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Fluid Hammer Phenomenon Aspects on Circular Ducts

Assistant professor **Fănel Dorel ȘCHEAUA**[1]

[1] "Dunărea de Jos" University of Galați, MECMET Research Center, fanel.scheaua@ugal.ro

Abstract: *Theoretical aspects related to fluid circulation through circular pipes under pressure with a certain velocity value are presented while the valve is sudden or slow closed at a certain moment. The model represents the non-permanent fluid circulation type through circular pipes frequently encountered in the case of hydraulic applications, in the work installations operation, with a need for stopping and restarting according to the existing operating work body needs. For this purpose, special devices capable to adjust the fluid flow rate are mounted in the circuit represented by valves which by their action have the possibility to interrupt the hydraulic flow stream in the circuit when needed. When the valve closes suddenly there are high overpressure efforts acting on the duct walls that far exceed the registered pressure value in the above permanent fluid circulation regime. This paper describes the theoretical aspects for fluid hammer phenomenon for the case of a rigid circular steel duct. A numerical fluid flow analysis on the virtual model of the pipe with closing element is made and the results are presented in order to highlight the specific fluid pressure and velocity values that occur when closing the valve.*

Keywords: *Fluid flow, fluid hammer, pressure, three-dimensional modelling, CFD*

1. Introduction

The model of non-permanent flow through pressure pipelines is highlighted, which is characteristic for the machines and industry equipment hydraulic installations operation, which depending on the requirements and needs of the working body have the possibility to interrupt and connect the installation to the system pressure source. Due to the intermittent nature of the pressurised fluid flow, high stresses appear on the installation duct walls due to the created overpressures that far exceed the value of the nominal pressure of the installation operating in permanent flow of working fluid forming important stresses on the pipe wall.

Considering the presented aspects, it is necessary a proper dimensioning of the installation pipes that are subjected to important stresses due to the intermittent operation regime and the non-permanent fluid flow regime. [1-5]

2. Fluid hammer characteristics

By abruptly closing the flow section of the hydraulic network pipes, the formation and propagation of specific pressure waves in the fluid region inside the pipe is ensured as a result of the sudden handling of the closing elements that determine the increase of pressure values in the respective fluid area considering the compressibility of the working fluid.

In the case of forced or gradual closing of the hydraulic installation valve, an overpressure is produced first, then an underpressure, the process having a cyclical character until the pressure values are balanced at the nominal value.

This pulsating process has a direct influence on the hydraulic network pipe through cyclic stresses on the pipe wall.

The phenomenon is also observable for the velocity variation case or the the installation pump shutdown when a subpressure is first registered followed then by an fluid overpressure, the process being repeated cyclically along the discharge line of the system pump.

The pipe elasticity coefficient must be taken into account, as well as the load losses that occur during the fluid circulation.

In the case of steel pipe it cannot be considered rigid so that the forced compression of the working fluid causes the elastic deformation of the pipe wall registered with a certain delay time due to the significant difference between the pipe material elasticity modulus and the working fluid and the inertia of the pipe material which cannot instantly follow the cyclic process of compressing and decompressing the liquid.

The pipe material low rigidity has the effect of attenuating in time the propagation velocity characteristic values of the pressure waves appeared as a result of the hammer fluid. 00

3. Theoretical aspects regarding the fluid hammer

The characteristic equations of the fluid hammer phenomenon are necessary for the analytical study in case the non-permanent flow registered within a circular pipe with diameter (D), fed from a tank containing liquid with free surface located at the height given by the dimension (z). The thickness of the pipe wall d is considered, and the elasticity modulus of the pipe material is (E).

The working fluid has the specific gravity range, the density (ρ) and the modulus of elasticity (e).

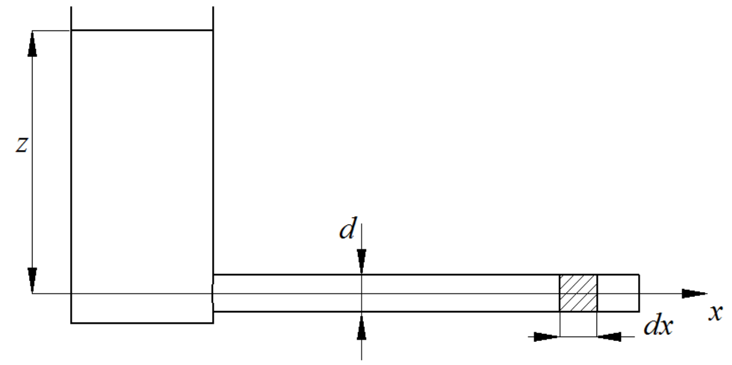


Fig. 1. Fluid particle motion within circular duct 0

For the analytical study of the fluid hammer it is necessary to determine the change of the velocity and the fluid pressure in time along the circular pipe length.
The equation of motion results from applying Newton's law to a fluid particle located within the main fluid stream inside the pipe.
The forces acting on the particle are represented by the mass forces (weight) and the surface forces given by pressure and viscosity. The weight has a vertical component and the viscosity forces are neglected, so the only forces taken into account are the pressure forces between two points on different sections.
The overpressure appears on the duct section from the shut-off valve with a higher value than the nominal flow pressure registered at the moment before the valve shut-off. 0
Together with the pressure waves propagation along the circular pipe length, the relation for the pressure forces resultant can be written as follows: 0

$$F_p = \frac{\pi D_c^2}{4}\left(p + \frac{\partial p}{\partial x}dx\right) - \frac{\pi D_c^2}{4}p = \frac{\pi D_c^2}{4}\frac{\partial p}{\partial x}dx \tag{1}$$

$$\sum F = ma = \rho\frac{\pi D_c^2}{4}dx\frac{\partial v}{\partial t} = \frac{\pi D_c^2}{4}\frac{\partial p}{\partial x}dx \tag{2}$$

The relation for particle fluid motion that describes the connection between the fluid flow velocity and height functions related to space and time can be written as: 0

$$\frac{\partial v}{\partial t} = g\frac{\partial z}{\partial x} \tag{3}$$

Taking into account the pipe wall stresses and the fluid compressibility values, the continuity equation can be written to describe the fluid hammer phenomenon. 0

$$dV = dV_1 - dV_2 \tag{4}$$

It is considered that the working fluid volume is modified with the forced compression that determines the pipe wall deformation by increasing the momentary volume. 0

$$dV = (Q_1 - Q_2)dt = \frac{\pi D_c^2}{4}\left[v - \left(v - \frac{\partial v}{\partial x}dx\right)\right]dt = \frac{\pi D_c^2}{4}\frac{\partial v}{\partial x}dxdt \quad (5)$$

Hooke's law describes the increase in the diameter value based on the unit effort depending on the pipe material elasticity modulus. 0

$$dV_1 = \pi d_c \frac{dD_c}{2}dx;\ dD_c = \frac{d\sigma}{E}d_c;\ d\sigma = \frac{D_c dp}{2\delta} \quad (6)$$

$$dV_1 = \pi D_c \frac{dD_c}{2}dx = \frac{\pi}{2}\frac{d\sigma D_c^2}{E}dx = \frac{\pi}{4}\frac{D_c^3}{\delta E}dpdx \quad (7)$$

For the fluid hammer case, the pressure values change in time is more important than the space change and the relation for the conveyed fluid volume variation in the increase direction can be adopted as the following form: 0

$$dp = \frac{\partial p}{\partial x}dx + \frac{\partial p}{\partial t}dt \quad (8)$$

$$\frac{\partial p}{\partial t} >> \frac{\partial p}{\partial x} \Rightarrow dp = \frac{\partial p}{\partial t}dt \quad (9)$$

The change in fluid volume can be calculated as follows with the relation: 0

$$dV_1 = \frac{\pi D_c^3}{4\delta E_c}\frac{\partial p}{\partial t}dtdx \quad (10)$$

Fluid volume compression causes the decrease of the initial volume according with the relation: 0

$$dV_2 = -\frac{1}{\varepsilon}Vdp = -\frac{1}{\varepsilon}\frac{\pi D_c^2}{4}dx\frac{\partial p}{\partial t}dt \quad (11)$$

The continuity equation can be considered that establishes the relationship between the volume functions and the circulated fluid level. 0

$$\frac{\pi D_c^2}{4}\frac{\partial v}{\partial x}dxdt = \frac{\pi D_c^3}{4\delta E_c}\frac{\partial p}{\partial t}dtdx + \frac{1}{\varepsilon}\frac{\pi D_c^2}{4}dx\frac{\partial p}{\partial t}dt \quad (12)$$

Because the pressure can be considered as $p = \gamma z$ and after simplification the continuity equation is obtained as: 0

$$\frac{\partial v}{\partial x} = \left(\frac{1}{\varepsilon} + \frac{1}{E_c}\frac{D_c}{\delta}\right)\gamma\frac{\partial z}{\partial t} \quad (13)$$

Fluid hammer phenomenon determines the pressure waves appearance whose propagation along the circular pipe is described by the specific propagation equation. This equation is obtained from the derivation in relation to space and time of the equation of motion and continuity. With a special notation introduced and derivation in range with space and time the propagation equations are obtained: 0

$$\frac{g}{a^2} = \left(\frac{1}{\varepsilon} + \frac{1}{E_c}\frac{D_c}{\delta}\right)\gamma \quad (14)$$

$$\frac{\partial^2 z}{\partial x^2} = \frac{1}{a^2}\frac{\partial^2 z}{\partial t^2};\ \frac{\partial^2 v}{\partial x^2} = \frac{1}{a^2}\frac{\partial^2 v}{\partial t^2} \quad (15)$$

The disturbances produced as a result of the fluid stopping after JUKOVSCHI are described as follows: 0

$$dp = -\rho \frac{dx}{dt} dv \quad (16)$$

$\frac{dx}{dt} = c_p$ representing the pressure wave propagation velocity.

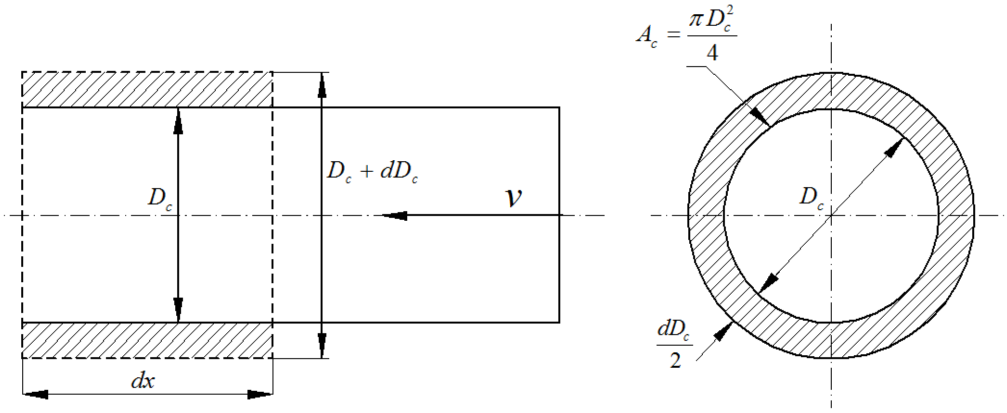


Fig. 2. Pressure disturbances on a circular duct (dx) length and radial deformation (dD_c) 0

The pressure increase maximum value within the pipe is considered at complete valve closing, which means fluid velocity reduction to zero value: 0

$$\Delta p = -\rho c_p v \quad (17)$$

After a time interval (dt) the pressure disturbance has reached a length of pipe (dx) and the fluid mass contained in this space is: 0

$$dm = \rho A_c dx \quad (18)$$

Another fluid amount reaches this region which by braking remains in space (dx): 0

$$d(dm) = \rho A_c dv dt \quad (19)$$

The extra fluid mass acts to change the fluid density (ρ) and for pipe radial deformation (dD_c): 0

$$d(dm) = dx(A_c d\rho + \rho dA_c) \quad (20)$$

By equalizing the relations, it is obtained: 0

$$A_c dv dt = dx(A_c d\rho + \rho dA_c) \quad (21)$$

$$dv = -c_p\left(\frac{d\rho}{\rho} + \frac{dA_c}{A_c}\right) \quad (22)$$

Replacing with the fluid compressibility coefficient $\left(\beta = \frac{1}{\varepsilon}\right)$ is obtained: 0

$$\frac{d\rho}{\rho} = \beta dp = \frac{dp}{\varepsilon} \tag{23}$$

Modification of the pipe section is described by the term $\left(\frac{dA_c}{A_c}\right)$, with $A_c = \frac{\pi D_c^2}{4}$: 0

$$\frac{dA_c}{A_c} = \frac{\frac{\pi D_c dD_c}{2}}{\frac{\pi D_c^2}{4}} = 2\frac{dD_c}{D_c} \tag{24}$$

Considering the Hooke law can be written: 0

$$d\sigma = E_c \frac{dD_c}{D_c} = \frac{D_c dp}{2e} \Rightarrow 2\frac{dD_c}{D_c} = \frac{D_c dp}{eE_c} = \frac{dA_c}{A_c} \tag{25}$$

$$dv = -\frac{dp}{\rho c_p} = -c_p\left(\frac{dp}{\varepsilon} + \frac{D_c dp}{eE_c}\right) \Rightarrow c_p = \sqrt{\frac{1}{\frac{\rho}{\varepsilon} + \frac{\rho D_c}{eE_c}}} \tag{26}$$

It is known that the ratio $\frac{\varepsilon}{\rho} = c_0^2$ represents the sound velocity within the respective fluid, further can be written:

$$c_p = \frac{c_0}{\sqrt{1 + \frac{\varepsilon D_c}{eE_c}}} \tag{27}$$

The obtained relation represents the analytical expression that describes the pressure waves propagation velocity through elastic circular pipes, also called the JUKOVSCHI-ALLIEVI relation.
It can be seen that the propagation velocity depends on the pipe diameter (D_c), the wall thickness (e), the pipe material elasticity modulus (E_c), as well as the elastic properties of the fluid in the pipe (ε). 0

4. Pressure wave propagation

The calculation is performed in order to determine the specific pressure wave propagation velocity values for high density polyethylene pipes, with a diameter of 110 mm, but for different pressure groups, which means different values of the pipe wall thickness.
The specific values of the pipe wall thickness and the pressure groups at which they can be used are presented in Table 1.

Table 1: The pipe wall thickness and pressure values 0

Polyethylene pipes (PE 100)							
Pn=6 bar	Pn=6 bar	Pn=8 bar	Pn=10 bar	Pn=12.5 bar	Pn=16 bar	Pn=20 bar	Pn=25 bar
$e\,[mm]$							
4	4.2	5.3	6.6	8.1	10	12.3	15.1

The specific values of the pressure wave propagation speed were calculated using the JUKOVSCHI-ALLIEVI formula, and the results are presented in the figure 3 diagram.

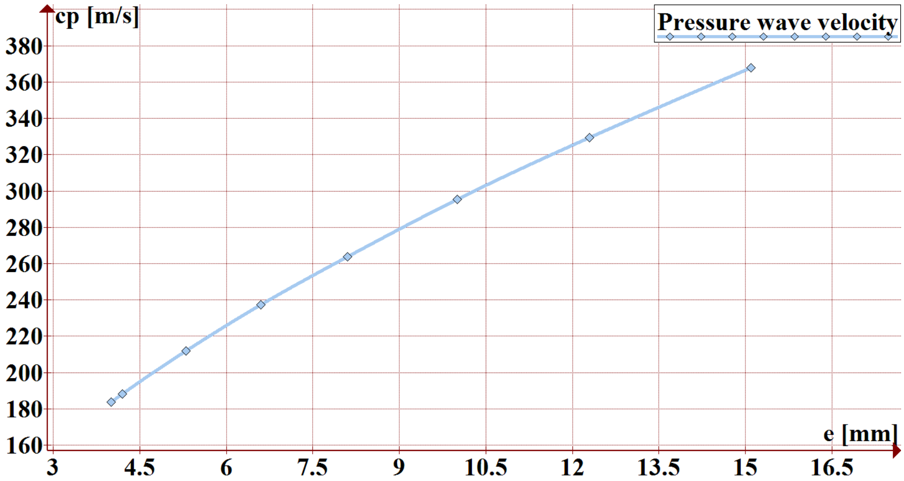
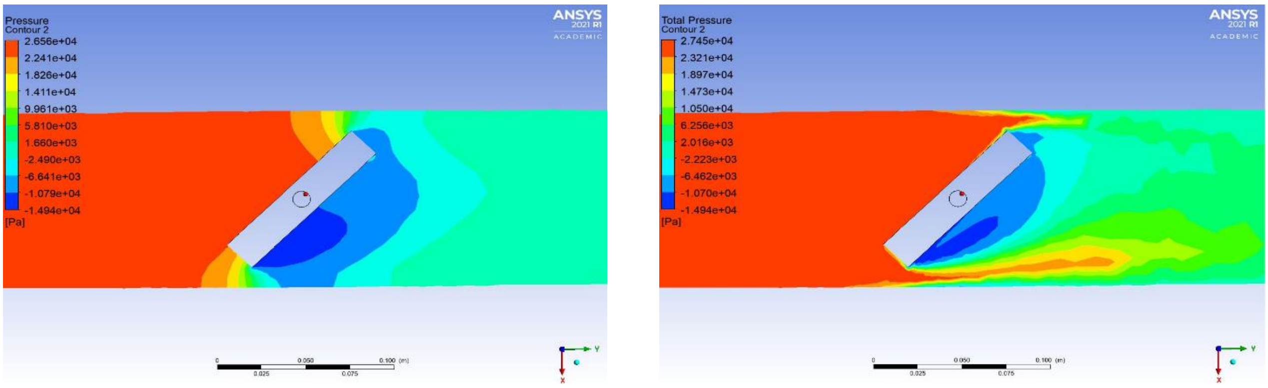


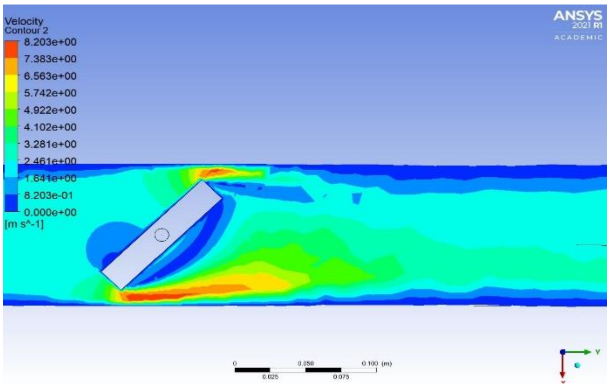
Fig. 3. Pressure wave propagation velocity function of pipe wall thickness

5. Numerical analysis on pipe virtual model

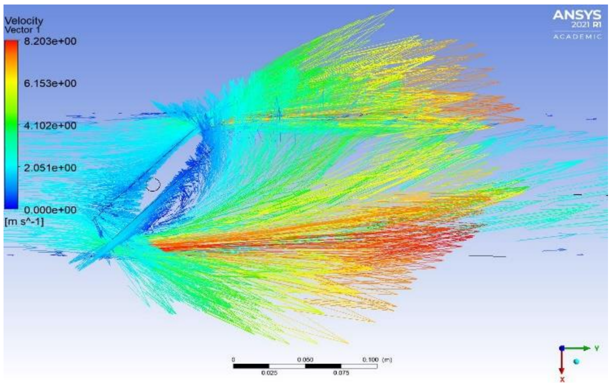
The numerical analysis method performed with ANSYS Fluent is used in order to highlight the fluid hammer effect on the virtual model of a high-density PE pipe with a diameter of 110 mm.
Water inlet with a velocity of 2 m/s is declared, being circulated inside the pipe, and at half distance a valve is placed which is in the half-open position at an angle of 45 degrees to the vertical direction.
The valve position forms a resistance to the fluid flow through the pipe, so that an increase in pressure values is obtained in the valve upstream region, and in the space between the closing element and the pipe wall flow velocity increased rates are obtained (fluid is laminated in the restricted area).
The results are presented in figure 4 in terms of pressure and velocity in the analyzed fluid area, being highlighted the specific values in the valve area which is considered as a resistance in the fluid flow path.



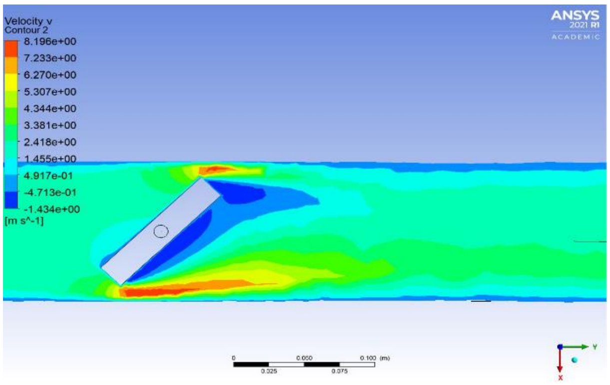
a) pressure values b) total pressure values



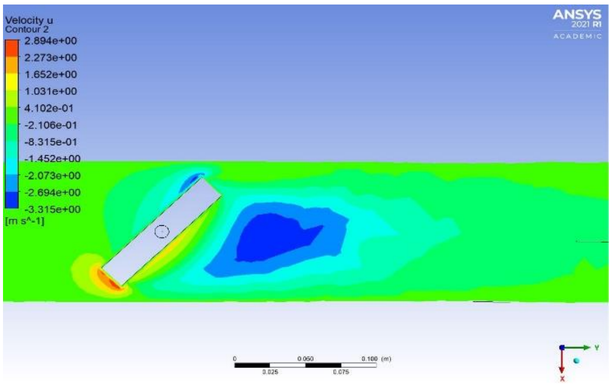
c) contour velocity values



d) velocity vector values



d) contour velocity v values



e) velocity vector u values

Fig. 4. Fluid flow analysis results

It can be seen that when the valve is suddenly closed, a maximum pressure value is obtained in the area upstream of the valve, and the flow velocity values record the maximum in the area between the valve wall and the pipe wall where the fluid is forced to flow.
The results indicate that for this model of pipe is not exceeded the maximum pressure value of 6 bar for which the pipe is designed to withstand, but depending on the values of circulation speed this value can be exceeded, this being an unfavourable case in practice.

6. Conclusion

The theoretical aspects related to the fluid hammer phenomenon were presented in this paper, being highlighted the importance of this phenomenon for the fluid flow through a circular pipe.
The case of high-density polyethylene pipes used for urban water circulation was presented.
The specific values of the pressure wave propagation velocity were calculated for different wall thicknesses corresponding to the working pressure groups for which they are used.
A numerical analysis was also performed for water flow through the 110 mm outer diameter polyethylene pipe.
For a declared value of the circulation speed of 2 m/s, an increase of the total pressure of up to 2.7 atm in the area upstream of the shut-off valve was obtained.
The fluid velocity values are maximum in the area between the pipe wall and the valve wall reaching the values of approx. 8 m/s, which explains the fact that in this area the fluid is forced to circulate through lamination.

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