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Simulations of severe slugging during depressurization of an oil/gas pipeline

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Dynamic simulators for pipelines with multiphase flow have proved to be important computational tools for both design and operational support of oil and gas production systems. One important aim of such simulators is to predict the arrival time and magnitude of outlet liquid transients after production changes made by an operator of a pipeline. A multiphase flow simulator (OLGA-94.1) with a two-fluid model has been applied to simulate depressurization of a pipeline during a shutdown procedure. During depressurization liquid slugs may form and propagate towards the outlet. The importance of the numerical method for predictions of such transients is demonstrated by using an Eulerian, finite difference, implicit, upwind scheme both with and without a front tracking scheme. First the initial conditions for the depressurization is established from a shut-down simulation where the production at the inlet is closed down, and the liquid comes to rest at low points along the pipeline. A realistic depressurization is simulated by opening a choke at the outlet of the pressurized pipeline. The numerical scheme without front tracking (standard scheme) gives outlet gas and liquid flow rates which are smeared out in time due to numerical diffusion. Simulations with the front tracking scheme give intermittent gas-liquid flow arriving as sharp fronts at the outlet. The total remaining fluid in the pipeline after the depressurization is larger when using the standard scheme.

Keywords: *depressurization, severe slugging, slug tracking*

1. Introduction

In the petroleum industry, the use of multiphase transportation systems is increasingly common. The design of multiphase transportation systems, however, requires more planning and represents a higher degree of technological challenges than the design of ordinary oil/gas transportation systems. Hence during the design of the multiphase transportation system, the performance of simulators is of great importance. The flow regime that probably causes most problems and requires special attention in multiphase flow is slug flow. Slug flow includes: terrain induced slugs, startup slugs, normal quasi steady state slugs and transients following changes in production. All these flow phenomena are characterized by rather sharp holdup gradients propagating through the system as well defined liquid entities. Knowing the sizes of these liquid slugs is important in order to determine the capacity of the so-called slug catcher at the receiving facility.

The dynamic, one-dimensional multiphase flow model OLGA (Bendiksen *et al.*, 1991) includes both one-, two-, and three-fluid models to describe one-phase, two-phase and three-phase flow in pipelines, respectively. The standard model is Eulerian and uses

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an upwind finite difference numerical scheme with an implicit time integration. This scheme is prone to numerical diffusion of sharp slug fronts and tails and thus fails to predict correct slug sizes. However, OLGA also includes a slug tracking model. The slug tracking model is based on the same Eulerian scheme as used in the standard two-fluid model, but superimposed on this scheme is a Lagrangian type front-tracking scheme. Each slug tail or front is described with a Lagrangian coordinate which gives the position of the tail or front as function of time. When the positions of the discontinuities are known, the standard Eulerian numerical scheme can be modified with corrected mass fluxes, gravity terms, etc. The slug fronts and tails are thus described in a non-diffusive way. This hybrid Lagrangian-Eulerian scheme is applied for regions with slug flow, while the standard Eulerian scheme is applied for the other regions.

This paper presents simulation results for depressurization of an oil/gas pipeline. Both the ordinary two-fluid model and the slug tracking model are used.

Depressurization of oil/gas pipelines is a standard procedure that is performed after a shut-down period when the fluid has reached sea-bed temperature. At such low temperatures the light components of the hydrocarbon mixture and the water form hydrates above a certain critical pressure. The value of this critical pressure depends on the composition of the hydrocarbon mixture and the amount of water present. The depressurization procedure is performed in order to avoid formation of hydrates or to remove hydrates that have been formed. Hydrates are similar in consistence to ice or slush and may totally block the pipeline if they appear during production.

First we present the physical models and the numerical methods. Second the simulator is verified against large scale start-up slug experiments. Then the simulations of depressurization are shown, followed by the concluding remarks.

2. Physical model

The slug tracking model (Straume *et al.*, 1992) was implemented for the dynamic one-dimensional two-phase flow option (Bendiksen *et al.*, 1991) in the three-phase flow code OLGA. Here we will shortly describe the two-fluid and slug tracking models and we refer to the above citations for the detailed descriptions.

2.1. *The two fluid model*

The simulation of hydrocarbon mixture transport in pipelines is based on the conservation of mass, momentum and energy. These conservation principles are expressed on one-dimensional form formally obtained by integration of the physical laws over the pipe cross section. This entails that the different phases coexist in the same points, see Ishii (1975). The interactions between the phases and between fluid and the pipe wall must be modelled. The flow patterns in two-phase flow vary considerably. In OLGA these different patterns have been grouped into four flow regimes, stratified, annular, slug and bubble flow. The basic equations are the same for all regimes while the closure reations (e.g. wall and interfacial friction) vary. The transitions between the four regimes are treated as an integral part of the model.

In the two-fluid model in OLGA a droplet field has been included for stratified and annular flows. Conservation of mass is thus expressed for the gas, liquid at the wall and liquid droplet fields, separately, whereas only two (gas-droplet core and liquid at the wall) momentum equations are applied. An equation for pressure is developed from the mass conservation equations. OLGA is also provided with a mixture energy conservation equation. However, energy calculations has only partly been performed in this work. Fluid properties are tabulated as function of pressure and temperature. The conservation equations for mass, momentum and energy as well as the pressure equation are presented below.

Conservation of mass

Gas phase:

$$\frac{\partial}{\partial t}(\alpha\rho_g) = -\frac{1}{A}\frac{\partial}{\partial z}(A\alpha\rho_g U_g) + \Psi_g + G_{sg} \tag{1}$$

Liquid phase at the wall:

$$\frac{\partial}{\partial t}(\beta\rho_l) = -\frac{1}{A}\frac{\partial}{\partial z}(A\beta\rho_l U_l) - \Psi_g\frac{\beta}{\beta+\gamma} - \Psi_e + \Psi_d + G_{sl} \tag{2}$$

Liquid droplets:

$$\frac{\partial}{\partial t}(\gamma\rho_l) = -\frac{1}{A}\frac{\partial}{\partial z}(A\gamma\rho_l U_d) - \Psi_g\frac{\gamma}{\beta+\gamma} + \Psi_e - \Psi_d + G_{sd} \tag{3}$$

where t and z are time and axial coordinate, respectively. α, β, γ are the gas, liquid film, and liquid droplet volume fractions, ρ is the density, U is the velocity, and A is the pipe cross section area. Subscripts g, l and d indicate gas, liquid and droplets, respectively. Ψ_g is the mass transfer rate between the phases, Ψ_e, Ψ_d are the droplet entrainment and deposition rates and G_{sf} is the mass source of phase f.

Conservation of momentum

Gas/liquid droplet core:

$$\frac{\partial}{\partial t}(\alpha\rho_g U_g + \gamma\rho_l U_d) = -(\alpha+\gamma)\left(\frac{\partial p}{\partial z}\right) - \frac{1}{A}\frac{\partial}{\partial z}(A\alpha\rho_g U_g^2 + A\gamma\rho_l U_d^2) - \frac{\tau_g S_g}{A} - \frac{\tau_i S_i}{A}$$
$$+ \Psi_g\frac{\beta}{\beta+\gamma}U_a + \Psi_e U_l - \Psi_d U_d + g(\alpha\rho_g + \gamma\rho_l)\cos(\phi) \tag{4}$$

Liquid at the wall:

$$\frac{\partial}{\partial t}(\beta\rho_l U_l) = -\beta\left(\frac{\partial p}{\partial z}\right) - \frac{1}{A}\frac{\partial}{\partial z}(A\beta\rho_l U_l^2) - \frac{\tau_l S_l}{A} + \frac{\tau_i S_i}{A} - \Psi_g\frac{\beta}{\beta+\gamma}U_a$$
$$- \Psi_e U_l + \Psi_d U_d + g\beta\rho_l\cos(\phi) - g\beta(\rho_l - \rho_g)D\sin(\phi)\frac{\partial\beta}{\partial z} \tag{5}$$

where subscript i indicates interface, p is pressure, τ is shear stress, S are the wetted perimeter, D is the pipe diameter, g is the gravitational acceleration, U_a is the velocity of the condensing or evaporating gas and ϕ is the pipe angle with the vertical. Sources (G_{sf}) are assumed to enter at an angle of 90 degrees to the pipe wall, carrying no net momentum and are therefore not present in the momentum equations.

Pressure equation

An equation for the pressure is obtained by expanding the transient terms in the mass conservation equations (using the relation $\rho = \rho(p)$), dividing by the densities and adding the resulting equations. The pressure equation, also named the volume conservation equation, becomes

$$\left[\frac{\alpha}{\rho_g}\left(\frac{\partial\rho_g}{\partial p}\right)_{T,R_s}+\frac{1-\alpha}{\rho_l}\left(\frac{\partial\rho_l}{\partial p}\right)_{T,R_s}\right]\frac{\partial p}{\partial t}=-\frac{1}{A\rho_g}\frac{\partial(A\alpha\rho_g U_g)}{\partial z}-\frac{1}{A\rho_l}\frac{\partial(A\beta\rho_l U_l)}{\partial z}$$

$$-\frac{1}{A\rho_l}\frac{\partial(A\gamma\rho_l U_d)}{\partial z}+\Psi_g\left(\frac{1}{\rho_g}-\frac{1}{\rho_l}\right)+G_{sg}\frac{1}{\rho_g}+G_{sl}\frac{1}{\rho_l}+G_{sd}\frac{1}{\rho_l} \quad (6)$$

T is the temperature and R_s is the gas mass fraction.

Conservation of Energy

The mixture energy conservation equation reads

$$\frac{\partial}{\partial t}\left[m_g\left(E_g+\frac{1}{2}U_g^2+gh\right)+m_l\left(E_l+\frac{1}{2}U_l^2+gh\right)+m_d\left(E_d+\frac{1}{2}U_d^2+gh\right)\right]=$$

$$-\frac{\partial}{\partial z}\left[m_g U_g\left(H_g+\frac{1}{2}U_g^2+gh\right)+m_l U_l\left(H_l+\frac{1}{2}U_l^2+gh\right)\right.$$

$$\left.+m_d U_d\left(H_d+\frac{1}{2}U_d^2+gh\right)\right]+H_s+U \quad (7)$$

where E is the internal energy per unit mass, h is the elevation, H_s is the entalphy from mass sources and U is the heat transfer from the pipe walls. The walls may be totally insulated, or composed of layers of different thickness, heat capacity and conductivity. The wall description may change along the pipeline.

The above set of conservation equations are written in a general form in order to apply for all flow regimes. Observe, however, that certain terms are ignored for certain flow regimes; e.g. inside slugs all droplet terms are dropped. In order to close the equation system, initial and boundary conditions, closure laws for friction in the two momentum equations, models for droplet entrainment and deposition as well as relations for mass transfer between the phases, are introduced. Details are given in Bendiksen *et al.* (1991).

2.2. *The slug tracking model*

The slug flow model in the standard two-fluid model operates with an average slug flow with no information about individual slugs. The slug tracking model on the other hand introduces slug tail and front positions for each slug and follows the propagation of these discontinuities through the pipeline. In this work we are interested in the propagation of the so-called start-up slugs during a depressurization of the pipeline. The criterion for initiation of a slug front or tail is then a large abrupt change in liquid holdup. Hydrodynamic slug flow (shorter slugs originating from waves) is modelled by the average slug from regime. It should be mentioned that also these types of slugs may be modelled by the slug tracking model (see Straume *et al.* 1992). Inside the individual slugs the bubbly flow regime is applied. Between each slug initiated by the slug tracking model all four regimes stratified, annular, bubbly and average slug flow may exist.

After the initiation of a slug, the front and tail positions, Z_f and Z_t, are changing in accordance with

$$Z_f^{new}=Z_f^{old}+U_f\Delta t, \quad (8)$$

$$Z_t^{new}=Z_t^{old}+U_t\Delta t. \quad (9)$$

Here U_f and U_t are the front and tail velocities and Δt is the time step. Slug fronts and tails are treated separately. They may propagate in different directions and independently change propagation direction during the simulation. The model distinguishes between two types of fronts/tails; a bubble nose type which typically is the tail of the liquid slug and a level/breaking front type. The transition between these two types is dynamic and governed by pipe inclination angle, propagation direction and liquid velocity in the liquid slug. A nose is characterized by a large bubble which propagates into the liquid slug. Bubble nose correlations are then applied to calculate the velocity of the tail U_t (or possibly the front U_f),

$$U_t = C_0 U_{ls} + U_0. \tag{10}$$

Here C_0 depends on the inclination of the pipe and U_0 is the bubble rise velocity in stagnant liquid. If, on the other hand, a tail or front is of type level/breaking front, its velocity is calculated from a volumetric balance. For a front the velocity is then given by

$$U_f = U_{mix,sl} + Q_g + Q_d + Q_l. \tag{11}$$

Here $U_{mix,sl}$ is the gas and liquid mixture velocity (the total superficial velocity) in the liquid slug close to the tail or the front. Q_g, Q_d and Q_l are the volumetric fluxes of gas, droplets and liquid film across the tail or front. The above volumetric fluxes are given by

$$Q_l = (1 + \alpha_B - \gamma_B)(U_f - U_{lB}) \tag{12}$$

$$Q_d = \gamma_B(U_f - U_{dB}), \qquad Q_d > 0 \tag{13}$$

$$Q_d = 0, \qquad \text{otherwise} \tag{14}$$

$$Q_g = k_1 \frac{S_i}{D}(U_f - U_{lB}) - k_2, \qquad Q_g > 0 \tag{15}$$

$$Q_g = \alpha_s(U_f - U_{gs}), \qquad Q_g < 0 \tag{16}$$

where indices B, s and f indicate bubble, slug and liquid film, respectively. α and γ are volumetric fractions of gas and droplets, respectively. k_1 and k_2 are constants. Equation (15) applies when gas is entrained into the liquid slug by a breaking front and is generally valid for near horizontal flow (Nydal and Andreussi, 1991), only.

3. Numerical method

We will shortly describe the numerical methods and refer to Bendiksen *et al.* (1991) and Straume *et al.* (1992) for more detailed descriptions.

The physical problem, as formulated in the previous section, yields a set of coupled first order non-linear, one-dimensional partial differential equations with rather complex non-linear coefficients. These equations are solved numerically applying a direct, multiple step, semi-implicit time integration scheme. First, the momentum and pressure equations are solved. Then, the mass equations for liquid film and droplets and the mass equation for the gas are solved. Finally, the energy equation is solved. OLGA uses a finite difference numerical method with a staggered mesh where temperatures, pressures and fluid properties (volume variables) are defined in cell midpoints while velocities and fluxes are defined at cell boundaries. Fluxes are modelled upwind due to numerical stability. However, this scheme is prone to numerical diffusion (Straume *et al.*, 1992) and physical discontinuities are smeared out. Due to the shortcomings of

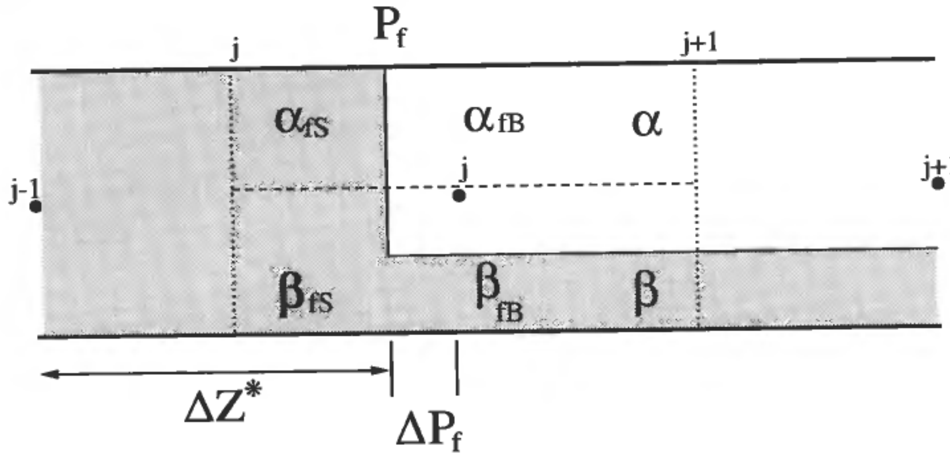

Figure 1. Example with front of long liquid slug in cell j.

this scheme, and the need for more accurate predictions of the different types of slug flow, the slug tracking model was developed. By introducing a Lagrangian front tracking scheme superimposed on the Eulerian scheme described above, the sharp discontinuities are well predicted and at the same time the numerical stability is retained.

In the slug tracking model, cells with discontinuities are identified and divided into two parts with bubble flow and separated flow on each side of the discontinuity. Phase fractions and phase velocities representative for each flow regime are then calculated. This is done within the frame of the two-fluid model, and the basic grid of the two-fluid model is not altered. However, terms in the conservation equations of the two-fluid model are modified. This concept is sketched in Fig. 1, where the front of a long liquid slug is present within cell j. The cell is then divided into a liquid slug part with gas fraction α_{fS} and a slug bubble part with gas fraction α_{fB}. The average gas fraction is denoted α. The corresponding liquid fractions are denoted β_{fS}, β_{fB} and β. To simplify the picture, the droplets are disregarded in this description. For the mass equations, only the mass transport over the cell boundaries are affected by the front tracking option. In the ordinary two-fluid model, the liquid transport over boundary $j+1$ in Fig. 1 for flow towards the right is given by

$$W_{l,j+1} = m_{l,j} U_{l,j+1} A_{j+1} \tag{17}$$

where $m_{l,j} = \rho_{l,j}\beta_j$ is the liquid mass per volume in cell j and A_{j+1} is the pipe cross section area at boundary $j+1$. In the slug tracking model this mass transport, for $U_{l,j+1} > 0$, is modified to

$$W_{l,j+1} = \rho_{l,j}\beta_{fB,j} U_{l,j+1} A_{j+1} \tag{18}$$

which is still an upwind type scheme. The void fractions, α_{fS} and α_{fB} are calculated from volumetric balances. Similar modifications apply to all mass transport terms in the mass and pressure equations and there are also similar modifications in the momentum equations, see Straume *et al.* (1992).

To exemplify the numerical diffusion mechanism of the discontinuities we consider the case shown in Fig. 1, but with no liquid ahead of the slug front ($\beta_{fB} = 0$, $\beta_{j+1} = 0$, etc.). This could be the situation in a vertical riser and physically no liquid would flow across boundary $j+1$ until the front reaches this boundary. Equation (18) describes this situation correctly, whereas equation (17) immediately would transfer liquid across boundary $j + 1$. Since an implicit time integration is used, erroneous mass transfer is obtained at neighbour boundaries as well and the discontinuity is effectively smeared out.

4. Verification

Large scale start-up slug experiments

A realistic test of the method is provided by comparisons with a series of start-up slug (Hedne, 1989) and terrain induced slug (Linga, 1987) experiments from the SINTEF[1] Multi-phase Flow Laboratory, see Bendiksen *et al.* (1990) and Straume *et al.* (1992).

In the start-up slug experiments the pipeline (total length of 995 m, and ID of 19 cm) has a dip of length 2×25 m, 205 m downstream of the inlet with inclination of $\mp 5°$. The fluids are naphta and nitrogen at a system pressure of 45 bar. The experiments are started by emptying the pipeline of liquid, filling the dip with naphta, and driving the slug out of the pipeline by increasing the inlet gas flow rate from zero to a steady state value in 5–30 s.

The liquid holdup at three positions (249, 279, and 420 m from the inlet) are shown in Figs. 2a–c for one particular gas flow rate (4 m/s). The standard scheme significantly smears out the slug (dashed line in Fig. 2a–c). In fact, gas has penetrated the 50 m long slug after it has propagated only 60 m in this case. The integrated amount of liquid transported, however, is reasonably well predicted over a much longer distance. Applying the front tracking scheme (dash-dotted lines in Fig. 2a–c), the slug is not diffused, and the tail and front positions of the slug compares well with the experiment. In Fig. 2d the effect of grid refinement is shown for both schemes. A halving of the cell lengths entails only small modifications in the results and the large differences in the predictions with the two schemes prevail.

5. Simulation of depressurization

The simulations are performed as follows:

1 First constant production is simulated with a total mass flow rate of 65 kg/s at the inlet. The temperature of the fluid at the inlet is 85°C and the pressure at the outlet is 70 bar.

2 Thereafter the pipeline is shut down by reducing the total mass flow rate at the inlet linearly to 0 over 100 seconds. At the outlet a valve is closed over 10 seconds. The pipeline is then kept shut-down for about 139 hours (500 000 seconds) until the fluid temperature equals that of the surroundings, which is 5°C, and the liquid comes to rest at the low points of the pipeline. A sketch of the pipeline profile (excluding riser and platform piping) and the holdup profile along the pipeline after 130 hours of stagnation are shown in Figs. 3a and 3b, respectively. It is seen that the liquid has accumulated at the 5 low points of the pipeline.

3 The pipeline is then depressurized for about 55·5 hours (200 000 seconds). This is done by opening a choke at the outlet. The downstream pressure of the choke is 1 bar.

[1] The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology.

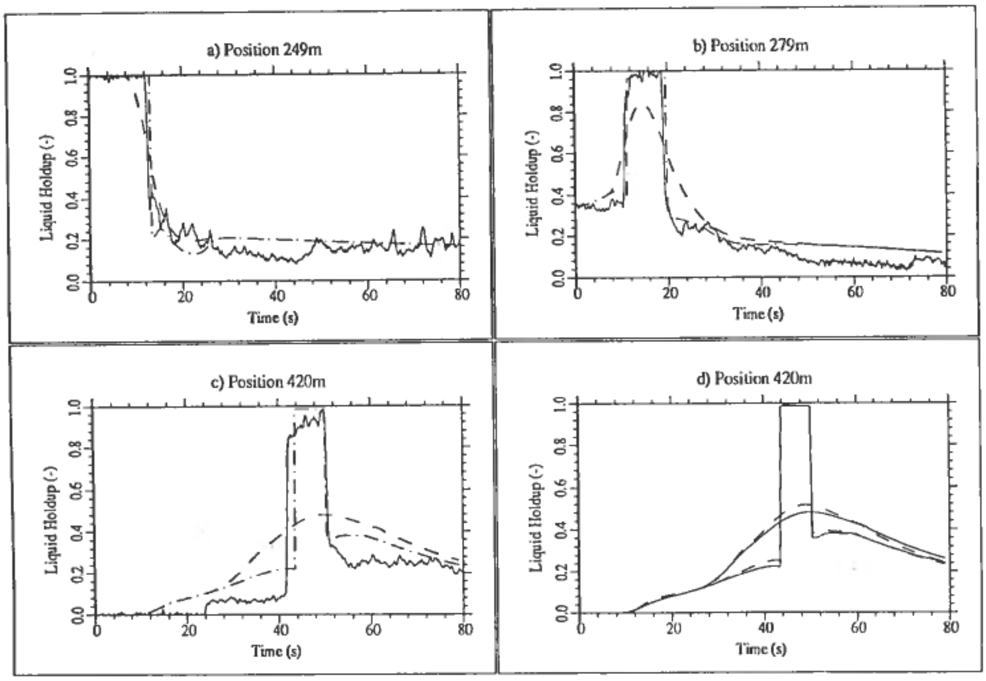

Figure 2. Predicted and measured liquid holdup at three positions; a) 249 m, b) 279 m and c) 420 m in experiment 6612 (4·0 m/s) (— Experiment, –.–. The front tracking scheme, - - - - Standard scheme). d) Grid sensitivity test. Predicted liquid holdup at position 420 m. — Original cell lengths, - - - - halved cell lengths.

It should be mentioned that the energy calculations are not performed for point 3, the depressurization of the pipeline, since such calculations are not yet included in the slug tracking model. The weakness of the standard upwind scheme is demonstrated in Figs. 3c–d. These figures contain two holdup profiles predicted with the two schemes/models along the pipeline when the choke at the outlet has been open for 500 and 900 seconds, respectively. The standard scheme has smeared out the liquid slugs. With the front tracking scheme the slugs are not diffused.

Time plots in the cell upstream of the choke show that the standard upwind scheme predicts a total liquid mass flow rate that is smooth in time, see Fig. 4a. The front tracking scheme, however, predicts two large liquid slugs leaving the pipeline. At the most, the liquid mass flow rate predicted by the front tracking scheme is more than four times larger than the rate predicted by the standard upwind scheme. The accumulated liquid flow out of the pipeline is plotted in Fig. 4b. The front tracking scheme gives a higher value than the standard upwind scheme. Plots of pressure and holdup in the cell upstream of the choke are shown in Fig. 4c and 4d. While holdup is smeared out for the upwind scheme, the front tracking scheme shows that two liquid slugs will pass this cell. This is reflected by the pressure curve which falls when the slugs pass the cell. The standard upwind scheme gives a smooth pressure curve.

It was five liquid slugs in the pipeline before the depressurization procedure was started. Looking at Fig. 4, however, it can be seen that only two liquid slugs leave the pipeline. In order to find out what has happened to the remaining three slugs, a more detailed study is required. First we look at Fig. 5 where the total number of slugs in the pipeline versus time is plotted. It is seen that all the original five slugs first disappear.

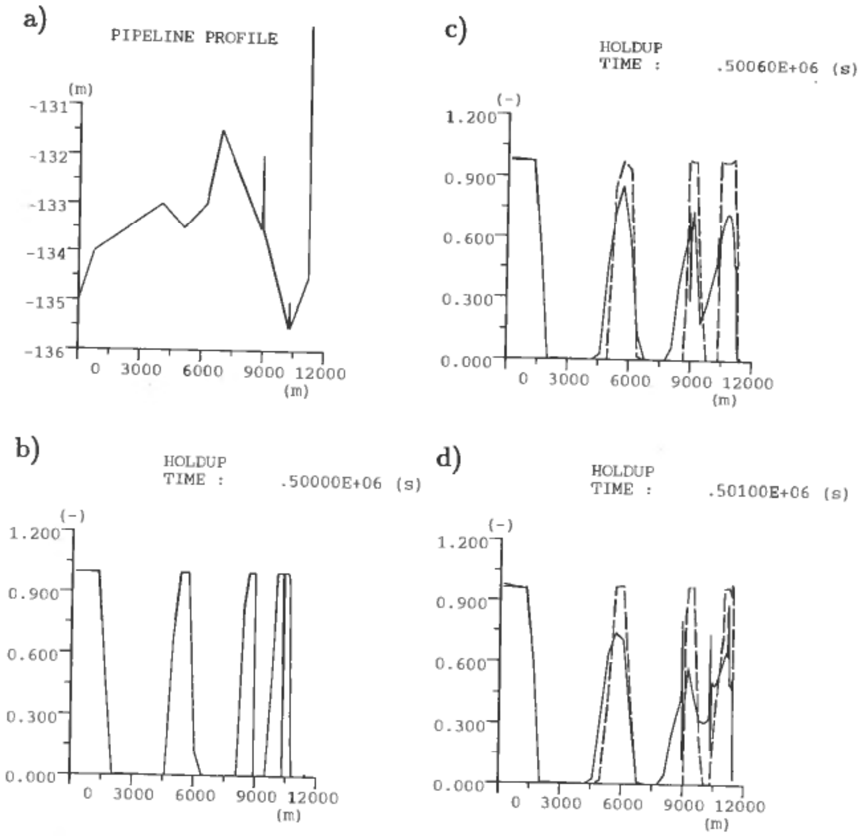

Figure 3. a) The pipeline profile (without riser and platform piping). b) The holdup profile along the pipeline after 139 hours of shut-down. c) Holdup profile when the choke at the outlet has been open for 500 seconds. d) Holdup profile when the choke at the outlet has been open for 900 seconds. (— standard scheme, - - - front tracking scheme).

Then a new slug is created, which quickly disappears. At the end of the simulation time, when the flow has come to rest, four slugs are present in the pipeline. Figs. 6–7 show plots of the front and tail positions of the ten slugs that are detected in the pipeline during the entire simulation time.

- It is seen that slug number one disappears at about 4500 meters down the pipeline. This is caused by a too low holdup gradient at the front such that the criteria for a slug front is no longer fulfilled.
- The 2nd and 5th slugs disappear because the tail overtakes the front. That is, the slug bubble penetrates the liquid slug leaving only a liquid film behind.
- Slugs number 3 and 4 are the only ones that actually propagate through the whole pipeline and finally pass through the choke.

After all the original slugs have disappeared, five new slugs are created.

- Slug number 6 vanishes in the same way as slugs number 2 and 5.
- The slugs 7, 8, 9 and 10 are stagnant slugs. However, when the production is started again, these slugs will start to move towards the end of the pipeline.

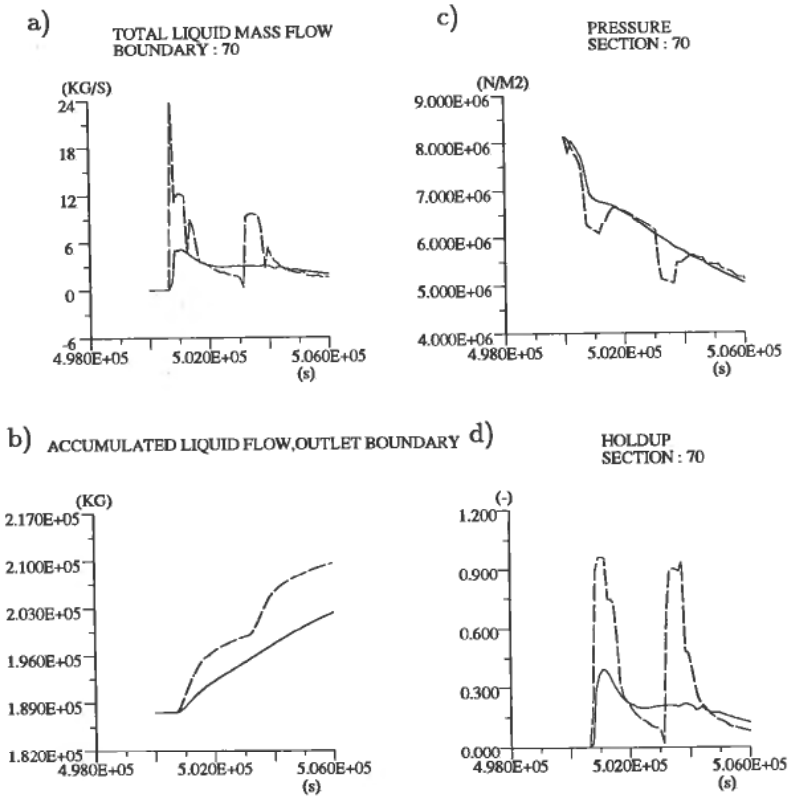

Figure 4. a) Time plot of the total liquid mass flow rate in the cell upstream of the choke. b) Time plot of the accumulated liquid flow out of the pipeline. c) Time plot of pressure in the cell upstream of the choke. d) Time plot of holdup in the cell upstream of the choke. (— standard upwind scheme, - - - front tracking scheme).

6. Conclusion

A two-fluid model with a standard upwind numerical scheme as well as a front tracking scheme has been used for simulating a depressurization procedure. The standard scheme is of the Eulerian type and uses an implicit, upwind cell, finite difference technique. Such schemes are prone to numerical diffusion of sharp discontinuities. In addition, with this type of scheme slug flow is treated in an average manner and there is no information of individual slug details such as their length and velocity. The slug tracking model uses a Lagrangian type front tracking scheme that is superimposed on the implicit, upwind Eulerian scheme described above. The slug fronts and tails are thus described in a non-diffusive way and detailed information about each slug is also available.

With the standard upwind scheme the predicted total liquid mass flow rate out of the pipeline was smooth in time. Simulations with the front tracking scheme, however, predicted two large liquid slugs leaving the pipeline. At the most, the liquid mass flow rate predicted by the front tracking scheme was more than four times larger than the rate predicted by the standard upwind scheme. Also the accumulated liquid flowing out of the pipeline during depressurization was larger when the slug tracking model was used. From the slug tracking model we also found that only two of the initially five slugs were transported out. During the simulation five more slugs were initiated and four slugs

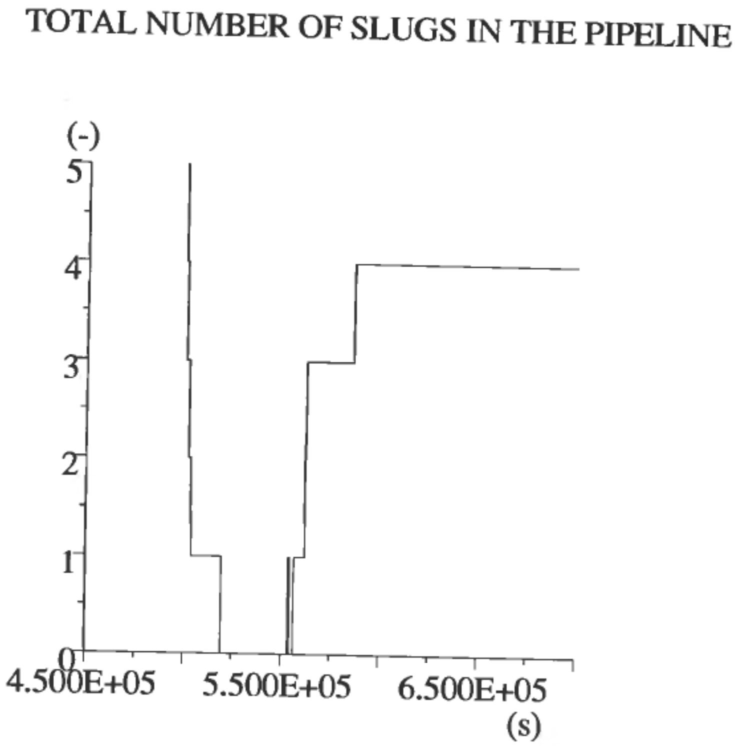

Figure 5. Total number of slugs in the pipeline as function of time when the front tracking scheme is used.

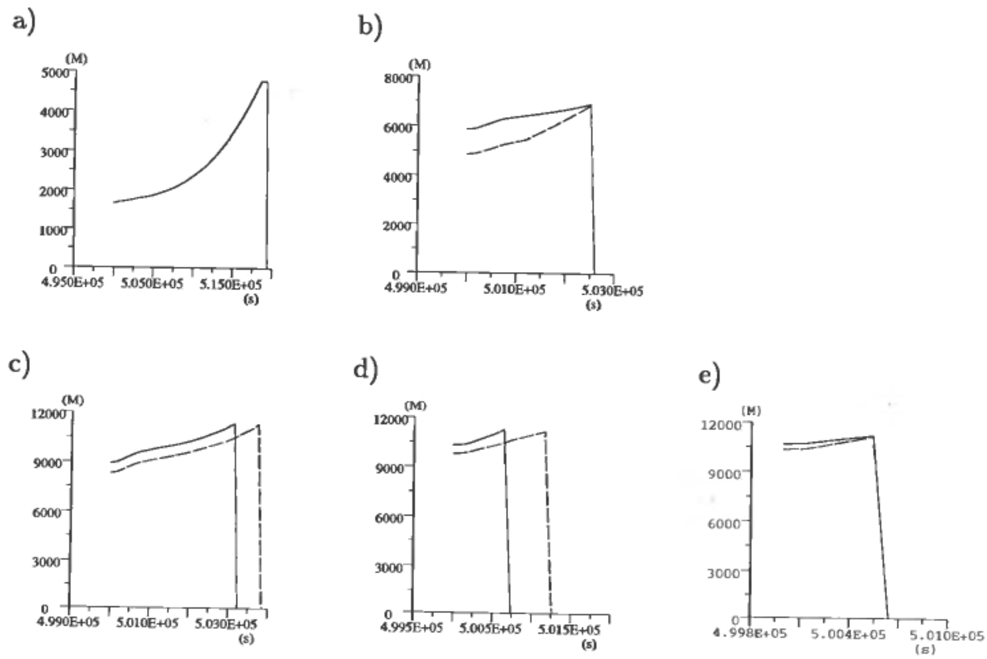

Figure 6. Time plots of the slug-front (—) and -tail (- - -) positions. a) Slug number 1. b) Slug number 2. c) Slug number 3. d) Slug number 4. e) Slug number 5.

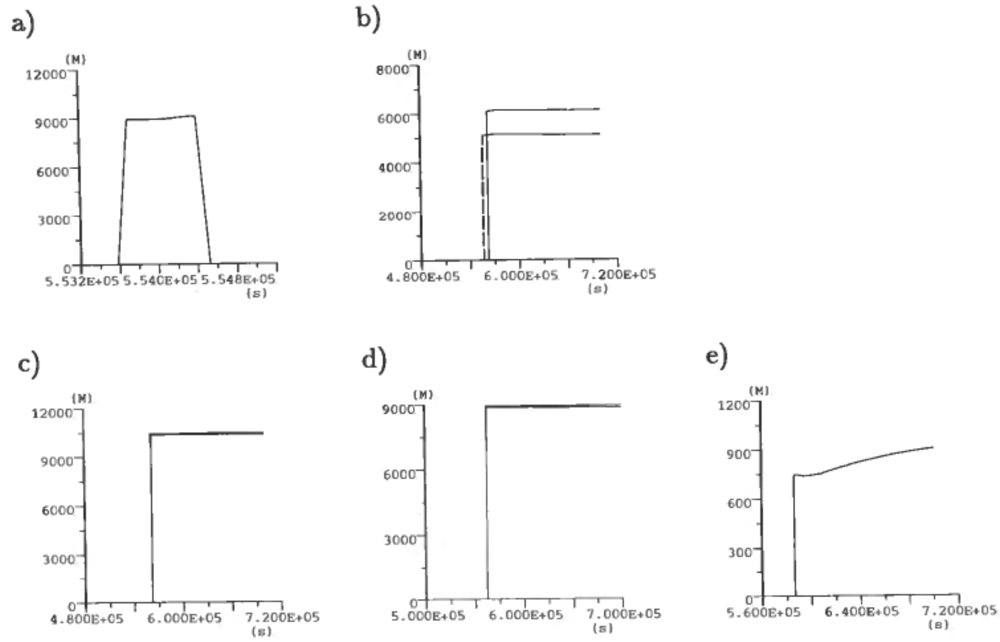

Figure 7. Time plots of the slug-front (—) and -tail (- - -) positions. a) Slug number 6. b) Slug number 7. c) Slug number 8. d) Slug number 9. e) Slug number 10.

disappeared. At the end of the simulation, when the system had come to rest, four stagnant slugs were present in the pipeline.

The overall conclusion is that when making good tools for the design of multiphase pipeline systems both the basic physical models as well as the numerical scheme must be addressed. Especially we have seen that by applying a front tracking technique, slugs can be treated individually and the sharp holdup discontinuities at the slug fronts and tails can be handled in a non diffusive way. The result is a very different prediction of the liquid flow out of the pipeline compared with predictions using a standard Eulerian scheme.

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