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MECHANICS

Water-column mass losses during the emptying of a large-scale pipeline by pressurized air

Janek Laanearu[a*], Qingzhi Hou[b], Ivar Annus[a], and Arris S. Tijsseling[c]

[a] Department of Mechanics, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia
[b] School of Computer Science and Technology, and State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, 300072 Tianjin, China
[c] Department of Mathematics and Computer Science, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

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Abstract. In many industrial applications the liquid trapped inside long pipelines can cause a number of problems. Intrusion of the pressurized air on top of the water column inside the horizontal pipeline can result in a less or more mixed stratified flow. The dynamics of a moving air–water front during the emptying of a PVC pipeline with the diameter-to-length ratio 1 : 1100 were experimentally and theoretically studied. In the experiments, the water was driven out of the pipeline with an initial upstream air pressure of 2 barg and a 4.5 m high downstream-end siphon, where the water outflow was restricted by a valve that was closed 11%. The measured discharges and water-level variations are analysed together with Control Volume modelling results. During the 'forced' (not only gravity-driven) emptying process, both the downstream-end drainage and *tail leakage* behind the moving air–water front decreased over the full water-column length. The water-column mass loss due to the *tail leakage* is referred to as *holdup*. The Zukoski dimensionless number is used to parameterize the relative shortening of the water column associated with the unidirectional movement of the air–water front along the large-scale horizontal test section of the pipeline, where surface-tension effects and minor losses at joints and turns are negligible.

Key words: pipeline, air–water interactions, two-phase flow, unsteady flow, Reynolds number, Froude number, Zukoski number.

INTRODUCTION

Two-phase unsteady flow in a pipe where the liquid flows along the bottom and the gas flows above it can reveal different dynamics and flow patterns due to instability and mixing. In the case of free-surface stratified flow, no mixing between the liquid and the gas occurs, and the flow has open-channel like dynamics. In the case of mixed stratified flow the fluids (e.g. water and air) are mixed, and the flow reveals dynamic effects due to compressibility. Simultaneous occurrence of free surface and mixed stratified flow conditions appears often in gravity-driven-flow pipelines, but most design criteria do not consider the causes of air entrainment (Pozos et al., 2010). Two-phase flow is also present in various pressurized flow hydraulic applications, such as water-distribution networks, fire-fighting systems, and in pipeline cleaning and priming. In water-distribution networks, air enters into the pipeline system from different sources. Air release/vacuum valves or open standpipes can introduce air into the system when the hydraulic grade line (HGL) drops below the pipeline elevation. Also, water in industrial applications contains dissolved air (about 2% at room temperature and atmospheric pressure) and at high points of the undulating pipeline profile where the HGL falls below the pipeline elevation, the dissolved air is released from the water. Water systems maintenance procedures require certain operations that involve the emptying of pipelines. When the gravity-driven flow is too slow or where it is not

* Corresponding author, janek.laanearu@ttu.ee

possible to empty the pipe due to the pipeline elevation profile, water is expelled from the system by pressurized air. In oil pipelines the emptying operation for the removal of the liquid products requires injection of an inert gas like nitrogen (Martinoia et al., 2012).

The filling and emptying procedures require careful attention in order to prevent air pocket formation. When the moving water column is suddenly stopped, pressure surges result (Bergant et al., 2010, 2011; Martin and Lee, 2012), which can cause various types of damage to the system. In the case of a pipe under static pressure in which a valve is suddenly opened, a depression wave propagates into the system (Collins et al., 2012). Local and distributed cavitation can occur in a pipeline when the liquid pressure drops to the level of the vapour pressure (Bergant and Simpson, 1999; Bergant et al., 2006).

Detailed experimental investigations of the two-phase unsteady flow in an industrial-scale pipeline were carried out in Delft, The Netherlands, during 2009, within the EC Hydralab III project. This project provided access to a range of large-scale experimental facilities available in European countries. The test rig consisted of a nominal 250 mm diameter and 275 m long PVC pipeline with an upstream pipe bridge, elevated 1.3 m above the horizontal pipeline axis, and a downstream steel pipe siphon of 4.5 m height. The water tower with a constant head of 25 m was used to supply water in the filling experiments and the high-pressure air tank of 70 m^3 volume was used to supply air in the emptying experiments (Laanearu and van ’t Westende, 2010). A depression wave propagated in the system after opening the downstream-end valve for emptying the pipeline (Laanearu et al., 2012). Fast transients deliberately generated in the system were investigated separately from the principal pipeline filling and emptying experiments (Bergant et al., 2011). For this specific purpose a bypass valve was installed at the downstream end of the siphon, 1 m above the ground floor. To complete hydraulic characterization of the pipeline, steady-state flow measurements were performed before the principal filling and emptying experiments took place.

The pipeline apparatus and its hydraulic characteristics are briefly introduced in the present study. The shortening Control Volume (CV) model based on the mass conservation principle is then used to establish the relationship between the velocities of air–water fronts moving rectilinearly along the horizontal pipeline. The water-column mass loss due to the *tail-leakage* effect is taken into account in the formulae with a *holdup* coefficient, which represents the cross-sectional area in the pipe occupied by the air. Measured flow rates and water levels, which characterize well the transition from full-pipe-diameter flow to stratified flow (free-surface flow) during the emptying process, are used to estimate the velocity of the leading air–water front, representing the last fully filled cross-section of the water column. Experimental results are compared with CV model predictions by Laanearu et al. (2012). A new parameterization (based on the Zukoski dimensionless number) of the air–water interactions (two-phase unsteady flow) for the pipeline emptying process is proposed.

PIPELINE APPARATUS

Prior to the emptying experiments the pipeline was filled with water from a supply tower, using valves V0 and V2 (Fig. 1). During the pipeline filling, air at atmospheric pressure initially present in the system was replaced with water by keeping the downstream valves V4 and V5 completely open. Then the water-column motion was gradually brought to rest by simultaneously restricting the outflow using valve V4 and reducing the inflow into the pipeline using valve V2. The static water column was pressurized from the air tank by opening valves V1 and V3. Check valve V6 was used to prevent any water coming into the pressurized air system. The upstream air in the tank was set to 2 bar gauge (barg). The siphoned outflow restriction condition was set by closing 11% (position 10°/90°) of valve V4. The emptying process was started by a rapid (~0.1 s) opening of valve V5 (Fig. 1).

The PVC pipeline itself was constructed of six straight sections I–VI (see pipeline layout in Fig. 2). The pipeline included a 8.75 m long vertical-plane pipe bridge and a 6.45 m long horizontal-plane 180° turn. Ten measurement sections (MS) were placed along the PVC pipeline (Fig. 2). Three transparent sections (2, 4, and 10) were present, and 19 instruments were installed at seven measurement sections (1, 3, 5, 6, 7, 8, and 9). The bolted connection joint between the downstream end of the pipe bridge and the upstream end of the

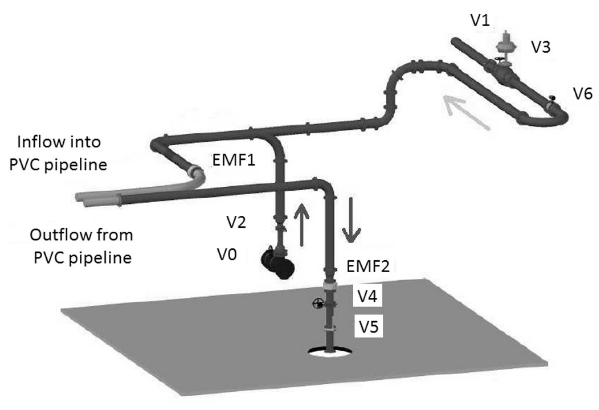

Fig. 1. Valves (V0–V6) at the system’s steel-pipe extensions and water flow meters (EMF1 and EMF2). Flow directions are indicated by arrows.

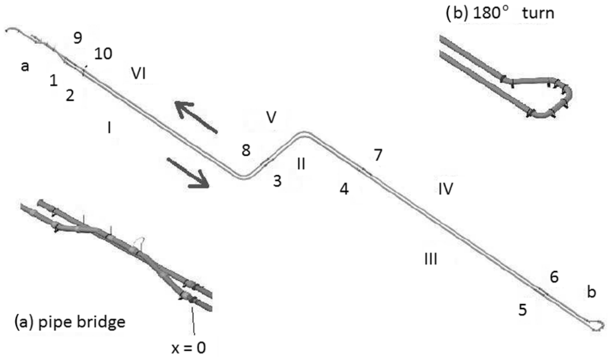

Fig. 2. PVC pipeline. I–VI – Straight sections (I 39.9 m, II 11.9 m, III 66.6 m, IV 66.4 m, V 12.1 m, and VI 48.6 m). Vertical plane pipe bridge (a) and horizontal plane 180° turn (b) are shown separately. Measurement sections (i.e. transparent and instrumental sections together) are indicated by numbers 1–10.

first straight section (I) was defined as the axial coordinate system reference point $x = 0$, with positive direction toward the outlet.

The 100 Hz sampling-frequency recordings of pressure, water level, void fraction, and temperature were performed along the pipeline during the two-phase unsteady flow measurements. Three transparent sections (MS2, MS4, and MS10) with $x = (3.2, 4.0)$ m, $(68.0, 68.7)$ m, and $(249.2, 249.9)$ m, respectively, were used to visualize the flow processes. Two-phase flow was recorded by a Sony DXC-990P camera with the frame rate of 25 fps. Two electromagnetic flow meters (EMF) were used to measure the inflow and outflow discharges (see Fig. 1). Air flow was measured by the vertex flow meter, positioned upstream of valve V6 (not shown in Fig. 1). Deltares' 32-channel data acquisition system DAQ was used to record synchronized flow rate (water inflow Q1 located at $x = -14.2$ m and water outflow Q2 located at $x = 270.3$ m); pressure (P1s, P3t, P3b, P5s, P7s, P8s, and P9s) located at $x = 1.6$ (side), 46.6 (top, bottom), 111.7, 183.7, 206.8, and 252.8 m, respectively; temperature (T1s, T3s, and T9s), located at $x = 1.6, 46.6,$ and 252.8 m, respectively; water level (WL1, WL3, WL5, WL7, WL8, and WL9) located at $x = 1.7, 46.4, 111.7, 183.7, 206.8,$ and 252.9 m, respectively; and void fraction (VF1s, VF6s, and VF9s) located at $x = 0.5, 141.9,$ and 251.7 m, respectively. Uncertainties of the measurements are reported in (Hou et al., 2012).

A total of 78 steady-state flow measurements were accomplished between the principal filling and emptying experiments. Energy (EGL) and hydraulic (HGL) grade lines for the steady-state flow velocity 4.02 m/s, corresponding to the Reynolds number of 948'170, are shown in Fig. 3. The steady-state flows were performed with fully open valves V0, V2, V4, and V5, and fully

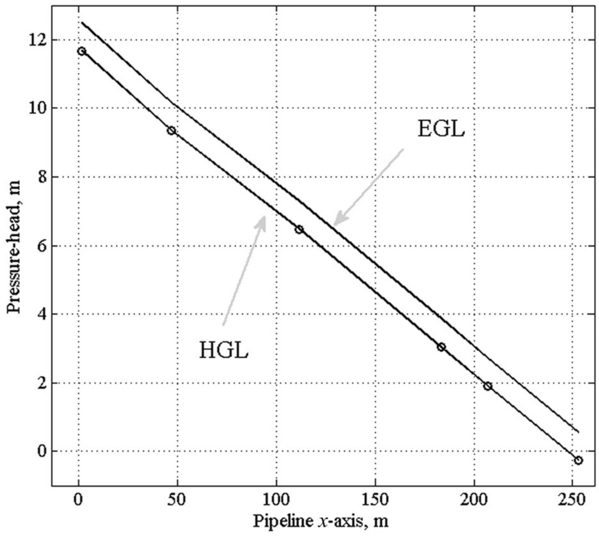

Fig. 3. Energy grade line (EGL) and hydraulic grade line (HGL) of steady-state flow (velocity 4.02 m/s) along the 251.2 m long PVC pipeline between the measurement sections MS1 [$x = (0, 2.0)$ m] and MS9 [$x = (251.2, 253.2)$ m].

closed valves V1 and V3 (Fig. 1). The HGL is almost a straight line, and thus the minor losses due to 0° joints and 45° and 90° bends of different radii can be ignored. The frictional loss of 11.9 m corresponds to the slope 0.0475 of the hydraulic gradient, representing the major loss in the hydraulic system.

According to the Darcy–Weisbach formula, the estimated friction factor 0.0136 at Reynolds number 948'000 corresponded to the pipeline relative roughness 0.00011 (Laanearu and van 't Westende, 2010). The minor loss coefficient of the 180° turn was estimated to be 0.0574, and thus the local minor loss of 0.0472 m can be ignored for the long pipeline (diameter-to-length ratio 1 : 1100). The pipeline outflow conditions were fixed by the relative positions of valve V4, with a position 0°/90° (0% closing) corresponding to the maximum opening and a position 90°/90° (100% closing) corresponding to the fully closed situation. The minor loss coefficient of the outlet was estimated to be 3.64 for the 11% closed valve V4 (Laanearu et al., 2012).

CONTROL-VOLUME MODEL

In the pipeline emptying process the mass losses are due to the water outflow from the pipeline and the *tail leakage* behind the moving air–water front. The main water-column mass losses are modelled within the framework of a shortening CV mass conservation principle. The aim of the theoretical analysis herein is to establish a relationship between the air–water front velocities associated with the process of transition to free-surface flow of the water column, moving rectilinearly along the horizontal pipeline. Essentially two air–water fronts appear due to air intrusion on top of the water column (Fig. 4). The 'primary' air–water front at Control Surface *1-1* (CS *1-1*) in Fig. 4 is associated with the movement of the 'last' fully filled cross-section and has velocity U_1. The 'secondary' air–water front is associated with the stratified flow 'vertical' boundary and has velocity U_2 at CS *1-1*. The outflow velocity is U at CS *0-0*. The shortening Control Volume, which contains water that fully fills the pipeline (CV in Fig. 4), has fixed surfaces at the pipeline walls and at the downstream end of the PVC pipeline, at coordinate position $x = 261.2$ m (see Fig. 2). Thus the CS *0-0* in Fig. 4 has a fixed position. In the present model the moving CS *1-1* in Fig. 4 is associated with two velocities: (1) at the upper section of CS *1-1* the water is moving with the velocity U_1 and (2) at the lower section of CS *1-1* the water is moving with the velocity U_2, allowing the intrusion of air on top of the 'lost' water column when $U_1 > U_2$. Now the air-cavity celerity of the two-phase flow is defined as a relative speed $c = U_1 - U$, where U is the outflow velocity. Without *tail leakage* (i.e. $U_1 = U_2 = U$) the air-cavity celerity c is zero, and only one planar air–water front moves along the pipeline.

The mass loss due to the *tail leakage*, which is the complement of *air intrusion*, is included in the CV model by the *holdup* coefficient α, under the condition that the amount of water-column mass left behind per unit length is $\rho(1-\alpha)A$, where ρ is water density and A is pipe cross-sectional area (cf. Bozkus and Wiggert,

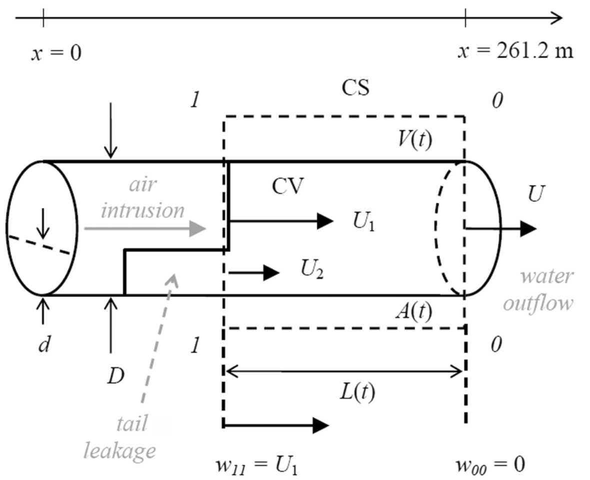

Fig. 4. Control Volume (CV) model framework and notations. CS – Control Surface; x – pipeline axis; U – water-column velocity; U_1 and U_2 – stratified flow velocities; D – pipe diameter; d – centre-line water depth; V – CV size in m^3; A – CS size in m^2; V – CV water-column length; *1-1* – moving CS; *0-0* – stationary CS; w_{11} – CS *1-1* velocity; w_{00} – CS *0-0* velocity.

1997). Thus the cross-sectional area occupied by intruded air is αA, with $0 < \alpha < 1$. No air intrudes on top of the water column if $\alpha = 1$ and no air is present in the pipeline if $\alpha = 0$.

Considering the shortening CV with *tail leakage* behind the moving primary air–water front, the CV mass changes can be modelled by an ordinary differential equation:

$$\frac{dM}{dt} = -\rho A(1-\alpha)(U_1 - U_2) - \rho AU, \qquad (1)$$

where the mass inside the CV is $M = \int \rho dV$, with V being the CV volume. In deriving Eq. (1) it was assumed that the water velocity at CS *1-1* was determined by the air–water front velocities U_1 and U_2 as indicated in Fig. 4. It should be noted here that for the single planar surface of the air–water front (i.e. $U_1 = U_2 = U$) the mass in the CV is decreasing only due to the mass outflow (ρAU).

In the case of clear distinction between the water in the lower part of the pipe and the air in the upper part, corresponding to a free-surface stratified flow, and the definite vertical water front surface at CS *1-1*, with mass conservation, the relationship between the CS velocities (U_1 and U_2) and the water outflow velocity (U) becomes as follows

$$U_2 = \frac{\alpha}{(1-\alpha)}\left[\frac{U}{\alpha} - U_1\right]. \qquad (2)$$

According to the simplifications considered herein, Eq. (2) yields no net volume flux through the CS *1-1* relative to the outflow rate AU by considering *holdup* $A_i = (\alpha A, (1-\alpha)A)$ for $v_i = (U_1, U_2)$, respectively, i.e. $\sum A_i(v_i - U) = 0$. It is noted here that for 'stationary *holdup*', i.e. $U_2 = 0$ and $0 < \alpha < 1$, Eq. (2) is considerably simplified, and the movement of the 'last' fully filled cross-section of the water column has velocity $U_1 = U/\alpha$ (cf. Laanearu et al., 2012).

The following dimensionless numbers are useful in characterizing the two-phase unsteady flow during the emptying process of the large-scale pipeline:

Reynolds number, which is related to the water-column velocity U:

$$\mathbf{Re} = \frac{UD\rho}{\mu}, \qquad (3)$$

Froude number, which is related to the stratified-flow velocity U_2:

$$\mathbf{Fr} = \frac{U_2}{\sqrt{gD}}, \qquad (4)$$

Zukoski number, which is related to the stratified-flow velocity U_1 relative to the velocity U:

$$\mathbf{Zu} = \frac{c}{\sqrt{gD}}. \quad (5)$$

In the dimensionless quantities D is the pipe diameter, g is the acceleration due to gravity, and μ is the dynamic molecular viscosity. The Reynolds number **Re** (Eq. (3)) is proportional to the water outflow velocity U. The Froude number **Fr**, defined by Eq. (4), and the Zukoski number **Zu**, defined by Eq. (5), are both dependent on the air-cavity movement yielding a stratified flow inside the pipeline. It is well known from classical two-phase flow experiments that during the gravity-driven emptying of a horizontal pipe, with a closed end upstream and an open end downstream under atmospheric pressure conditions, the air cavity propagates upstream along the pipe with a nearly constant celerity (Zukoski, 1966; Benjamin, 1968). The emptying experiments herein confirm that such a propagating air cavity also occurs in the pressure-driven emptying of the tested horizontal pipeline.

EXPERIMENTAL RESULTS

The initial condition of the representative emptying run analysed here was well established. The emptying process was started by manual opening of valve V5 (Fig. 1). Initially the water was driven out by compressed air of 2.1 barg, with the pressure decreasing of –1.40 kPa/s during 45 s. The water-level measurements indicated that stratified flow appeared at measurement sections MS3 [x = (46.1, 48.1) m], 5 [(110.0, 112.0) m], 7 [(182.0, 184.0) m], 8 [(205.2, 207.2) m], and 9 [x = (251.2, 253.2) m], and was not permanently present at MS1 [x = (0, 2.0) m]. Sony DXC-990P camera images captured during the primary air–water front passing the transparent sections MS2 and MS10 are shown in Fig. 5. A more or less planar air–water front originates from the PVC pipe bridge initially, and the pressurized flow remains stratified up to the end of the pipeline.

Estimating the *holdup* during the pipeline emptying process, it is essential to determine the outflow rate $Q_{\text{out}} = AU$ and the *tail-leakage* flow rate $Q_{tail} = A(U_1 - U)$. The volume flux balance $A(U_1 - U) = (1-\alpha)A(U_1 - U_2)$ holds according to Eq. (2). The primary air–water front velocity (U_1) can be directly calculated from the water-level changes (cf. Hou et al., 2014). Experimentally determined parameters and the corresponding CV model results by Laanearu et al. (2012) can be found in Table 1. The water-level elevations at measurement sections 1, 3 5, 7, 8, and 9 show that the slope of the water surface tends to decrease over time, indicating decelerating motion inside the free-surface water part. The secondary air–water front velocity (U_2) according to Eq. (2) is in the range from –0.06 to 0.94 m/s, which corresponds to subcritical flow conditions with **Fr** = (0.04, 0.69). However, the primary air–water front velocity U_1 is one order of magnitude larger than the velocity U_2 at every instant that this air–water front travels between MS1 and MS9.

The experimental findings in Table 1 show some deviations from the CV model results by Laanearu et al. (2012). This can be explained largely by the averaging procedure in the estimated velocity U_1 and also by simplifications in the CV modelling. Note that the main simplification considered in the CV model by Laanearu et al. (2012) was based on the assumption that the stratified flow behind the water column was at rest, i.e. **Fr** = 0, corresponding to the 'stationary *holdup*'. In that respect the agreement between the experimental and CV modelling results is acceptable at instants shortly after the smallest flow acceleration, corresponding to the 'inflection point' in the flow-rate curve at 18.6 s.

The leading air–water front unidirectionally travelled the distance 251 m between the PVC pipeline measurement sections MS1 and MS9 in 37 s. The air pressure was particularly uniform instantaneously along the pipeline, being 1.93 barg at instant 8.5 s and 1.42 barg at instant 45 s, when the air–water front passed sections MS1 and MS9, respectively. Mixed (water–air) stratified flow was almost absent, i.e. free-surface stratified flow was mainly present. The transition between the fully and partially water-filled pipeline sections was similar to a rarefaction-like surface wave, with the subcritical (**Fr** < 1) receding stream behind the tail of the water column, having a velocity U_2 less than 1.0 m/s, compared to a maximum outflow velocity of 8.3 m/s. At every instant the primary air–water front velocity (U_1) was at least one order of magnitude larger than the secondary air–water front velocity U_2.

The main water-column mass loss during the pipeline emptying was due to the outflow (about 90% of the total mass loss). The mass loss due to the *tail-leakage* effect was considerably smaller (about 10% of the total mass loss). The air–water front surface inside the large-scale pipeline was not planar due to the formation of an air cavity on top of the water column. In the present study the splitting of the leading air–water front in the stratified flow was studied with the shortening CV model based on the mass-conservation principle, allowing the derivation of the relationship between the water-column outflow velocity U, the primary air–water front velocity (U_1), the secondary air–water front velocity (U_2), and the *holdup* coefficient (α). The experiment confirmed that the condition $U_1 >> U_2$ holds, which explains why a significant amount of water remains inside the pipeline after the first air penetrates through the outlet. Splitting of the air–water front changed the

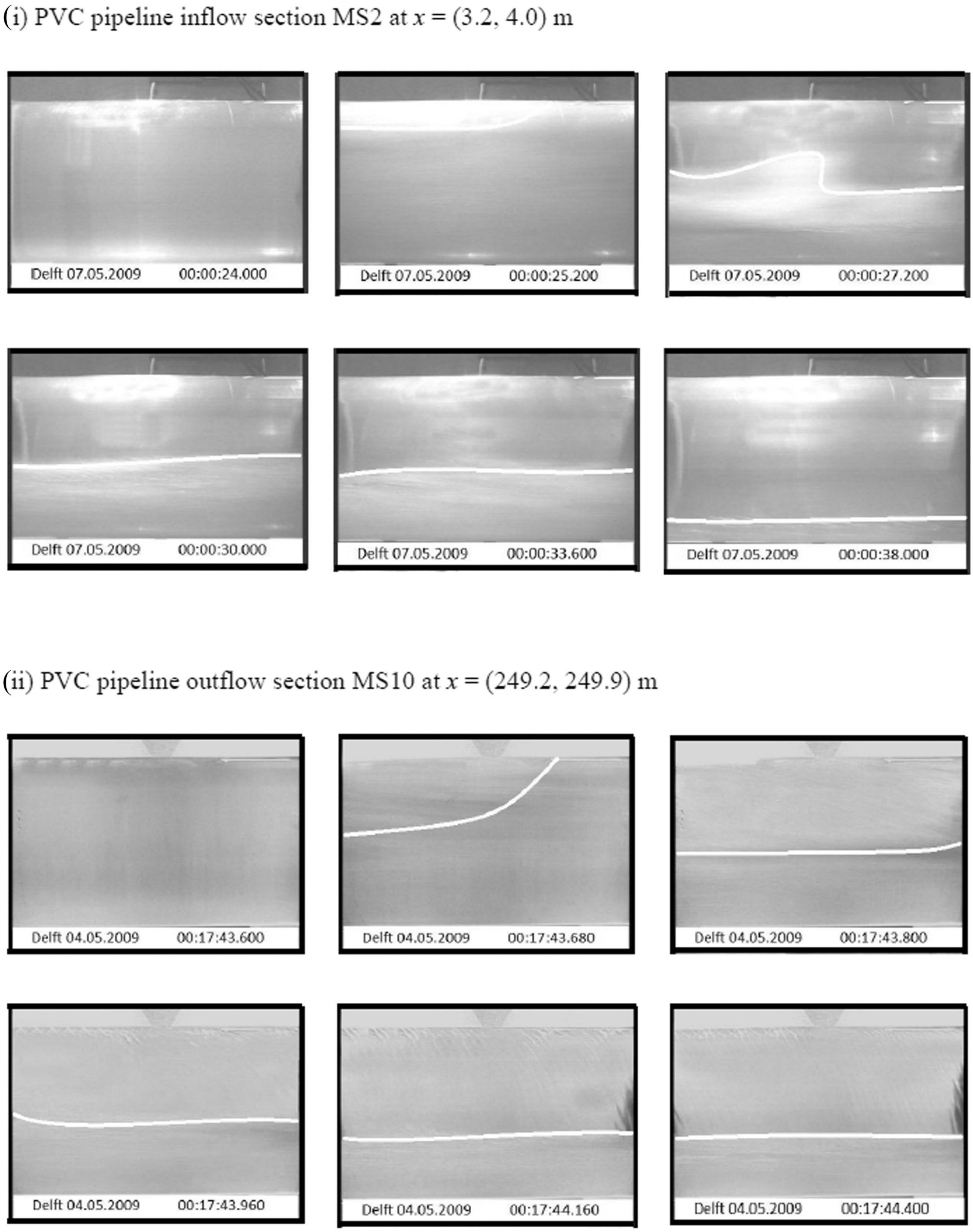

Fig. 5. Sony DXC-990P camera images of the air–water front passing the transparent sections (i) MS2 and (ii) MS10. A white guiding line is included in the camera images to denote approximate surface position between water and air.

Table 1. Experimental results and CV-modelling results by Laanearu et al. (2012) (grey columns). MS – measurement sections, x – coordinate point, t – arrival time of the leading air–water front, α – *holdup* coefficient, c – air-cavity celerity, $\dot{m}_{\text{out}}$ – measured mass outflow rate, $\dot{m}_{tail}$ – control volume mass loss rate due to *tail leakage*, **Re** – Reynolds number, **Zu** – Zukoski number

MS	x, m	t, s	α		c, m/s		$\dot{m}_{\text{out}}$, kg/s	$\dot{m}_{tail}$, kg/s		**Re**	**Zu**	
1	1.69	8.41	0.93	0.99	0.38	0.01	185.3	16.6	0.25	1.00×10^6	0.25	0.00
3	46.4	16.17	0.86	0.94	0.76	0.30	217.7	33.1	13.0	1.18×10^6	0.50	0.20
5	111.7	26.93	0.92	0.90	0.49	0.57	243.1	21.2	24.6	1.31×10^6	0.32	0.37
7	183.7	36.96	0.89	0.83	0.68	1.15	282.7	29.7	49.9	1.53×10^6	0.45	0.75
8	206.8	39.87	0.86	0.80	1.08	1.44	298.7	46.9	62.9	1.62×10^6	0.71	0.95
9	252.9	45.08	0.90	0.72	0.78	2.25	350.7	34.0	97.7	1.90×10^6	0.51	1.48

two-phase unsteady flow dynamics considerably. It was demonstrated that within the framework of the shortening CV model based on the mass- and momentum-conservation principles (Laanearu et al., 2012) the pipeline emptying with a planar air–water front (i.e. without the *tail-leakage* effect) would last around 9 s (i.e. 1.25 times) longer. It was also found that the experimentally determined quantities $(\alpha, c, \dot{m}_{\text{out}}, \dot{m}_{tail})$ showed the lowest deviations from the CV-model results at instants shortly after the smallest flow acceleration occurred. The simple CV modelling of the air–water interactions is essential in interpreting the two-phase unsteady flow experimental results in the large-scale pipeline, where mass changes inside the CV are due to moving boundaries and density changes.

DISCUSSION

Pipe filling

The pipeline emptying dynamics is similar to the filling dynamics in many aspects. For instance, it was demonstrated by Hou et al. (2014) that the water–air front that enters into the large-scale pipeline also splits into two water fronts during the filling process. However, the along-flow pressure gradient is different in the pipeline emptying and filling processes. It was also found that the air intrusion is less important for the global filling process according to agreeable rigid-column numerical modelling results obtained (Hou et al., 2014). This may be explained by the compressed air part on top of the advancing water column associated with its temperature changes. During the pipeline filling process temperature changes around 1 K for the stratified flow situation were observed. In comparison, the compressed air on top of the water column had no pressure gradient for the pipeline emptying process.

Modelling aspects

In the present study the development of free-surface flow during the emptying process was treated similarly to the *holdup* model approach by Bozkus and Wiggert (1997) for slug flow. However, the CV model equations developed by Bozkus and Wiggert (1997) include several assumptions that are not directly used for the pipeline filling and emptying situations. In the present CV model, air entrainment occurs on top of the liquid, and the moving water column does not lose its mass at a constant rate due to gravity and shear effects at pipe walls. Thus a more general approach is introduced herein for this mass loss, which is also referred to as *holdup* and implies the percentage of the pipe cross-section area through which the mass loss takes place. In the study by Tijsseling et al. (2014) the *holdup* coefficient $(\beta = 1 - \alpha)$ was introduced such that the cross-sectional area of the layer of liquid left behind the water column is βA. In the corresponding CV model by Tijsseling et al. (2014), the *tail-leakage* volume lost at every time step Δt is defined as the difference between the volume produced by the boundary motion of the CV water column air–water front and the outflowing volume during every time step, i.e. $\beta A U_1 \Delta t = A U_1 \Delta t - A U \Delta t$. This corresponds to CV model *tail-leakage* volume of the present study at every time step, e.g. $\beta A (U_1 - U_2) \Delta t = A U_1 \Delta t - A U \Delta t$, when the case of 'stationary *holdup*', i.e. $U_2 = 0$, is considered. In both models a single planar surface of the air–water front exists when $U_1 = U_2 = U$. One advantage of the present theoretical approach is that the water column mass loss due to *tail leakage* is associated with two velocities: (1) the velocity U_1 at the upper section of the air–water front and (2) the velocity U_2 at the lower section, allowing air entrainment into water when $U_1 > U_2$.

Applying the conservation of momentum principle to the deforming CV and considering relative motion in the momentum equation yields a 'residual momentum' problem. The 'residual momentum' changes due to the boundary and internal motions of the non-inertial CV can be represented by an integral coefficient (Laanearu et al., 2014). It was demonstrated by Laanearu et al. (2012) that this coefficient is essentially needed to establish agreement between the experimental and theoretical results. In the present case the water column had a velocity discontinuity at CS *1-1*, i.e. the velocity near the air–water front did not have the same profile as the velocity inside the water column, i.e. far downstream from the front (e.g. at CS *0-0*).

CONCLUSIONS

Mainly free-surface stratified flow developed inside the horizontal pipeline part during its emptying by compressed air. It was found that about 90% of the total water-column mass loss was due to the outflow during the pipeline emptying. About 10% of the total water-column mass loss was due to the *tail-leakage* effect. The Zukoski dimensionless number **Zu** was close to its critical value (≈0.5) at instants when the water column had its minimum acceleration during the two-phase unsteady flow. The fundamental fluid-dynamics problem herein was related to the internal motion due to the air-cavity dynamics in the pressurized pipe. The transition process between the full-pipe-diameter flow and the stratified flow needs more attention in any future experiments of this kind. Also detailed velocity measurements (Particle Image Velocimetry (PIV) or Laser Doppler Anemometry (LDA)) are needed to determine the velocity distribution in the two-phase unsteady flow due to the compressed air entrainment into the water column.

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Kahefaasilise (vesi ja õhk) mittestatsionaarse voolamise massihulga kaod tööstusliku mõõtmega survetorustiku veest tühjendamisel suruõhuga

Janek Laanearu, Qingzhi Hou, Ivar Annus ja Arris S. Tijsseling

Voolamise massihulga kadu pikas torustikus on probleemiks mitmes tööstuslikus rakenduses. Suruõhu juhtimisel läbi veega täistäidetud survetoru võivad kaasneda erinevalt segunenud õhu ja vee voolamised. On esitatud õhu ja vee frontaaleralduspinna dünaamika eksperimentaalsed ning teoreetiliselt analüüsitud tulemused suuremõõtmelises PVC-torustikus, mille diameetri ja pikkuse suhtarv on 1 : 1100. Täistäitega survetorustikust vee eemaldamiseks on kasutatud suruõhku ülerõhuga 2 baari (2 barg) ja 4,5 m kõrgust sifooni tingimusel, et vee väljavoolu takistus on määratud 11% suletud klapiga. Mõõdetud vooluhulkade ja veetasemete diskreetseid muutusi on kasutatud kahefaasilise mittestatsionaarse voolamise parameetrite – rõhulise voolamise tingimustes õhu efektiivne elavlõige (α), õhukaverni liikumiskiirus (c), voolamise massihulga kaod ($\dot{m}_{\text{out}}, \dot{m}_{tail}$) ning dimensioonitud suhtarvud (**Re**, **Fr**, **Zu**) – määramiseks. Õhu ja vee dünaamilist interaktsiooni survetorustiku veest tühjendamisel suruõhuga on integraalselt modelleeritud kontrollmahumeetodil. Survetorustiku tühjendamisega kaasneb voolamise massihulga kadu nii vee torustikust väljavoolu ($\dot{m}_{\text{out}}$) kui ka õhu ja vee frontaaleralduspinna liikumisega seotud *tail leakage*-efektiga ($\dot{m}_{tail}$). Kontrollmahumeetodil tuletatud matemaatilises erimudelis on kasutusele võetud ühesuunaliselt liikuv kontrollpind, mis võimaldab analüüsida õhu ja vee frontaaleralduspinna *splitting*'iga seotud dünaamikat. Mudeldamisega on näidatud, et kahefaasilise mittestatsionaarse voolamise dünaamika survetoru veest tühjendamisel sõltub oluliselt õhu ja vee kontrollpinna pidevast jagunemisest erinevate kiirustega liikuvateks osapindadeks, mille määrab voolamise õhu efektiivne elavlõige. Õhu ja vee frontaaleralduspinna jagunemise parametriseerimiseks on kasutusele võetud Zukoski dimensioonitu suhtarv (**Zu**), mis arvestab õhukaverni liikumise dünaamikat ja võimaldab hästi määrata survetorustiku horisontaalse lõigu täistäitega osa suhtelist lühenemist.