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Abstract

In recent years, there have been rapid advances in the field of transient multiphase simulators due to the fact that they have proven to be accurate and reliable for the vast majority of cases in the oil and gas industry. The primary objective of this study is to validate LedaFlow software, a new transient multiphase simulator under development by Total, ConocoPhillips, SINTEF and KOGT. Two well flow cases were chosen, the cleanup of a gas well and the liquid loading in a gas well due to the fact that they offer valuable information for the production and process team. The possibility of its validation against the field data and well established transient simulator, OLGA, puts LedaFlow further into the development of the reliable CFD tool for the oil and gas industry. In addition, literature review was done for both cases in order to extend the knowledge of existing physical models and valuable experience from the other fields.

Prediction of brine flow rates expected during the simulation of the clean-up case was challenging. The availability of the operational data from the operations made it valuable for comparison with the model results and its possible tuning. The challenges for modeling are described and several parameters were tested for sensitivity. As a result, a better match was found by modifying input parameters and setting up, one of them is the gas-liquid friction factor. For the time being, it is not recommended to use LedaFlow to simulate clean up operations due to discrepancies with the field data. Although significant improvements have been required in order to produce satisfactory results.

The case of liquid loading in a gas well, literature review shows a broad range of correlations for Turner’s model to predict the critical gas rate. Two main roots of the liquid onset are stated as: liquid film reversal and droplet entrainment mechanism. Liquid loading is a highly transient phenomenon and it is advantageous to apply dynamic multiphase flow model to take into account both mechanisms. In this study LedaFlow is implemented to predict the onset of the liquid loading in the gas well, on the basis of the test data, and compare with the results acquired from running an OLGA simulation on the same data. The approach employed to modeling the well inflow, with several production zones, reproduced a better correlation between the OLGA results and the field data than the LedaFlow results. In general, the results from LedaFlow lay on the conservative side unlike OLGA that overestimates the value of wellhead pressure and gas rate for liquid onset. Therefore, for further simulations using both software, it is safe to say that the true value will be between OLGA and LedaFlow. The

challenge of matching the field data possibly lays within uncertainties in the information from the experiments, as detailed log data from the operation is missing.

A part of this study is devoted to the presentation of 1D and Q3D multiphase flow models, which are implemented in LedaFlow software, and used for predicting flow with coexisting continuous and dispersed phases. The 1D model is validated against the two well flow cases.

Interpreting the results is the key factor in understanding the physics behind the complex mechanisms and the further refinement of the models. Therefore, a part of this study is devoted to assessing the models, correlations and formulae used in the transient calculations performed by the software.

The general development of models to describe complex physics for well flows tends to move from empirical correlations towards mechanistic ones. However, high demands of the accuracy of the simulation results require constant development of CFD type codes. LedaFlow, a rapidly developing tool, has the structure that allows users to change the code, thus making it very flexible and accessible. The new functionality of Q3D development requires research but has a potential to meet the future demands and need of the oil and gas industry.

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Part 1. Introduction

Challenges the petroleum industry faces nowadays are various and numerous. It is a combination of the fact that operators are developing fields in harsher environments and that there has been an increase in tie-in fields thus increasing the distance between the well head and the platform. Multiphase fluids, complex geometry, distant pipelines provide a range of challenges that a production engineer must handle. Therefore, it is important to assess these issues prior to developing and during the operation of a field, to ensure the maximum return on capital invested.

The last 50 years of constant developments in one-dimensional modeling have highlighted the need for better prediction of flow patterns, pressure drops, and liquid holdups along the pipelines. However, these models still have gaps to be filled due to crude simplifications and empirical correlations. One of the most significant current discussions is a capability to predict flow transitions and detailed flow distributions. Central to the entire development of the existing models, is the concept of 3D modeling techniques. Nowadays, 3D Computational Fluid Dynamics (CFD) models present the results that qualitatively and quantitatively surpass results given by 1D models.

The major concern with 3D models is in direct simulation of interface evolution. However, a lot of attention needs to be paid to large-scale interfaces such as waves that coexist with bubble and droplets flow, along with deposition and entrainment. In addition, the research focuses on the challenge of large-scale spatial and temporal features without defining flow regimes. It is hoped that these challenges can be addressed via the further development of LedaFlow, a next generation transient simulator, which has 1D and quasi-3D models; a complex network solver; and an algorithm to couple models of different dimensions. The quasi-3D (Q3D) allows simulating sufficiently long sections of a pipe to predict flow development and flow regimes [1].

The biggest challenge for developing CFD tools is within required experimental and field data in order to verify them and improve them. These experiments are expensive and there is a lack of the required instrumentation. The real drawback of CFD tools today lies in the accuracy of predictions and sensitivity to the user input and the choice of equations. Complex physics description, complex geometry of the pipelines to test bring out a challenge of resource consumption regarding the time expenditure for the simulations to run, amount of data generation and its storage. These are the issues that have to be improved to meet the requirements dictated by the industry. Nevertheless, CFD tools are capable of providing detailed information when modeled correctly.

This study has a general learning objective of testing configuration and modeling of vertical flow in transient regime in the gas wells using LedaFlow 1D model.

The study objectives and structure

The main objective of this study is to assess the ability of the transient multiphase flow simulator, LedaFlow (v. 2.33.090), to give good predictions when it comes to the well flow cases. It is specifically aimed to evaluate and validate LedaFlow simulations of a gas well clean-up and liquid loading in a gas well. The review of the recent research within transient simulations of these operations helps to understand the challenges within CFD tools. In order to develop LedaFlow, see the weak points in the models and make improvements, the results from the simulations are compared with the field data and another CFD tool, OLGA (v. 5.3.2.4). The main questions addressed in the study are predictions of volumes and rates of completion fluid in the clean up case, and the wellhead pressure and critical gas rate for liquid loading onset.

This study has been divided into four parts. It begins by the introduction and overview of CFD tools complexity of today. It goes on to provide a general overview of flow assurance and its inherit challenges.

Part 2 describes the well flow cases for the simulation using the LedaFlow software. Literature research was carried out for both well clean up and liquid loading cases in order to evaluate the update possibilities of 1D modeling and, closure models, and correlations used. The assessment of the prediction quality by LedaFlow draws attention to the code and closure models used.

Part 3 is devoted to the flow modeling description implemented in LedaFlow. 1D model calculations show the major equations used for the transient performance. A concept of Q3D model is shortly presented for an overview.

Finally, the conclusions and recommendations for future work are defined.

2. Total E&P Norway

This chapter presents the overview of the Total Group in general and Research and Development department in Stavanger, Norway in particular. It mainly bases on the information from the official website of the company [2].

2.1 Global energy group

Total is the fifth largest international oil and gas company with production of 2,83 million barrels of oil equivalent per day and provided reserves of 10,7 billion barrels of oil equivalent by end of 2010. Total operates in more than 130 countries and has 92,855 employees. All aspects of the petroleum industry are presented in the company's activities: including upstream operations (oil and gas exploration, development and production, LNG) and downstream operations (refining, marketing and trading, shipping of crude oil and petroleum products). Total produces base chemicals as well as chemicals for industrial and consumer markets. Besides coal-mining and power generation, Total is developing and investing in next generation energy activities such as solar, biomass and nuclear ones.

2.2 Research and Development in Norway

TOTAL E&P NORGE is part of the TOTAL Group, involved in exploration and production of oil and gas on the Norwegian continental shelf, and produces approximately 300,000 barrels of oil equivalents every day. One of the six Total research centers is located in Norway. The R&D team in Stavanger consists of 7 professional full-time staff employees and about three internships each year. It focuses on the topics related to the Norwegian continental shelf, and the annual research budget in Norway is approximately NOK 200 million. The main areas or research are flow performance, subsea technology, subsurface, gas dispersion and marine environmental issues. An example of the joint industry (JIP) project that Total works on in cooperation with other companies and institutes is the LedaFlow project. This is by far the largest and one of the most important R&D project ever undertaken by Total.

3. Flow performance issues

Flow assurance mainly deals with providing reliable and safe fluid transportation from wells to processing facilities. To meet the requirement studies include analysis of thermal, hydraulic and production challenges that design, operation and maintenance of the systems face during field development. Multiphase dynamic software are used to perform analysis of the design and operational phases, further changes in compositions and flow rates.

The main aim with flow assurance is to "keep the flow path open" to ensure uninterrupted flow of produced hydrocarbons from reservoirs to host facilities in any environment at minimum capital and operating costs. The concept has appeared with the deepwater field developments and deals with problems common to all oil and gas companies.

There are two main groups of problems the flow assurance covers, depending on their origin:

- Problems related to physicochemical characteristics of the fluid which can cause solid deposition and, as a result, restriction to flow or full blockage. The main key factor to these issues is temperature and pressure. Corrosion/erosion issues are also associated with this category.
- Problems related to multiphase flow instabilities and thermal issues that might cause critical or un-operated conditions.

The first group of problems is connected to the deposit and/or plugging of production lines. Formation of hydrates, deposition of wax, asphalthenes, naphtenates and mineral deposits are the issues that engineer would evaluate the associated risk, determine the preventive means in normal and upset conditions, and define recommendations.

Flow assurance is one of areas within petroleum industry that uses simulation tools in order to ensure proper operation of design made by an engineer. To obtain reliable calculations, it is needed to understand the physical phenomena and to represent them in a way of good modeling. The tools require different competencies within many disciplines such as thermodynamics, chemistry, hydraulics, mechanics and etc. The simulator uses these models to produce qualitatively correct results. This thesis is mainly focused on a new simulation tool, LedaFlow, but also on comparing the field data with OLGA.

Part 2. Well flow cases

This part describes the well flow cases for the simulation using LedaFlow tool. Literature research is done for both well clean up and liquid loading cases in order to evaluate the update possibilities of 1D modeling and models and correlations used. The assessment of the prediction quality by LedaFlow draws attention to the code and closure models used.

4. Literature research on clean up case. Definition of well clean-up operation

The chapter gives information on the first of the well flow cases for investigation with the help of LedaFlow. It starts with the definition of the clean-up operation, followed by the literature review on the topic and description of the operational data and its validation against the software.

There is a significant amount of information on the definition of well clean-up operation. There are several that are chosen to be presented in the literature study. Espen Krogh et al. give the following description of a well clean-up operation that was published in the SPE paper applied for the Åsgard Field [3]. "Clean-up operations of oil and gas wells take place in the starting up and testing of the new drilled wells. To perform an optimal clean-up operation is important for the production properties of complex wells". "The well tubing and horizontal bores in openhole completions are normally filled with mud, packer fluid and base oil or similar completion fluids prior to start-up. Before the well is set in production these fluids are removed in a clean-up/testing operation. The reservoir pressure is normally the driving force for the clean-up, but in some cases additional artificial lift such as gas-lift may be applied to help weak production zones to start producing. "Due to highly dynamic nature of the clean-up process, it is beneficial to use transient multiphase flow simulator." "Historically clean-up operations have been planned and undertaken based on data from available models and logs, typically reservoir and production models, petrophysical, geological and PVT data, giving information about available pressure, production zone strength (productivity) gravity pressure drop and steady state tubing pressure drop. Recently, the use of dynamic flow models in design and planning of such operations have started to emerge in the industry. A dynamic model enables detailed modeling of flow, pressure and gas/oil/completion fluid fractions in the well and production zones with time, and can predict the transient behavior during start-up. "

Many researchers look into dynamic flow simulation of a well clean-up operation referring to the SPE 109829 paper written by SPT Group about different applications of dynamic simulation using OLGA software [4]. The paper reveals definition of well clean-up operation as well as kick-off. "Well clean-

up is defined as the period (from static initial conditions) when drilling and completion fluids are still coming out of the well, with producing hydrocarbons.
Well kick-off is defined as the period from the initial static conditions until steady flow conditions are reached, and only reservoir fluids are produced.
The minimum rate and time required to clean –up (or kick-off) the well are of extreme importance.
Dynamic simulation is a powerful technique for defining:

- Minimum rate and time to clean-up the well
- Size of testing equipment
- Multi-layer production results (commingling or with zone isolation and control)
- Influence on WHT when producing at different rates or when different layers are produced
- Well completion design – comparing for instances the multiphase flow behavior of a big-bore with a monobore completion during clean-up and production
- Well integrity / annular pressure – by including in the model a closed annulus filled with fluids, the internal pressure increase due to the heating-up effect caused when opening the well (producing hotter fluids), can be predicted ensuring it is below the allowed pressure limit.

Different well clean-up scenarios can be evaluated. The unloading scenarios can be planned and the relevant aspects compared.
The need for gas lift gas to clean-up the well can be evaluated, considering an empty or full of fluids flowline. Any "what if" scenario can be simulated prior to final well completion design and test equipment selection, and well in advance of actual operations.

As for the earlier publications on transient simulations of well clean-up operations, there are several ones to mention. One of them is done by Mantecon [4], Kerem, Prout and Oudeman [5] and Xu, Uv and Hu [6]. Mantecon states that transient simulations are valuable complementary to the steady state flow analysis. Using the latter only there is a lack of prediction of possible transient events that occur during production conditions. He comes up with a list of application for the transient simulations in wells for well clean-up and well kick-off by use of gas lift, as well as guidelines for use the model in well engineering.
Bin Hu, Egil Henrik and Zheng Gan Xu [6] studied the co-flow of reservoir fluids and Non-Newtonian drilling/completion mud in long multilateral horizontal wells. In the study they focused on the evaluation of different parameters like mud yield stress, wellbore inclination, velocity slip between reservoir and completion fluid. Kerem, Proot and Ouderman [7] presented the results of analysis of the inflow performance and inflow distribution of one smart and two problematic conventional long and tortuous horizontal well in Brunei. The simulations showed that the problems in the conventional well are not that significant, and that inflow control valves in the smart wells add value. The wells were simulated from the startup until the early production phase; in this case it was mud removal and

stabilized well flow. The results of the rates and pressures from the simulation for the two conventional wells matched with the available well test measurements. Moreover, the result justifies the smart well completion.

Krogh, Mjaaland and Sletfjerding [3] performed a clean-up case study of a dual branch long horizontal well at the Åsgard field. The model included eleven production zones located in the main and lateral wellbores, as well as sand screens with inflow control devices. The results of the simulations were part of planning the operation, and, after the performing the operation, were compared to the well test data to be able to tune the model. Successful tuning confirmed that dynamic simulations being a useful tool to predict and understand the behavior of a clean-up operation.

Duplat, Dong, Hu and She [8] worked on the model which involves the simultaneous transient flow of nitrogen, brine and reservoir hydrocarbons. The dynamic simulation tool was used in order to decide the minimum drawdown to ensure successful clean-up operation of an offshore oil well, as well as ramp-up steps to avoid sand production, estimation of total amount of liquid produced to confirm the topside has enough liquid handling capacity. The procedure of the clean-up operation was divided into two phases. The first phase involved nitrogen injection to remove brine from the GL string and annulus. The challenge of this stage was to determine the optimal nitrogen rates and choke openings in order to avoid large water peak rates at topsides. The second phase consisted in water removal in the well remaining below the gas lift valve together with the reservoir fluid. The important part of the phase was ramping up in small drawdown steps to avoid sand production. Some limitation in terms of volumes of oil produced, nitrogen injection pressure, water flow rates were taken into account. Along with the base case, sensitivities to various PI and well restart after 5 hour shut-in were done. Among such uncertainties as reservoir pressure, GOR, productivity index and the lack of Cv curves the main one remained to be the losses of brine into formation which are not accounted for. This is the reason for disagreement between the water cut predicted and real one. The time predicted for the operation corresponded well with the real operation. Nitrogen rates and choke openings and downhole pressure measurements were useful references although comparison with field data and modeling tuning were not performed.

It seems that the existing research within transient simulations clean up operations focuses mainly on the different settings and partly some parameter sensitivity study, but lacking the information about the description of the physics involved, the models and correlations comparison. Each case is very specific to the well completion and geometry, reservoir peculiarities and difficult to take general recommendations for the study.

4.1 Carina and Aries Fields

This part of the study gives an idea of the Carina and Aries fields, as the clean up case is taken from one of the well operations data. The information is mainly taken from the offshore.technology.com website [9].

Total Austral is a representative actor of its French headquarters in the Argentine market. The company has oil and gas assets, as well as produces, exploits, transports and distributes crude and gas derivatives in the country. It operates the Carina and Aries fields that are located in the province Tierra del Fuego, Antartida e Islas del Atlantico Sur in Argentina and lie in the offshore block CMA-1. The project is the biggest offshore natural gas production project in Argentina and it is the world's most southerly natural gas production facility. The fields are around 30 km and 80 km off the coast. They will produce a total of about 556 billion cubic meters of natural gas, 3.4 million tones of condensate and 2.4 million tones of LPG by 2027. The main customers for gas production are major cities and industrial centers.

Figure 1 Drilling with jack-up at the Aries field by Offshore technology.com

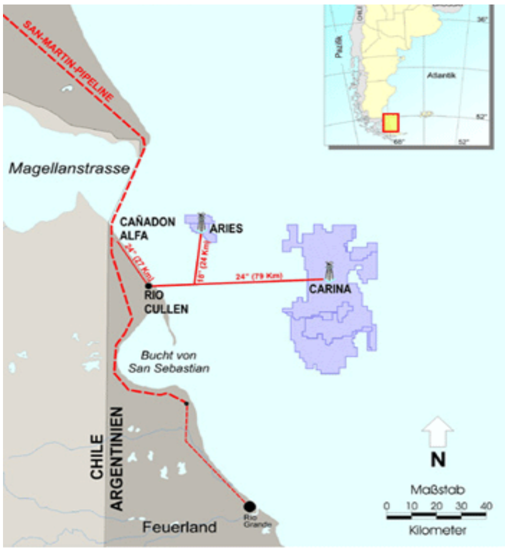

Figure 2 The location of Carina and Aries field by Offshore technology.com

Three partners are participating in the development: Total Austral (37.5%) on behalf of Wintershall (37.5%) and Pan American Energy (25%). The company invested $440m in the development of the fields.

The Aries field was discovered in 1981. It is over 12 km long and 4 km wide, the water depth is between 60 m and 80 m. By 1995 four test wells had been drilled, and 2D and 3D seismic explorations had been carried out. The reserves are located in the Hydra and Agro reservoir rocks at a depth of 1,600 m. The gas from that field has very high condensate content.

The two fields are developed by conventional steel platforms a shown on the figure 1. The topsides were produced in the port of Veracruz in Mexico.

As for the infrastructure, a network of pipelines over 100km long has been installed to connect the wells to the main processing plants, which is located on the coast.

A well clean-up operation took place before the start of the well production to avoid injecting the mud-cake and the brine in the production installations. Starting the production with low flow rates and burning the gas, the well is "cleaned" from the brine and mud-cake. For the well, 9 5/8" tubing is chosen for the simulation of the well clean-up simulation.

4.2 LedaFlow validation

The first step in investigation of the software applicable to well clean-up case is to acquire the necessary field data (geometry, boundary and initial conditions). These are important input parameters to ensure the right results.

The simulations both in OLGA and LedaFlow were done by Jamal Moufidi during his internship in 2011. The case that Jamal was working with is considered to be a base case and all the flowing modifications were employed to it. The results from OLGA and LedaFlow were compared with the field data. It was noted that OLGA gave good prediction and managed to track main changes during the simulation. LedaFlow, however, required more investigation and improvement. Unlike OLGA it failed to catch draining of the well during the first hours, when the biggest volume of the brine flow rate takes place.

Since OLGA gave good results, there was no need to rerun the case in OLGA, and even more, OLGA input file was converted to be an input file for LedaFlow. A script file (*.qs) was generated and uploaded in the script editor. To obtain the corresponding LedaFlow case, the script was run. There are certain differences between the codes when it comes to valve and well models. Therefore, valve opening fraction at different time points were matched to the field data in both software but still slightly different.

Oil-well inflow can be described by either linear (productivity index (PI) type or quadratic well models. For the gas wells cases a quadratic well model is preferred but, since LedaFlow does not support full Forcheimer law description, a linear PI model was used in both software. It is applicable for liquid unloading cases in gas well as it is the liquid rates that we are interested in.

General influx model [10]

A general model for local mass influx $\dot{m}$ per unit length [kg/s/m] is expressed in the following way:

$$\dot{m} = f(p_{well}, p_{res}; \dots) \tag{1}$$

where p_{res} is the reservoir pressure in the vicinity of the wellbore location.

Different functions f will apply for producing and injecting wells. The mass influx appears as source terms in the corresponding equations for mass, momentum and energy conservation. The total mass can be divided onto different phases by:

- Calculating a total mass influx according to (1) and then split into phases according to a separate model.
- Calculate mass influx for the individual phases.

General assumptions for the implementation of the well model:

1. Influx is purely radial.

2. The influx fluid can be described by a black oil model (without water).

3. The pressures in the reservoir and in the producing zones of the well are above the bubble point pressure, so that all produced fluid is in the liquid state.

4. Influx is described using a linear model, consistently with the previous assumption.

5. All the produced liquid is added to the continuous liquid field in the wellbore.

6. An arbitrarily number of influx zones may be specified for each pipe.

7. The effects of influx on friction factor correlations and regime transition models are ignored.

LedaFlow has two well models: Linear PI well and Single Quadratic PI well. Linear model was used for the inflow from the reservoir to the well. The mass flow rate is calculated in different ways for the two models.

Linear PI well model:

$$\dot{m} = [PI(p_{res} - p_{well}) - PI_0]\Delta x \quad \text{for} \quad p_{res} - p_{well} > PI_0/PI \tag{2}$$

$$\dot{m} = [II(p_{res} - p_{well}) + II_0]\Delta x \quad \text{for} \quad p_{res} - p_{well} < -II_0/II$$

$$\dot{m} = 0 \quad \text{otherwise.}$$

It is valid for Darcy flow of an incompressible or nearly incompressible fluid of phase ϱ, where q_ϱ is a volumetric well flow rate per unit length well of produced phase or filed ϱ, and PI is the corresponding productivity index.

$$PI = \frac{2\pi \cdot \lambda_\varrho}{\ln\left(\frac{r_{eff}}{r_{well}} + s + c\right)}, \tag{3}$$

where λ_ϱ is phase mobility, s is the skin parameter and c take into account geometry and pressure history effects. The phase mobility takes the following form:

$$\lambda_\varrho = \frac{K k_\varrho}{\mu_\varrho}, \tag{4}$$

where K is the absolute permeability, k_ϱ and μ_ϱ are the relative permeability and viscosity of phase ϱ respectively.

Single Quadratic PI well model:

$$(p_{res} - p_{well}) \cdot \Delta x = A + B\dot{m} + C\dot{m}|\dot{m}| \quad (5)$$

$$A = A_{prod}; B = B_{prod}; C = C_{prod} \quad \text{for} \quad p_{res} - p_{well} > \frac{A_{prod}}{\Delta x}$$

$$A = -A_{inj}; B = B_{inj}; C = C_{inj} \quad \text{for} \quad p_{res} - p_{well} < -\frac{A_{inj}}{\Delta x}$$

4.2.1 Well test data. Initial conditions. Boundary conditions [11]

The well test data is received from the production team at Total Group and retrieved from the report of Jamal Moufidi. The well is full of the completion brine with the specific gravity 1.10. The liquid level is balanced with the reservoir pressure (150m below the wellhead).

During clean-up operation both the brine from the well and the brine that was lost/injected into the reservoir formation during the completion run-in hole operation are produced.

Stepwise opening of the surface choke-valve up to Q_{gas} = 1.4MMSm^3/d was done to take all the brine to the surface tanks before the well was connected to the gas production network. The graph below shows the field rates of water, oil and gas, as well as the rate of gas at the separator.

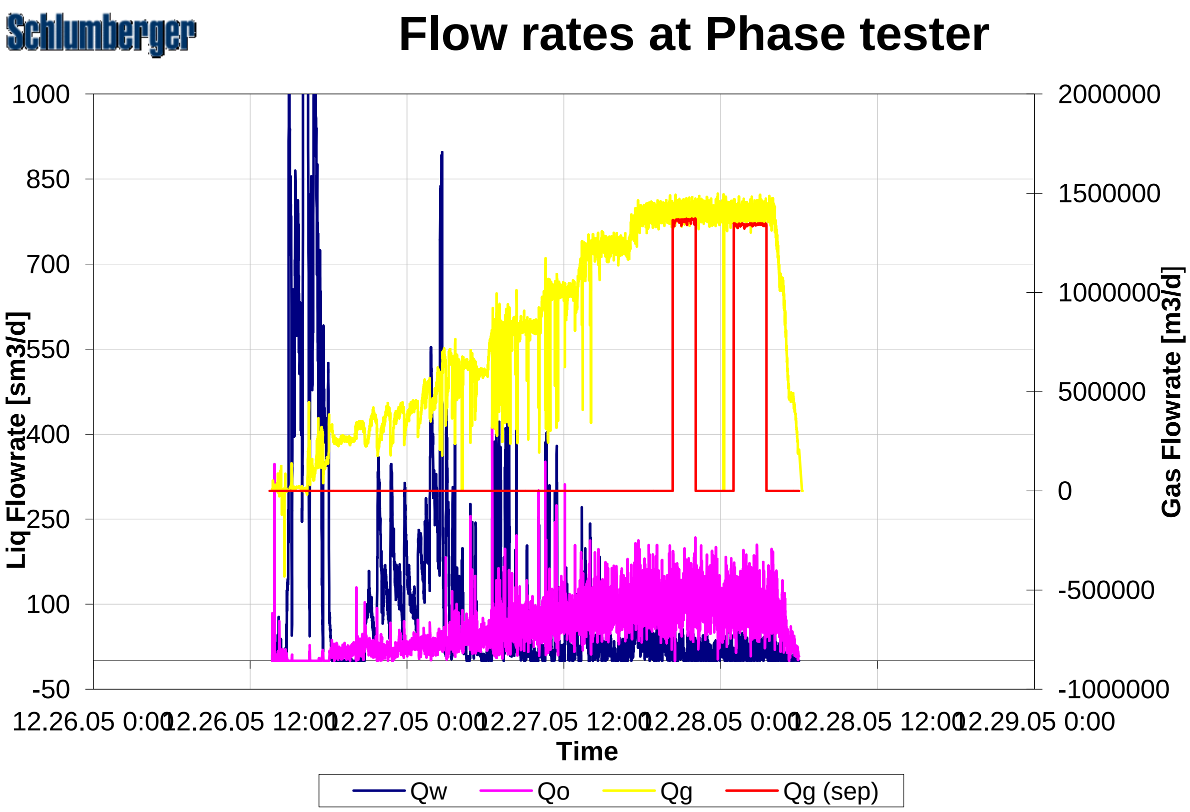

Figure 3 Field measurements of flow rates at multiphase meter

Permeability data, reservoir type, well diameter, position of the well in the reservoir and fluid data were processed by the team of production and reservoir engineers to calculate an inflow performance relationship (IPR) for each permeability zone. These IPRs were then converted into PI values, which were used for the 10 production zones within well model in LedaFlow. The zones are 1 meter long each starting from the bottom of the well at 1484 m.

The first step in constructing a model was building elevation profile of the well. It is a long slant gas producer well (78° inclination) with a 300 m horizontal drain. It is 1500 m TVD deep and 4700 m MD.

The geometry of the well is presented on the picture below. The geometry used in the simulations is modified in order to get few points for the simulation as it is important to keep the trend of the well geometry.

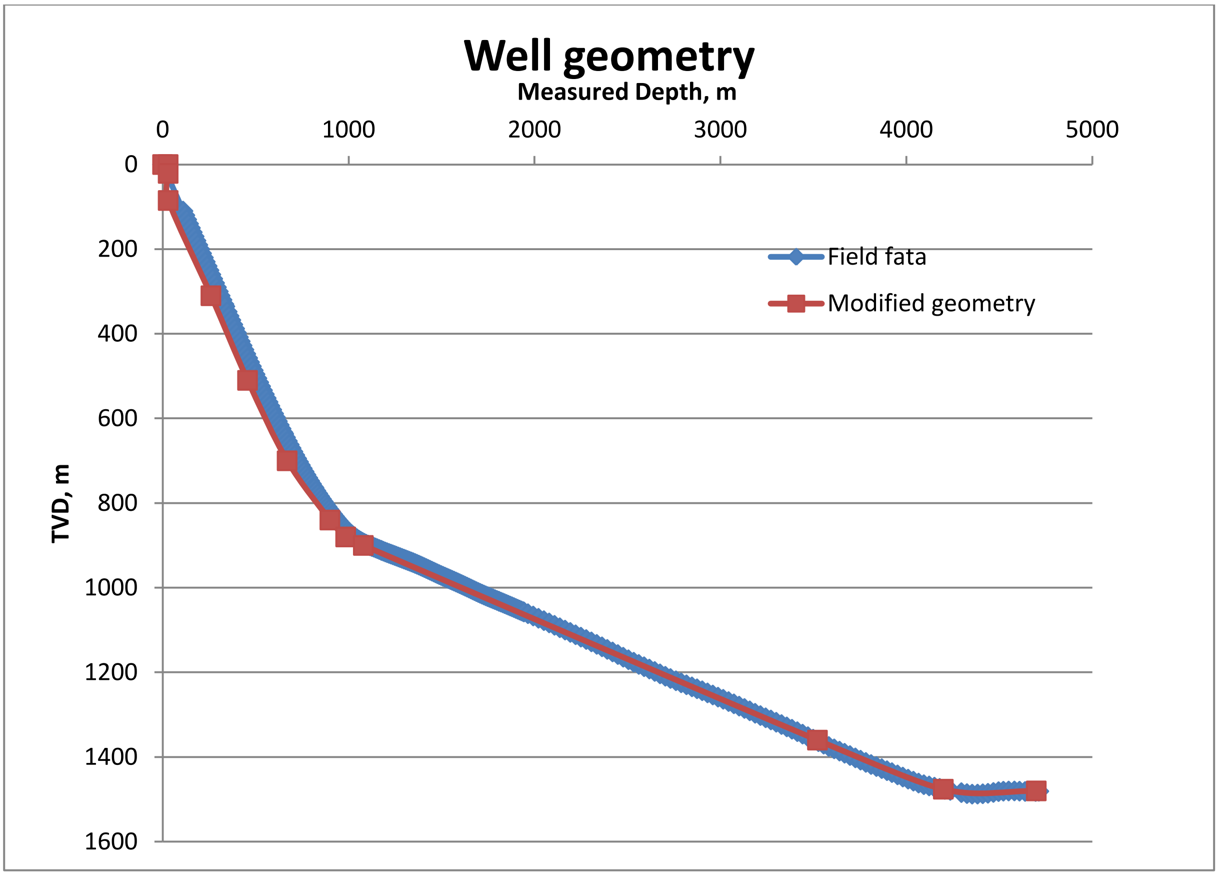

Figure 4 Well geometry for the simulation

It was found that LedaFlow failed to give the same water rates in the first hours of the operation [11]. In the graph below it is clear that after some time LedaFlow gives the right trend but not in the beginning of the simulation. This is the challenge that this study focuses on.

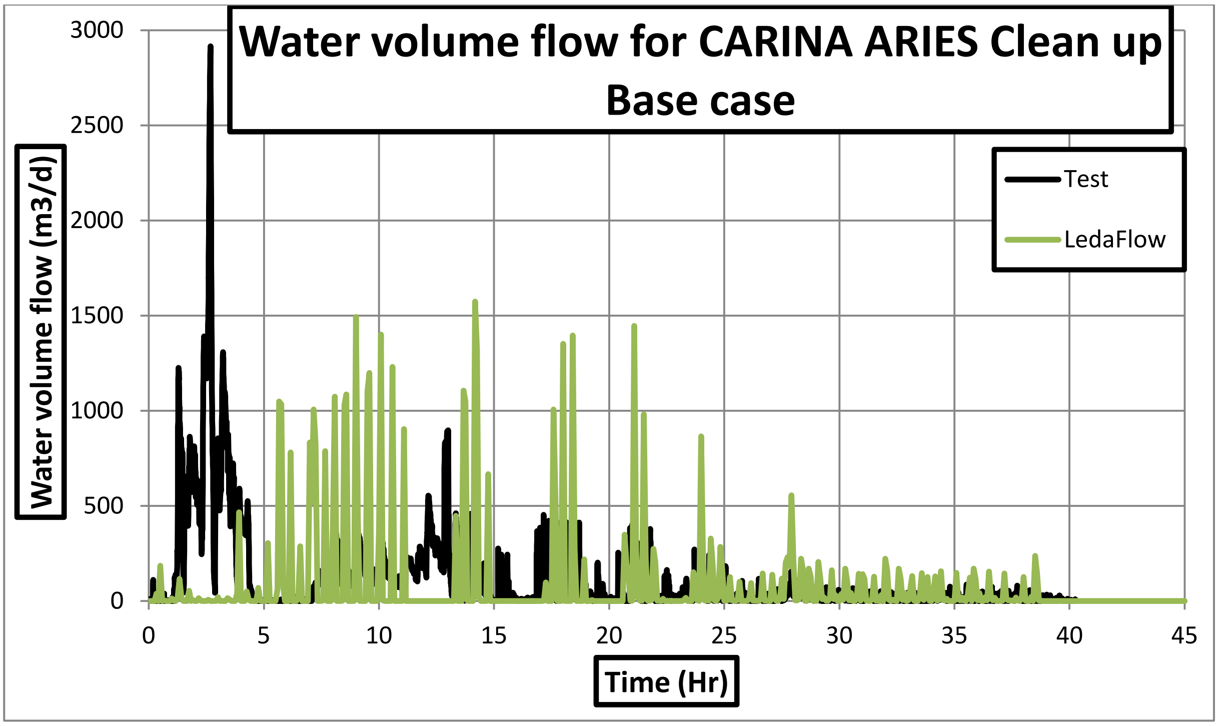

Figure 5 Base case results of LedaFlow simulation in comparison with the field data

From the graph above it is clear that about 5 hours of operation, after the arrival of the big volume of brine, the flow was choked, thus there is no water coming at the surface. After couple of hours the choke seems to be opened again, slowly this time, and water flow rates first increase and then drop as the remaining volume of brine decreases in the well. This is difficult to check as the log data from this operation is not available. Another uncertainty comes from the measurements of the Multiphase Flow Meter from the field, there is no information about its position and conditions for readings (time averaging, temperature, pressure). The values from LedaFlow are taken at flowing wellhead pressure.

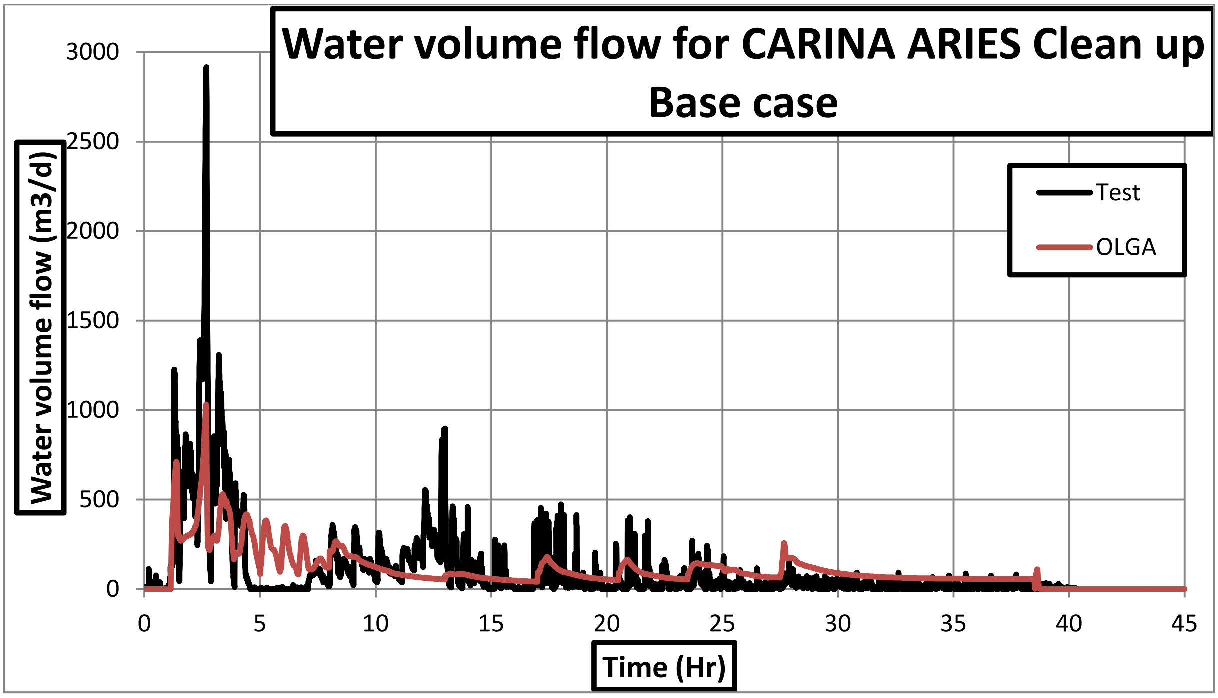

Figure 6 Base case results from OLGA simulation in comparison with field data

It can be noted that OLGA gives a good match of the trend in terms of major peaks of the flow rates and general continuous flow of brine but fails to represent the small hydrodynamic change in the flow. LedaFlow is better in terms of catching the small peaks and slugs but not the major one in the beginning. However, the most important challenge is to catch the large amount of liquid in the beginning than to predict he small peaks as the first liquid to come should be matched with the separator capacity. Besides, no continuous flow is simulated. It looked like LedaFlow simulated the possible backflow of the liquid, especially after the major slug. It is possible to see that Leda gives higher peaks for the slugs but then goes to zero. Some of this trend corresponds to the operational data. It could be due to strong choking in the field in order to avoid too big slugs for the separator to handle the volumes to arrive. After choking some of the liquid might flow back or the gas rate is not enough to build up to lift the liquids to the surface. Therefore, it might be a possible explanation of the fact that the values for the rates going down to zero. Another explanation could be a small amount of production water as it usually happens at the beginning of well life.

4.3 Sensitivity analysis

To pinpoint the root for the problem, it was decided to rule out possible user mistakes in terms of input parameters for initial and boundary conditions, models used such as well models and valves. Several parameters were chosen such as valve opening fraction, well filled with gas, interfacial friction factor, Productivity Index.

4.3.1 The effect of valve opening

The graph below shows the simulation with a valve completely opened. The table shows the valve open fraction equal to 1.

Table 1 Valve opening fraction used for study its effect on the water flow rates

Time,hr	Valve Opening fraction
0	0
0,000556	1
30	1

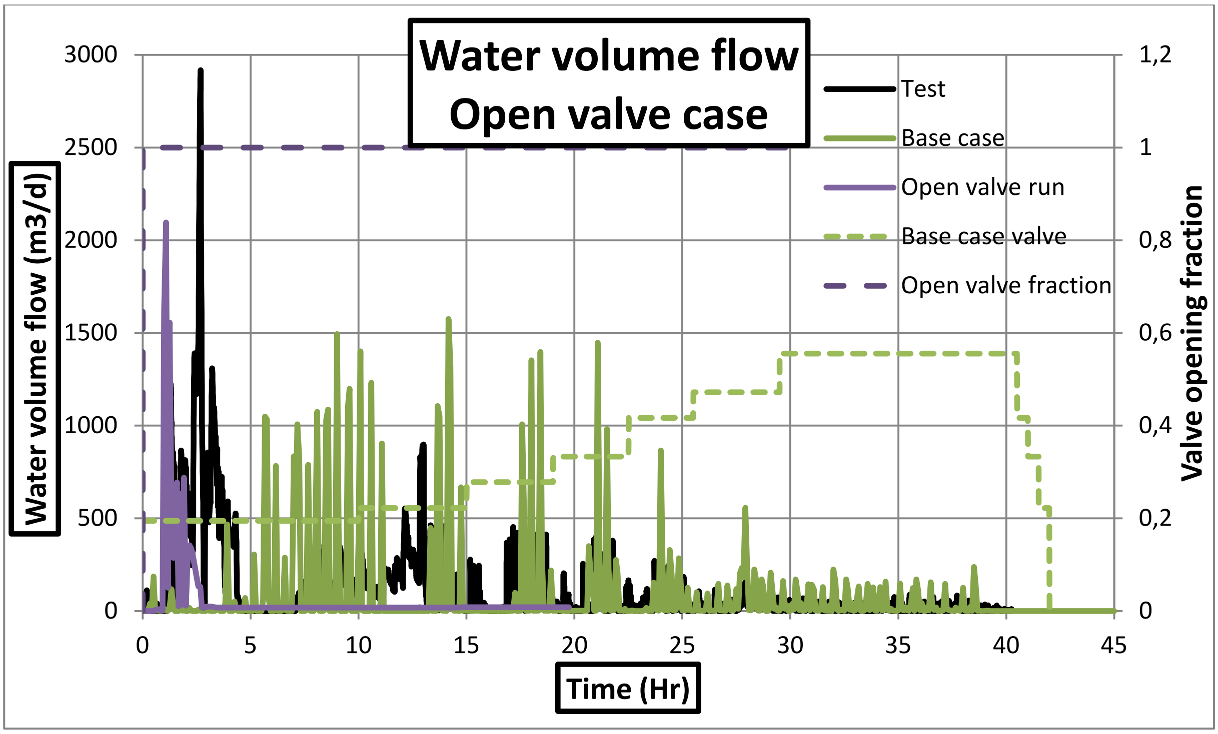

Figure 7 The effect of valve open case on the water volume flow prediction

As a result of this simple check it was noted that valve opening fraction could be the parameter which needs tuning with care as the water flow rates are very sensitive to it. LedaFlow gave quite a big slug in the beginning but not of the same magnitude as in the real case. All small slugs were not caught by the software although a choke is fully opened. A continuous minor flow was expected under this condition but LedaFlow was pessimistic with the volumes of liquid to be cleaned out of the well.

4.3.2 The effect of source model

Another test was run with the source instead of the well module. The total mass rates were applied for the source taken from the field data. This gave a big slug of water in the beginning which was expected but the set up of this simulation is far from the real life as the point with the simulation was to see the predictions of the water rates and not to impose them as input data.

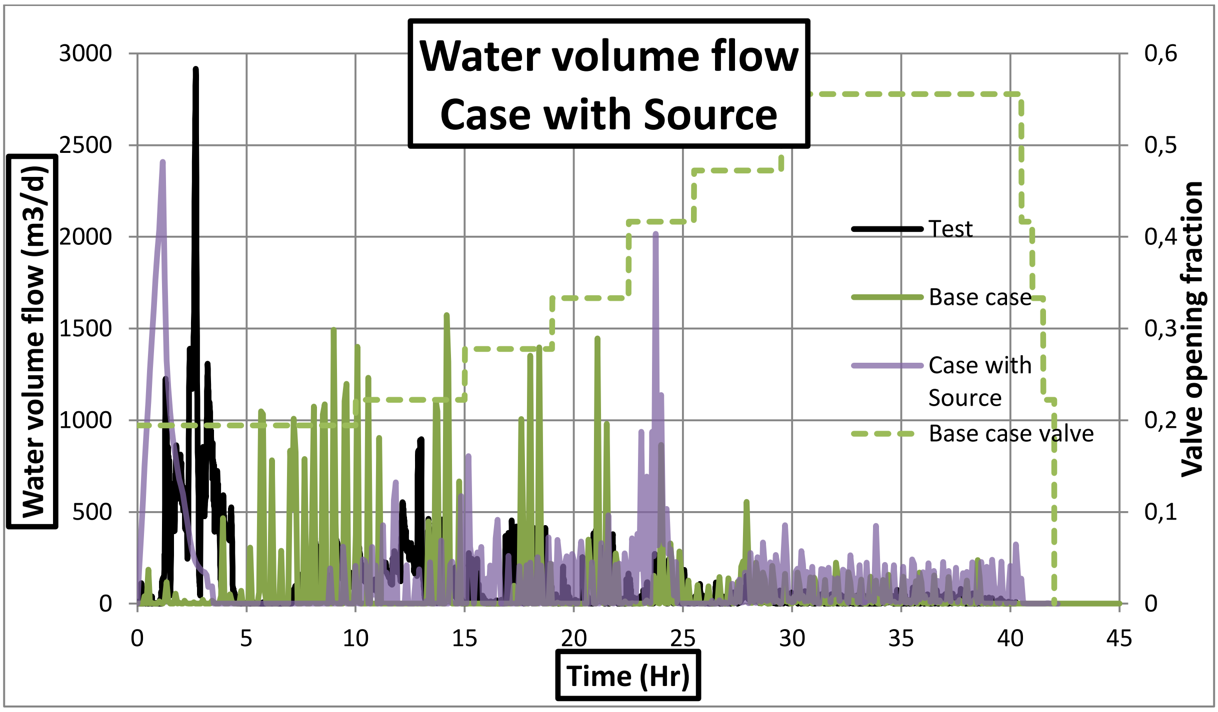

Figure 8 The effect of case with source simulation on water volume flow prediction

Somewhat better results are achieved as a result of this test. A big slug is out of the well but without good match on the general trend.

4.3.3 The effect of Productivity Index

Another parameter that was tested on the water flow rates was Productivity Index. As it was stated before Productivity Index was calculated for each zone from the reservoir parameters. Since this kind of information was missing, different values for PI was chosen to test.

Table 2 Input values of productivity and injectivity indices for the case set up

Time, s	PI	II
0	0	0,0004
1800	0,5	0,0004
1860	0,5	0,004
7200	0,5	0,004
7560	0,5	0

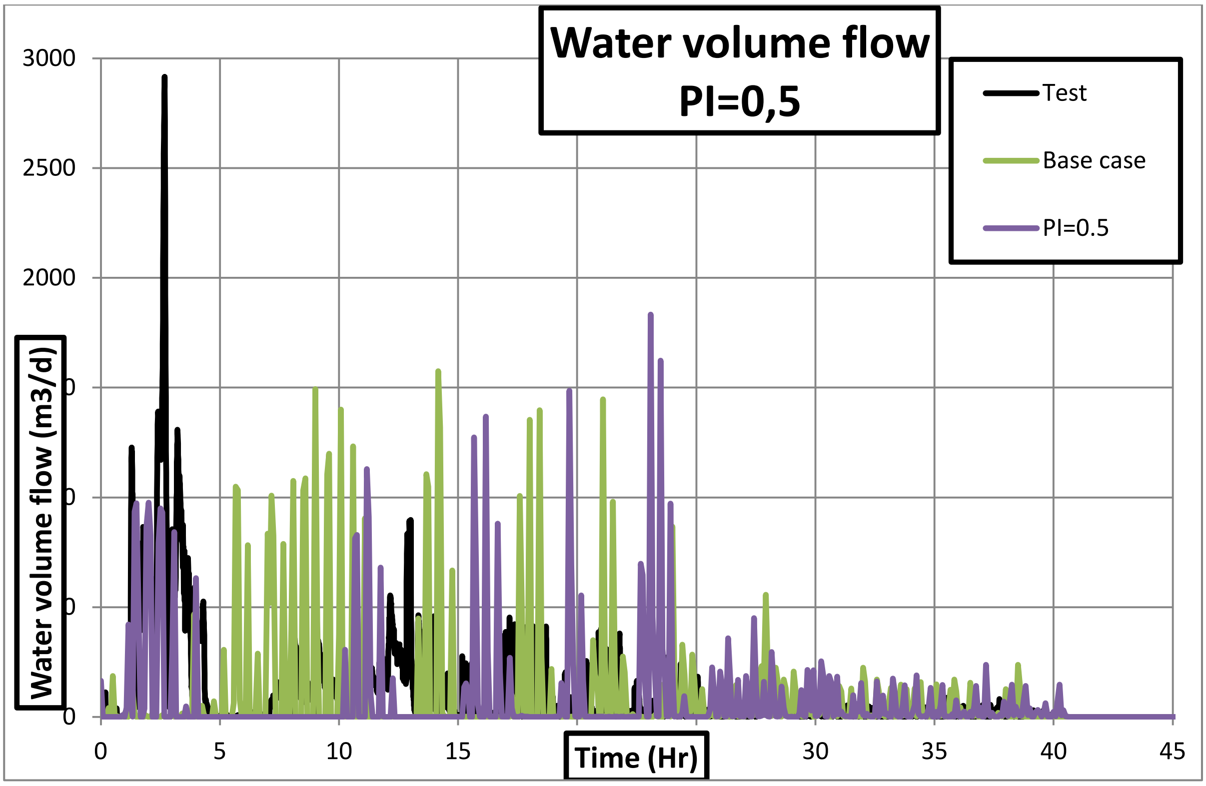

Figure 9 The effect of productivity index case on water volume flow prediction

In general, the productivity indices, choke position and opening fractions were adjusted to make the well produce the measured gas flow-rate with the measured wellhead pressure. A reservoir inflow zones is always characterized by its productivity and its injectivity. In case the bottomhole pressure becomes higher than the reservoir static pressure, the model must be able to simulate the subsequent fluid injection into the reservoir. Moreover, in OLGA and LedaFlow model, the simultaneous possibility to produce or inject helps the numerical stability of the computation. In the case of a clean-up operation, no injection usually happens except if gas-lift is used in the riser and the choke is not open enough.

A considerable amount of time and effort was devoted to matching flow rates of water, mass gas rates and bottomhole pressure changing initial conditions and valve opening fraction both in OLGA and LedaFlow files. As for initialization conditions, several were tested, well half full with brine, well filled with gas only, well with volume faction of water of 0,88. The first two simulations were run with phase split from PVT file used for the transient calculations. Below there is a case set up presented chosen for comparison with OLGA. The setup for both software were chosen to be initialized as wells filled with gas. The valve opening fractions were chosen to be identical in OLGA and LedaFlow with the consistent time steps. The same values for PI and II were used for the production zones for the both software.

Table 3 Input parameters for a gas filled well simulation

Time, s	PI	II	Vg	Vo	Vw
0	4,00E-07	4,00E-05	1	0	0
7200	4,00E-07	4,00E-05	1	0	0
7560	4,00E-06	0.01	1	0	0

Table 4 Valve opening fraction with time

Time, s	Opening Fraction
0	1
7200	1
7236	0
36000	0
36036	0.1944
54000	0.1944
54036	0.2222
68400	0.2222
68436	0.2778
81000	0.2778
81036	0.3333
91800	0.3333
91836	0.4167
106200	0.4167
106236	0.4722
145800	0.4722
145836	0.5556
147600	0.5556
147636	0.4167
149400	0.4167
149436	0.3333
151200	0.222
151236	0

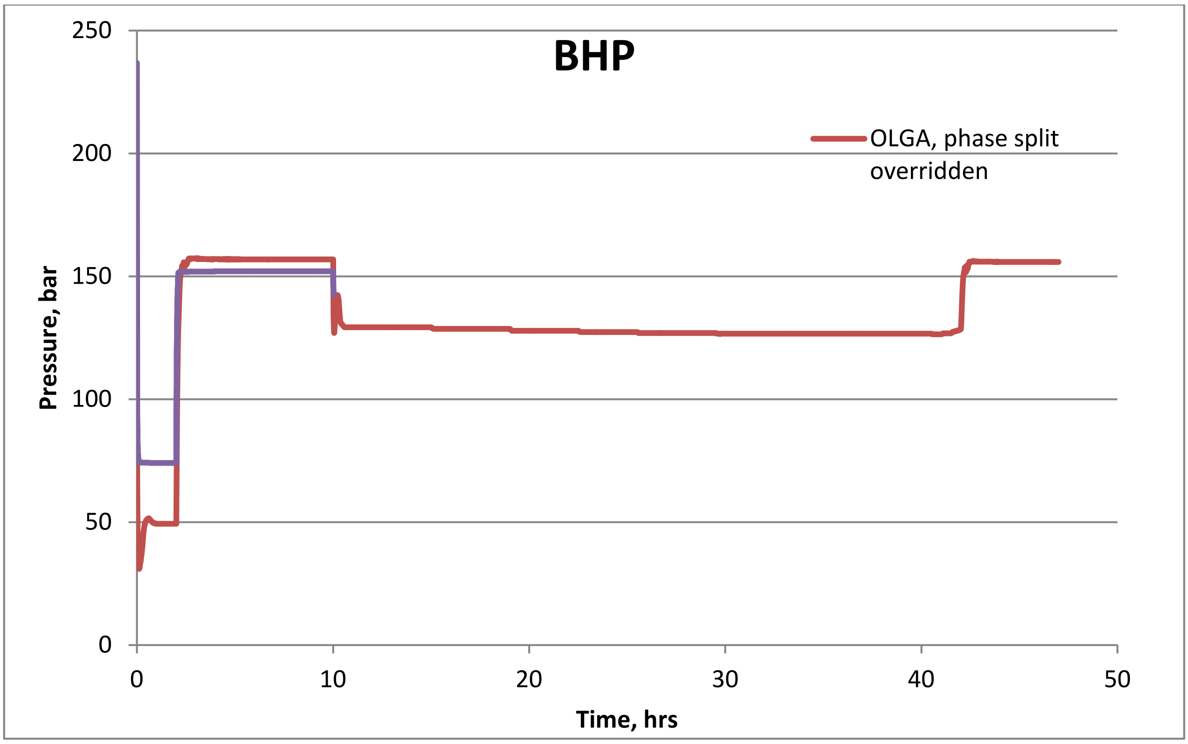

Figure 10 Bottomhole pressure with time

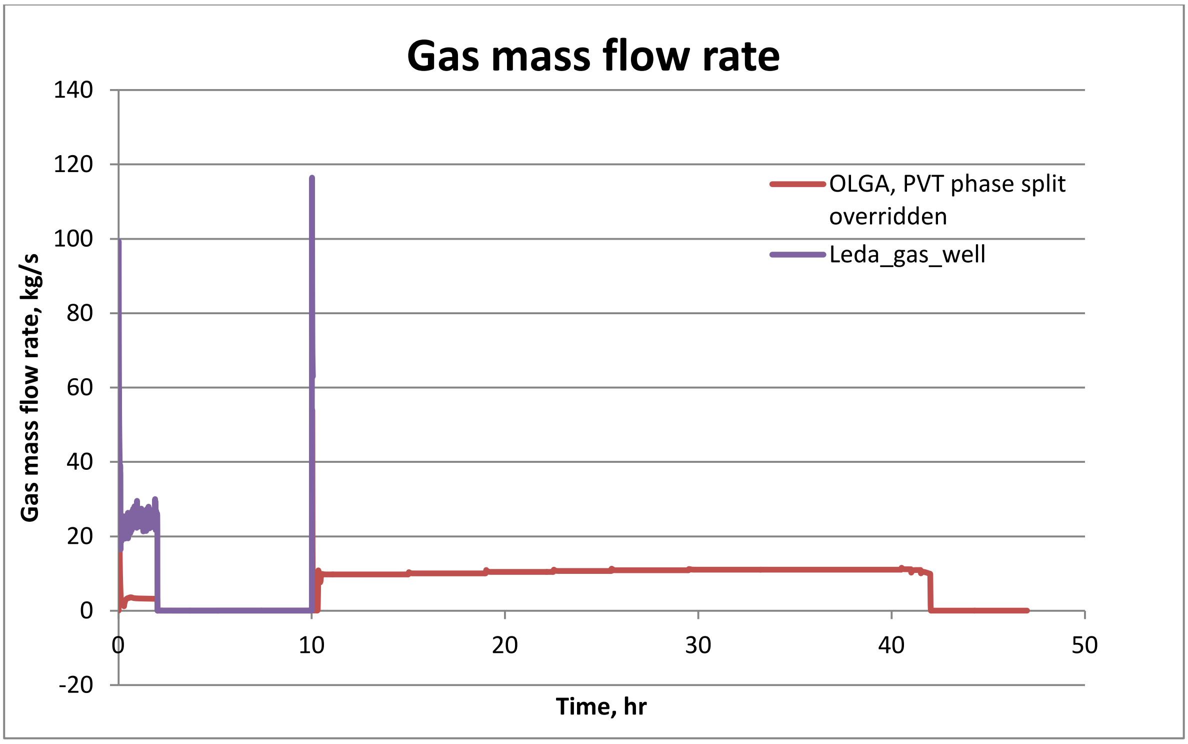

Figure 11 Gas mass flow rate with time

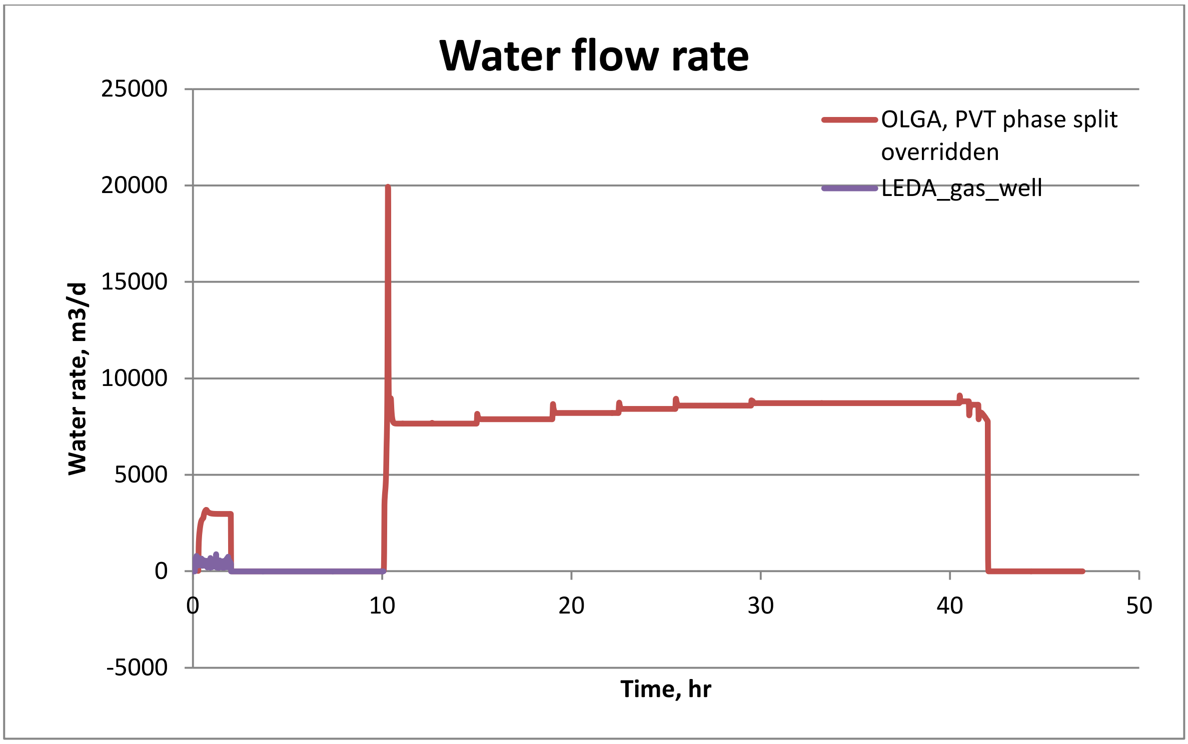

Figure 12 Water flow rates with time

From the graphs above it is clear that the values of bottomhole pressure and gas and water rates do not match with the ones from OLGA. Using the same initial and boundary conditions, choke opening fractions implies that the reason can be not within the user defined input parameter but within the closure models used for the 1DModel implemented in LedaFlow.

These are snapshots taken from 3D Visualization tool in LedaFlow to have an idea of water volume fraction change as the simulation progresses.

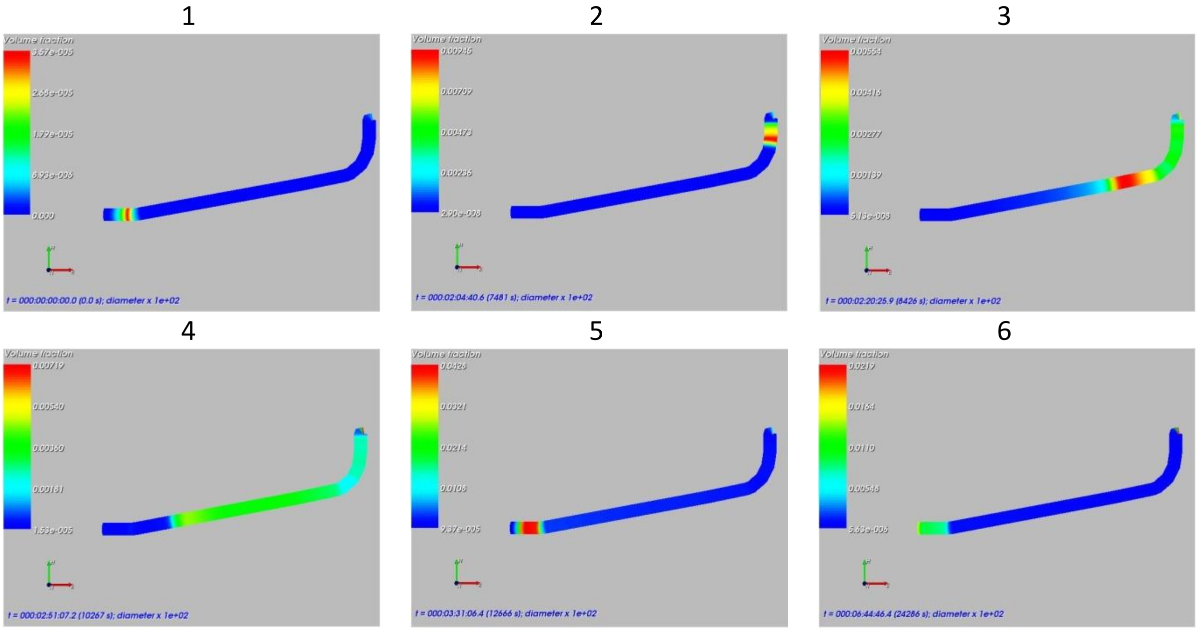

Figure 13 Water volume fraction change throughout the simulation when the well is empty, i.e. Vg=1 at all times

The 1 slide shows the initial condition of the well before the simulation, there is no water inside, only some at the production zones. As the simulation proceeds, there is some water is carried up as a film and at some point, at the top part of the well, the film gets thicker and starts flowing backwards (slide 2). Due to gravity the water keeps descending down the well (slide 3). At slide 4 the water film gets spread along the less inclined part of the well. At the end the water accumulates at the bottom of the well (slide 5). At slide 6 water is transported as film again.

Another test was run with the following setting: first the well is empty and then there is some water to produce, which is according to the test values at the end of operation.

Table 5 Input parameters for a gas filled well simulation

Time, s	PI	II	Pres	Tres	Vg	Vw
0	4,00E-07	4,00E-05	152	81	1	0
7200	4,00E-07	4,00E-05	152	81	0,95	0,05
7560	4,00E-06	1,00E-20	152	81	0,95	0,05

Table 6 Valve opening fraction with time

Time, s	Opening Fraction
0	1
7200	1
7236	0
36000	0
36036	0.1944
54000	0.1944
54036	0.2222
68400	0.2222
68436	0.2778
81000	0.2778
81036	0.3333
91800	0.3333
91836	0.4167
106200	0.4167
106236	0.4722
145800	0.4722
145836	0.5556
147600	0.5556
147636	0.4167
149400	0.4167
149436	0.3333
151200	0.222
151236	0

Below are the snapshots of the simulation. The water volume fraction changes with time.

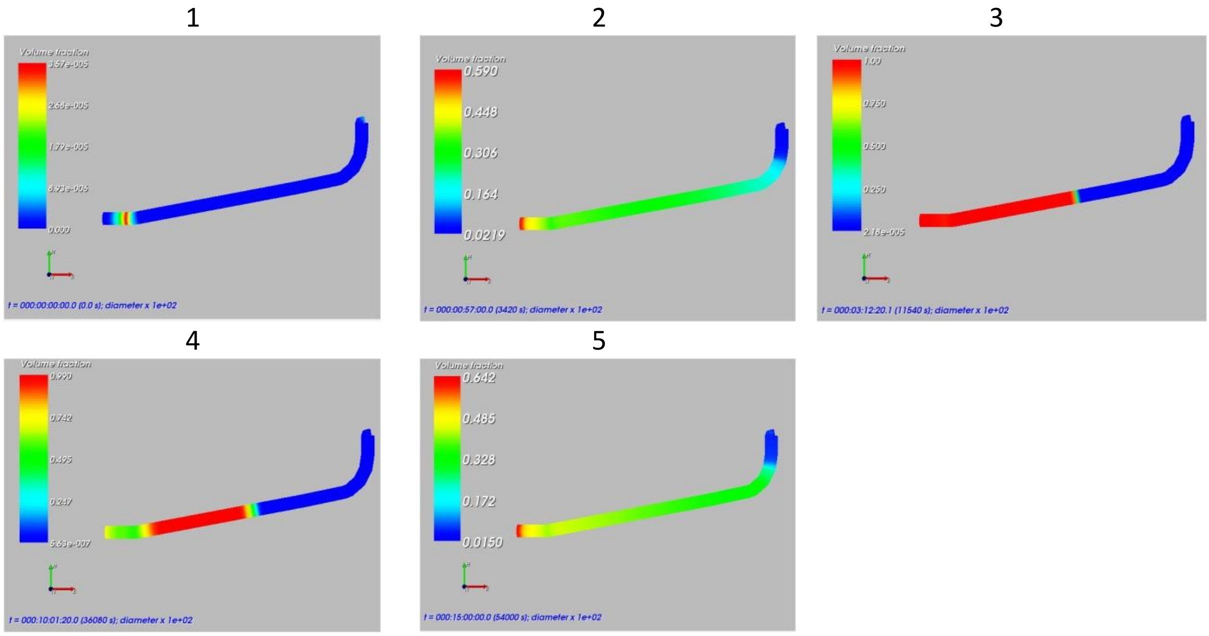

Figure 14 Water volume fraction change throughout the simulation when the case is initializes empty but varying afterwards

The above slides show the sensitivity of the water volume fraction change with slightly modifies volume fractions of gas as the simulation progresses. In the beginning there is no water, only gas is present, i.e. Vg = 1 (slide 1). At some moment formation water starts to flow into the well at the production zone (slide 2). As more water comes into, it accumulates at the lowest part of the well. Apparently the gas rate is not enough to lift it as one slug, but it possibly just bubbles through the liquid column to the surface (slide 3-4). At the end the water gets injected or, if the inflow of the gas changes, gets lifted up to the surface (slide 5).

One of the possible reasons could be the way LedaFlow treats a possible countercurrent flow which could exist in real operation. When the liquid flows back to the well and the gas is flowing upward but too weak to drag the liquid. In that case it was suggested that it is the slip calculations that needed a closer investigation. In case of counter-current flow, the flow regime is always chosen to be stratified/annular in LedaFlow. The reason for this is the difficulty of calculation the local flow quantities in slug flow in counter-current flow. In many cases, the slug flow equations will not have a true solution and search for the true one will result in big time usage.

Jørn Kjølaas, SINTEF, works closely on the well cases focused on that issue, came up with certain modifications performed on the base case. In the memo Leda Well Clean-up [12], Jørn Kjølaas gives an overview of counter-current flow treatment in LedaFlow. It seems that the ad hoc assumption of stratified/annular flow in the case of counter-current flow can lead to large over-estimations of the gas-liquid slip. LedaFlow gives too pessimistic results of the gas rate required to remove the liquid in a well. A solution was suggested to deal with overestimation of the gas-liquid slip: to modify the gas-liquid friction factor such that the steady state gas-liquid slip does not exceed the gas-liquid slip predicted by the slug flow model.

The average gas fraction in slug flow, as defined by the unit cell model:

$$\alpha_g^{UCM} = \frac{USG + \alpha_g^s\left(u_B - u_g^{bub}\right)}{u_B}, \qquad (6)$$

where USG is the superficial gas velocity, α_g^s is the gas fraction in slugs, u_B is the slug bubble velocity and u_g^{bub} is the velocity of the gas bubbles in the slugs.

The corresponding slip velocity in slug flow is calculated in the following way:

$$\Delta u^{UCM} = \frac{USG}{\alpha_g^{UCM}} - \frac{USL}{1-\alpha_g^{UCM}}, \qquad (7)$$

where USL is the superficial liquid velocity.

Therefore, the steady-state momentum equation for gas/liquid can be written as:

$$-\alpha_g \frac{\partial p}{\partial x} - F_{wg} - \frac{S_i}{2A} f_i \rho_g |\Delta u| \Delta u - \alpha_g \rho_g g \sin\varphi = 0$$
$$-\alpha_l \frac{\partial p}{\partial x} - F_{wl} + \frac{S_i}{2A} f_i \rho_g |\Delta u| \Delta u - \alpha_l \rho_l g \sin\varphi = 0 \qquad (8)$$

where p is the pressure, α_l is the liquid volume fraction, A is the pipe cross section area, Fwg is the gas-wall friction force, Fwl is the liquid-wall friction force, Si is the interface perimeter, fi is the interfacial friction factor, Δu is the gas-liquid slip velocity, ρ_g is the gas density and ρ_l is the liquid density.

Combining the equations and eliminating the pressure gradient, one can get:

$$\left(\frac{1}{\alpha_l} + \frac{1}{\alpha_g}\right) \frac{S_i}{2A} f_i \rho_g |\Delta u| \Delta u - \frac{F_{wl}}{\alpha_l} + \frac{F_{wg}}{\alpha_g} - \left(\rho_l - \rho_g\right) g \sin\varphi = 0 \qquad (9)$$

The interfacial friction factor can then be expressed:

$$f_i = \frac{\frac{F_{wl}}{\alpha_l} - \frac{F_{wg}}{\alpha_g} + \left(\rho_l - \rho_g\right) g \sin\varphi}{\left(\frac{1}{\alpha_l} + \frac{1}{\alpha_g}\right) \frac{S_i}{2A} \rho_g |\Delta u| \Delta u} \qquad (10)$$

The equation is then used to calculate the effective friction factor for slug flow f_i^{UCM}, by putting in the slug flow slip velocity Δu^{UCM}:

$$f_i^{UCM} = \frac{\frac{F_{wl}}{\alpha_l} - \frac{F_{wg}}{\alpha_g} + \left(\rho_l - \rho_g\right) g \sin\varphi}{\left(\frac{1}{\alpha_l} + \frac{1}{\alpha_g}\right) \frac{S_i}{2A} \rho_g \left|\Delta u^{UCM}\right| \Delta u^{UCM}} \qquad (11)$$

Finally, to avoid that the gas-liquid slip Δu exceeds that predicted by the slug flow model ΔuUCM, we select the largest interfacial friction factor of those given by the stratified/annular model and slug flow model:

$$f_i = \max\left[f_i^{STRAT}, f_i^{UCM} \right] \qquad (12)$$

The suggested setup had the following changes with regards to the above described modifications. Wellhead pressure was gradually reduced from 5 bar to 1.5 bar. For initialization the following values were used: II = 0, PI = 4.00E-06, where II = 4.00E-06 was kept for 30 minutes to adjust water level. Valve is set open for 30 minutes, closed for 2 hrs and gradually open up to 20%.

Table 7 Input parameters for the clan up case, including modifications

@Wellhead:

Time, hr	P, bar	Vg
0	5	1
0.55	5	1
0.72	1.5	1

Well zones:

Time, hr	PI	II
0	4.00E-06	4.00E-06
0.5	0	4.00E-06
2	0	4.00E-06
2.1	4.00E-06	0

Time, hr	Vavle opening fraction
0	1
0.5	1
0.52	0
2	0
…	…
42	0.2

Here are the snapshots of the water volume fractions from the test run before the gas-liquid friction factor was changed.

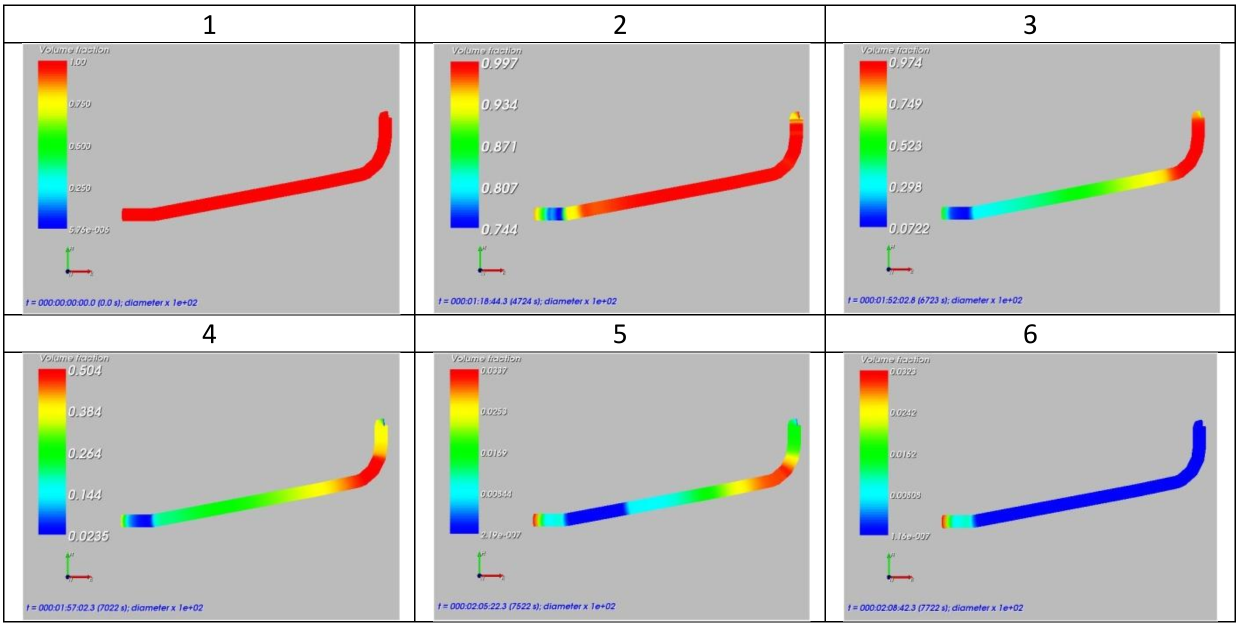

Figure 15 Water volume fraction change along the well before the change of the gas-liquid friction factor

The slide 1 shows that the well is initialized to be full of water. Some time later (slide 2) gas starts to flow inside the well. It bubbles through the liquid column. When the gas rates increases the gas get compressed until it overwins the hydrostatic weight of the water column and pushes the liquid in slugs up (slide 3-5). So, at the end the remaining water from the formation is lifted up as film at the well walls.

The graph below presents the final resulting flow rates of gas and water taking into account all the modifications done as a result of all the findings throughout the study of the clean up case.

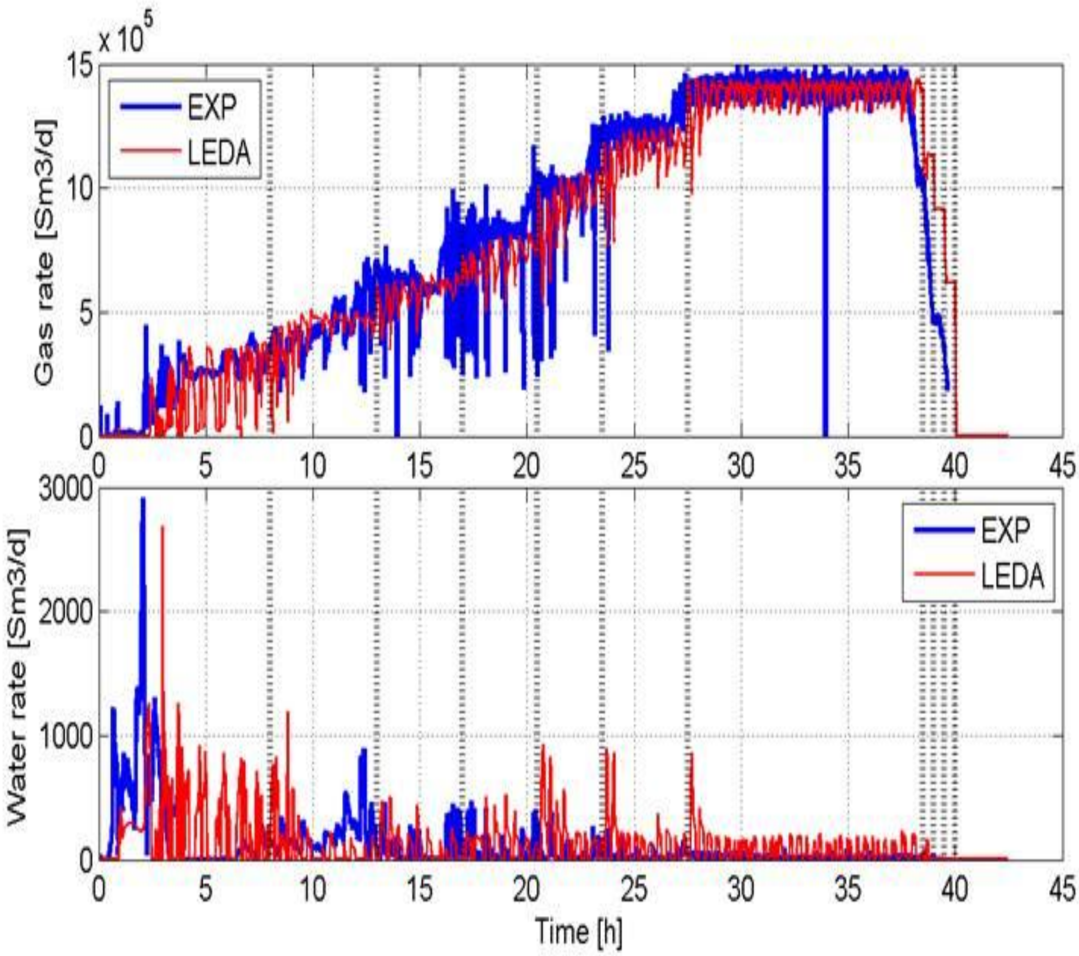

Figure 16 LedaFlow simulation results: gas and water rates in comparison with the field data

A considerable improvement is noticed in comparison with the base case. A continuous water slug is given by LedaFlow in the beginning of the simulation, but not of the same magnitude as expected. As for the gas rates, LedaFlow manages to reproduce the main trend. Some differences could be explained by the uncertainties of the field data, like the multiphase meter measurements, a detailed logging of the operation, choke position and tuning to the field data. Nevertheless, more work should be done in order to improve the results of the simulation in order to meet the requirements of better matching with the field data.

5. Liquid loading in gas well

The following chapter gives information about the second case that this study focuses on, the liquid loading in the gas well. Besides definition, an extensive literature review is presented as well. The results about the critical gas velocity are compared with the field data and simulations done in OLGA.

5.1 Definition of the phenomenon [13]

Liquid loading is one of the most common problems in gas producing wells. It occurs at some point of gas production when it is not sufficient enough to lift the associated liquids to surface. The picture below describes the sequence of events taking place during liquid loading (Veeken et al 2003).

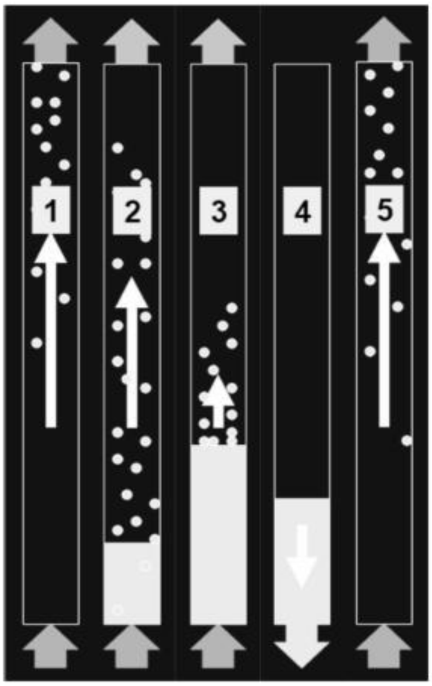

Figure 17 Liquid loading mechanism in a gas well from [13]

1. Both gas and liquid are produced to the surface.

2. The velocity of the gas decreases and it is insufficient to lift liquids, liquid flow reversal occurs. Liquid accumulates at the bottom of the well.

3. Due to liquid accumulation, the bottomhole pressure increases, the gas flow rate keeps decreasing, until the well stop flowing.

4. The accumulated liquid is re-injected to the formation when the bottomhole pressure becomes higher than the near wellbore pressure. During the reinjection, the near wellbore pressure recharges.

5. The near well bore pressure becomes high enough to lift the liquid column, the well starts to flow again.

Therefore, the technical abandonment pressure and the ultimate recovery are decided by the liquid loading. Hence it is important to predict the onset of liquid loading helps operators in reducing costs by reducing the number of shutdowns and optimizing the production.

Many methods follow Turner et al. (1969) and Lea et al. (2003) controlling factor in predicting liquid loading, who state that there exists such a critical velocity (critical gas rate) below which a static liquid column start developing. Duggan (1961) introduced the concept of a critical minimum-wellhead-gas velocity for the onset of liquid loading. The paper of Turner et al. came up with a film-moving model and entrained-droplet model to predict the above mentioned condition. Basing on the analysis of the field data the researcher came up to conclusion that the film-movement model did not present the condition. As for the entrained-droplet model, it was based on the force balance of a droplet entrained in a high-velocity gas flow, equating the upward drag and downward gravity forces on the largest possible liquid droplet, which, in its turn, was determined by Weber number.

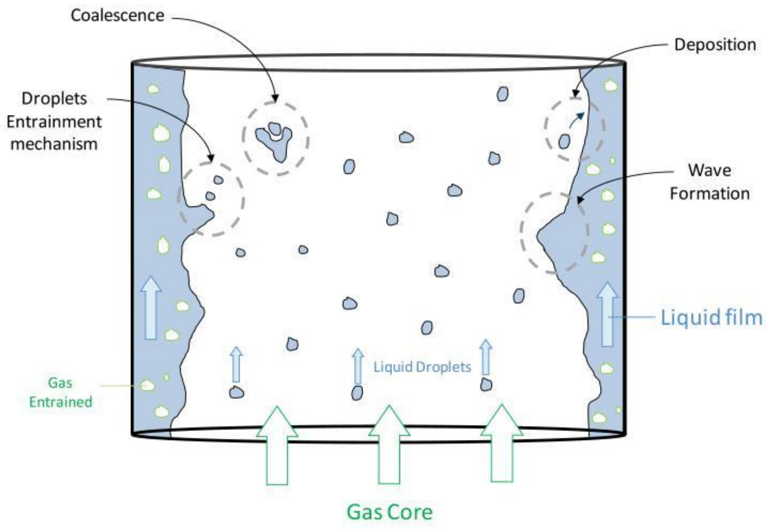

Figure 18 Annular flow regime from [13]

From the flow regime description the liquid loading can be explained by transition from the annular flow regime to slugging or churn flow. Lea e al. (2004) described several possible flow regimes in gas wells. The widely known and used flow pattern in flow regime prediction was suggested by Taitel et al. [14] (1980). Ansari et al. 1994 [15], Taitel et al. 1980, Lea et al 2004 [16] came up to the conclusion that annular flow regime is a condition for lifting liquids from the well, i.e. according to Taitel et al. flow pattern map, the superficial gas velocity should be greater than the boundary of slug/annular transition.

Lea and Nickens [16] (2004) state the following signs of liquid loading as sharp drops in the decline curve, onset of liquid slugs at the surface, an increasing difference between the tubing and casing pressures with time, and sharp changes in pressure gradient data. They also came up with suggestions to reduce liquid loading by a smaller tubing size to increase gas velocity above the critical Turner one; installation of compressor to lower the tubinghead pressure, a plunger lift in order to lift liquids with the gas pressure during shutdowns, installation of pump; liquids foaming; gas lift to decrease the pressure loss in the tubing and increase gas velocity. Further improvement of Turner criterion was done by Guo et al. [17] (2006).

Desheng Zhou and Hong Yuan [18] (2010) studied the similar points in methods of Taitel et al. (1980) by slug/annular flow transition boundary and Turner et al. [19] (1969) with the entrained-droplet model. They state that the only difference is in units, so Turner's model is in field units and Taitel's boundary condition is in SI-units. Neither of models is based on the amount of gas in a gas flow. Turner et al. states that during the annular flow regime liquid accumulates on the well walls as a liquid film due to impingement of entrained liquid drops and the vapor condensation, whereas gas flows in the middle as a gas core with some liquid droplets. The liquid film moves up dragged by a faster moving gas core. Wallis [20] (1969) published a model to estimate the liquid entrainment into the gas core. With increasing gas velocity, the liquid film decreases, and for a very high gas velocity, all liquids are entrained into the gas flow. Barnea [21] (1987) made studies on the liquid film effecting the annular regime and came up with the modified boundary transition between slug and annular flows. He pointed out two mechanisms involved: liquid film bridging and liquid film instability. If the liquid film is thick enough it might bridge the gas core and start flow partly downward. Hence liquid film thickness requires calculations. According to Barnea, to fulfill the bridging criterion, the liquid film holdup should be greater than 0.12. This model is applicable to oil wells. Ansari et al. (1994) used the model for pressure drop calculation for oil wells.

As it is possible to see a great amount of authors have suggested modification to Turner's model. But it was pointed out the fact that Turner's model is independent of the amount of liquid flowing. As with large liquid rates, droplets start to coalescence and the droplet models for most critical velocity expressions is not valid anymore. Oudeman [22] (1990) noticed that Turner criterion is not god to predict when the well will die, which may occur at lower rates. Sutton et al. [23] (2003) gives examples when wells operate at subcritical rates and comes up with the methods for analyzing this phenomenon. He presented the parameters that make up Turner's model. The values of interfacial tension for the gas-condensate are to be corrected. They also noted that under certain circumstances like low pressure, and cool reservoir, liquid loading is more controlled by the downhole conditions.

Niek Dousi et al [24] (2006) presents the report on field data which show the existence of subcritical "metastable" flow rates, at which the well still produces even with liquid loading. A simple conceptual model is given which helps to understand and interpret the data.

Desheng Zhou and Hong Yuan [18] present the paper with the new model which includes the effect of the amount of liquid on critical velocity calculation, with the data from Turner et al (1969) and Coleman et al. (1991) used for validation.

Turner's Model

$$v_{crit-T} = 1.593\frac{[\sigma(\rho_l-\rho_g)]^{1/4}}{\rho_g^{1/2}}, \tag{13}$$

where v_{crit-T}, ft/sec, is the critical velocity from Turner's model; σ, dunes/cm, is interfacial tension; ρ_l, lbm/ft^3, is liquid density; and ρ_g, lbm/ft^3, is gas density.

The corresponding critical rate is calculated in the flowing way:

$$q_{crit-T} = \frac{3060 p v_{crit-T} A}{Tz}, \quad (14)$$

where q_{crit-T} is the critical ate from Turner's model, Mscf/D; p is in-situ pressure, psia, A is the flow area of a conduit, ft^2; and T is in-situ temperature, °R.

From the found 20% underestimation, the critical velocity and critical rate from the entrained-droplet model are, respectively,

$$v_{crit-T} = 1.2 v_{crit-T} \quad (15)$$

$$q_{crit-T} = 1.2 q_{crit-T}$$

Coleman et al. (1991) applied the model to the well data and got a satisfactory match. However, it was reported that no upward adjustment needed in case of lower wellhead pressure. They came up to a conclusion that there are factors that significantly influence critical velocity calculation, such as wellbore diameter and pressure; whereas gravity, interfacial tension, and temperature had little effect.

Turner et al. (1969) concluded that wellhead conditions are control factors for liquid loading. Using wellhead conditions allows simplifying calculations for pressures and temperatures along the tubings.

Table 9 in chapter 5.3 gives an idea of existing models and there comparison with the field data and the results of the OLGA and LedaFlow simulations. These models are very simplified and easy to use for a quick check but do not take into account important factors. Therefore, transient calculations give more correct and reliable results basing on complex closure models especially developed for multiphase flows in complex geometries and conditions.

5.2 Liquid loading in a gas well

The case of liquid loading is simulated in LedaFlow and compared with the OLGA measurements done in 2009 on gas well LACQ143 which is situated in southwest France. The field data come from the production team at Total and retrieved from the report of Jamal Moufidi [11].

Architecture of the well

The architecture of the well is presented schematically below. There are several changes in sections and materials in comparison with the detailed one. The choice of such architecture is defined by the nature of the formation and the extension of the tubing during the life of the well is planned due to reduction of the frictional pressure drop.

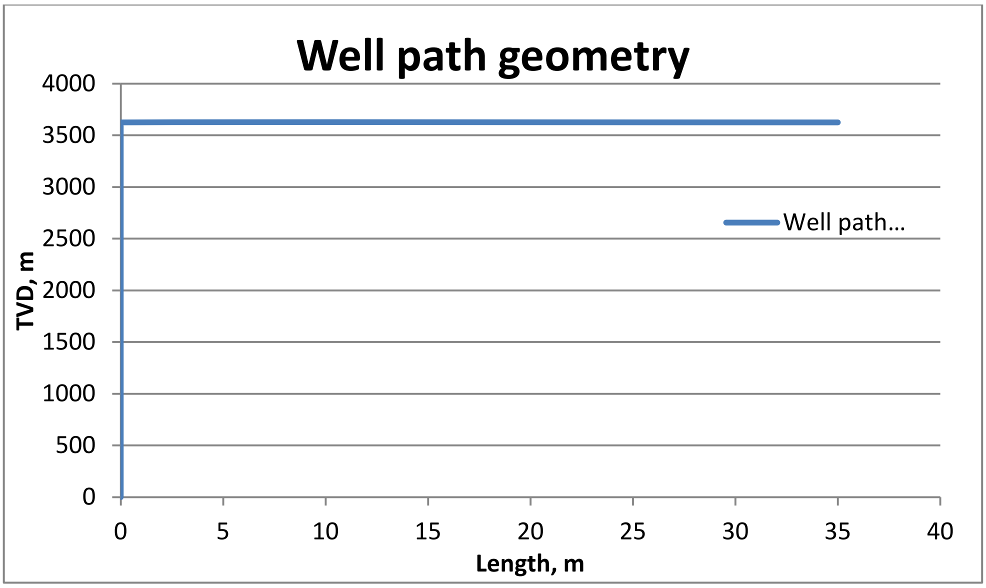

Figure 19 Well path geometry for a liquid loading case

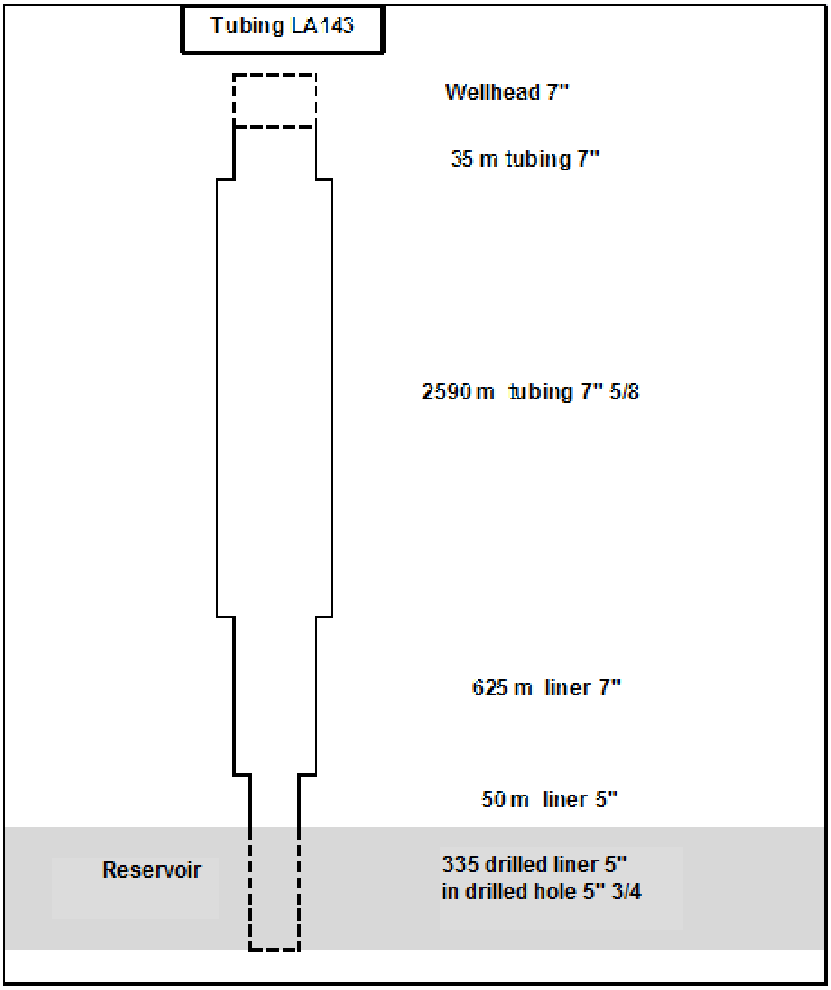

Figure 20 Completion profile of the well

Flow in wellbore

Three-phase flow is to be produced from the well (liquid: oil, water and gas). Figure 20 shows sudden expansion (tubing) sections and contractions (nipples), thus the hydraulic disturbances are expected.

The nature of the flow is determined by the field velocities of the gas and liquid (water and oil), as described in the figure below. To lift the liquid up to the surface, an annular flow regime is needed, i.e. the sufficient gas velocity.

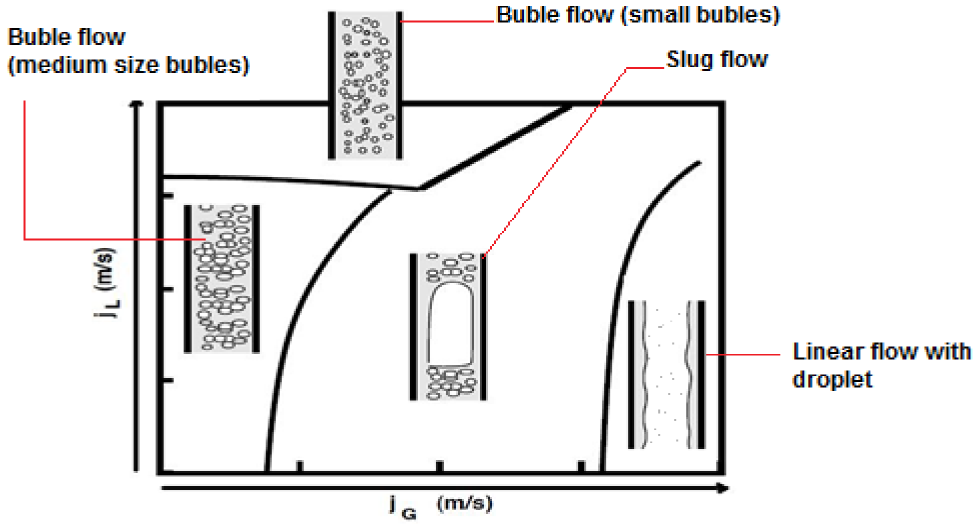

Figure 21 Flow pattern map

In the beginning of the operation the gas velocity is high enough to provide annular flow regime and lifting of the oil and water. As reservoir pressure gets depleted, the bottomhole pressure increases and gas velocity due to small pressure drop decreases. As soon as the gas velocity is below critical, the liquid film starts falling down:

- Reversal flow and accumulation of liquid downstream the extensions.
- Gas acceleration zone (with smaller diameter), where the gas velocity prevents the liquid film from falling down.

In the case of this well, the diameter of the tubing is big and due to weak liquid production, slugging is unlikely to happen, thus the flow is in ascending or descending annular regime. Due to the accumulation of the liquid, bubble flow is possible.

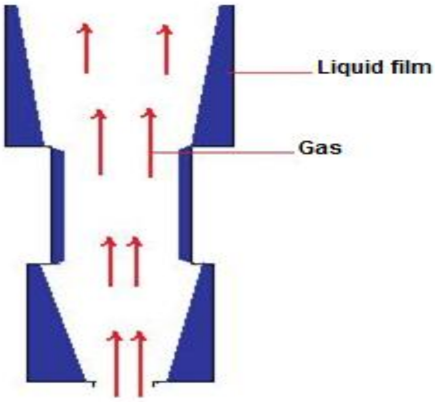

Figure 22 Annular Flow in gas Wellbore with restriction

When the gas velocity becomes weak even in the section with smaller diameter, the liquid falls down and accumulates in the drilled section, and stops the gas inflow to the well. At some point the production became unstable, and, according to the injection and production capacity, it can stay unstable for several months before the well dies.

To understand the transient behavior of liquid loading process in detail and validate LedaFlow results, the test from the well is used.

Test from gas well

The sketch of the well is shown below, with $P_{res} = 17$ Bar. a and $P_{sep} = 4$ Bar. a.

The gas inflow is controlled by modifying the bottom hole or wellhead pressure through the choke on the surface.

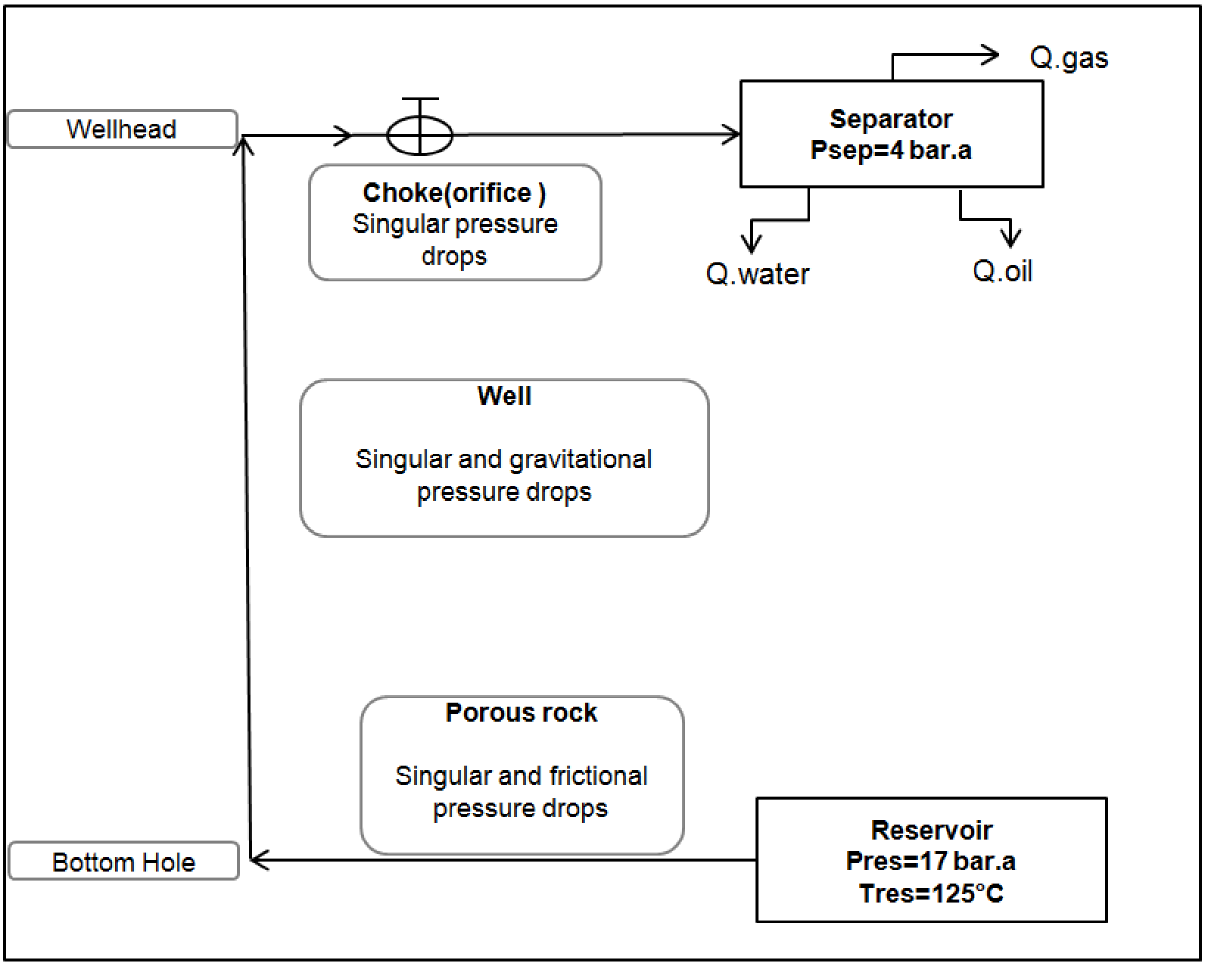

Figure 23 Functional scheme for a producer well

Reference measures for the well

Only limited number of tests was performed in the well as they cause a reduction in production and come in conflict with gas sales contract requirements. A well test was performed with the change in the opening ratio of the choke by step of time, in order to highlight the condition under which the “liquid loading” commences.

Each step was sufficiently long (~48 hours) to allow the stabilization of the two-phase flow.

With the choke fully opened, the maximum well flow rate was $227\ k.Sm^3/d$, with the wellhead pressure of $P_{wh} = 7\ \text{Bar.a}$

This well is “depleted”, but it still produces with only $P_{res} = 17\ \text{Bar.a}$ as static pressure in $3500m$ deep. This is possible due to the good productivity, caused by natural fractures that increased the global permeability.

The water vapor rate on gas reservoir at these conditions (17 Bar.a ET 125°C) is about 10% molar. The steam condensation in the well is a production of several m^3 of water per day on the surface. By closing the choke stepwise, the wellhead pressure increases, thus the gas flow from the reservoir reduces.

The following steps were performed during the test.

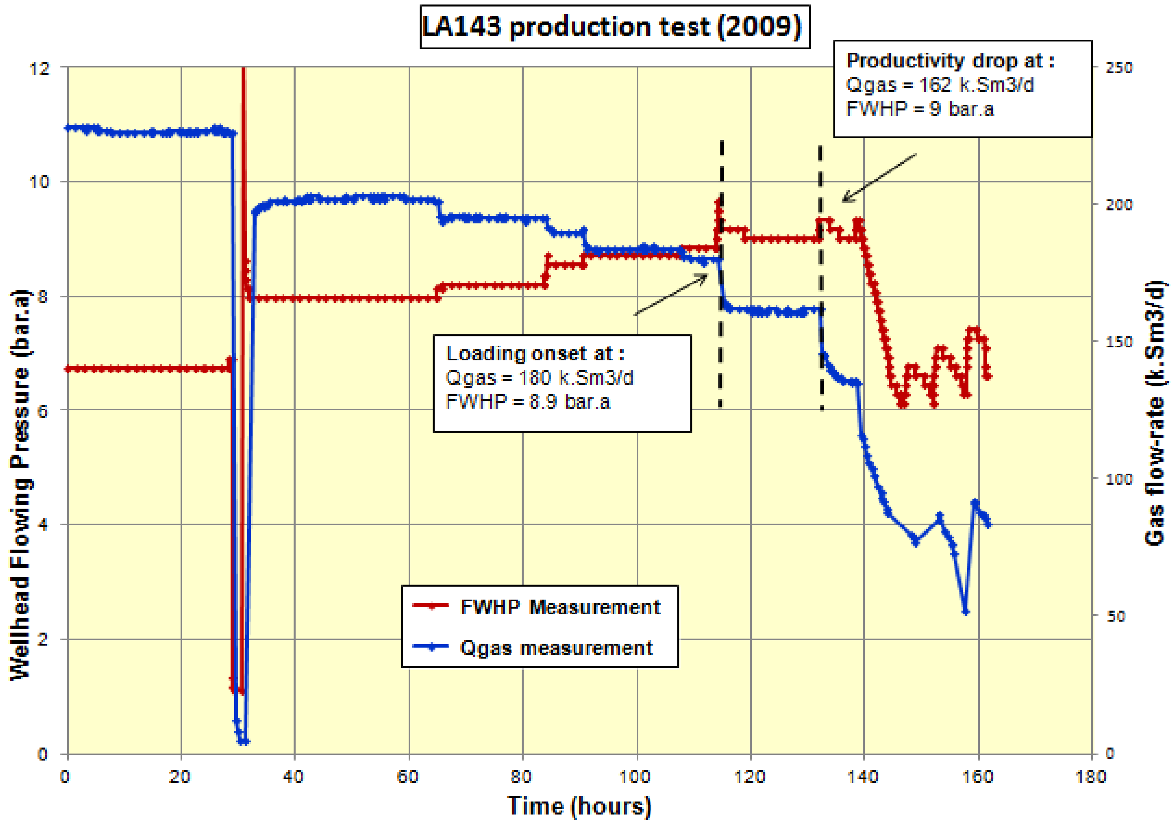

Figure 24 Temporal evolution of wellhead data

Table 8 Flow rate steps during the test

Wellhead P (bar.a)	Q.gas (k.Sm3/d)
6.7	227
8.0	202
8.2	195
8.7	184
9.0	162

When the wellhead pressure reaches the value of 9,3 Bar. a, the gas flow rate and wellhead pressure collapse simultaneously. This corresponds to the point when all the liquid falls down to the well.

- ⇨ The pressure falls due to the hydrostatic pressure caused by the accumulated water column in the well.
- ⇨ The water column grows in height, the bottomhole pressure increase, which leads to the decrease of gas flow rate.

During this test the well became unstable with pressure oscillations and irregular production half of the general one. The last stable gas volume flow rate which was able to lift continuously the liquid was noted to be $Q_{gv} = 162\ k.Sm^3/d$ and wellhead pressure of $P_{wh} = 9\ Bar.a$.

5.3 LedaFlow validation

The choke opening fraction was reduced stepwise until a simultaneous collapse in the wellhead pressure and the gas flow rate was observed.

The same configuration of the well with the same boundary conditions was simulated in OLGA in order to compare the results.

The main differences appear in modeling:

- ➢ Choke representation (e.g. FROZEN correlation on OLGA)
- ➢ Vertical hydrodynamic model
- ➢ Field representation by static pressure and productivity index ($m^3/d/bar$), used to vary the reservoir outflow in function of the bottom hole pressure.

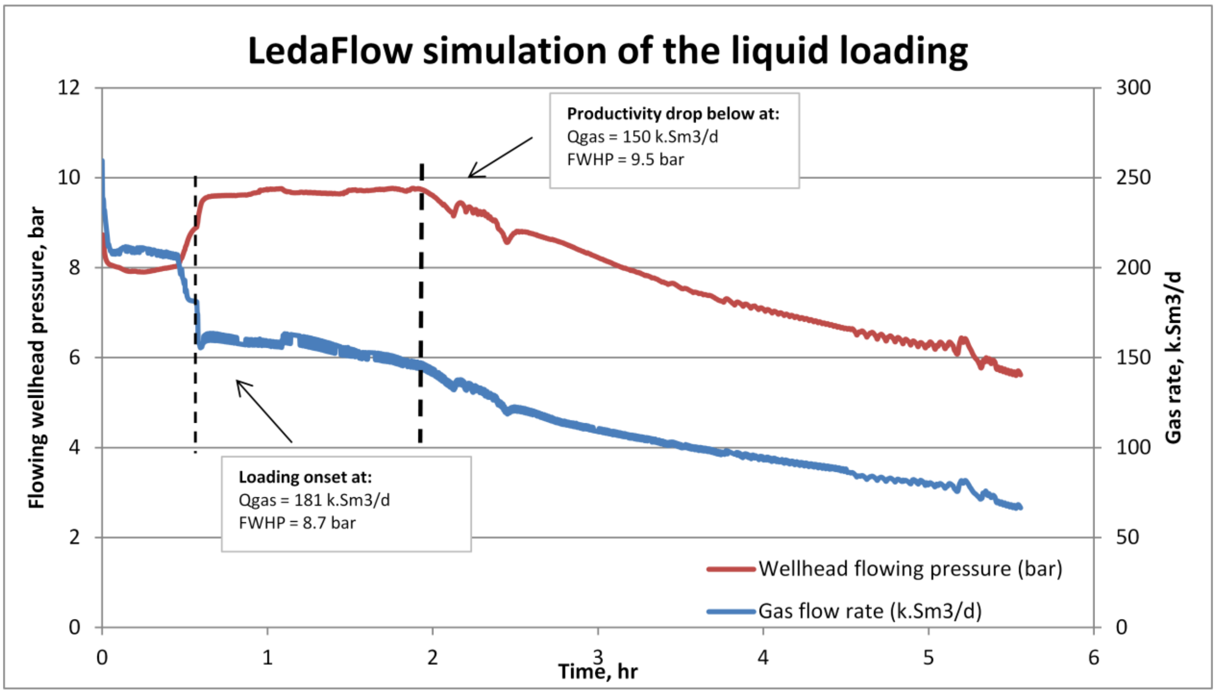

Figure 215 FWHP and gas rate with time at the end of the simulation

The graph above gives an idea of changes in flowing wellhead pressure with time and corresponding changes in gas rates at standard conditions. The liquid loading begins at FWHP = 8.7 bar and Qgas = 181 k.Sm3/d. The last stable point with rate of 150 kSm3/d is approximately at 9, 5 bar at the wellhead.

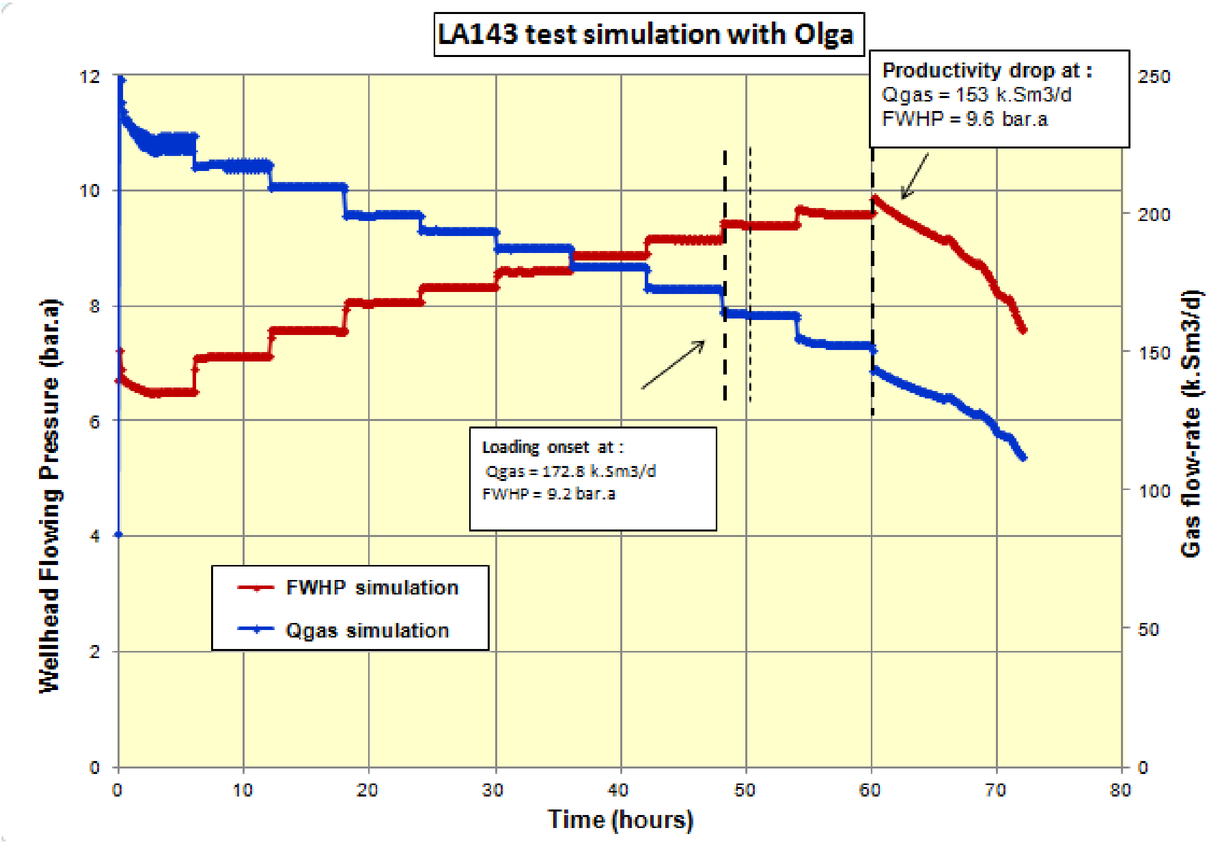

Figure 22 Liquid loading simulation results from OLGA

The liquid loading begins at FWHP = 9.2 bar and Qgas = 172.8 k.Sm3/d. The last stable point with rate of 153 kSm3/d is approximately at 9, 6 bar at the wellhead.

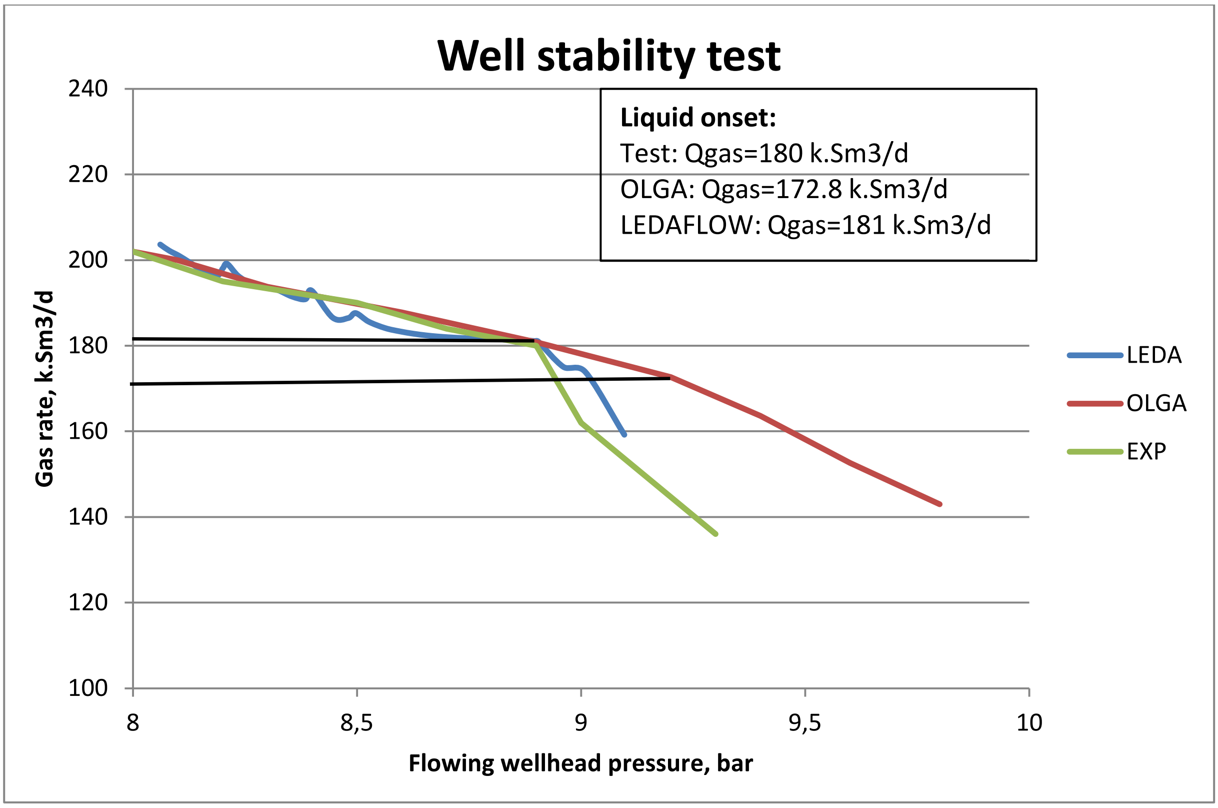

Figure 23 Well stability analysis

The graph above shows all three results of the well stability analysis. All three curves have a distinct change when the liquid loading begins. LedaFlow seems to give an accurate result, with a small underestimation, while OLGA gives an overestimation. Therefore, LedaFlow is on the conservative side of the prediction. The results might be a bit different from the ones done by SINTEF, as the choke position was chosen differently. LedaFlow: choke is placed at 3631m along the pipe. In the base case the choke was placed closer to the separator (boundary condition for the outlet). The values for the wellhead pressure and water flow rates were read off at the cell close to the riser top to avoid influence of the choke and boundary conditions. The improved results due to moving the choke can be explained by the elimination of the backflow from the horizontal pipe. The pipe angle is zero here, so the backflow must be caused by the level gradient (dh/dx).

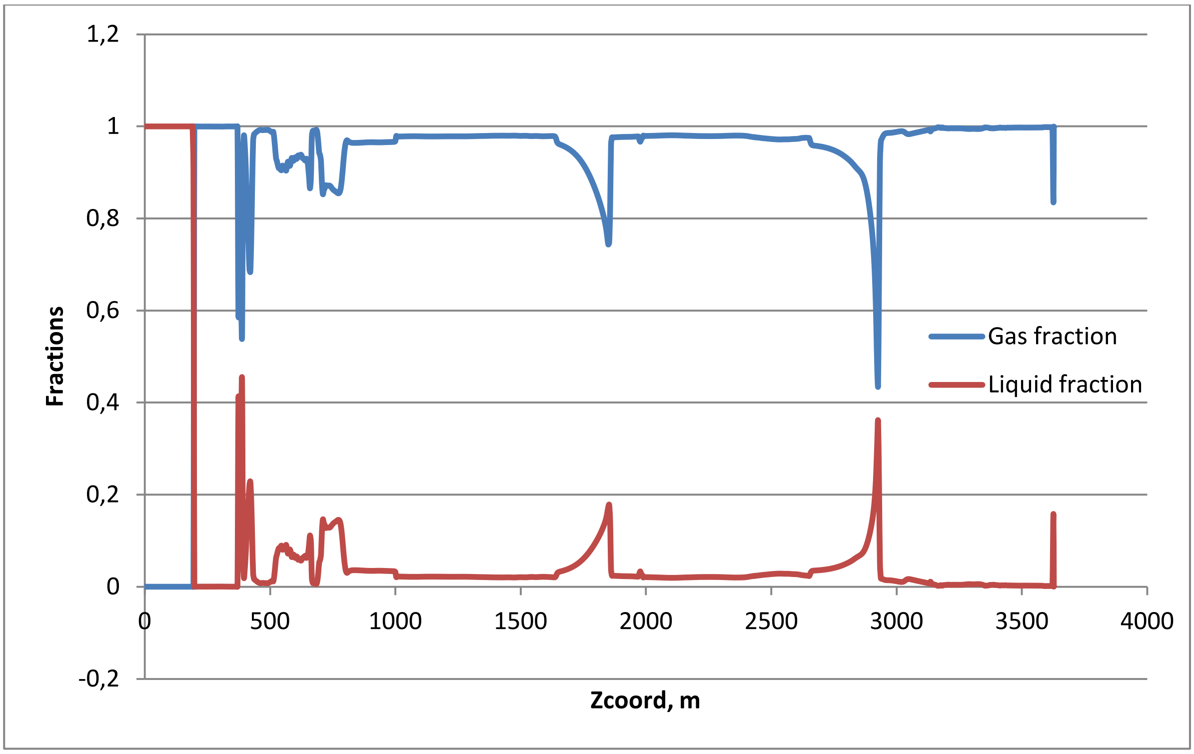

Figure 24 Liquid and gas fractions along the well at the end of simulation

During the liquid loading along the pipe there are changes in the fraction of gas and liquid. The changes mostly take place with increase and decrease in diameter of the well. Therefore, different mechanisms take place in the flow, like liquid film reversal and droplet entrainment.

It appears that the maximum thickness of the condensation film on the wall is reached at the top of the well, with the liquids cooled. Here the diameter 7’’5/8 is the largest and the gas velocity is the smallest. The gas velocity increases through the choke and stratified smooth flow regime is expected.

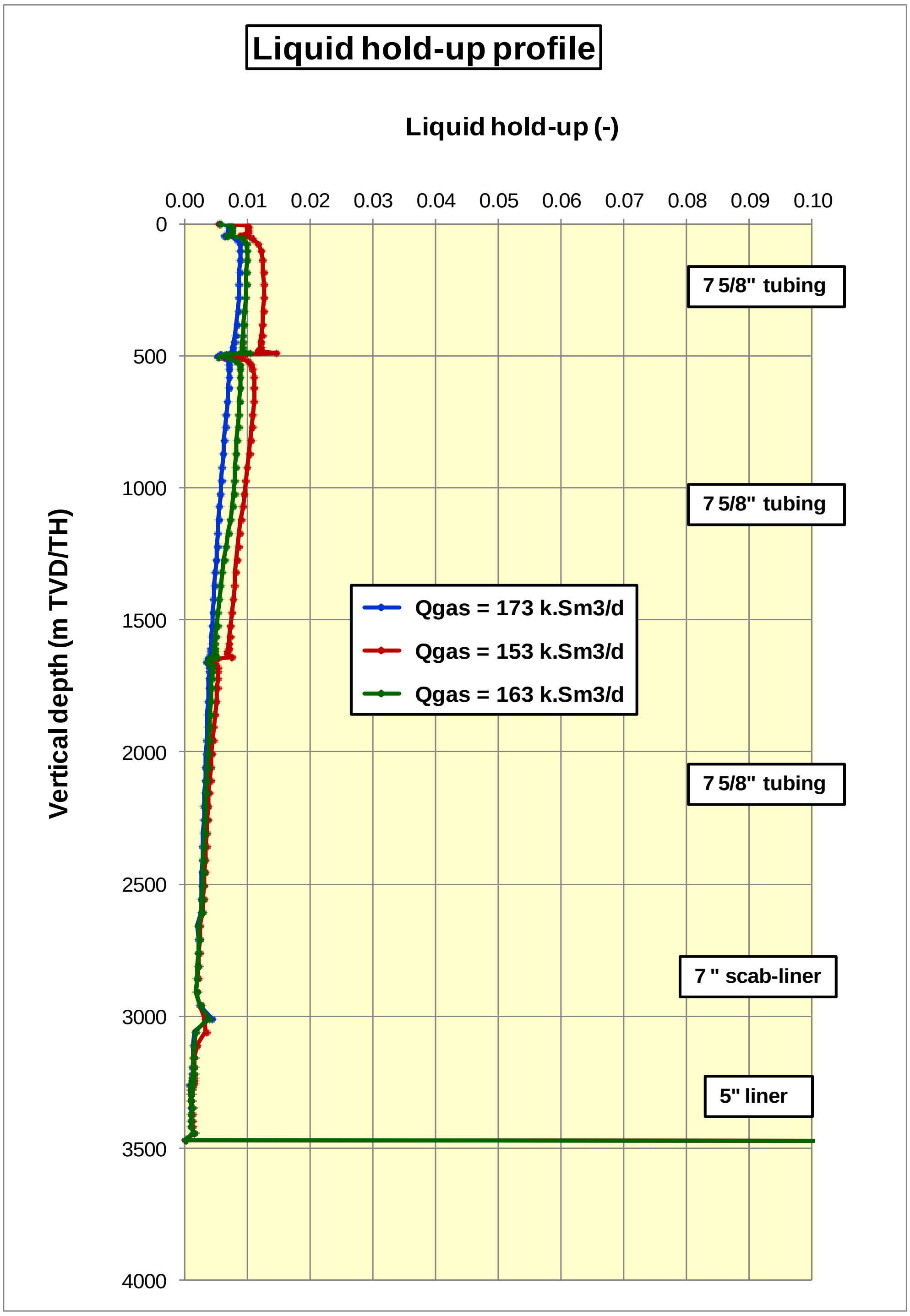

Figure 25 Liquid hold up along the well from OLGA

The graph above shows the results from OLGA simulation: as long as the liquid film is lifted by the gas the film is thin, when gas flow decreases, the liquid film thickness increases. In the limit of lifting, the film occupies 1% of the tubing section which represents a thickness of 0.9 mm.

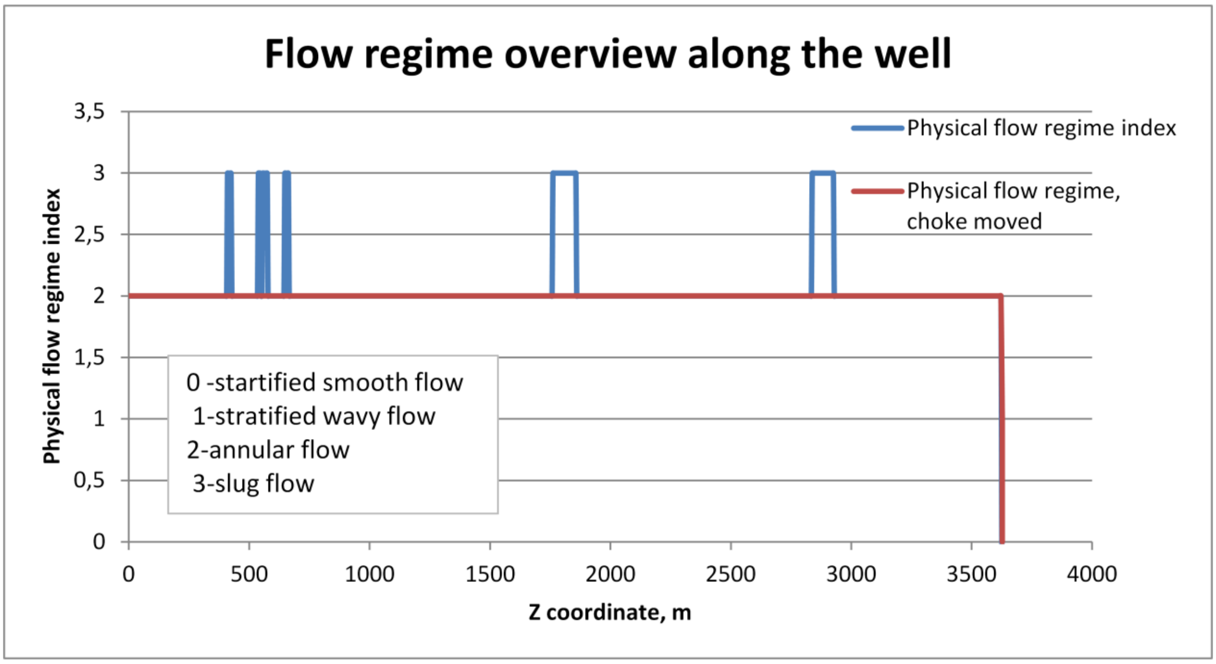

Figure 30 Flow regimes along the tubing

The restrictions from the completion solution in this well influence the flow regime along the well. In the graph above the blue curve represents the flow regime along the pipe with the original position of the choke. When the choke is moved in order to avoid liquid accumulation, the flow regime changes and stays annular, this, in turn, allows the successful lifting of the liquid to the surface.

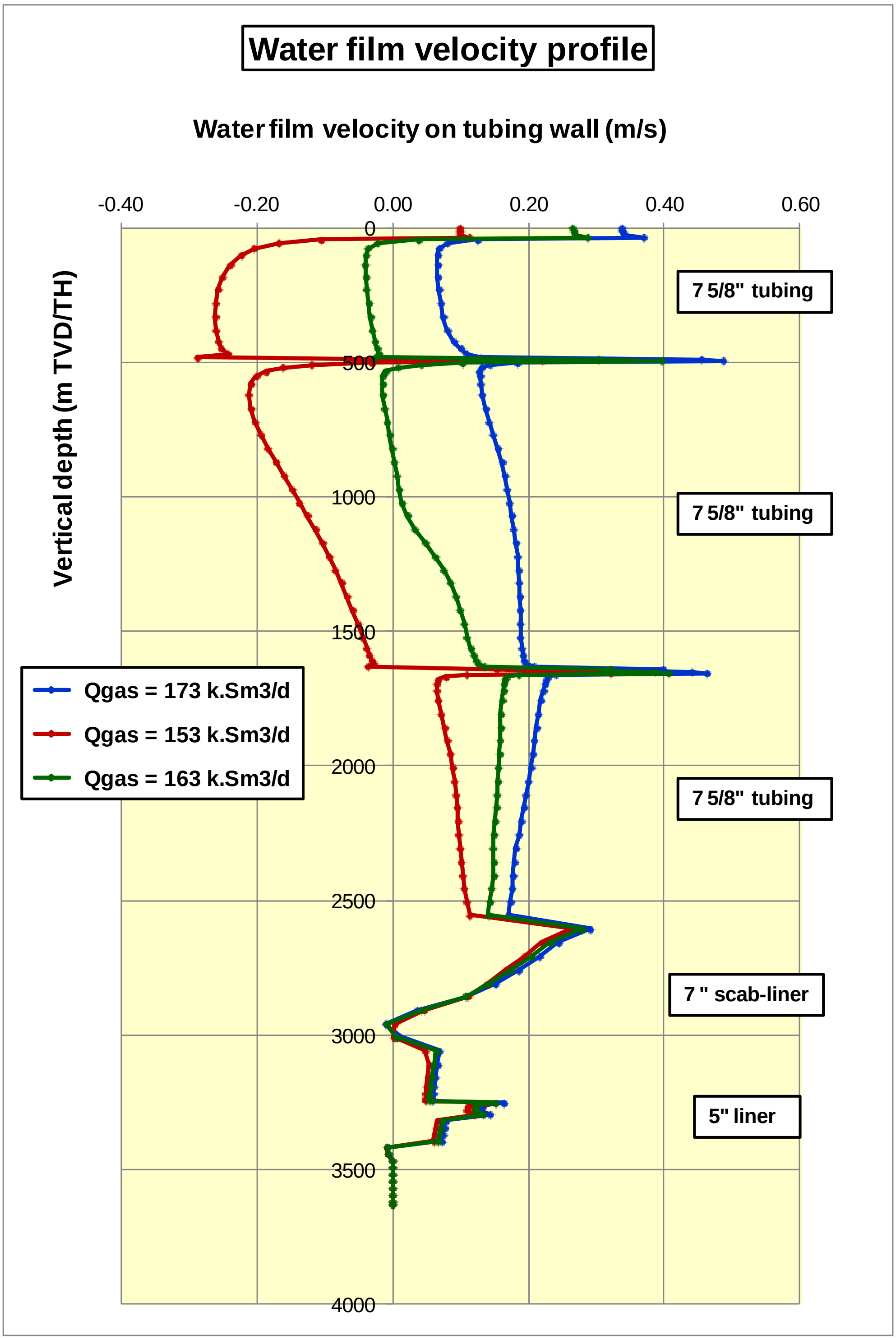

Figure 31 Water film velocity profile from OLGA

This graph shows that in the OLGA simulation, well production collapses below $Q_{gv} = 153\ k.Sm^3/d$ while the liquid film becomes negative (i.e. descendent) $Q_{gv} = 163\ k.Sm^3/d$.

There is a reaction time between the start of the liquid film reversal and when this descending flow generated enough additional pressure drops to destabilize or kill the well.

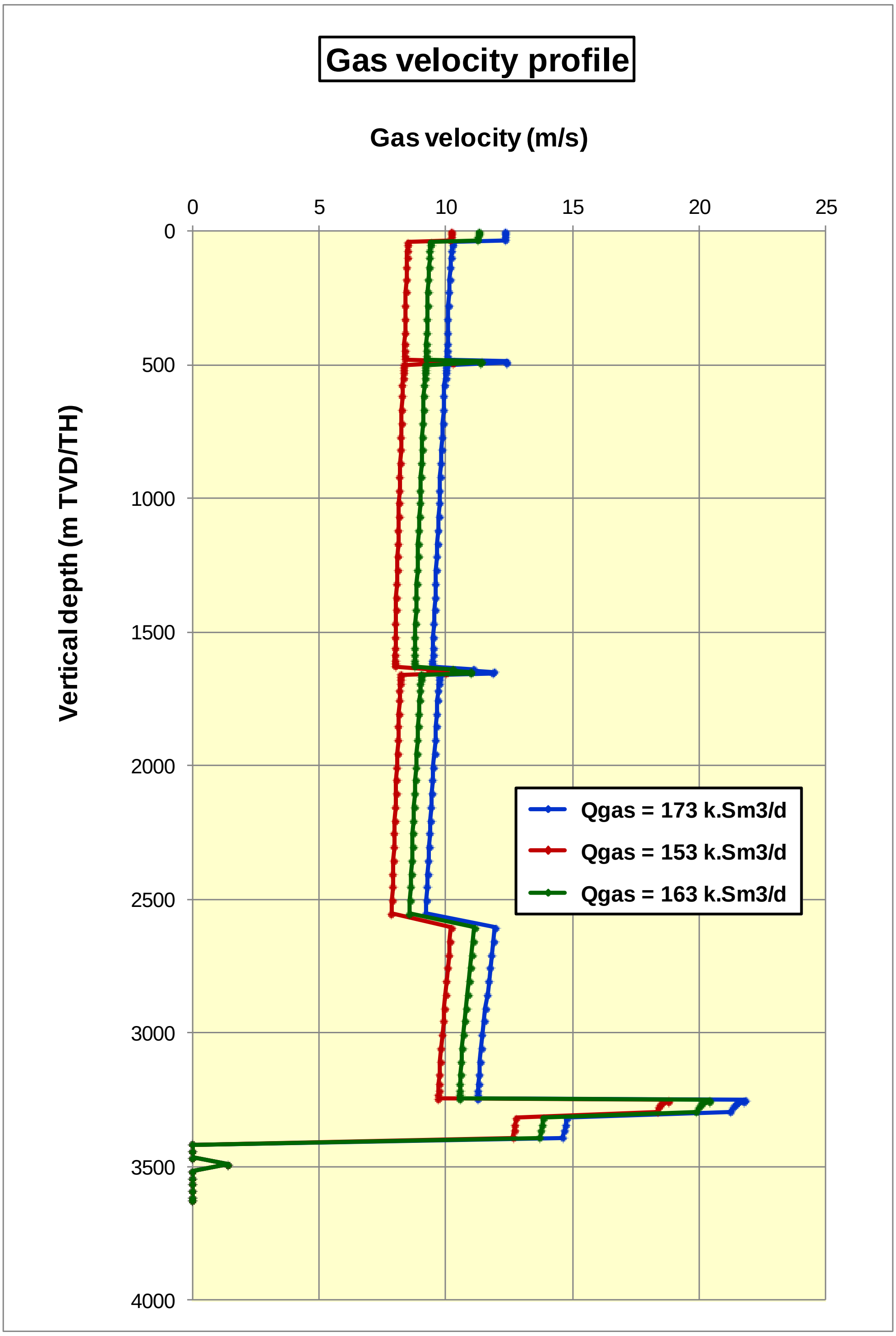

Figure 32 Gas velocity profile along the well from OLGA

This gas velocity profile shows that the liquid on the wall begins to descend (ref.163 $k.Sm^3/d$) at the top of the tubing 7" 5/8 when the gas velocity is 9.3m/s. Production drop happens later (ref.163 $k.Sm^3/d$) when the gas velocity drops below 8.4m/s. Therefore, the critical gas velocity to lift the film is $9.3 m/s$ for $P_{wh} = 9.6$ Bar. a. From the field data it is known that the critical velocity reaches the value of 9.5 m/s.

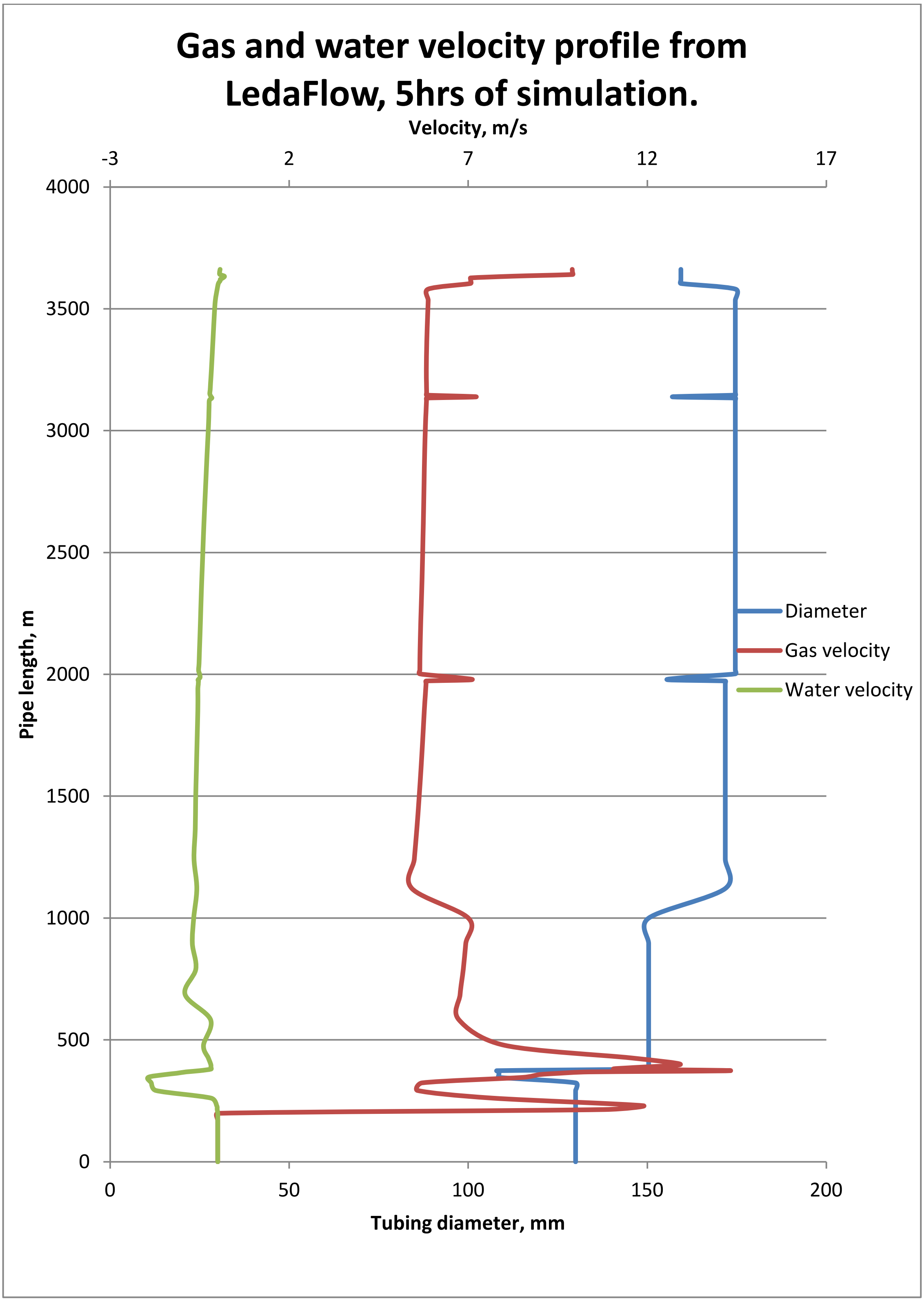

Figure 33 Gas and water velocity profile along the well from LedaFlow after 5 hours of simulation

From the graph above it is clear that the water film has a positive velocity at the top of the well, which requires a gas velocity of approximately 8.4 m/s.

The simulated results correspond to the liquid loading process in general. At the bottom of the well during the liquid loading, when the water and oil accumulate and as a result, bottomhole pressure increases and is higher than reservoir pressure, i.e. the liquid in injected back to the formation. In the field operations, when the liquid column gets its maximum value, wells usually get shut-in during this process. At this time point the tubinghead pressure will increase and might be of the same value as the reservoir pressure. After starting up the well, some time will be needed in order to bring the well back on stream. As soon as the liquid column reduces, the bottomhole pressure reduces and gas starts to bubble up to the surface. Some wells have a natural gas lift effect after some time of shut in. This reduces the column of the liquid and gives a natural start up of the flow.

The following table sums up the results produced by the LedaFlow and OLGA software, as well as some well known empirical models. These models are summarized in the SPE paper 153724 on Gas-well liquid loading probed with advanced instrumentation [25].

Table 9 Annular flow transition models, their respective superficial gas velocities at the beginning of annular flow

Aurthor	Model	Vsg (m/s)	Remark
Taitel et al. (1980), based on Turner's single drop model	$V_{SG} = \frac{3.1[\sigma g(\rho_l - \rho_g)]^{0.25}}{\rho_G^{0.5}}$	9.95	The model shows that transition to annular flow is independent of liquid superficial velocity and pipe diameter. Droplet cloud or drop concentration was not taken into account.
Pan and Hanratty (2002)	$V_{Gcr} = 40\sqrt{\frac{\sigma}{D\sqrt{\rho_l\rho_G}}}$	9.14	V_{Gcr} is the critical gas velocity. The model is independent of liquid superficial velocity.
Wallis parameter (1962)	$V_G^* = \frac{V_{SG}\rho_G^{0.5}}{\sqrt{\sigma g(\Delta\rho)}} \approx 1$	0.18	Commonly referred to as flow reversal point criterion. Transition is independent of liquid superficial velocity and flow conduit diameter. A small values means the superficial gas velocity is high enough to avoid flow reversal.
Field data	No single correlation was used; the result reflects complex calculations on the basis of possibly different closure models.	9.5	The values are somewhat close. Using CFD software allows including several parameters to give a value at any point of the well.
OLGA		9.3	
LedaFlow		8.4	

The values used for the calculations are taken at the flowing wellhead condition (Pwh = 9bar, Twh = 52C). Although these very simplified correlations give a quiet close value to the field data, but they are valid only at wellhead conditions and do not include such parameters as liquid superficial velocity and/or flow conduit diameter. On the basis of evidence in the table and prominent literature in gas-well liquid loading mentioned earlier, the authors of the paper come up to the conclusion that "the transition boundary from wispy to concurrent annular is independent of the amount of liquid in the gas stream, the pressure, and the flow area. Also, the transition boundary from concurrent to mist annular flow may not depend on any of these factors". As a result, the objective of the study within boundary transitions shifts to the transition boundary from slug to annular flow. The authors did not consider a possibility of the counter current flow within annular regime, which is taken into account by the OLGA and LedaFlow computations. Therefore, the software results are believed to reflect not only the complex flow conduit geometry, but different flow conditions, that influence fluid properties, and counter current flows.

Part 3. LedaFlow modeling

This part is devoted to the flow modeling description implemented in LedaFlow. Major equations for the 1D transient calculations are presented.

6. LedaFlow

The chapter gives a general idea of LedaFlow software development, as well as detailed description of system structure. A short summary of existing numerical modeling is linked to the modeling in LedaFlow, both 1D and Quasi-3D. The closure and flow models are presented with the relevant correlations.

6.1 Historical background [10]

By the beginning of the 9o's the multiphasee transport of oil, gas and water in pipelines was well researched. The industry was ready to design new transport systems that would be completed with precipitation and possible deposition of wax, hydrates, scale, asphalthenes and even sand. With challenges of deep water fields, harsh environment and longer tie-backs a demand in increase of accurate and detailed information and flow predictions is always there. The idea of developing such a software tool that will make it possible to work with several dimensions and capturing the effect of complex multiphase phenomena belongs to SINTEF. LedaFlow was founded with the cooperation with ConocoPhillips and Total (JIP: Joint Industrial Project).The companies joined not only the funding but also the devotion in constant contribution to the development of the project with professional expertise and active validation work. The first version of the software, LedaFlow 1D, is launched and commercialized by Konsberg Oil and Gas Technologies. As KOGT states it "LedaFlow is an efficient and user-friendly stand-only tool for transient multiphase flow analysis and flow assurance design in engineering studies [26]". Besides, it is integrated with K-Spice dynamic process simulation tool and can be applied for digital oil fields and Integrated Operations.

6.2 The LedaFlow system structure [10]

LedaFlow is composed of 3 main parts:

• **The client** and the **script engine** which are the user interfaces enabling problem definition, running calculations, analyses of result and communication with the database

• **The database** which stores the data (cases, input and results of computations)

• **The server** which performs the calculations, accesses the database to fetch input parameters and save results into the database.

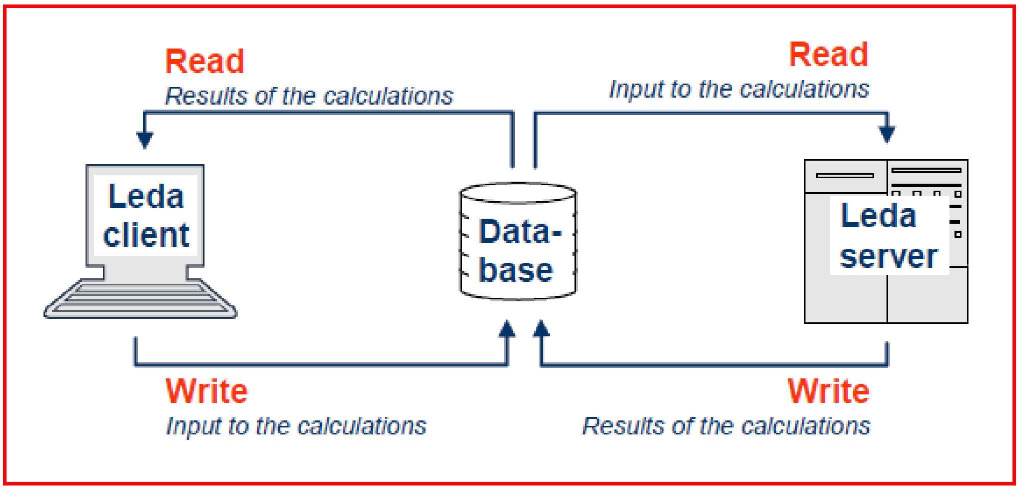

Figure 26 LedaFlow system structure

Database storage

All output variables are stored in the database and can be viewed without re-running of cases.

Script language

It enables standardization of flow assurance workflows and decisions as well as it provides text-based configuration files that is very easy and quick to use. There is an automated analysis algorithm with decision points and a possibility of parametric study for better steps in the future simulations. A possibility to transfer results to excel or other data format is very useful. LedaFlow allows importing existing multiphase models which is a complementary when dealing with a new tool. One of the useful options of the new software is its powerful visualization tool.

The description of the design is based on the information published by KOGT [27]. Design of oil and gas production systems, supporting at all project phases. Transient multiphase flow simulator helps to choose the right level of investment when it comes to choosing the optimal flowline diameter, hydrate control method or the right slug catcher size. Moreover, it enhances return-on-investment by providing the possibility to shorten the commissioning time, optimize well start-up and shut-down, minimize use of chemicals and inhibitors, ensure optimal well allocation, reduce number of multiphase meters and allocate revenue to wells. In general, LedaFlow allows reducing risk of problems connected to flow assurance, for instance, slugging, wax and hydrate formation, leakages, corrosion and erosion. Design and operation issues, like modeling and monitoring of well and flowlines, processing facilities, optimization of gas lift, become approachable with LedaFlow.

During the presentation of LedaFlow the partners announced very promising capabilities of the software: "transient analysis for normal conditions, turndown, shutdown, start-up, depressurization, line packing, terrain slugging, liquid surge in gas condensate systems, gas lift impact on flow conditions, thermal design of flowlines, thermodynamic inhibitor tracking, compositional tracking, pigging and converging and diverging networks [28]".

A new platform

The LedaFlow platform is built according to the latest Information Technology standards and tools. It serves the objective of ensuring a robust solution by providing a fully implicit network solver. Numerical methods implemented are accurate and robust. The simulation speed is increased by multiprocessor calculations. A powerful database platform is intended for collaboration between cases and sharing the results.

The LedaFlow platform uses modular system architecture in order to ensure easy development of specialized versions and connection with other applications like hydrate and wax formation models. For advanced users it is possible to use script for input rather than the graphical user interface which give quick and efficient access to perform parametric studies, probabilistic analyses and risk assessment.

6.3 Numerical Modeling

This part is focused on the description of the numerical modeling and is based on the information provided by KOGT n the company's website [29].

6.3.1 Overview of numerical models [30]

The numerical simulations of multiphase flow face two main challenges such as the representation of the interface evolving in time, and the evaluation of the force term contribution. There exist several discrete approaches and among those it is possible to point put two main strategies in coupling the interface evolution challenge to the Navier-Stokes equations discretized on a fixed grid.

The first strategy suggests tacking explicitly the interface position with the help of markers that describe the interface, i.e. front tracking, the methods that were introduced by Peskin and Glimm et al. There is a special class of front tracking methods which includes the immersed boundary method by Peskin and the immersed interface method by LeVeque and co workers. The evolution of the interface is done by Lagrangian advection of the markers, whereas the surface tension force calculation is done with discrete approximation of the delta function around the interface. With the help of geometric identities the interface points are used to calculate normal vectors and curvatures. Using explicit description is a very powerful method since it allows taking into account such general models of the interface as elastic forces in immersed boundary and interfacing implementation. The requirement of interaction of marker points and fluid grid in order to describe advection and interface forces makes it difficult to use these methods. Besides that, implementations are affected by unphysical changes of area/volume of the respective fluid. To give an accurate representation, the markers should e replaced as the interface changes.

As for the second strategy, the interface is described implicitly, i.e. front-capturing. The first researchers within these methods were Harlow and Welch who proposed the marker-and-cell method or a volume tracking method. The marker particles that were used to reconstruct the position of the interface are replaced with a marker function. This approach was suggested by Noh&Woodward who introduce the volume-of-fluid (VOF) method. VOF has a variable for fraction of the first fluid on the total fluid for each cell. Using the volume fractions it is possible to reconstruct the position of the interface, e.g., by defining line segments. Scardovelli & Zaleski and Sethian give a detailed representation, including higher order schemes. Increasing or decreasing the volume fraction which depends on the composition of the neighboring cells and the velocity field, makes it possible to implement the advection of the interface. There are several approaches into include surface tension force into VOF: one of them is to use discrete delta functions together with the reconstructed interface, another one uses the continuous surface tension approach proposed by Brackbill, Kothe and Zemach. Implying the VOF method gives volume conservation and a natural mechanism for breakup and coalescence of bubbles. Although it is more complicated to implement the reconstruction of the interface and the interface motion in the VOF methods.

The VOF methods work on the discrete level provided by the level set method proposed by Osher & Sethian and applied to two-phase incompressible flow by Sussman, Smereka & Osher. There exists another method, phase field method, suggested by Jacqmin for the simulation of two-phase flow.

Numerical solution Method for LedaFlow [31]

The transport equations are solved with a coupled pressure based technique which is close to Vasquez & Ivanov (2000) method, which in its turn represents an extension of the SIMPLE class of algorithms (Patankar, 1980). The implicit solver employs first order-time discretization and up to third-order in space (convective terms). The linear equations are solved with a Gausian elimination or a selection from Krylov methods.

6.3.2 LedaFlow Modeling

A unique ability to simulate and give visualization of slug, waves, bubbles and droplets in a multiphase pipeline flow was implemented in Quasi 3D (Q3D) and cross section profile modules.

The profile model (2D) gives cross section velocity profile of the flow. Basing on a consistent CFD formulation Q3D model defines multidimensional dynamics of the flow and distributions of the phases.

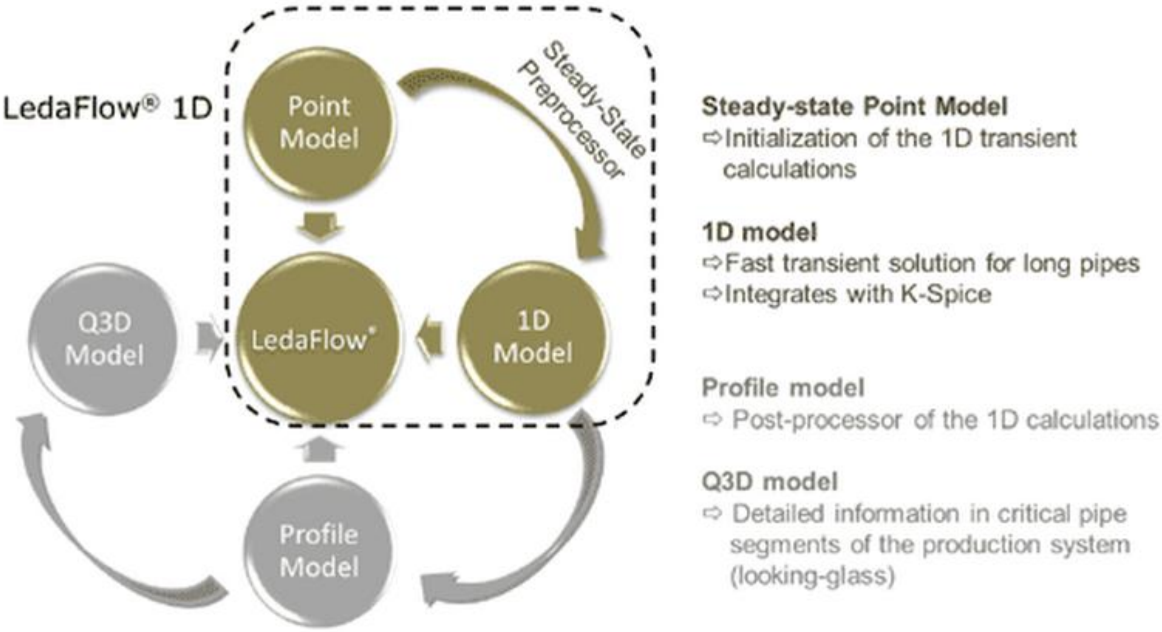

Figure 35 LedaFlow models [27]

At present, the models in LEDAFLOW include:

• The **1D model** which predicts the flow of a multiphase system (2-phase oil and gas, or 3-phase oil and water and gas) by using separate fields (4 fields for 2-phase systems, 9 fields for 3-phase systems) which are characterized with volume fractions, field velocities, enthalpy, particle size (bubbles and droplets), physical properties, temperature, and composition. Heat and mass transfer, compositional tracking, valve models and controllers, and models for wells are made available in the 1D module.

• A **Steady-State Pre-Processor** (SSPP) or **Point Model** is used for initializing 2- and 3-phase 1D calculations, with any combination of thermal and compositional models. It supports simple converging network cases with a single pressure boundary and cases with one pressure inlet and one outlet.

• The **Leda-Q3D Modeling** which is based on a multi-fluid multi-field representation of the N-phase turbulent pipe flow resolving it across the pipeline cross section and in the axial direction. It has a unique capability of tracking the Large-Scale Interfaces between the phases where it provides special models for interfacial momentum transport. In order to reduce the CPU time and keep the calculations feasible (especially for very long pipes), the slice-averaging concept is introduced while keeping account of pipe-wall contribution to the shear stress, turbulent kinetic energy production and so on. Besides, an individual transport equation for the size of dispersed particles (bubbles & droplets) is provided. In the current version, the Q3D model can also account for the gas compressibility assuming a constant value for $\partial\rho/\partial p$. Modeling multiphase flow in vertical bends and curved pipes is also made available by calculating the Coriolis and Centrifugal forces in the momentum equations. The code is parallelized and is capable of handling massive computations for very long pipes and risers with fine grid resolutions.

By **Leda-Q3D** technology, a complete transient quasi three-dimensional modeling of the complex multiphase pipe flows is made available which provides engineers and scientists with more detailed data for their analyses. In addition to the 2- and 3-phase pipe flows, the **Q3D** model can also compute single phase pipe flow as well as single phase and multiphase flow in two-dimensional channels.

• The **Profile Model** which is a steady-state 2-dimensional model acting as a coupling between 1-D and Q3D models.

LedaFlow also provides the following capabilities:

- Coupled 1D pipes
- Parallel computation

LedaFlow has separate momentum equations for gas, water and oil; therefore, user gets improved calculation of the oil-water momentum exchange and resulting slip. It provides independent temperatures for gas, oil and water phases which give better prediction of wax and hydrate formation.

Non-equilibrium Pressure/Volume/Temperature: diffusivity determines the phase change rate. LedaFlow uses non-equilibrium concept which is very critical/important for simulation of fluid flow in wells, well start-up and well stability problems, as well as design of interconnecting piping in LNG plant.

Another advantage over existing tools is the non-equilibrium modeling concept. PVT tables or full compositional modeling makes it possible to deal with different compositions. With the help of the internal PVT server it is possible to define hydrocarbon components, inhibitors and other compounds.

LedaFlow is based on representation of physical and compositional properties of three-phase flow. The approach includes detailed of liquid dispersions and gas bubbles in liquid phase, as well as, possibility to model multiphase flows with solid particles like sand and hydrates.

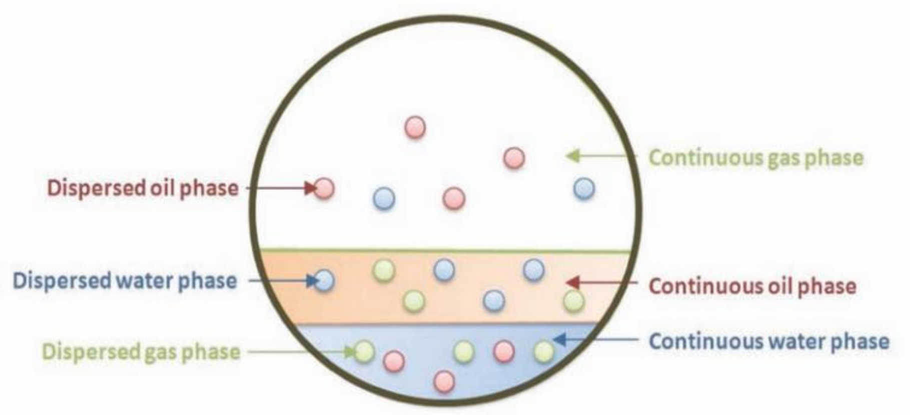

Figure 36 Field approach [32]

LedaFlow includes 9 mass equations, 3 momentum equations which results in improved oil-water momentum exchange and slip calculations, 3 energy equations which provide more accurate temperature and heat loss predictions.

6.4 LedaFlow 1D Model [32]

A number of models published and presented by the developing partners give an insight onto the model that employs a two-fluid-four-filed modeling concept to simulate the thermo- and hydrodynamics of a gas-liquid flow.

LedaFlow 1D employs one set of conservation equation of mass, momentum and energy for each field, which altogether make up for 12 equations.

The standard one-dimensional model two-fluid-four-field model uses four sets of equations, one for each field [33]:

Mass conservation equations:

$$\frac{\partial \alpha_k \rho_k}{\partial t} + \frac{\partial}{\partial x}(\alpha_k \rho_k u_k) = \sum_{i \neq k} \Gamma_{ki} + \Gamma_{kext} \tag{16}$$

Momentum conservation equations:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k u_k) + \frac{\partial}{\partial x}(\alpha_k \rho_k u_k u_k) = -\frac{\partial \alpha_k P_k}{\partial x} - \alpha_k \rho_k g sin\boldsymbol{\theta} + \frac{\partial \alpha_k \tau_k}{\partial x} + P_{int}\frac{\partial \alpha_k}{\partial x} + \sum_{i \neq k} F_{ki} - F_{kw} +$$

$$i \neq k \Gamma ki uki + \Gamma kext ukext \quad (17)$$

Energy conservation equations:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k h_k) + \frac{\partial}{\partial x}(\alpha_k \rho_k u_k h_k) = \frac{\partial}{\partial x}\left(\alpha_k k_k \frac{\partial}{\partial x} T_k\right) + \alpha_k \frac{DP}{Dt} + Q_{kw} + \sum_{i \neq k} Q_{ki} + \Gamma_{kext} h_{kext} \tag{18}$$

where k –index fields, k = 1,2,3,4; u-average field velocity; t-time; x-coordinate along the pipe; α-field volume fraction; ρ- field density; Γ_{kext}- net external mass source, such as, mass extraction from the system and mass injection into the system; Γ_{ki}- net mass flow rate obtained by field k from field i; τ_k- the shear stress of field k in the axial direction; P_k- field pressure; P_{int}- pressure at the large-scale interface (for stratified flow); g- the gravity; $\boldsymbol{\theta}$**-** pipe inclination angle; F_{ki}- forces due to interfacial friction of field k with other fields; F_{kw}- wall friction force; u_{kext}- velocity of external mass source; h_k- enthalpy of field k; k_k- effective thermal conductivity of field k; T_k- temperature of field k; P – system pressure (average pressure $P = \sum \alpha_k P_k$); Q_{ki}- interfacial heat transfer rate of field k with other fields; Q_{kw}- heat transfer rate of field k at pipe wall; h_{kext}- enthalpy of external mass source.

As for relationship between field pressure, P_k and the pressure at interface,P_{int}, it is assumed that for flow regimes other than stratified:

P = $P_k = P_{int}$

The gradient of the stress in the pipe axial direction $\frac{\partial \alpha_k \tau_k}{\partial x}$ is relatively small, therefore, can be neglected.

The momentum expression for flow regimes other than stratified one can be written from equation (17):

$$\frac{\partial}{\partial t}(\alpha_k \rho_k u_k) + \frac{\partial}{\partial x}(\alpha_k \rho_k u_k u_k) = -\alpha_k \frac{\partial P_k}{\partial x} - \alpha_k \rho_k g sin\boldsymbol{\theta} + \sum_{i \neq k} F_{ki} - F_{kw} + \sum_{i \neq k} \Gamma_{ki} u_{ki} + \Gamma_{kext} u_{kext} \quad (19)$$

Linear relationship between pressures is used for the stratified flow, as they are function field volume fraction, field density and pipe inclination angle. The pressure terms from equation (17) can be written as:

$$-\frac{\partial \alpha_k P_k}{\partial x} + P_{int} \frac{\partial \alpha_k}{\partial x} = - - \alpha_k \frac{\partial P_k}{\partial x} + G_p(\alpha, \rho, D) g cos\boldsymbol{\theta} \quad (20)$$

where $G_p(\alpha, \rho, D)$ is an explicit function of field volume fraction, field density and pipe diameter. Therefore, the momentum conservation equation for the stratified flow can be written as:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k u_k) + \frac{\partial}{\partial x}(\alpha_k \rho_k u_k u_k) = -\alpha_k \frac{\partial P_k}{\partial x} + G_p(\alpha, \rho, D) g cos\boldsymbol{\theta} - \alpha_k \rho_k g sin\boldsymbol{\theta} + \sum_{i \neq k} F_{ki} - F_{kw} + i{\neq}k\Gamma kiuki{+}\Gamma kextukext \quad (21)$$

6.4.1 Closure models [33]

A set of physical models is used to solve the above mentioned equations in order to describe the mass, momentum and energy exchanges between fields and between field and pipe wall. The models are legible for well -defined flow regimes, such as bubbly flow, stratified flow, slug flow and annular flow. Each regime should be defined in order to follow the transitions in regimes.

There exist four groups of closure models:

- Flow geometry: sizes of dispersed fields, like bubbles and droplets [34], identification of flow regime, parameters related to geometry of different flows.
- Interfacial mass transfer: droplet entrainment and deposition [35], bubble entrainment and coalescence, interfacial mass transfer due to phase change (by black-oil model).
- Momentum exchanges: wall friction [36], interfacial frictions in the contact of two fields, momentum exchanges due to mass transfer.
- Energy exchanges: wall heat transfer, interfacial heat transfer, relationship between temperature and enthalpy.

There are some process components developed for valves, controllers, wells, pipe bends as well as heat transfer between pipeline and sea water environment. All models are developed for compressible fluids.

6.4.2Flow models

Flow regime [14]

In LedaFlow, there are three main gas-liquid flow regimes: stratified/annular flow, slug/churn flow and bubbly flow. Stratified flow is available for horizontal and inclined pipe; the annular is valid for vertical pipes with large inclination angle. There is a number of input parameters for calculation of regime transition, like pipe properties, fluid physical properties, field volume fractions and velocities. According to the pipe inclination, there specified two cases: upward vertical and horizontal inclined.

The flow regime determines the geometrical distribution of the phases, which influences the calculation of pressure drop and holdup on coarse grids.

In stratified/annular flow, the gas and liquid are assumed to flow in two separate zones, possibly with liquid droplets in the gas. For nearly horizontal pipes, the gas is assumed to flow on top of the liquid film, whereas in nearly vertical pipes, the liquid is assumed to flow as a film covering the entire pipe circumference.

In bubbly flow, the gas is present in the form of bubbles inside the liquid, while liquid covers the entire pipe wall.

In slug (churn) flow the Unit Cell Model is used, where the flow is considered as a sequence of slugs and slug bubbles. The slugs are liquid-continuous (possibly with gas bubbles), while the flow in slug bubbles is stratified/annular. Thus, slug flow is a mixture of bubbly flow and stratified/annular flow. In the case of slug flow, the local field fractions, velocities and slug fraction are calculated assuming that the flow is fully developed.

The importance of choosing the stratified/annular flow regimes assumption is discussed partly with regards to counter-current flow in the clean up case, i.e. LedaFlow modifications for the simulation. To deal with the overestimation of the gas-liquid slip in counter-current flow, the gas-liquid friction factor needs to be modified.

Flow regime transition model [37]

Slug and non-slug flow

To calculate liquid slug length fraction the unit-cell model for slug model is used:

$$F_S = \frac{L_S}{L_S + L_B} \qquad (22)$$

where F_S is the liquid slug length fraction, L_S is the liquid slug length, L_B is the slug bubble length.

The void fraction in liquid slug is calculated explicitly first such as the mixture velocity of the liquid slug section is equal to the mixture velocity of the whole flow if the flow is fully developed.

The phase flux is constant relative to the slug bubble front, thus the solution of the force balance in slug bubble sections gives the volume fractions and velocities of the phases in the slug bubble section.

$$F_S = \frac{U_{sg} - (\alpha_g u_g)^B}{(\alpha_g u_g)^S - (\alpha_g u_g)^B} \qquad (23)$$

If 1>F_S>0, the slug flow regime is present. If the gas fraction in the slug is greater or equal to that in bubbly flow, the flow regime is bubbly one. The remainder is the stratified/annular flow.

Stratified and annular flow

The following assumptions are valid: flat interfaces in horizontal pipes and pure annular geometry in vertical ones. For intermediate angles, the wetted perimeters and interface areas are calculated with the help of a weighted average of the two situations.

$$W_{annular} = MIN\left(\frac{1+e^{-0.2(85-60)}}{1+e^{-0.2(|\theta|-60)}}, 1\right) \qquad (24)$$

where θ is the pipe angle in degrees.

For the horizontal case superficial velocities of gas and liquid, volume fractions and velocities are calculated first. With the help of Kokal and Stanislav correlation [38], it is decided whether the flow is bubbly, as the wall friction in liquid phase is calculated as for stratified flow. If the flow is bubbly flow, the devoted subroutine will export the regime identification as bubbly, otherwise, it will continue. If the gas volume faction is very small (10^{-5}), the code will treat the flow as bubbly.

To identify between slug flow and stratified slow, the code uses the flow geometry. The subroutine uses the slug instability model by Woods and Hanratty [39] to filter the stratified regime. Firstly the bubble volume fraction in the liquid slug is calculated, whereas the liquid velocity u_l of stratified flow at the given flow rate condition is calculated according to the stratified flow model. The latter one does not take into account droplets and bubbles; it is assumed that the flow is steady-state. It is the force balance for each phase that is used for u_l calculation:

$$-\alpha_l \frac{\partial p}{\partial x} - \alpha_l \rho_l g sin\theta - F_{l,wall} - F_{gl} = 0 \qquad (25)$$

$$-\alpha_g \frac{\partial p}{\partial x} - \alpha_g \rho_g g sin\theta - F_{g,wall} - F_{lg} = 0$$

Eliminating the pressure gradient, the equation takes the following form:

$$(\rho_g - \rho_l) g sin\theta - \frac{F_{l,wall}}{\alpha_l} + \frac{F_{g,wall}}{\alpha_g} - F_{gl}\left(\frac{1}{\alpha_l} + \frac{1}{\alpha_g}\right) = 0 \quad (26)$$

This equation is solved iteratively by bi-section method in order to get u_l. It can be further simplified by assuming the interfacial friction is two times the gas wall friction coefficient.

For the upward vertical flow, with low gas flow rate (α_g<10 − 5), the flow is identified as bubbly. It is set as bubbly if the gas volume fraction is less than 0.15. If the gas volume fraction is between 0.25 and 0.52, Kokal and Stanislav model is used to decide between bubbly and slug flow. If the liquid flow rate is very low α_l<10 − 5), the flow is identified as annular. If the gas volume fraction is larger than 0.52, McQuillan and Whalley model [40] is implemented to decide between slug and annular flow.

For the upward vertical flow the following is applied:

- The correlation for the liquid holdup [41]:
  $$\alpha_{cl;S} = 1 - \frac{u_{mix}}{u_{mix} + 83(\frac{g\sigma\Delta\rho}{\rho_l^2})^{0.25}} \quad (27)$$
- If the flow is non-slug one, the bubbly or annular flow is defined, i.e. the limit for liquid holdup is set to 0.52. If the value if holdup is above it, then the flow is bubbly, otherwise it is annular one.
- The interfacial friction between gas and liquid in the slug bubble zone is solved from annual flow formulation with Wallis's correlation [20].
- $L_S = 10D$.

Non-slug flow

If the flow is defined as non-slug one, there are here flows considered; stratified, bubbly and annular. For all flow regimes, droplets and bubbles diameters are calculated. Basing on the structure of the flow, the interfacial area and the wall wetting area are calculated. There are three correlations for calculating the average droplet diameter, the ones by Azzopardi [42], Hinze [43]and Azzopardi et al. [44]. As for the calculation of bubble diameter, the correlation of Hesketh et al. [45] is used.

6.5 LedaFlow 3D Model

The following section of the theory study is based on the paper presenting a 3D multiphase flow model [31].

6.5.1. Conceptual model Q3D

Q3D phase-based model equations are derived from the general 3D multi-field equations. There are several steps in achieving that: first of all, the full 3D equations for the fields related to a layer; second step would be the field equations are combined to phase ones, therefore, the number of equations is reduces; the final step is slice averaging, i.e. analytical integration the phase model over the slices of pipe. The last step allows reducing the problem from 3D to 2D case of pipe flow. The steps are reviewed in general one by one.

6.5.1.1 3D equations for the field pertaining to a layer

The layer concept includes a number of fluid continuous layers that constitute the total flow. A phase can be as dispersed or suspending field within a layer, i.e. one suspending field and Nph-1 dispersed fields, with the boundary conditions at the inlet, outlet, and at LSI's that separate the layer from other fluid-continuous layers.

The general 3D equations include the field equations for suspending and dispersed phases in a particular layer, interactions of fields within a layer. Mass and momentum conservation equations as well as turbulent kinetic energy equations are formulated here.

6.5.1.2 3D equations for phases

The formulated field equations are combined into phase equations. As a result, the number of equations is reduced and some of the otherwise necessary closure models cancel out. To make a transition from the field model to the phase model it is needed to sum over the Nph fields that belong to the same phase in the Nph different layers. This concept differs from the mixture model that implies the summation over the different fields in one layer. After summing the LSI's are internal to the new phase equations, therefore, all interfacial terms describing the transfer processes at LSI's come out in the phase equations and are modeled. Now that the domain on which equation are defined from layer volume to the total domain volume, the layer field equations share the same points in space.

6.5.1.3 2D pipe flow equations for phases

Analytically integrating over degenerated slices (horizontal lines) and dividing by the local slice width gives slice-averaging, i.e. the eexpressing of the primary variables is done by their slice-averaged counterparts. During the averaging operations wall shear stress terms and other new closure models come out.

For all present fields Eulerian volume-and ensemble-averaged turbulent transport equations are derived. The single-phase volume-averaged Navier-Stokes equations are the first steps [46]. Multiphase flow is split into fields, so that flow consists of different regions with suspended droplets, particles and bubbles by one fluid. The total number of fields includes each fluid continuous region and all possible types of dispersed constituents. Therefore, there are nine fields in a three-phase flow. If there exists a liquid film on the wall, one more field is added.

For each continuous region volume averaging is applied to provide generic transport equations for the continuous and the dispersed fields.

With the help of appropriate closure models for the integral in the momentum equation, a model for the transient 3D flow inside different continuous regions of the flow is obtained.

In order to separate gas- and liquid-continuous regions, the large-scale interface (LSI) concept is used. Besides that, it is responsible for shear stress transfer between different fluid-continuous regions, bringing droplets and bubbles to the respective continuous regions as well as receiving depositing bubbles and droplets at the same time. The LSI is defined as the physical interface where local volume fractions pass the phase inversion boundary.

Turbulence is defined by a filter-based multiphase model, where turbulent dissipation is identified by an algebraic closure. After conditional ensemble-averaging of the transport equations, the conservation equations for turbulent flow are defined. Averaging takes place over the possible turbulent realizations of the flow. So, the large-scale features are resolved by the model, whereas features smaller than the filter used are modeled. The LSI approach is applicable for the four field transport equations. Individual transport equations are used for to evolve the turbulent energy for each of the two fluids. Adding up the field transport equations results in defining phase transport equations for phase specific quantities. It is noted that mass transfer terms for transfer between bubble and continuous liquid disappear formally. However, an inaccuracy is introduced in interfacial cells due to lacking the possibility to discriminate between bubble and continuous gas velocity.

The large-scale interfaces (LSI) a concept of wall functions is implemented; so that the shear stresses from both sides of the interface are approximated by the rough-wall wall functions presented by Asrafian & Johansen 2007 [47].

To add the turbulence production in LSI cells the same functions are applied. To include the effect of non-resolved waves a density corrected Charnok model [48] is used.

Dealing with the dispersed droplet and bubble sizes, their local Sauter mean diameters are used. The convective evolution equations (Laux & Johansen 1999, Laux, 2003) are used in order to enclose the spatial development of bubble and droplet sizes, where the droplet size entrained from the LSI needs a specific model.

Wall functions concept is used to describe the interaction with solid walls. it is used in CFD and presented in the paper of Asrafian & Johansen 2007.

LedaFlow Q3D, a quasi-3D, is a version of the 3D done by averaging the flow over horizontal slices in order to reduce the computational time without losing the flow physics. Q3D is basically a two-dimensional approach which allows simulating quite long pipe sections to analyze flow development and transitions of flow regimes. The figure below illustrates the pipe cross section to show how the transport equations are spatially averaged over each slice.

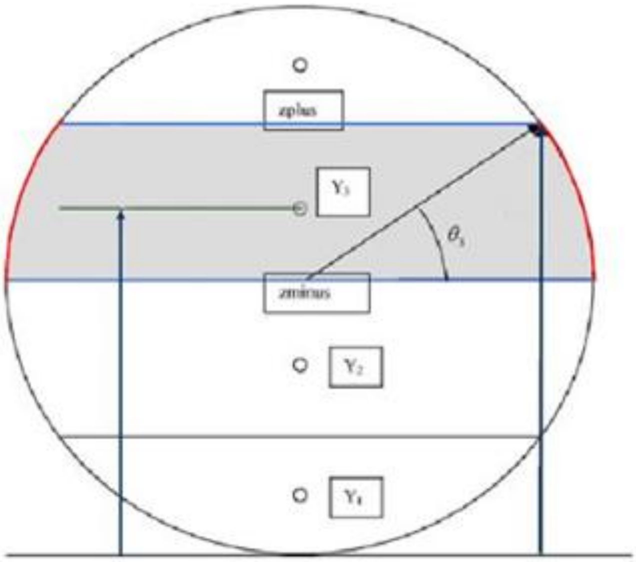

Figure 27Outline of the Q3D geometry. The walls are colored red are the external boundary to the grey colored slice [31]

Therefore, there are two-dimensional Q3D transport equations with fluxes at the wall treated as boundary conditions. The slice averaging takes the following form:

$$\langle\theta\rangle \equiv \int_{-z\frac{1}{2}(y)}^{z\frac{1}{2}(y)} \theta dz, \tag{28}$$

where z(y) is the slice width.

Formal averaging of the transport equations gives Q3D-averaged fields.

Mass-averaged Q3D velocity component take form as:

$$u_{g,j}^{Q3D} \equiv \frac{\langle\varepsilon_g u_{g,j}\rangle}{\langle\varepsilon_g\rangle} \tag{29}$$

Therefore, the liquid momentum equation looks like:

$$\frac{\partial}{\partial t}\left(\varepsilon_l \rho_l u_{l,i}\right) + \frac{\partial}{\partial x_j}(\varepsilon_l \rho_l u_{l,j} u_{l,i)=-}\varepsilon_l \frac{\partial}{\partial x_i} P + \varepsilon_l \rho_l g_i - \left\{f_g \frac{\varepsilon_l \rho_l}{t_{p,droplet}} + f_l \frac{\varepsilon_g \rho_g}{t_{p,bubble}}\right\}\left(u_{g,i} - u_{l,i}\right) - \left\{f_g \frac{\rho_l}{t_{p,droplet}} \overline{u"_{g,\iota}} + f_l \frac{\rho_g}{t_{p,bubble}} \overline{u"_{l,\iota}}\right\} + \frac{1}{\Delta V} \sum_{CV\ faces}^{6} (\hat{\tau}_{eff,l} - \alpha_l \rho_l \langle u""_{l,i} u""_{l,i} \rangle)\, \overrightarrow{n_{CV}} A_{l,CV} + f_g \varepsilon_l \frac{\partial \tau_{g,ji}}{\partial x_j}$$

(30)

All fields are slice averaged over the pipe width. In the term $\alpha_l \rho_l \langle u""_{l,i} u""_{l,i} \rangle$, $u""_{l,i}$ is the deviation between the local 3D velocity component and QD-averaged value. The term expresses a mixing stress due to the flow geometry. Similar terms are in scalar transport equations and might influence axial dispersion.

Conclusion and discussion

This study has given an account of, and the reason for, the widespread use of transient multiphase simulators applicable to the well flow cases. The main investigation has focused on the LedaFlow predictions of completion fluid flow rates in the first hours of the simulation and the onset of the liquid loading in a gas well. The aims of this investigation: to evaluate and validate LedaFlow simulations of a gas well clean-up and liquid loading in a gas well, to perform literature research and study the models used for 1D modeling. The main questions addressed in the study were predictions of volumes and rates of completion fluid in the clean up case, and the wellhead pressure and critical gas rate for liquid loading onset.

The preliminary results of the study were modified and show that improvements have been achieved. The results of the investigation of user defined parameters show that modifying wellhead pressure, diameter of the tubing, productivity and injectivity indices to the real case gave improved results. The main findings were done within the gas-liquid friction factor in case of counter-current flow. Further investigation is needed in order to pinpoint the possible areas of detailed research. The current study of clean up case was only examined using 1D transient model, whilst the Q3D looking glass functionality could be used not only to get detailed information on the part of the pipe with regard to hydrodynamics, but also to validate the above mentioned functionality.

As for the liquid lading case, the results were somewhat satisfying with the acceptable error margin. LedaFlow was able to simulate the changes within bottomhole, and wellhead pressures and the resulting gas and liquid velocities profile development with time along the complex geometry of the well. LedaFlow results, being on the conservative side unlike OLGA, prove that it can be used for modeling in the case of liquid loading in a gas well.

This study was undertaken in order to enhance knowledge and understanding of multiphase flow as a part of Master Degree studies, and a detailed insight into complex physics that happen during these highly dynamic operations. It gives confidence and understanding for a production engineer in performing the daily routine of production optimization, flow assurance. For the operators this type of study gives reduced risk, increases production and reduced down time.

Whilst this study did not solve the roots of the challenge that possibly lie within the code, LedaFlow has shown, in terms of clean up case, it did partly substantiate that improvements needed to be done within user defined parameters, especially with initial and boundary conditions, well model, tuning choke model and closure models. The best result can be achieved under condition of the access to the detailed field or experiment data which reduces a number of uncertainties.

Since the results of the sensitivity study support the idea that more research is needed in testing the well flow cases using LedaFlow. Further research should therefore concentrate on the investigation of counter-current flows, single well model with varying PI and II, and gas lifting liquid cases. It would be interesting to compare experiences of engineers in setting up the clean up case in OLGA and LedaFlow within Total group. The results could be applied to the dynamic well clean up flow simulation for field start up planning and kick off of the wells after shut ins.

Dynamic simulations in LedaFlow have proven to be of value throughout the wells life cycle, and it has potential to become a valued tool in modeling of many operations, especially as the current focus is in developing CFD type codes that support decision making throughout the wells life cycle.

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