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Recreating Riser Slugging Flow Based on an Economic Lab-sized Setup ⋆

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Abstract: As a kind of periodic phenomenon, the slugging flow in the offshore oil & gas production addresses a lot of attentions, due to its limitation of production rate, periodic overload processing facilities, and even direct cause of emergent shutdown. This work studies the emulation of the riser slugging flow in the offshore oil & gas production, by constructing an economical lab-sized setup in the university campus. Firstly, the construction and used components for the lab setup are illustrated; then, the constructed setup is validated by checking the consistency with some existing typical riser slug model, besides extensive experimental tests. The theoretical analysis and experimental results show that this simple setup can recreate the key features of slugging flow phenomenon with reasonable preciseness, and it serves as a good platform for further slug control study.

Keywords: Modeling, offshore, oil & gas, periodic, production, system.

1. INTRODUCTION

The oil and gas industry has spent a lot of time and effort in optimizing the production. One area of interest is the reduction of slug in pipeline and riser systems. Some operating conditions leads to undesired flow regimes, since they cause varying flow rates and pressures in the system. Both the flow and pressures can either be constant or follow sinusoidal periodic cycles. When the flow and pressures are varying in cycles, the production rate will be significantly reduced with regards to the safety issues and sometimes the fluctuation may lead to system shut down. There exist several consequences of having these oscillations: liquid overflow and high pressure in the separators, overload on gas compressors, fatigue caused by repeating impact, high frictional pressure drop, low production and production slop, (Hill and Wood (1994)). The slug flow is the flow pattern creating the biggest oscillations as shown in fig. 1 where a number of different flow patterns in a vertical pipeline are illustrated.

Being able to avoid the slug flow in the pipelines is of big economic interest. For this reason it is important to be able to predict the flow regime before the production starts, so that problems can be avoided. Traditionally flow maps are designed for each unique system from empirical data, (Hewitt and Roberts (1969)). It is indicating which flow pattern is represented in steady-state. It is noted that the flow maps are open-loop maps, with no control feedback loops represented.

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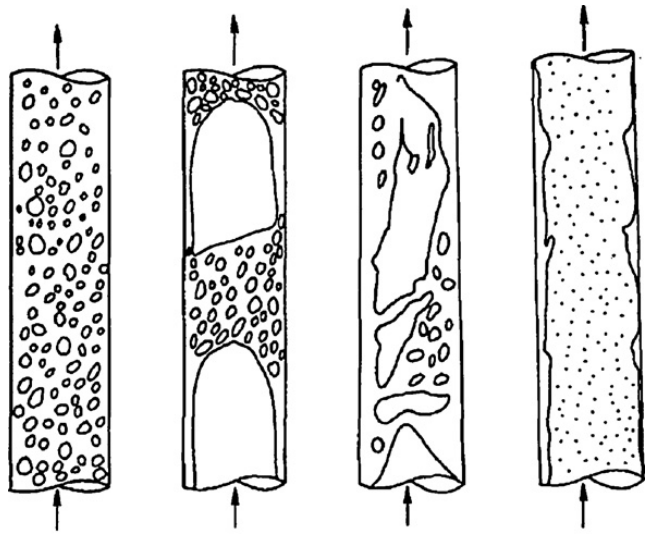

Fig. 1. Different flow patterns. From left to right: Bubble flow, slug flow, churn flow, annual flow and wispy annular flow (Taitel et al. (1980)).

There exist different kinds of slug, based on the operating conditions. Some can be caused by the physical appearance in both horizontal and vertical pipelines, and some due to transient response related to pigging, start-up, blow-down, and changes in the pressures or flow rates, (Sivertsen et al. (2010)). The flow maps are only showing the steady-state operation. Because of this a more detailed description of the phenomena is necessary to understand all the possible outcomes including those caused by the transient response.

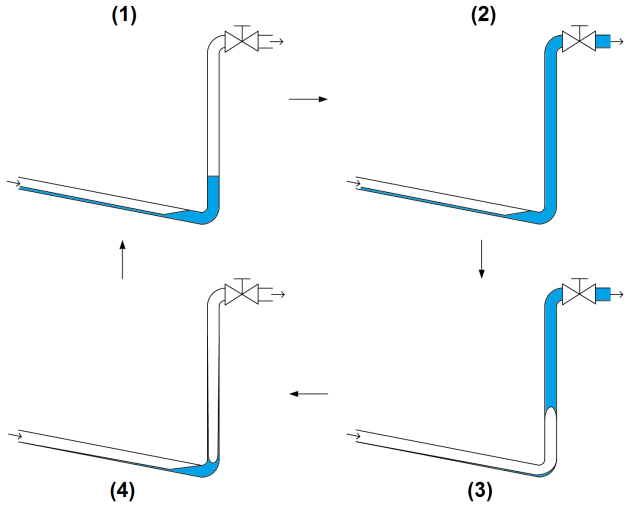

Fig. 2. Illustration of the cyclic behavior in a riser pipeline when slug occurs. A controllable choke valve is located at the top of the riser.

A dynamical model has been investigated in this paper to examine the slug phenomena.

A physical lab setup has been constructed to recreate the riser slug phenomenon. In the real offshore case, the horizontal pipelines can be over 30 km long, where the vertical pipelines rarely extend 200 m, (Dansk Undergrunds Consortium (2012)). However for practical reasons the dimensions have, naturally, been down-scaled. Fig. 2 shows the periodic slugging behavior of a vertical riser pipeline: (1) Liquid accumulates in the bottom of the riser. (2) When more gas and liquid enters the system, the pressure will increase and the riser will be filled with liquid. (3) After the blocked gas has built up, the pressure will be large enough to blow the liquid out of the riser. (4) After the blow-out, the liquid will start to build up in the bottom of the riser and the cycle repeats.

Some riser slug models have been proposed by Jahanshahi and Skogestad (2011), where a 4 state model has been developed, and Meglio et al. (2009), where a 3 state model has been developed. Earlier studies of a small-scale setup has been developed by Baardsen (2003). Some model-based control strategies of slugging is mentioned in Meglio et al. (2012). Furthermore Ogazi et al. (2010) and Isaac et al. (2011) has proven that control of the flow and slugging can increase production.

Even though a number of lab setups for studying slugging flow at different universities and companies have been observed, the intention is to construct a lab setup in order to get a first-hand experience and later serve as a good test platform for advanced slug control, before considering the real-life implementation and tests.

The rest of the paper is organized in the following: Section 2 illustrates the lab facility constructed for this work; Section 3 introduces simple models of the choke valve and separator, along with a typical riser model (Meglio et al. (2009)); Section 4 validates the consistency between the lab testing with mathematical model simulations; and we conclude the paper in Section 5, followed up with the discussion and future work in Section 6.

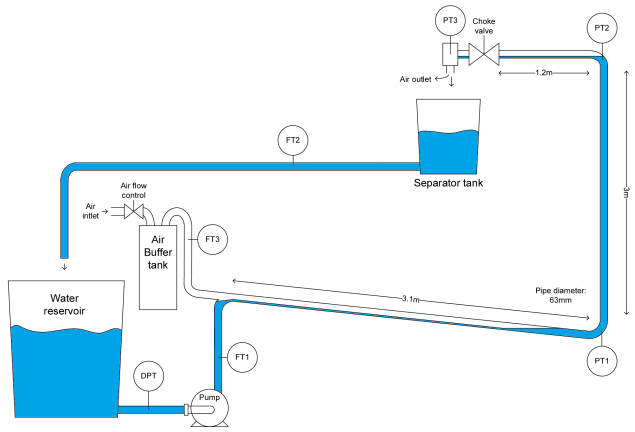

Fig. 3. Overview of the constructed lab-setup. Length of horizontal pipeline is 3.1 m, height of riser is 3 m, and length from riser to choke valve is 1.2 m. All pipe diameters are 6.3 cm.

2. CONSTRUCTION OF LAB SETUP

This section describes the constructed lab setup, including sensors, actuators and optimal operating conditions for generating slug flow.

2.1 Economics and Diagram

A lab-setup has been developed at the university campus. The setup is constructed using existing pumps at the campus, purchased piping, fittings and sensors and borrowed actuators from local companies. The total cost of the setup is around 10,000 DKK [1] . However without borrowing any equipment the cost would be around 2-3 times as much. A diagram of the setup can be seen in fig. 3 and a picture of the setup can be seen in fig. 4.

It consists of horizontal and vertical pipes to simulate a real pipeline/riser system. Water is transported through the pipeline and riser to the choke valve and afterward to the separator and back to the water reservoir to close the loop. Air is injected at the start of the pipeline, transported through the system and let out after the choke valve.

The angle of the horizontal pipe can be adjusted from 0° to 20°, and the placement of the air injection can be moved from start of the pipeline to the bottom of the riser to facilitate different scenarios (e.g. only riser).

2.2 Transmitters and actuators

In the lab-setup sensors from Bürkert, Danfoss, Endress+Hauser, Fischer & Porter, and Haenni are used. Mounting positions can be seen in table 1 and fig. 3.

A choke valve from Koei Industry is used. It is mounted on top of the riser between two pressure sensors.

2.3 Recreating slugging flow

The main focus of the lab setup is to recreate the slug, which occurs on platforms when pumping oil, water and gas.

[1] 1,340 euro, 1,790 USD.

Fig. 4. On the left is the separator and air injection and behind it is the vertical pipe. In the middle is the water tank, next to it is the pumps and on the far right is the computer used for control and measurements.

Table 1. Transmitters

Transmitter type	Name	Mounting position
Pressure transmitter	DPT1	Over pump
Mass flowmeter (water)	FT1	After pump
Mass flowmeter (air)	FT3	Pipeline air inlet
Pressure transmitter	PT1	Bottom of riser
Pressure transmitter	PT2	Top of riser
Pressure transmitter	PT3	After choke valve
Mass flowmeter (water)	FT2	After separator

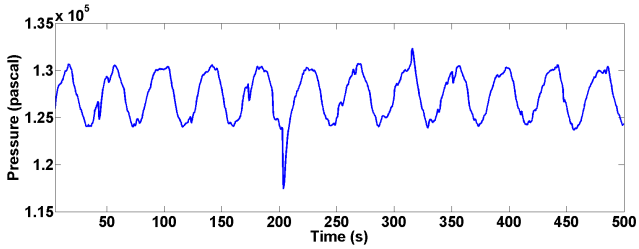

Fig. 5. A plot from PT1 at the bottom of the riser with constant water and air flow and the choke valve at 50% opening.

Behavior and stability of severe slugging has been investigates by Taitel (1986), which has been used to determine the running conditions for this setup.

In the constructed lab setup different water and air injection settings can generate slug with different conditions. Fig. 5 shows a data plot over 500 seconds from PT1 at the bottom of the riser with constant water and air flow of respectively 0.1 kg/s and 1.72×10^{-4} kg/s and the choke valve at 50% opening. These inflow conditions achieved best results when recreating periodic slugging flow.

This periodic phenomenon is resolved when closing the choke valve. Measuring the maximum and minimum pressure of PT1 for several opening references will give a map of the steady state dynamics of the system. This plot is called the bifurcation map and can be seen at fig. 6. It is observed that there exist two bifurcation maps: One where the choke valve opening is decreasing (blue line), and one where the choke valve opening is increasing (red line). It is observed that the system behaves differently depending on whether the choke valve opening is decreasing or increasing.

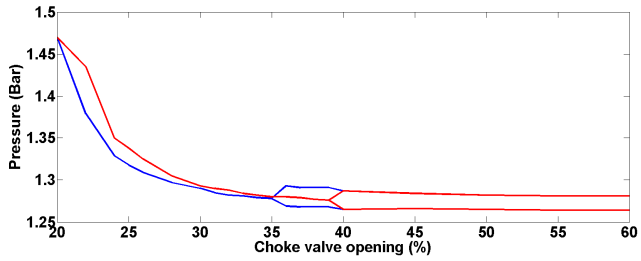

Fig. 6. Bifurcation map. Blue line is for decreasing choke valve opening and red line is for increasing. At 35% the periodic slugging phenomenon will start fading and at 39% the phenomenon returns.

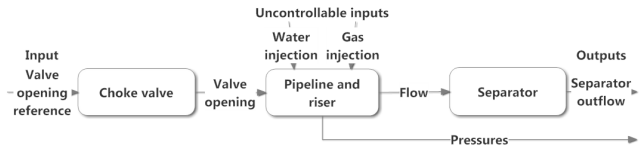

Fig. 7. The connection between the three subsystems: choke valve, pipeline/riser model, and separator model.

3. MATHEMATICAL MODEL

The model of the lab setup consist of three parts. The choke valve, pipeline/riser model, and separator model. The three subsystem's correlation is showed in fig. 7.

3.1 Choke valve

The choke valve used in the lab setup does not have an internal controller. It is controlled by input voltage in the range: -24 to 24 V in an open-loop system. Therefore a PI controller has been developed to design a closed-loop system with valve opening reference as input and actual opening as output. The controller is designed based on Ziegler-Nichols method (Franklin et al. (2010)) and tuned manually.

The closed-loop system can be approximated as a first order system without time delay, as the choke valve has fast dynamics.

$$G_{valve}(s) = \frac{K}{\tau \cdot s + 1} \tag{1}$$

The System Identification Toolbox in MATLAB is used to determine the unknown parameters: K and τ. An experiment with different opening reference steps has been used, where both the input and output are known.

The resulting first order equation corresponding to our lab setup is:

$$G_{valve}(s) = \frac{1}{0.68 \cdot s + 1} \tag{2}$$

3.2 Pipeline/riser model

Pipeline/riser model developed by Meglio et al. (2009) consists of three differential equations based on mass balance principles. The model contains three volumes.

Two of these are gas filled and separated by a virtual valve which causes a gas build up within the riser due to the gas is blocked at this location. The build up of gas causes an increasing pressure in the volume before the virtual valve(V_{eb}) until it is sufficient to flow through, which causes the pressure to drop and the process repeats. The last volume is liquid filled.

The three differential equation are as follows:

$$\dot{m}_{g,eb}(t) = (1-\epsilon)\omega_{g,in}(t) - \omega_g(t) \tag{3}$$
$$\dot{m}_{g,r}(t) = \epsilon \cdot \omega_{g,in}(t) + \omega_g(t) - \omega_{g,out}(t) \tag{4}$$
$$\dot{m}_{l,r}(t) = \omega_{l,in}(t) - \omega_{l,out}(t) \tag{5}$$

$m_{g,eb}$ is the mass of the gas before the virtual valve. $m_{g,r}$ are the mass of gas after the virtual valve. $m_{l,r}$ are the mass of liquid in the entire system. ω_g is the gas flow through the virtual valve. ϵ determines the amount of gas directly bypassing the virtual valve. $\omega_{l,in}$ and $\omega_{g,in}$ is the liquid and gas flow into the system, respectively. $\omega_{l,out}$ and $\omega_{g,out}$ is the liquid and gas flow out of the choke valve, respectively. Two valve equations gives the flow through the system and each has a tuning parameter. C_c is a tuning parameter for the choke valve, and C_g is for the virtual valve.

3.3 Separator

The outflow of liquid and gas of the pipeline/riser is running into a separator tank. Here, the main purpose is to separate the liquid from the gas.

To create a model of this process, the following equation is considered:

$$A \cdot \dot{h}_{tank}(t) = Q_{in}(t) - Q_{out}(t) \tag{6}$$

This is based on the continuity theorem:

$$\dot{V(t)} = q_{netto}(t) \tag{7}$$

q_{netto} is the net volumetric flow, A is the area of the tank, h_{tank} is the height of the tank, and Q_{in} and Q_{out} are the in- and output water flows of the separator. It is assumed that it is a cylindrical water tank.

Another relationship is considered:

$$Q_{out}(t) = K \cdot \sqrt{h(t)} \tag{8}$$

K can be used as a tuning parameter, but is depending on a number of parameters. It can be obtained from the following equations:

$$Q(t) = A_{outlet} \cdot v(t) \tag{9}$$

Where A_{outlet} is the area of the outlet and v(t) is the fluid velocity.

Bernoullis Law can be used to describe the relationship between the outflow velocity v(t) and the liquid level in the tank.

$$v(t) = \sqrt{2gh(t)} \tag{10}$$

Knowing the physical meaning of K, can extend the model expression:

$$\dot{h}(t) = \frac{1}{A_{tank}} \cdot Q_{in}(t) - \frac{K}{A_{tank}}\sqrt{h(t)} = \frac{1}{A_{tank}} \cdot Q_{in}(t) - \frac{K_t \cdot A_{outlet} \cdot \sqrt{2g}}{A_{tank}}\sqrt{h(t)} \tag{11}$$

K_t is a tuning parameter used for the validation. is tuned to have the value 0.18, to fit the settling time of the validation tests.

4. VALIDATION

Besides the physical parameters, there are 5 tuning parameters available: C_c, C_g, ϵ, V_{eb}, and K_t. The first four are included in the pipeline/riser model and the last, K_t, is included in the separator model. These are the parameters which will be used to make the model fit the small-scale setup at the university. At this stage they have been tuned manually.

There are no height transmitter placed in the separator, hence the separator height is not being validated.

To obtain the best model fit, the outputs of the model has to be tuned with the parameters. The outputs are the pressures and the flows, and will be adjusted individually.

4.1 Pressure output

Some physical parameters included in the model are the riser pipe areal A and radius r, the volume of the riser V_r, the temperature inside the riser T and the mean inclination of the riser θ. These are known directly from the lab setup. The temperature is considered constant throughout the system.

Other parameters are tuned within the Simulink simulation to make the model fit the measurements. The parameters are the volume of the retained gas bubble (V_{eb}), the distribution of gas going directly through the virtual valve compared to gas retained (ϵ).

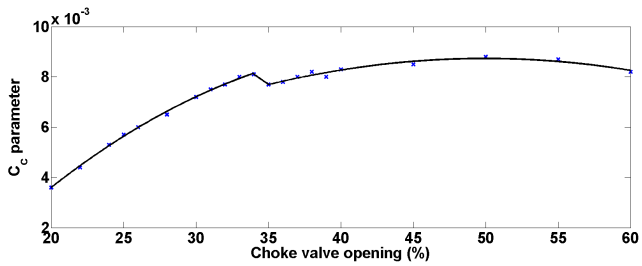

Fig. 8. Tendency lines for the C_c parameter with decreasing choke valve opening. Points are fitted to a pair of second order functions.

Two input-varying parameters are C_c and C_g. Both varies based on the choke valve opening. From experiments the parameters have been adjusted to fit the simulated model for different opening references. The choke valve opening is plotted with the tuned parameter values. Fig. 8 - 10 shows

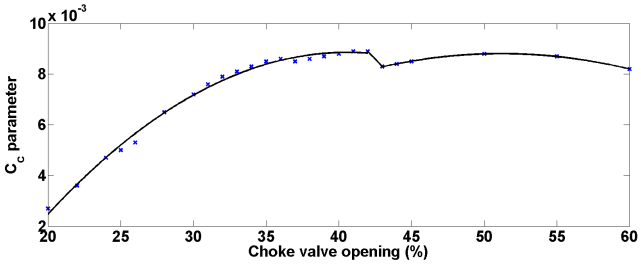

Fig. 9. Tendency lines for the C_c parameter with increasing choke valve opening. Points are fitted to a pair of second order functions.

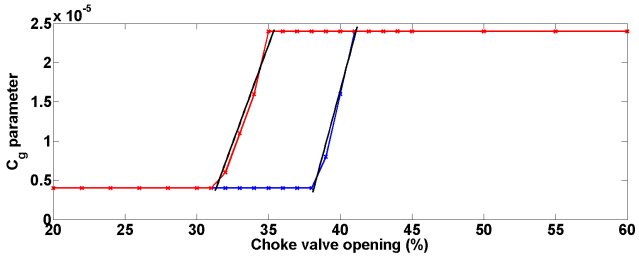

Fig. 10. Tendency line for the C_g parameter. The blue line shows the parameter with increasing choke valve opening. The red line shows the parameter with decreasing choke valve opening. Points are fitted to linear functions.

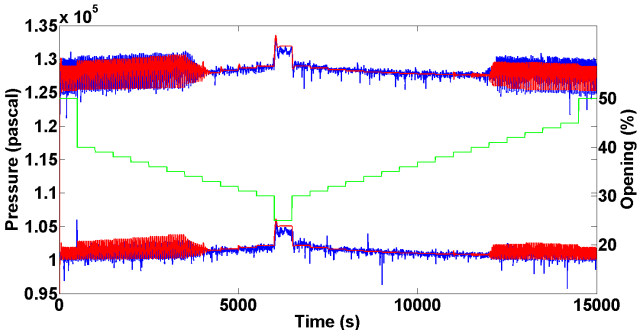

Fig. 11. Simulated riser/pipeline pressure(red) compared to measured pressure(blue). The bottom pressure has the highest pressure value. The green line indicates the opening of the choke valve.

these plots together with tendency lines. This functional expression is used to calculate the parameters based on the choke valve opening. The parameters are also depending on if the choke valve is opening or closing, or rather if the system has been stabilized or not.

The model is validated by comparing simulation results with a new independent test set. The resulting simulation compared to the measurement data are seen at fig. 11. The red line is the simulated pressure, the blue line is measurement data and the green line is opening reference. Both the topside pressure and the bottom pressure is seen. The bottom pressure has the highest pressure value.

The system will oscillate until stabilized by decreasing the choke valve. This is observed in fig. 12 where the system is stabilized around 35% opening reference. The amplitude of the unstable bottom pressure oscillation is 0.06 bar and the period is 59 seconds. The measurements have some

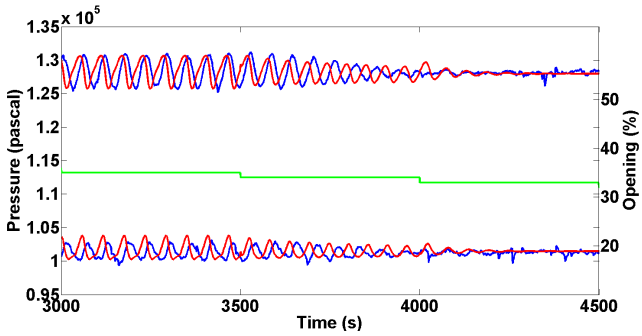

Fig. 12. Simulated riser/pipeline pressure(red) compared to measured pressure(blue). The bottom pressure has the highest pressure value. The frequency and amplitude roughly corresponds to measured data. The green line indicates the opening of the choke valve. This figure is a close-up of fig. 11 around the stabilization point.

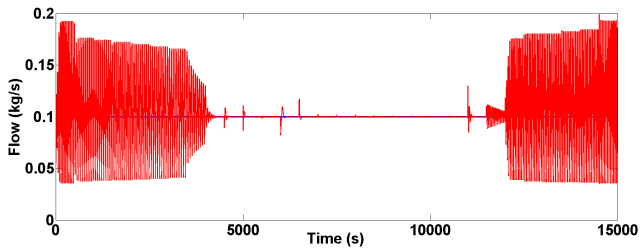

Fig. 13. Simulated liquid output flow (red) compared to measured input flow (blue).

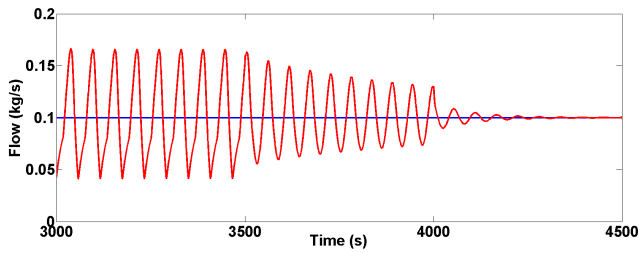

Fig. 14. Simulated liquid output flow (red) compared to measured input flow (blue). The flow is stabilized simultaneous with the pressure. This figure is a close-up of fig. 13 around the stabilization point.

fluctuations which is caused by noise and backflow which is not considered in the model. The measurements have been filtered.

4.2 Flow output

The simulated liquid output flow of the pipeline/riser is showed in fig. 13. The red is the simulated output flow and the blue line is the measured input liquid flow. As seen the Flow is oscillating around the constant input flow and is stabilized simultaneous with the pressure with some small oscillations when the choke opening reference is changed. Fig. 14. shows the flow when stabilized and 15 shows the accumulated output liquid compared to the accumulated measured liquid input.

A test of the separator outflow is carried out for the validation of K_t. Here the separator tank is filled with

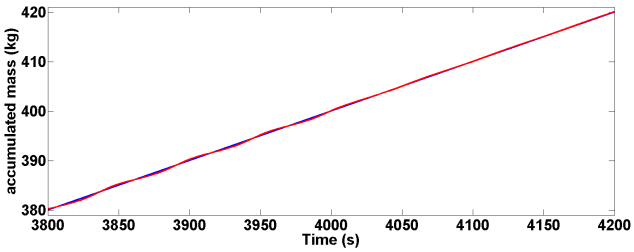

Fig. 15. Accumulated simulated liquid output flow (red) compared to measured input flow (blue).

water, before opening the manual choke valve on the separator outlet, to determine if the settling time of the model fits the real measurements. K_t is tuned to have the value 0.18, to fit the settling time of the test.

5. CONCLUSION

An economical lab-sized setup has been designed and constructed in the university lab, which is able to recreate the riser slug phenomena observed on offshore platforms. The measurement data from the setup are verified against a tuned model with good results. Thereby, the developed setup and corresponding model can be confidently applied for further slug control purpose.

6. FUTURE WORK

In the future a controller for the lab setup will be designed. The validated model can be used in a controller scheme. Model predictive control (MPC) using the validated model will be used in the future, to develop an optimal controller. This controller will be compared to other types of feedback controllers to determine if the there is any advantage using the MPC scheme.

If the results of the closed-loop system including the MPC are good for the lab setup at the university, a model of a real-scale offshore plant could be created to design a corresponding controller for this plant. Some Danish oil & gas companies have shown interest in these results and the possibility of implementation.

There are no controllable choke valve placed after the separator, hence the separator height is not being considered as a controlled output. For future work the lab setup can be extended with this actuator and incorporated into the mathematical model. This has been done in Sayda and Taylor (2007) and Yang et al. (2010). A closed separator without atmospheric pressure would be preferable and yield better results.

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