Incident analysis of a fuel loading line

Jos van 't Westende[1], Ivo Pothof[1,2], Anton Heinsbroek[1], Michiel Tukker[1], Wim Guijt[3]

[1] Deltares | Delft Hydraulics, department of Industrial Hydrodynamics
[2] Delft University of Technology, Civil Engineering & Geosciences
[3] Shell Global Solutions International BV, Pipelines & Offshore Technology (GSUP)

ABSTRACT

This paper discusses a post mortem incident analysis of a fuel loading line from a tank farm to a loading platform. The DN 250 mm GRE pipeline failed during start-up of the system, which was caused by an uncontrolled filling of a partially drained pipe section. Numerical simulations show that an integrated analysis (e.g. start-up after an incorrect shutdown) is required to determine the proper operating procedures. If this integration is not taken into account during the design of a pipeline system then, even in case of geometrically simple loading lines, incidents can result from a lack of awareness of the importance of operating procedures and loading sequences.

Keywords: operating procedures, loading line, pipe rupture, failure mode, two-phase flow

1. INTRODUCTION

Loading lines for the transmission of petrochemical liquids appear to be the rather simple pipe systems, as the design pressures are low. However, numerous incidents have occurred in the past, caused by a variety of circumstances.
The dynamic phenomena during filling of a 3.1 km long fuel transfer line are analyzed in this paper. Fuel is transferred through a buried 2.55 km DN 250 mm GRE pipeline from storage tanks to vessels for export, having steel piping connections at both ends.
The loading line was pressurized prior to loading operations, in accordance with operating procedures being adopted over 15 years without any problems. During this 'packing' operation, the GRE pipeline failed suddenly under excessive axial loading. Due to a lack of monitoring data there was no possibility to confirm the definite cause of the excessive surge pressures. Figure 1 shows the resulting damage to the GRE-joint.
Looking at the pipeline elevation profile, a section of the pipeline is susceptible to cavitation. Even a limited cavitation volume in the pipeline can result in uncontrolled filling of the cavity. The cavity collapse creates a significant pressure surge throughout the loading system. Simulations were carried out to confirm that the presence of a limited cavity at an elevated section of the pipeline can indeed result in surge pressures, which are significantly above the original design pressure of the system.

Figure 1: Damage to GRE-joint due to excessive axial loads.

The results of liquid-vapour simulations for this incident are presented.. Based on these simulations the paper describes improvements in operating procedures of transfer pipelines.
Section 2 summarizes the loading line properties and the normal shutdown and start-up procedures. Section 3 describes the modelling approach, which was applied to simulate

the uncontrolled filling of the pipeline, including a validation case. In section 4, we present the results of the simulations. Section 5 discusses improvements to the operating procedures, from which more generalised design guidelines are derived. Our concluding remarks are summarised in section 6.

2. SYSTEM DESCRIPTION

2.1 Key data

The system is shown schematically in Figure 2.

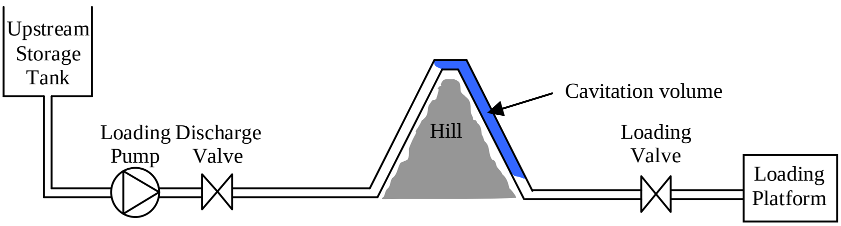

Figure 2: Schematic overview of the loading system.

The liquid fuel that is being transported has a density of 750 kg/m^3, and a vapour pressure of 10 Pa. The bottom level of the upstream storage tank is located approximately 30 m above sea level. The tank has its maximum filling height of 16 m. A steel pipe of 235 m length connects the storage tank with the loading pump and upstream discharge gate valve. Figure 3 shows the characteristics of the pump and discharge valve.

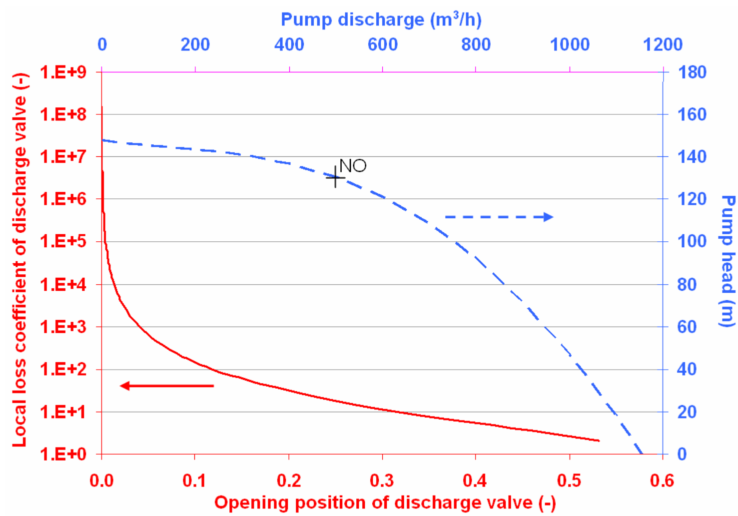

Figure 3: QH-characteristics of loading pump and local-loss coefficient characteristic of discharge valve as a function of its opening position.

The fuel is transported from the loading pump to the loading platform through a 2.55 km long DN 250 mm GRE (Glass fibre Reinforced Epoxy) loading line. The GRE pipeline has a high point about 43 m above sea level, approximately 180 m downstream of the loading pump. Approximately 300 m downstream of the high point, the pipeline is at about 6 m above sea level, from where it remains at this elevation. In Figure 4 shows the pipeline geometry. The maximum acceptable surge pressure of the GRE pipeline is 22 barg.

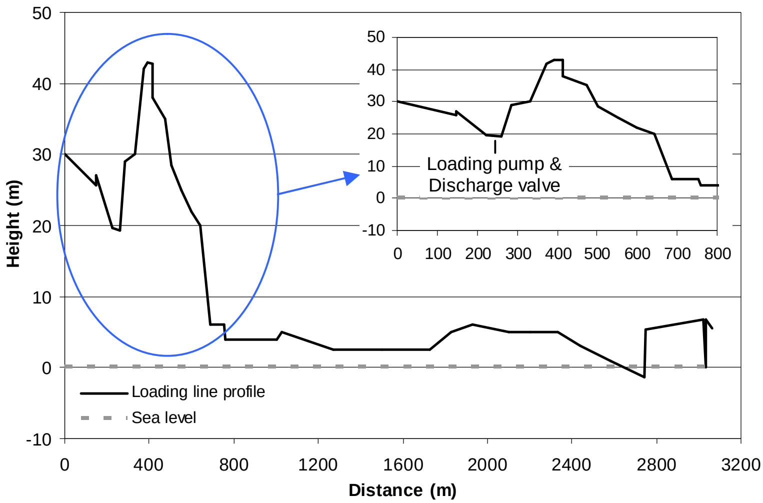

Figure 4: Loading line profile and sea level.

2.2 System operations

Operation of the loading line is performed manually: both the upstream pump discharge valve and the downstream loading valve are locally operated by individual operators, communicating via walkie-talkies. The operators were familiar with start-up procedures. Written start-up procedures, however, were lacking. The detailed understanding of operating procedures and especially specific requirements such as packing operations deteriorated over time.

Under normal operation, the system is shutdown after completion of the loading operation, leaving the loading pipe fully filled and pressurized. Assuming the preceding shutdown procedure has been done correctly, the start-up procedure requires the loading line to be pressurized ('packing'), prior to start of the fuel loading operation.

Packing of the loading line is performed with the loading pump that is started up against a closed pump discharge valve. With the loading pump running at full speed, the pump discharge valve opens slowly while the downstream loading valve remains closed. Having pressurized the entire loading system (up to about 15 barg pressure resulting from the pump shut-in pressure and static head), the downstream loading valve is slowly opened.

During normal operation, the liquid velocity of the fuel in the GRE pipe amounts up to about 3 m/s, and the pressure in the GRE pipe is about 11 barg just downstream of the pump.

When the loading pipeline contains gas pockets or vapour cavities, the packing of the loading line can result in a fast and uncontrolled priming of the pipeline. Such a rapid priming scenario is known to be a very dangerous operation (1). When the fast moving filling liquid front collides against a liquid column at rest or another obstruction (e.g. a valve), significant pressure waves are generated which move throughout the pipeline system. This often results in significant damage to the system, especially for systems normally operating at lower pressures.

Considering the pipeline elevation profile, the high point in the pipeline is susceptible to cavitation. If the upstream discharge valve is closed before the downstream loading valve, a column separation at the high point in the loading line very likely occurs. Also an unintended pump trip (e.g. due to a power failure), or a small undetected leakage in the pipeline system can cause a vapour cavity appearing at the high point. If during start-up the downstream loading valve would be opened prior to opening of the upstream discharge valve, cavitation can occur as well.

When a cavitation volume is present in the pipeline, a refill procedure needs to be initiated to avoid rapid uncontrolled filling of the pipeline resulting in excessive peak pressures. Therefore, a check on the presence of a vapour cavity in the pipeline should be part of the normal start-up procedure.

3. NUMERICAL SIMULATION

To calculate the acceleration of a liquid column in an empty pipeline, we make use of the rigid column approach, similar to the approach by Razak (3) or Liou (4). To validate our computations, we have simulated one of the filling experiments presented in the literature (2). In this experiment, a horizontal pipeline with an inner diameter of 35 mm and a total length of L_{tot} = 10 m is connected to an upstream reservoir with a constant absolute upstream head of 32.46 m (reference level is the pipe centreline). The initial length of the liquid column length is 5 m. The downstream end of the pipe is closed, i.e. filling occurs against an air pocket of constant mass with an initial atmospheric pressure ($H_{a,t=0}$ = 10.37 m).

Note that this experiment differs from the rapid filling of the loading line because the downstream boundary condition of the experiment is a compressible air volume (varying downstream pressure), whereas the boundary condition for the rapid filling of the loading line is a constant vapour pressure.

From the energy equation applied between a point at the water surface of the reservoir and the front of the liquid column the acceleration of the liquid column can be deduced:

$$\frac{du}{dt} = \frac{g}{L_f}\left(\left(H_{res} - H_a\right) - f_D \frac{L}{D}\frac{u|u|}{2g} - \left(1 + \xi_{entr}\right) H_u \right) \qquad \textbf{(1)}$$

in which:

g	is the gravitational acceleration (= 9.81 m/s^2),
L_f	is the length of the liquid column (m),
H_{res}	is the upstream reservoir head at the entrance of the pipeline (m),
H_a	is the downstream air pressure head at the end of liquid column (m),
f_D	is the Darcy friction factor (-),
D	is the pipe diameter (m),
u	is the liquid column velocity (m/s),
ξ_{entr}	is the local loss due to the entrance, 0.08 (-), and
H_u	is the head due to kinetic energy (m).

The variation of the downstream air pressure head, H_a, is computed with the following differential equation:

$$\frac{dH_a}{dt} = -k \frac{H_a}{L_a} u \qquad \textbf{(2)}$$

in which:

k is the polytropic exponent (-), and

L_a is the length of the air column ($L_a = L_{tot} - L_f$) (m).

Equations 1 and 2 are solved numerically using a second-order Adams-Bashforth scheme. The time step is 0.01 s. The Darcy friction factor is assumed to be constant at a value of f_D = 0.035, corresponding to a hydraulic wall roughness of about 0.3 mm. At each time step, n, the instantaneous acceleration, du/dt, and change of air pressure head, dH_a/dt, is calculated. The velocity and length of the liquid column and the air pressure head at the next time step, n+1, are computed using:

$$u[n+1] = u[n] + \left(\frac{3}{2}\frac{du}{dt}[n] - \frac{1}{2}\frac{du}{dt}[n-1] \right) dt \qquad \textbf{(3)}$$

$$L[n+1] = L[n] + \left(\frac{3}{2}u[n] - \frac{1}{2}u[n-1] \right) dt \qquad \textbf{(4)}$$

$$H_a[n+1] = H_a[n] + \left(\frac{3}{2}\frac{dH_a}{dt}[n] - \frac{1}{2}\frac{dH_a}{dt}[n-1] \right) dt \qquad \textbf{(5)}$$

Figure 5 compares the results of our computations for the downstream air pressure head with the experimental data.

The results of the simulation and the experiments show a good agreement. The first oscillation period is 1.28 s in the computations against 1.2 s in the experiments (i.e. an overprediction by 6.7%). The maximum pressure in the computations is 55 m against 49.1 m in the experiments (i.e. an overprediction by 12%).

4. CASE STUDY: FILLING INCIDENT

During packing of the loading line the GRE pipeline failed near the location of the GRE/steel transition piece where the buried pipeline becomes above ground piping. Having commissioned the loading pump from the control room, the operator opened the pump discharge valve which packed the loading system. Leakage from the pipeline was reported soon afterwards, and the loading pump was stopped from the control room.
From the analysis of the failed GRE joint it appeared that the line failed under excessive axial loading (see Figure 1), which was caused by surge pressures in the system. The definite root cause could not be established, but can most likely be attributed to the existence of vapour pockets/volumes in the system and/or an incorrect sequence adopted to pack the line.

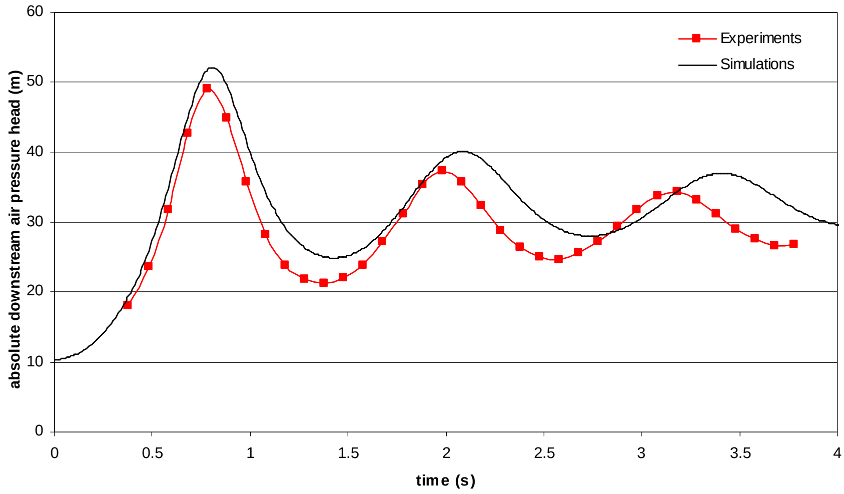

Figure 5: Time development of the absolute downstream air pressure head.

To confirm the impact of vapour pockets in the loading line during packing operations, the rapid uncontrolled filling of the loading line has been simulated using the approach described in section 3. The input for the simulations is as follows:

- The cavitation volume exists only in the downhill part downstream of the high point.
- The total upstream head is the sum of the atmospheric pressure head (= 13.78 m), the upstream reservoir head (H_{res} = 46 m) and the varying delivery head of the pump minus the head loss over the discharge valve, i.e. the upstream head depends on the flow rate and valve position,
- The total downstream head is the sum of the constant vapour pressure head (= 1.36 mm) and the elevation of the front of the filling liquid column, i.e. the downstream head is decreasing in time.
- The discharge valve opens in 8 s linearly from opening position 0 to 0.5.
- The Darcy friction factor is: f_D = 0.023 (corresponding to a hydraulic roughness of 0.5 mm).
- The maximum allowable surge pressure peak is 7 bar (which is equal to the maximum allowable incidental pressure of 22 barg minus the shut-in pressure of 15 barg).
- The initial length of the liquid column is 415 m.
- The length of the vapour (cavitation) column is varied between 0 and 500 m (i.e. the maximum liquid column length is 915 m).

When the filling liquid column hits the stagnant liquid column at the downstream side, a pressure wave will propagate through the loading pipeline. This pressure is estimated using the Joukowski relation, i.e.

$$\Delta p_{max} = \rho g \Delta H_{max} = \rho \, c \, \Delta u \quad \text{[bara]} \qquad \textbf{(6)}$$

in which: c is the wave speed through the GRE pipeline (= 700 m/s), and
ρ is the density of the liquid.

Figure 6 shows the velocity of the filling liquid column as a function of its filling length (taken between the upstream tank and the filling liquid front). The maximum velocity is 5.55 m/s for a total liquid column length of about 455 m. Hence, if the cavitation volume has a length of (455-415=) 40 m the maximum Joukowski surge pressure is expected.

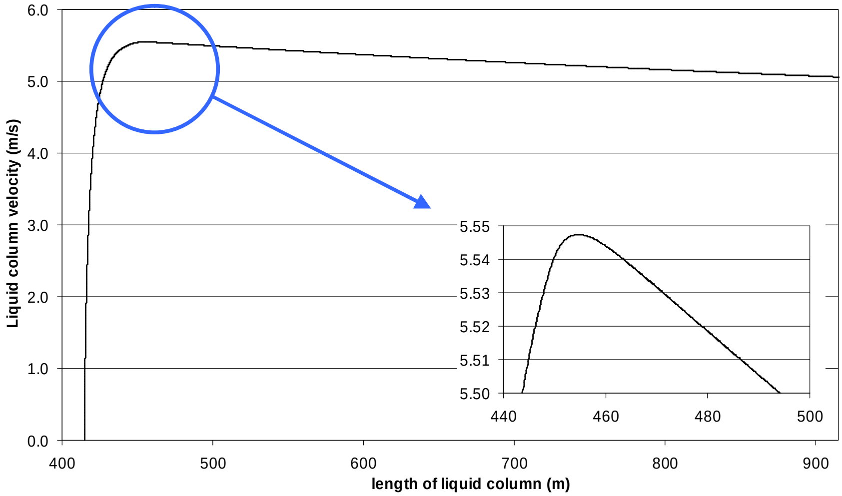

Figure 6: Velocity of liquid column as function of its total length.

Figure 7 shows the Joukowski pressure for cavitation volumes of various lengths, using eq. 6. From this it is clear that a cavitation volume length in the range of 0.7 to 500 m will result in a Joukowski surge pressure exceeding the maximum allowable value of 7 bar.

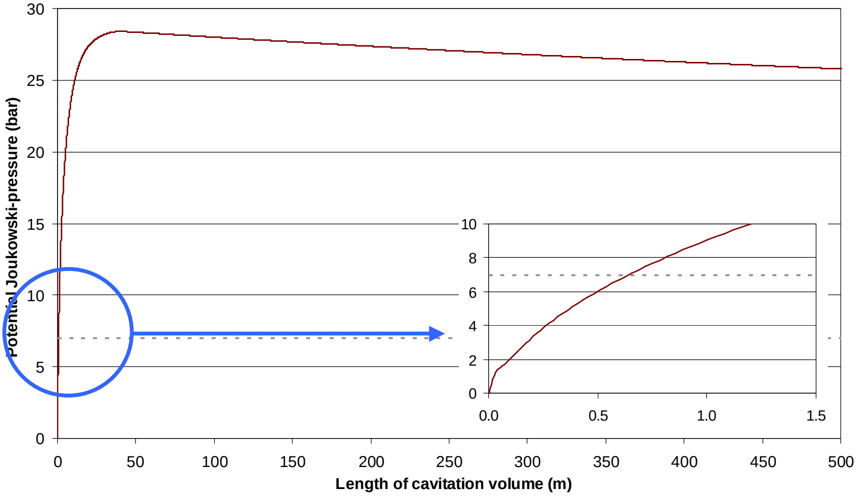

Figure 7: Resulting Joukowski pressure upon impact of the filling liquid column with the downstream liquid column in rest. The maximum allowable pressure peak is shown as well (gray dashed line).

No information could be obtained of the shut-down procedure adopted prior to the filling incident, as no SCADA system is installed for the manually operated loading line. Therefore, it is not possible to estimate a priori the length of the cavitation volume in the pipeline. However, our analysis has shown that even a very limited cavitation volume having a short length can already result in unacceptably high pressures.
It should be noted that a cavity of only 0.7 m length corresponds to only 0.035 m^3 of volume. A minor undetected leakage from the loading line thus could have caused an inadmissible cavity. Also, when the loading valve is closed only 0.25 s after closure of the discharge valve a cavity of 0.7 m can be created (assuming a liquid velocity of 3 m/s during normal operation).

5. DISCUSSION

Filling incidents can be prevented when sufficient information of the status of the system is available. For example, simple pressure measurements can detect the presence of vapour cavities prior to the packing procedure. When a vapour cavity is detected, an emergency filling procedure should be followed instead of the standard packing procedure.

If, for this specific loading line, filling is done by gravity only, e.g. via a bypass-line parallel to the loading pump, the maximum allowable pressure peak is 17 bar (which is equal to the maximum allowable pressure of 22 barg minus the shut-in pressure due to gravity of 5 barg). Figure 8 shows that filling by using gravity only results in a maximum Joukowski pressure of about 15 bar for a cavitation length of 500 m. Thus, using gravity only, the total maximum pressure remains below 22 barg, because of *i)* a lower shut-in pressure of the loading line, and *ii)* reduced filling velocities.
Filling of a maximum cavity length of 500 m, using gravity only, will only take about 3 minutes; control of the upstream discharge valve is not critical. When the upstream storage tank is nearly empty, gravity is still able to push the fuel to the high point in the loading line. Hence, for this specific loading line, filling using gravity loading only is an acceptable filling procedure.
Having filled the loading line completely, the loading pump can be started against a closed downstream loading valve.

In general, all start-up procedures should be designed following an integrated hydraulic study in which the emergency shutdown and normal start-up are considered consecutively; the first determines the initial conditions for the last. In this way, the worst initial conditions for start-up can be assessed, making the final design of the start-up procedure more robust and safer. A practical consequence of this approach is that the operator (or a SCADA system) must perform several checks, such as the verification of the initial system pressure, before executing the normal start-up procedure. If the system pressure is lower than some threshold value, cavities may be present and a careful refilling procedure is required. The general conclusion from these observations is that the presumed initial conditions for normal operations should be verified before the normal operations are executed.

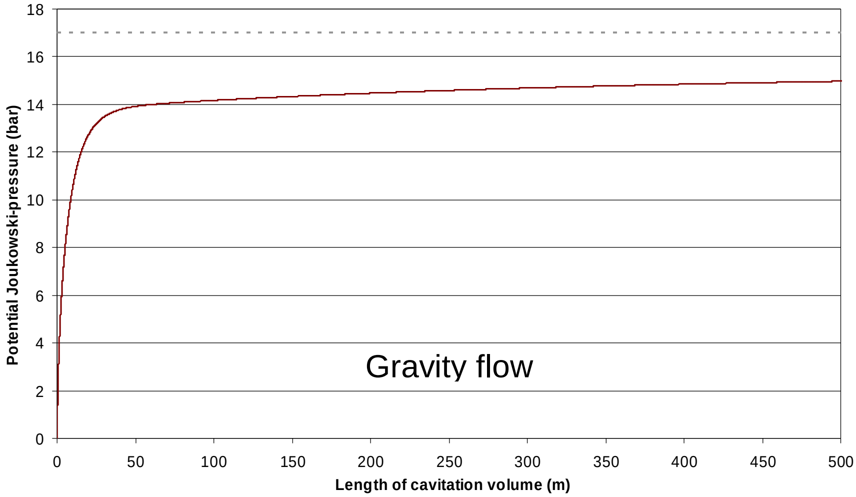

Figure 8: Resulting Joukowski-pressure when the filling liquid column hits the downstream liquid column in rest (gravity flow). The maximum allowable pressure peak is shown as well (gray dashed line).

Our simulations have been validated against laboratory experiments of limited scale only. To the authors' knowledge, a filling experiment on an intermediate/large scale does not yet exist. Therefore, we are planning to carry out new filling experiments in a large test rig. A new multiphase flow loop is being constructed at the Deltares | Delft Hydraulics site. This flow loop will have a length of 300 m, of which 120 m can be flexibly modified to create an arbitrary elevation profile with up to 7.5 m elevation difference. The inner diameter of the loop will be 200 mm, with a pressure rating of 16 barg. Water, air and small amounts of sediment can be used in the loop. Also, as part of the Hydralab III program (5), we will test the filling of a horizontal pipeline with various boundary conditions: upstream boundary conditions up to 2 barg head, and downstream boundary conditions are free or have restricted air outflow.

6. CONCLUSIONS

We have analysed a pipeline failure in a fuel loading line from a tank farm to a loading platform, which was attributed to uncontrolled rapid filling of a partially drained pipe. Looking at the pipeline elevation profile, a section of the pipeline is susceptible to cavitation. Consequently, vapour volumes can be present in case the shutdown procedure is not performed correctly, or when there is a small undetected leakage in the system.
The analysis of the uncontrolled filling was performed using a rigid liquid column approach adopting a second-order accurate numerical scheme. The numerical model was validated against existing laboratory scale experiments (2).
From applying the numerical approach to the case study of filling a partially drained pipeline, we conclude that even for small vapour volumes the Joukowski pressure peak is already unacceptably high. This pressure peak is caused by the collision of the fast moving filling liquid column on the stagnant downstream liquid column. Gravity loading of the pipeline, i.e. bypassing the loading pump, reduces the Joukowski pressure peak to

an acceptable level. This is caused by the significantly reduced filling velocities and by the lower shut-in pressure of the loading line.
From the analysis of this case study it is clear that both the start-up procedure and the shutdown procedure should be carefully established and should include the interaction between these operations. An incorrectly performed shutdown procedure may give unacceptably high pressure surges and can create unexpected startup conditions for the system.

7. REFERENCES

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