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AIR POCKETS IN PIPELINE SYSTEMS

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Curgerile mixte apă-aer în sisteme sub presiune pot să apară în conductele şi galeriile amenajărilor hidrotehnice (centrale hidroelectrice, staţii de pompare, sisteme de colectare a apelor pluviale etc.) provocând variaţii de presiune care au uneori urmări catastrofale. La centralele hidroelectrice acumularea unor cantităţi mari de aer se poate produce prin conductele captărilor secundare, galerii de aducţiune, castele de echilibru, conducte forţate etc. În staţiile de pompare curgerea bifazică apare la sifoanele utilizate pentru prevenirea curgerii inverse din bieful superior. Lucrarea îşi propune să urmărească influenţa prezenţei pungilor de aer din sistemele de conducte sub presiune, asupra presiunii din întregul sistem.

Mixed flows or two phase flows (air-water) in pressurized systems can arise in pipe systems of hydroelectric schemes and pumping stations, causing fluctuations in pressure which sometimes can do significant damage. In hydropower plants, the air entrainment can take place at the inflow location such as drop chamber, inlet or intake or because of mass oscillation between the reservoir and conduit system. Siphon outlets of pump discharge channels are frequently used at pumping station for the prevention of backflow from upstream. For effective operation it is necessary to evacuate air downstream from siphon. The purpose of the paper is to study the influence of air pockets trapped in pipeline systems over the entire system pressure.

Key words: two phase-flow, air pocket, transient flow, pipeline system.

1. Introduction

The presence of air in pipeline systems can result in problems such as loss of carrying capacity, disruption of the flow, reduced pump and turbine efficiency, effects on pipe materials and pipeline structure; it can also change the fluid properties and create environmental concerns at the point of discharge, as fallows:

- air pockets reduce the effective pipe cross section, which results in a reduction in pipe hydraulic capacity;
- the bulk properties of the fluid (a mixture of air and water) are changed; this concerns mainly the density and the elasticity.
- the presence of air changes the structure of flow turbulence and possibly the wall shear as well;

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- air bubbles introduce vertical momentum into the flow due to their buoyancy and may thus have significant effects on the flow field;
- in hydraulic transients, the presence of large air pockets results in pressure waves that are strongly damped and deformed. However, it has also been found that small accumulations of air may have an adverse effect on pressure transients, actually enhancing the surge pressures experienced;
- air accumulation in a system may lead to disruption of the flow and such effects as blow-out or blow-back. For instance, air entrained at a hydraulic jump may not be able to move downstream with the flow and instead 'blow back' through the jump. This can lead to vibration and structural damage and can cause instabilities of the water surface;
- the presence of air can reduce pump and turbine efficiency. When air-mixed water is fed into a turbine there is a drop in output and efficiency is reduced. It can also cause waterhammer pressures. Admission of air to a pump can cause a loss of priming;
- in ferrous pipelines the presence of air enhances corrosion by making more oxygen available for the process;
- sealing, a transition from part-full to pipe full flow, can cause vibrations of the structure and surging of the flow can accompany it;
- air can produce false readings on measuring devices;
- cooling water systems have additives in the water for anticorrosion and this increases foaming of the water.

In order to measure, to control or to dispose the air that is found in pipelines, it is important to understand the various ways in which air can enter a pipe system:

- entrainment at the inflow location such as a drop chamber, inlet or intake;
- entrainment at the outflow location – for instance, sea outfalls may operate under varying tidal levels and the outlet may be located above the sea level;
- entrainment due to vortices at inlet or intake;
- turbulence in shafts;
- hydraulic jump – the flow within a pipe system may change from gravity to surcharged flow and under these conditions a hydraulic jump may form;
- direct pumping – direct pumping of air into a system may be carried out to reduce cavitation pressure;
- pumps – there may be insufficient submergence on the pump or vortices may form at the inlet causing air to be entrained into the system;
- lines filling or emptying – air transport can occur during filling and emptying of pipelines. The air movement along the pipeline can be slow during filling and can become trapped at high points in the system;
- gas formation through biological activity;
- at sections under negative pressure air can leak in at joints and fittings;

- negative pressures at the inlet to the pipe.

2. Background

Two phase flow with large air pockets is present in pipes of hydropower plants, pumping stations or sewer systems, causing many unpleasant situations and accidents during operation. For example:

- the headrace from Raul Mare, where, because of secondary intakes (Netiş and Bodu), air is aspired along with water, which lead to apparition of air pockets that flow gravitationally upstream or forced downstream. Penetration of these air pockets could lead to serious failures, as it happened in 1998, when the vane chamber has been damaged because the violent increase of pressure when a very large air pocket was released [1];
- siphons on the large discharge pipes from pumping stations, which block the backward flowing of water and draining of downstream basin, are fitted with air valves. Faulty operation of this valves can lead to formation of air pockets, or can allow flows with free surface which decrease pump efficiency [2];
- apparition of air pockets in sewer systems because of rapid water filling (in case of high intensity precipitations, above the designed values of the pipeline systems). High pressure variation provoked by appearance and releasing of air pockets can cause major damages in pipes, like the incidents from Minneapolis, Minnesota State, USA [3] and from Edmonton, Alberta, Canada [4].

Therefore, to avoid these problems it is important to block the entrapment of air and the movement of the air pockets through the system with high velocity. If this is not possible, the air pockets have to be taken out of the system. Considerable costs incur in providing air release valves and chambers, and in deepening pipe trenches so as to provide the minimum gradients thought necessary to enable air bubbles and pockets to move towards the valves. If the accumulated air can be moved hydraulically out of the pipe system, then potentially large cost savings are possible. At present there are a number of often contradictory recommendations for assessing how air may be moved through a pipe system.

3. Governing equations

The change in the volume of an air pocket inside a control volume, within the horizontal pipe where U is flow velocity can be written as

$$\frac{dV_a}{dt} = -AU, \qquad (1)$$

where V_a is the air pocket volume, A is the cross-sectional area of the pipe, and t is time.

The momentum equation of the water column is

$$\frac{dU}{dt} = -g\frac{H - H_0}{x} - \lambda\frac{U|U|}{2D} - \frac{U^2}{2x}, \tag{2}$$

where H is the air pressure head, λ is the wall friction factor, x is the length of the water column and g is the gravitational acceleration (9,81 m/s^2).

The governing equation for the air phase is [7]

$$\frac{dH^*}{dt} = -k\frac{H^*}{V_a}\frac{dV_a}{dt} = k\frac{H^*}{V_a}Q_a, \tag{3}$$

where Q_a is the air discharge out of the orifice, H^*, is the absolute air pocket pressure head and k is the polytropic exponent.

From the investigations over the impact of varying the polytropic exponent, k, (from 1.0 to 1.4) for adiabatic air pressure oscillation in an air chamber [8] was found that k = 1.4 gave the best fit to the experimental data (the asterisk denotes the absolute pressure head).

The air discharge, Q_a, can be expressed by

$$Q_a = \mu A_0 Y\sqrt{2g\frac{\rho}{\rho_a}(H^* - H_b^*)} = \mu A_0 Y\sqrt{2g\frac{\rho}{\rho_{a0}}\frac{\rho_{a0}}{\rho_a}(H^* - H_b^*)}, \tag{4}$$

where H^*_b is the absolute initial air pocket pressure head, μ is the discharge coefficient, which can be taken from conventional hydraulic tables for compressible flows through orifices and nozzles.

The expansion factor, Y, can be expressed as [7]

$$Y = \sqrt{\frac{k}{k-1}\left(\frac{H_b^*}{H^*}\right)^{2/k}\frac{1-(H_b^*/H^*)^{(k-1)/k}}{1-H_b^*/H^*}}. \tag{5}$$

If H^*/H^*_b, is greater than 1.89, the orifice is choked and the discharge can be calculated by

$$Q_a = \mu A_0\sqrt{g\frac{\rho}{\rho_a}H^*}\sqrt{k\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}. \tag{6}$$

When the water column reaches the end of the pipe, the impact pressure of the water column can be calculated by

$$H_2 = H_1 + \frac{a}{g}\left(U_1 + \frac{a}{B} - \sqrt{\left(\frac{a}{B}\right)^2 + 2U_1\frac{a}{B} + \frac{2gH_1}{B}}\right) \tag{7}$$

where a is the velocity of the pressure wave when the water column reaches the orifice.

The coefficient B is defined as

$$B = \left(\frac{A}{A_0} \right)^2 + \zeta - 1 \tag{8}$$

where ζ is the minor loss coefficient of the orifice which can be neglected since it is very small compared with A/A_0. U_1 and H_1, are, respectively, the velocity and pressure head at downstream section.

When applying equation (7), care must be taken in determining the appropriate value of pressure wave speed, since it is quite sensitive to the air content in the flow. For example, the wave speed in a pipeline containing water with 5% air content is only 20% of that without air [9]. Since the air entrained in the water column during the filling process is difficult to determine, the wave speed cannot be theoretically calculated. Therefore, a measured value of wave speed is needed to apply equation (7). Consequently, this analytical model is not a predictive tool but rather, provides a means of exploring and explaining the behavior of this phenomenon [4].

4. The influence of air pockets on transient flow in a rapidly filling horizontal pipeline

The observations from the physical experiments of a rapidly filling horizontal pipe [5] which was initially dry confirmed that air trapped in a rapidly filling pipe can induce high peak pressures, especially when air leakage occurs.

The experiments revealed that there are three types of pressure oscillation patterns in a rapidly filling horizontal pipe, depending on the relative size of the leakage orifice.

When no air is released or orifice sizes are small, the cushioning effects of the air pocket prevent the water column from impacting on the pipe end and, from generating high waterhammer pressures. However, the maximum pressure experienced may still be up to four times the upstream driving pressure. In this case, the pressure oscillation pattern has a long period, and the peak pressure remains relatively constant for a given initial air volume and upstream driving head.

When the orifice size is very large, the air cushioning effect vanishes and the water column can easily impact on the pipe end, inducing a waterhammer impact pressure. In this case, the maximum pressure decreases with increasing orifice size, since for the larger orifice sizes, water escapes and mitigates the waterhammer effect.

For intermediate orifice sizes, the pressure oscillation pattern consists of both long period pressure oscillations (while the air pocket persists) followed by short period pressure oscillations (once waterhammer dominates). In this case, the maximum observed pressures increase rapidly with increasing orifice size, since the cushioning effect of the air pocket decreases as the air release rate increases. The highest maximum pressures (up to fifteen times that of the upstream head) were observed at the upper limit of this intermediate region, which occurred at a fairly consistent orifice size.

If the pipe end is sealed or the orifice size is small, the water column contains a negligible amount of entrained air and approaches the pipe end along the bottom. The air trapped on top of the water acts as a shock absorber; therefore, the overall pressure oscillation pattern has a long period. If the orifice is large, the water column is highly air entrained and the water front is steep. In this case, the air release is significant and there is no visible air pocket trapped on top of the flow by the time that the water column reaches the pipe end. Without the trapped air pocket, the air cushioning effect vanishes and the water column can easily slam into the pipe end and induce a sharp and short period waterhammer pressure.

If the orifice is not large enough to allow for a significant air release, the water front contains a moderate amount of air and is steeper than that observed in the small air release case. After the water reaches the pipe end, some air is still trapped within the flow as bubbles or pockets whose random behaviors cause the pressure oscillation to have a long period, irregular pattern. When the last air pocket is released, the sharp and short period water impact pressure dominated, although the peak magnitude was mitigated by the earlier air cushioning effect.

In case of rapidly filling horizontal pipe which is partially full, for small air release situations, the maximum pressure magnitudes increase with the tailwater depth because the initial air volume is reduced. If the orifice is large, the tailwater is disturbed especially when the initial water column length is short; therefore air pockets are trapped and the orifice may be choked, resulting a lower water impact pressure on the pipe end.

The L-pipe system does not qualitatively alter the pressure oscillation pattern and maximum peak pressure magnitude and the gravity effect on reducing the pressure is obvious only when the initial water column is long and the air release from the vertical pipe is substantial [5]. The T-pipe configuration was shown to be able to mitigate the pressure surge during rapid filling, and was found to be especially effective in reducing the impact pressure when the air release was large.

The experimental results [4] suggest that the pressure peaks due to trapped air pocket compression and release are certainly high, enough to blow off manhole covers and explain sewer ruptures. For most manhole covers, the air leakage is negligible ($d/D \approx 0.002$). So, based on the observed results, a conservative estimate of the peak pressure (3 times the upstream head) would be 400 to 500 kPa. This is at least one order of magnitude greater than the structural loads that typical urban sewer systems are designed for.

4. Air pockets movement in sloping pipelines

Laboratory tests and numerical studies in which the air moved downward sloping pipes in the range of 0 to 22.5 degrees (0 to 1/24), concluded [6]:

- air moves freely upward sloping pipes under its own buoyancy with no flow. The velocities of air pockets in upwards sloping pipes are similar to the air pocket velocities observed in downward sloping pipes;
- air spreads widely along horizontal pipes with no flow;
- a critical velocity is required to move air pockets along horizontal and downward sloping pipes.

The equation for estimation of critical flow velocity for air pocket movement obtained from experimental shows the dependency of the critical flow velocity on the slope and air pocket size (and implicitly on the pipe diameter too) [6]. This equation was developed based on a range of air pocket sizes and the maximum values of critical velocity associated with each of the air pocket classes used. For engineering applications is advisable the application of a safety factor, S_f (for which in principle is suggested a value of 1.1).

$$\frac{v}{\sqrt{gD}} = S_f\left(0.56\sqrt{\sin S} + c\right) \tag{9}$$

where c equals: 0.45 for n < 0.06
0.50 for 0.06 ≤ n < 0.12
0.57 for 0.12 ≤ n < 0.30
0.61 for 0.30≤ n < 2

and v is the minimum flow velocity required for movement of an air pocket with size defined by the parameter n in a downward pipe of slope S and diameter D.

$$n = \frac{4V_a}{\pi D^3} \tag{10}$$

where V_a is the volume of the air pocket.

The applicability of this equation is as follows:

- downward slopes from 0 to 22.5 degrees (1/2.4). From other experimental researches is proven that the relation can be valid for slopes up to 40 degrees (1/1.19) and that beyond this slope the critical flow velocity may start decreasing with the slope in a power law relationship;
- air pockets with volume of 0.0005 liters to 5 liters, in a 150 mm diameter pipe. For larger air pockets the required critical velocity for pocket movement may not increase significantly (for pocket sizes above 5 liters being reasonable a value for c = 0.61);
- pipe diameter of 150 mm. But considering previous researches, the scale effects can be neglected due surface tension, and the results can be extended to larger pipe diameters.

Tests with hydraulic jumps in downward circular pipes suggested that the rate of air expulsion may be given by

$$\frac{Q_a}{Q} = 0.0025(Fr-1)^{1.8}, \qquad (11)$$

where Q_a is the air discharge, Q is the water flow, and Fr is Froude number. Other factors that strongly influence the rate are the actual flow conditions and cross-sectional shape of the pipe.

Also, is shown that for the same pipe diameter, the velocity of air pockets movement down the pipe is highly dependent on the pipe slope: the steeper the slope, the smaller the ratio air pocket velocity/critical flow velocity becomes. The time required to remove an air pocket in a steeper pipe can be several times greater than in a mild slope.

In upward slopes, even in very mild slopes (less than 2 degrees) air pockets would move for static conditions, thus not requiring a threshold velocity.

The presence of air pockets have been shown, in certain circumstances to cause both high and low pressure fluctuations which are sufficiently large to potentially cause pipe fracture and pipe failure. This therefore highlights a need for consideration of the transient wave interaction with entrapped air pockets during design stage.

A larger pocket of air has the potential to act as an energy accumulator, which absorbs the transient pressures in a piped system.

A small pocket of air has the potential to severely exacerbate maximum peak pressures.

Experimental results have highlighted that a small or large air pocket can be defined in terms of its effect upon pressure transients, but there are limits upon size/volume, outside of which, these effects do not occur. This therefore suggests that a critical spectrum of air pocket volume exists for a particular pipeline configuration and additionally, a further critical size is relative to the actual location of the air pocket within the pipeline.

Greater pressure enhancement occurs when small pockets of air are placed towards the upstream section of the pipeline. Larger pockets of air can also enhance pressures when located downstream locations, depending on pipeline configuration.

5. Conclusion

There are many ways to reduce or to control large pressure transients in pipeline systems. It is known from modeling and experimental studies that the air-induced pressure is severe only when all of the following conditions are satisfied:

- the filling is rapid or the flow backup is intensive and fast;
- the air is able to be trapped;

- there are exits for air release and the size of the exits are intermediate.

Based on these conditions, the following measures are recommended:

- *to reduce the risk of flow backup and rapid filling*, the inflow rate should be reduced by appropriate inlet controls. The dimensions of sewer pipes should be enlarged if economically possible. In-line and off-line storage devices should be constructed. Adequate standby power and sump storage for pumped systems should be provided. The design of interceptors and drop-inlets should consider energy dissipation. The systems should be well maintained to prevent clogging;
- *to reduce the entrapment in pipelines***,** air vents should be placed in the crown of conduits to release the air moving along the crown of the conduit. The variation of pipe section should be smoothly transited, and the changes in section areas should not be large (i.e. the difference of pipe sizes of the adjacent segments should not be too big).

To reduce the air release pressure, a surge tank or air chamber should be upstream of the surge location. The size of the air release valve should be carefully determined to avoid high impact pressure.

From the planning and design points of view, great attention should be paid to the locations where the air-related pressure surges are likely to occur since air entrapment and air release are local events. Usually the downstream end of the sewer system or dead ends formed by the sewer stubs should be carefully planned and designed since these are the areas in which surge-events are likely. Appropriate junction design in these areas is significant in reducing pressure surges.

With respect to the concern of system response to air pressure transients, drainage sewer systems should be designed in such a manner that small disturbances in one reach will not be amplified upon entering a succeeding reach. The natural periods of adjoining reaches must be sufficiently different from each other.

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