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MODELING OF TWO PHASE FLOW EXPANSION INSTABILITIES IN LONG RISERS OR WELLS

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ABSTRACT

Oil and gas from offshore reservoirs can flow as multiphase mixtures through well tubings, sub-sea flow lines and through risers to floating receiving facilities. Dynamic flow simulators are used to analyse the flow stability of such systems. Different model concepts are discussed and compared for the case of expansion driven flow instabilities. This is a class of flow instability where even a small amount of trapped gas upstream a riser base can cause oscillating flows due to expansion effects as the gas propagates along the riser. Some qualitative experiments have been made in a small scale setup to demonstrate the flow instabilities.

INTRODUCTION

Unstable flows pose serious operational threats to the safe and reliable operation of sub-sea oil-gas pipelines. “Severe slugging” or “riser slugging” denotes the flow instability where an upstream gas volume is compressed and blows the accumulated liquid out of the riser at regular intervals. This flow instability requires a significant upstream gas volume in comparison with the riser length. Flows in very long risers or wells can become unstable also due to the effect of the gas expansion in the riser. Even small amounts of upstream trapped gas can induce flow oscillations, as the gas expands and causes a flow acceleration which takes the rest of the entrapped gas into the riser. Gas can potentially be trapped due to pipeline undulations (or jumper configurations) or well undulations (horizontal wells).

Severe slugging has been studied experimentally since long [1],[2],[3],[4] and such cases are also used as reference cases for dynamic flow simulators [5]. Expansion driven flow oscillations in risers are much less studied, often referred to as a density wave phenomena for gas lift cases. Gas can be injected into a riser to enhance the production rate from the reservoir by reducing the static head of the mixture in the riser. Even with a critical gas lift valve, ensuring a constant gas mass injection rate, density wave instabilities can be observed. For sub-critical valves, a similar flow instability as for severe slugging can occur, as the gas line can now provide the upstream compressibility needed for unstable flows (“casing heading”) [6],[7].

The following discussion relates to the flow instabilities of small amounts of trapped gas upstream a long risers or a long well. This is a flow case which does not strictly classify as severe slugging or as density waves, and such cases are not reported in the literature.

The following gives the results of some qualitative small scale experiments, and a discussion on modeling options for such flow dynamics.

EXPERIMENTS

A small scale, air-water setup was established in order to qualitatively investigate the flow dynamics in long risers. For simplicity, the gas and liquid flows were separately controlled. The inlet liquid flow was connected to an overflow tank, in order to provide constant pressure boundary conditions, and the gas was injected at constant gas mass flow rates into an undulated section of a flexible pipe upstream the riser, see Figure 1 for a schematic view and Figure 2 for photographs.

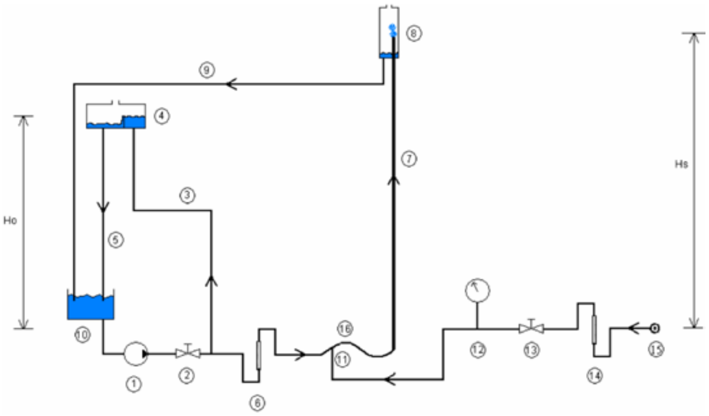


Figure 1 Schematics of the experimental setup. Inner pipe diameter is 20 mm, riser length is 6.2 m.

Table 1 Flow regimes during the flow cycles in the riser

ID in Figure 9	Component
1	Pump
2	Choke
3	Flexible hose 16 [mm] internal diameter
4	Weir
5	Flexible hose 20 [mm] internal diameter
6	Flowmeter water
7	Riser plexiglass 16 [mm] internal diameter
8	Separator
9	Flexible hose 20 [mm] internal diameter
10	Water tank
11	Air injection point
12	Manometer
13	Choke
14	Flowmeter air
15	Compressed air supply 1 [barg]
16	Bend for injected gas to accumulate

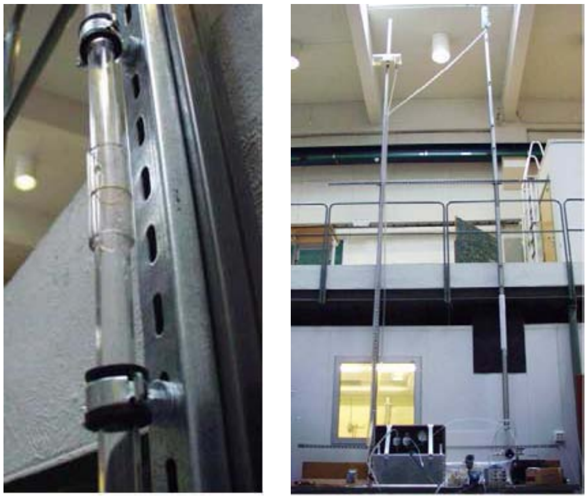


Figure 2 Photograph of small scale setup

Figure 3 Flow regimes during the flow cycles in the riser

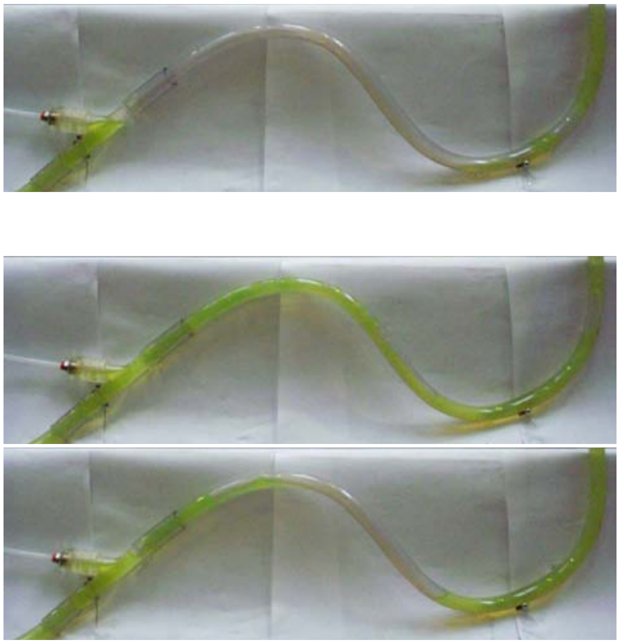


Figure 4 Gas accumulation and flushing at the bend.

Pictures taken during the flow oscillations are shown in Figure 3 and 4. At suitable gas flow rates and inlet pressures (heights of the overflow tank) gas can accumulate at the bend. When the gas reaches and penetrates the bend, it enters and flows up the riser towards lower pressure. The expansion gives a higher gas fraction in the riser, a lower pressure at the riser base, increased inflow of liquid and a flushing of the entrapped gas. Short risers would yield stable flows, long risers can cause sufficient expansion to provide flow oscillations.

The experiments were made with a tank level both below (simulating gas lift) and above the pipe outlet (simulating continuous production).

FLOW MODELS

This type of dynamic two phase flows can be resolved by numerical integration of the 1D mass and momentum equations in time and along the pipe. In a “two fluid model” the set of equations are solved for each phase, even in regions where one of the phases is not present.

When formulating the flow models, the targeting time and length scales must be determined. If each individual gas and liquid slug is to be numerically resolved, the computational grid must be smaller than the bubble-slug flow scale, and the gas-liquid fronts should be resolved sharply, with a minimum of numerical diffusion. If a larger time and length scale is sufficient in the dynamic simulations, then the numerical grid size must be consistent with the underlying averaged flow model and the averaging scales.

Two fluid model

A two fluid model consists of a set of conservation equations for each phase. For isothermal flows, the 1D mass and momentum equation for phase k (k=gas or liquid) are:

$$\frac{\partial \alpha_k \rho_k}{\partial t} + \frac{\partial W_k}{\partial x} = \Psi_k$$
$$\frac{\partial W_k}{\partial t} + \frac{\partial W_k U_k}{\partial x} = -\alpha_k \frac{\partial p}{\partial x} - F_k \pm F_i - G_k + O_k$$

For field k, $W_k = \alpha_k \rho_k U_k$ the momentum pr. unit volume. ρ_k is the phase density of the phase in field, α_k is the cross sectional phase fraction, U_k is the cross section averaged velocity, Ψ includes all the mass transfer terms (phase change and mixing terms), p is the pressure, F_k is the wall friction, F_k is the interface friction, G is the gravity and O_k includes various other momentum transfer terms, such as level gradient terms, phase change and droplet exchange terms and possibly correction terms to render the set of equations well posed

The friction terms are normally formulated with a friction factor, as for pipe flows:

$$F_k = \frac{1}{2} \lambda \rho_k U_k^{\ 2} \frac{S_k}{4A}, \quad F_i = \frac{1}{2} \lambda_i \rho_g U_g - U_l)^2 \frac{S_i}{4A}$$

λ is the friction factor, S is the wetted perimeter length and A is the pipe cross section area. The gravity term depends on the pipe inclination, φ

$$G_k = \alpha_k \rho_k g \sin \varphi$$

The set of equations are discretized and solved numerically. The evolution of the flow along the pipe can then be computed from given initial and boundary conditions.

Averaged model for small scale dynamics

Discretizing the pipeline into very small grid segments may give too long computational times, as the number of grid points becomes very large and the time step accordingly small. It is also a challenge to formulate friction models in the two fluid model to be valid for flows on a scale where three dimensional flow effects becomes important, e.g. breaking waves, slug fronts and tails. A pipe segment which is long enough to contain many waves or slugs can be considered as a one dimensional flow with averaged properties.

The approach in the OLGA model [8], and similar models is to regard small scale wavy and slug flow as averaged flows. The wall and interface friction terms F_k , F_i must then be formulated specifically for the different flow regimes ranging from smooth stratified to wavy, slug and bubbly flows. These flow regime dependent models must also be supplemented with flow regime transition criteria, providing the conditions for choosing the different flow regimes at each pipe location and time instant.

This type of flow model can then not be expected to reproduce the details in the slug flow regime as observed in the experiments in Figure 3. Small scale slug flow is then regarded as averaged flow, on length scales larger than the scales in Figure 3. The large scale system oscillations should, however, be captured.

Resolving slug flow scales

Front capturing

There are basically two different strategies for numerical models aiming at resolving also the individual wave and slug dynamics. One is the capturing approach, where friction models for stratified flow are retained throughout the evolution from separated smooth flow to wavy or slug flow. The flow regime transition then occurs as a result of the flow model itself (unstable stratified flow) and transition criteria are then not needed. After a slug is formed by the liquid bridging the pipe cross section, some front identification procedure is nevertheless needed in order to supply the appropriate local flow models (slip and friction relations in the slug, and possibly gas entrainment into the liquid front). The numerical schemes should also be made to limit the numerical diffusion of propagating gas-liquid fronts.

Slug tracking

Front capturing schemes need a grid refinement such that the lengths of the grid cells are much smaller than the wave/slug scale. A coarser grid is possible in a front tracking scheme, where the grid now move with the fronts. This can be an attractive intermediate concept, where the slug/wave scale is resolved but not requiring a grid much smaller than that scale, and without numerical diffusion of the fronts. The penalty of increasing the grid size is the need for flow regime transition criteria, in order to initiate liquid slugs from stratified flows.

The OLGA model includes a sub grid slug tracking model, allowing for a closer interfacing of a front tracking model with the standard scheme with averaged slug/wave flow models. In a sub grid front tracking scheme, the averaged pressure and velocities are solved on a large and fixed grid. The grid may contain several liquid slugs that are tracked with front coordinates ensuring mass flow conservation across the fronts. The momentum equations on the larger grid assembles the friction and gravity contributions from the sub grid slugs and bubbles. The pressure equation is based on a volumetric flow balance, where the densities are related to the pressure through state equations, as for the standard scheme. The fluxes in the pressure equation is now according to the local phase fractions at the front, given by the sub grid tracking scheme, and not the averaged phase fraction in the grid as for the standard scheme.

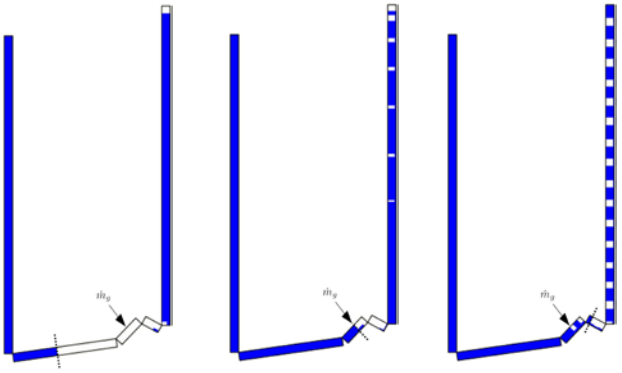
A pure slug tracking scheme (named Sluggit) [9] is also tested for the current riser case. In this scheme, a hybrid formulation is used where a two fluid model is applied on a staggered grid in the bubble region, and an integral momentum balance is solved on a moving grid for the liquid slug. The slug is incompressible, and the liquid velocity is determined from the momentum balance on an open and moving control volume. The pressure on each side of the slug is a result of compression or expansion of the gas bubbles. A bubble nose propagation, where the bubble moves in relation to the liquid velocity in the slug, is imposed. The slug front propagation is according to the mass flow balance across the front. Slugs can be formed after accumulation in bends or initiated from a stratified-slug flow transition criterion.

This is a quite simplistic basic formulation for the case of slug flow. A major challenge in this work is the slug initiation and the grid management, as the dynamic creation and deletion of liquid slugs and bubbles gives disturbances to the flow. In the present case, a gas bubble at the point of the gas source needs to be initiated in the liquid flow. After some accumulation time, a small bubble is initiated and allowed to grow in time from a source which has a time constant. This is made in an attempt to minimize the disturbance of introducing a bubble with a finite bubble length.

FLOW SIMULATION

The riser case has been simulated with a two fluid model, applying averaged flow formulations for wavy and slug flow. The OLGA model was used for these simulations as well as for slug tracking simulations with a sub grid model. The pure slug tracking case was simulated with the Sluggit model.

Figure 5 shows screenshots of the animation for the different modes of flows as the gas injection rate is increased. Gas is periodically accumulating in the small bend at the riser base for small gas flow rates and steady flows occur at higher rates.



a) Small gas rate b) larger gas rate c) stable flow

Figure 5 From unstable to stable flows with increasing gas flow rate (Sluggit)

The amplitudes in the pressure oscillations at the riser base were recorded, and the results are shown together with the simulation results in Figure 6. Slug tracking gives a larger unstable region than the standard two fluid model, all models show larger pressure amplitudes than in the experiments. More careful experiments, with higher riser lengths need to be made.

Simulated pressure and liquid flow rates in time are given in Figures 7-9. The figures also show screenshots of the animation of the results. The animations are made with an exaggerated diameter/length ratio of the pipes, in order to visualize the liquid fraction more clearly.

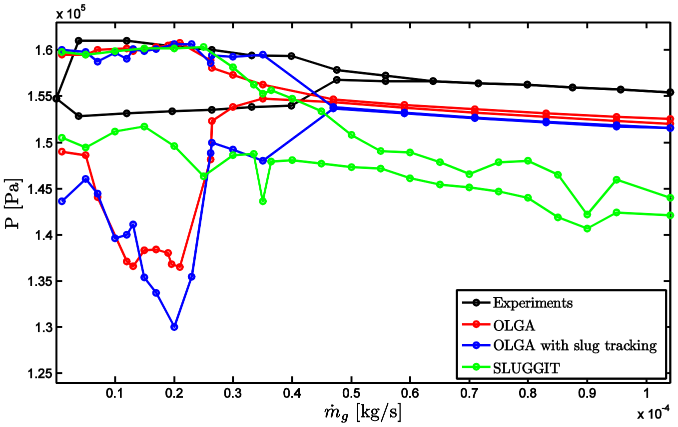
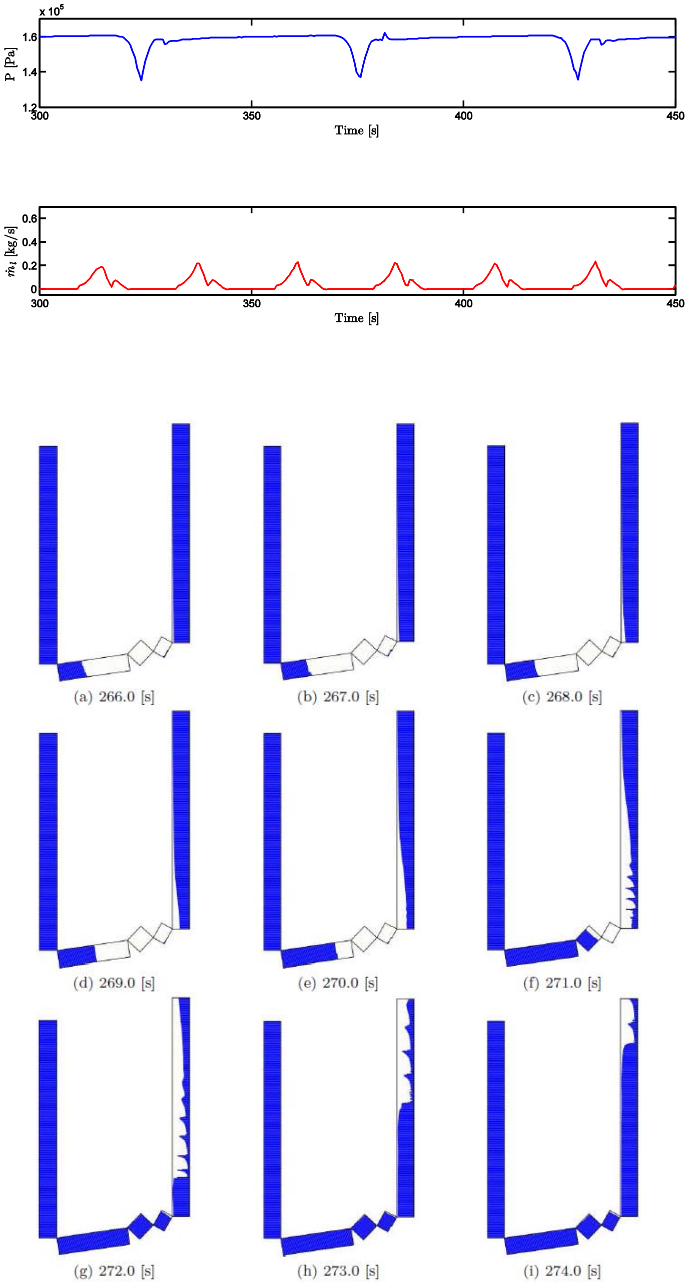


Figure 6 Amplitudes in pressure oscillations at riser base



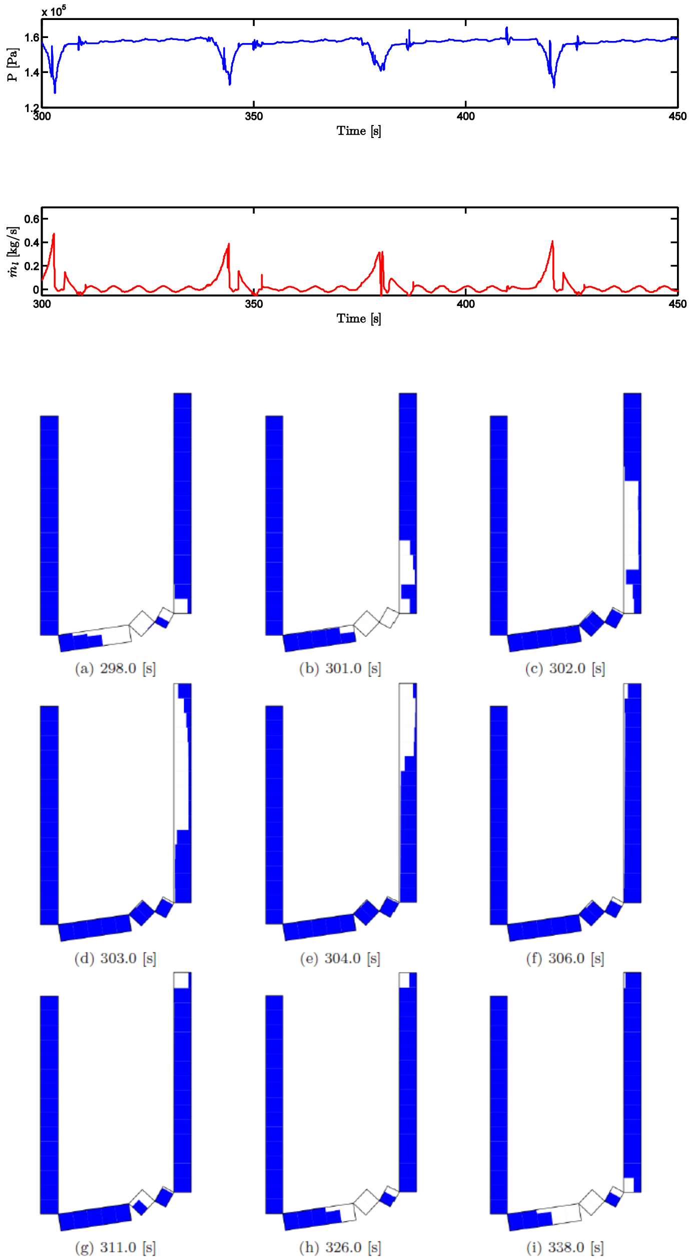
(a) 266.0 [s] (b) 267.0 [s] (c) 268.0 [s]

(d) 269.0 [s] (e) 270.0 [s] (f) 271.0 [s]

(g) 272.0 [s] (h) 273.0 [s] (i) 274.0 [s]

Figure 7 OLGA standard scheme
Pressure and liquid flow rate. Gas flow rate 2 10^{-5} kg/s

The standard two fluid model was simulated with a fine grid, which is smaller than the averaging length for the slug flow. The small scale dynamics is therefore according to a slip model for averaged slug flow, and the wavy structure in the fine grid simulation in Figure 7 is therefore not physical, but the liquid fraction should be consistent with the liquid fraction in averaged slug flow .



(a) 298.0 [s] (b) 301.0 [s] (c) 302.0 [s]

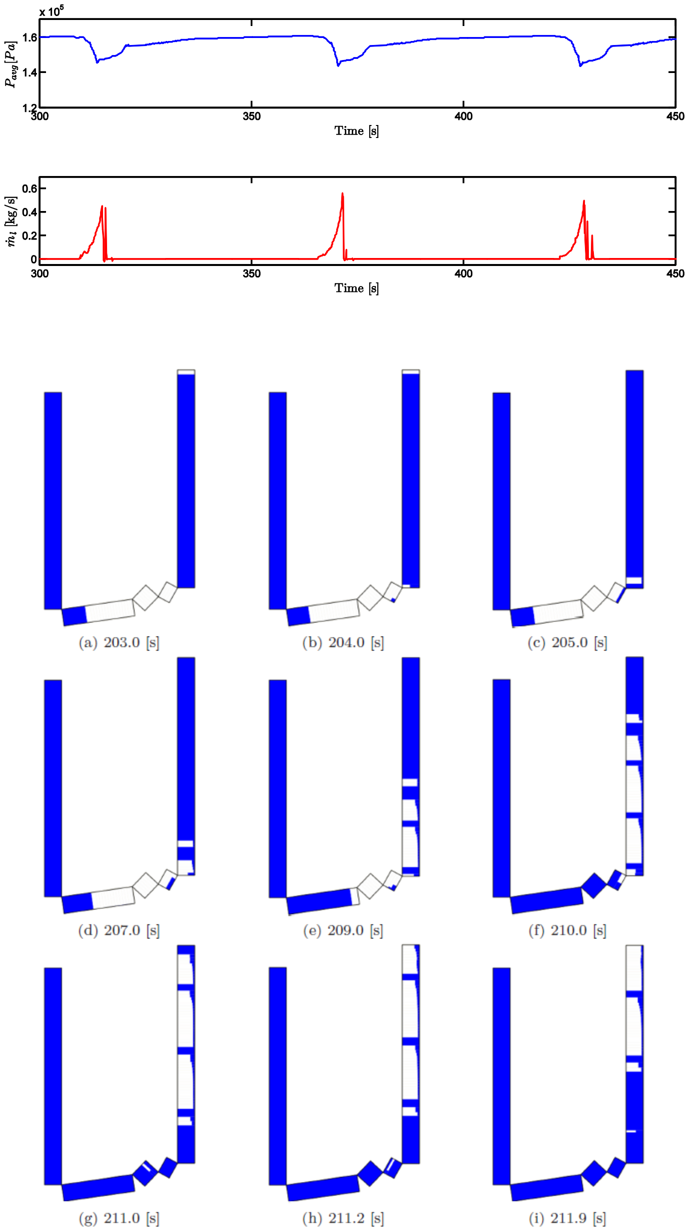
(d) 303.0 [s] (e) 304.0 [s] (f) 306.0 [s]

(g) 311.0 [s] (h) 326.0 [s] (i) 338.0 [s]

Figure 8 OLGA slug tracking
Pressure and liquid flow rate. Gas flow rate 2 10^{-5} kg/s

The sub grid slug tracking model as simulated with OLGA gives sharp fronts, but longer oscillation times. The Sluggit results look similar, but gives even longer oscillation times.

The slug tracking simulations do depend on the model parameters related to slug and bubble initiation, and it is difficult to avoid grid dependencies in such models.



(a) 203.0 [s] (b) 204.0 [s] (c) 205.0 [s]
(d) 207.0 [s] (e) 209.0 [s] (f) 210.0 [s]
(g) 211.0 [s] (h) 211.2 [s] (i) 211.9 [s]

Figure 9 Sluggit slug tracking
Pressure and liquid flow rate. Gas flow rate 2 10^{-5} kg/s

CONCLUSIONS

The problem of expansion driven instabilities is demonstrated with a small scale experimental setup. Local gas accumulation upstream the riser base can be periodically flushed through the bend due to gas expansion along the riser.

The flow phenomenon has been simulated with a standard two fluid model (OLGA) and with slug tracking models (OLGA and Sluggit). Flow instabilities are reproduced by the models, but with varying accuracy, the standard model coming closest to the experimental results.

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