Buletinul Ştiinţific al Universităţii "POLITEHNICA" din Timişoara
Seria HIDROTEHNICA
TRANSACTIONS on HYDROTECHNICS

Tom 55(69), Fascicola 2, 2010

Experimental Stand for the Study of Unsteady Water Flow through Pipelines and Pipe Networks

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Abstract - This paper presents the physical model developed by authors for the study of hydraulic shock in a ring type distribution network. Using hydraulic similarity criteria, the ring shaped stand models the Amara village, Ialomita County, water supply network. In order to analyze the network behaviour in different types of consumption variation, the network is connected to a computerized measuring unit, developed on a LabVIEW platform (National Instruments) that provides measurement, real-time display (graphical and / or tabular) of physical quantities collected from the sensors attached to the network.
Keywords: pipeline network, water distribution, transient, physical modelling.

1. INTRODUCTION

The complexity of the transients in water supply systems, the assumptions and limitations of various equations that govern motion sometimes raise doubts on the scope of applicability and the limits of these equations. Transient analysis using specialized software packages carried out in parallel with physical modelling may improve understanding of the hydraulic shock physical phenomena and the ability to predict and control this phenomenon in pressurized hydraulic systems engineering design and operation.

2. PHYSICAL MODEL DESCRIPTION

Hydraulic experimental facility, in which determinations were made, is a loop from an existing ring network, reduced proportionally, 20 times, on the basis of hydraulic similarity principles.

The trial stand has the following components:

- rectangular supply basin, with the dimensions L = 90cm, l = 60cm, h = 40cm;
- HDPE (high density polyethylene) supply pipeline of Ø40mm in diameter, 2.30m in length;
- HDPE network ring (PE80, SDR17, 5 PN6) composed of tubes of two diameter values: D_n 40mm nominal diameter (with e_n=2,30mm pipe wall thickness and D_{int}=35,40mm inner diameter) and D_n 20mm (with e_n=1,60mm and D_{int}=16,80mm), according to the scheme in Fig. 1 and Fig. 3.

The rectangular supply basin is located on a 2,40m high support (Fig. 4). Inside the basin, the water column has a height of 30cm, resulting in a water volume of approximately 160 liters. The water level in the tank is maintained constant by the use of a valve with float, which closes the water supply when the maximum height is reached.

Basin water supply is assured from the internal water supply network of the laboratory through a Ø20mm diameter HDPE pipe.

The experimental model is suppled with water by a HDPE Ø40mm pipe, connected to the bottom of the reservoir.

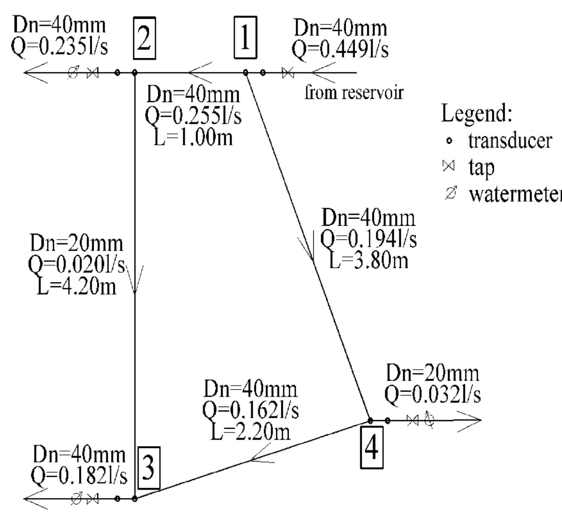

Fig. 1. - Ring network scheme

For a good water movement control, each node of the loop is equipped with flow and pressure measuring devices, as follows (Fig. 2):

- tap, with a maximum opening at 90° (angle between the tap lever and the pipe axis);
- pressure transducer, connected to the computer;
- water meter for determining the quantity of water discharged in a given unit of time.

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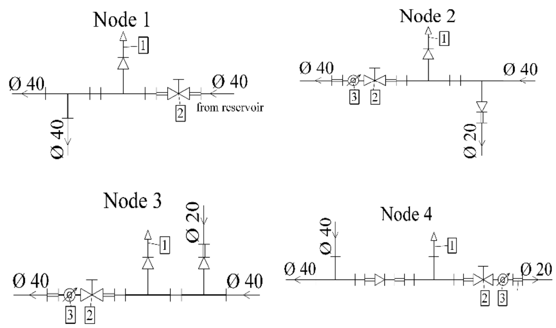

Fig. 2. - Details of mounting the network nodes
1 – transducer; 2 – tap; 3 – watermeter

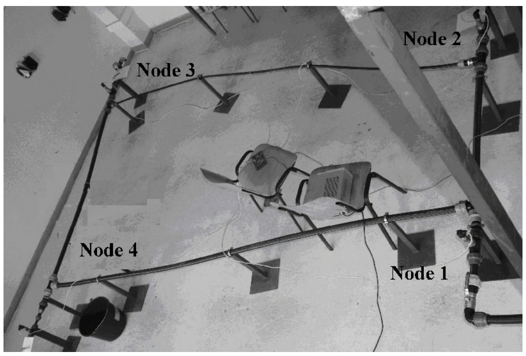

Fig. 3. - Top view of the experimental stand

Fig. 4. - View during the experiments

Network loop water intake is by the node no. 1, D_n *40mm* and distribution to consumers is by the other three nodes, which have the following features: node no. 2 and node no. 3 have D_n 40mm and node no. 4 D_n20mm. The four sides of the loop consist of HDPE pipes of different diameters, as follows: the 2-3 side has D_n 20mm in diameter, and the other sides, 1-2, 3-4, and 4-1 have D_n 40mm in diameter.

3. HYDRAULIC SIMILARITY CRITERIA

The design of the physical model was achieved by hydraulic similarity with the real situation, on the basis of the following criteria:

- geometrical, with respect to the reduction of the diameters and lengths of pipes;
- kinematic, with respect to the proportional reduction of pipe flow rate;
- dynamic, with respect to the network nodes pressure proportional reduction.

Knowing that both model and in nature water movement are subjected to *Newton's law*.

$$\vec{F} = m \cdot \vec{a} \tag{1}$$

where: ***F*** - force, ***m*** - mass, ***a*** - acceleration ;
the analyze of particle motion in an arbitrarily chosen X direction, will be made such as the forces that produce movement are expressed by correspondent relationships:

- nature

$$F_n = m_n \frac{d^2 X_n}{dT_n^2} \tag{1.a}$$

- model

$$F_m = m_m \frac{d^2 X_m}{dT_m^2} \tag{1.b}$$

where:
F_n and F_m - relevant forces;
m_n and m_m - corresponding masses;
X_n and x_m - proper distances;
T_n and T_m - fraction of time.

According to *Froude law of similarity*, in most cases of modeling, the main force determining the motion is the force of gravity.

Thus, geometric similarity is required to report all relevant lengths are one and the same:

$$\frac{X_m}{X_n} = (L)_\lambda \tag{2}$$

where: $(L)_\lambda$ - coefficient of similarity.

Given the analyzed parameters, the corresponding similarity coefficients have the form presented in Table 1.

Table 1 - Similarity coefficients

Type assimilation	Feature	Similarity coefficients
physics	length / diameter	$(L)_\lambda$
kinematics	flow	$\left(L^{\frac{5}{2}} \cdot \sqrt{\frac{\gamma}{\rho}}\right)_\lambda$
dynamics	pressure	$(L \cdot \gamma)_\lambda$

where: γ- volumetric weight of water, ρ - density of water.

The laboratory stand reproduces, on the basis of the main hydraulic principles, an existing water supply network, reduced by the similarity coefficient $(L)_\lambda$ = 20. The results are presented in Table 2÷ Table 5.

Table 2 – Pipe diameters of the ring network, the model and field

Pipeline section	Model pipe diameters (HDPE tube) [mm]			Diameter reducing coefficient	Real pipe diameters (metal pipe) [mm]			
	D_n	wall thickness	D_{int}		D_{int} calculated	D_{int} standard	wall thickness	D_n
intake	40	2,3	35,4	20,00	708	711	11,9	734,8
1-2	40	2,3	35,4		708	711	11,9	734,8
2-3	20	1,6	16,8		336	323,9	7,9	339,7
3-4	40	2,3	35,4		708	711	11,9	734,8
1-4	40	2,3	35,4		708	711	11,9	734,8
output 2	40	2,3	35,4		708	711	11,9	734,8
output 3	40	2,3	35,4		708	711	11,9	734,8
output 4	20	1,6	16,8		336	323,9	7,9	339,7

Table 3 – Flow rate in pipe sections

Pipeline section	Model flow rate [l/s]	Flow rate reduction factor	Real pipeline flow rate [l/s]
intake	0,449	1788,85	803,196
1-2	0,255		456,158
2-3	0,02		35,777
3-4	0,162		289,794
1-4	0,194		347,038
output 2	0,235		420,381
output 3	0,182		325,571
output 4	0,032		57,243

Table 4 – Lengths of pipe network

Pipeline section	Length of pipeline design [m]	Length reduction factor	Pipeline lenght field [m]
1-2	1	20,00	20
2-3	4,2		84
3-4	2,2		44
1-4	3,8		76

Table 5 – Pressures in the ring network nodes

Node	Model node pressure [mCA]	Pressure reduction factor	Real node pressure [mCA]
1	1,949	20,00	38,97
2	1,823		36,45
3	1,820		36,39
4	1,898		37,96

4. MEASUREMENT AND CONTROL SYSTEM

Each node of the loop is equipped with a pressure transducer type MBS-1AB08 33-2811 (Danfoss product) (Fig. 5).

Fig. 5 - pressure transducer 33 MBS

The pressure transducer MBS 33 is designed for use in almost all industrial applications and provides a reliable measurement of pressure, even in difficult environmental conditions. The flexible sensor covers an output signal 4 ÷ 20 mA and a gap measuring pressures from 0 ÷ 1 bar to 0 ÷ 600 bar at operating temperatures of -40 ÷ +85^o C. The pressure transducer MBS 33 has an excellent vibration stability, robust construction and a high conversion EMC / EMI to meet the most stringent industrial requirements.

Computerized measurement system can provide measurement, real-time display (graphical and / or tabular) of physical quantities collected from sensors attached to the network.

Given the academic use of the measurement system (in the Ovidius University), the solution chosen is based on the use of hardware and software for the acquisition of data contained within a particular ***starter-kit***.

Measurement and control system consists of the following components:

a) Local application developed in LabVIEW programming environment;

b) Data acquisition card NI PCI MIO 16XE-50, 16bit resolution;

c) NI SCB-block connections 68LP (Fig. 6).

d) Excitation system consists of pressure transducers:

- instrumentation power source 0-30Vdc;
- instrumentation 55Ω resistors.

Fig. 6 - Block connections NI SCB-68LP

The signal from each sensor is collected as a voltage at the ends of the instrumentation resistance .

Fig. 7 and Fig. 8 present, for example, " Block Diagram", and respectively "Front Panel" of the program “Pressure Measurement.vi”.

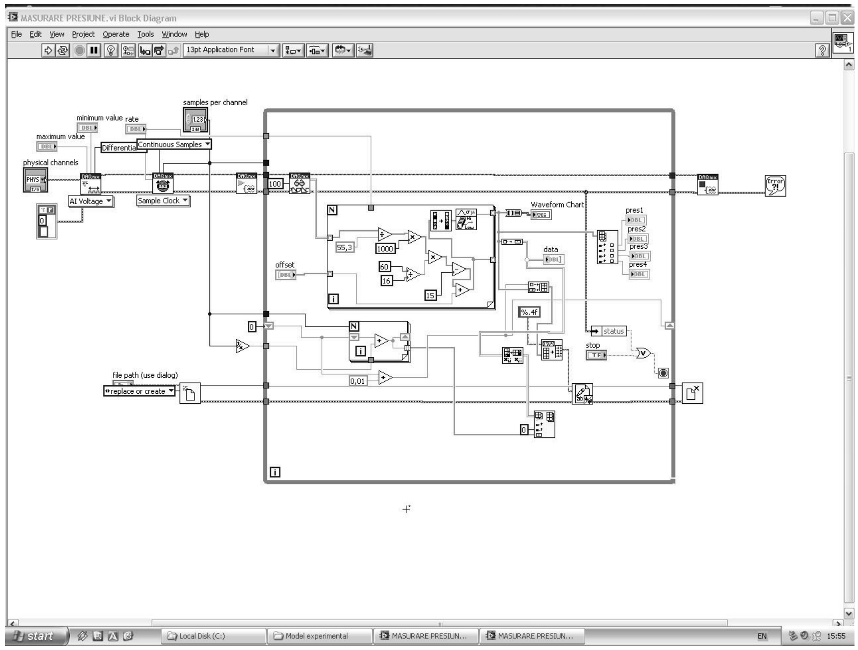

Fig. 7 - Block Diagram of the “Pressure Measurement.vi”

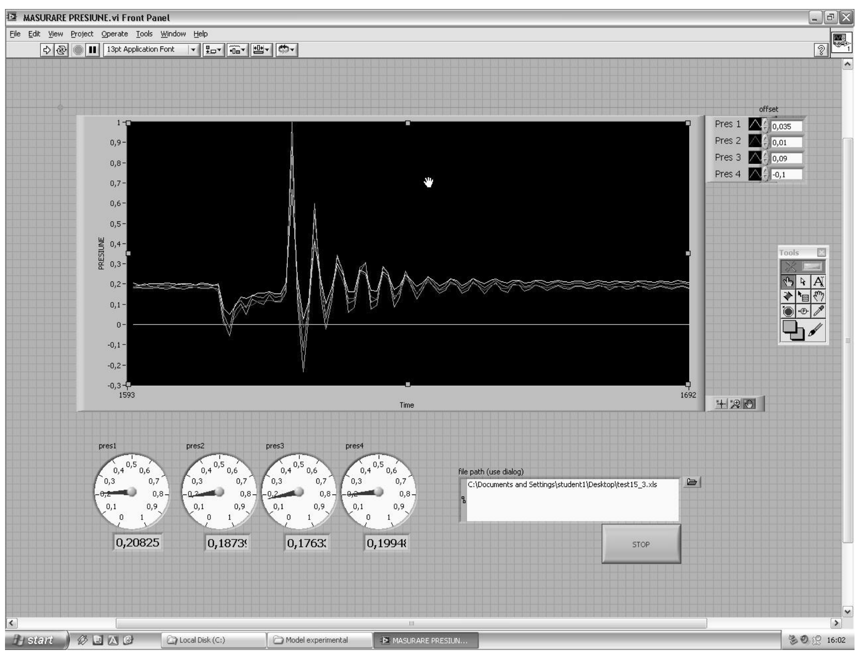

Fig. 8 - Front Panel LabVIEW Platform for the “Pressure Measurement.vi”

5. EXPERIMENTAL METHOD

Experimental measurements, made on the physical model presented above, aimed the analysis of the transient flow regime, taking as reference regime the steady flow of water through a ring shaped pipeline network.

The occurrence and deployment of the hydraulic shock phenomenon due to disturbances induced in the network loop by valves manoeuvres were investigated according to:

- valve opening angle, α;
- mode of the valve operation ;
- valve opening duration.

The following cases of network operation and handling of valves were simulated:

- sudden manoeuvre of a single valve;
- sudden manoeuvre and simultaneous operation of two valves;
- sudden manoeuvre and simultaneous operation of three valves.

The type of valves allowed measurements to be made at various angles of opening, α: 30°, 45°, 60° and 90°.

Our investigations were conducted on two main directions:

- the determination of the flow rates in each node, in steady state operation, at different variants of opening angle α. The flow rates in nodes 2, 3 and 4 stand for the real flow rates of the network consumers. Therefore, we aimed to establish the valve opening angle corresponding to the real flow rate of these consumers.

- the determination of pressures and related instant water flow rates in each node, in unsteady regime operation. The unsteady movement was provoked by sudden manoeuvres of valves, in different combinations.

The average water flow rate in each network node was determined in the case of steady, simultaneous operation of the three valves in the nodes N2, N3 and N4, at each following value of the opening angle, α: 30°, 45°, 60° and 90°. It was assumed that the steady state regime is established 10s after the valves opening.

The unsteady regime was induced by the valve obturator operating modes. The measurement was carried out following the sequence:

- sudden opening of valves at a prior established angle;
-water instant flow rate measurement at two moments: $t_1 = 1$ s; $t_2 = 2$ s
- sudden closing of the valves;
-continuous pressure variation recording.

To ensure greater accuracy of experimental data, a set of three measurements has been made for each opening angle, α,. The discharge in node N1 is obtained by summing the flows determined in the other three nodes.

6. RESULTS

The experimental results with respect to the water flow rate in steady state regime are presented in Table 6, for each network node.

A more intuitive presentation of these data is graphically made the Fig. 9.

Table 6 – Determination of the flow rate, in the case of steady and simultaneous operation of the three valves

Angle of tap opening α [degrees]	Discharge [l/s]			
	Node 2	Node 3	Node 4	Node 1
30	0,420	0,320	0,087	0,827
45	0,725	0,607	0,148	1,480
60	0,939	0,759	0,189	1,887
90	1,100	0,808	0,208	2,116

The curves plotted in Fig. 9 represent the water flow rate in each node of the experimental network loop. The curve for node 1 depicts, in fact, the water intake variation.

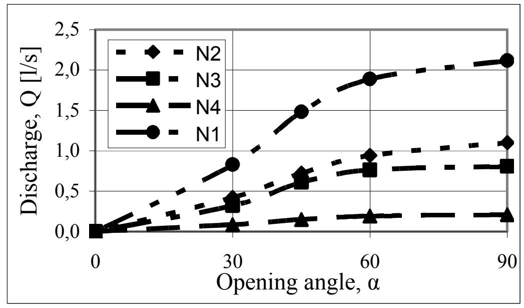

Fig. 9-Variation of average flow rate, in the case of steady and simultaneous operation of the three valves, for different opening angles, α.

Simultaneously with the flow measurements, pressure variation was recorded by each sensor installed in the ring network nodes during each entire experiment..

Pressure values were collected and recorded using the program "MASURARE PRESIUNE.vi" (Pressure Measurement.vi).

The following simulated operating modes are presented bellow:

- opening - closing after 10 sec. of the three valves: N2, N3 and N4 (Fig. 10);
- opening - closing after 10 sec. of two valves: N2 and N3 (Fig. 11);
- opening - closing after 10 sec. of two valves: N2 and N4 (Fig. 12);
- opening - closing after 10 sec. of two valves: N3 and N4 (Fig. 13).

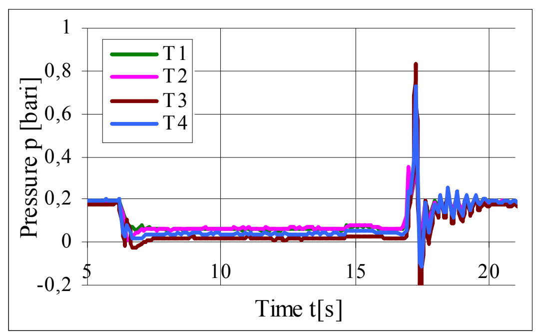

Fig. 10 - Changes in pressure when opening the three valves simultaneously, $\alpha = 90°$

In Fig. 10 , the notation T1, T2, T3, T4 refers to the pressure transducers of the corresponding nodes of the network, namely, N1, N2, N3, N4.

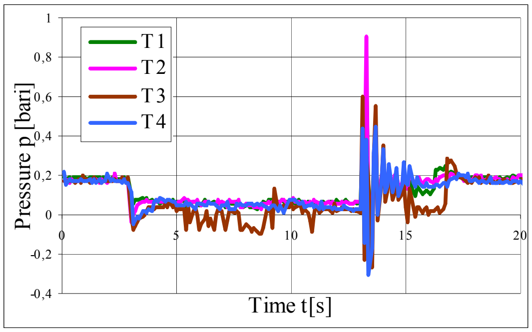

Fig. 11 - Pressure variation in the case of simultaneously opening of the valves in node2 and node3, α= 90°

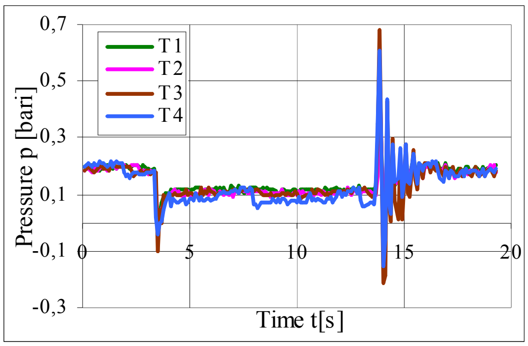

Fig. 12 - Pressure variation in the case of simultaneously opening of the valves in node2 and node4, α= 90°

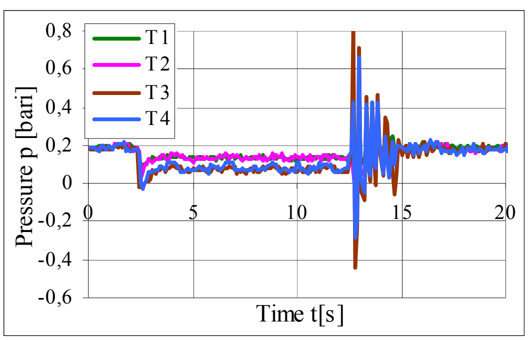

Fig. 13 - Pressure variation in the case of simultaneously opening of the valves in node3 and node4, α= 90°

Analyzing pressure variation graphs presented above (Fig. 10 ÷ Fig. 13) the minimum and maximum values of pressure at sudden valve closure and the transducers that are recording these values can be determined (Table 7).

Table 7 - Minimum and maximum pressure values

Tap handle	p_{min}		p_{max}	
	[bari]	Node	[bari]	Node
N2–N3–N4	-0,20	N3	0,81	N3
N2-N3	-0,30	N4	0,90	N2
N2-N4	-0,21	N3	0,68	N3
N3-N4	-0,42	N3	0,80	N3

7. CONCLUSIONS

The experimental determination presented above lead to the following conclusions:

1. On the basis of the graphic representation of average flow rate variations, in the case the three water distributing valves are simultaneously open (Fig. 9), one can determine the exact opening angle of each valve obturator, to ensure on the model the correspondent flow rate requested by the consumer.

Thus:

- N2 distribution ensures the flow rate ***Q=0.235l/s*** by opening the valve at an angle ***α=17°***;
- N3 distribution ensures the flow rate ***Q=0.182l/s*** by opening the valve at an angle ***α=18°***;
- N4 distribution ensures the flow rate ***Q=0.032l/s*** by opening the valve at an angle ***α=10°***.

2. Analyzing the results it was found that the worst situation is the case the valves deliver their maximum discharge that means the valves are suddenly opened / closed to / from ***90°***, in any combination.

3. The opening of a valve results in an immediate vacuum, followed by some pressure oscillations. The steady state flowing regime is established after 3÷4s.

4. According to Table 7 it may be noticed that the N3 node of the ring network is considered the most unstable, and also, the necessary time for pressure oscillation attenuation in this node is maximal.

5. The highest and lowest pressure values, in sudden closure cases, are obtained when the valve obturators are simultaneously acting in the nodes N2-N3 or N3-N4. The difference between the highest and lowest recorded pressure is about 1.20 bars.

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