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CONTROL OF THE FLOW RATE IN AN OUTFLOW LINE

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Abstract: In this paper, the control of liquid flow is studied. An elastic line that transports elastic liquid is investigated. The effect of control on a hydraulic impact at the outflow line is discussed. Mathematical model of impact propagation is presented. The congruence of measured and computed results is demonstrated.
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Keywords: Flow rate control, Transport of elastic liquid in an elastic pipeline, Hydraulic impact measurement and simulation, Water head control.

1. INTRODUCTION

The control of liquid flow in the pipeline network invokes a range of secondary effects. Some previous results of authors were published at IFAC platform in (Nevřiva, 1999), (Demčáková and Nevřiva, 2000). In this paper, the hydraulic impact caused by the flow control is studied.

The generation, propagation and suppression of a hydraulic impact are discussed. The hydraulic impact analysis is based on both the measurement and simulation. The transport of an elastic liquid by the long elastic pipeline is assumed. Experimental data are presented.

2. THE LINE

The motivation to the study was the need to eliminate some problems that occurred in a hydro power station conduit. At the conduits, there is very difficult to arrange the measurements presented below. In this paper, the cognate problem is illustrated on the line shown in Fig. 1. The pipeline supplies water into a reservoir in the chemical factory of MCHZ Ostrava. The flow of water is controlled by the valve. The valve divides the line in two parts. The inflow line (A) goes from waterworks to the valve. The outflow line (B) goes from the valve to the reservoir. The valve represents the near end of the outflow line. The far end of the outflow line is connected to the reservoir.

The length of the outflow line is 805 m. The line is constructed from two parts. The internal diameter of the parts is 0.1 m and 0.15 m, respectively. The line is made from steel.

The experimental data presented in this paper refer to two sets of measurements made in MCHZ Ostrava in March 2000 and May 2001.

The first set of measurements helped to verify the analytical model of the process. Pressure waves in P1 and P2 were measured besides other parameters. Fig.3 relates to the first set of measurements. The second set of measurements was made with the goal to test the hydraulic impact control and propagation. Pressure waves in P1 and P3 were measured besides other parameters. The leakage valve was installed in the position of P2. Figures 2,4 and 5 relate to the second set of measurements.

3. HYDRAULIC IMPACT ORIGIN

Let us start with the simple case when the valve operates in an on/off mode. The valve breaks up the constant steady flow in the pipeline.

The hydraulic impulse in the inflow line has been described in many publications. The impact is a result of transformation of kinetic energy of liquid in inflow line to potential one. The closing of the valve has to be controlled with respect to the impact in the inflow line. The impact and the valve closing progress simultaneously. The control of a water head value can be transferred to the valve closing control.

In the outflow line, the significant pressure impact appears some tens second after the valve is locked, see Fig. 2. It may be more dangerous then the impact in the inflow line. To control the value of hydraulic impact in the outflow line, the valve must be carefully operated. The Fig. 1 helps to explain the effect. Let us select the situation that corresponds to Fig.2.

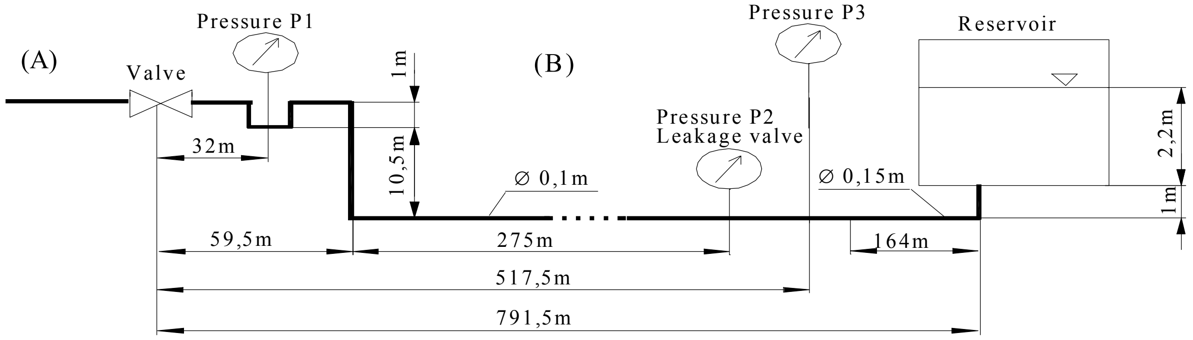

Fig. 1 The pipeline.

The mass of water in the secondary line is about 6500 kg. Its rate of flow is about 0.0065 m^3s^{-1}. The valve closes in less then 0.5 s. The water column in the outflow line does not stop immediately after the valve closes. Due its inertia, the water continues in its movement to the reservoir. The distribution of pressure in the line changes. Behind the valve, the pressure is near to zero. It is a pressure of saturated steam.

The speed of the water decreases then due both the friction and the pressure in the reservoir. Its speed at the near end reaches its zero value in about 10 seconds. Then its movement reverses. In about 22

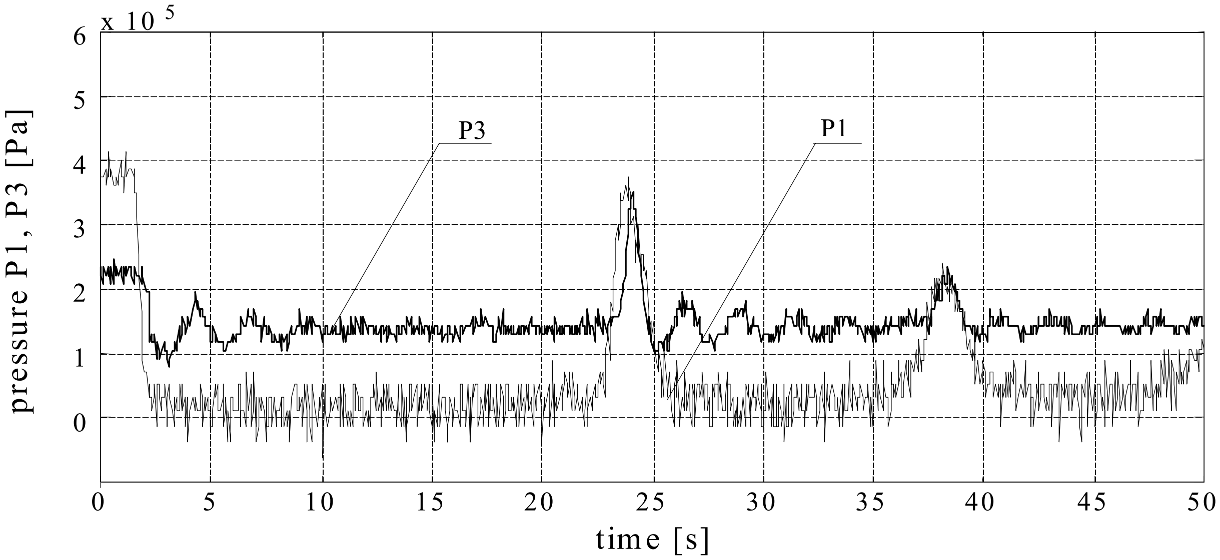

Fig. 2 The pressure impact. The pressure waves in positions P1 and P3.

seconds, the mass of water strikes the valve. It results in the pressure impact, see Fig. 2.

Note that the all measurements presented here have been made in the safe line mode. The initial water flow and the water level in the reservoir were decreased to values suitable for the experiment. In standard working conditions, the pressure impact could have destructive effects.

Hydraulic impact advances in the outflow line at a rate κ that is near to the rate of acoustic wave. Friction, liquid compression and the line expansion damp down the impact value.

The time lag between the water flow interruption and the hydraulic impact generation makes the control of a hydraulic impact in the outflow line more difficult then that in the inflow one.

The value of hydraulic pressure impact in the outflow line is controlled by the speed with which the valve closes. The calculation of the valve-closing curve convenient to the actual line can be made by means of simulation. The congruence of the simulation results with the measured valves is limited by both the accuracy of mathematical model and its calculation.

The water inertia, hydraulic friction, elasticity of pipeline, elasticity of liquid, the pressure at the reservoir and other parameters determine the pressure impact caused by valve opening. The impact occurs and progresses in both parts of the line. There is not a significant time lag between the valve opening and impact generation. The impact can be simply controlled. It will not be discussed here.

4. MATHEMATICAL MODEL

The mathematical model of the process describes the dynamics of the water flow in the secondary line. The mathematical model was developed in (Demčáková and Nevřiva, 2000). It describes both the water flow and the hydraulic impact propagation. The process is determined by the equations as follows.

4.1 Equation of continuity

$$v\,\rho\,\left(\frac{\partial F}{\partial p}\frac{\partial p}{\partial x}+\frac{\partial F}{\partial T}\frac{\partial T}{\partial x}+\frac{\partial F}{\partial x}\right)+F\,\rho\,\frac{\partial v}{\partial x}+$$
$$+F\,v\left(\frac{\partial \rho}{\partial p}\frac{\partial p}{\partial x}+\frac{\partial \rho}{\partial T}\frac{\partial T}{\partial x}\right)+\rho\,\left(\frac{\partial F}{\partial p}\frac{\partial p}{\partial t}+\frac{\partial F}{\partial T}\frac{\partial T}{\partial t}\right)+$$
$$+F\,\left(\frac{\partial \rho}{\partial p}\frac{\partial p}{\partial t}+\frac{\partial \rho}{\partial T}\frac{\partial T}{\partial t}\right)=0 \qquad (1)$$

4.2 Newton equation

$$\frac{\partial p}{\partial x}+\rho\,v\frac{\partial v}{\partial x}+\rho\frac{\partial v}{\partial t}+\rho\,g\frac{\partial z}{\partial x}=0 \qquad (2)$$

4.2 Bernoulli equation

$$\frac{\partial}{\partial t}\left(\rho\left(c\,T+\frac{v^2}{2}\right)\right)+\frac{\partial}{\partial x}\left(\rho\,v\left(c\,T+\frac{v^2}{2}\right)\right)+\frac{\partial}{\partial x}(p\,v)$$
$$+\frac{\partial}{\partial x}(\rho\,v\,g\,z)=0 \qquad (3)$$

where

$$\rho=\frac{\rho_0}{\exp\left(\frac{1}{K}(p_0-p)\right)\exp(\beta\,(T-T_0))} \qquad (4)$$

$$F=F_0\,\exp\left(\frac{dn}{E.d}(p-p_0)\right)\exp(2\,\alpha\,(T-T_0)) \qquad (5)$$

and where

c = internal energy of liquid
d = wall thickness of the pipeline
dn = internal diameter of the pipeline
E = modulus of elasticity
F = cross sectional area of the pipeline
g = acceleration of gravity
K = liquid elasticity bulk modulus
l = length of pipeline
p = pressure of liquid
t = time
T = temperature of liquid
TG = ambient temperature
v = flow velocity of liquid
x = coordinate along pipeline axis
z = elevation of the pipeline
α = bulk expansivity of pipeline
β = bulk expansivity of liquid
γ = heat transfer coefficient
λ = friction factor of liquid
ρ = density of liquid

5. MODEL ADAPTATION

There are about 20 parameters in the model. The values of parameters can be precisely defined in tasks relating either to very simple or to very prestige problems.

In a frequent industrial task discussed, a great mass of liquid is transported in a long line. There are not special demands on the transport. The continuous and safe passage of the fluid is required. It is possible to adapt model parameters to reach the best congruence of the measured and simulated data. There has to be well-founded arguments for such an attempt. Only a limited number of parameters is reasonable to modify by the procedure.

In the model discussed, two parameters were optimized to reach the optimal correspondence of measured and computed water head time lag. The liquid elasticity bulk modulus K was set of about 20 percent down the tabulated value. Consequently, the friction factor of liquid λ was set of about 5 percent off the standard value. The cause of difference in K and λ lays in the inaccurate assessment of amount of air, which is dissolved in the water.

The model adaptation was validated by the second set of measurements. The time delay between hydraulic impulses in P1 and P3 was determined, see Fig. 3. It defines the velocity κ of impulse propagation. Relation between liquid elasticity bulk modulus K and velocity κ is given by a simple expression.

6. MODEL IMPLEMENTATION

To simulate the process, the analytical form of model set above was transformed to a form suitable for standard numerical methods.

Two numerical models were constructed. The first model is a finite element one. The finite element model is of a great computational accuracy but it cannot be calculated in real time.

To achieve the near real-time computation, the semi-difference model was constructed. The semi-difference model divides the line in 40 sections. The non-linear partial differential equations introduced above are transformed to the corresponding sets of 41 ordinary non-linear differential equations. The resulting set of equations is solved using the Runge-Kutta method of the second order with integration step size control.

7. MODEL ACCURACY

The mathematical model describes the impact with limited accuracy. Numerical solution of the original model equations adds a remarkable numerical error to the simulation results.

At the finite element model, the accuracy of the computed impact value is better then 10 percent. At the difference model, the computed value differs from the measured value in about 20 percent. The limited accuracy of the difference model results mainly from the limited number of the line sections. See Fig. 3. It causes the excessive oscillations in the numerical solution. The oscillations also contribute to the peaks in computed impulses. Numerical error resulting from Runge-Kutta integration is of small value and can be omitted.

Numerical determination of the first impact time lag value is more accurate. In both models, the calculated time lag values correspond with measurement with accuracy of about 2%.

The Fig. 3 shoves the good congruence of measured and simulated waveforms in the time interval of about 20 seconds. After the hydraulic impact is generated, additional turbulence and steam bulbs occur in the liquid. The compressibility of water changes. The model equations do not describe this process. The correspondence of the next reflected impacts is less accurate. Hereafter, only the first hydraulic impact will be considered.

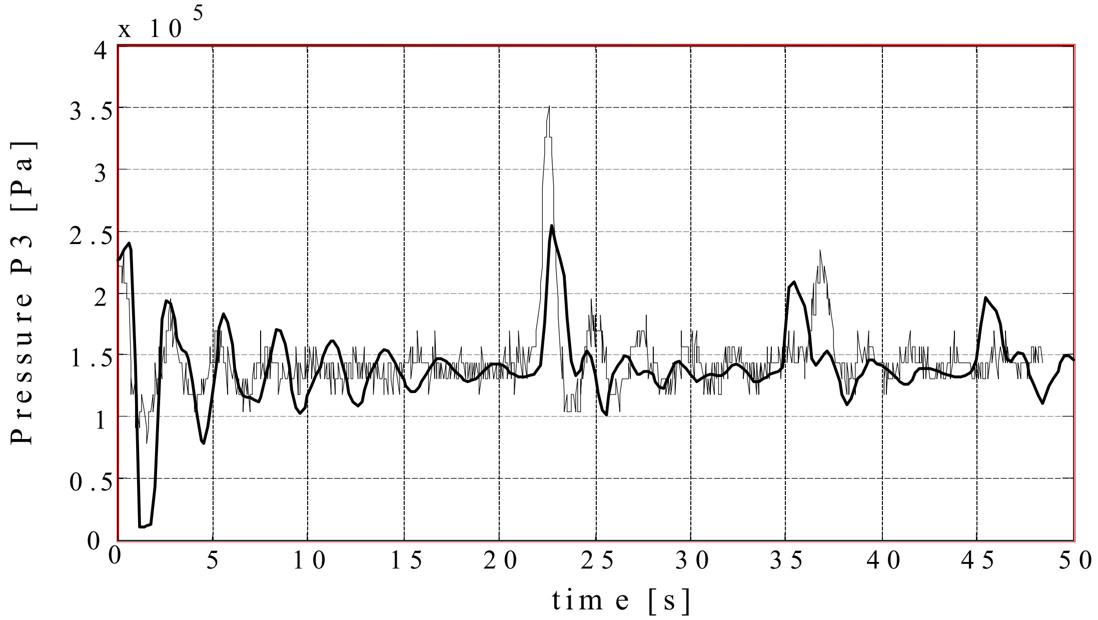

Fig. 3 The pressure in the position P3. The congruence of measured and simulated waveforms. Pressure gauge for P3 $\geq 1.10^5$ Pa was used.

8. HYDRAULIC IMPACT CONTROL

The optimal flow rate control has to consider the value of hydraulic impact in the outflow line. In the case discussed, the time optimal control leads to the minimal valve closing time. Maximal allowable value of generated impact defines the control constraint.

The value of the impact depends on the time derivation of the flow rate. The valve speed is defined as a time derivation of the valve active passage cross section value. It is a function of time that reflects the speed with which the valve closes the line.

The presented measurements discuss the case when the valve closes with constant valve speed. Fig. 4 presents the results for three different choices of the valve closing time. It shows that there is not a simple relation between the valve speed and the magnitude of generated impulse. The value of a water head in the outflow line and its actual time lag is only a moderately affected by the speed with which valve closes. The hydraulic impact generated in the inflow line supports sufficient amount of water to the outflow line during the closing time interval. It postpones the impact generation but does not prevent it. To prevent the hydraulic impact, the valve speed has to decrease, in its absolute value, almost exponentially.

The predictive control of the hydraulic impact was tested. The model of the line was used for the prediction. The model was updated by pressure values measured on both ends of the outflow line. The expected hydraulic impact value was calculated for adapted parameters of exponentially decreasing valve speed. The optimal value of the valve speed was find by iterations.

Note that the optimal valve speed setting leads to the time consuming computation. It cannot be made on PC computers in real time. As the pressure in reservoir changes slowly compared with the water head propagation, the optimal valve speed curves can be prepared off-line for slowly changing inflow pressure. The near end pressure and the near end to far end pressure difference are the parameters of the optimal control.

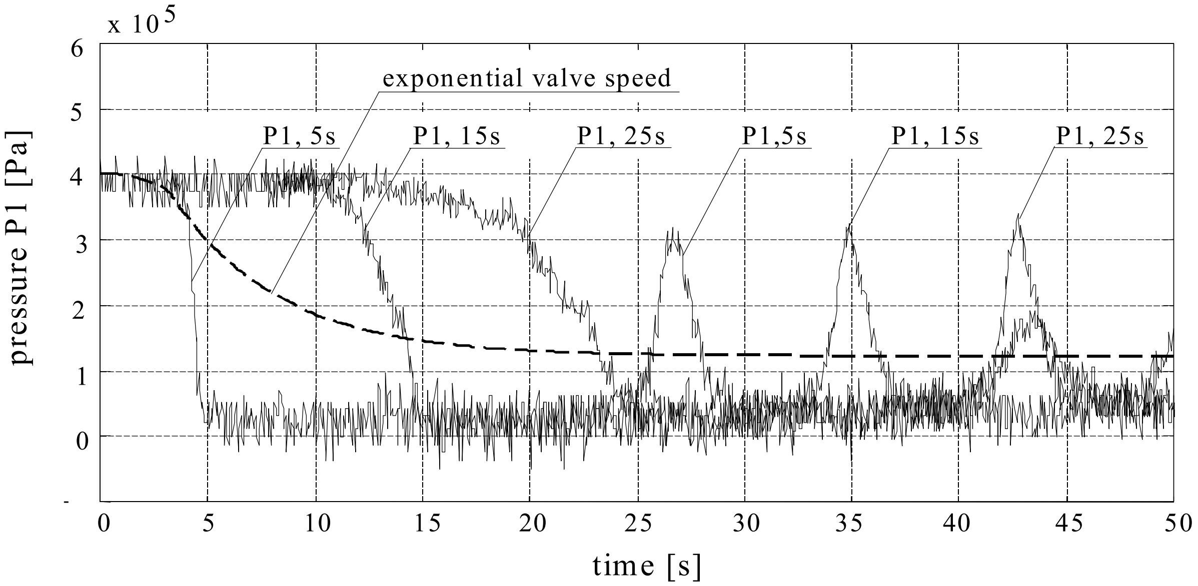

Fig. 4 The flow rate control. Valve closes with constant valve speed. The pressure P1 corresponding to the valve closing time of 5, 15 and 25 seconds is shown.

9. SUPPRESSION OF HYDRAULIC IMPACT BY PARAMETERS CHANGE

The hydraulic impact propagation can be controlled by the line parameter change. The arrangement of experiment is as follows. The pressure of liquid is measured at the near end of the outflow line. The measurement detects the impact generation behind the valve. When the impact generation is detected, the controller suppresses the modulus of elasticity of the next section of line. This part of the line works as a damper. In the virtual application, the control opens an air chamber connected to the line. The suppression of the impact by the air chamber result from the lesser modulus of bulk elasticity of the air in the chamber. The air chamber serves as a shock absorber. The effect of the leak is similar to the one of air chamber. The Fig. 5 shoves the hydraulic impact suppression due the leakage valve opening for selected values of valve flow rate. The valve was opened to atmosphere.

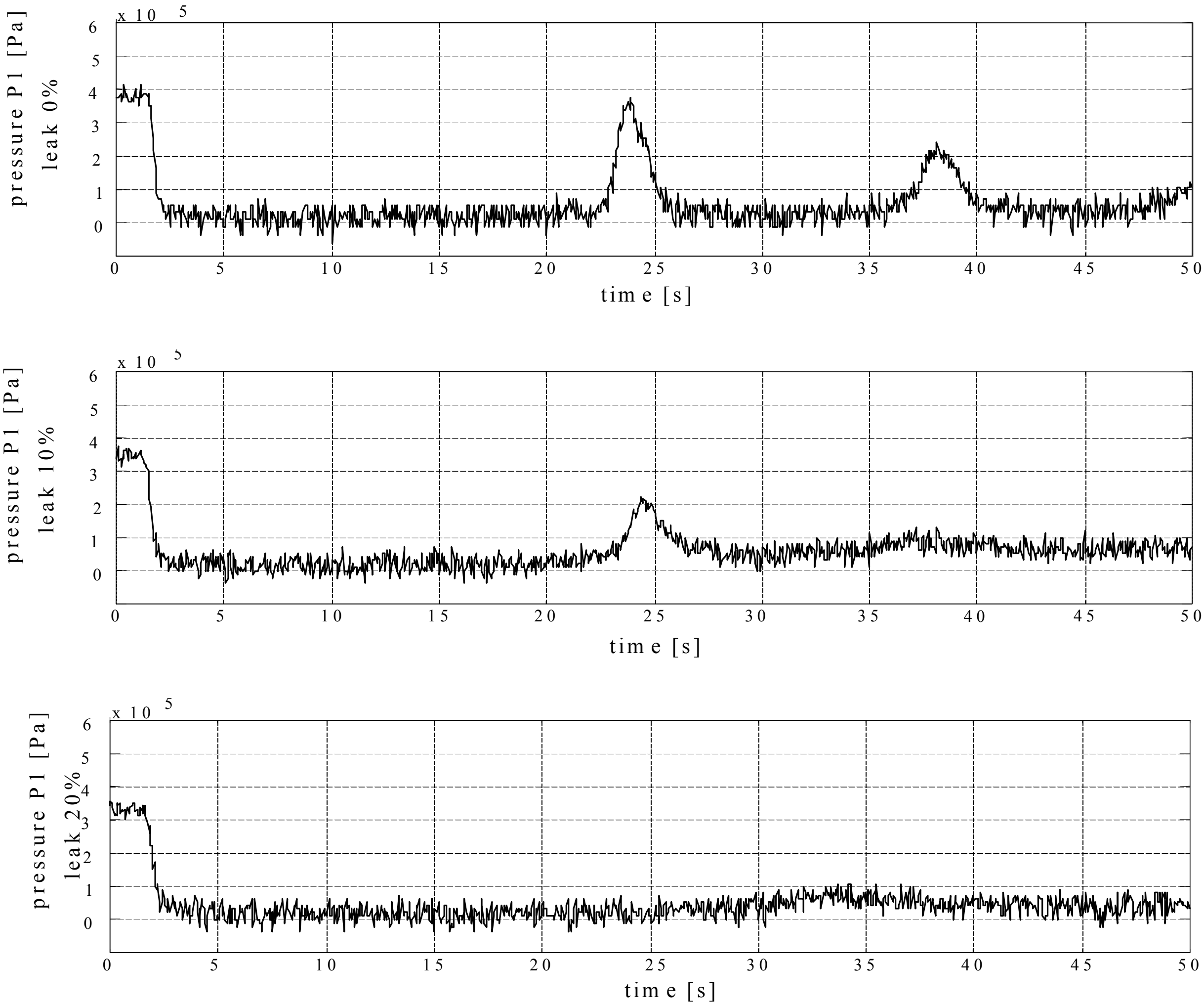

Fig. 5 The parametric control. The hydraulic impact suppression due the valve opening control is shown for valve flow rate of 0, 10 and 20 percent of the line flow rate. The valve opens to atmosphere.

Any leakage to atmosphere dumps the hydraulic impact. This fact can be used for the leak detection. The method was experimentally tested on lines of length less then 10 ν where ν is a rate of acoustic wave in the line. Instead of hydraulic impact, an acoustic signal was used. Results of experiment lead to conclusion that the leakage of about 1 percentage can be reliably detected. It is better accuracy then is the accuracy of pressure measurement. As to the leakage location, the method seems to be less accurate then standard methods based on measurements of steady state values.

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