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EFFECTS OF AIR ENTRAINED BY WATER IN PUMPING INSTALLATION

CONSTANTIN Anca[1], STANCIU Tamara[2], NITESCU Claudiu[1]
[1] “Ovidius” University of Constanta, aconstantina@univ-ovidius.ro
[2]Diver’s Center, Constanta

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Abstract: Small amounts of air may be entrained by water flowing in a pumping installation deliberately or by accident. Presence of air modifies the physical properties of water and allows a greater influence of temperature on the flow parameters. Turbulence increases due to the air bubbles in a non homogenous flow. Celerity decreases, therefore air provides a good protection of the pumping installation from the hydraulic shock. The paper presents the investigation on a pumping discharge duct and its hydraulic equipment, made by numerical simulation, in the case of biphasic flow.

1. INTRODUCTION

In almost all usual water pumping installations, in which water is untreated, we may say that the flow is a multiphase one, due to the air bubbles and small solid particles spread out through the water. In comparison with the one phase flow, the flow parameters register modification when this multiphase flow is taken into account. In the subsequent discussion it will be considered only a biphasic flow, namely air –water mixture, at small volume fraction of free air. The presence of free air dispersed in water decreases the celerity, protecting the pumping system from hydraulic shock. On the other side, the presence of air may result in the occurrence of pressure, flow rate or volume fraction oscillations that alter the operation of the system and decreases the reliability of the mechanical components [1]. The trend toward higher rotational speeds of pumps leads to higher flow velocities that may enhance the fluid/structure interactions. It may be noticed that small amounts of dispersed air bubbles in water has either positive or negative consequences. Therefore, the study of biphasic flow in pumping installation could reveal important aspects regarding the fluid/solid interaction.

2. THEORETICAL CONSIDERATION UPON THE EFFECTS OF AIR ENTRAINED BY WATER IN A PUMPING INSTALLATION

2.1. CELERITY REDUCTION

The speed of propagation of pressure wave in a water pipeline depends both by water compressibility and pipe wall elasticity. The relation (1) stands for celerity in a single liquid phase.

$$c_0 = \left(\frac{E_l}{\rho_l}\right)^{1/2}\left(1+\frac{E_l}{E_c}\frac{D}{e}k\right)^{-1/2} \tag{1}$$

where ρ_l -water density, $\left[{}^{kg}/_{m^3}\right]$; E_l -modulus of elasticity of water, $\left[{}^{N}/_{m^2}\right]$;

E_c -modulus of elasticity of the pipe wall, $\left[{}^{N}/_{m^2}\right]$; e-pipe-wall thickness, $[m]$;

D-pipe’s diameter, $[m]$; k-coefficient depending on the pipe’s type of pose.

This velocity may be considerably reduced if a small amount of air bubbles is entrained by the liquid. If the volume fraction of air rises up to 5%, the celerity decreases to a value less than the speed of sound in still air. There have been developed many studies that showed a good agreement between theory and experiment. Relation (2) is recommended for celerity calculus in air –water biphasic mixtures [2].

$$c_\alpha = \left(\frac{E_l}{\rho_l}\right)^{1/2}\left[\left(1-\frac{m_\alpha RT}{p}\right)\cdot\left(1+\frac{m_\alpha RT}{p^2}\cdot E_l+\frac{E_l}{E_o}\frac{D}{e}k\right)\right]^{-1/2} \tag{2}$$

where R -air constant, $\left[{}^{J}/_{(kg\cdot K)}\right]$; T -absolute temperature, $[K]$;

p -absolute pressure, $\left[{}^{N}/_{m^2}\right]$; m_α -air mass on biphasic unit volume, $\left[{}^{kg}/_{m^3}\right]$;

g-gravitational acceleration, $g = 9{,}81\,{}^{m}/_{s^2}$

Assuming the air mass on biphasic unit volume to be constant, that means the air dissolution and liberation are neglected, the term $\frac{m_\alpha RT}{p^2}\cdot E_l$ has an important weight on celerity at small pressures. This term may be negligible at pressures exceeding 40 bar [2].
We may conclude that air, in small amounts, deliberately or accidentally introduced in water, offers a good way to protect the duct from the extreme values of pressure, which occur during water hammer.

2.2. INCREASE OF TURBULENCE

In the discharge duct of a pumping installation, the Reynolds number reaches high values, so that the flow is fully turbulent. The main equations governing the flow are momentum transport equation and mass conservation equation, written for mean velocity values.
The use of Reynolds-averaged Navier-Stokes equations introduces a new term, the Reynolds stress tensor that depicts the interaction between the fluctuating velocities [3].
The most proper model for the turbulent flow of the biphasic fluid was considered to be the non homogenous model. The gas velocity differs from the liquid velocity, as showed in the relation (7). Therefore the bubbles movement results in additional turbulence. The term S in the relation (8) stands for this source of turbulence.
The two phases are subjected to the same pressure field and their volume fractions calculated at normal pressure are related by:

$$\alpha_l = 1-\alpha_g \tag{3}$$

The mathematic model includes the following equations:
The momentum equation for the biphasic fluid:

$$\alpha_l\rho_l\frac{\partial u_l}{\partial t}+\alpha_l\rho_l u_l\cdot\nabla u_l = -\nabla \mathrm{p}+\nabla\cdot\left[\alpha_l(\eta_l+\eta_T)\left(\nabla u_l+\nabla u_l{}^T-\frac{2}{3}(\nabla\cdot u_l)I\right)\right]+\alpha_l\rho_l g \tag{4}$$

where η_l-dynamic viscosity of water, [Pa*s]; η_T-turbulent viscosity, [Pa*s]; $\eta_T = \rho_l C_\mu\frac{k^2}{\varepsilon}$;

α_l-volume fraction of water, $\left|{}^{m^3}/_{m^3}\right|$.

The continuity equation for low fraction of gas:

$$\nabla u_l = 0 \tag{5}$$

Transport equation for the fraction of gas:

$$\frac{\partial \rho_g \alpha_g}{\partial t} + \nabla\left(\alpha_g \rho_g u_g\right) = 0 \tag{6}$$

The right member of this relation is zero because we've assumed there is no change of mass between the two phases.

Gas velocity is given by the relationship:

$$u_g = u_l + u_s \tag{7}$$

u_s-relative velocity. This velocity can be calculated assuming the balance between viscous drag forces and pressure forces on the bubbles.
Two more transport equations are added to this model [5]: one for turbulent kinetic energy, k, and one for dissipation rate, ε. Both equations have *S* as a turbulence source term:

$$S = -C_k \alpha_g \nabla p \cdot u_s \tag{8}$$

The mathematic model presented above allows the calculation of the velocity, pressure, air volume fraction and turbulence field in a hydraulic system in which the continuous phase is water and the dispersed one is free air. On this basis, the drift and lift forces acting on a mechanical component may be calculated. The presence of air modifies the flow parameters registered in one phase flow, thus the interaction fluid/solid is altered.

2.3. HYDRAULIC RESISTANCE VARIATION DUE TO THE AIR PRESENT IN WATER

The operating point of a pumping installation is graphically represented by the intersection of the pump characteristic curve and the pipeline characteristic one. In one phase flow, instability of the operation point may occur due to a non-monotonic pump characteristic. Two-phase flows can exhibit a range of similar instabilities. Usually, the instability is the result of a non-monotonic pipeline characteristic rather than a complex pump characteristic. At high Reynolds numbers the frictional losses are proportional to the square of the mass flow rate, thus the pressure drop on a mechanical component will be $\Delta p \sim \dot{m}^2$. It results that the pressure drop will increase in biphasic flow, due to the decreased density of the mixture [1]. Considering a hydraulic resistance for each mechanical component:

$$R_i = \frac{\Delta p_i}{\dot{m}} \tag{9}$$

the entire equivalent resistance of the pipeline may be determined, according to the configuration of the system. The pipeline characteristic curve may be modified by the presence of air in water. Therefore, instability could occur if the pipeline characteristic were non-monotonic. It is useful to determine by numeric simulation the behaviour of each mechanical component when air is entrained by the pumped water.

3. BIPHASIC FLOW THROUGH A PUMPING DISCHARGE DUCT. CASE STUDY

A specific case was studied by numeric simulation, aiming to reveal the advantages and the disadvantages induced by the biphasic air-water flow in a pumping installation. The operating point for a 12NDS pump, in open circuit, is given by the discharge Q and head *H*:

$Q = 0{,}106\ m^3/s$

$H = 14\ m$

The discharge duct Dn300 mm is horizontal and equipped with a check valve of butterfly type.

There were conducted two separate numerical simulations in order to determine the difference between the single water flow and the biphasic air-water flow. The first simulation was regarding the extreme values of pressure during the hydraulic shock. The second aimed to reveal the modification of pressure drop on the valve and of the hydrodynamic forces acting on the obturator of the valve.

3.1. RESULTS REGARDING EXTREME VALUES OF PRESSURE DURING WATER HAMMER

The extreme values of pressure in the pipeline during the hydraulic shock were calculated first in the case of a single phase flow and than in the case of a biphasic one, with the volume fraction of free air in the range of 0,5-10%. Simulation was carried out using a special computer program designed to solve the hydraulic shock equations by the method of characteristics. It was considered the case of power failure.

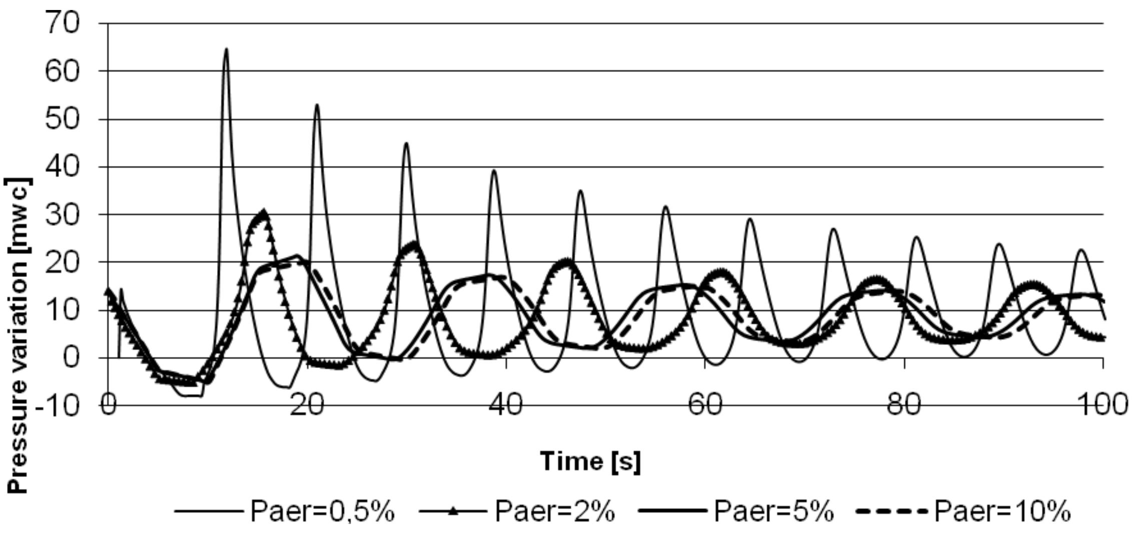

Fig.1 Pressure variation in the pipeline during hydraulic shock, considering increasing volume fraction of air in water

The extreme pressure values obtained in the case of no protection are $p_{max} = 130\ mwc$ and $p_{min} = -10\ mwc$. The results for the pressure variation in the presence of small amounts of free air are represented in fig.1. It may be noticed that the maximum value of pressure decreased to 20 mwc in the presence of 10% air. Further more, the minimum value increased to -5 mwc This attenuation of the extreme values is a result of decreased celerity.

3.2. RESULTS REGARDING PRESSURE DROP AND MODIFICATION OF LIFT AND DRAG FORCES IN THE CHECK VALVE

The geometry of the valve was simplified, as may be seen in fig.2. The flow characteristics were determined in a longitudinal section of duct of 2,2 m in length. There are compared two cases of flow: a turbulent steady flow and a turbulent steady flow with turbulence induced by the air bubbles. In fig.2 it may be seen the turbulence field in the case with added turbulence induced by bubbles. The maximum value of turbulence increased two times.

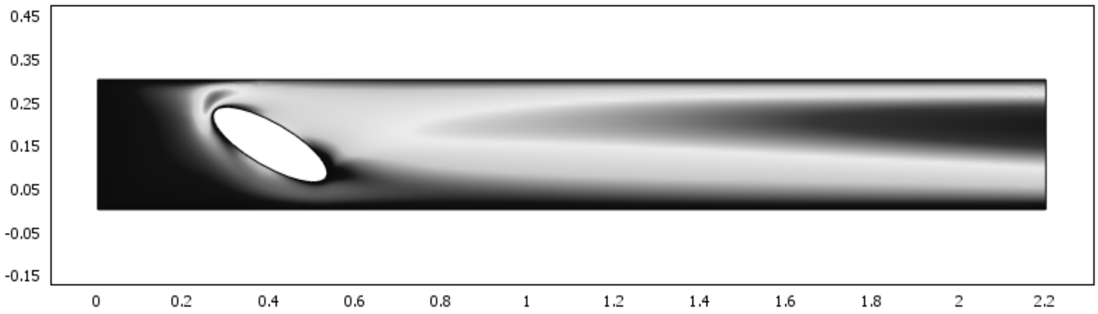

Fig.2. Turbulent viscosity field in a horizontal pipeline equipped with butterfly type valve, considering the turbulence induced by the bubbles. The maximum value is 2,46 Pa.s, approximately two times greater than in the case of neglecting the bubbles. The dimensions on the diagram are in [m].

The pressure drop on the check valve also increased. In fig.3 it may be noticed that the pressure drop remains almost constant with the increasing volume fraction of free air, in a homogenous turbulent flow, but when the bubble movement is taken into account, the pressure drop rises as the volume fraction of gas is greater.

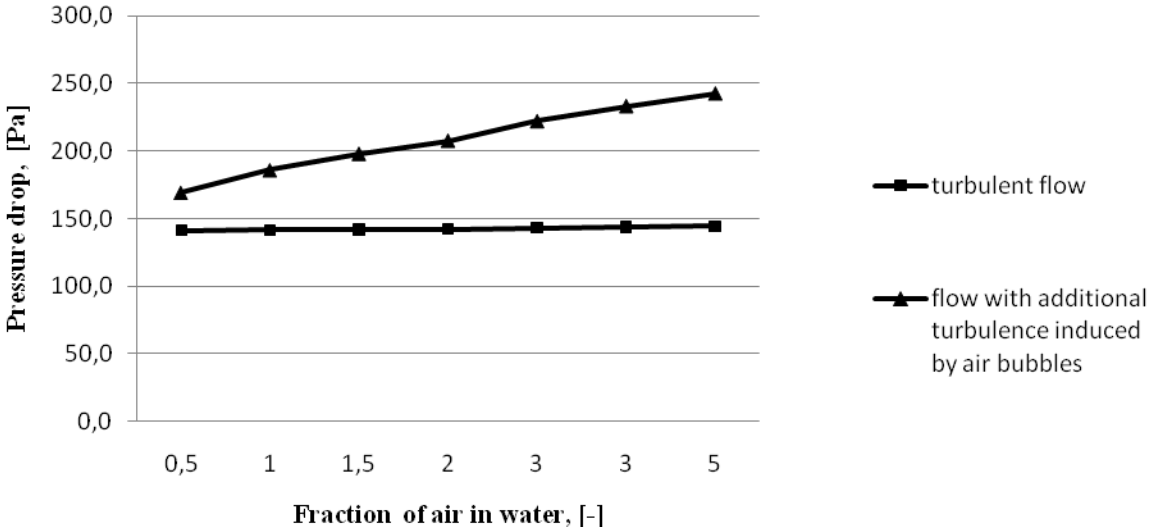

Fig.3.Pressure drop as a function of air volume fraction

The two components of the hydrodynamic force, the lift and the drag forces, also vary when free air is present in water. Their variation was calculated taking in consideration the reduced values, that means each value of force was divided by the correspondent value for single liquid phase flow, in the same conditions. The reduced drag force has the same allure as the pressure drop. It increases faster with the volume fraction of gas; in the case the bubble induced turbulence is considered.

The reduced lift force, represented in fig.4, is decreasing with the increasing α_g, in the case of simple turbulent flow. But when the turbulence induced by the bubbles is considered, the lift force has a parabolic variation, with a minimum at $\alpha_g = 2\%$. That means the model of flow must be careful chosen in the case of biphasic fluid. The lift force variation may result in oscillation of the obturator that means a source of flow perturbation in the pumping installation. Consequently, the flow rate varies according to the change in position of the obturator and instability may occur in installation.

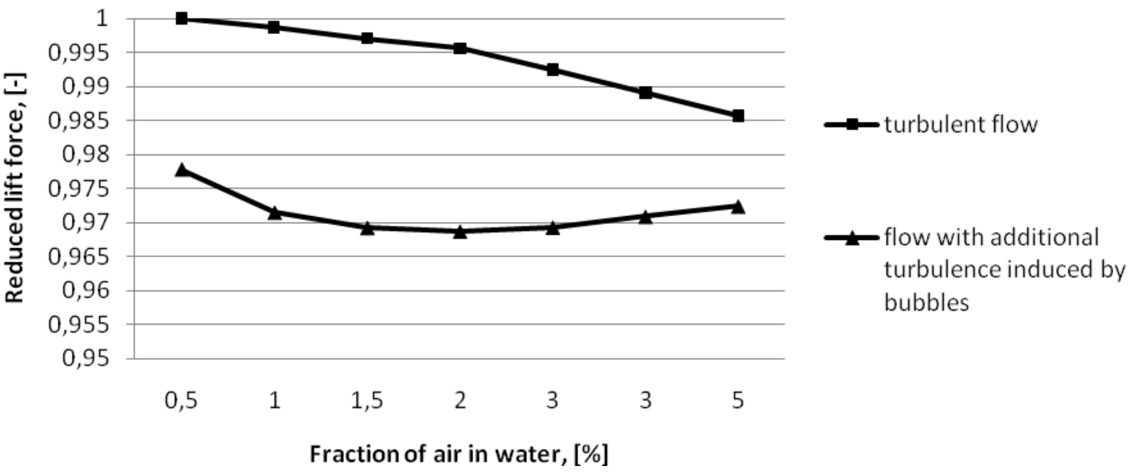

Fig.4.Reduced lift force acting on the valve obturator, as a function of air volume fraction

4. CONCLUSIONS

The biphasic flow parameters for a pumping discharge duct were studied by numerical simulation, at different values of the volume fraction of air, in a range of 0,5-5%.

The presence of small amounts of free air in water results in a greater elasticity of the fluid and the celerity decreases to values for which the extreme pressures, during the hydraulic shock, aren't a threat of damage for the pumping installation. This is an important and apparently cheap means of protection. But we consider that it might be efficient only in closed pumping circuit, otherwise the air must be continuously supplied into the pipeline.

In the case of accidentally entrainment of air, the volume fraction of free air is impossible to control. So, the parameters of biphasic flow differ from the case of a single liquid flow case. Considering the normal operation case, the pressure drop on each mechanical component increases which results in an increased hydraulic resistance, at the same mass flow rate. The pipeline characteristic curve may become non monotonic.

The presence of air bubbles determines fluctuation of the lift force acting on the rotational mechanical components, thus instability may occur when the volume fraction of gas increases.

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