is the flow direction, which is inclined at an angle α with the horizontal. The forces acting on the fluid element are the pressure forces on the transverse sides of the element, the pressure force from the wall on the element because of the area change, the friction force because of the wall shear stress and the weight of the element. These forces must equal the time rate of change of momentum of the element.

$$pA - (pA+\frac{\partial(pA)}{\partial x}\delta x) + (p+\frac{1}{2}\frac{\partial p}{\partial x}\delta x)\frac{\partial A}{\partial x}\delta x - \tau_0\pi D\delta x - \rho gA\delta x\sin\alpha = \rho A\delta x\frac{dv}{dt} \qquad (2.1)$$

With only the terms of first order in δx this becomes

$$\frac{\partial p}{\partial x}A + \tau_0\pi D + \rho gA\sin\alpha + \rho A\frac{dv}{dt} = 0 \qquad (2.2)$$

If the shear stress is assumed to be the same as for steady flow, it can be written as

$$\tau_0 = \rho\frac{fv|v|}{8} \qquad (2.3)$$

with f the Darcy-Weisbach friction factor from the equation

$$\Delta p = \frac{\rho fLv^2}{2D} \qquad (2.4)$$

In reality the flow however is unsteady, and equation (2.4) underestimates the real pressure loss. Zielke[5] finds the shear stress in unsteady laminar flow to consist of two parts: a steady state part and a part that contains weighted past velocity changes. The high frequency components of the transients are attenuated more then the low frequency components. This results in an overall faster attenuation of the pressure waves and a distortion of the waves (fig. 2.2). For reasons of simplicity the steady state shear stress will be used in this thesis.

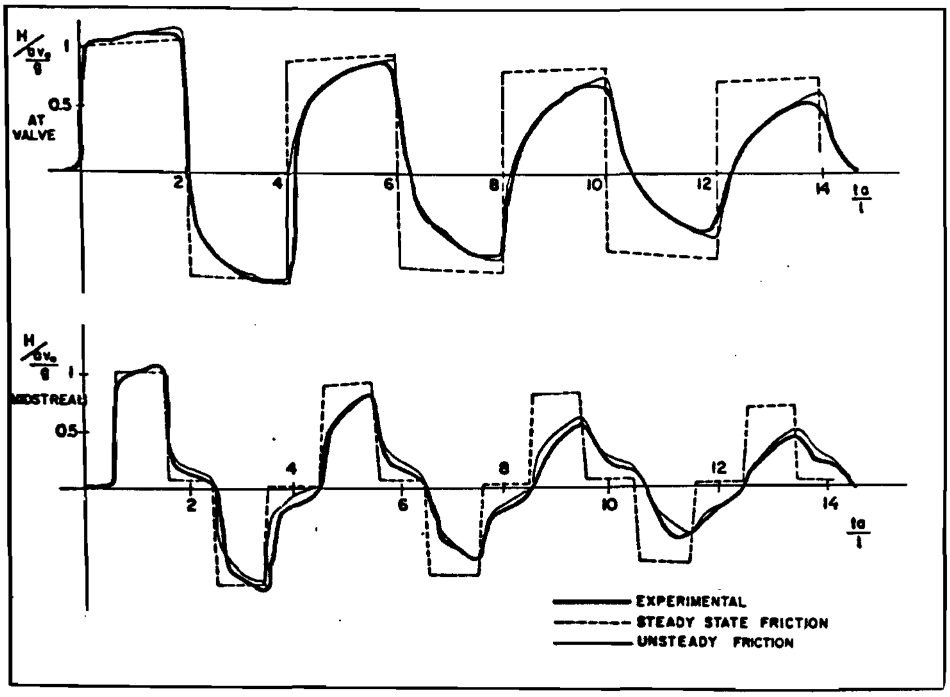

figure 2.2 attenuation and distortion of pressure waves[5]

Inserting equation (2.3) in equation (2.2) and dividing by ρA gives

$$\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{fv|v|}{2D} + g\sin\alpha + \frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} = 0 \qquad (2.5)$$

This is the first waterhammer equation (p instead of H).

The continuity equation.

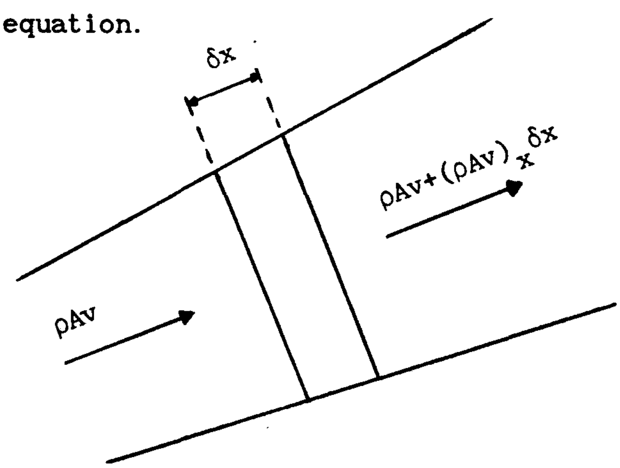

figure 2.3 control volume for continuity equation

Looking at figure 2.3 it can be seen that the continuity equation can be written as

$$\frac{\partial(\rho A v)}{\partial x} + \frac{\partial(\rho A)}{\partial t} = 0 \qquad (2.6)$$

This equation states that the time rate of change of the mass per unit length (ρA) is equal to minus the gradient of the mass flow (ρAv). Rewriting this equation in terms of two total derivatives and one partial derivative the result is

$$\frac{1}{A}\frac{dA}{dt} + \frac{1}{\rho}\frac{d\rho}{dt} + \frac{\partial v}{\partial x} = 0 \tag{2.7}$$

with

$$\frac{d}{dt} = \frac{\partial}{\partial t} + v\frac{\partial}{\partial x} \tag{2.8}$$

The next task is to write the total derivatives in equation (2.6) in terms of pressure. By looking at these two terms it is clear that $\frac{1}{A}\frac{dA}{dt}$ is a contribution of wall properties and $\frac{1}{\rho}\frac{d\rho}{dt}$ is a contribution of fluid properties. In case of a very flexible wall the density term is negligible and in case of a very rigid wall the area term is negligible. The fluid properties are incorporated in the density term via the definition of the bulk modulus of a fluid

$$K = \rho\frac{dp}{d\rho} = \rho c^2 \tag{2.9}$$

with c the sound wave velocity in the fluid. Now it follows that

$$\frac{1}{\rho}\frac{d\rho}{dt} = \frac{1}{K}\frac{dp}{dt} \tag{2.10}$$

The wall properties are incorporated in the area term via a stress-strain relationship. If the inner circumference of the pipe is πD and it changes by an amount Δ then the cicumferential strain is given by $\varepsilon_c = \frac{\Delta}{\pi D}$ or $\Delta = \varepsilon_c \pi D$. The new area is now $\frac{1}{4}\pi\,(1+\varepsilon_c)^2 D^2$, so the change is (first order in ε) $\frac{1}{2}\pi\varepsilon_c D^2$. Now write

$$\frac{1}{A}\frac{dA}{dt} = 2\frac{d\varepsilon_c}{dt} \tag{2.11}$$

This circumferential strain ε_c depends on the circumferential unit stress σ_c and the axial unit stress σ_a according to

$$\varepsilon_c = \frac{\sigma_c}{E} - \mu\frac{\sigma_a}{E} \qquad (2.12)$$

in which

E = Young's modulus of elasticity

μ = Poisson's ratio

Referring to figure 2.4 it can be seen that the circumferential unit stress is related to the pressure inside the pipe via the equation

$$\sigma_c = \frac{pLD}{2eL} = \frac{pD}{2e} \qquad (2.13)$$

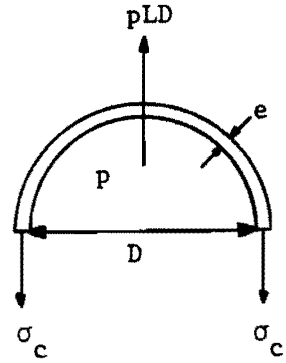

figure 2.4 forces on a semicylinder

Three cases can now easily be distinguished concerning the axial unit stress.

1) If the pipe is completely free to move in axial direction then σ_a=0 and

$$\varepsilon_c = \frac{\sigma_c}{E} = \frac{D}{2eE}\,\Delta p \qquad (2.14)$$

2) If the pipe is anchored at one end only then

$$\sigma_a = \frac{\frac{1}{4}\pi D^2 \Delta p}{\pi D e} = \frac{D\Delta p}{4e}$$

$$\varepsilon_c = (1-\mu)\frac{D}{2eE}\Delta p \qquad (2.15)$$

3) If the pipe is anchored against all longitudinal motion then ε_a=0 and

with the other stress-strain relation

$$\varepsilon_a = \frac{\sigma_a}{E} - \mu\frac{\sigma_c}{E} \tag{2.16}$$

the result is

$$\varepsilon_c = (1-\mu^2)\frac{D}{2eE}\Delta p \tag{2.17}$$

Equation (2.7) can now be rewritten as

$$\frac{1}{\rho}\frac{dp}{dt} + a^2\frac{\partial v}{\partial x} = 0 \tag{2.18}$$

with

$$a^2 = \frac{K/\rho}{1 + \frac{K}{E}\frac{D}{e}c_1} \tag{2.19}$$

and for each case

1) $c_1 = 1$

2) $c_1 = 1 - \frac{\mu}{2}$

3) $c_1 = 1 - \mu^2$

From further evaluation of the continuity and momentum equation it will follow that the constant a represents the wave velocity of pressure waves in the fluid filled pipe. If the pipe wall is relatively thick ($\frac{D}{e}<25$) Wylie and Streeter give a different constant c_1 for each case because the stress in the wall is not uniform. Thick walled pipe:

1) $c_1 = \frac{2e}{D}(1+\mu) + \frac{D}{D+e}$

2) $c_1 = \frac{2e}{D}(1+\mu) + \frac{D}{D+e}(1-\frac{\mu}{2})$

3) $c_1 = \frac{2e}{D}(1+\mu) + \frac{D}{D+e}(1-\mu^2)$

2.4 The characteristic method

For the two partial differential equations (2.5) and (2.18) no general solution is available. To be able to obtain a numerical solution, the two equations will be transformed to four total differential equations by the method of characteristics. Write

$$\frac{1}{\rho}\frac{\partial p}{\partial x} + v\frac{\partial v}{\partial x} + \frac{\partial v}{\partial t} + g\sin\alpha + \frac{fv|v|}{2D} + \lambda\left[\frac{1}{\rho}\left(\frac{\partial p}{\partial t} + v\frac{\partial p}{\partial x}\right) + a^2\frac{\partial v}{\partial x}\right] = 0 \tag{2.20}$$

with λ an unknown parameter. Rearranging this

$$\frac{1}{\rho}\lambda\left[\left(v+\frac{1}{\lambda}\right)\frac{\partial p}{\partial x} + \frac{\partial p}{\partial t}\right] + (v+\lambda a^2)\frac{\partial v}{\partial x} + \frac{\partial v}{\partial t} + g\sin\alpha + \frac{fv|v|}{2D} = 0 \tag{2.21}$$

With total derivatives this can be written as

$$\frac{1}{\rho}\lambda\frac{dp}{dt} + \frac{dv}{dt} + g\sin\alpha + \frac{fv|v|}{2D} = 0 \tag{2.22}$$

together with

$$\frac{dx}{dt} = v+\frac{1}{\lambda} = v+\lambda a^2 \tag{2.23}$$

so

$$\lambda = \pm\frac{1}{a} \tag{2.24}$$

Combining (2.22), (2.23) and (2.24) this results in the characteristic equations

$$\frac{1}{\rho a}\frac{dp}{dt} + \frac{dv}{dt} + g\sin\alpha + \frac{fv|v|}{2D} = 0 \tag{2.25}$$

$$\frac{dx}{dt} = v+a \tag{2.26}$$

C^+

$$\frac{1}{\rho a}\frac{dp}{dt} - \frac{dv}{dt} - g\sin\alpha - \frac{fv|v|}{2D} = 0 \tag{2.27}$$

$$\frac{dx}{dt} = v-a \tag{2.28}$$

C^-

These equations state that along the curves (2.26) and (2.28) equations (2.25) and (2.27) are valid respectively. The curves are not straight lines in general because v and a depend on time and place. If however small intervals are considered then the curves can be thought of as straight lines. At one time t_1 the pressure and velocity being known at every x, the velocity and pressure at any later instant can be calculated by integrating equations (2.25) and (2.27) along their characteristic lines (fig. 2.5).

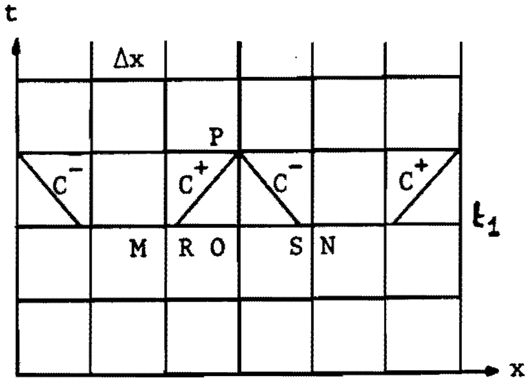

fig. 2.5 characteristic method with specified time intervals[1]

If a first order integration is used the finite difference forms of equations (2.25) and (2.27) are

$$p_P - p_R + a\rho(v_P - v_R) + a\rho g\Delta t\sin\alpha + \frac{f v_R|v_R|}{2D}\Delta t = 0 \qquad (2.29)$$

$$x_P - x_R = (v_R + a_R)\Delta t \qquad (2.30)$$

$$p_P - p_S - a\rho(v_P - v_S) - a\rho g\Delta t\sin\alpha - \frac{f v_S|v_S|}{2D}\Delta t = 0 \qquad (2.31)$$

$$x_P - x_S = (v_S - a_S)\Delta t \qquad (2.32)$$

In the solution of these equations for p_P and v_P first v_R, p_R and v_S, p_S are determined with a linear interpolation between M and O and O and N respectively. Now from equations (2.29) and (2.31) p_P and v_P can be calculated. In order to obtain a stable solution it is necessary to chose Δx and Δt in such a manner that $\Delta t(V+a)\leq\Delta x$. Furthermore it is advisable to chose these variables in such a way as to minimize interpolation errors; i.e. $\Delta t(V+a)\cong\Delta x$.

At a boundary one of the equations (2.29) or (2.31) is replaced by a boundary condition that specifies p_P or v_P or a relation between the two. Changes in pipe characteristics such as diameter, material and so on are also treated as boundary conditions. Examples of boundary conditions are

1) A dead end; with boundary condition v=0.
2) A constant height of the reservoir level. Refering to figure 2.6 the boundary condition is

$$p(0,t) = p_0 + \rho gh - \frac{1}{2}\rho v^2 \qquad (2.33)$$

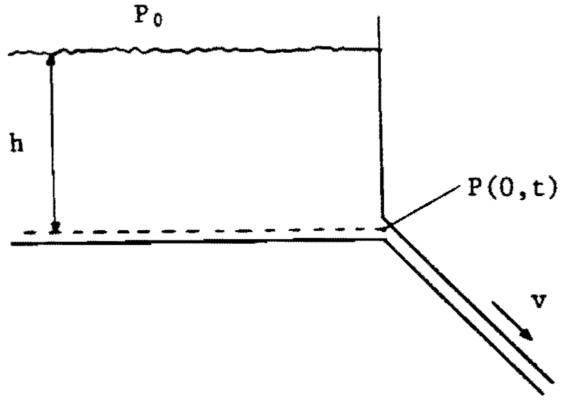

figure 2.6 flow from upstream reservoir through pipe

3) A valve. For a valve it is assumed that

$$\Delta p = \zeta \frac{1}{2}\rho v^2 \qquad (2.34)$$

with ζ a dimensionless parameter depending on the valve geometry and valve opening and Δp the pressure loss over the valve.

4) A series connection (fig. 2.7).

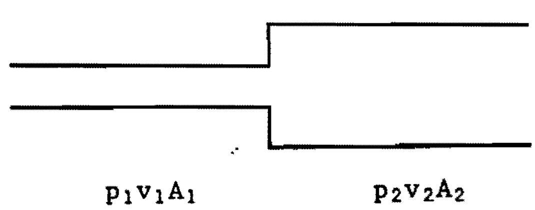

figure 2.7 a series connection

The boundary condition at the connection is found with help of the

Bernoulli equation and continuity of the flow

$$v_1A_1 = v_2A_2$$

$$p_1 = p_2 \qquad (2.35)$$

5) An air chamber. For the air chamber (fig. 2.8) the pressure is considered to be the same throughout the volume.

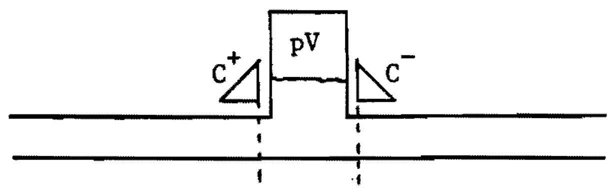

figure 2.8 pipe with airchamber

The gas is assumed to follow a reversible polytropic relation

$$pV^n = C \qquad (2.36)$$

in which p is the absolute pressure and V the volume of the gas. The exponent n depends on the thermodynamic process followed by the air in the chamber. For a perfect gas and an isothermal process n=1, for an isentropic process n=1.4. In calculations often an average of 1.2 is used. From C^+ $(p_1+\rho a_1 v_1)$ is known and from C^- $(p_2-\rho a_2 v_2)$ is known. With $p_1=p_2$ and

$$V = V_0 + (v_2-v_1)A\Delta t \qquad (2.37)$$

the pressure and velocities can be calculated.

2.4 The simplified equations

Equations (2.5) and (2.15) can be simplified and combined to the one dimensional wave equation which is more accessible to direct interpretation. By neglecting $v\frac{\partial p}{\partial x}$ compared to $\frac{\partial p}{\partial t}$ and $v\frac{\partial v}{\partial x}$ compared to $\frac{\partial v}{\partial t}$ and assuming frictionless horizontal flow the result is

$$\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\partial v}{\partial t} = 0 \tag{2.38}$$

$$\frac{1}{\rho}\frac{\partial p}{\partial t} + a^2\frac{\partial v}{\partial x} = 0 \tag{2.39}$$

Combining these equations yields the one dimensional wave equation

$$\frac{\partial^2 \xi}{\partial t^2} - a^2\frac{\partial^2 \xi}{\partial x^2} = 0 \tag{2.40}$$

with ξ=p or ξ=v.
From this it can be concluded that the constant a^2 is the square of the wavespeed. The general solutions of (2.38) and (2.39) are

$$p-p_0 = f\left(t-\frac{x}{a}\right) + F\left(t+\frac{x}{a}\right) \tag{2.41}$$

$$v-v_0 = \frac{1}{\rho a}\left[f\left(t-\frac{x}{a}\right) - F\left(t+\frac{x}{a}\right) \right] \tag{2.42}$$

$F\left(t+\frac{x}{a}\right)$ represents a pressure wave travelling in the -x direction and a pressure wave travelling in the +x direction is represented by $f\left(t-\frac{x}{a}\right)$. Because for the wave $t\pm\frac{x}{a}$ = constant, $v\frac{\partial p}{\partial x}$ and $v\frac{\partial v}{\partial x}$ can be written as

$$v\frac{\partial p}{\partial x} = \pm\frac{v}{a}\frac{\partial p}{\partial t} \text{ and } v\frac{\partial v}{\partial x} = \pm\frac{v}{a}\frac{\partial v}{\partial t}$$

Because usually a»v the assumption leading to (2.38) and (2.39) is validated.

Equations (2.38) and (2.39) can also be written in a characteristic form (v. Dongen[6]). Multiplying (2.38) with ρa and (2.39) with ρ and subsequently adding yields

$$\left(\frac{\partial}{\partial t} + a\frac{\partial}{\partial x}\right)(p + \rho a v) = 0 \tag{2.43}$$

substracting yields

$$\left(\frac{\partial}{\partial t} - a\frac{\partial}{\partial x}\right)(p - \rho a v) = 0 \tag{2.44}$$

The equations state that $(p+\rho av)$ is constant along the characteristic C^+ with slope $\frac{\partial x}{\partial t}=a$ and $(p-\rho av)$ is constant along the characteristic C^- with slope $\frac{\partial x}{\partial t}=-a$. With the help of equations (2.43) and (2.44) reflections at various boundaries can easily be determined.

Consider the flow from an upstream boundary with constant height through a pipe (fig. 2.9).

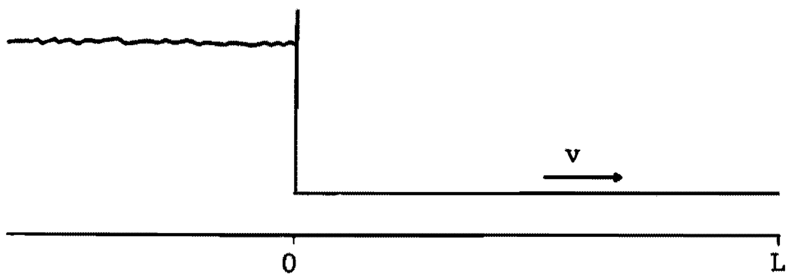

figure 2.9 flow from reservoir through pipe of length L

At time t_0 the flow is instantaneously shut off at x=L. Because there is no friction the pressure is everywhere the same. The resulting pressure waves and interactions can be shown in an x-t diagram (fig. 2.10).

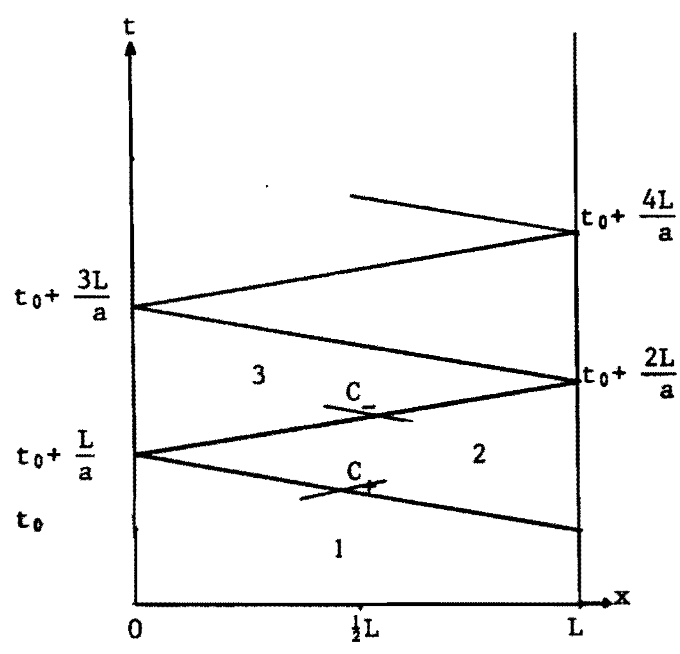

figure 2.10 reflections of pressure waves

Before time t_0 the velocity is v_1 and the pressure p_1. At time t_0 a pressure wave is generated that travels with speed a upstream. The velocity behind the wave is zero and with the C^+ characteristic: $p_1+\rho av_1=p_2+\rho av_2=p_2$. The wave is reflected at the reservoir. If the pressure at the reservoir is constant (p_1), the velocity behind the reflected wave can be found with the C^- characteristic: $p_2 - \rho a v_2 = p_2 = p_1 - \rho a v_3$. So $v_3 = -v_1$. This procedure can be repeated after every reflection to give the pressure and velocity behind the reflection. At time $t = t_0 + \frac{4L}{A}$ the situation is the same as at time t_0. In figure 2.11 the pressures at x=L and $x = \frac{1}{2}L$ are shown as a funtion of time.

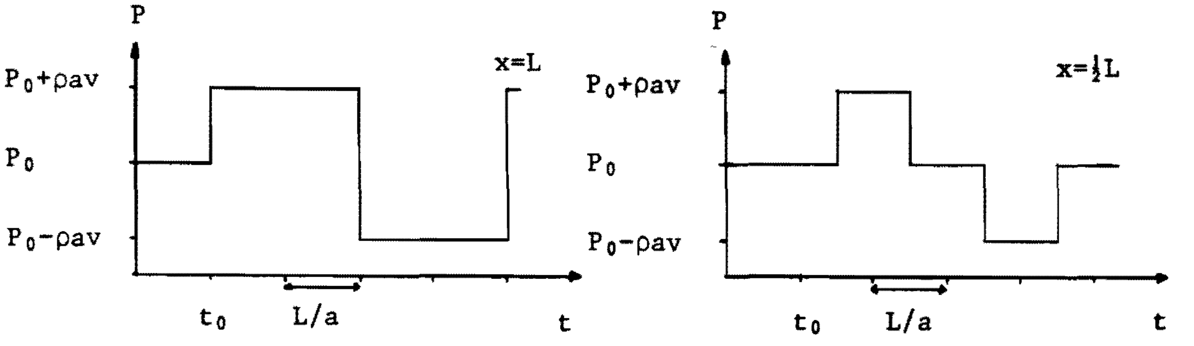

figure 2.11 pressures at x=L and at $x=\frac{1}{2}L$

A series connection can be handled in a similar way. Suppose at one instant of time a steady flow is shut off at the downstream end. The generated pressure wave travels upstream (fig. 2.12 from right to left) and arrives at the connection where part of the wave will be reflected and part of it transmitted as shown in figure 2.12. With the assumption of continuity of pressure and flow the pressures and velocities behind the transmitted and reflected wave are found to be

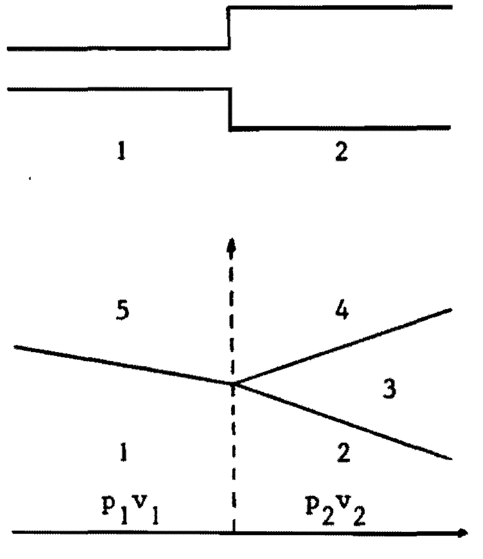

figure 2.12 reflections at series connection

$$p_4 = p_2 + \left[\frac{2a_1A_2}{a_1A_2+a_2A_1}\right]\rho a_2 v_2 \qquad (2.45)$$

$$v_4 = \frac{a_1A_2-a_2A_1}{a_1A_2+a_2A_1} v_2 \qquad (2.46)$$

$$p_5 = p_4 \qquad (2.47)$$

$$v_5 = \frac{A_1}{A_2} v_4 \qquad (2.48)$$

If a transmission coefficient t is defined as the jump in pressure behind the connection divided by the original jump in pressure and a reflection coefficient r defined by the reflected pressure jump divided by the original jump then

$$t = \frac{p_5-p_1}{p_3-p_2} = \frac{2a_1A_2}{A_1a_2+a_2A_1} \qquad (2.50)$$

$$r = \frac{p_4-p_3}{p_3-p_2} = \frac{a_1A_2-a_2A_1}{a_1A_2+a_2A_1} \qquad (2.51)$$

2.5 Surge tank and airchamber

If the time of pressure build-up is very large compared to the time it takes the pressure wave to travel through the system then a theory can be used in which the watercolumn is considerd rigid. Such a theory is often used for surge tanks and airchambers because they impose a low frequent pressure change on the system with a period much larger than the period of pressure wave reflections.

Surge tanks and airchambers are two means that are often used to control fluid transients. The difference between the two is that a surge tank has an open connection to the atmosphere and an air chamber does not. In the treatment of the surge tank Parmakian[2] will be followed.

For a simple surge tank (fig. 2.13) with no friction it is assumed that it takes up the energy of the flowing column of fluid at the moment the control gate at L is closed.

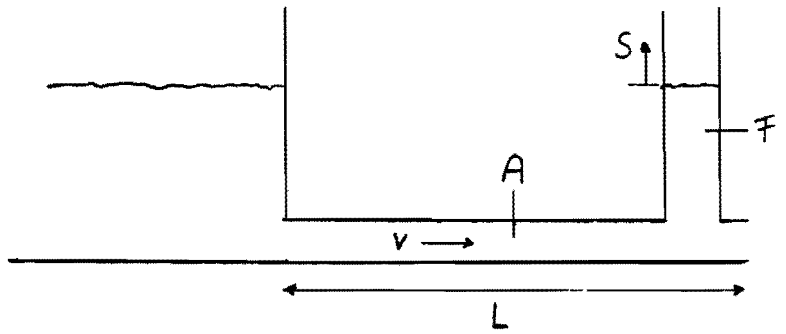

figure 2.13 valve closure with surge tank

The flowing mass is equal to ρAL. At the moment the gate closes a force of magnitude pA acts on the water column causing it to stop. The deceleration of the watercolumn is

$$-\frac{dv}{dt} = \frac{gS}{L} \tag{2.52}$$

The rise of the surge tank level can be written as

$$F\frac{dS}{dt} = Av \tag{2.53}$$

Combining these equations leads to the differential equation

$$\frac{d^2S}{dt^2} + \frac{Ag}{FL}S = 0 \tag{2.54}$$

$$t=0:\ \ S=0,\ \frac{dS}{dt} = \frac{Av_o}{F}$$

with solution

$$S = \frac{Av_o}{F}\sqrt{\frac{FL}{Ag}}\ \sin\sqrt{\frac{Ag}{FL}}\ t \tag{2.55}$$

In real applications hydraulic losses because of friction or of throttling of the surge tank may be important. This leads to a somewhat different analysis; see e.g. Wylie and Streeter[1] and Parmakian[2].
For an airchamber (fig. 2.14) without friction the analysis of the surge tank can be folowed.

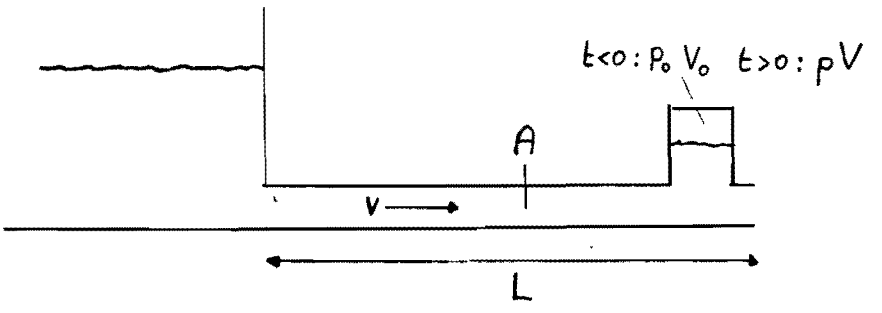

figure 2.14 valve closure with airchamber

Assuming for the air in the airchamber to follow the relation

$$pV^n = p_oV_o^n \tag{2.56}$$

with absolute pressures, this can be linearized to

$$V = V_o \left(1 + \frac{1}{n} - \frac{1}{n}\frac{p}{p_o}\right) \tag{2.57}$$

Writing Newton's second law as

$$-\frac{dv}{dt} = \frac{p}{\rho L} \tag{2.58}$$

and applying the continuity equation to the airchamber

$$-\frac{dV}{dt} = vA \tag{2.59}$$

the result is

$$\frac{d^2p}{dt^2} + \frac{nAp_o}{V_o\rho L}\,p = \frac{nAp_o^2}{\rho LV_o} \tag{2.60}$$

$$t=0:\ p=p_o,\quad \frac{dp}{dt} = \frac{nv_oAp_o}{V_o} \tag{2.61}$$

with solution

$$p = p_o + P \sin \omega_o t \tag{2.62}$$

in which

$$P = v_o \sqrt{\frac{nAp_o\rho L}{V_o}} \tag{2.63}$$

$$\omega_o^2 = \frac{nAp_o}{V_o\rho L} \tag{2.64}$$

3 The experimental set-up

3.1 Introduction

To study the unsteady flow or waterhammer due to valve closure for the specific pump configuration of figure 3.1 a new set-up was built.

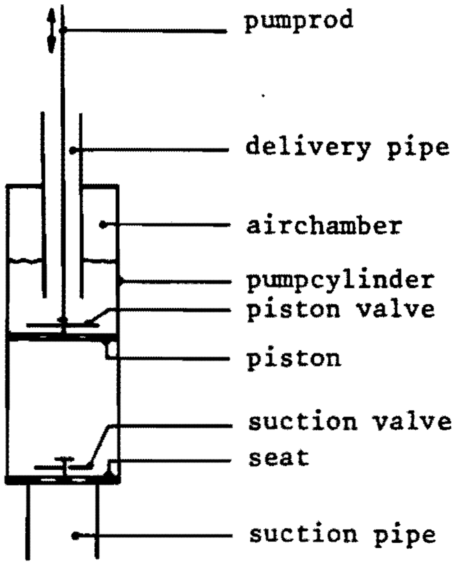

figure 3.1 specific pump configuration

Because direct measurement of pressure transients in the pump would probably give a very complex signal to analyse, and to start the experiments with only the most essential elements, the pump was simplified as much as possible. The basic configuration that resulted consists of a delivery-pipe, a test cylinder representing the pump cylinder, a valve/seat combination and a drain-pipe (fig. 3.2).

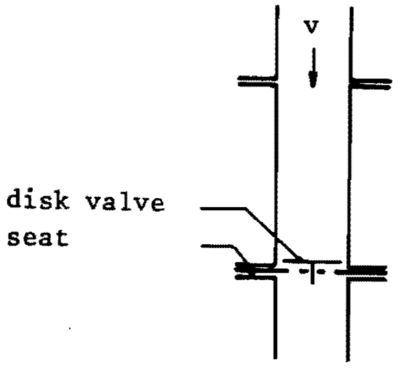

figure 3.2 basic resulting configuration

The idea is to first fix the valve in opened position, turn on the flow and then set the valve loose. Because of the downward flow the valve closes and produces a pressure transient or waterhammer wave. In order to simulate a real pump configuration, the test cylinder was modified stepwise as shown schematically in figure 3.3. The goal of the stepwise modification was the determination of the influence of subsequent changes on the pressure transients.

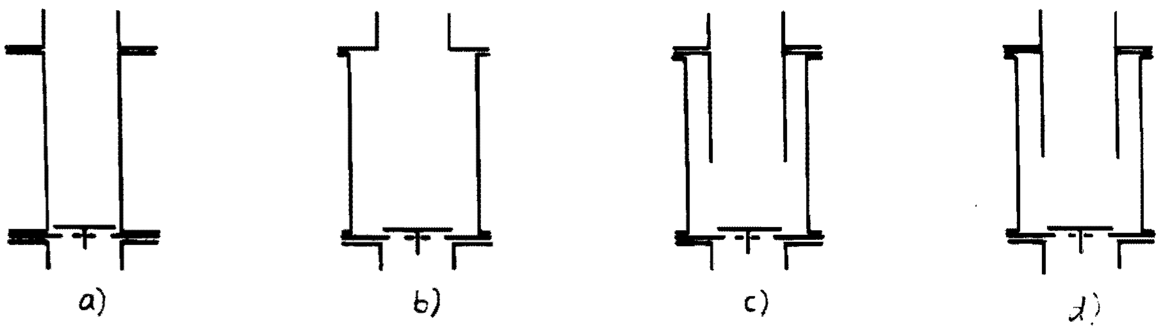

figure 3.3 stepwise modification of the test cylinder

3.2 The set-up

The experimental set-up can best be described with the help of figure 3.4. The water is drawn from a large already existing water reservoir on top of the roof. From this reservoir the delivery-pipe extends down to the test cylinder. For the delivery-pipe, which is not straight down from the reservoir because of obstructions that would be in its way, 2" galvanised gas pipe is used because it is also used in real pumps and it is cheaper than brass.

Directly under the reservoir a valve (A) is mounted to shut off the flow. At three places along the pipe brass pressure connections are fitted to allow for the installation of pressure transducers. The valve can be operated from the ground-floor.

The brass test cylinder (fig.3.5) is connected at the upper end to the end flange of the delivery-pipe and at the lower end it is connected to the valve mechanism. The standard test cylinder has one pressure connection, the enlarged test cylinder (appendix A) has two pressure connections and a small channel with valve to let out the air or to pump air into the cylinder. In the design of the standard test cylinder an O-ring groove was made in the lower face of the top flange. The enlarged cylinder with internal pipe of fig. 3.3 c) can now be constructed by sawing off the the lower 75 mm of the standard cylinder and hanging the upper part in the enlarged cylinder.

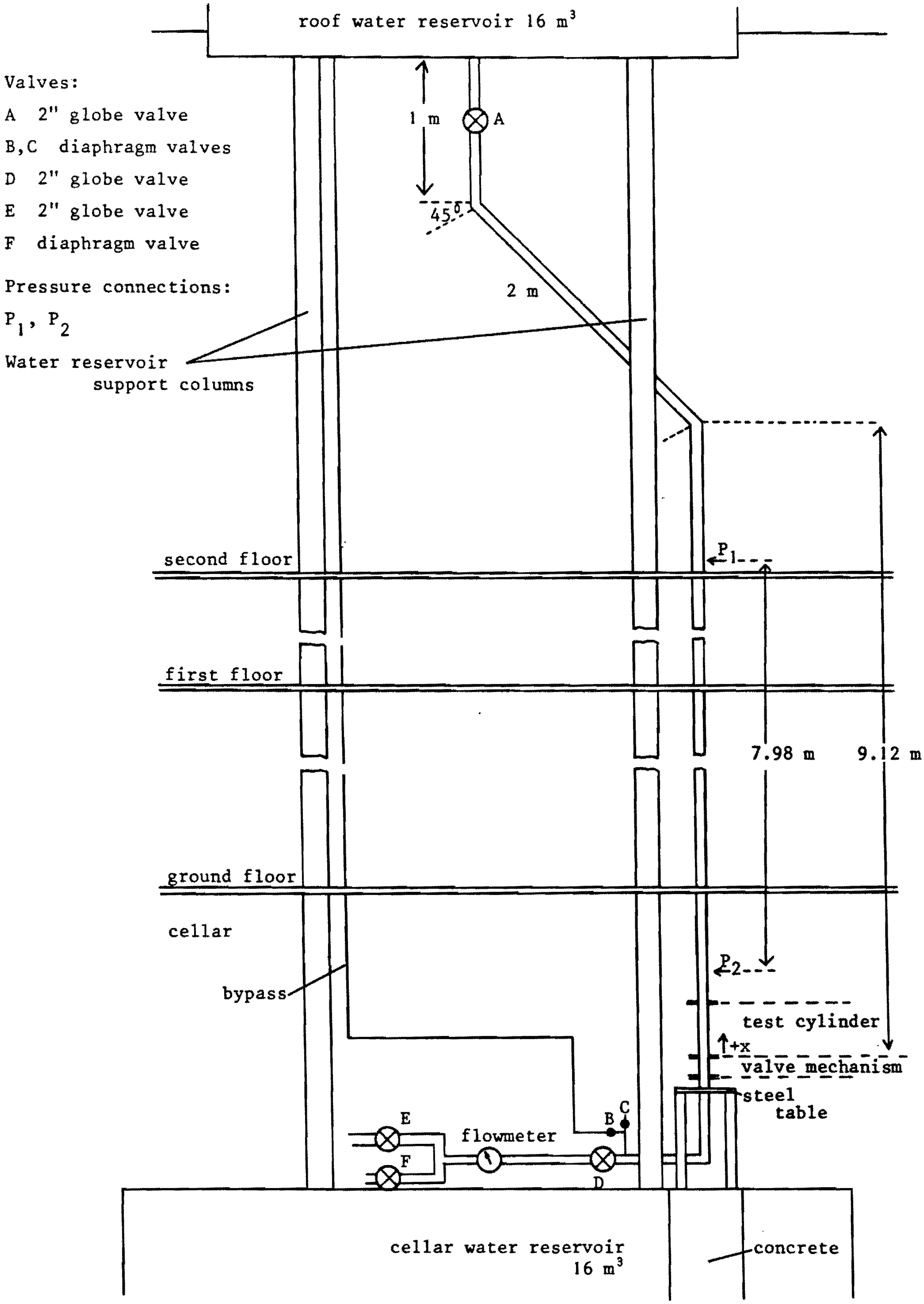

figure 3.4 the experimental set-up

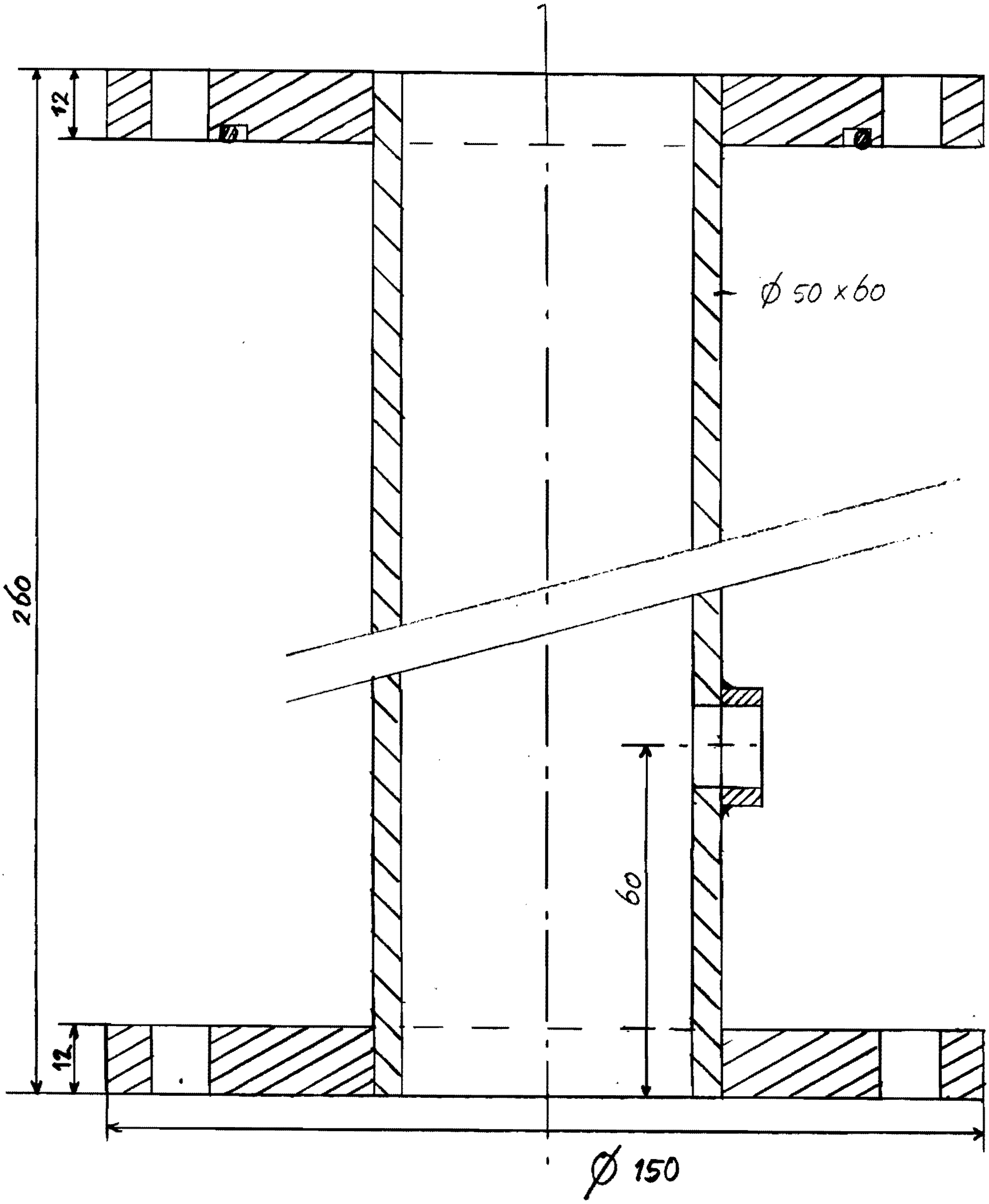

figure 3.5 the standard test cylinder

For the operation of the valve a valve mechanism was designed (fig. 3.6). At the upper end it is connected to the test cylinder and at the lower end to the set-up support. The mechanism consists of a shaft that can rotate with an eccentric and a spring holder mounted on it. If there is no flow and the pressures above and below the valve are equal, the spring is just strong enough to lift the valve. Before the flow is turned on, the eccentric is placed with its sharp edge just below the valve shaft so that when the flow is turned on the valve shaft rests on the eccentric. By turning the eccentric a little further the valve will be set loose, and it closes under influence of the flow. Control of the mechanism is possible from the ground-floor. A pressure connection is situated 45 mm below the top face of the seat.
The last part in the description of the set-up is the support and steady flow control. A more detailed view of this part is given in figure 3.7The support consists of a small steel table with four legs mounted on an existing concrete block. The drain-pipe with the top flange connected to the table with four bolts hangs through a hole in the middle of the table . With these bolts it is possible to change the height of the top flange several centimeters in order to facilitate the mounting of the test cylinder. When the test cylinder is installed and all bolts are tightened the set-up is considered rigidly fixed between the reservoir on the roof and the steel table.
The remaining part has an airation valve (B), a bypass valve (C) which is connected to the roof reservoir, a valve (D) which can quickly turn on and turn off the flow, a flow meter and two steady flow control valves (E,F), a 2" globe valve (E) for the rough adjustment of the flow and a 2" diaphragm valve (F) for the fine adjustment. Valve D can be operated from the ground-floor. From the two control valves the water flows through reinforced plastic hoses into the existing cellar water reservoir. If necessary water can be pumped from the cellar reservoir to the roof reservoir.

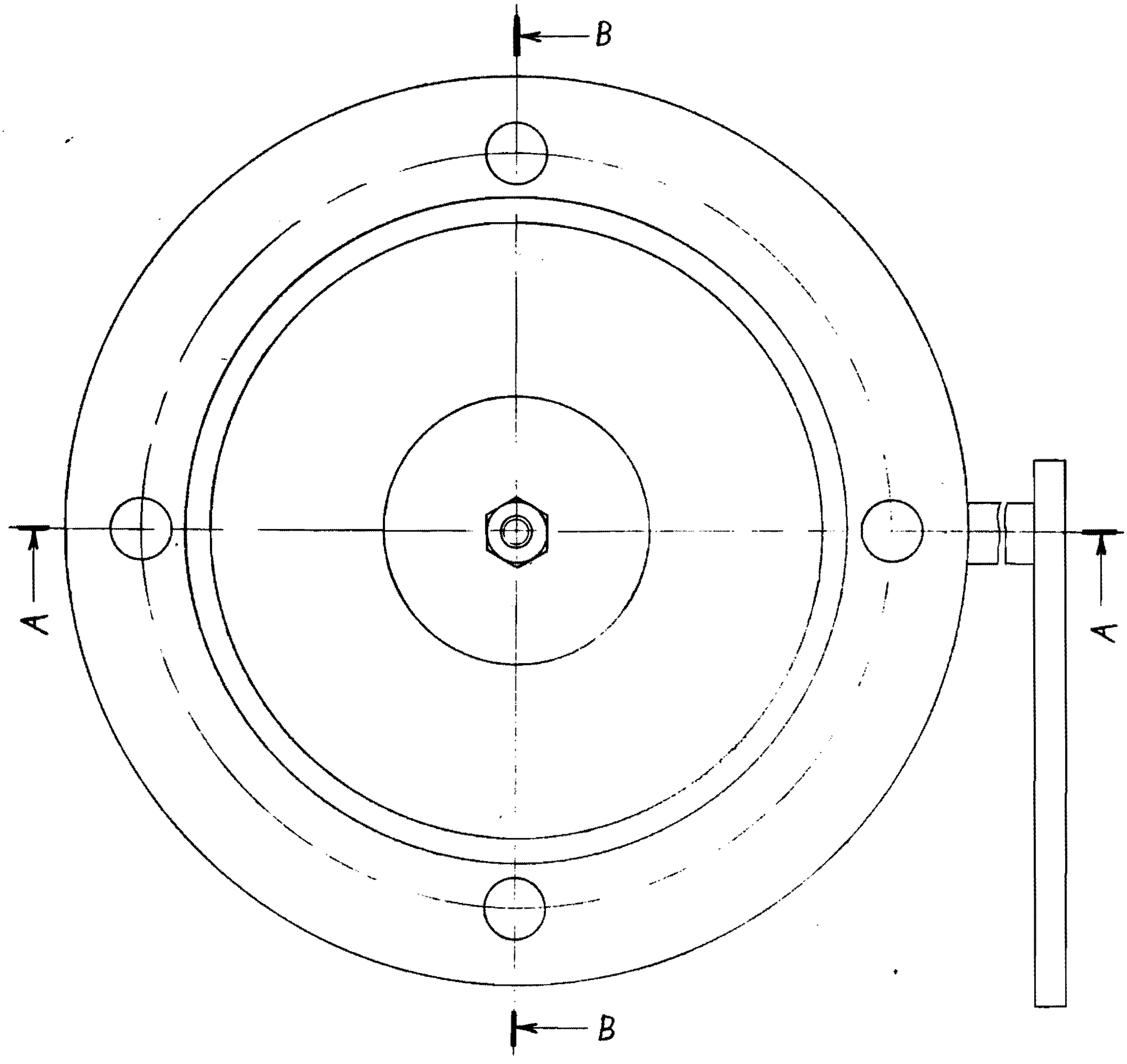

figure 3.6 valve mechanism top view

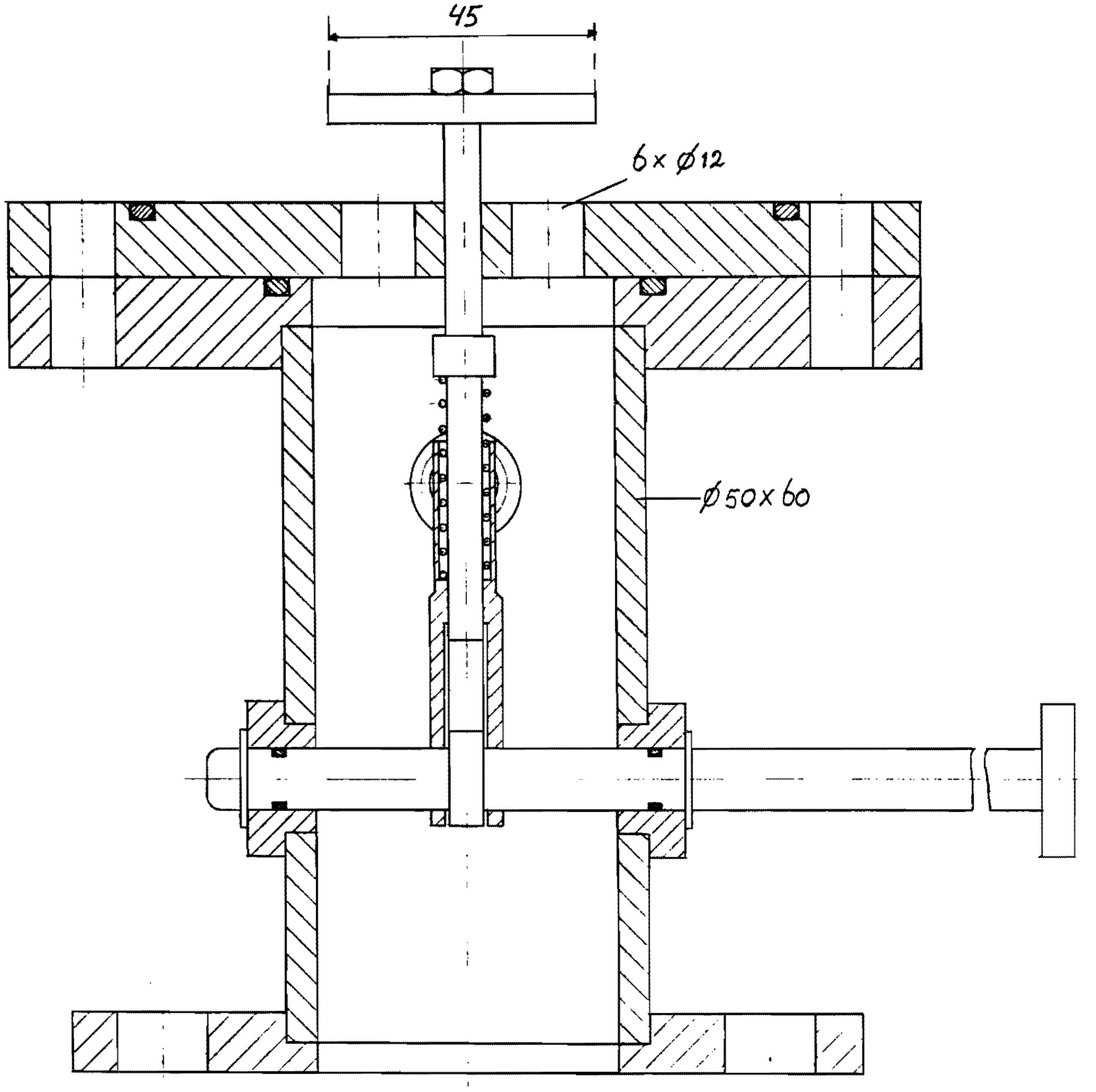

figure 3.6 valve mechanism view A-A

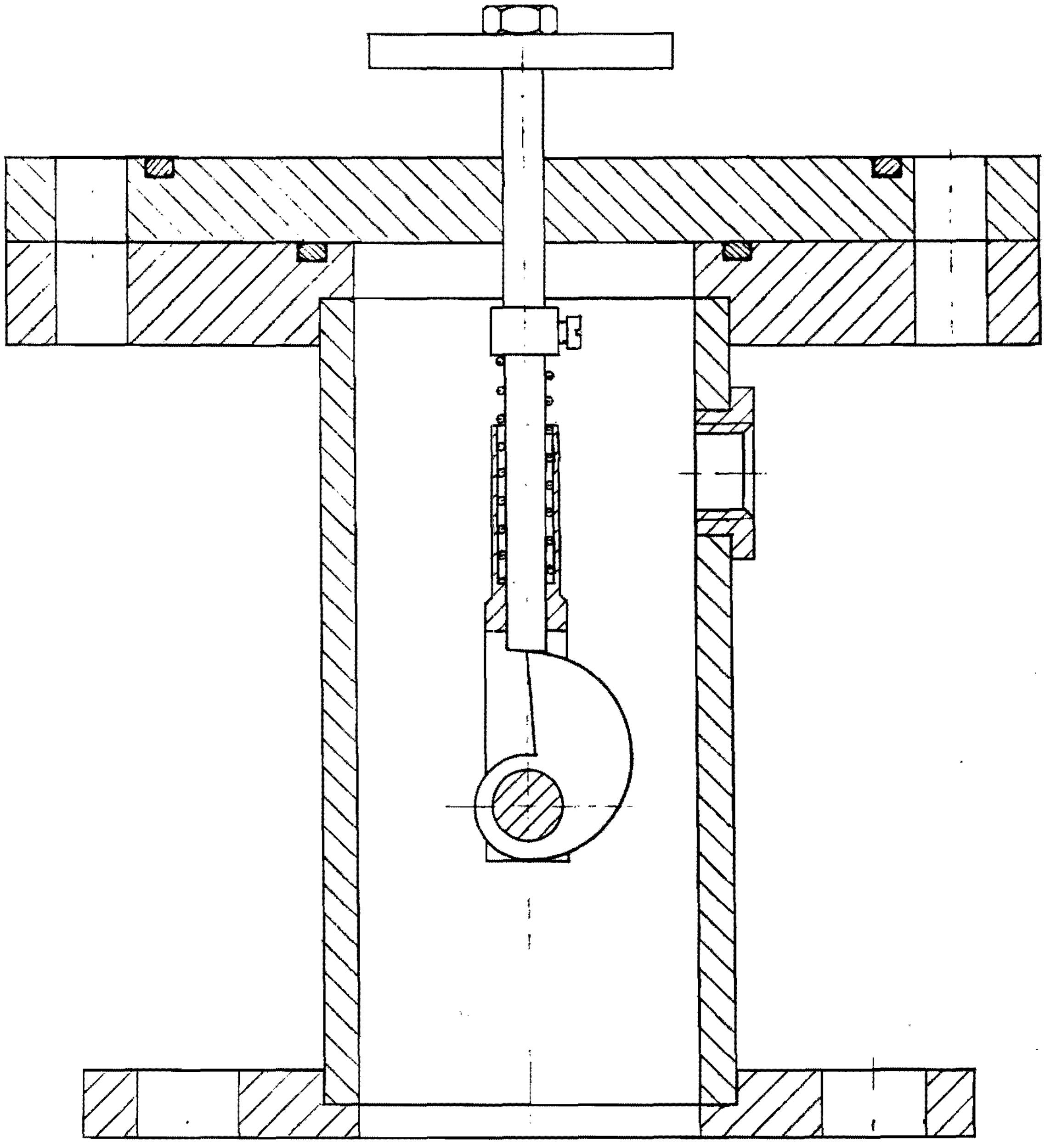

figure 3.6 valve mechanism view B-B

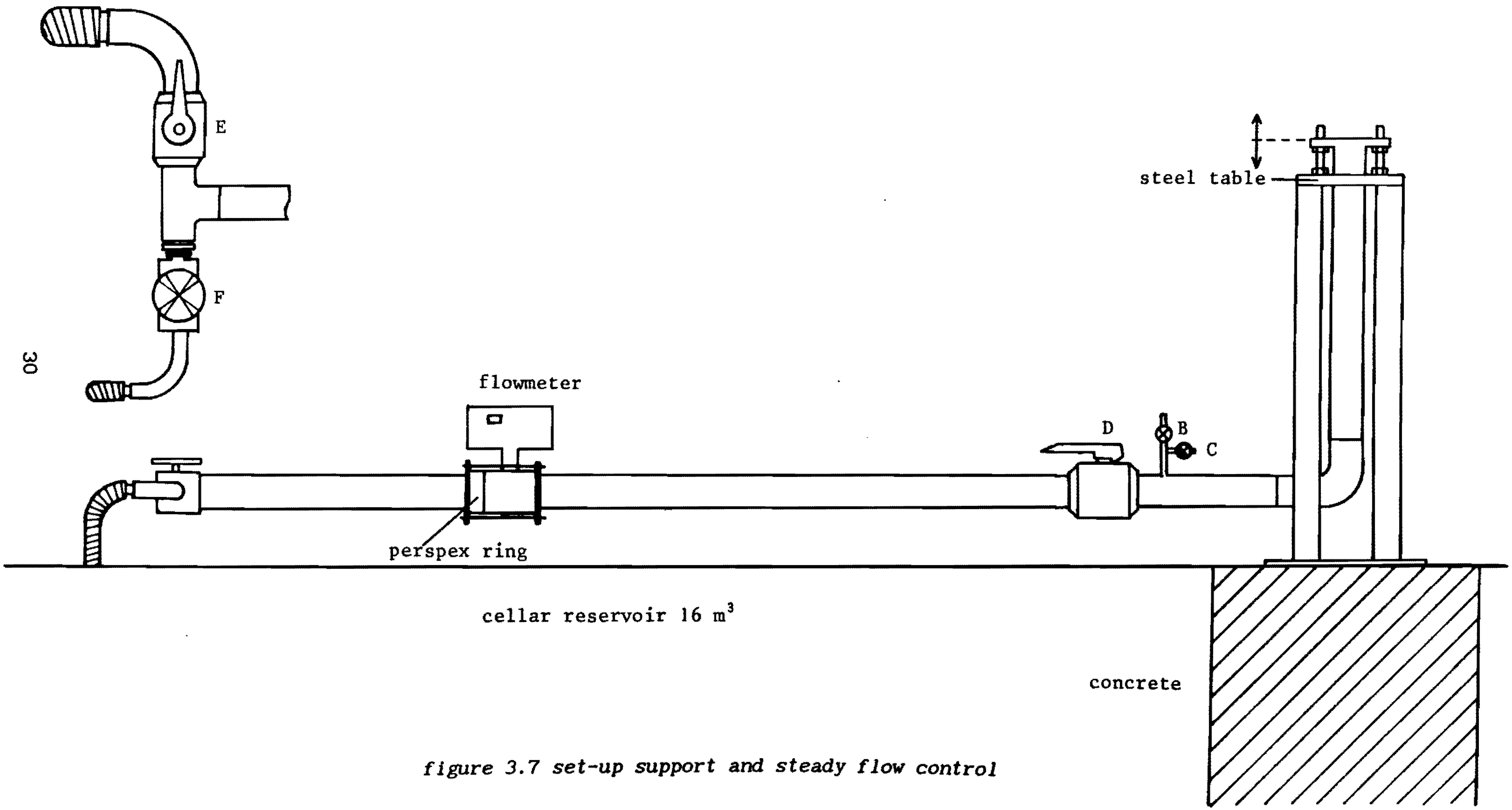

figure 3.7 set-up support and steady flow control

3.3 Measurement equipment and experimental procedure

The pressure transducers that were used, were of the type Druck PDCR 810 (15 Barg. range) with a flush fitting. An amplifier (bandwith ch.1: 104 kHz, ch.2: 58 kHz, ch.3: 58 kHz, ch.4: 58 kHz) was used to produce a stronger signal. Its amplification was chosen in such a manner that a 10 V output was obtained for a pressure of 15 at. The results of the static calibration of the transducers are given in appendix C. The transient behaviour of the transducer/amplifier combination was determined by mounting transducer 1 in a shock tube and measuring the step response (appendix C). The resulting time constant $\tau \approx 10$ μs together with the manufacturers data on the pressure transducer gave reason to believe that the transient behaviour is completely determined by the amplifier. Measurement of the drift is also shown in appendix C.

Two Polar DS 102 8 bit transient recorders were used to monitor the pressure transients. From these recorders the data can be read by an IBM compatible computer through its serial port. The data are stored on a floppy disk for further evaluation. The triggering of the transducers is done internally on the signal. Steady flow was measured with an electromagnetic flow transducer (Flowtec DMI 6531) from Endress and Hauser.

The experimental procedure is as follows. Before the system is filled with water all pressure transducers are set to zero output. Next the eccentric is placed with the sharp edge just below the valve shaft in such a manner that when a flow is applied the shaft rests on the eccentric. Now valves B,C,E and F are closed, D opened and finally A opened. The sytem now fills with water. Valves E and F are thenopened to let out the air left in the system. Bubbles can be seen flowing through the perspex ring alongside the flowmeter. If no more bubbles are seen the desired flow is set with valves E and F . By turning the eccentric a little the disk valve is set loose and the closing generates a pressure transient. To open the disk valve, valve D is closed and valve B opened to make the pressures above and below the disk valve equal. The spring is now strong enough to open the disk valve. Next the eccentric is again placed under the valve shaft and after closing valve B and opening valve D the experiment can be repeated with a different flow or sample frequency.

4 Experiments and results

4.1 Introduction

The experiments that were carried out can be divided into five groups.

1) Measurement of steady flow characteristics of the system. These are the steady flow friction coefficient f of the 2" gas pipe and the steady flow pressure drop over the valve/seat combination.
2) Unsteady flow experiments with the standard test cylinder. The experiments were intended as a testcase for the unsteady flow behaviour of the standard configuration.
3) Unsteady flow experiments with the enlarged test cylinder to study the influence of a sudden change in diameter.
4) Unsteady flow experiments with the enlarged test cylinder with internal pipe and no air.
5) Unsteady flow experiments with the enlarged test cylinder with airchamber.

4.2 Steady flow characteristics

The steady flow friction coefficient was determined by measuring the pressures at x=50 cm and at x=848 cm above the seat for various flows. With equation (2.4) the friction coefficient could be calculated. The results are presented in figure 4.1.
The pressure drop over the valve/seat combination was measured with a pressure transducer 60 mm above the seat and one 45 mm below the seat. This was done for various valve heights and flows. The flow was always downward. The results are given in figure 4.2.

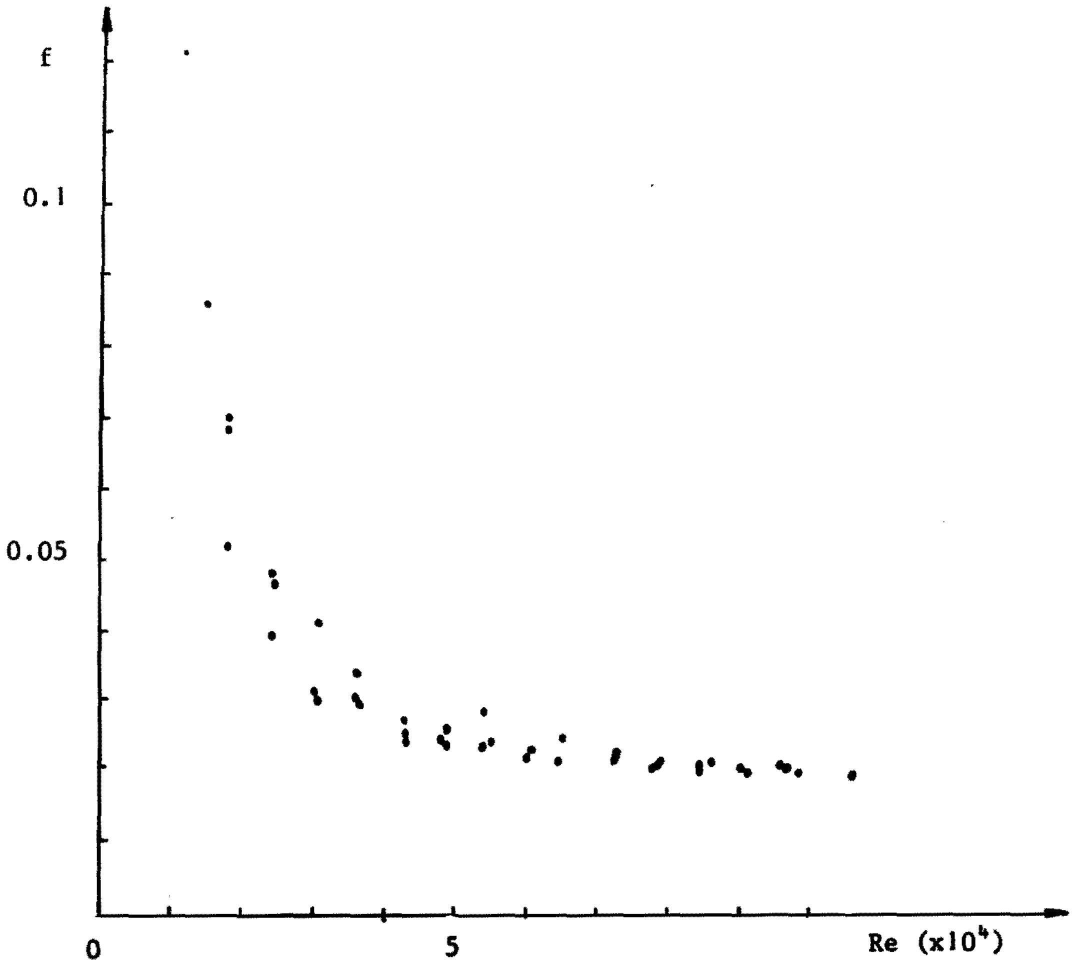

figure 4.1 steady flow friction coefficient

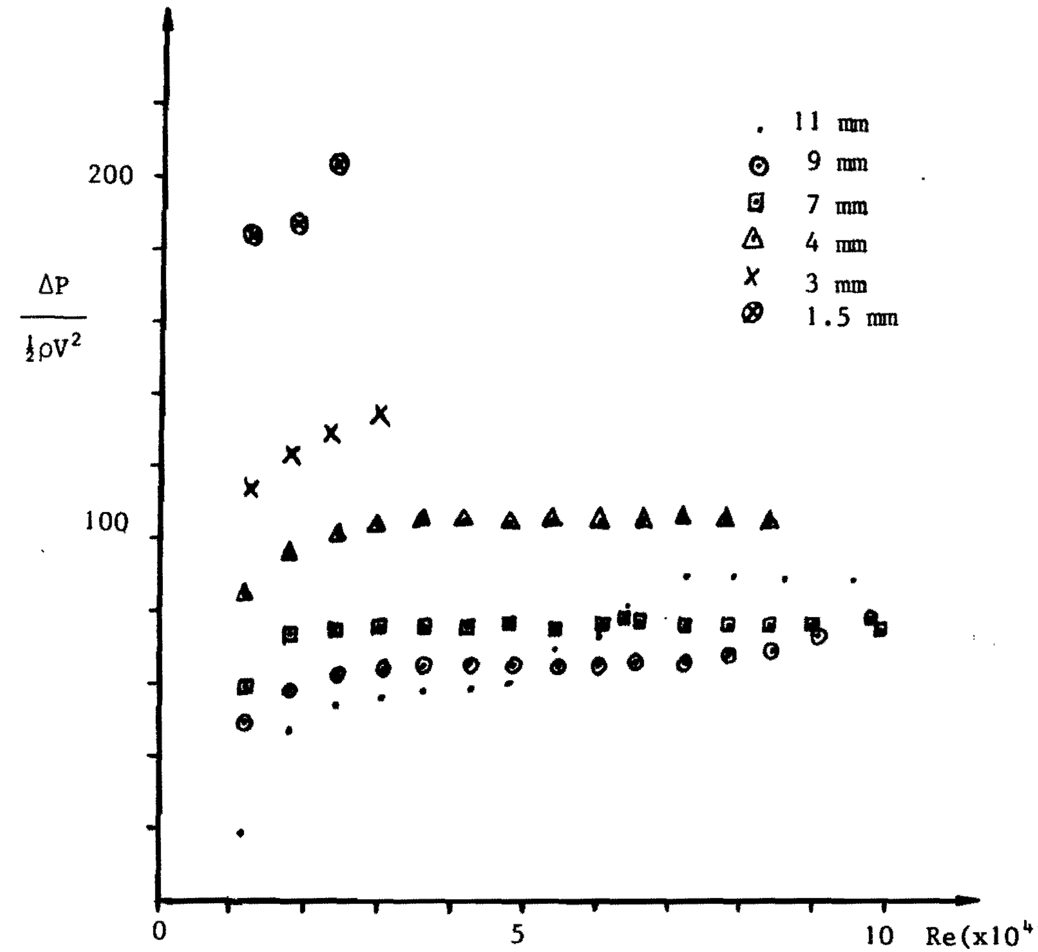

figure 4.2 pressure drop over valve/seat combination

4.3 Standard test cylinder

During the experiments with the standard test cylinder the pressures were measured at four places: p1 at x=848 cm, p2 at x=50 cm, p3 at x=6 cm and p4 at x=-4.5 cm. Examples of measured pressure transients are given in figure 4.3. Channels 1 and 2 were triggered simultaneously to the signal of channel 1 with a pretrigger of 50%. Channels 3 and 4 were triggered on the signal of channel 3 with a 50% pretrigger. The sample-rate for all signals was 4 kHz. The zero of the time scale is arbitrary and the pressure is relative to the atmospheric pressure. The horizontal line before the start of the transients represents the steady flow pressure.

At the moment the valve closes two pressure waves are generated. Above the valve a compression wave travels up the delivery pipe in the direction of the roof reservoir. First the wave reaches pressure transducer 3 in the standard test cylinder at x=6 cm (fig. 4.3 c)) and increases the pressure at this point. On its way up the compression wave passes pressure transducers 2 and 1 and reflects at the reservoir as an expansion wave. It now travels downward and reflects at the closed valve and so on. From this the expected pressure time diagrams should look like figure 2.11 a) for transducers 2 and 3 and like figure 2.11 b) for transducer 1. This means that a pressure rise of ρav is expected and a period of $4L/a$. The wavespeed is determined by measuring the time it takes the wave to travel the distance from transducer 2 to transducer 1; a distance of 798 cm. The result and the calculated wavespeeds are shown in table 4.1.

	$a_{calculated}$	$a_{measured}$
2" gas pipe	1360 m/s	1368 ±10 m/s
standard test cylinder	1323 m/s	
enlarged test cylinder	1220 m/s	

Data used in calculation are given in appendix B.
In the calculation the coefficient c_1 for thick wall theory is used and the pipe is considered free in axial direction.

Table 4.1 wavespeeds

Flow :
.50 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
1
Sample freq. :
4.00 (kHz)
Volt. range :
5.00 (V)
Steady press. :
51.50 (kPa)
Pmax: 305.91
Pmin: -56.43

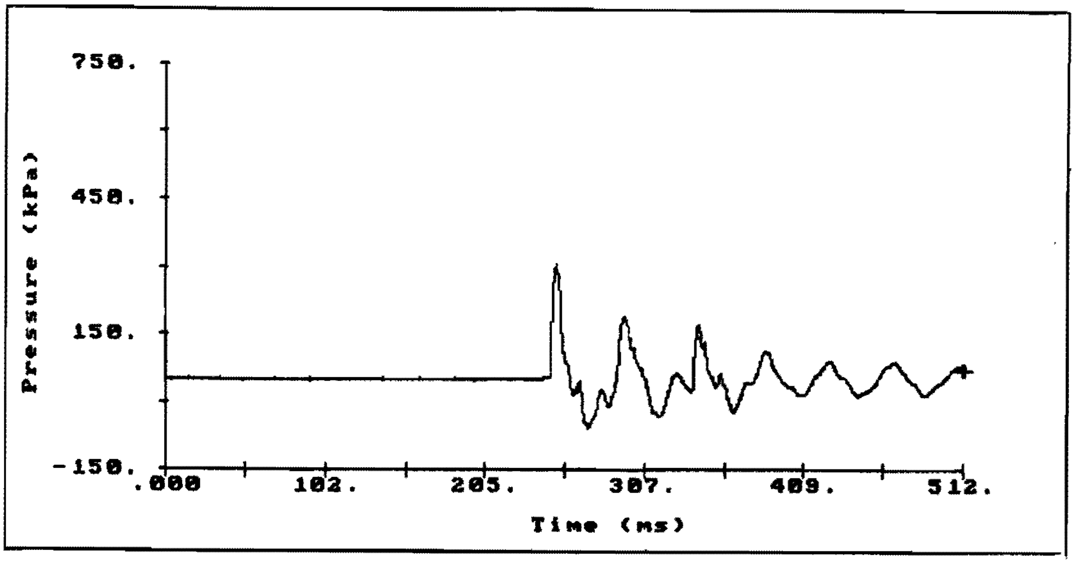

figure 4.3 a) pressure p1 at x=848 cm

Flow :
.50 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
2
Sample freq. :
4.00 (kHz)
Volt. range :
5.00 (V)
Steady press. :
131.10 (kPa)
Pmax: 431.46
Pmin: -76.84

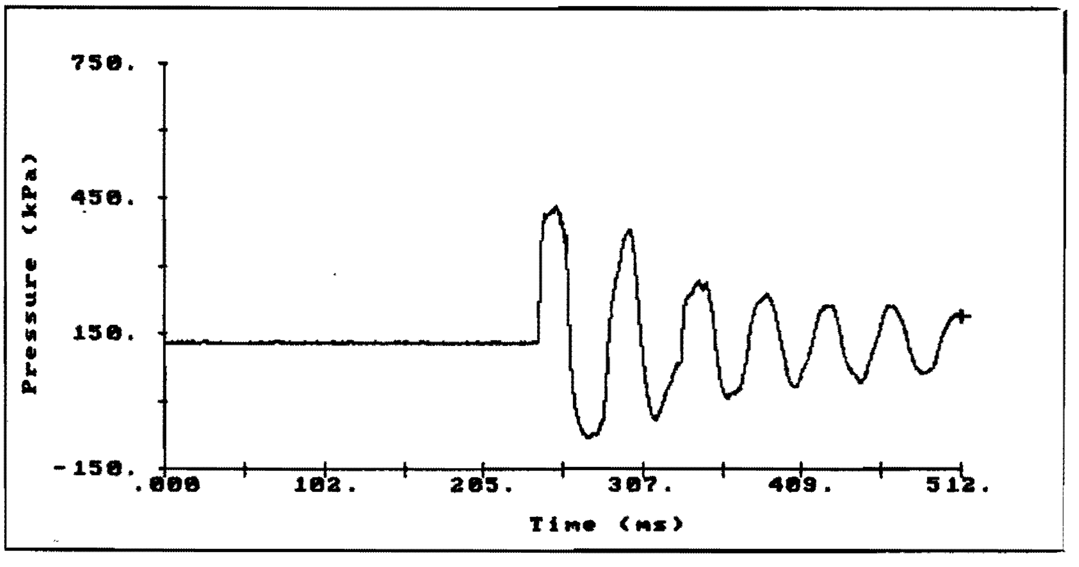

figure 4.3 b) pressure p2 at x=50 cm

Flow :
.50 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
3
Sample freq. :
4.00 (kHz)
Volt. range :
5.00 (V)
Steady press. :
133.80 (kPa)
Pmax: 411.71
Pmin: -62.20

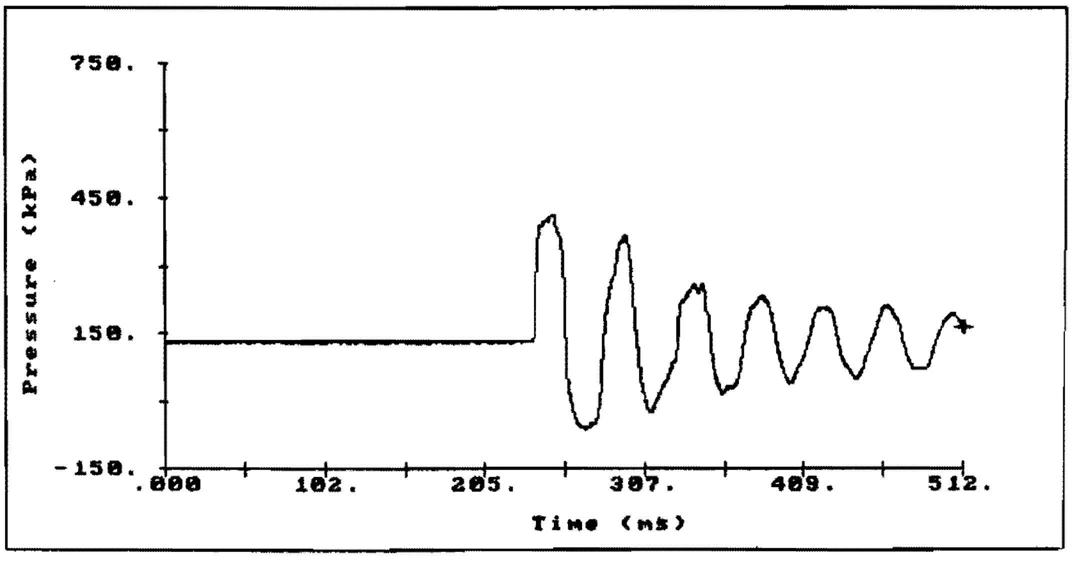

figure 4.3 c) pressure p3 at x=6 cm

Flow :
.50 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
4
Sample freq. :
4.00 (kHz)
Volt. range :
5.00 (V)
Stat. press. :
135.70 (kPa)
Pmax: 136.58
Pmin: -89.07

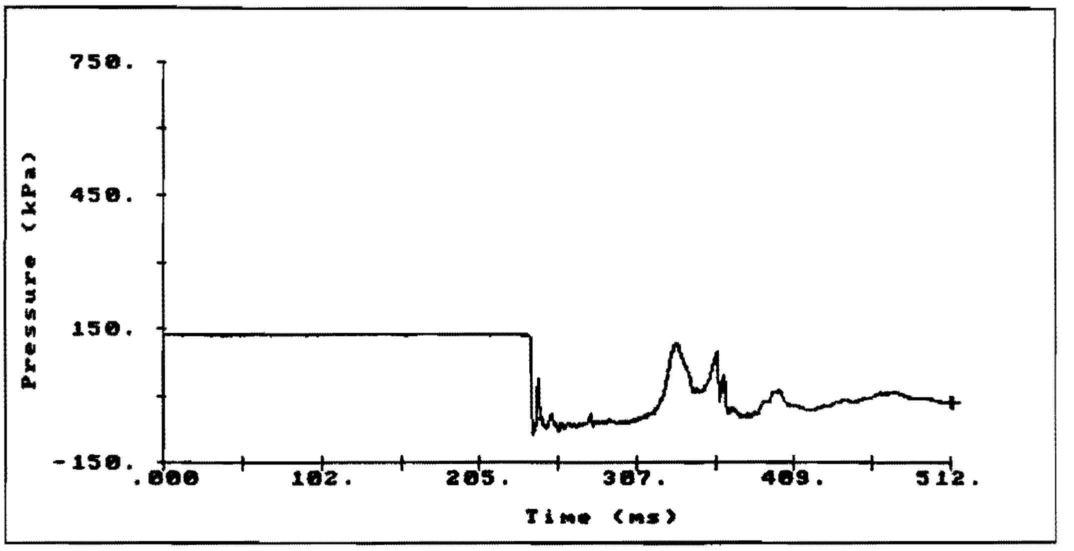

figure 4.3 d) pressure p4 at x=-4.5 cm

Flow :
.50 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
1
Sample freq. :
100.00 (kHz)
Volt. range :
5.00 (V)
Stat. press. :
52.00 (kPa)
Pmax: 323.73
Pmin: 50.49

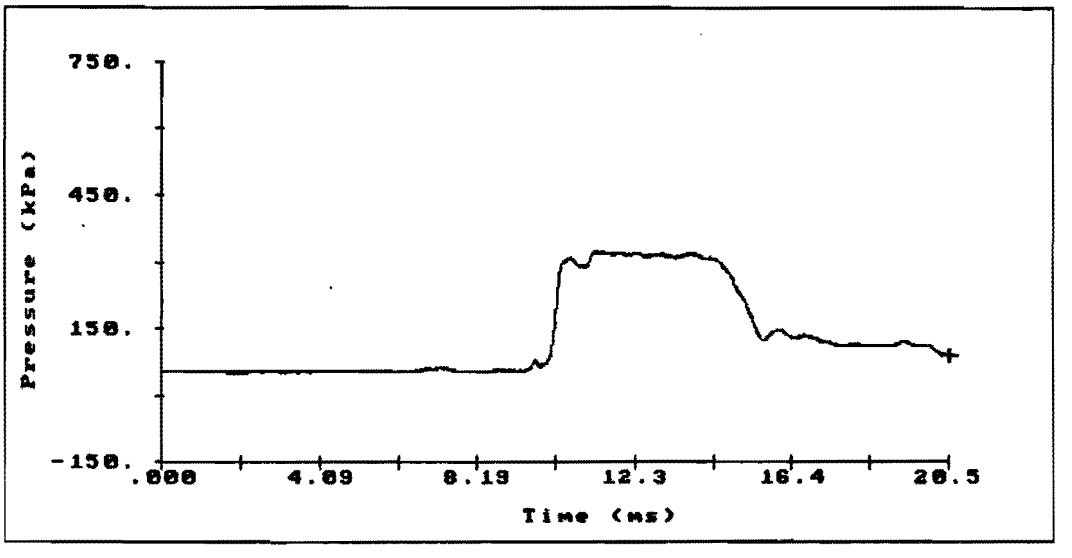

figure 4.4 a) pressure p1 at x=848 cm

Flow :
.50 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
3
Sample freq. :
100.00 (kHz)
Volt. range :
5.00 (V)
Stat. press. :
134.70 (kPa)
Pmax: 441.32
Pmin: 130.32

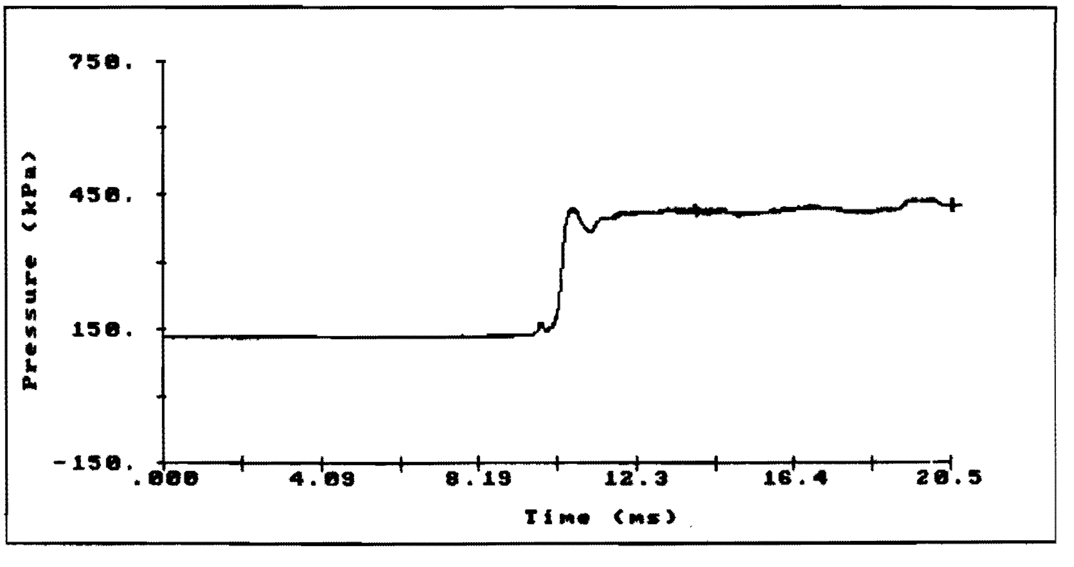

figure 4.4 b) pressure p3 at x=6 cm

Transients are recorded for five different flows and for various sample frequencies ranging from 2 kHz to 100 kHz. The bandwidth of 58 kHz for the amplifier was not importantin the experiment because the fastest transients that were expected were of the order of the smallest interval (length of the test cylinder) divided by the wave velocity: $L_t/a \cong 0.195$ ms or ±5100 Hz.

From the measurements with a sample frequency of 100 kHz the time of pressure build-up was determined by estimating the time it takes from the start of the transient until a steady pressure is reached. In figure 4.4 this time was estimated to be 2 ms Figure 4.4 a) allows an estimation of the time it takes the wave to travel from transducer 1 to the reservoir and back. This time was found to be 5.1 ms which does not agree with the distance from transducer 1 to the reservoir and the measured wave speed: $2L'/a=5.7$ ms (L'= distance from p1 to reservoir, a= wavespeed in gas pipe).

The results of the measured pressure jumps (maximum in the pressure signal minus the steady flow pressure) are presented in table 4.2. A short discussion of the inaccuracies that apply to the table are given in appendix D. Bearing these inaccuracies in mind it can be seen that the absolute error in the measured pressure jumps cannot account for the variations in the jumps. It is likely that the closing of the valve is not reproducable for a chosen flow and thus influences the pressure jump.

For a flow of 0.5 l/s the measured jump Δp2 and the calculated jump ρav in the gas pipe agree within the accuracies given; for larger flow this is not true. Because the measured values are always greater and $\Delta p2/\rho av$ is more or less constant it seems that a systematic error is introduced or the phenomenon is not exactly described with a pressure jump of ρav.

For the pressure jump in the standard test cylinder the same conclusion applies but now the measured jump is always less than the calculated jump ρav.

The large difference in pressure jump between Δp1 and Δp2 can not be explained with steady flow friction because this would give a pressure loss of just $\Delta p=\rho f L v^2/2D \approx 46$ Pa.

Below the valve an expansion wave is generated (fig.4.3 d)). This wave

V	f_s	q	2" gas pipe ρav	Δp1	Δp2	Δp2/ρav	test cylinder ρav	Δp3	Δp3/ρav
V	kHz	l/s	kPa	kPa	kPa		kPa	kPa	
10	4	0.500	310	280	330	1.06	337	316	0.94
10	4	0.500	310	280	329	1.06	337	321	0.95
5	2	0.503	311	279	337	1.08	338	312	0.92
5	4	0.500	310	266	312	1.01	337	309	0.92
5	4	0.495	306	264	319	1.04	333	302	0.91
5	10	0.500	310	272	321	1.04	337	309	0.92
5	20	0.500	310	269	324	1.05	337	309	0.92
5	40	0.500	310	269	315	1.02	337	312	0.93
5	100	0.500	310	272	324	1.05	337	307	0.91
10	4	0.750	464	419	503	1.08	504	483	0.96
10	10	0.750	464	430	491	1.06	504	483	0.96
10	10	0.750	464	401	492	1.06	504	471	0.93
10	20	0.758	470	440	518	1.10	510	498	0.98
10	100	0.750	464	419	498	1.07	504	483	0.96
10	4	1.00	619	568	663	1.07	672	638	0.95
10	20	1.01	625	582	666	1.07	679	652	0.96
10	100	1.00	619	580	675	1.09	672	638	0.95
10	4	1.25	774	705	835	1.08	841	757	0.90
10	20	1.25	774	719	826	1.07	841	801	0.95
10	100	1.25	774	729	841	1.09	841	810	0.96
10	2	1.50	929	807	974	1.05	1008	860	0.85
10	4	1.51	934	885	1003	1.07	1015	978	0.96
10	20	1.51	934	879	1003	1.07	1015	973	0.96
10	100	1.51	934	879	1003	1.07	1015	973	0.96

V : voltage range of the pressure transducer
f_s : sample frequency
q : flow
ρav: calculated pressure jump; for 2" gas pipe with measured wavespeed, for standard test cylinder with calculated wavespeed
Δp1: pressure jump at x=848 cm
Δp2: pressure jump at x=50 cm
Δp3: pressure jump at x=6 cm

Table 4.2 pressure jumps

is subject to many partial reflections on its way to the cellar reservoir, which make a quantative analysis impossible. Comparison of the pressure just above (p3) and just below (p4) the valve in figure 4.5 reveals that the valve opens and closes twice after the first closure.

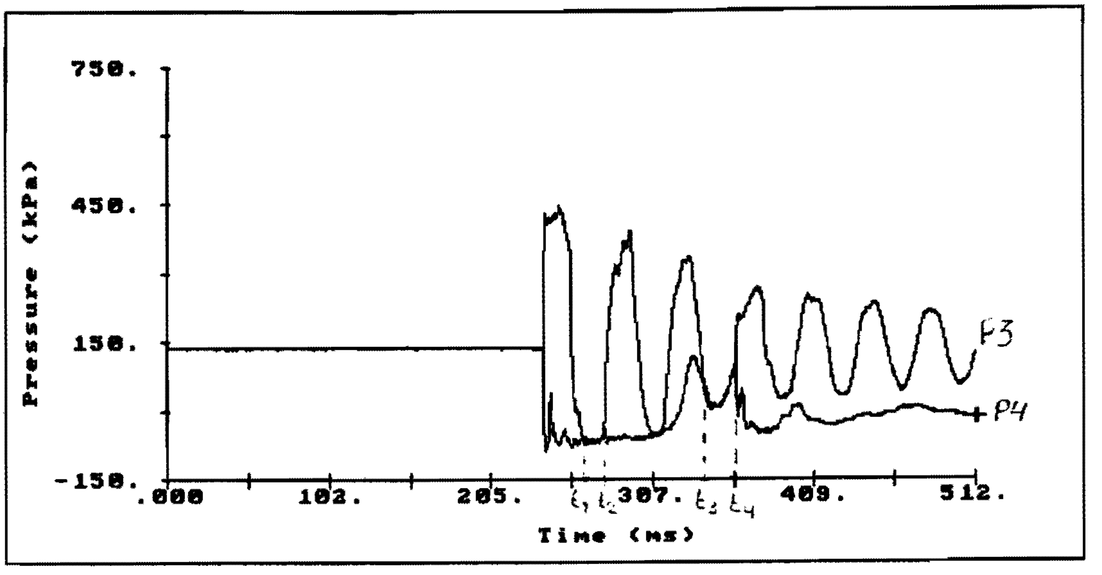

figure 4.5 comparison of the pressure above (p3) and below (p4) the valve

The first time the valve opens at t_1 (pressures equal) and closes at t_2 and the second time it opens at t_3 and closes at t_4. At the moment of closure a positive jump in pressure can be seen for p3 and a negative jump for p4. This phenomena of opening and closing is not always the same which again indicates that the valve does not always close in the same manner. Determination of the period of the reflections (the wave travelling the length of the pipe four times)was done with the measurements with a sample frequency of 4 kHz and 2 kHz. The resulting period was 40±1 ms. This does not agree with the expected value of 4L/a ≈ 36 ms. A possible explanation may be the release of gases dissolved in the water which greatly influences the wavespeed[1]. The items of cavitation and gas release are not investigated in this thesis.

Finally a simulation of the pressure wave propagation in the set-up was performed with the program TUBE (appendix F). The goal of this simulation was merely to see what would be the influence of steady flow friction on the propagation and damping of a pressure wave through the configuration. A flow of 0.5 l/s was chosen which implies 0.227 m/s in

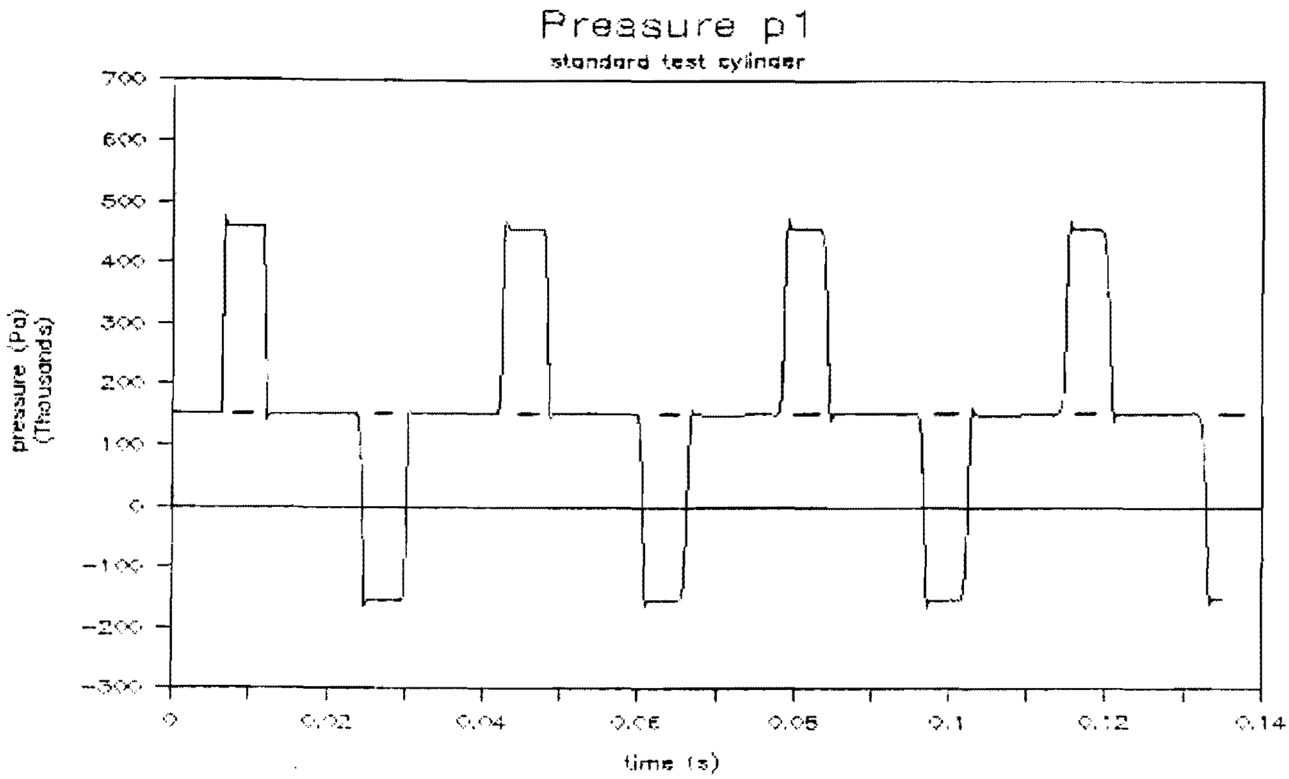

figure 4.6 a) computed pressure p1

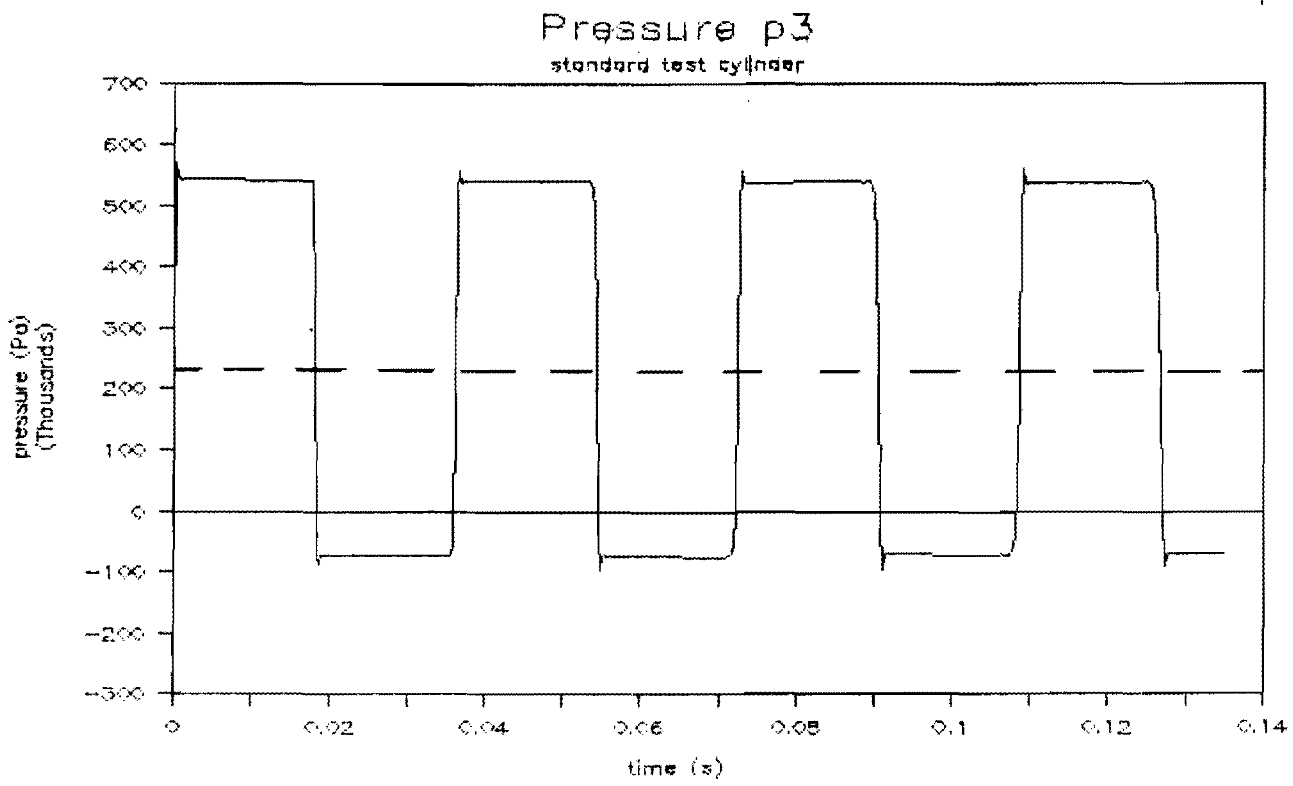

figure 4.6 b) computed pressure p3

the gas pipe and f=1.2 (fig 4.1).It was instantaneously stopped producing a pressure jump of magnitude ρav, with a and v of the standard test cylinder. The pressures are not taken exactly at x=6 cm and x=848 cm because of computational reasons. The results of the computation are shown in figure 4.6. The broken line represents the steady flow pressure.

Although the overall form of the calculated pressure can be recognized in the measured pressures of figures 4.3 a) and 4.3 c) the deviations are very large. The pressure jump in both computed figures is 312 kPa. This agrees well with the measured jumps in p3 and p2 but not with the jump in p1 which is only ≈270 kPa for a flow of 0.5 l/s. This result proves that the steady flow friction is not responsible for the pressure loss from p2 to p1. The computed period agrees with the theoretically expected value of 36 ms. The minimum pressure in the computed figures is negative even though absolute pressures were used. The cause of this lies in the fact that in the computation the phenomena of gas release and cavitation were not included. This is one effect causing a difference between measured and computed results. Other effects having influence are the opening and closing of the valve and frequency dependend friction. The effect of steady flow friction is negligible as seen from the computed pressure.

4.4 Enlarged test cylinder

The pressure transducers were kept at the same places as they were for the standard test cylinder, and the same measuring procedure was followed. Examples of the measured pressure transients are shown in fig. 4.7. These transients resemble fig. 4.3 very closely, not only regarding the form but also regarding the height of the pressure jump.

Comparison of the pressures above and below the valve (fig. 4.8) shows that in this configuration the valve also opens (t_1) and closes (t_2) after the first closure.

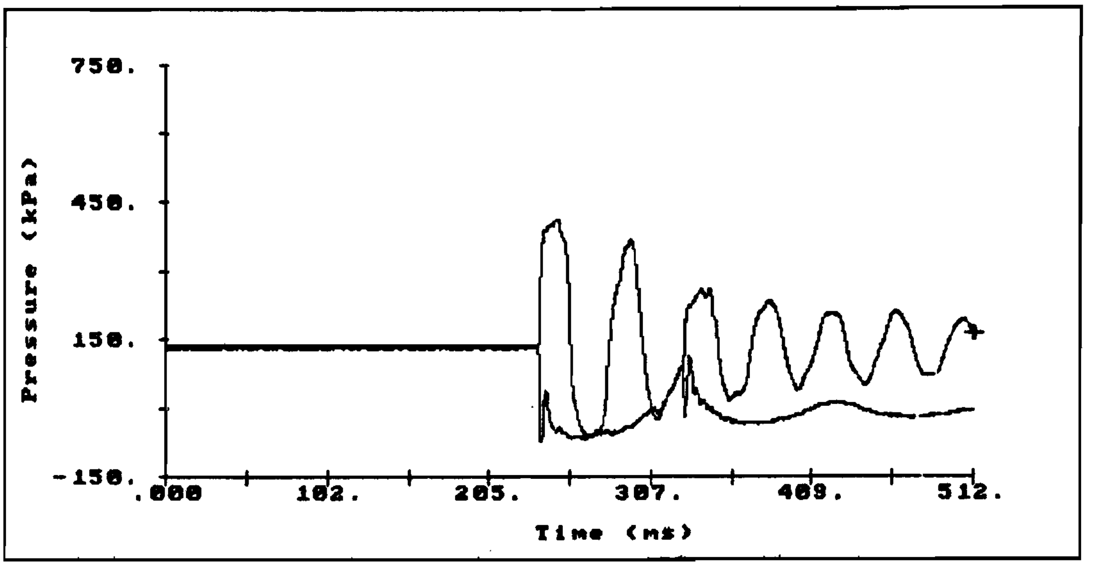

figure 4.8 comparison of pressures above (p3) and below (p4) the valve

From figure 4.9 the time of pressure build-up is estimated to be approximately 2.5 ms.

The results of the measured and calculated pressure jumps are shown in table 4.3. The most striking thing about this table is the large difference between the calculated pressure jumps in the enlarged test cylinder and the measured pressure jumps Δp3. This difference can be explained with the help of the reflection coefficient of equation (2.51) and figure 4.10.

Flow :
.50 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
1
Sample freq. :
4.00 (kHz)
Volt. range :
5.00 (V)
Stat. press. :
52.10 (kPa)
Pmax: 317.79
Pmin: -77.22

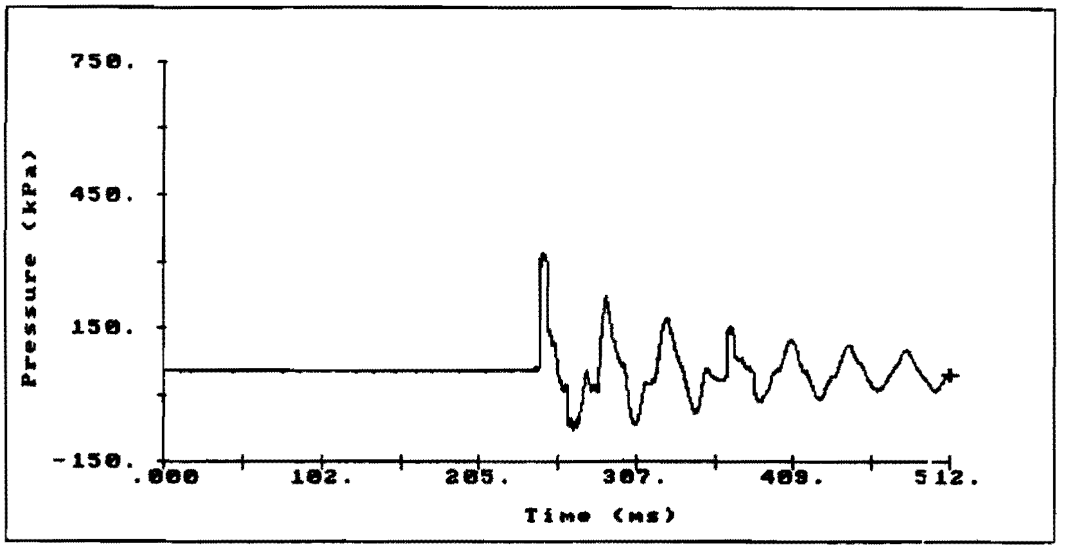

figure 4.7 a) pressure p1 at x=848 cm

Flow :
.50 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
2
Sample freq. :
4.00 (kHz)
Volt. range :
5.00 (V)
Stat. press. :
131.60 (kPa)
Pmax: 443.28
Pmin: -85.70

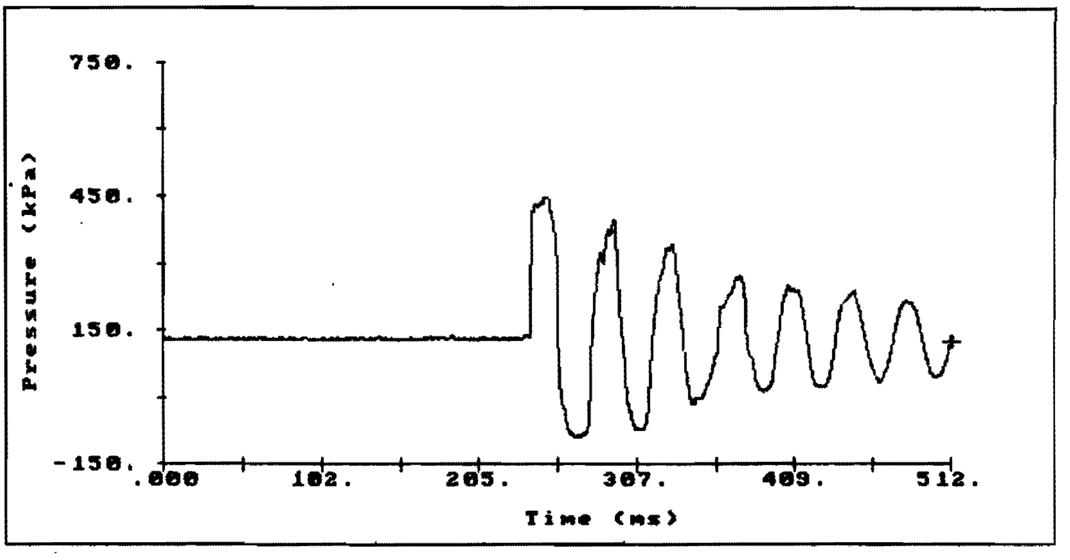

figure 4.7 b) pressure p2 at x=50 cm

Flow :
.50 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
3
Sample freq. :
4.00 (kHz)
Volt. range :
5.00 (V)
Stat. press. :
134.90 (kPa)
Pmax: 444.29
Pmin: -71.09

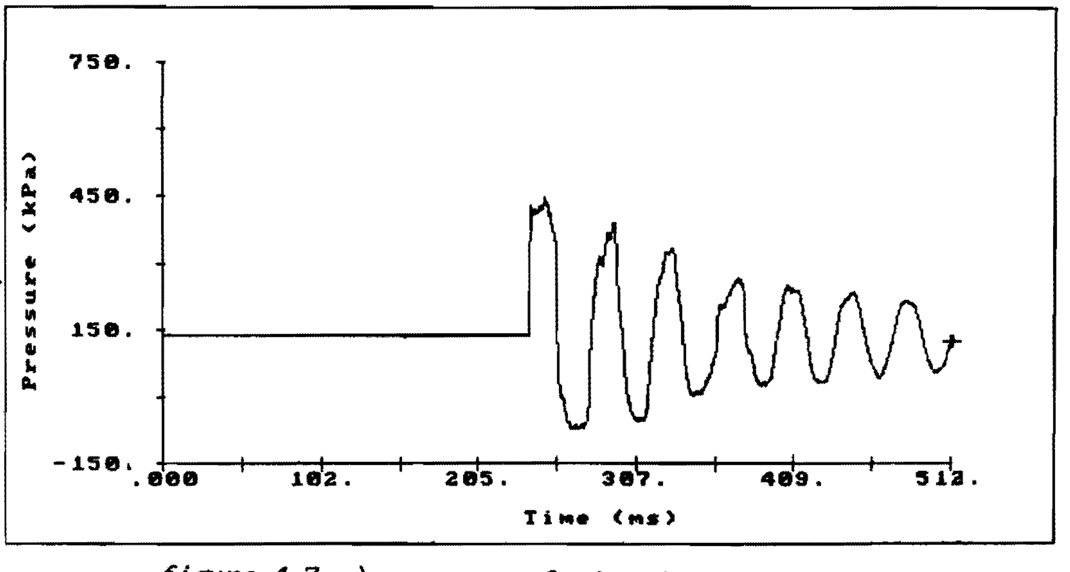

figure 4.7 c) pressure p3 at x=6 cm

Flow :
.50 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
4
Sample freq. :
4.00 (kHz)
Volt. range :
5.00 (V)
Steady press. :
136.70 (kPa)
Pmax: 139.55
Pmin: -68.29

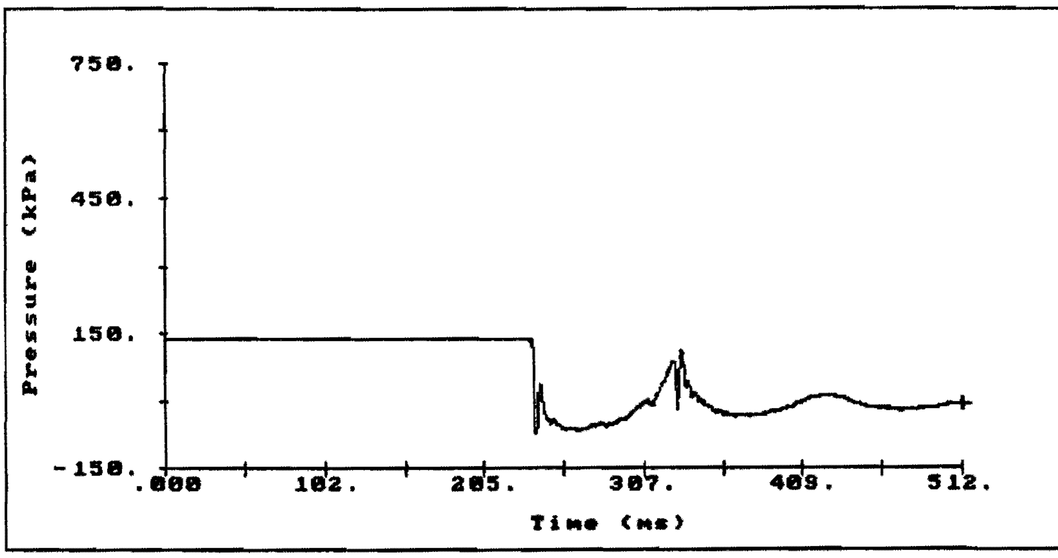

figure 4.7 d) pressure p4 at x=-4.5 cm

Flow :
.50 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
1
Sample freq. :
100.00 (kHz)
Volt. range :
5.00 (V)
Stat. press. :
51.30 (kPa)
Pmax: 308.88
Pmin: 50.49

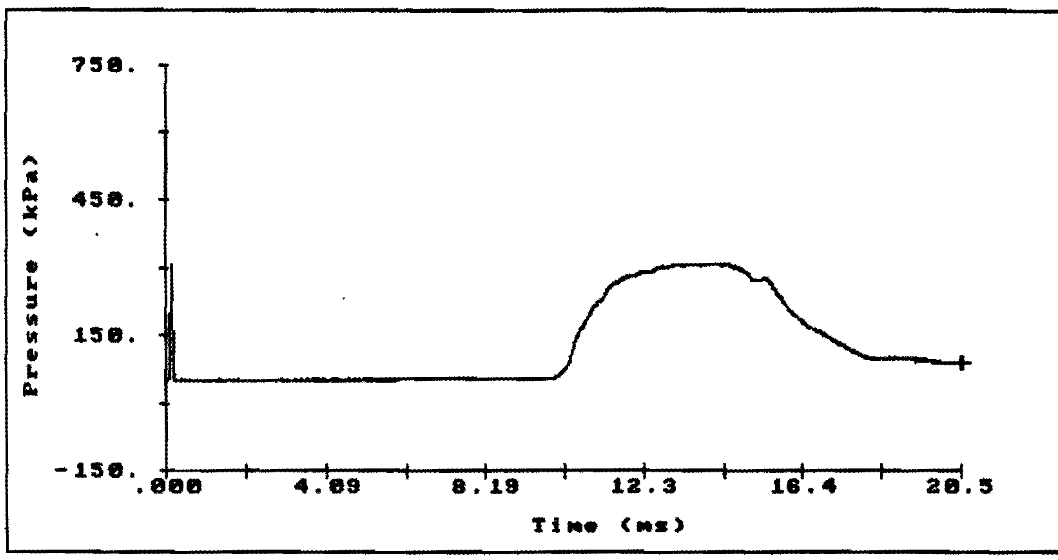

figure 4.9 a) pressure p1 at x=848 cm

Flow :
.50 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
3
Sample freq. :
100.00 (kHz)
Volt. range :
5.00 (V)
Stat. press. :
134.30 (kPa)
Pmax: 414.67
Pmin: 130.32

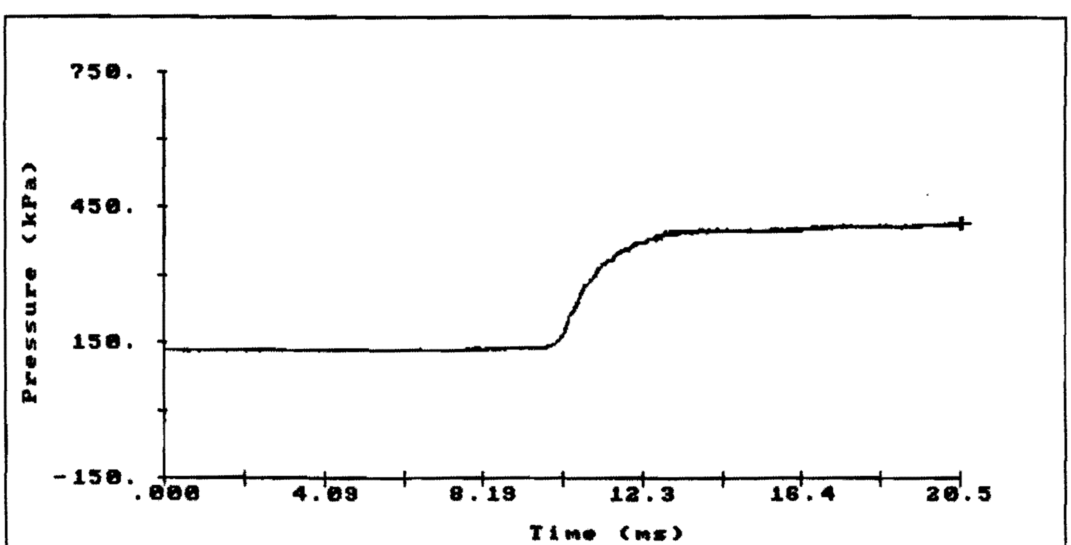

figure 4.9 b) pressure p3 at x=6 cm

			2" gas pipe				test cylinder		
V	f_s	q	ρav	Δp1	Δp2	Δp2/ρav	ρav	Δp3	Δp3/ρav
V	kHz	1/s	kPa	kPa	kPa		kPa	kPa	
5	2	0.498	309	242	297	0.96	78	269	3.45
5	2	0.498	309	248	294	0.95	78	281	3.60
5	4	0.498	309	254	300	0.97	78	278	3.56
5	10	0.498	309	251	300	0.97	78	281	3.60
5	20	0.498	309	254	303	0.98	78	284	3.64
5	40	0.498	309	257	303	0.98	78	284	3.64
5	100	0.498	309	258	303	0.98	78	281	3.60
5	100	0.498	309	258	306	0.99	78	280	3.60
10	2	0.755	467	400	478	1.02	119	452	3.80
10	10	0.753	466	406	501	1.08	119	476	4.00
10	20	0.750	464	406	489	1.05	118	464	3.93
10	100	0.750	464	406	478	1.02	118	452	3.83
10	2	1.25	774	668	798	1.03	197	750	3.81
10	10	1.25	774	674	798	1.03	197	750	3.81
10	10	1.25	774	675	798	1.03	197	756	3.84
10	20	1.25	774	674	804	1.04	197	756	3.84
10	100	1.25	774	674	804	1.04	197	738	3.75

Table 4.3 pressure jumps

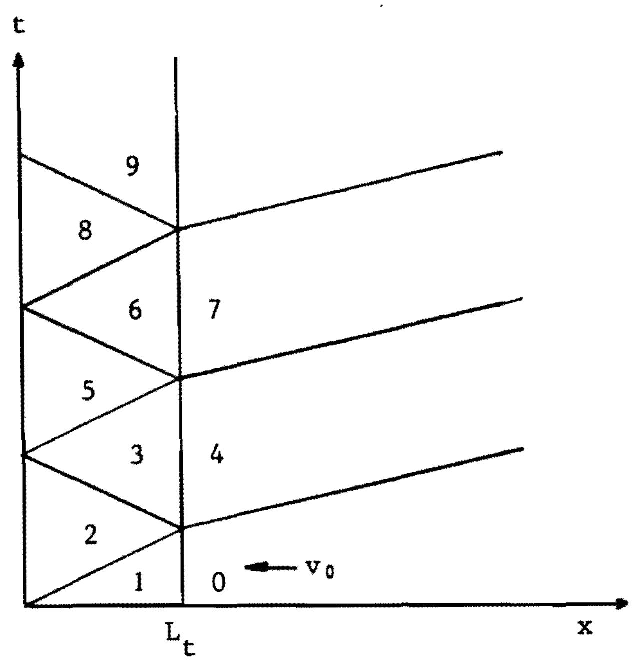

figure 4.10 reflections in the test cylinder

The figure shows an x-t diagram with $0<x<L_t$ representing the test cylinder and $x>L_t$ representing the gas pipe. On the boundary L_t continuity of flow is assumed and equal pressures on both sides. Initially the water flows in the -x direction and

$$A_0v_0=A_1v_1 \quad , \quad p_0=p_1$$

At time t=0 the valve at x=0 closes, so $v_2=0$ and with a C^- characteristic

$$p_1-\rho a_1v_1=p_2$$

Now because equation (2.51) and (2.46)

$$p_3=p_2+(p_2-p_1)r = p_1-\rho a_1v_1(1+r) \quad \text{and } v_3=rv_1$$

Going on like this the result is

$$p_5=p_1-\rho a_1v_1(1+2r) \qquad v_5=0$$

$$p_6=p_1-\rho a_1v_1(1+2r+r^2) \qquad v_6=r^2v_1$$

$$p_8=p_1-\rho a_1v_1(1+2r+2r^2) \qquad v_8=0$$

$$p_9=p_1-\rho a_1v_1(1+2r+2r^2+r^3) \qquad v_9=r^3v_1$$

and so on. This can also be written as

$$p_{3n}=p_1-\left[\frac{1+r}{1-r} (1-e^{n \ln r}) \right]\rho a_1v_1$$

The maximum pressure that can be reached is equal to

$$p_1-\rho a_1v_1\left(\frac{1+r}{1-r} \right) = p_0-\rho a_0v_0$$

See also van Steenhoven and van Dongen[10].

For the enlarged test cylinder (L_t=0.26 m, A_t=0.0079 m^2, a_t=1220 m/s) and the gas pipe (A=0.0022 m^2, a=1368 m/s) the reflection coefficient is r=0.60. This can give a maximum pressure jump of $4\rho a_1 v_1$. That the values in column $\Delta p3/\rho av$ are not equal to 4 is probably caused by frequency dependent friction and the fact that the valve does not close instantaneously.

Figure 4.11 shows a simulation of a flow of 0.5 l/s for the configuration with enlarged test cylinder shut down instantaneously. Although the differences between the measured transients (fig. 4.7 c)) and the computed transients are large, the computed pressure jump p3 of 312 kPa agrees well with the measured jump p3 of 280 kPa. The computed time of pressure build-up is approximately 3.5 ms which is also of the order of the measured time of pressure build-up of 2.5 ms.

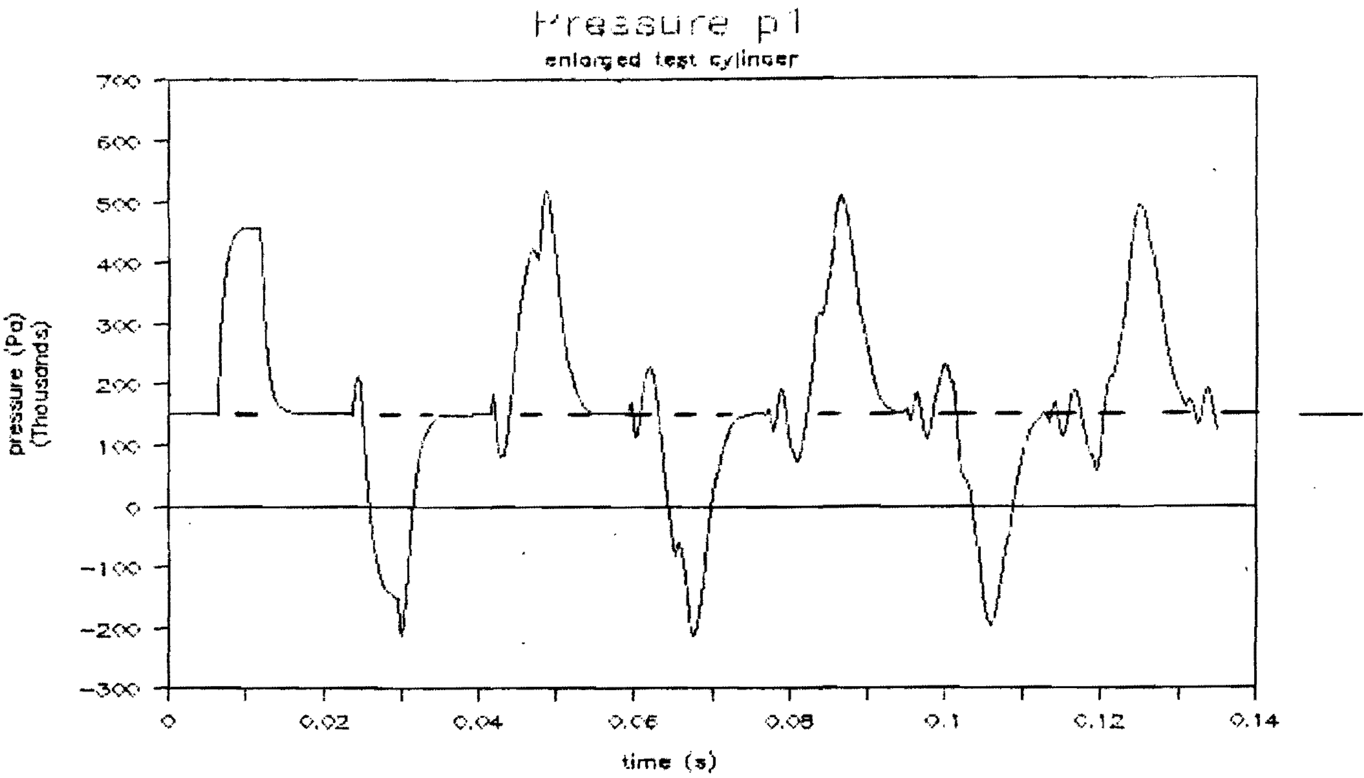

figure 4.11 a) computed pressure p1

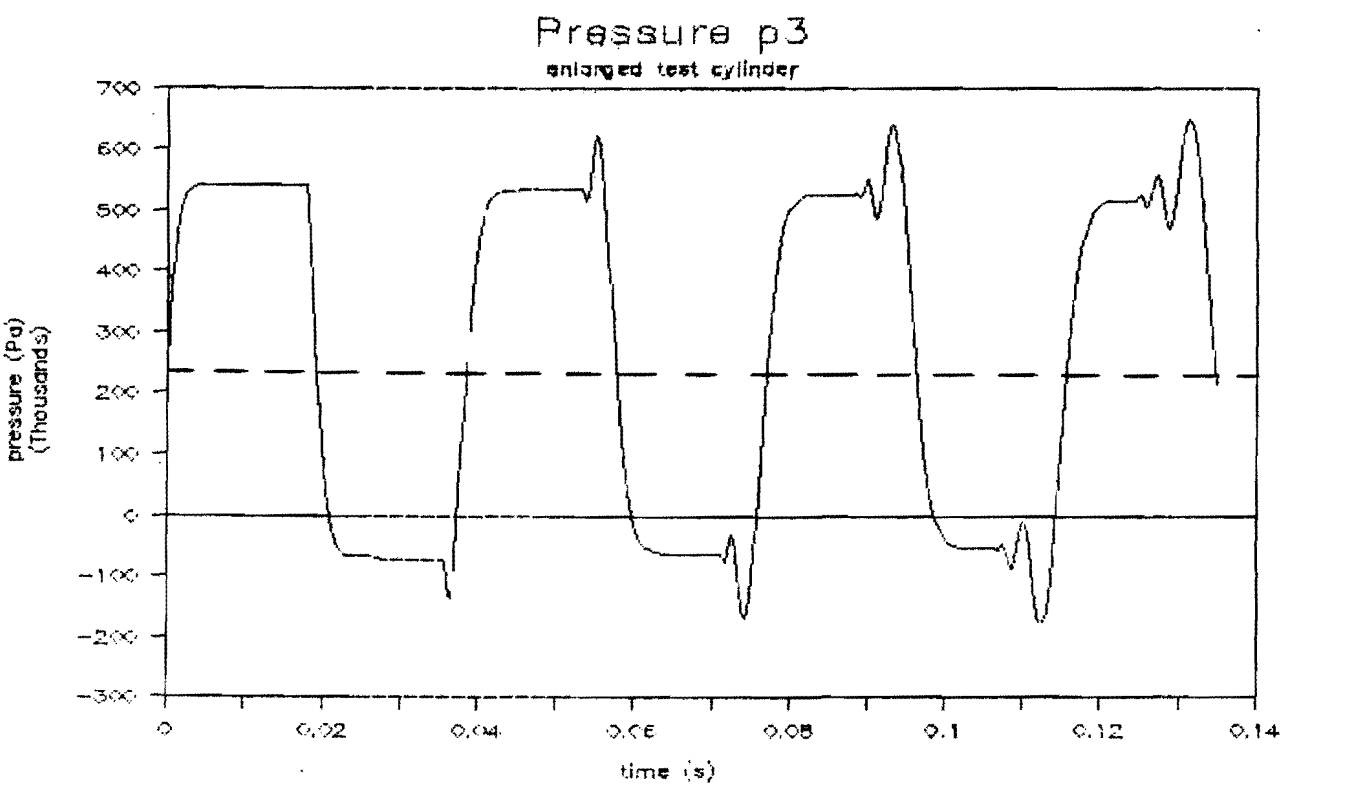

figure 4.11 b) computed pressure p3

4.5 Enlarged test cylinder with internal pipe

Figure 4.121 again shows a schematic view of the enlarged test cylinder with internal pipe. Points A,B and C are pressure connections; A and B situated in the enlarged test cylinder, C in the drain-pipe.

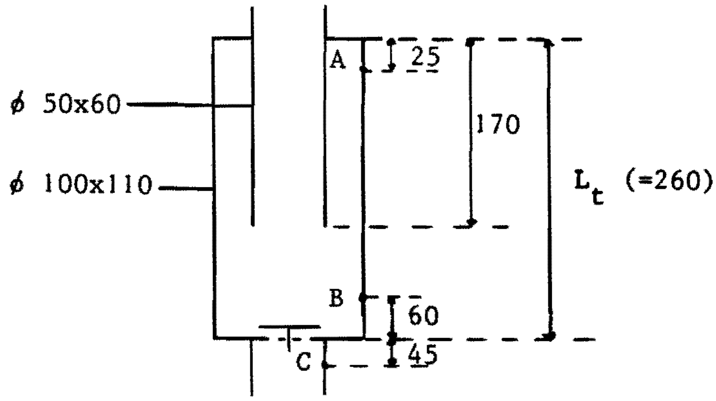

figure 4.12 enlarged test cylinder with internal pipe

During the first series of measurements with the configuration the pressure transducers were located as follows: p1 at x=848 cm, p2 at x=50 cm, p3 at x=6 cm (point B) and p4 at x=-4.5 cm (point C). Examples of the measured pressures are given in figure 4.13.

From figure 4.13 the time between two successive maxima was measured to be 67 ms for the first two maxima and 62, 60 and 58 ms for subsequent pairs of maxima. Figures 4.14 a) and 4.14 b) show p1 and p3 respectively for a sample frequency of 100 kHz. The time of pressure build-up is estimated from fig. 4.14 b) to be approximately 10 ms. Superposed on the signal of fig. 4.14 b) a small periodical signal can be seen with period 8.6 ms. This agrees well with the time it takes the pressure wave to travel the lenght of the test cylinder four times: 8.5 ms.

The results of the measurements of the maximum pressures due to the closing of the valve are shown in table 4.4.

A second series of measurements was started with transducer 3 at point A and transducer 4 at point B. The experiments gave no differences in pressure between points A and B.

Flow :
.50 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
1
Sample freq. :
2.00 (kHz)
Volt. range :
5.00 (V)
Stat. press. :
42.60 (kPa)
Pmax: 213.84
Pmin: -17.82

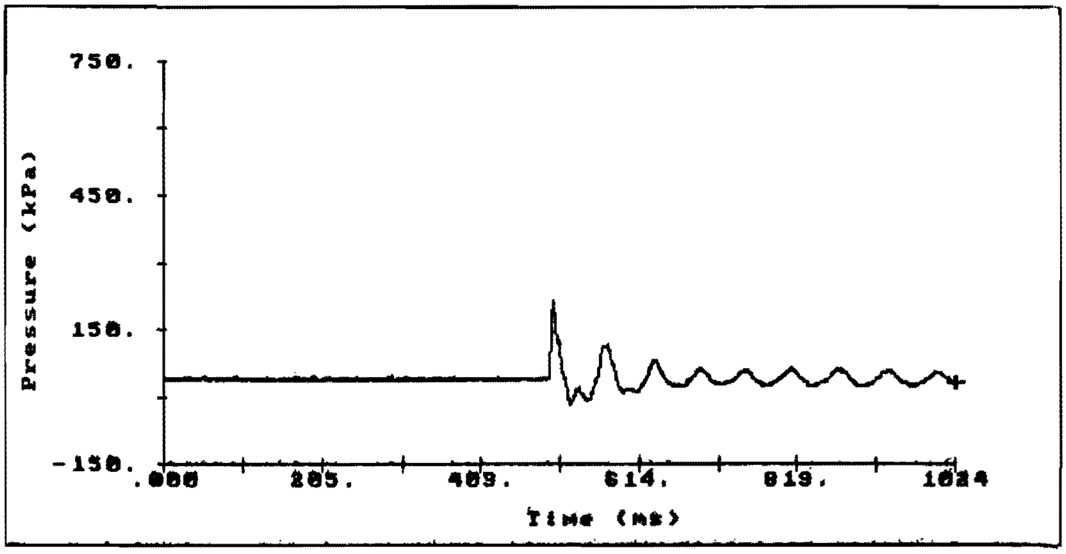

figure 4.13 a) pressure p1 at x=848 cm

Flow :
.50 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
2
Sample freq. :
2.00 (kHz)
Volt. range :
5.00 (V)
Stat. press. :
121.50 (kPa)
Pmax: 393.04
Pmin: -11.82

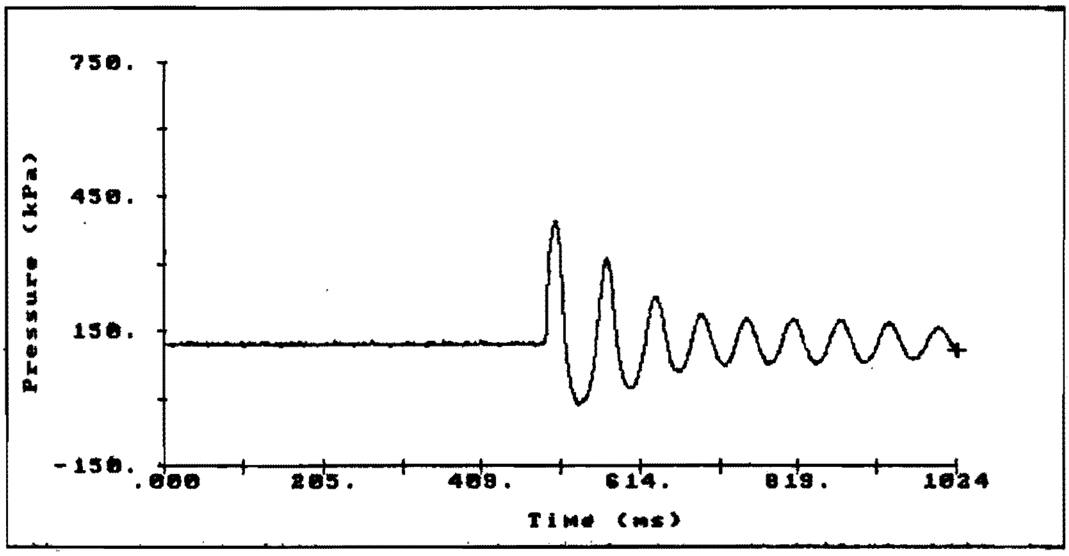

figure 4.13 b) pressure p2 at x=50 cm

Flow :
.50 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
3
Sample freq. :
2.00 (kHz)
Volt. range :
5.00 (V)
Stat. press. :
124.90 (kPa)
Pmax: 382.09
Pmin: -2.96

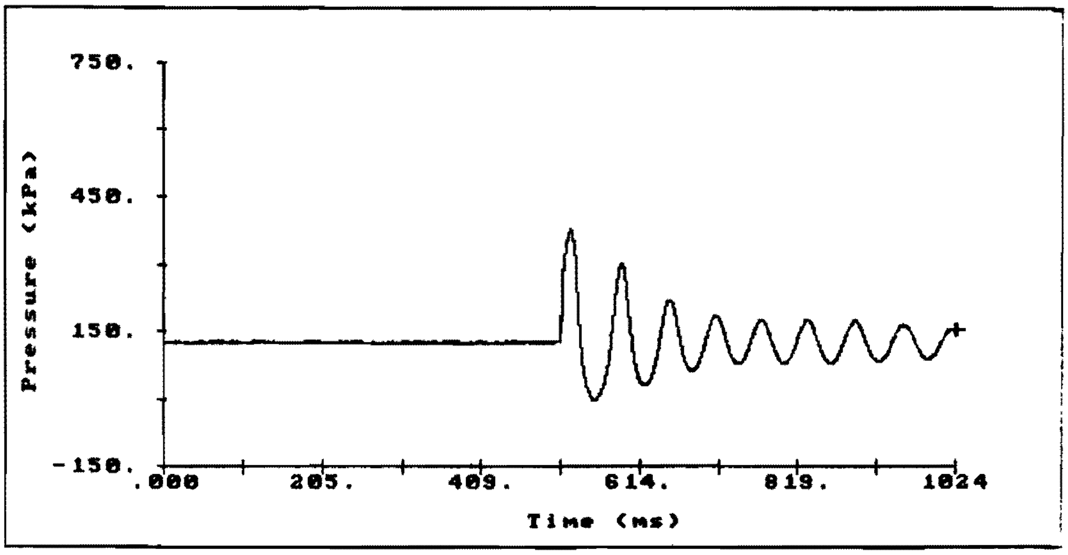

figure 4.13 c) pressure p3 at x=6 cm

Flow :
.50 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
4
Sample freq. :
2.00 (kHz)
Volt. range :
5.00 (V)
Stat. press. :
127.20 (kPa)
Pmax: 130.64
Pmin: -56.41

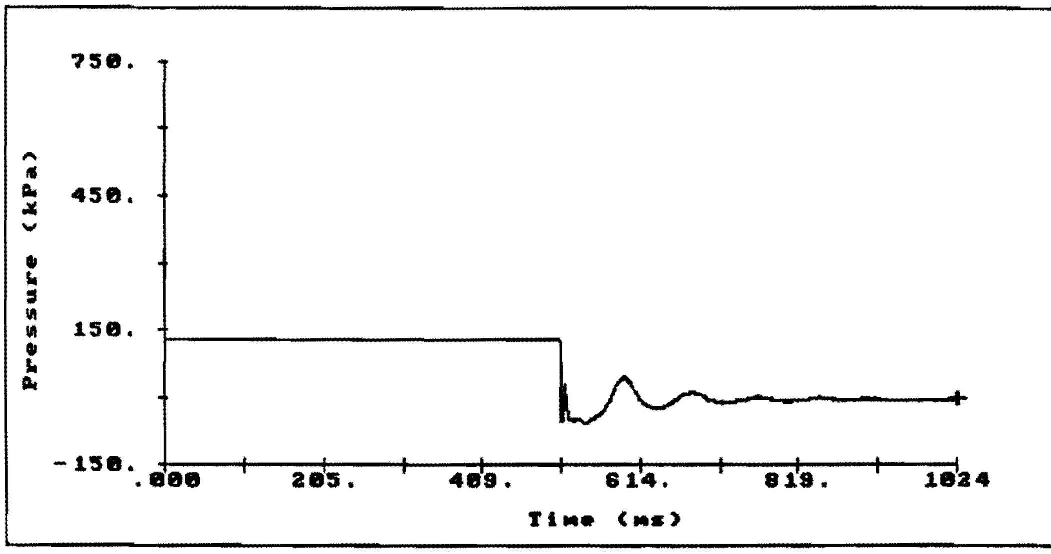

figure 4.13 d) pressure p4 at x=-4.5 cm

Flow :
.49 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
1
Sample freq. :
100.00 (kHz)
Volt. range :
5.00 (V)
Steady press. :
42.30 (kPa)
Pmax: 255.42
Pmin: 38.61

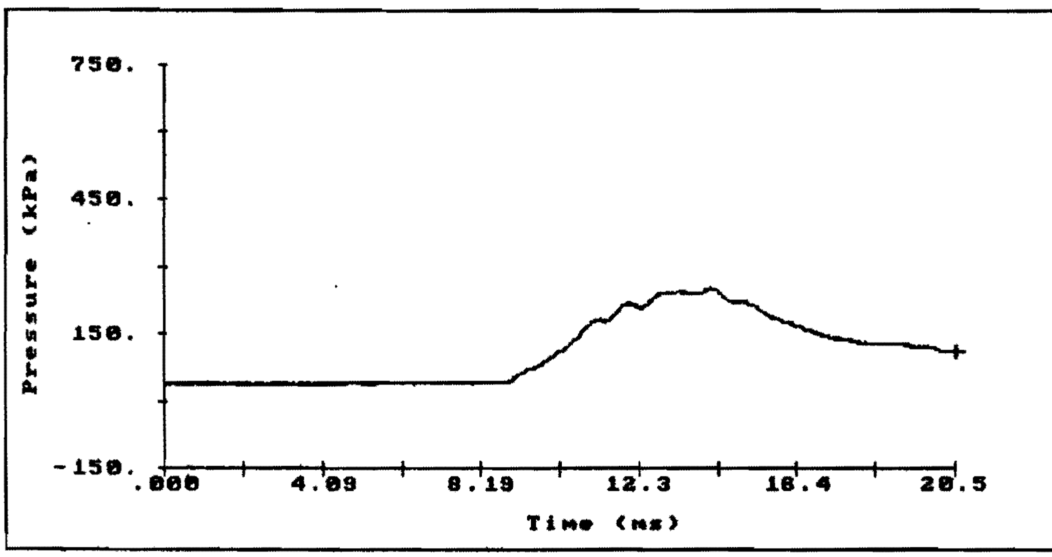

figure 4.14 a) pressure p1 at x=848 cm

Flow :
.49 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
3
Sample freq. :
100.00 (kHz)
Volt. range :
5.00 (V)
Steady press. :
124.80 (kPa)
Pmax: 399.86
Pmin: 124.40

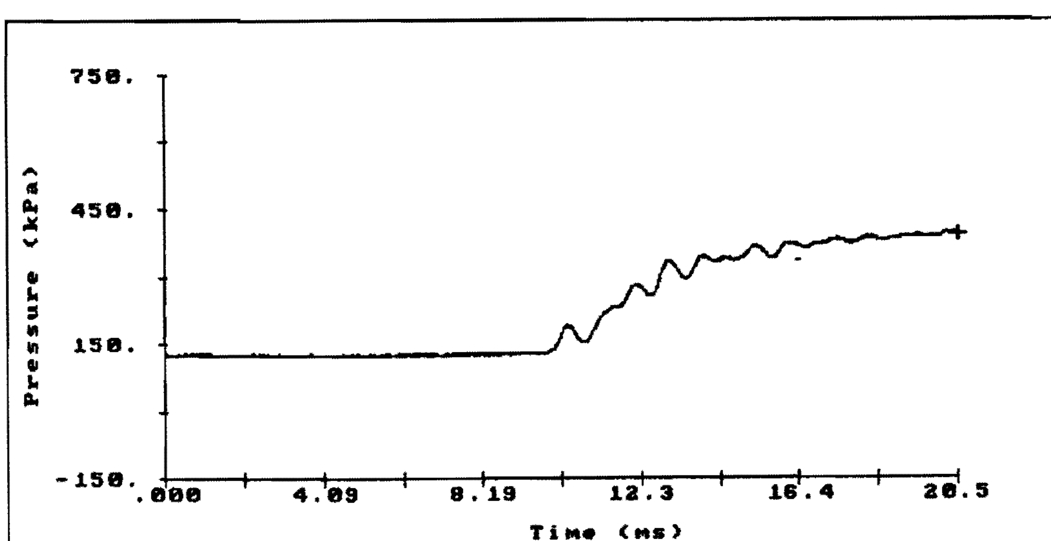

figure 4.14 b) pressure p3 at x=6 cm

V	f_s	q	2" gas pipe ρav	$\Delta p1$	$\Delta p2$	$\Delta p2/\rho av$	test cylinder ρav	$\Delta p3$	$\Delta p3/\rho av$
V	kHz	l/s	kPa	kPa	kPa		kPa	kPa	
5	2	0.500	310	171	272	0.88	79	257	3.25
5	4	0.493	305	180	275	0.90	78	253	3.24
5	10	0.500	310	207	295	0.95	79	278	3.51
5	20	0.500	310	210	298	0.96	79	275	3.48
5	40	0.493	305	207	295	0.97	78	278	3.56
5	100	0.493	305	213	298	0.98	78	275	3.53
5	2	0.750	464	341	455	0.98	118	429	3.64
5	4	0.750	464	356	458	0.99	118	430	3.64
5	10	0.750	464	359	458	0.99	118	430	3.64
5	20	0.750	464	362	458	0.99	118	433	3.67
5	100	0.750	464	362	461	0.99	118	423	3.58
10	2	1.25	774	653	796	1.03	197	771	3.91
10	4	1.26	780	660	814	1.04	199	765	3.84
10	10	1.25	774	665	816	1.05	197	771	3.91
10	20	1.25	774	660	810	1.05	197	765	3.88
10	100	1.25	774	660	814	1.05	197	748	3.80

Table 4.4 pressure jumps

4.6 Enlarged test cylinder with airchamber

The configuration of paragraph 4.5 is now filled with a certain amount of air denoted by h in figure 4.15.

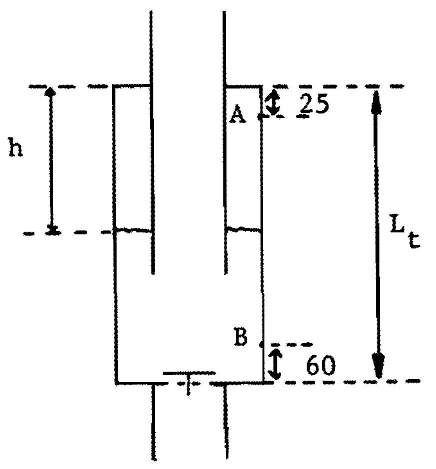

figure 4.15 enlarged test cylinder with air chamber

During the experiments the pressure transducers were installed as follows: p1 at x=848 cm, p2 at x=50 cm, p3 at x=23.5 cm (point A) and p4 at x=6 cm (point B). The experiments were performed for a flow of 1.25 l/s and amounts of air equivalent to h=150 mm, h=105 mm and h= 60 mm, and for a flow of 1.0 l/s with h=60 mm.

Examples of the measured transients with h=150 mm are given in figure 4.16. In the figures a low frequency oscillation with period T and superposed on it a high frequency oscillation that is not constantly present can be seen. This high frequency oscillation manifests itself at the start of the transient and again a time $\Delta\tau$ later. It is not always on the top of the low frequency oscillation as might be thought from fig. 4.16. The times T and $\Delta\tau$ are the same for all signals in one experiment. An exception is signal p3 in the airchamber where no high frequency signal is present. It seems that the water-air boundary acts as a low pass filter.

From p3 (fig. 4.16 c) it is clear that the low frequency pressure variation is not a sine and that $p3_{max}-p3_{steady}$ is larger than $p3_{steady}-p3_{min}$. With the linearized airchamber theory of paragraph 2.5 the expected period T_{lin} of oscillation would be

Flow :
1.25 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
1
Sample freq. :
1.00 (kHz)
Volt. range :
2.00 (V)
Stat. press. :
44.20 (kPa)
Pmax: 74.84
Pmin: 29.70

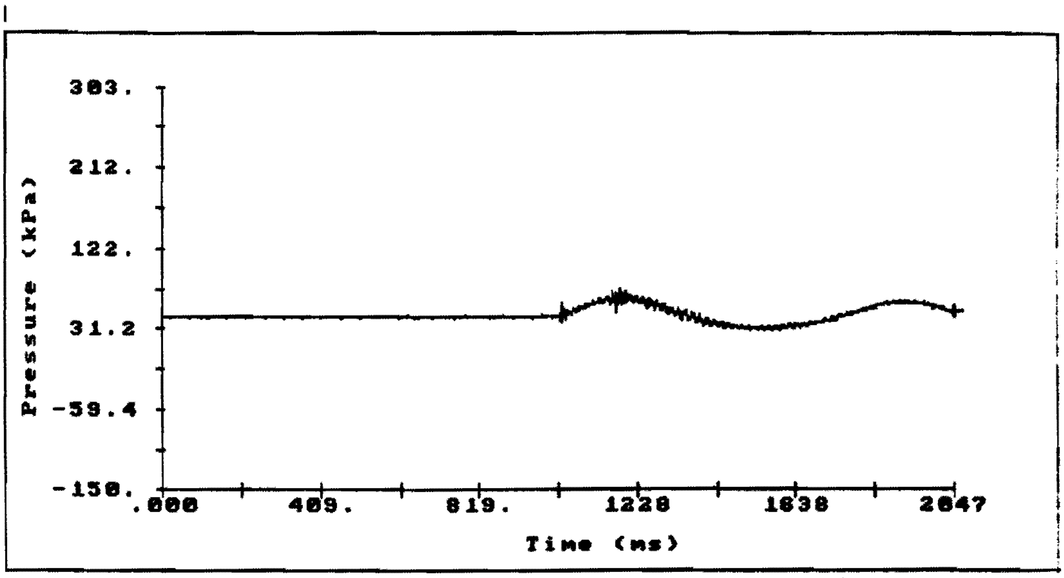

figure 4.16 a) pressure p1 at x=848 cm

Flow :
1.25 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
2
Sample freq. :
1.00 (kHz)
Volt. range :
2.00 (V)
Stat. press. :
124.30 (kPa)
Pmax: 197.41
Pmin: 82.75

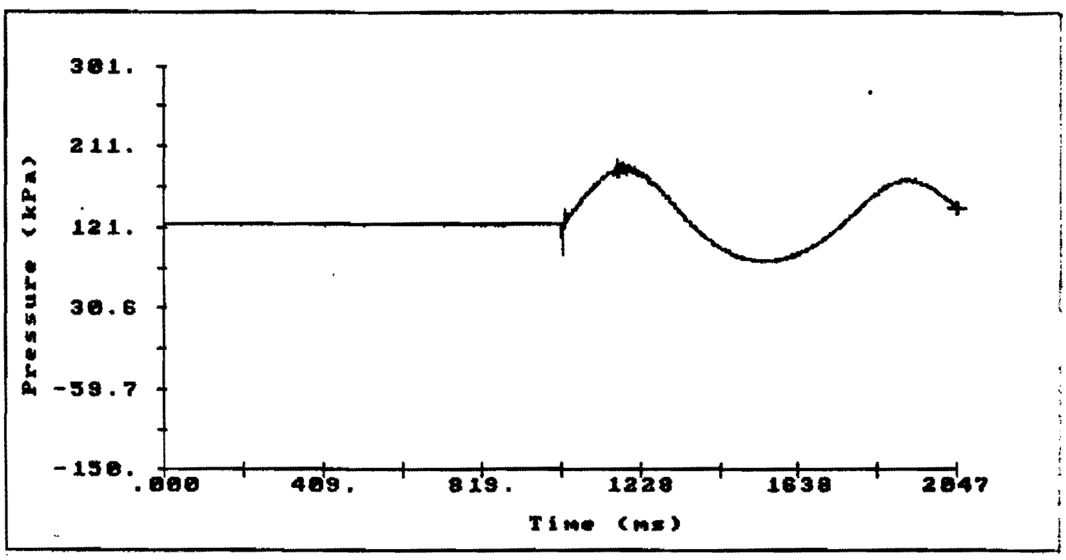

figure 4.16 b) pressure p2 at x=50 cm

Flow :
1.25 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
3
Sample freq. :
1.00 (kHz)
Volt. range :
2.00 (V)
Stat. press. :
125.40 (kPa)
Pmax: 189.56
Pmin: 84.12

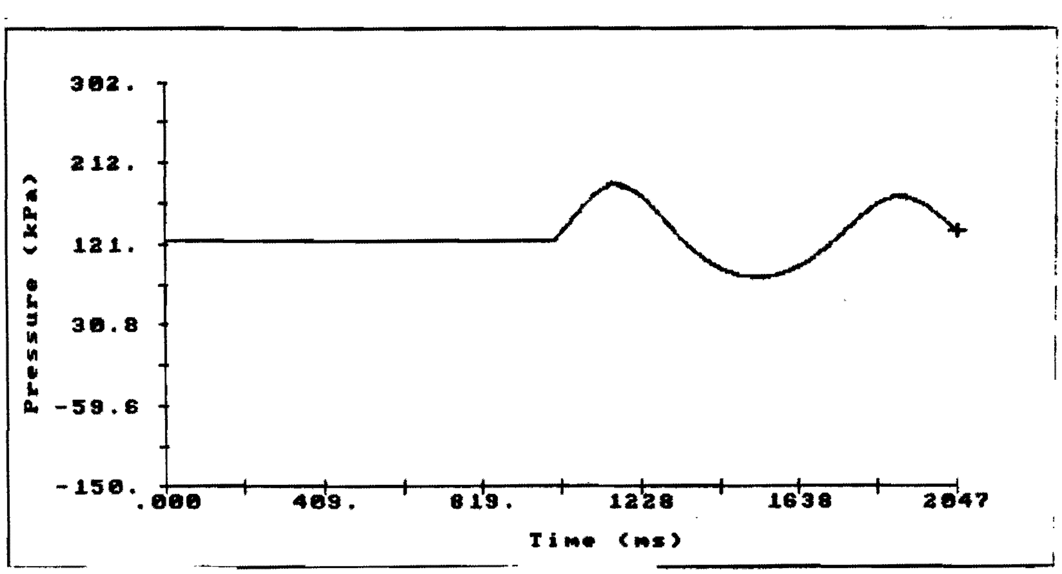

figure 4.16 c) pressure p3 at x=23.5 cm

Flow :
1.25 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
4
Sample freq. :
1.00 (kHz)
Volt. range :
2.00 (V)
Stat. press. :
127.80 (kPa)
Pmax: 205.46
Pmin: 85.51

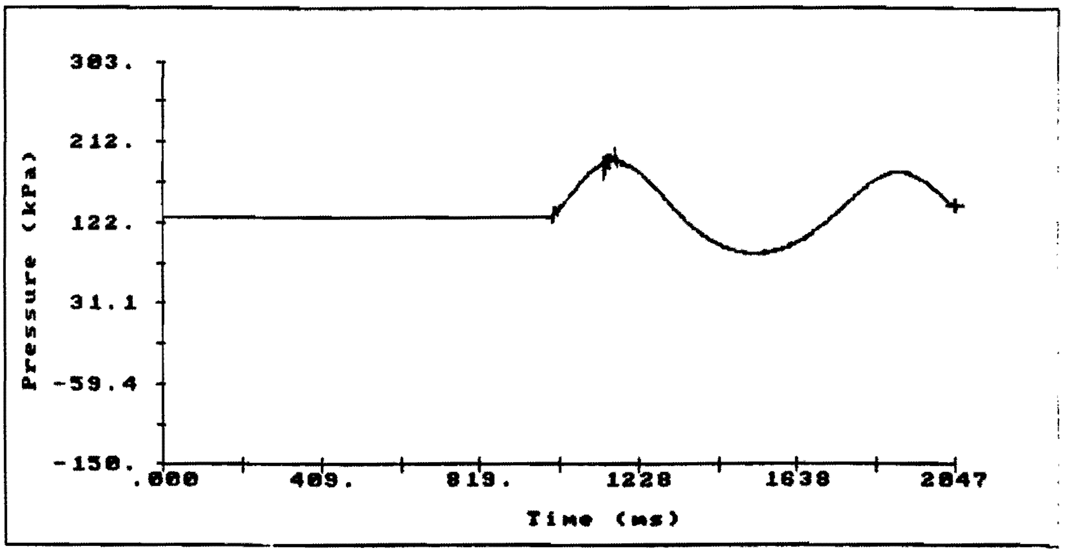

figure 4.16 d) pressure p4 at x=6 cm

Flow :
1.25 (l/s)
Valve height :
11.00 (mm)

Transducer no. :
4
Sample freq. :
100.00 (kHz)
Volt. range :
2.00 (V)
Steady press. :
127.50 (kPa)
Pmax: 217.34
Pmin: 67.70

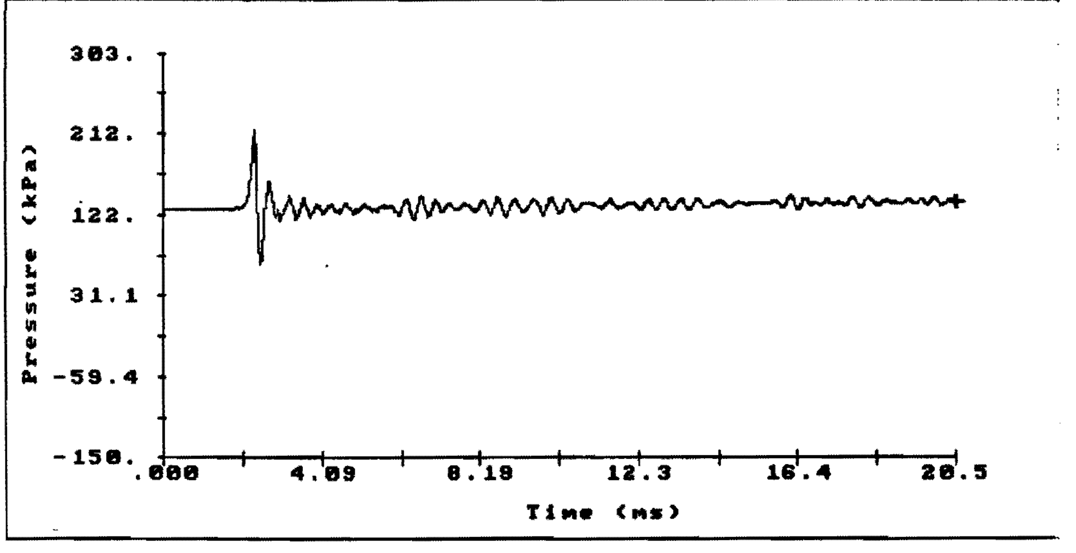

figure 4.17 a) pressure p4 at x= 6 cm

$$T_{lin} = \frac{2\pi}{\omega} = 2\pi \left[\frac{nAp_0}{V_0 \rho L} \right]^{-\frac{1}{2}}$$

and the amplitude P_{lin}

$$P_{lin} = v_0 \left[\frac{nAp_0 \rho L}{V_0} \right]^{\frac{1}{2}}$$

The measured and calculated periods and amplitudes are compared in table 4.5.

An experiment with a sample frequency of 100 kHz (fig. 4.17) reveals the period τ of the high frequency oscillation by measuring the time between two successive peaks. The measured period τ=±0.4 ms agrees with the period that would be expected from reflection of the pressure wave against the air-water surface: $4(L_t-h)/a_t$=0.36 ms with L_t the lenght of the test cylinder and a_t the wavespeed in the test cylinder. The measured and calculated periods and the measured pressure jumps of the high frequency oscillation are shown in table 4.6.

h	q	$p3_{steady}$	$\Delta p3^+/P_{lin}$	$\Delta p3^-/P_{lin}$	T/T_{lin}
mm	l/s	kPa			
150	1.26	125	1.14	0.73	0.95
105	1.25	124	1.16	0.73	0.95
60	1.25	124	1.18	0.71	0.98
60	1.00	124	1.15	0.72	0.97

Table 4.5 amplitudes and periods

h	q	$\Delta p1$	$\Delta p2$	$\Delta p4$	$\tau/[4(L_t-h)/a)]$
mm	l/s	kPa	kPa	kPa	
150	1.25	45	62	90	1.11
105	1.25	96	109	116	1.18
60	1.25	132	139	144	1.21
60	1.00	98	105	126	1.21

Table 4.6 pressure jumps

5 Conclusions and suggestions

The first conclusion that can be drawn is that the set-up is very suitable for monitoring the pressure waves and their interaction with the system as long as the waves are not reflected from the roof reservoir. After reflection at the reservoir at the reservoir several phenomena that are not fully understood occur and trouble the interpretation of the signal.
The simple simulation program with only steady flow friction can reasonably describe the first pressure jump close to the valve. After the first reflection and far from the valve the pressure transients are not well described. This is probably due to frequency dependend friction and because the items of gas release and cavitation are not included in the model. Furthermore repeated opening and closing of the valve troubles the simulation.
Another conclusion is that the pressure wave propagation in the set-up can be divided into two cases.
One case in which the pressure build-up is accurately and essentially described with pressure waves generated by the closing of the valve and reflecting at various obstructions and interacting with parts of the set-up. This description with the help of pressure waves is essential if the time of pressure build up is smaller or of the order of the time of reflections. The experiment with the standard test cylinder falls in this category.
In the other case the pressure build-up can best be described with a quasi-static approach in which overall characteristics of the set-up are used. This approach can be used if the time of pressure build-up is much larger than the time of reflections of the pressure waves. The experiments with the airchamber fall in this category. It must be said that the method with the pressure waves can be used in this case also, although it is cumbersome.
The experiments with enlarged test cylinder and enlarged test cylinder wtih internal pipe are intermediate cases in which the methods of description overlap.
As a last conclusion it can be said that the airchamber works very well

as a means of reducing the maximum pressure and that its behaviour is reasonably described with linear theory.
As a suggestion for further experiments with the set-up it may be worth-while to install a force transducer at the first elbow above p1 to monitor the vibration of the set-up.
In order to study the effect of pressure waves on the pump rod a long pump rod can be suspended from the roof through the delivery pipe into the test cylinder. If at the lower end of the pumprod a piston without valve is made and at the upper end a force transducer is installed, then the experiments described in this thesis can be repeated, while monitoring also the force in the pumprod.
Another interesting experiment would be the use of a very elastic material such as PVC as a test cylinder.

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Laboratory of Fluid Dynamics and Heat Transfer; Dept. of Physics
Eindhoven University of Technology
internal report R 813 A October 1986

10 Steenhoven, A.A. van, Dongen M.E.H. van
Model studies of the aortic pressure rise just after valve closure
J. Fluid Mech. (1986), vol. 166, pp. 93-113

Appendix

Appendix A

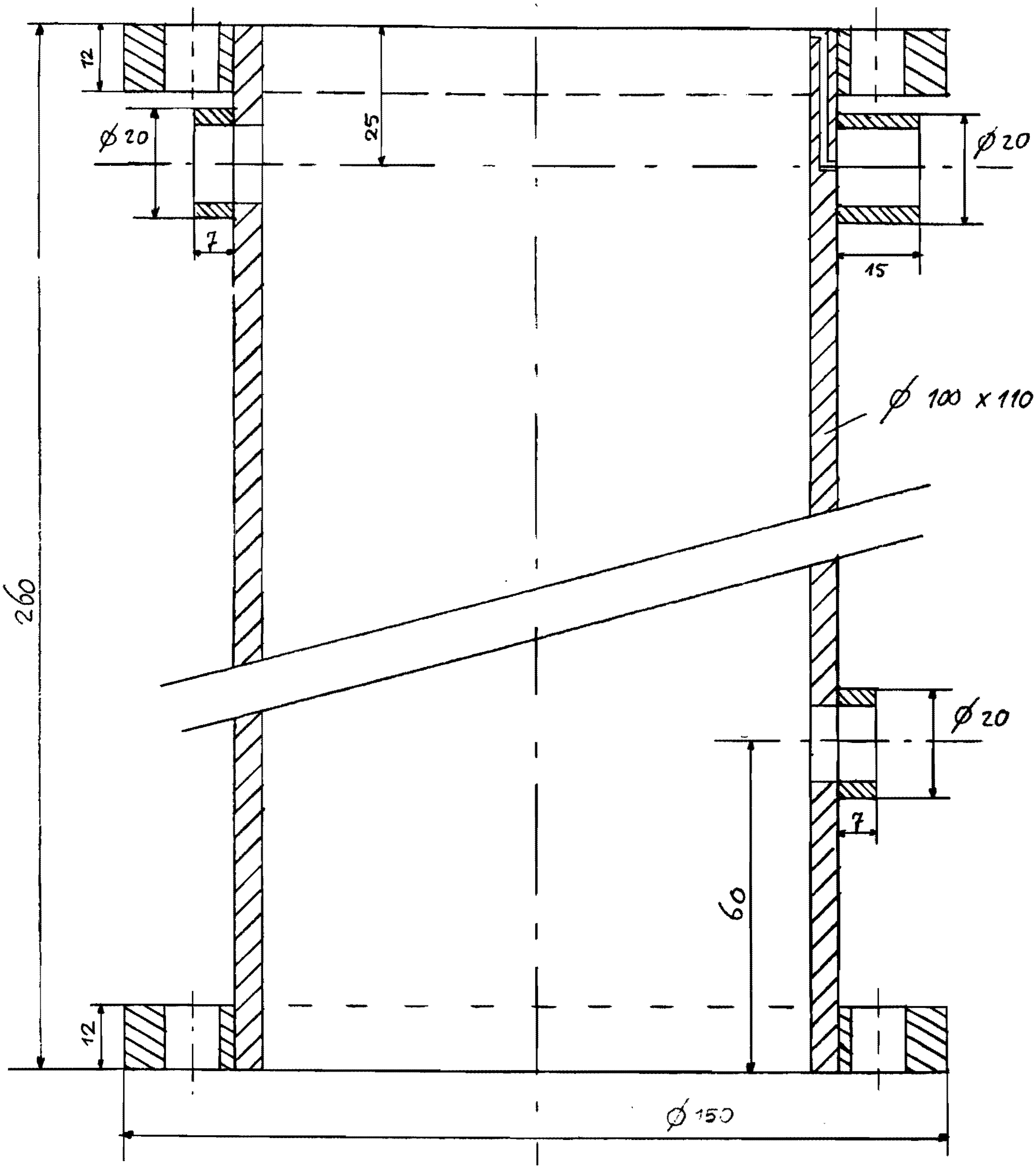

figure A1 enlarged test cylinder

Appendix B

$\rho_{water} = 998.2\ kg/m^3$
$K_{water} = 2.2$ GPa
$E_{brass} = 100$ GPa
$\mu_{brass} = 0.36$
$E_{steel} = 207$ GPa
$\mu_{steel} = 0.3$

2" gaspipe	D=53 mm	e=3.65 mm
50×60 brass pipe	D=50 mm	e=5 mm
100×110 brass pipe	D=100 mm	e=5 mm

These data are compiled from Wylie and Streeter[1], Chaudry[3] and Polytechnisch Zakboekje[7].

Appendix C

The pressure transducers

The numbering of the pressure transducers is as follows

nr 1	PDCR 810	serial nr 227806
nr 2	PDCR 810	serial nr 227808
nr 3	PDCR 810	serial nr 227809
nr 4	PDCR 810	serial nr 227806

A static calibration of the pressure transducers was performed. The least squares lines obtained from these data are:

transducer	V_{out} (V)
1	0.0043+0.0066*p
2	0.0054+0.0066*p
3	0.0084+0.0066*p
4	0.0026+0.0066*p

with p in kPa.

The relative deviations from the least squares lines are given in fig. C1.

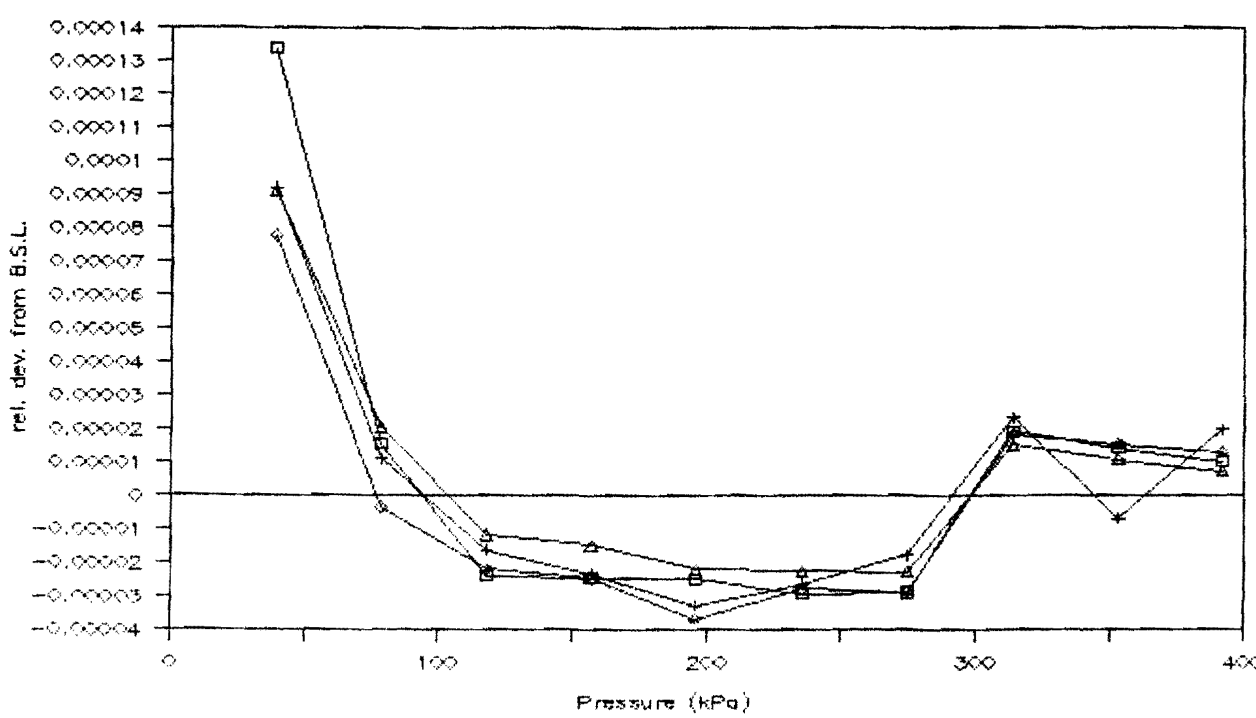

figure C1 relative deviations from least squares lines

With the calibration set-up it was not possible to go beyond 4 at although the transducers are for 15 barg range.
The amplifier and transducer drift after switching on is shown in figure C2. After about one hour the output is constant, but after several hours of experimenting zero drifts of 10 mV were measured.

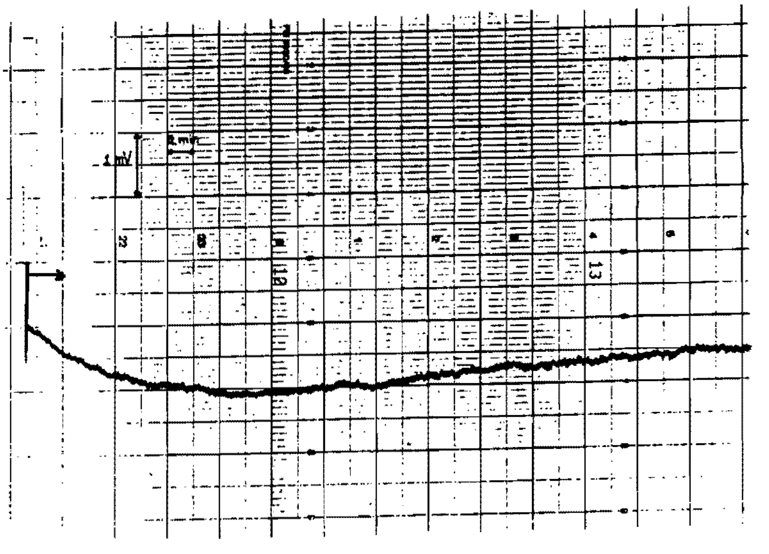

figure C2 amplifier/transducer drift after switching on

The dynamic behaviour of the transducers is tested by installing transducer nr 1 in a shock tube. The result is shown in figure C3. From this figure the time constant (0-63%) is found to be $\tau \approx 10$ μs. Becuase the bandwidth of the used channel (1) is 104 kHz and of the other channels 58 kHz the transient behaviour of the transducer/amplifier combination is determined by the bandwidth of the amplifier.

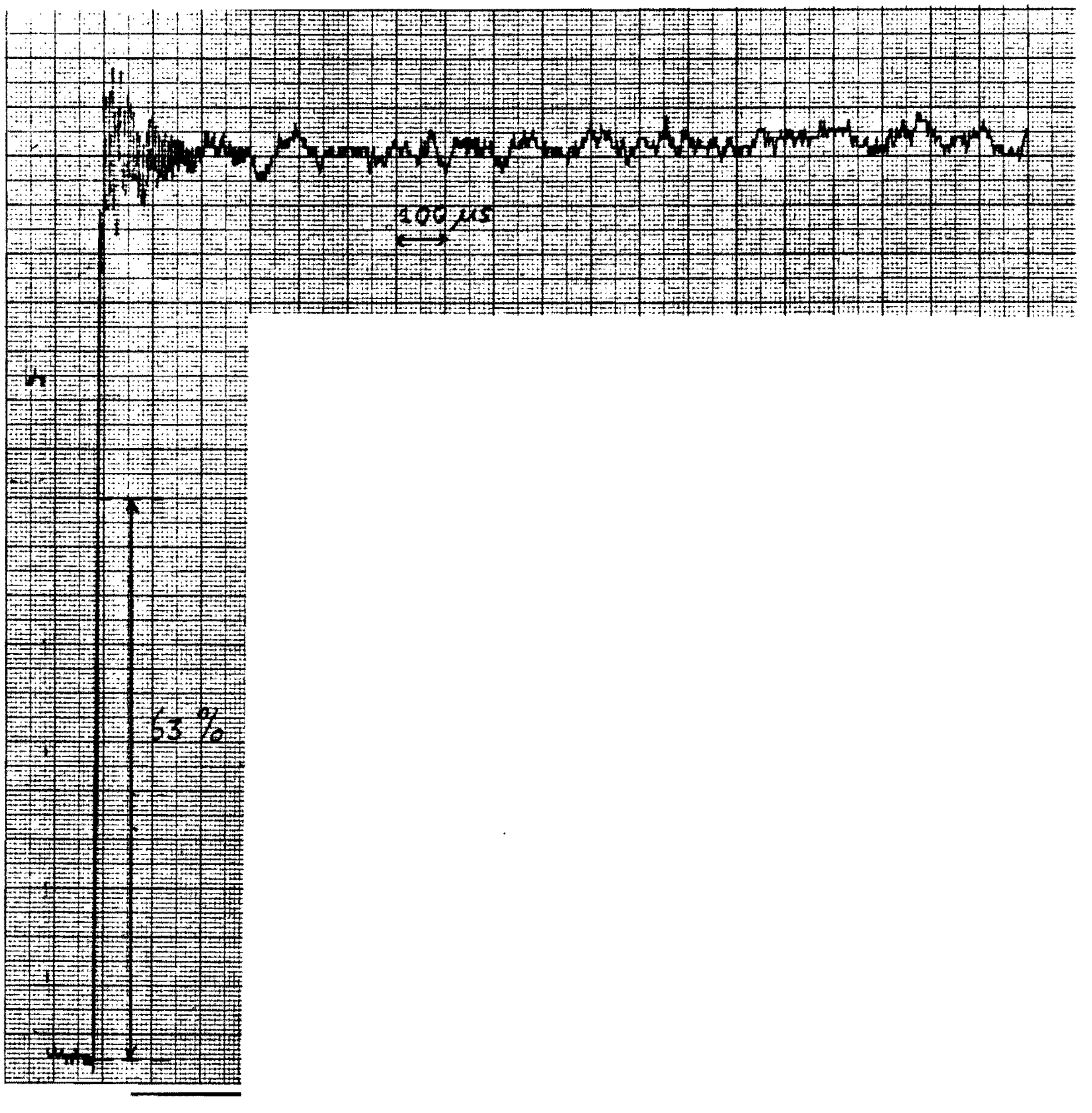

figure C3 dynamic behaviour of the transducer/amplifier

Druck Limited
Fir Tree Lane, Groby, Leicester LE6 0FH
Leicester (0533) 878551, Telex 341743
Facsimile (0533) 875022

SPECIFICATION

Date	23-FEB-88
Sales number	F0 438
Transducer Type	PDCR 810
Serial Number	227806
Part No.	D810-12
Pressure Range	15 Barg
Supply Voltage	10 Volts
Zero Offset	0 +/- 3 mV
Span	100 +/- 3 mV
Non-Linearity & Hysteresis	max +/- 0.1% BSL
Temperature Error Band	max +/- 0.5% FRO
Compensated Temperature Range	0 C to +50 C
Pressure Connection	None Fitted
Electrical Connection	
Cable Length	1 MTR
Positive Supply	Red
Negative Supply	White
Positive Output	Yellow
Negative Output	Blue
Screen	See Application Data
Mounting Torque	20 NM
Calibration	Orange

Calibration Traceable To National Standards

APPLICATION DATA

1 Supply voltage may be up to a maximum of 12 volts. Transducer sensitivity and current consumption will be proportional to supply voltage.

2 Current consumption will not exceed 9 mA for stated supply voltage.

3 Zero offset can be nulled using a 250 Kohm potentiometer across the output terminals with the wiper connected to the negative supply via a 250 Kohm resistor.

4 For best temperature stability, the transducer must be operated into a load impedance of > 50 Kohm.

5 A calibration resistor may be connected between negative supply and the 'calibration' terminal. The precise resistor value will depend upon the individual transducer, but may be approximated from this formula: rcal=1000/vcal, where rcal is in Kohm and vcal is the required output in mV.

6 A shunt calibration resistor may be connected between the negative supply and the negative terminal to produce a positive output. The output obtained may be temperature sensitive. In case of difficulty, refer to the manufacturer.

7 If a power supply earth is to be used, then the positive side should be earthed.

8 Following conventional practice, the cable screen is not connected to the transducer body.

CALIBRATION DATA

Span 99.69 mV at 23 C

Deviations from Best Straight Line

Pressure (Barg)	0.00	0.00	3.03	6.07	9.10	9.10	12.13	15.17	15.17
(PSI)	0.00	0.00	44.00	88.00	132.00	132.00	176.00	220.00	220.00
% Span	0.07	0.07	-0.03	-0.08	-0.08	-0.08	-0.03	0.08	0.08

Thermal Zero shift

Temperature (C)	0	23	50
% Span	0.01	0.00	-0.10

Thermal Span shift

Temperature (C)	0	23	50
% Span	0.13	0.00	0.04

Temperature Error Band for 0 to 50 C +/- 0.10 % FRO

Druck Limited
Fir Tree Lane, Groby, Leicester LE6 0FH
Leicester (0533) 878551, Telex 341743
Facsimile (0533) 875022

SPECIFICATION

Date	23-FEB-88
Sales number	F0 438
Transducer Type	PDCR 810
Serial Number	227808
Part No.	D810-12
Pressure Range	15 Barg
Supply Voltage	10 Volts
Zero Offset	0 +/- 3 mV
Span	100 +/- 3 mV
Non-Linearity & Hysteresis	max +/- 0.1% BSL
Temperature Error Band	max +/- 0.5% FRO
Compensated Temperature Range	0 C to +50 C
Pressure Connection	None Fitted
Electrical Connection	
Cable Length	1 MTR
Positive Supply	Red
Negative Supply	White
Positive Output	Yellow
Negative Output	Blue
Screen	See Application Data
Mounting Torque	20 NM
Calibration	Orange

Calibration Traceable To National Standards

APPLICATION DATA

1 Supply voltage may be up to a maximum of 12 volts. Transducer sensitivity and current consumption will be proportional to supply voltage.

2 Current consumption will not exceed 9 mA for stated supply voltage.

3 Zero offset can be nulled using a 250 Kohm potentiometer across the output terminals with the wiper connected to the negative supply via a 250 Kohm resistor.

4 For best temperature stability, the transducer must be operated into a load impedance of > 50 Kohm.

5 A calibration resistor may be connected between negative supply and the 'calibration' terminal. The precise resistor value will depend upon the individual transducer, but may be approximated from this formula: rcal=1000/vcal, where rcal is in Kohm and vcal is the required output in mV.

6 A shunt calibration resistor may be connected between the negative supply and the negative terminal to produce a positive output. The output obtained may be temperature sensitive. In case of difficulty, refer to the manufacturer.

7 If a power supply earth is to be used, then the positive side should be earthed.

8 Following conventional practice, the cable screen is not connected to the transducer body.

CALIBRATION DATA

Span 99.47 mV at 23 C

Deviations from Best Straight Line

Pressure (Barg)	0.00	0.00	3.03	6.07	9.10	9.10	12.13	15.17	15.17
(PSI)	0.00	0.00	44.00	88.00	132.00	132.00	176.00	220.00	220.00
% Span	0.02	0.00	0.00	-0.01	-0.01	-0.02	0.00	0.01	0.01

Thermal Zero shift

Temperature (C)	0	23	50
% Span	-0.04	0.00	0.02

Thermal Span shift

Temperature (C)	0	23	50
% Span	0.01	0.00	0.07

Temperature Error Band for 0 to 50 C +/- 0.06 % FRO

111

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Facsimile (0533) 875022

SPECIFICATION

Date	23-FEB-88
Sales number	F0 438
Transducer Type	PDCR 810
Serial Number	227809
Part No.	D810-12
Pressure Range	15 Barg
Supply Voltage	10 Volts
Zero Offset	0 +/- 3 mV
Span	100 +/- 3 mV
Non-Linearity & Hysteresis	max +/- 0.1% BSL
Temperature Error Band	max +/- 0.5% FRO
Compensated Temperature Range	0 C to +50 C
Pressure Connection	None Fitted
Electrical Connection	
Cable Length	1 MTR
Positive Supply	Red
Negative Supply	White
Positive Output	Yellow
Negative Output	Blue
Screen	See Application Data
Mounting Torque	20 NM
Calibration	Orange

Calibration Traceable To National Standards

APPLICATION DATA

1 Supply voltage may be up to a maximum of 12 volts. Transducer sensitivity and current consumption will be proportional to supply voltage.

2 Current consumption will not exceed 9 mA for stated supply voltage.

3 Zero offset can be nulled using a 250 Kohm potentiometer across the output terminals with the wiper connected to the negative supply via a 250 Kohm resistor.

4 For best temperature stability, the transducer must be operated into a load impedance of > 50 Kohm.

5 A calibration resistor may be connected between negative supply and the 'calibration' terminal. The precise resistor value will depend upon the individual transducer, but may be approximated from this formula: rcal=1000/vcal, where rcal is in Kohm and vcal is the required output in mV.

6 A shunt calibration resistor may be connected between the negative supply and the negative terminal to produce a positive output. The output obtained may be temperature sensitive. In case of difficulty, refer to the manufacturer.

7 If a power supply earth is to be used, then the positive side should be earthed.

8 Following conventional practice, the cable screen is not connected to the transducer body.

CALIBRATION DATA

Span 100.16 mV at 23 C

Deviations from Best Straight Line

Pressure (Barg)	0.00	0.00	3.03	6.07	9.10	9.10	12.13	15.17	15.17
(PSI)	0.00	0.00	44.00	88.00	132.00	132.00	176.00	220.00	220.00
% Span	0.02	0.01	-0.01	-0.02	-0.02	-0.02	-0.01	0.02	0.02

Thermal Zero shift

Temperature (C)	0	23	50
% Span	-0.09	0.00	0.01

Thermal Span shift

Temperature (C)	0	23	50
% Span	0.02	0.00	-0.09

Temperature Error Band for 0 to 50 C +/- 0.05 % FRO

Druck Limited
Fir Tree Lane, Groby, Leicester LE6 0FH
Leicester (0533) 878551, Telex 341743
Facsimile (0533) 875022

SPECIFICATION

Date	23-FEB-88
Sales number	F0 438
Transducer Type	PDCR 810
Serial Number	227807
Part No.	D810-12
Pressure Range	15 Barg
Supply Voltage	10 Volts
Zero Offset	0 +/- 3 mV
Span	100 +/- 3 mV
Non-Linearity & Hysteresis	max +/- 0.1% BSL
Temperature Error Band	max +/- 0.5% FRO
Compensated Temperature Range	0 C to +50 C
Pressure Connection	None Fitted
Electrical Connection	
Cable Length	1 MTR
Positive Supply	Red
Negative Supply	White
Positive Output	Yellow
Negative Output	Blue
Screen	See Application Data
Mounting Torque	20 NM
Calibration	Orange

Calibration Traceable To National Standards

APPLICATION DATA

1 Supply voltage may be up to a maximum of 12 volts. Transducer sensitivity and current consumption will be proportional to supply voltage.

2 Current consumption will not exceed 9 mA for stated supply voltage.

3 Zero offset can be nulled using a 250 Kohm potentiometer across the output terminals with the wiper connected to the negative supply via a 250 Kohm resistor.

4 For best temperature stability, the transducer must be operated into a load impedance of > 50 Kohm.

5 A calibration resistor may be connected between negative supply and the 'calibration' terminal. The precise resistor value will depend upon the individual transducer, but may be approximated from this formula: rcal=1000/vcal, where rcal is in Kohm and vcal is the required output in mV.

6 A shunt calibration resistor may be connected between the negative supply and the negative terminal to produce a positive output. The output obtained may be temperature sensitive. In case of difficulty, refer to the manufacturer.

7 If a power supply earth is to be used, then the positive side should be earthed.

8 Following conventional practice, the cable screen is not connected to the transducer body.

CALIBRATION DATA

Span 99.70 mV at 23 C

Deviations from Best Straight Line

Pressure (Barg)	0.00	0.00	3.03	6.07	9.10	9.10	12.13	15.17	15.17
(PSI)	0.00	0.00	44.00	88.00	132.00	132.00	176.00	220.00	220.00
% Span	0.07	0.08	-0.04	-0.08	-0.08	-0.06	-0.03	0.08	0.07

Thermal Zero shift

Temperature (C)	0	23	50
% Span	-0.08	0.00	-0.04

Thermal Span shift

Temperature (C)	0	23	50
% Span	0.06	0.00	0.11

Temperature Error Band for 0 to 50 C +/- 0.05 % FRO

Appendix D

Inaccuracy

Flowmeter DISCOMAG DMI 6531

The manufacturer indicates an inaccuracy of 1% of the measured value for the range that was used during the experiments.

Velocity

Because of the inaccuracy of the pipe diameter of 1% together with the inaccuracy in flow the inaccurcy in velocity will be 3%.

Wavespeed

The inaccuracy in calculated wavespeed is estimated at 1%.
The inaccuracy in measured wavespeed is estimated at 0.7%.

Pressure

The inaccuracy in calculated pressure jumps is estimated at 4%.
The output of the amplifier for the pressure transducers shows an absolute error of ±10 mV due to drift and temperature effects.
If the error in the transient recorder data is taken to be 1/2 bit, this means an absolute error of 20 mV for the 5 V range, and an absolute error of 39 mV for the 10 V range. This means that the absolute error will be 30 mV or 4.5 kPa for the 5V range and 49 mV or 7.4 kPa for the 10 V range.

Appendix E

The measuring program

The program to read the data from the two transient recorders is written in ASYST. It can if desired also save the data on a floppy disk, make a picture, print the picture and print steady flow pressure, maximum pressure and minimum pressure.
Before using the program at least 'Up and Running with ASYST'[8] should be read to get familiar with the peculiarities of the language and to learn how to start programs.
The program is named RS232RD.ASY and it is started with the GO command at the OK prompt of ASYST. A menu line then shows the possible actions.
Main menu

F1 GET DATA	reads successively four channels from the transient recorders via the serial port.
F2 PROCESS DATA	invokes process data menu
F3 SAVE	saves the data read by the computer on floppy disk
F4 READ	reads a data file from floppy disk
F5 PRT SCR	makes a screen dump on the printer
F6 QUIT	aborts the program

Process data menu

F1 PLOT SIGNAL	plots a signal with adapted scales on the screen
F2 ZOOM	invokes the ASYST ARRAY.READOUT and READOUT>POSITION commands
F3 PRT SCR	makes a screen dump on the printer
F4 PRT DATA	prints flow, voltage range of the transient recorder, sample frequency, steady flow pressure and maximum and mininimum pressures for each signal
F5 MAIN	invokes main menu

```
1 0 5 79 WINDOW {TXT.WINDOW}
0 0 0 79 WINDOW {TOPLINE}
24 0 24 79 WINDOW {BOTLINE}
1 0 23 17 WINDOW {COMM}
1 0 23 79 WINDOW {TXT}
INTEGER DIM[ 1024 ] ARRAY 232BUF
INTEGER DIM[ 2048 ] ARRAY DATA
INTEGER DIM[ 4 , 1024 ] ARRAY PACK.WAVES
INTEGER DIM[ 4 , 2048 ] ARRAY WAVES
REAL DIM[ 4 ] ARRAY X.COEFF
REAL DIM[ 2048 ] ARRAY X.ARRAY
REAL DIM[ 2048 ] ARRAY Y.ARRAY
REAL DIM[ 5 , 3 ] ARRAY SPECIFICS
REAL DIM[ 4 , 2 ] ARRAY PMAX/MIN
REAL SCALAR X.MAX
REAL SCALAR Y.MAX
INTEGER SCALAR ?SAVED
INTEGER SCALAR SIGNAL
INTEGER SCALAR SAME.GRAPH
64 STRING COMM
80 STRING MENU.LINE
14 STRING FILENAME
0 ?SAVED :=
0.006602 X.COEFF [ 1 ] :=
0.006635 X.COEFF [ 2 ] :=
0.006620 X.COEFF [ 3 ] :=
0.006604 X.COEFF [ 4 ] :=

: PRESS.SPACE.WHEN.READY
  CR ." Press space when ready."
  BEGIN
    KEY 32 =
  UNTIL
;

: RS.VU
  NORMAL.COORDS
  0. 0. VUPORT.ORIG
  1. 0.75 VUPORT.SIZE
;

: RS232.VU
  RS.VU
  NORMAL.COORDS
  HORIZONTAL AXIS.FIT.OFF GRID.OFF LINEAR
  VERTICAL AXIS.FIT.OFF GRID.OFF LINEAR
  0. 0. AXIS.ORIG
  1. 1. AXIS.SIZE
  WORLD.COORDS
  VERTICAL 0. 255. WORLD.SET NO.LABELS
  HORIZONTAL 0. 2048. WORLD.SET NO.LABELS
  NORMAL.COORDS 0.5 0.5 AXIS.POINT
  DOTTED
  8 1 AXIS.DIVISIONS
```



```
;

: RS232.LABELS
  WORLD.COORDS
  20 250 POSITION " 255" LABEL
  20 132 POSITION " 127" LABEL
  20 5 POSITION " 0" LABEL
  1044 5 POSITION " 1024" LABEL
  1960 5 POSITION " 2048" LABEL
  1024 127 POSITION
  CURSOR.OFF
;

: RS232.GRAPH.INSTALL
   {TXT.WINDOW} SCREEN.CLEAR HOME
   RS232.VU
   XY.AXIS.PLOT
   RS232.LABELS
   OUTLINE
;

: RS232.INSTALL
  COM1
  9600 0 8 2 RS232.MODE
  9600 SET.BAUD
  2 SET.STOP.BITS
  232BUF []RS232.BUFFER
  RS232.POL.MODE
  DSR.ON
;

: CHANGE.TRANSD.SETTINGS
  SIGNAL :=
  CR ." Steady pressure (mv)      : " #INPUT X.COEFF [ SIGNAL ] /
      SPECIFICS [ SIGNAL , 3 ] :=
;

: CHANGE.GLOBAL.SETTINGS
  CR ." Comment                  : " "INPUT COMM ":=
  CR ." Flow (l/s)               : " #INPUT SPECIFICS [ 5 , 1 ] :=
  CR ." Valve height (mm)        : " #INPUT SPECIFICS [ 5 , 2 ] :=
  CR ." Sample frequency (kHz)   : " #INPUT SPECIFICS [ 1 , 1 ] :=
  CR ." Amplitude range (V)      : " #INPUT SPECIFICS [ 1 , 2 ] :=
;

: GET.SPECIFICS
  {TXT}
  BEGIN
   SCREEN.CLEAR HOME
   CHANGE.GLOBAL.SETTINGS
   5 1 DO
       CR ." Channel nr.: " I .
       I CHANGE.TRANSD.SETTINGS
       SPECIFICS [ 1 , 1 ] SPECIFICS [ I , 1 ] :=
```

```
       SPECIFICS [ 1 , 2 ] SPECIFICS [ I , 2 ] :=
    LOOP
  CR ." Are these specifications correct? " "INPUT
  " jJyY" "WITHIN
  UNTIL
  DROP
;

: TOPLINE
   {TOPLINE} SCREEN.CLEAR HOME
   1 ?SAVED =
   IF ." File: " FILENAME "TYPE 3 SPACES COMM "TYPE
   ELSE ." File not saved!"
   THEN
   PREVIOUS.WINDOW
;

: BOTLINE
  {BOTLINE} SCREEN.CLEAR HOME
  MENU.LINE "TYPE
  PREVIOUS.WINDOW
;

: ?OVERFLOW
  DATA []MIN/MAX
  0 = IF BELL CR ." ****** UNDERFLOW ******" THEN
  255 = IF BELL CR ." ****** OVERFLOW ******" THEN
;

: ?SAME.GRAPH
   CR ." In same graph? " "INPUT " JjYy" "WITHIN
   IF 1 SAME.GRAPH :=  DROP
   ELSE 0 SAME.GRAPH :=
   THEN
;

: READ.DATA.PLOT
  RS232>BUFFER
  232BUF DUP UNPACK DATA :=
  DATA Y.DATA.PLOT
  ?OVERFLOW
  1 * DP>SP
;

: DATA.TO.WORLD
   5 1 DO
       SPECIFICS [ I , 3 ] X.COEFF [ I ] *
       SPECIFICS [ I , 2 ] / 255 * FIX
       WAVES [ I , 1 ] -
       WAVES XSECT[ I , ! ] +
       DP>SP
   LOOP
   LAMINATE LAMINATE LAMINATE
   WAVES :=
```



```
;

: MAX.MIN.PRESS
   5 1 DO
       WAVES XSECT[ I , ! ] FLOAT
       255 / SPECIFICS [ I , 2 ] * X.COEFF [ I ] /
       []MIN/MAX PMAX/MIN [ I , 1 ] :=
                 PMAX/MIN [ I , 2 ] :=
   LOOP
;

: READ.4.CHANNELS
  1 SAME.GRAPH :=
  GRAPHICS.DISPLAY
  RS232.INSTALL
  RS232.GRAPH.INSTALL
  5 1 DO
      SAME.GRAPH 0 =
      IF VUPORT.CLEAR
         RS232.GRAPH.INSTALL
      THEN
      SCREEN.CLEAR ." READING CHANNEL " I .
      READ.DATA.PLOT
      PRESS.SPACE.WHEN.READY
      4 I = NOT
      IF ?SAME.GRAPH
      THEN
  LOOP
  CR ." Please wait "
  AXIS.DEFAULTS
  LAMINATE
  LAMINATE
  LAMINATE
  PACK.WAVES :=
  PACK.WAVES UNPACK WAVES :=
  0 ?SAVED :=
  NORMAL.DISPLAY
  GET.SPECIFICS
  DATA.TO.WORLD
  MAX.MIN.PRESS
  TOPLINE
  BOTLINE
;

: CREATE.DATA.FILE
   FILE.TEMPLATE
   1 COMMENTS
   REAL DIM[ 5 , 3 ] SUBFILE
   INTEGER DIM[ 4 , 1024 ] SUBFILE
   END
   SCREEN.CLEAR HOME
   ." Name of the file to create? "
   " B:" "INPUT " .DAT" "CAT "CAT FILENAME ":=
   FILENAME DEFER> FILE.CREATE
```

```
;

: WRITE.DATA.FILE
   FILENAME DEFER> FILE.OPEN
   COMM 1 >COMMENT
   1 SUBFILE SPECIFICS ARRAY>FILE
   2 SUBFILE PACK.WAVES ARRAY>FILE
   FILE.CLOSE
;

: SAVE.DATA
   SCREEN.CLEAR HOME
   CREATE.DATA.FILE
   WRITE.DATA.FILE
   1 ?SAVED :=
   SCREEN.CLEAR
   TOPLINE
   BOTLINE
;

: READ.DATA.FILE
   FILENAME DEFER> FILE.OPEN
   1 COMMENT> COMM ":=
   1 SUBFILE SPECIFICS FILE>ARRAY
   2 SUBFILE PACK.WAVES FILE>ARRAY
   FILE.CLOSE
;

: READ.FILE
   SCREEN.CLEAR HOME
   ." Name of the file to read? "
   " B:" "INPUT " .DAT" "CAT "CAT FILENAME ":=
   CR ." Please wait "
   READ.DATA.FILE
   PACK.WAVES UNPACK WAVES :=
   DATA.TO.WORLD
   MAX.MIN.PRESS
   1 ?SAVED :=
   TOPLINE
   BOTLINE
   SCREEN.CLEAR HOME
;

: VU.1
   NORMAL.COORDS
   .25 .10 VUPORT.ORIG
   .80 .80 VUPORT.SIZE
;

: WAVE.VU
   NORMAL.COORDS
   HORIZONTAL GRID.OFF AXIS.FIT.OFF AXIS.ON 0 2 LABEL.POINTS
   VERTICAL GRID.OFF AXIS.FIT.OFF AXIS.ON 0 2 LABEL.POINTS
   .15 .15 AXIS.ORIG
```



```
   .75 .75 AXIS.SIZE
   .025 .008 TICK.SIZE
   .5 .8 TICK.JUST
   .15 .15 AXIS.POINT
   CURSOR.OFF
;

: WAVE.WORLD
   WORLD.COORDS
   HORIZONTAL
   0. X.MAX WORLD.SET LINEAR
   VERTICAL
   LINEAR
   SPECIFICS [ 1 , 2 ] 10. =
   IF -150. 1500. WORLD.SET 10 11 AXIS.DIVISIONS
   ELSE SPECIFICS [ 1 , 2 ] 5. =
        IF -150. 750. WORLD.SET 10 6 AXIS.DIVISIONS
        ELSE -150. Y.MAX WORLD.SET 10 10 AXIS.DIVISIONS
        THEN
   THEN
   XY.AXIS.PLOT
   OUTLINE
   SOLID
   NORMAL.COORDS
   0 CHAR.DIR
   0 LABEL.DIR
   0.5 0.05 POSITION
   " Time (ms)" LABEL
   90 CHAR.DIR
   90 LABEL.DIR
   0.02 0.3 POSITION
   " Pressure (kPa)" LABEL
;

: ZOOM
   ARRAY.READOUT
   NORMAL.COORDS
   .7 .975 READOUT>POSITION
   WORLD.COORDS
;

: WRITE.SPECIFICS
   CR ." Flow            : " SPECIFICS [ 5 , 1 ] . ." (l/s)"
   CR ." Valve height    : " SPECIFICS [ 5 , 2 ] . ." (mm)"
   CR
   CR ." Transducer no. : " SIGNAL .
   CR ." Sample freq.    : " SPECIFICS [ SIGNAL , 1 ] . ." (kHz)"
   CR ." Volt. range     : " SPECIFICS [ SIGNAL , 2 ] . ." (V)"
   CR ." Steady press.   : " SPECIFICS [ SIGNAL , 3 ] . ." (kPa)"
;

: PLOT.SIGNAL
   SCREEN.CLEAR GRAPHICS.DISPLAY
   {COMM} SCREEN.CLEAR HOME VU.1
```

```
TOPLINE BOTLINE
WAVE.VU
0 SAME.GRAPH :=
BEGIN
 CR ." Which signal? " #INPUT SIGNAL :=
 2048 1 - SPECIFICS [ SIGNAL , 1 ] / X.MAX :=
 SPECIFICS [ SIGNAL , 2 ] X.COEFF [ SIGNAL ] / Y.MAX :=
 2048 RAMP 1 - SPECIFICS [ SIGNAL , 1 ] / X.ARRAY :=
 WAVES XSECT[ SIGNAL , ! ] FLOAT 255 / SPECIFICS [ SIGNAL , 2 ] *
 X.COEFF [ SIGNAL ] / Y.ARRAY :=
 SAME.GRAPH 0 =
 IF VUPORT.CLEAR
    WAVE.VU
    WAVE.WORLD
 THEN
 WORLD.COORDS
 X.ARRAY Y.ARRAY XY.DATA.PLOT
 {COMM} SCREEN.CLEAR HOME
 WRITE.SPECIFICS
 CR ." Pmax: " PMAX/MIN [ SIGNAL , 1 ] .
 CR ." Pmin: " PMAX/MIN [ SIGNAL , 2 ] .
 CR ." Plot another? " "INPUT " JjYy" "WITHIN ?DUP
 IF ?SAME.GRAPH DROP
 THEN
 NOT
UNTIL
NORMAL.DISPLAY BOTLINE TOPLINE
{TXT} SCREEN.CLEAR HOME
;

: STOP
  NORMAL.DISPLAY
  CLEAR.FUNCTION.KEYS
  STACK.CLEAR
  ABORT
;

: MAIN.MENU.LINE
  " GET DATA      PROCESS DATA      SAVE      READ      PRT SCR      QUIT "
  MENU.LINE ":=
  BOTLINE
  RESTORE.FUNCTION.KEYS
;
: PRINT.DATA
  SCREEN.CLEAR HOME
  13 2 FIX.FORMAT
  CR ." Output also to printer? " "INPUT " jJyY" "WITHIN
  IF OUT>PRINTER DROP
  THEN
  CR CR FILENAME "TYPE 5 SPACES ." Date: " "DATE "TYPE
  CR ." Comment: " COMM "TYPE
  CR
  CR ." Flow            : " SPECIFICS [ 5 , 1 ] . ." (l/s)"
  CR ." Valve height    : " SPECIFICS [ 5 , 2 ] . ." (mm)"
```



```
  CR ." Sample freq.    : " SPECIFICS [ 1 , 1 ] . ." (kHz)"
  CR ." Volt. range     : " SPECIFICS [ 1 , 2 ] . ." (V)"
  CR
  CR ." Transducer      :          1          2          3          4
  CR ." Steady press.   : " SPECIFICS [ 1 , 3 ] . SPECIFICS [ 2 , 3 ] .
      SPECIFICS [ 3 , 3 ] . SPECIFICS [ 4 , 3 ] .
  CR ." Max. press.     : " PMAX/MIN [ 1 , 1 ] . PMAX/MIN [ 2 , 1 ] .
      PMAX/MIN [ 3 , 1 ] . PMAX/MIN [ 4 , 1 ] .
  CR ." Min. press.     : " PMAX/MIN [ 1 , 2 ] . PMAX/MIN [ 2 , 2 ] .
      PMAX/MIN [ 3 , 2 ] . PMAX/MIN [ 4 , 2 ] .
  CR CR -1. 4. FIX.FORMAT
  CONSOLE
;

: PROCESS.MENU
  STORE.FUNCTION.KEYS
  F1 FUNCTION.KEY.DOES PLOT.SIGNAL
  F2 FUNCTION.KEY.DOES ZOOM
  F3 FUNCTION.KEY.DOES SCREEN.PRINT
  F4 FUNCTION.KEY.DOES PRINT.DATA
  F5 FUNCTION.KEY.DOES MAIN.MENU.LINE
  F6 FUNCTION.KEY.DOES NOP
  " PLOT SIGNAL      ZOOM      PRT SCR      PRT DATA      MAIN "
  MENU.LINE ":=
  BOTLINE
;

: MAIN.MENU
  F1 FUNCTION.KEY.DOES READ.4.CHANNELS
  F2 FUNCTION.KEY.DOES PROCESS.MENU
  F3 FUNCTION.KEY.DOES SAVE.DATA
  F4 FUNCTION.KEY.DOES READ.FILE
  F5 FUNCTION.KEY.DOES SCREEN.PRINT
  F6 FUNCTION.KEY.DOES STOP
  " GET DATA      PROCESS DATA      SAVE      READ      PRT SCR      QUIT"
  MENU.LINE ":=
  BOTLINE
;

: GO
   SCREEN.CLEAR {TXT}
   TOPLINE
   MAIN.MENU
   INTERPRET.KEYS
;
```

Appendix F

The simulation program

The computer program TUBE was written in Fortran77. It allows the computation of a pressure wave travelling through four connected pipes with a constant height reservoir at the upstream end, and an instantaneously closing valve at the downstream end. The program uses the method and equations described in paragraph 2.3 (see also Wylie and Streeter).

Most important parameters.

NX: number of place steps

NT: number of time steps

p0: pressure at the bottom of the reservoir

DT: time step

N1,N2,N3,N4: number of computational sections the four pipes are divided in; NX must be N1+N2+N3+N4.

P1(),P2(),P3(),P4(): arrays with pipe characteristics

P..(0): lenght of the pipe

P..(1): wavespeed in the pipe

P..(2): Δx in the pipe

P..(3): sine of the angle of inclination

P..(4): diameter of the pipe

NX1,NX2,NX3: places for which pressure and velocity for each time step are saved

```
C       INITIALISATION ROUTINE FOR VELOCITY AND PRESSURE AT TIME 0
C       ********************************************************
        SUBROUTINE INIT(DT,RHO,P1,P2,P3,P4,FL,N1,N2,N3,N4,P,L,NX,NT,OUT)
        REAL PI,DT,RHO,FL,P,L,OUT(0:NX,0:1,1:2),P1(0:5),P2(0:5),
     *       P3(0:5),P4(0:5)
        INTEGER NX,NT,I,J,K,N1,N2,N3,N4,NN
        PI=3.1415927
        DO 10 K=1,2
           DO 11 J=0,1
              DO 12 I=0,NX
              OUT(I,J,K)=0.
 12           CONTINUE
 11        CONTINUE
 10     CONTINUE
        DO 13 I=0,N1
           OUT(I,0,1)=4.*FL/(PI*P1(5)*P1(5))
           OUT(I,0,2)=P-RHO*9.81*FLOAT(I)*P1(2)*P1(4)
     *                -0.5*RHO*OUT(0,0,1)*OUT(0,0,1)*
     *                (1.+P1(3)*FLOAT(I)*P1(2)/P1(5))
 13     CONTINUE
        NN=N1+1
        DO 14 I=0,N2
           OUT(NN+I,0,1)=4.*FL/(PI*P2(5)*P2(5))
           OUT(NN+I,0,2)=OUT(N1,0,2)-RHO*9.81*FLOAT(I)*P2(2)*P2(4)
     *                -0.5*RHO*OUT(NN,0,1)*OUT(NN,0,1)*
     *                (1.+P2(3)*FLOAT(I)*P2(2)/P2(5))
 14     CONTINUE
        NN=N1+N2+2
        DO 15 I=0,N3
           OUT(NN+I,0,1)=4.*FL/(PI*P3(5)*P3(5))
           OUT(NN+I,0,2)=OUT(NN-1,0,2)-RHO*9.81*FLOAT(I)*P3(2)*P3(4)
     *                -0.5*RHO*OUT(NN,0,1)*OUT(NN,0,1)*
     *                (1.+P3(3)*FLOAT(I)*P3(2)/P3(5))
 15     CONTINUE
        NN=N1+N2+N3+3
        DO 16 I=0,N4
           OUT(NN+I,0,1)=4.*FL/(PI*P4(5)*P4(5))
           OUT(NN+I,0,2)=OUT(NN-1,0,2)-RHO*9.81*FLOAT(I)*P4(2)*P4(4)
     *                -0.5*RHO*OUT(NN,0,1)*OUT(NN,0,1)*
     *                (1.+P4(3)*FLOAT(I)*P4(2)/P4(5))
 16     CONTINUE
        RETURN
        END

C       LINEAR INTERPOLATION BETWEEN VM AND VO TO DETERMINE VR
C       AND BETWEEN PM AND PO TO DETERMINE PR
C       *****************************************************
        SUBROUTINE UPSTR(A,DEL,VM,PM,VO,PO,VR,PR)
        REAL A,DEL,VM,PM,VO,PO,VR,PR
        VR=((VM-VO)*DEL*A+VO)/(1.-(VM-VO)*DEL)
        PR=PO+(PM-PO)*DEL*(VR+A)
        RETURN
        END
```

```
C       LINEAR INTERPOLATION BETWEEN VN AND VO TO DETERMINE VS
C       AND BETWEEN PN AND PO TO DETERMINE PS
C       *****************************************************
        SUBROUTINE DWNSTR(A,DEL,VN,PN,VO,PO,VS,PS)
        REAL A,DEL,VN,PN,VO,PO,VS,PS
        VS=(VO+(VN-VO)*DEL*A)/(1.+(VN-VO)*DEL)
        PS=PO-(PN-PO)*DEL*(VS-A)
        RETURN
        END

C       C+ CHARARTERISTIC
C       ****************
        REAL FUNCTION CHRTC1(DT,RHO,LA,VR,PR)
        REAL DT,RHO,VR,PR,LA(0:5)
        CHRTC1=PR+LA(1)*RHO*VR-LA(1)*RHO*9.81*DT*LA(4)-
     *        LA(1)*RHO*LA(3)*VR*ABS(VR)*DT/(2.*LA(5))
        RETURN
        END

C       C- CHARACTERISTIC
C       ****************
        REAL FUNCTION CHRTC2(DT,RHO,LA,VS,PS)
        REAL DT,RHO,VS,PS,LA(0:5)
        CHRTC2=PS-LA(1)*RHO*VS+LA(1)*RHO*9.81*DT*LA(4)+
     *        LA(1)*RHO*LA(3)*VS*ABS(VS)*DT/(2.*LA(5))
        RETURN
        END

C       ROUTINE TO DETERMINE V AND P FOR THE NEXT TIME STEP
C       FOR A NOT BOUNDARY POINT
C       ***********************************************
        SUBROUTINE MIDPNT(DT,RHO,LA,VM,PM,VO,PO,VN,PN,V,P)
        REAL DT,RHO,VM,PM,VO,PO,VN,PN,VR,PR,VS,PS,V,P,LA(0:5)
        CALL UPSTR(LA(1),DT/LA(2),VM,PM,VO,PO,VR,PR)
        CALL DWNSTR(LA(1),DT/LA(2),VN,PN,VO,PO,VS,PS)
        P=(CHRTC1(DT,RHO,LA,VR,PR)+CHRTC2(DT,RHO,LA,VS,PS))/2.
        V=(CHRTC1(DT,RHO,LA,VR,PR)-CHRTC2(DT,RHO,LA,VS,PS))/
     *   (2.*LA(1)*RHO)
        RETURN
        END

C       ROUTINE FOR A SERIES CONNECTION OF TWO PIPES
C       ****************************************
        SUBROUTINE SCONN(DT,RHO,LP1,LP2,LVM,LPM,LVO1,LPO1,LVO2,LPO2,LVN,
     *                   LPN,LV,LP)
        REAL DT,RHO,LVM,LPM,LVO1,LPO1,LVN,LPN,LVO2,LPO2,LV,LP,LVR,LPR,
     *       LVS,LPS,HELP1,HELP2,A,B,C,LP1(0:5),LP2(0:5)
        CALL UPSTR(LP1(1),DT/LP1(2),LVM,LPM,LVO1,LPO1,LVR,LPR)
        CALL DWNSTR(LP2(1),DT/LP2(2),LVN,LPN,LVO2,LPO2,LVS,LPS)
        HELP1=CHRTC1(DT,RHO,LP1,LVR,LPR)
        C=HELP1-CHRTC2(DT,RHO,LP2,LVS,LPS)
        HELP2=LP1(5)*LP1(5)/(LP2(5)*LP2(5))
        B=RHO*(LP1(1)+LP2(1)*HELP2)
```

```
      IF (LP1(5).EQ.LP2(5)) THEN
         LV=C/B
      ELSE
         A=0.5*RHO*(1-HELP2*HELP2)
         LV=(B-SQRT(B*B-4.*A*C))/(2.*A)
      ENDIF
      LP=HELP1-RHO*LP1(1)*LV
      RETURN
      END
C     **************** MAIN PROGRAM *****************

      INTEGER I,J,K,L,NX,NT,N,N1,N2,N3,N4,NX1,NX2,NX3
      REAL P1,P2,P3,P4,LENGTH,DT,HELP4,P0,PRSRVR,FLOW,PLACE1,PLACE2,
     *     PLACE3,RESULT,T0,VELOC,PRESS,HELP1,HELP2,HELP3,T,RHO,PON,VON
      PARAMETER (NX=103,NT=1500)
      DIMENSION RESULT(0:NX,0:1,1:2),P1(0:5),P2(0:5),P3(0:5),P4(0:5),
     *          PLACE1(0:500,1:2),PLACE2(0:500,1:2),PLACE3(0:500,1:2)
      K=0
      L=0
      RHO=998.2
      FLOW=0.0005
      P0=120000.
      PRSRVR=120000.
      LENGTH=12.4
      DT=0.00009
      N1=8
      N2=16
      N3=74
      N4=2
      P1(0)=1.0
      P1(1)=1368.0
      P1(2)=P1(0)/FLOAT(N1)
      P1(3)=0.12
      P1(4)=-1.0
      P1(5)=0.053
      P2(0)=2.0
      P2(1)=1368.0
      P2(2)=P2(0)/FLOAT(N2)
      P2(3)=0.12
      P2(4)=-0.707
      P2(5)=0.053
      P3(0)=9.12
      P3(1)=1368.0
      P3(2)=P3(0)/FLOAT(N3)
      P3(3)=0.12
      P3(4)=-1.0
      P3(5)=0.053
      P4(0)=0.26
      P4(1)=1244.0
      P4(2)=P4(0)/FLOAT(N4)
      P4(3)=0.0
      P4(4)=-1.0
      P4(5)=0.1
      NX1=33
      NX2=98
      NX3=102
      CALL INIT(DT,RHO,P1,P2,P3,P4,FLOW,N1,N2,N3,N4,
     *          P0,LENGTH,NX,NT,RESULT)
      PON=RESULT(N1+N2+N3+N4+3,0,2)
      VON=RESULT(N1+N2+N3+N4+3,0,1)
      PLACE1(0,1)=RESULT(NX1,0,1)
      PLACE1(0,2)=RESULT(NX1,0,2)
      PLACE2(0,1)=RESULT(NX2,0,1)
      PLACE2(0,2)=RESULT(NX2,0,2)
      PLACE3(0,1)=RESULT(NX3,0,1)
      PLACE3(0,2)=RESULT(NX3,0,2)
C     FOR TIME STEP 1 TO NT
      DO 120 J=1,NT
C     UPSTREAM BOUNDARY
      CALL DWNSTR(P1(1),DT/P1(2),RESULT(1,0,1),RESULT(1,0,2),
     *            RESULT(0,0,1),RESULT(0,0,2),VELOC,PRESS)
      HELP1=CHRTC2(DT,RHO,P1,VELOC,PRESS)
      RESULT(0,1,1)=-P1(1)+SQRT(RHO*RHO*P1(1)*P1(1)-2.*RHO*
     *              (HELP1-P0))/RHO
      RESULT(0,1,2)=HELP1+RHO*P1(1)*RESULT(0,1,1)
C     PIPE 1
      DO 121 I=1,N1-1
         CALL MIDPNT(DT,RHO,P1,RESULT(I-1,0,1),RESULT(I-1,0,2)
     *               ,RESULT(I,0,1),RESULT(I,0,2),RESULT(I+1,0,1),
     *                RESULT(I+1,0,2),RESULT(I,1,1),RESULT(I,1,2))
  121 CONTINUE
C     FIRST SERIES CONNECTION
      CALL SCONN(DT,RHO,P1,P2,RESULT(N1-1,0,1),RESULT(N1-1,0,2),
     *           RESULT(N1,0,1),RESULT(N1,0,2),RESULT(N1+1,0,1),
     *       RESULT(N1+1,0,2),RESULT(N1+2,0,1),RESULT(N1+2,0,2),
     *       VELOC,PRESS)
      RESULT(N1,1,1)=VELOC
      RESULT(N1+1,1,1)=VELOC*P1(5)*P1(5)/(P2(5)*P2(5))
      RESULT(N1,1,2)=PRESS
      RESULT(N1+1,1,2)=PRESS+0.5*RHO*(VELOC*VELOC-
     *                 RESULT(N1+1,1,1)*RESULT(N1+1,1,1))
C     PIPE 2
      DO 122 I=N1+2,N1+N2
         CALL MIDPNT(DT,RHO,P2,RESULT(I-1,0,1),RESULT(I-1,0,2)
     *               ,RESULT(I,0,1),RESULT(I,0,2),RESULT(I+1,0,1),
     *                RESULT(I+1,0,2),RESULT(I,1,1),RESULT(I,1,2))
  122 CONTINUE
      N=N1+N2+1
C     SECOND SERIES CONNECTION
      CALL SCONN(DT,RHO,P2,P3,RESULT(N-1,0,1),RESULT(N-1,0,2),
     *            RESULT(N,0,1),RESULT(N,0,2),RESULT(N+1,0,1),
     *         RESULT(N+1,0,2),RESULT(N+2,0,1),RESULT(N+2,0,2),
     *         VELOC,PRESS)
      RESULT(N,1,1)=VELOC
      RESULT(N+1,1,1)=VELOC*P2(5)*P2(5)/(P3(5)*P3(5))
      RESULT(N,1,2)=PRESS
      RESULT(N+1,1,2)=PRESS+0.5*RHO*(VELOC*VELOC-
     *                RESULT(N+1,1,1)*RESULT(N+1,1,1))
```

```
C      PIPE 3
       DO 123 I=N+2,N+N3
          CALL MIDPNT(DT,RHO,P3,RESULT(I-1,0,1),RESULT(I-1,0,2)
      *              ,RESULT(I,0,1),RESULT(I,0,2),RESULT(I+1,0,1),
      *               RESULT(I+1,0,2),RESULT(I,1,1),RESULT(I,1,2))
  123  CONTINUE
       N=N1+N2+N3+2
C      THIRD SERIES CONNECTION
       CALL SCONN(DT,RHO,P3,P4,RESULT(N-1,0,1),RESULT(N-1,0,2),
      *              RESULT(N,0,1),RESULT(N,0,2),RESULT(N+1,0,1),
      *           RESULT(N+1,0,2),RESULT(N+2,0,1),RESULT(N+2,0,2),
      *           VELOC,PRESS)
       RESULT(N,1,1)=VELOC
       RESULT(N+1,1,1)=VELOC*P3(5)*P3(5)/(P4(5)*P4(5))
       RESULT(N,1,2)=PRESS
       RESULT(N+1,1,2)=PRESS+0.5*RHO*(VELOC*VELOC-
      *                  RESULT(N+1,1,1)*RESULT(N+1,1,1))
C      PIPE 4
       DO 124 I=N+2,N+N4
          CALL MIDPNT(DT,RHO,P4,RESULT(I-1,0,1),RESULT(I-1,0,2)
      *              ,RESULT(I,0,1),RESULT(I,0,2),RESULT(I+1,0,1),
      *               RESULT(I+1,0,2),RESULT(I,1,1),RESULT(I,1,2))
  124  CONTINUE
       N=N1+N2+N3+N4+3
C      DOWNSTREAM BOUNDARY
       CALL UPSTR(P4(1),DT/P4(2),RESULT(N-1,0,1),RESULT(N-1,0,2),
      *           RESULT(N,0,1),RESULT(N,0,2),VELOC,PRESS)
       HELP1=CHRTC1(DT,RHO,P4,VELOC,PRESS)
       RESULT(N,1,1)=0.
       RESULT(N,1,2)=HELP1
       K=K+1
       IF (K.EQ.3) THEN
           L=L+1
           PLACE1(L,1)=RESULT(NX1,1,1)
           PLACE1(L,2)=RESULT(NX1,1,2)
           PLACE2(L,1)=RESULT(NX2,1,1)
           PLACE2(L,2)=RESULT(NX2,1,2)
           PLACE3(L,1)=RESULT(NX3,1,1)
           PLACE3(L,2)=RESULT(NX3,1,2)
           K=0
       ENDIF
       DO 125 I=0,NX
          RESULT(I,0,1)=RESULT(I,1,1)
          RESULT(I,0,2)=RESULT(I,1,2)
  125  CONTINUE
  120  CONTINUE
       OPEN(9,STATUS='NEW',FILE='P1')
       WRITE(9,FMT=100) ((PLACE1(J,I),I=1,2),J=0,500)
       CLOSE(9,STATUS='KEEP')
       OPEN(10,STATUS='NEW',FILE='P2')
       WRITE(10,FMT=100) ((PLACE2(J,I),I=1,2),J=0,500)
       CLOSE(10,STATUS='KEEP')
       OPEN(11,STATUS='NEW',FILE='P3')
       WRITE(11,FMT=100) ((PLACE3(J,I),I=1,2),J=0,500)
       CLOSE(11,STATUS='KEEP')
  100  FORMAT(2E10.3)
       STOP
       END
```