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# Small scale severe slugging experiments with several risers

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# MASTER THESIS

for

Student Ingrid Sofie Solstad

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## Small scale severe slugging experiments with several risers

*Småskala forsøk med ustabil strøm og flere stigerør*

**Background and objective**
Severe slugging in flowline-riser systems is a well known phenomenon, where liquid accumulates in the riser and blows periodically out and into the receiving separator. This unstable flow is to be avoided in subsea oil-gas pipeline transport, and the phenomenon was indeed a strong motivation for the first development of dynamic flow simulators. The flow mechanisms of severe slugging can be reproduced in small scale experimental setups, and a portable two phase flow laboratory is available for this purpose.
Some field installations involve several risers coming from a common manifold. Some experiments show that non-symmetric flow distribution is then possible. This flow phenomenon has been demonstrated qualitatively in a small scale experimental setup in a student project. Further experiments are now suggested with quantitative measurements, and with variations in number and geometry of the risers.

**The following tasks are to be considered:**

1 Improvement of the experimental setup, with instrumentation for flow rates and pressure.

2 Experiments at severe slugging conditions: flow maps, pressure amplitudes and frequencies

4 If possible, comparisons with simulations. Diverging pipe network is not a computational feature in all available simulators (e.g. OLGA, LedaFlow)

5 Reporting

-- " --

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

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Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☒ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 14. January 2014

Olav Bolland
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# ABSTRACT

Severe slugging is a multiphase flow phenomenon that can occur in flowline-riser systems when conditions allow it. Its periodical fluctuations in pressure and mass flow can cause operational problems in downstream processing facilities, and should be avoided. The occurrence of severe slugging in parallel riser systems is of interest due to the increasing need of subsea flow splitting during hydrocarbon production.

To investigate that issue, this work involves experiments done one a small-scale facility applying air and water to simulate a two-phase flow. Different geometries with dual risers are studied – both symmetrical and non-symmetrical. Pressure and flow rates have been recorded and registered in combination with visual observations. This in order to produce flow regime maps, as well as looking at changes in period and pressure amplitude.

Efforts were made towards stabilizing a severe slugging regime by using different sized risers. The results showed that adding a thinner riser had some success in stabilizing severe slugging in a non-symmetrical dual riser system. A symmetrical system did however not respond to this approach.

The results give reason to recommend further research in the matter of dual risers. Improvements of the facility, or by moving on to a larger experimental loop, can allow for better flow control, added measurements of the actual phase split and potential stability options, such as the thinner riser tested in this study.

# SAMMENDRAG

Alvorlig slugstrømning er et strømningsregime som kan oppstå i flerfasesystemer ved gitte betingelser og ofte i forbindelse med stigerør. Strømninger forløper periodisk, med store svingninger i trykk og massestrøm som potensielt kan forårsake driftsproblemer i prosesseringsanlegg nedstrøms i systemet. I forbindelse med at produksjon av hydrokarboner i større grad krever at flerfasestrømninger deles opp til flere stigerør, er forekomsten av alvorlig slugstrøm i disse av interesse.

Dette arbeidet involverer flere eksperimenter gjennomført på systemer med parallelle stigerør – både symmetriske og usymmetriske konfigurasjoner. Forsøkene har blitt gjort på en småskala anlegg som bruker vann og luft for å simulere tofasestrømning Trykkforløp og strømningsrate har blitt registrert i tillegg til visuelle observasjoner av strømningen. Dette har blitt brukt til å produsere regimekart for systemene. I tillegg har endringer i periode og amplitude blitt studert.

Stigerør med forskjellig diameter ble videre benyttet i forsøk på å stabilisere en alvorlig slugstrømning. Resultatene viser at et tynt stigerør har lyktes noe, men dette gjelder kun for et usymmetrisk oppsett. Det symmetriske systemet responderte ikke på denne tilnærmelsen.

På bakgrunn av resultatene er det anbefalt videre arbeid med parallelle stigerør. Det innebærer å enten forbedre det eksisterende testanlegget eller gjennomføre eksperimenter i større skala. Uavhengig av tilnærming, bør arbeidet inkludere målinger av den faktiske fasedelingen i tillegg til at systemer med forskjellig stigerørsdiameter bør undersøkes nærmere med tanke på stabilisering.

# PREFACE

This master thesis is submitted as a part of the M.Scs. degree in Industrial Process Technique at the Norwegian University of Science and Technology in Trondheim.

I would like to thank professor Ole Jørgen Nydal for supervising me on this project as well as giving me the opportunity to work in the lab. Post.doc. Nicolas La Forgia has been very helpful with the data acquisition part of the experiments, and given valuable lessons on LabView. The lab technicians have been very effective and helpful, in particular Martin Bustadmoen who has helped me fabricate parts for the loop.

Finally, my mom receives endless gratitude for proofreading and correcting my language as well as giving much needed encourage towards the end.

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# NOMENCLATURE AND ABBREVIATIONS

| | |
|---|---|
| **A** | Pipe cross section area [$m^2$] |
| $\mathbf{A_{G/L}}$ | Cross section area of gas/liquid flow [$m^2$] |
| **DUT** | Delft University of Technology |
| **FLNG** | Floating Liquid Natural Gas |
| **FPSO** | Floating Production, Storage and Off-loading |
| **H** | Holdup |
| **ID** | Internal Diameter |
| **LGR** | Liquid to gas ratio [$m^3/Nm^3$] |
| **NTNU** | Norwegian University of Science & Techology |
| $\mathbf{Q_G}$ | Gas volume flow [$Nm^3/hr$] |
| $\mathbf{Q_L}$ | Liquid volume flow [$m^3/hr$] |
| **STC** | Shell Technology Centre |
| $\mathbf{U_{SG}}$ | Superficial gas velocity [m/s] |
| $\mathbf{U_{SL}}$ | Superficial liquid velocity [m/s] |
| $\boldsymbol{\alpha_G}$ | Gas fraction |

# 1 INTRODUCTION

## 1.1 Motivation

Small-scale experiments on severe slugging with several risers have been conducted for this work with the main objective of creating flow regime maps for dual riser systems. Severe slugging, sometimes referred to as riser slugging, is a problematic flow regime that can occur in multiphase transport systems (1) – for instance when producing oil or gas from a reservoir. It is characterized by large variations in pressure and mass flow, causing potential damaging effects on receiving equipment such as separators or distillation towers. For severe slugging to occur, the geometry of the system need to have a local low-point available for liquid accumulation. The bend just before a riser can provide such a point. Furthermore, the gas must have sufficient compressibility, and the flow regime upstream of the bend must be stratified. When liquid block the bend, the upstream gas pressure will increase. At sufficient pressure levels, one that will equal the hydrostatic head of the accumulated liquid, gas will penetrate the bend blowing the liquid out of the riser. The blowout at severe slugging conditions can be extreme – liquid slugs can be of several times the riser length (2). The large oscillations in pressure and flow rates are dealt with accordingly at the receiving end of the flow line, and while there exists methods for slug control, not all of them are suitable for multiple riser systems.

A typical hydrocarbon reservoir can contain oil, gas and water, and hence production will be multiphase flow. As traditional reservoirs have been depleted while the demand for oil and gas is continuously increasing, it has been necessary to produce from smaller and/or more remote offshore fields that have previously not been economically viable. A Floating Production Storage and Off-loading unit (FPSO) can provide a cost-efficient alternative to the traditional platform (3), being mobile and hence able to move between reservoirs. For these types of floating units, the riser system must be designed to handle the mechanical stress imposed on it by waves or currents. A rigid riser used on traditional production platforms is only capable of handling some strain, and this limits their application, in particular when producing from great water depths (4). This is why flexible risers are rather applied. However, as flexible risers have a diameter limitation of approximately 12 inches (5), a large mass flow may have to be dealt with by several risers rather than one. For instance, the

Prelude Floating Liquid Natural Gas (FLNG) project recently initiated by Shell applies several flexible risers emerging from a manifold (6).

The combination of severe slugging and multiple risers is thus of particular interest, and is investigated through experiments done for this report. Large variations in pressure and flow rates, caused by the slugging regime, can add additional strain to the flexible risers as well as potentially damaging the receiving units on a floating vessel. This report will present a number of experiments on dual riser systems, done on a small-scale flow loop, where air and water will simulate two-phase flow. The main objective is to investigate and describe the propagation of severe slugging in such a system, accompanied by regime maps, periods and amplitude changes. The work can be seen as an extension of a preliminary study[1] that has been done in a qualitatively manner. To allow for a better evaluation of the flow, the experimental facility has since then been improved with instrumentation that allows for a quantitative evaluation of the systems in question. The results show that dual risers are prone to highly unstable flow regimes, especially for the low flow rates that are applied here. Furthermore, it is shown that varying riser diameters may help towards flow stabilization in a system exposed to severe slugging conditions.

## 1.2 Disposition

The following chapter gives an introduction to multiphase flow theory with a description of the terminology and equations used in the work. Illustrations of different flow regimes are also included, with emphasis on describing severe slugging in detail. Chapter 3 contains a literature review on phase splitting as well as severe slugging in dual riser systems. The preliminary study is described in detail in the following chapter. Finally, execution, discussion and conclusion on the actual experiment are found from chapter 5 and onwards.

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[1] Solstad IS. Small-scale experiments on severe slugging in parallel riser systems [Project Thesis]. Trondheim, Norway: Norwegian University of Science & Technology; 2014.

# 2 MULTIPHASE FLOW THEORY

The theory and equations presented in this chapter is necessary in order to clarify the terminology used later in the report. This includes equations, description of flow regimes and in particular the propagation of severe slugging. Its occurrence in single riser systems is described in detail in section 2.5.

## 2.1 Flow assurance and multiphase flow

Multiphase flow is in this context used to refer to a flow with more than one phase or component. A phase is defined as a class of matter with a defined boundary and a particular dynamic response to the surrounding flow/potential field (7).

The hydrocarbons that are found in wells and reservoirs are normally mixtures of both phases and components. Several types of hydrocarbons – paraffins, naphthenes and aromatics – can be mixed with water, sulphide, nitrogen, hydrogen and carbon dioxide (1). In order to assure predictable and secure delivery from a stream, it is necessary to accurately foresee the hydraulic behaviour in the flow lines. This can be affected by temperature, pressure, flow rates and other factors. The flow assurance line of work aims to provide such knowledge, since the single-phase characteristics are insufficient for describing the nature of these flows.

The structures and characteristics of multiphase flows can be described by flow regimes or flow patterns that illustrates the geometrical distribution of a flow moving through a section of a conduit. Different correlations are true for different flow patterns, and over time or length a pipe may experience changes in its regimes. This implies that mathematical correlations for multiphase flows are highly complex. The following section will present the possible flow regimes that can exist, along with a description of flow regime maps; however, it is necessary to first define some basic correlations.

## 2.2 Basic definitions of multiphase flow parameters

The following equations and definitions are some of the basic variables related to multiphase flow.

*Holdup*: the area fraction of the pipe that is occupied by liquid at the same instant. Can be denoted H or $\alpha_L$, where the former will be used here (8).

$$[1] \qquad H = \frac{A_L}{A}$$

Consequently, the gas fraction can be derived. Similar to holdup, the gas fraction has no unit of measurement.

$$[2] \qquad \alpha_G = 1 - H$$

*Superficial velocity*: the average instantaneous velocity the phase (liquid or gas) would have if it occupied the whole cross-section of the pipe alone (8, 9), usually measured in metres per second. Here, Q [$m^3/s$] is the volumetric flow of the given phase.

$$[3] \qquad U_{SL/SG} = \frac{Q_{L/G}}{A}$$

*Phase velocity*: defined as the volume flow per phase area (9).

$$[4] \qquad U_{L/G} = \frac{Q_{L/G}}{A_{L/G}}$$

The relationship between liquid and gas flowing in the pipe is a useful parameter when comparing flow regimes for different cases and applications. It can be defined in both ways, gas-to-liquid or liquid-to-gas, as long as one is aware of the difference and is careful to use the same definition, at same conditions, when making comparisons to other cases. This report will use a liquid-to-gas ratio (LGR) at normal conditions, with units [$m^3/Nm^3$].

$$[5] \qquad LGR = \frac{Q_L}{Q_G}$$

## 2.3 Flow regimes

Typically, flow regimes for both horizontal and vertical pipes can be divided into two sub-groups; mixed and separated flow regimes. The mixed regimes have strongly coupled phases and primarily consist of *bubble*, *slug* and *churn* flow. Separated flows include *stratified* and *annular* flow, where the different phases can be observed as significantly separated. The different regimes are illustrated in Figure 2-1 and Figure 2-2.

In *bubble flow*, the liquid is continuous across the pipe cross-section and gas is dispersed as bubbles (9). It can exist in both horizontal and vertical pipelines, but buoyancy effects can be significant for horizontal flow, with bubbles located in the top cross section of the pipe, as illustrated in Figure 2-1, regime *iii)*.

*Slug flow* is a phenomenon that describes sequences of bubbles, often named Taylor bubbles (9), followed by a liquid slug. The bubble has a cross section equivalent to that of the pipe, separated from the wall by a thin liquid film. The slug may contain small traces of gas in the form of small bubbles that are being shed from the tail of the larger bubble section. Normal, or *hydrodynamic*, slugging in a horizontal pipeline tends to be relatively short (in terms of slug length), and is usually not an operational problem. *Severe slugging,* which is the focus of this study, differs from normal slug flow. This flow regime will be described in chapter 2.5.

*Churn flow* is the result of increasing superficial gas velocity compared to a slug flow, and the bubbles will become more distorted at the gas-liquid interface (8). Irregularities in liquid hold-up can be observed, as the portions of transported gas and liquid will vary.

In *annular flow* the liquid is dispersed as an annular film on the pipe wall, while the gas travels in the core with some liquid entrained (9). The size of the liquid droplets in the centre determines the nature of the annular flow – wispy annular flow will have large liquid droplets while annular mist flow have small ones.

*Stratified flow* consists of a gas and liquid layer separated by gravitational forces to form either a smooth or wavy interface (8). The manner of this interface depends on the superficial gas velocity – increasing this velocity will create waves on the liquid surface.

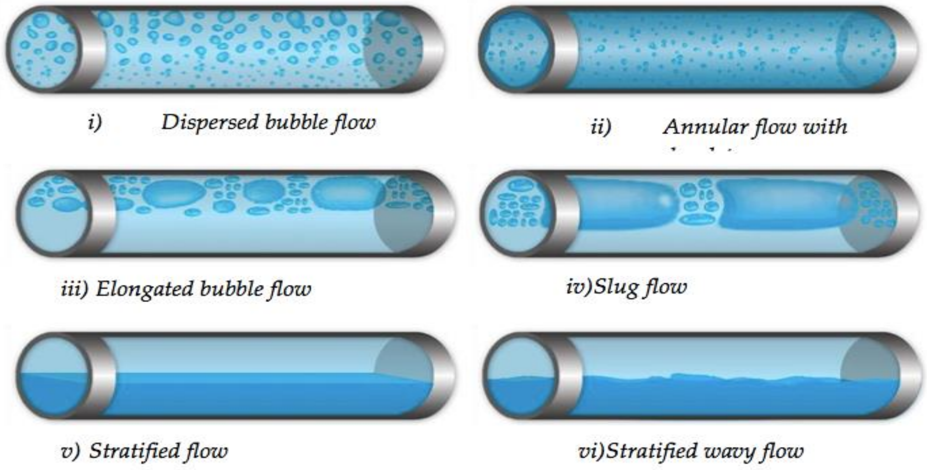


**Figure 2-1: Flow regimes for horizontal pipes (9)**

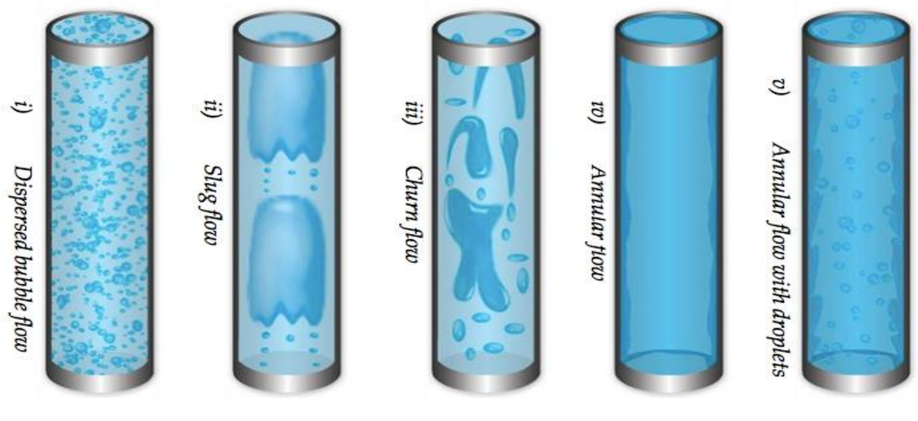


**Figure 2-2: Flow regimes for vertical pipe (9)**

## 2.4 Flow regime maps

A flow regime map attempts to predict the existence of different flow regimes and an example map is presented in Figure 2-3. The type of regime depends on several factors; flow rates and gas-liquid ratio, pipe geometry, fluid properties and pipe system (i.e. pipe length, inlet conditions and flow development). As such properties varies, it can be difficult to create generalized maps. Instead, they are usually made for certain flow parameters and pipeline inclination or diameter to give a relatively good indication on what type of flow one can expect. Most regime maps have superficial gas and liquid velocities on the x- and y-axis, but there are maps that use other parameters as well. The regime map in Figure 2-3 is valid for a horizontal pipeline.

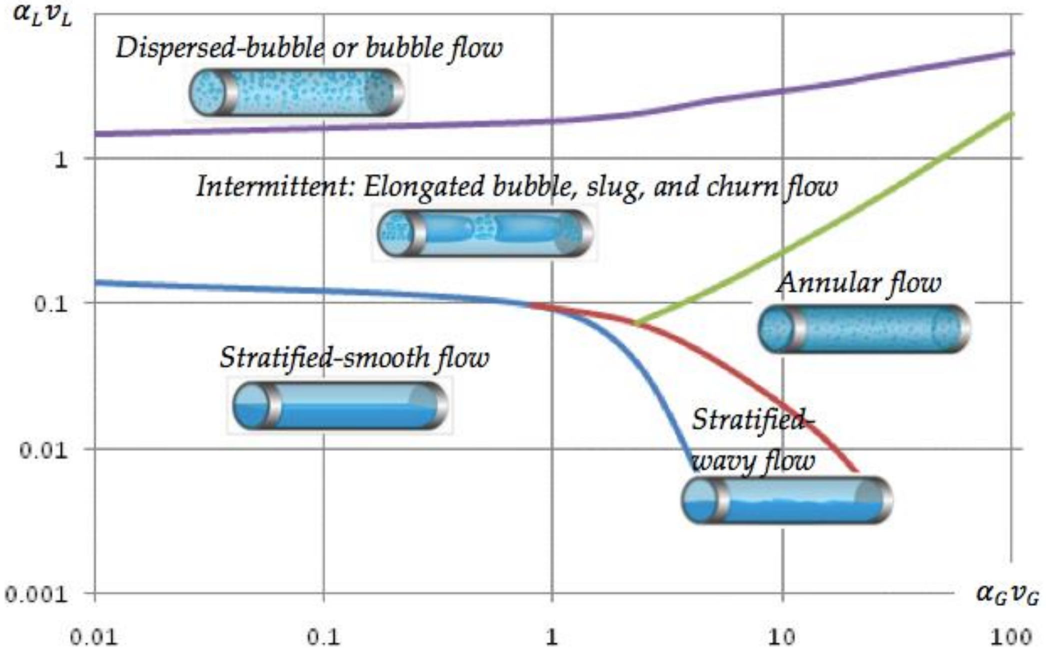
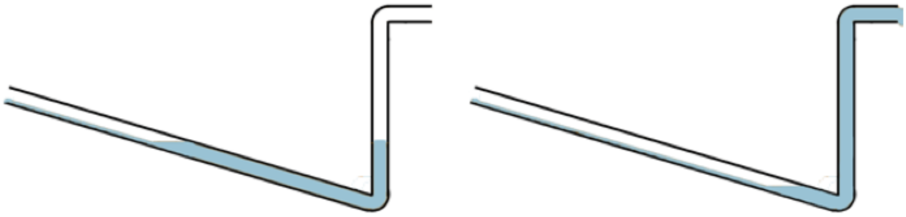


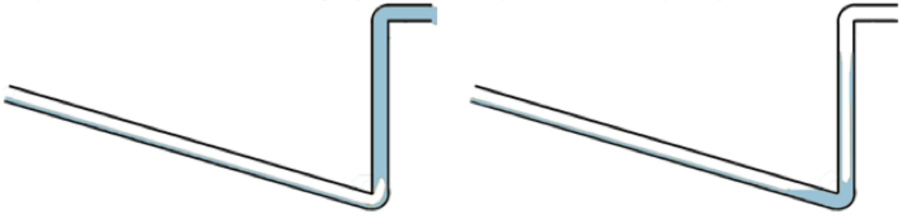
**Figure 2-3: Flow regime map for steady state horizontal flow (9)**

## 2.5 Severe slugging

The propagation of severe slugging can be divided into four stages, illustrated in Figure 2-4. Slug formation, slug production, bubble penetration and gas blowdown. In the first step, a pressure build-up is seen at the riser base as liquid is accumulating downstream the bend. As liquid reaches the outlet, the slug is produced until the gas reaches the riser base. In the third step, gas is again supplied to the riser, decreasing the hydrostatic pressure and hence increasing the gas flow. Finally, gas reaches the riser outlet, the pressure level is minimal and the liquid is no longer gas lifted. This initiates a new cycle.



*Gas pressure similar at both sides of liquid.* *Gas pressure builds up at upstream side.*



*Gas reaches lowest point and blows out the liquid.* *Much of the liquid and gas has escaped. The flow is reduced and some liquid falls back.*

**Figure 2-4: Severe slug formation (9)**

In single pipeline-riser systems, there are certain conditions that must be fulfilled in order for severe slugging to exist (8). The conditions are as follows:

- Local low point for liquid accumulation, i.e. a bend, riser base or uneven terrain
- Stratified flow upstream of the bend
- Suitable flow rates – the liquid-to-gas ratio needs to fall within a certain region of a flow regime map
- Sufficient gas compressibility – i.e. low pressure or large gas volume
- Downstream upward inclined pipe

In addition, severe slugging depends on the *length* of the upstream pipeline, which was initially discovered by Spedding and Ngyuen (10). This implies that it will be misleading to correlate “the boundary of severe slugging on a map with $U_{SL}$ and $U_{SG}$ as coordinates without specifying the pipeline length” (10), which is the case for the map in Figure 2-3.

## 2.6 Slug control

Currently, the conventionally applied methods for handling severe slugging include choking, gas-lift injection in the riser and slug catching facilities. Neither of these methods will be tested for the dual riser system, however, they are included here to clarify their existence.

Choking is proven to be highly effective (11). A riser choke will increase the backpressure to stabilize the flow, mitigating severe slugging. Drawbacks with choking include increased system pressure and decreased production rate, but compared to the possible issues related to severe slugging, these are minor compromises. Chapter 3 will look further into the affect of choking on dual riser systems.

A slug catcher is a rather massive construction of several T-junctions linked together. Gravity separates the phases, leading the gas to the upper arms and liquid to the declining branches. The slug catcher slows down the flow, but several junctions are needed in order to achieve sufficient separation. This makes it a very space-demanding unit, which strictly limits its application offshore.

Gas lift relies on injection of gas in the riser, decreasing the mixture density of the flow. This will mitigate severe slugging in the riser, as the gas will be able to penetrate the bend at a lower pressure. The resulting flow regime is usually normal slugging (11). Gas lift often requires large volumes of gas and can hence be impractical for some systems.

# 3 FLOW SPLITTING AND DUAL RISER SYSTEMS

The previous chapter have shown that a multiphase flow can take on several manifestations. The potential complexity of flow regimes that may exist in a single straight pipeline spans widely, so when introducing branches or geometry changes, predicting the flow can be difficult. Since the experiments in this report involve splitting a two-phase flow to dual risers, it is necessary to investigate available knowledge on flow splitting. Besides looking at flow splitting as an isolated event, there are two studies that will be described in detail because of their great relevance to the experiments done for this report. The two studies in question are described in depth in sections 3.1 and 3.2.

Flow splitting by using various junctions is a well-documented and applied technique, such as in the previous mentioned slug catchers. Several studies, for instance from Azzopardi and Hervieu (12) or Müller and Reimann (13), documents the partial phase separation that can happen when a multiphase flow is divided at a junction. As a result, further research into utilizing this partial phase split have emerged, for instance towards making simpler and more cost-efficient alternatives to separation vessels (14). However, the advantages a partial phase split can provide may also lead to problems for downstream processing units if the split is not accurately determined, leading to a sub-optimal design of downstream equipment. The actual split depends on different factors, such as flow regime, geometry of the junction, phase properties and applied backpressure. Some of these mechanisms have been extensively investigated, with empirical correlations for certain systems, for instance from Seeger, Reimann and Müllers papers on “Two-phase flow in a T-junction with horizontal inlet” (15). However, there is a lack of research done on splitters combined with downstream changes in geometry. Baker et. al (16) studied pairs of T-junctions, aiming at creating an efficient partial liquid-gas phase separator, while Azzopardi and Smith looked at the effect of orientation (17). The findings of the latter indicated that the “downstream geometry in the main pipe only affects the split if there is stratified flow in the pipe leading to the junction” – the junction in question being a horizontal or vertical side arm of the main pipe.

Flow splitting to dual riser systems has been studied at Delft University of Technology (DUT), in collaboration with the Shell Technology Centre (STC) in Amsterdam(18, 19). Two different geometries were examined, an impacting T and a non-symmetric splitter (side-arm splitter) respectively, diverted into two risers. Illustrations and numbering of the risers are shown in Figure 3-1. The study focused on phase split, pressure amplitude and variations as well as observed transient behaviour. Some of the results from DUT/STC will be presented in the following sections, particularly the conditions for whence severe slugging existed, which is of interest with respect to the experiments conducted in this report.

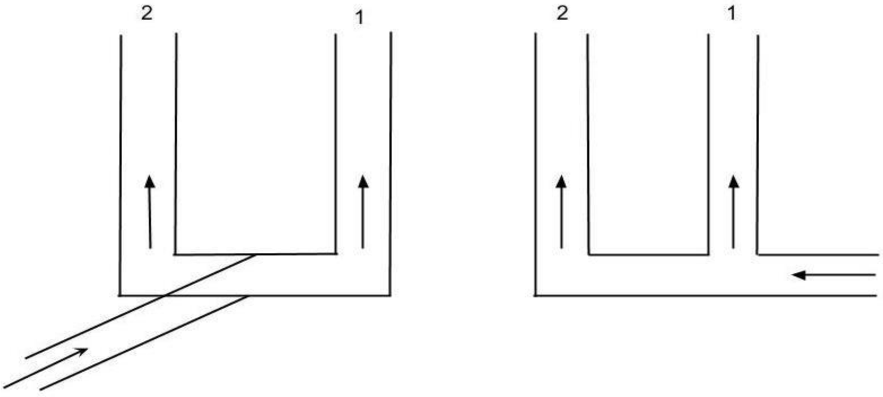


**Figure 3-1: Symmetrical T and sidearm splitter applied in the two different studies**

Both experiments used the same flow loop that consisted of a 100 m long horizontal pipeline upstream of the junctions. Water and air were used to simulate two-phase flow. The riser base and tops were equipped with choke valves, however, neither setups had equal riser height – riser 1 was close to one meter taller than riser 2. The horizontal flow line can alone lead to an assumption that severe slugging should not be present, as there is no local low point available for liquid accumulation (see section 2.5 on conditions for severe slugging). In addition, the symmetry of the junction with its respective risers should hinder full liquid blockage. However, as will be presented in the next sections, there were instance of normal and severe slugging for the systems at certain operational conditions.

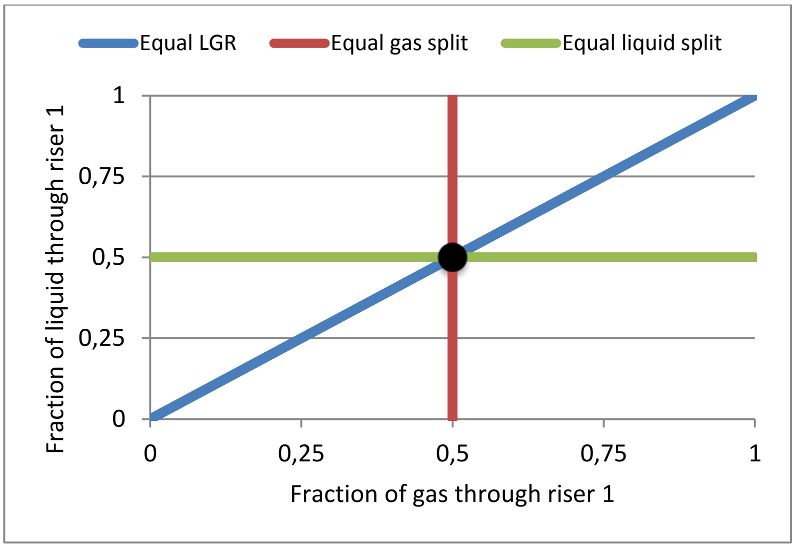


**Figure 3-2: Flow splitting diagram**

Figure 3-2 shows the different flow splitting lines where the blue line represents an equal LGR split. This line will give an equal LGR in both risers as well as in the incoming flow line. The second report on the impacting T-junction (19) refers to a field case of gas-condensate-liquid where it is desirable to achieve such a split, so as to easily design the parallel downstream facility.

## 3.1 Non-symmetric splitter to dual riser

The first report from DUT/STC was on the non-symmetric system (18), i.e. junction to the right in Figure 3-1. Primarily, the study investigated possible transient behaviour, phase split at the riser base and system pressures. The results presented here will focus on the parts that are relevant to experiments done for this particular report.

The flow regimes observed in the system varied with respect to the variances in mass flow and applied backpressure (i.e. valve openings), and the following table provides the observed flow modes for different volume flows.

| $Q_L$ m$^3$/hr | $Q_G$ Nm$^3$/hr | LGR | Mode |
|---|---|---|---|
| **0,5** | 30 | 0,017 | A |
| **1** | 30 | 0,033 | A |
| **2** | 30 | 0,067 | A |
| **0,5** | 60 | 0,0083 | A/B |
| **1** | 60 | 0,017 | A/B |
| **2** | 60 | 0,033 | C |
| **3** | 60 | 0,050 | C |

**Table 3-1: Observed modes for fully opened valves**

The different modes are described as follows:

A. Riser 1 produces gas and liquid as a hydrodynamic slug flow. An oscillating liquid column is observed in riser 2, where a negligible amount of gas is produced in the form of small bubbles.

B. Riser 1 produces single-phase gas, and is completely vacant of liquid. Riser 2 hence produces the liquid phase and the remaining gas as hydrodynamic slugs.

C. There is a continuous slug flow in both risers, but with a majority of gas in riser 1 and a majority of liquid in riser 2

As can be seen in Table 3-1, mode A was the only operation observed at low gas flow rates. This is explained by the non-symmetry of the splitter as well as different inertia of the phases. The liquid will prefer to overshoot the first riser while the gas will escape here, and the already low gas flow rate will promote a gravity dominated flow. This leads to an eventual flooding of riser 2, and hence the system stabilizes in mode A.

For the high gas flow rates, hysteresis and non-reproducibility was present in the formation of the modes. The increased gas flow rate was for the most part sufficient to support slug flow through riser 2 (i.e. mode B), but random instabilities, such as small variations in incoming flow rates, did at times cause flooding of riser 2 and hence a switch back to mode A. Mode C existed for high gas *and* liquid flow rates.

Partially closing the top valves led to new stable modes of operations, as well as an unstable cyclic behaviour. This cyclic mode was indeed a severe slugging in riser 2 – a gravity dominated flow in riser 2 leads to flooding, while the increased backpressure due to a partially closed valve in riser 1 caused growth of a severe slug in the former. When this reaches the top of the riser, the severe slug is produced and eventually a new cycle initiated. This cyclic behaviour was observed for different flow rates and applied choking, and for some combinations the periodicity was less clear. The severe slugging was initially unexpected for this particular geometry. However, as explained in the report, gravity dominated flow has, for single riser systems shown to "result in an increased tendency to give a severe slugging cycle" (18). Beside new transient operational modes, the choking did not succeed in reaching an equal phase split nor equal LGR split (ref. Figure 3-2) for any combinations of flow rates or valve openings.

## 3.2 Impacting T to dual risers

The subsequent report from DUT/STC aimed at investigating a symmetrical setup, using the same experimental facility. The splitter in the loop was replaced with an impacting T-junction followed by a 90° bend to each riser. With an exception of this replacement, the loop remains the same and the experiments had the same focus on phase split and flow behaviour.

Similar to the non-symmetric splitter, experiments were done with open and partially closed valves, and the following section will present the main findings, mainly focusing on the fully open valve results.

| **Gas flow rate Nm$^3$/hr** | **Liquid flow rate m$^3$/hr** | |
|---|---|---|
| | **0,5** | **3** |
| **20** | 0,025 | 0,15 |
| **40** | 0,0125 | 0,075 |

**Table 3-2: Test matrix and corresponding LGR for experiments at fully open riser valves**

Table 3-2 shows the flow rates applied for fully open riser top and base valves. The experiments can be divided into three different variations of these flow rates.

a) Low gas and low liquid flow rates
b) Low gas flow rate with increasing liquid flow rate
c) Increased gas and increased liquid flow rate

The first case showed an unsteady transient behaviour, where the system "switches between various modes without any observable cause" (19). All liquid and gas is flowing through riser 1, with a stagnant liquid column in the other, until the system switches and the production moves to riser 2. Averaging over a long time did not show any signs of symmetry in this switch. The production happened in the form of slug or churn flow. This unstable flip-flopping behaviour was mitigated when increasing the liquid flow rate (case b), where only one riser produces gas and liquid – here there is a preference to produce through riser 2, which is the shorter riser. The production is still in churn or hydrodynamic slug flow.

The final case, with high gas *and* liquid flow rates caused the phases to divide over both risers. Keeping the gas flow constant (at $Q_G$=40 Nm$^3$/hr) and gradually increasing the liquid flow, all data points, except for the highest, lies on the diagonal in Figure 3-2, i.e. equal LGR. The highest liquid flow rate (3 m$^3$/hr) did however cause an unclear abnormal behaviour, but ignoring this data point showed that increasing liquid throughput lead to an almost equal phase split where $F_{G,1} = F_{L,1} = 0{,}5$. The higher liquid momentum thus seems to overcome the slight asymmetry present due to differences in riser lengths.

| Gas flow rate Nm$^3$/hr | Liquid flow rate m$^3$/hr | |
|---|---|---|
| | **1** | **2** |
| **20** | 0,05 | - |
| **40** | 0,025 | 0,05 |
| **60** | 0,0167 | 0,033 |

**Table 3-3: Test matrix and corresponding LGR for experiments with partially choked riser valves**

The experiments were repeated while gradually closing the choke valves at the riser tops. The valves were subsequently closed from 100% to 6%, and Table 3-3 shows the different flow rates tested. For the low liquid flow rate ($Q_L$=1 m$^3$/hr), applied choking did not succeed in reaching an equal phase split for any accompanying gas flow. The results indicated that the gas phase is affected by choking to a greater extent than the liquid, as a broad range of valve positions causes the gas fraction to vary while the liquid fraction remains unchanged.

Increased gas flow and liquid flow rates seem to increase the symmetry of the phase split, and measurements now include the 50%-50% point. Still, there is a preference for the liquid to split equally over the two downstream branches, while the gas can be forced by varying the backpressure. The report does not mention what flow regimes were observed at these conditions.

### *Implications for present experiments*

The results from DUT and STC provide indications on how a two-phase flow may behave when divided over two risers. It is also stated how an equal phase split can be difficult to achieve in such a system. Choking will affect the phase split, especially the gas phase, but the non-symmetrical setup did not reach the equal phase split point.

Certain combinations of flow rates did however approach the 50%-50% point in the experiments with the impacting T. For this setup, they mention the necessity to improve the experimental facility towards complete symmetry. A completely symmetrical system is expected to give an equal distribution of both gas and liquid mass flow, but with different riser heights and various backpressures present, there was a clear preference of producing through riser 2, which was the shorter riser for both experimental setups.

The studies from Haandrikman et.al presented here gave motivation for the project work described in the next chapter.

# 4 QUALITATIVE SCREENING OF UNSTABLE FLOWS

The preliminary project work, "Small-scale experiments on severe slugging in parallel riser systems"[2], was done on dual riser systems with two geometrically different setups: an impacting T-junction gave a symmetricaetl setup and a sidearm branching gave a non-symmetrical setup. Illustration and numbering of the risers are equal to those in Figure 3-1. The experiments were done on a small-scale loop, with water and ambient air to simulate two-phase flow. As the title suggest, the occurrence of severe slugging was the main objective, and in order to facilitate that flow regime, the incoming pipeline had a downward inclination at an 18° angle to the junction. This was to promote liquid blockage at the riser bend. Illustrations of the loop can be seen in Figure 5-1 and Figure 5-2, as the same facility was used in the present study.

The preliminary study was purely qualitative, as the instrumentation on the loop was limited. Results were obtained from visual observation of the flow and slow-motion video recording. The findings gave motivation for improvement of the experimental setup to allow for a quantitative study. Some of the main results are presented here.

## 4.1 Symmetrical T-junction

The dual riser system did allow slugging, apparently at the same conditions as required for a single riser system. The blowout will also propagate symmetrically if the

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[2] Solstad IS. Small-scale experiments on severe slugging in parallel riser systems [Project Thesis]. Trondheim, Norway: Norwegian University of Science & Technology; 2014.

system itself is *completely* symmetrical. The gas split is highly sensitive to differences in backpressures (and hence riser height and levelling of the junction), and any irregularities on this symmetry will cause the gas to divide unevenly. Generally, such non-symmetries are immediately apparent, as blowout only occurs in one of the risers should they be present. Asymmetrical slugging could thus easily be promoted by adjusting the splitter base.

During severe (and symmetrical) slugging, the liquid flow is split across two risers. However, the maximum riser base pressure should in theory equal that of an identical single riser system, as the pressure in this point is a function of the hydrostatic head of the riser(s), and independent of the liquid volume. The gas flow, which in a single riser system would only have to lift one liquid column, is now put to blow twice the volume of liquid. The resulting blowout can appear less severe than in a single riser system, as the lower relative gas flow leads to higher gravity domination in the risers.

## 4.2 Non-symmetrical side arm

The side-arm system will only allow severe slugging in the first riser (see right illustration on Figure 3-1). The pressurized gas penetrating the bend will “meet” riser one first and hence only blow in this. The liquid column that has accumulated in the second riser will drop, and during blowout oscillate, before filling again starts in both risers. Thus, all liquid production happens in the first riser. The blowout will often proceed in two separate turns, especially for the highest liquid flow rates. The first blowout causes the liquid column in the second riser to drop, and this leads to a new liquid blockage at the riser base. The second blockage is only temporary, as the gas pressure still is high enough to penetrate the now reduced hydrostatic head of the riser. There are instances of liquid production in the second riser at very high liquid-to-gas ratios, when both risers are allowed to completely fill up before the gas pressure has increased enough to penetrate the bend. An insignificant amount of gas production occurs in riser two, as the occasional Taylor-bubble overshoots the first riser.

## 4.3 Conclusions made in the preliminary study

Identifying flow regimes and corresponding flow rates was difficult in this experiment. The gas flow rate was never constant due to the compressor working within a certain pressure interval and a highly sensitive gas valve. Keeping a constant gas flow rate would require a continuous manual adjustment of this valve. The recommendations for further work was thus to improve the instrumentation on the loop to allow for a better and quantitative study of the flow regimes.

# 5 EXPERIMENTAL FACILITY

## 5.1 Laboratory setup

The experiments have been conducted in the Multiphase Laboratory at NTNU in Trondheim, using the same mini-loop as for the preliminary project, with certain instrumental improvements – a transmitter for pressure recordings and an enhanced gas flow rate regulation. The loop is a small scale, easily transportable device for creating two-phase flow with water and ambient air. The different riser configurations and the complete laboratory setups are shown in Figure 5-1 and Figure 5-2. Flow line and risers are all of transparent material to allow for visual observation of the flow pattern.

A compressor draws air from the surroundings to a tank with a pressure interval at 1.5-2.5 bars. This is then connected to a low-pressure buffer tank that delivers air at approximately 1 bar through a flow meter, regulated by a resistance needle valve. This valve ensures constant gas flow rates. The water is fed from a centrifugal pump through a liquid flow meter controlled by a manual valve, and the gas and liquid is mixed at the pipeline inlet. Flow line and risers are of 16 mm internal diameter. The risers empty into a common open top separator that returns water to the tank and releases air to the ambient. The pressure transmitter is located at the start of the flow line, i.e. immediately after the inlet mixer, and has a range of 1-1.4 bara. It is positioned to measure the gas pressure, as the flow line has stratified flow at the inlet.

The junction (applied in both symmetrical and non-symmetrical setup) is manufactured from two pieces of acrylic pipe with an internal diameter of 16 mm, identical to the main flow line. The junction is rotated and equipped with appropriated hose connectors (i.e. a 90° bend to a riser) for the different geometries.

The following measurements or observations are taken:

- Gas and liquid flow rate at the inlet
- Inlet gas pressure in the flow line
- Flow visualization in flow line and risers
- Video recording at the risers

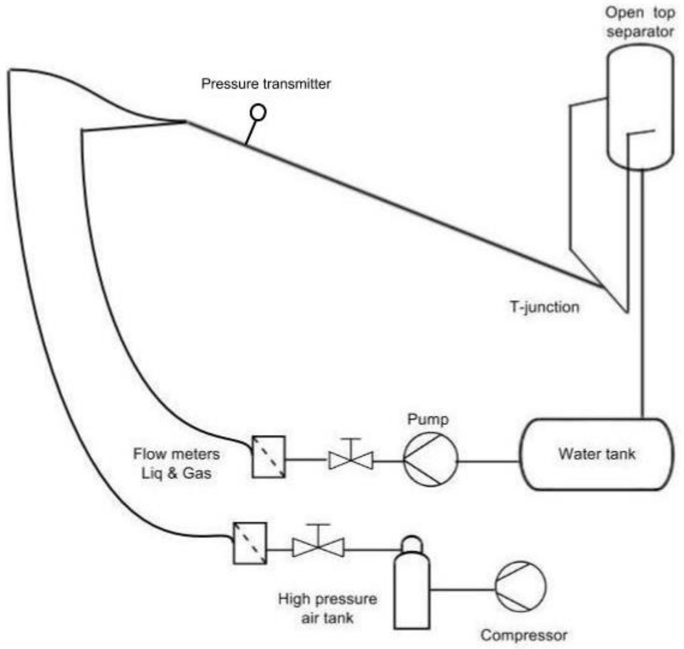

**Figure 5-1: Schematic of mini loop with T-junction**

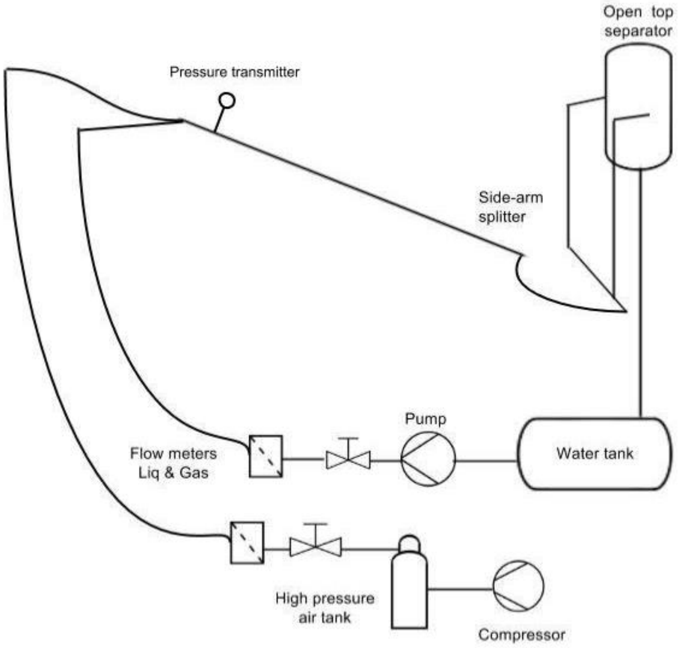

**Figure 5-2: Schematic of mini loop with side-arm splitter**

Photos and additional data regarding the loop and associated instrumentation are included in Appendix A.

## 5.2 Flow rates

For a typical field case where splitting form a single flow line is necessary, the liquid to gas ratio will normally not exceed 0.0002 $m^3/Nm^3$ at operational conditions (19). This is considerably less than what can be obtained in the lab, where the minimum LGR possible is approximately 0.02 $m^3/Nm^3$. Another distinction between experimental and real conditions is the pressure, at typically 100 bara in a field case and 1-2 bara in the lab, leading to considerable differences in gas density. Together, these restrictions also limit the range of flow regimes possible to achieve – annular flow will not be possible, and the low flow rates should result in a gravity dominated flow (19).

The measuring devices connected to the valves limit the flow rates achievable in the lab. The gas flow meter has a range up to 12 normal litres per minute, or 0.72 $Nm^3/hr$, while the liquid flow rate is limited to 150 l/hr (0,13 $m^3/hr$).

However, as severe slugging in single riser systems occurs at low gas and liquid flow rates (2), there is no reason to doubt the system capability to achieve severe slugging – which the preliminary project also proved. The range of flow rates and corresponding superficial velocities are summed up in Table 5-1, and several values within these intervals were also tested. Symmetric and non-symmetric system was tested for the entire range and combination of flow rates possible in order to create simplified regime maps. Where pressure charts are displayed, the corresponding flow rates are listed.

| **$Q_G$ [$Nm^3/hr$]** | $U_{SG}$ [m/s] | **$Q_L$ [$m^3/hr$]** | $U_{SL}$ [m/s] |
|---|---|---|---|
| **0.06** | 0.08 | **0.015** | 0.02 |
| **0.20** | 0.28 | **0.050** | 0.07 |
| **0.50** | 0.70 | **0.075** | 0.10 |
| **0.72** | 1 | **0.15** | 0.20 |

**Table 5-1: Volumetric flow rates and superficial velocities**

The flow rates and velocities are with respect to the inlet and flow line diameter. Initially, all piping have the same internal diameter, hence not affecting the superficial velocity. However, when exchanging one of the risers with a thinner pipe, the local velocity in this pipe will be different. The flow rates allows for an LGR variation between 0.02 and 2.5 $m^3/Nm^3$.

# 6 EXPERIMENTAL RESULTS

The experimental results are categorized into three sections – flow regimes with pressure recordings and regime maps, variation in period and amplitudes and different riser testing. The latter refers to cases where one riser has been exchanged with a smaller tube and tested at severe slugging conditions. The use of a thin riser paired with the regular one is done in an effort to see if this can have a stabilizing effect on the system.

## 6.1 Observed flow regimes

The symmetrical T-junction as well as the side-arm splitter was tested for the entire range and combinations of flow rates in order to identify flow regimes and transitions between these. Differentiating between types of flow proved to be challenging. The declining flow line paired with risers, as well as a strictly limited range of flow rates, the riser base is easily blocked. The flow regimes in the risers were either slug or churn, and the transition between the regimes is not easily observed. It is therefore chosen to separate the flow into three distinguished regimes – severe slugging, combined flow, and churn flow. Both systems showed all three types of flow, but with differences in preferred riser.

### 6.1.1 Non-symmetrical flow regimes

Being non-symmetrical, the phase split at the riser base for this system is uneven. It could be reasonable to assume that a stratified liquid flow would pass the first riser (due to gravitation) and only be produced through riser 1, and this would be true for higher gas flow rates, as proved by Prickaerts, Haandrikman and Henkes (18). However, the declining incoming flow line and the generally low flow rates promotes (the intentional) liquid blockage at the riser base. When the gas pressure eventually increases, the blowout will only happen in the first riser. In general, riser 1 is the only producing riser of the two, but as can be seen in the flow regime descriptions, with a few exceptions. Typical pressure recordings for the different regimes are also given, and Table 6-1 sums up the LGR ranges for the different regimes.

| Mode | Minimum LGR | Maximum LGR |
|---|---|---|
| **Churn flow** | 0,026 | 0,088 |
| **Unstable flow** | 0,046 | 0,235 |
| **Severe slugging** | 0,100 | 0,727 |

**Table 6-1: LGR range for non-symmetrical flow regimes**

### *Churn flow*

A relatively low LGR (less than 0.085 $m^3/Nm^3$) allows for continuous gas penetration through the bend. Riser 2 sees a short liquid column, with the occasional gas bubble. The only liquid production is found in riser 1 as water is being "dragged" by the high gas flow, and production can be characterized as a churn flow. The pressure recording shows very little variation.

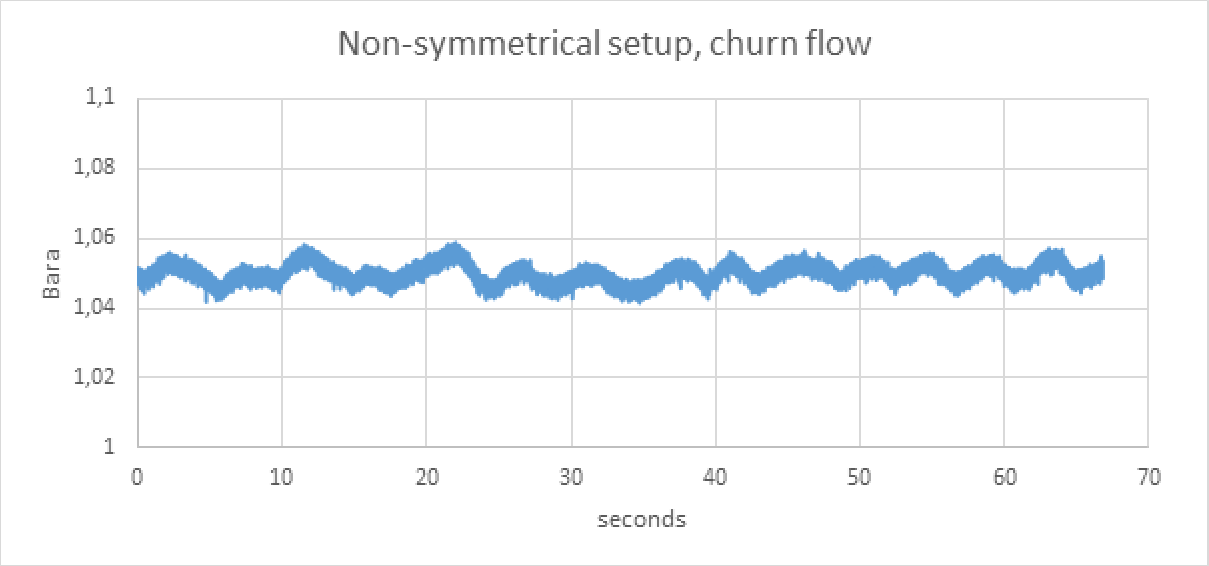

**Figure 6-1: Non-symmetrical system pressure, stable churn flow. $Q_L$=0,04 $m^3$/hr ($U_{SL}$=0,05 m/s) $Q_G$=0,36 $Nm^3$/hr ($U_{SG}$=0,50 m/s)**

### *Unstable flow*

A higher LGR causes partial liquid blockage at the riser base. Churn flow, or sloshing, is seen at the riser base, but the gas flow is not high enough to drag a sufficient amount of liquid up the riser. This leads to occasional complete blockage, released by blowouts in riser 1 at random intervals. This combination of churn flow released by severe slugging results in a non-cyclic pressure fluctuation. Riser 2 sees a liquid column, also with the occasional gas bubble, that drops at blowout and restores during churn flow.

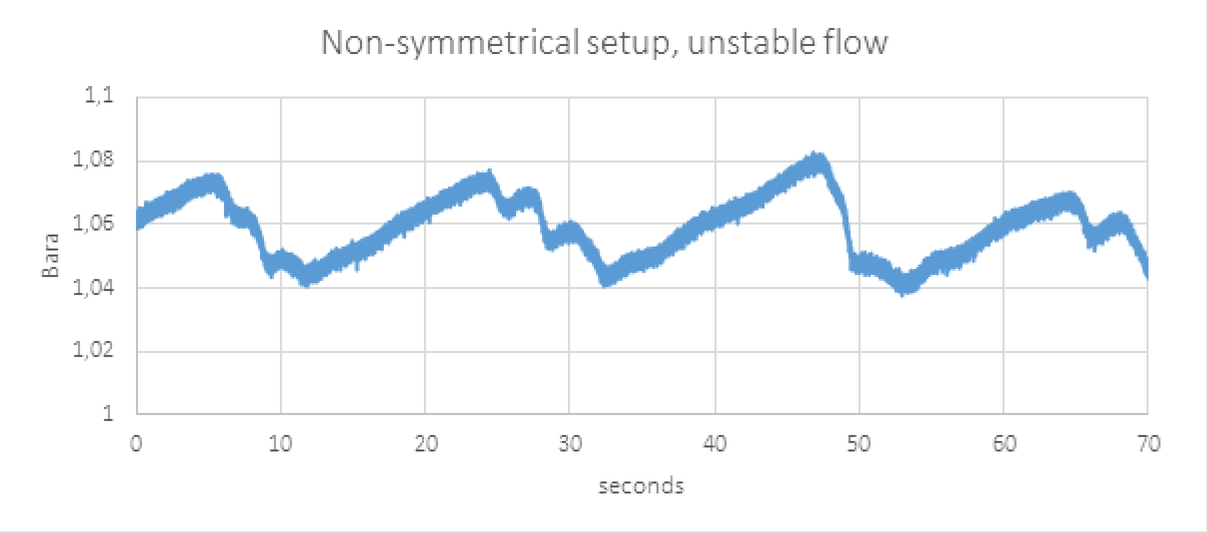

**Figure 6-2: Non-symmetrical system pressure, unstable flow.** $Q_L$=0,04 m$^3$/hr ($U_{SL}$=0,05 m/s) $Q_G$=0,24 Nm$^3$/hr ($U_{SG}$=0,33 m/s)

### *Severe slugging*

Sufficiently high LGR allows both risers to fill with liquid. Riser 2 can see some liquid production at highest liquid-to-gas ratios; just before the gas pressure reaches a sufficient level for blowout. The severe slugging occurs in riser 1, while the liquid column in the second riser drops. The blowout happens in two instances – as liquid in the first riser is pushed up, the water in riser 2 drops and a portion of this liquid is also blown through riser 1. This causes the plateau visible during blowout in the pressure chart. There is a small amount of gas production in riser two, as the occasional Taylor bubble overshoots the first riser.

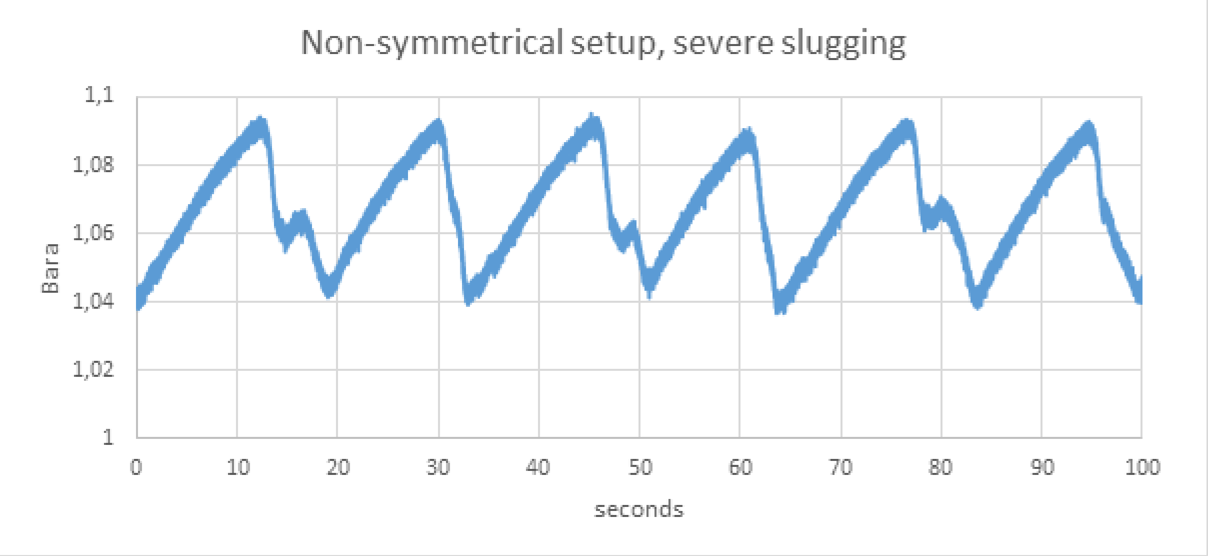

**Figure 6-3: Non-symmetrical system pressure, severe slugging.** $Q_L$=0,07 m$^3$/hr ($U_{SL}$=0,09 m/s) $Q_G$=0,24 Nm$^3$/hr ($U_{SG}$=0,33 m/s)

A regime map with the different modes is plotted for superficial gas and liquid velocities can be seen in Figure 6-4. There is a close to linear relationship in the intersections between the modes. However, the two intersections do not have the same linearity, nor is the transition from one mode to another completely distinct, but rather gliding.

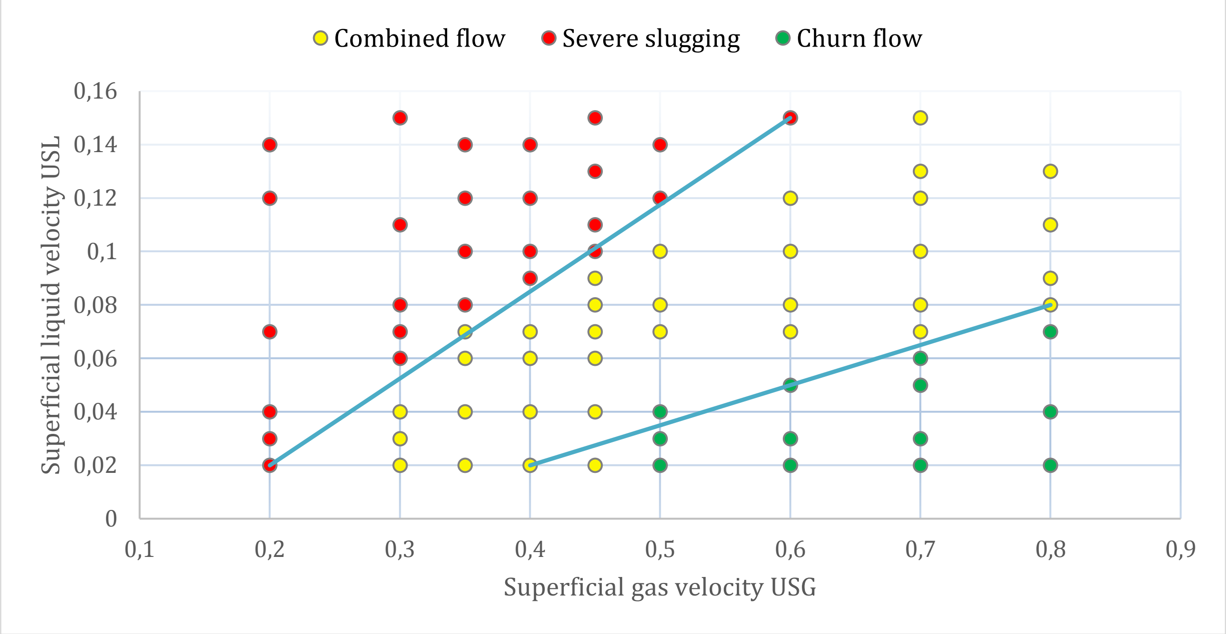

**Figure 6-4: Non-symmetrical regime map**

### 6.1.2 Symmetrical flow regimes

For the fully symmetrical setup, the different regimes are difficult to tell apart. For a large variation of flow rates, the system was unstable, showing different flow regimes even at constant flow rates. However, three different modes were defined, albeit with a gliding transition between.

| Mode | Minimum LGR | Maximum LGR |
|---|---|---|
| **Churn flow** | 0,059 | 0,176 |
| **Unstable flow** | 0,100 | 0,493 |
| **Severe slugging** | 0,333 | 1,493 |

**Table 6-2: LGR range for symmetrical flow regimes**

The ranges of liquid-to-gas ratio for the different modes are summed up in Table 6-2. As is visible from the table, the range overlaps in the transition from one mode to the next, but the overlap is not as big as for the asymmetrical setup.

### *Churn flow*

For low LGR, i.e. high gas flow paired with low liquid flow, both risers produce a continuous semi-stable churn and/or slug flow. The lowest LGR results in a steady churn flow, while increasing the ratio can give a combination of churn and hydrodynamic slugging. During slug flow, Taylor bubbles of different sizes are percolating through a liquid column in both risers. At times, a short blow, probably caused by irregularities in incoming flow rates, interrupts this steady flow, resulting in a bigger pressure drop.

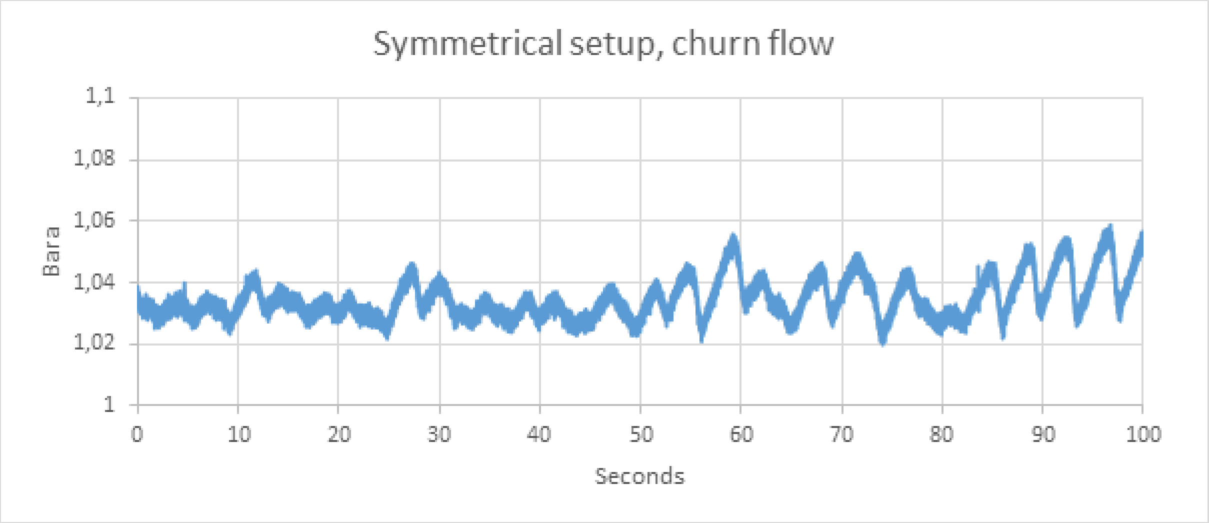

**Figure 6-5: Symmetrical system pressure, semi-stable flow. $Q_L$=0,08 $m^3$/hr ($U_{SL}$=0,11 m/s) $Q_G$=0,33 $Nm^3$/hr ($U_{SG}$=0,46 m/s)**

### *Unstable flow*

If the liquid rate is increased, the system becomes increasingly unstable. Production happens as slug or churn flow. However, only one riser will produce while the other maintains a liquid column oscillating around a constant average. At random intervals the producing riser empties completely, causing a big pressure drop in the system. More interesting is it that the system switches between risers. This flip-flopping behaviour can at times be related to the complete blowout of the producing riser, but normally it occurs without any apparent reason.

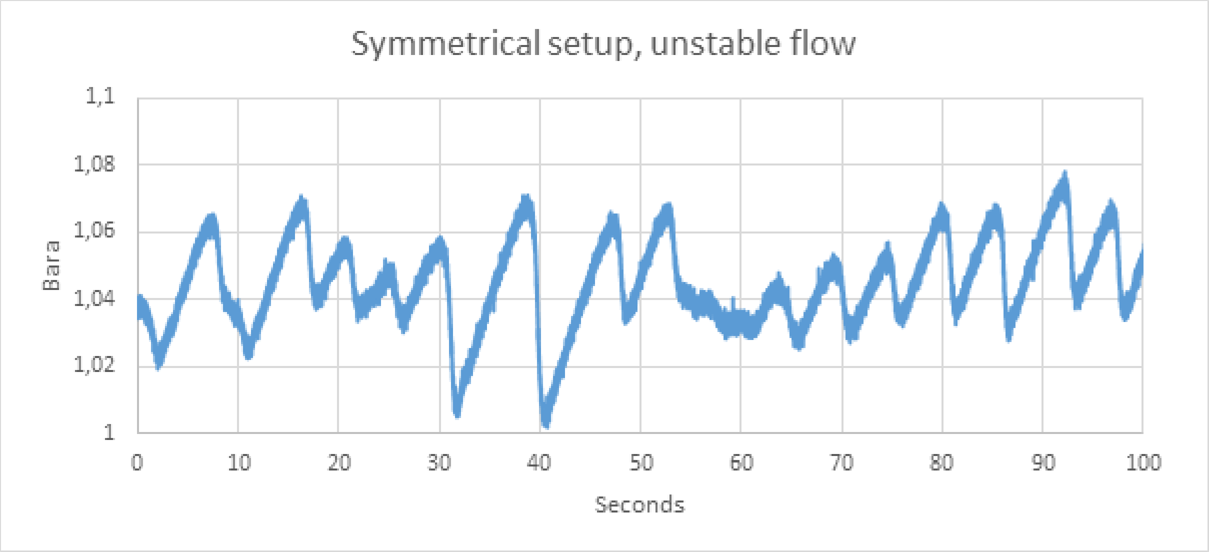

**Figure 6-6: Symmetrical system pressure, unstable flow. $Q_L$=0,08 m$^3$/hr ($U_{SL}$=0,11 m/s) $Q_G$=0,26 Nm$^3$/hr ($U_{SG}$=0,36 m/s)**

### *Severe slugging*

For sufficiently high liquid flow rates, complete blockage of the riser base was facilitated. The risers would fill up partially or completely, depending on the corresponding gas flow rate. As the system was symmetrical, blowout propagated in a symmetric fashion – the gas phase splits (apparently) equally over the two risers, leading to a single stage blowout in both. Consequently, the pressure recording is remarkably identical to how severe slugging propagates in a single riser system.

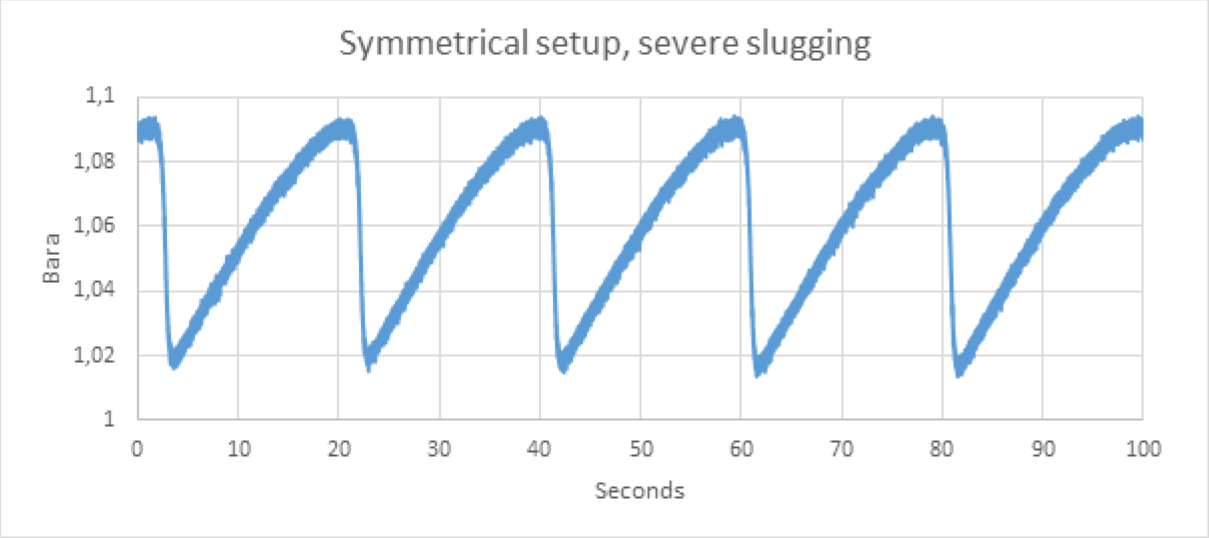

**Figure 6-7: Symmetrical system pressure, severe slugging. $Q_L$=0,08 m$^3$/hr ($U_{SL}$=0,11 m/s) $Q_G$=0,12 Nm$^3$/hr ($U_{SG}$=0,16 m/s)**

Compared to the side-arm setup, this system is significantly more sensitive to symmetry and potential disturbances. Should the risers or flow-line be exposed to events that momentarily compromises the symmetry of the system, the gas phase is immediately affected and the observed regime in the risers would become erratic. This is in particular visible during severe slugging, where irregularities can result in blowout in only one of the risers. This does however not affect the pressure recordings. Such inconsistencies can be variations in incoming flow or momentarily compromised symmetry due to the sheer force of severe slugging in the risers.

The regime map is plotted in Figure 6-8, and compared to the non-symmetrical map it is quite similar. However, the transition lines are close to parallel ($U_{SL} = 0,3*U_{SG}$), and there were fewer flow rates that allowed for severe slugging to exist.

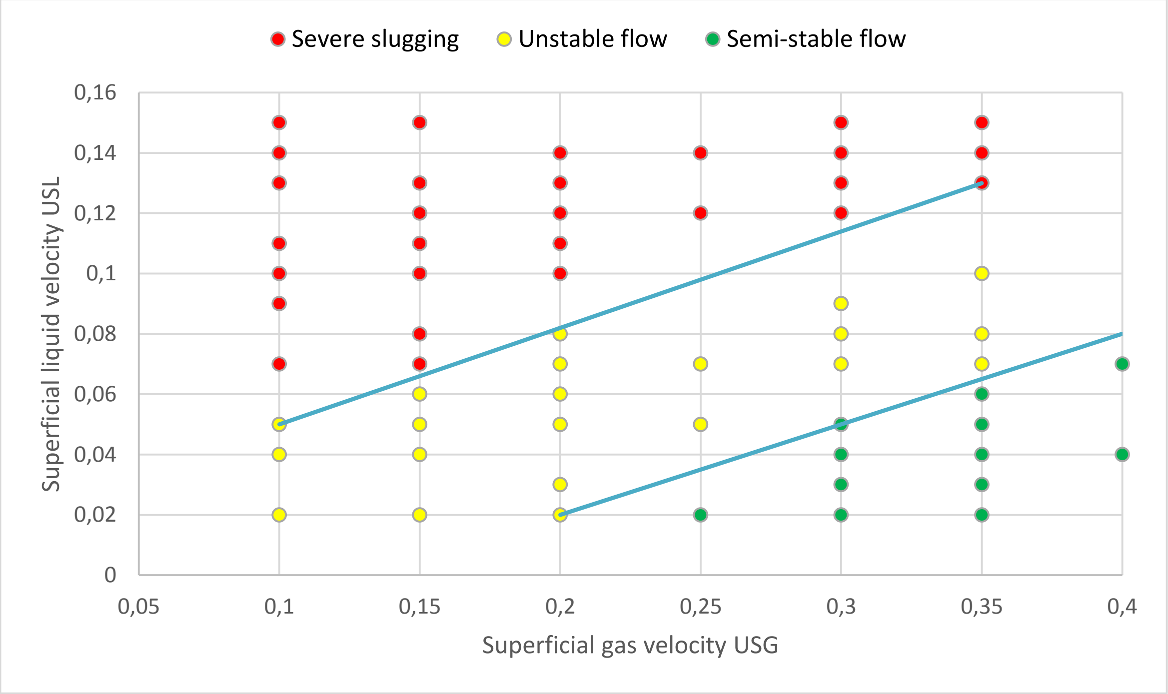

**Figure 6-8: Symmetrical regime map**

## 6.2 Change in amplitude and period

Continuous pressure recordings were done at constant liquid flow rate and increasing gas flow rate to look at the change in period time and pressure difference, i.e. amplitude. The results are plotted in Figure 6-9 through 6-10, but the data are also tabulated and can be seen in Appendix D.

### 6.2.1 Change in pressure amplitude

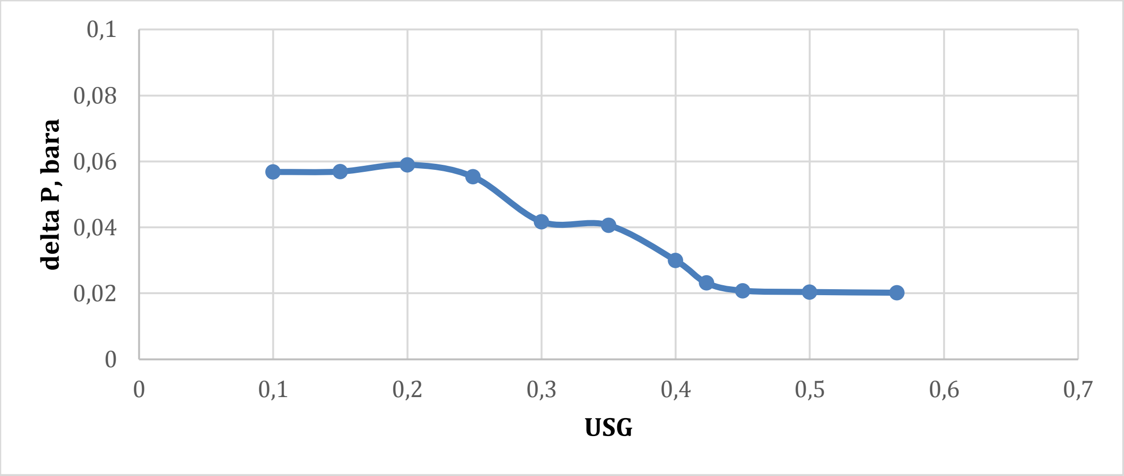

**Figure 6-9: Amplitude change for non-symmetrical system and increasing gas velocities ($U_{SG}$). Constant $U_{SL}$ = 0,11 m/s ($Q_L$=0,08 $m^3$/hr).**

Figure 6-9 shows the change in pressure amplitude for the non-symmetrical system, at constant $U_{SG}$ and varying $U_{SL}$. For this liquid velocity, the transition from severe slugging to unstable flow is found as $U_{SG}$ = 0,48 (see regime map in Figure 6-4). However, change in pressure amplitude is gradual and does not reveal where a regime transition may take place. This is because the unstable flow regime has the occasional severe slug blowout, giving high pressure differences. Even if the most cycles has a lower pressure difference than a severe slugging cycle, the average pressure difference will gradually decrease until it stabilizes at the highest gas velocities.

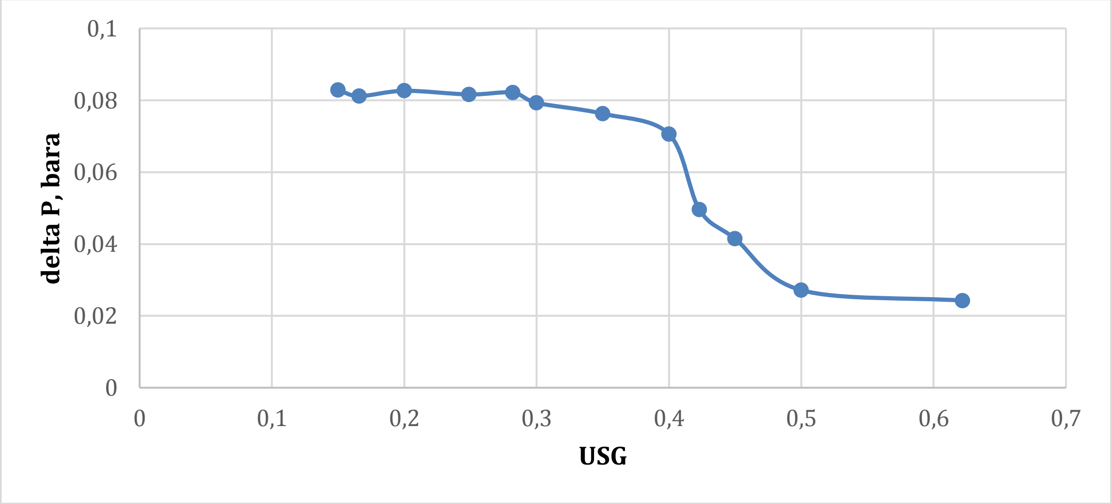

**Figure 6-10: Amplitude change for symmetrical system and increasing gas velocities ($U_{SG}$). Constant $U_{SL}$ = 0,11 m/s ($Q_L$=0,08 $m^3$/hr).**

The symmetrical setup has a higher maximum amplitude than the non-symmetrical one. Both systems produce similar max pressures, however, the symmetrical system has a larger pressure drop since blowout occurs in both risers. The non-symmetrical system only blows in one riser, causing liquid falling from the second riser to maintain some blockage and counteract a complete pressure drop, hence the differences in maximum amplitude.

The amplitude decrease seen at USL > 0,4 m/s for the symmetrical system is located close to the transition between unstable flow and churn flow in the regime map. Notably, the amplitude does not drop significantly prior to this. This is because during operation in the unstable region, severe slugs are sometimes allowed to grow, similar to the behaviour observed in the non-symmetrical system, leading to a high pressure difference. The two systems stabilize at approximately identical amplitudes.

At high LGR, where liquid is allowed to completely fill both risers before blowout, the maximum pressures in both systems are equal. However, as the asymmetrical setup only blows in one riser, the pressure drop here is smaller than for the symmetrical riser system – *given that the symmetrical system blows in both risers*. Thus, the non-symmetrical system will average at a higher pressure than the symmetrical one during a severe slugging cycle. There are however incidents where the symmetrical system, probably due to small asymmetries, only blows in one of the risers, and this is visible on pressure recordings as an incomplete pressure drop. Additional pressure recordings are provided in Appendix C, where this behaviour can be seen.

### 6.2.2 Change in period

The period, i.e. the duration of one cycle, has been plotted for both systems with constant $U_{SL}$ and varying $U_{SG}$, and can be seen in Figure 6-11 and Figure 6-12. The flow rates that are possible to obtain in the loop are relatively low, leading to highly gravity dominated flow regimes. Hence, none of the systems (symmetrical or non-symmetrical) are able to achieve constant pressure levels. Even at low LGR, sloshing or periods of slugging can be observed at the riser bases, causing the pressure to vary. In such a pressure variation, average period time can be found, even if the flow regime is not necessarily cyclic.

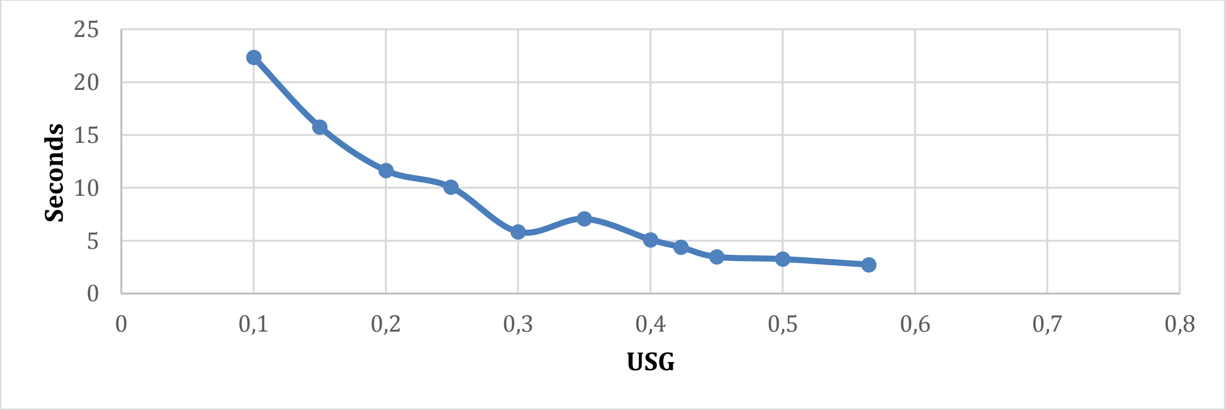

**Figure 6-11: Period time for non-symmetrical system with increasing gas velocities ($U_{SG}$). Constant $U_{SL}$ = 0,11 ($Q_L$=0,08 $m^3$/hr).**

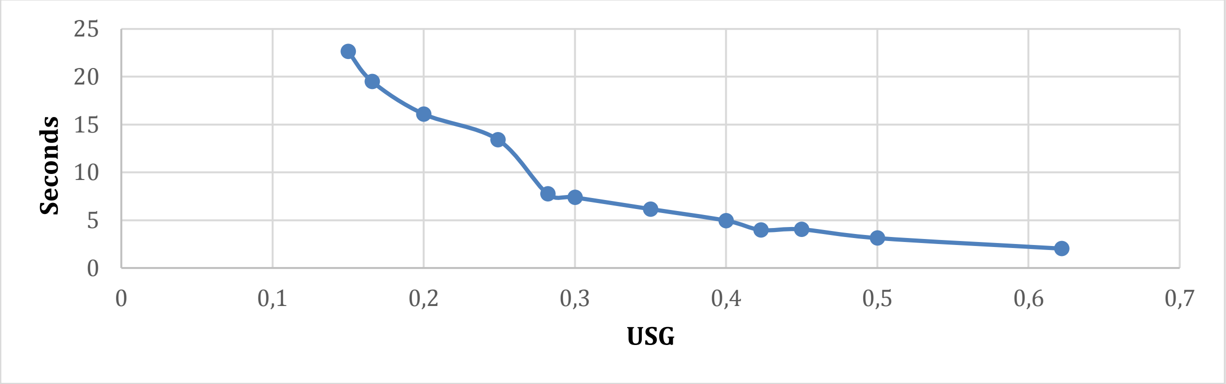

**Figure 6-12: Period time for non-symmetrical system with increasing gas velocities ($U_{SG}$). Constant $U_{SL}$ = 0,11 ($Q_L$=0,08 $m^3$/hr).**

As for the amplitude chart, the non-symmetrical period chart does not seem to give any indications towards where a regime transition is located. Instead, there is a steady decrease in period time, with the exception of one odd data point at $U_{SG}$ = 0,35. Compared to the symmetrical period chart, the two setups provide severe slugging at approximately identical frequencies. Additionally, they also stabilize at the same time period. However, the symmetrical period chart includes a rapid decrease at $U_{SG}$ = 0,25. This velocity can be located as the transition point from severe slugging to unstable flow (ref. flow regime map in Figure 6-8).

## 6.3 Different riser diameters

After locating areas of severe slugging, one riser was exchanged with a tube of a smaller diameter, namely ID = 6 mm. The second riser remained with an ID of 16 mm. There is a very sharp transition from the splitter base, which is also of 16 mm ID, to the thin riser. Three different setups were tested, as it was necessary to investigate a thin riser at both positions for the side-arm splitter. The setups are illustrated in Figure 6-13 below.

The three setups were tested for flow-rates that showed severe slugging in the original geometry, i.e. high LGR, to see whether the thin riser could stabilize the flow. The recordings for setups (a) to (c) are plotted together with the original pressure recordings, for the symmetrical and non-symmetrical setup respectively.

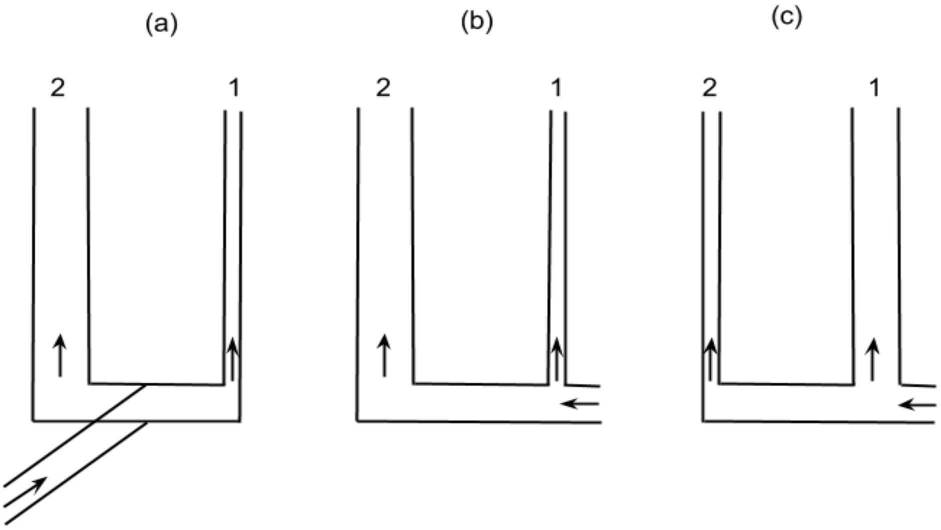

**Figure 6-13: Setups and numbering with different riser diameters**

### 6.3.1 Setup (a)

The setup that was originally symmetrical was only tested with a thin riser on one side of the splitter. Flow rates that previously resulted in symmetrical severe slugging would now only give production in the thicker riser, but still as severe slugging. The thin riser showed a liquid column that would drop slightly during blowout and restore during growth of the severe slug. The pressure recording is plotted together with the data for the setup with identical risers at equal flow rates. The thin riser setup does shorten the slugging period somewhat, as a smaller volume of liquid is necessary to fill the risers. However, even if the blowout only occurs in one riser this does not seem to affect the maximum pressure, with only a small difference in pressure drop at blowout.

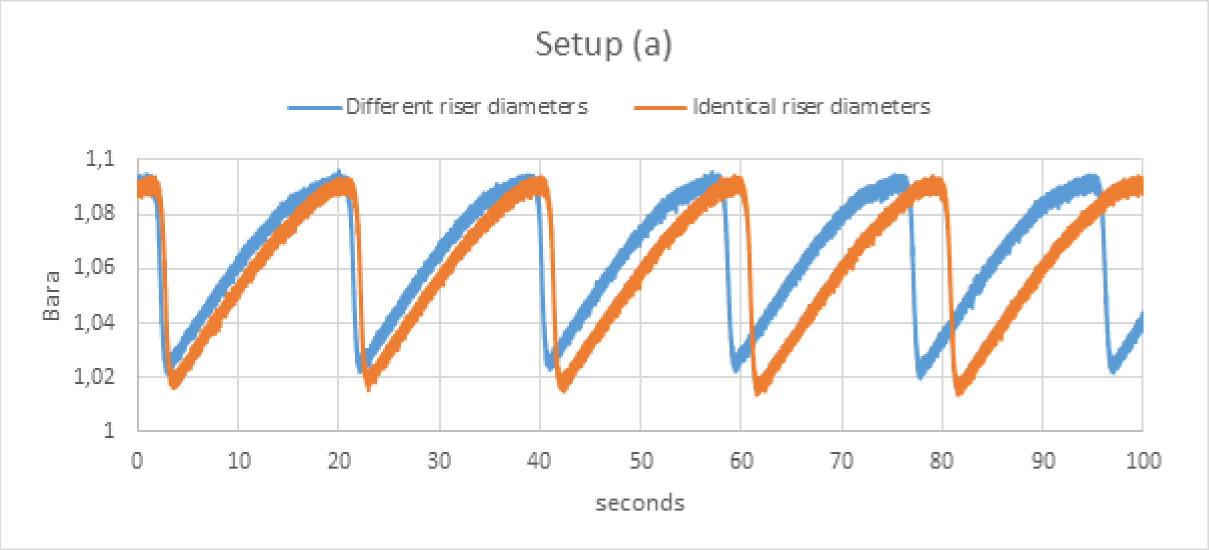

**Figure 6-14: Pressure recordings at setup (a) and corresponding original setup. $Q_L$=0,08 $Q_G$=0,12.**

### 6.3.2 Setup (b)

Previously, this setup with identical risers resulted in liquid production solely in riser 1 (see chapter 6.1.1); both for severe slugging and other flow regimes. When the side-arm was exchanged with the thinner pipe, the production of liquid is now divided over the two risers. A hydrodynamic (normal) slug flow is produced through both risers, however at a higher frequency in the thin one. At random interval, a complete blowout occurs in riser 2, followed by a loss of production in riser 1, before the slugging restores. This blowout is clearly seen in the pressure recording below, and the resulting maximum pressure drop is now similar to what a symmetrical system produces.

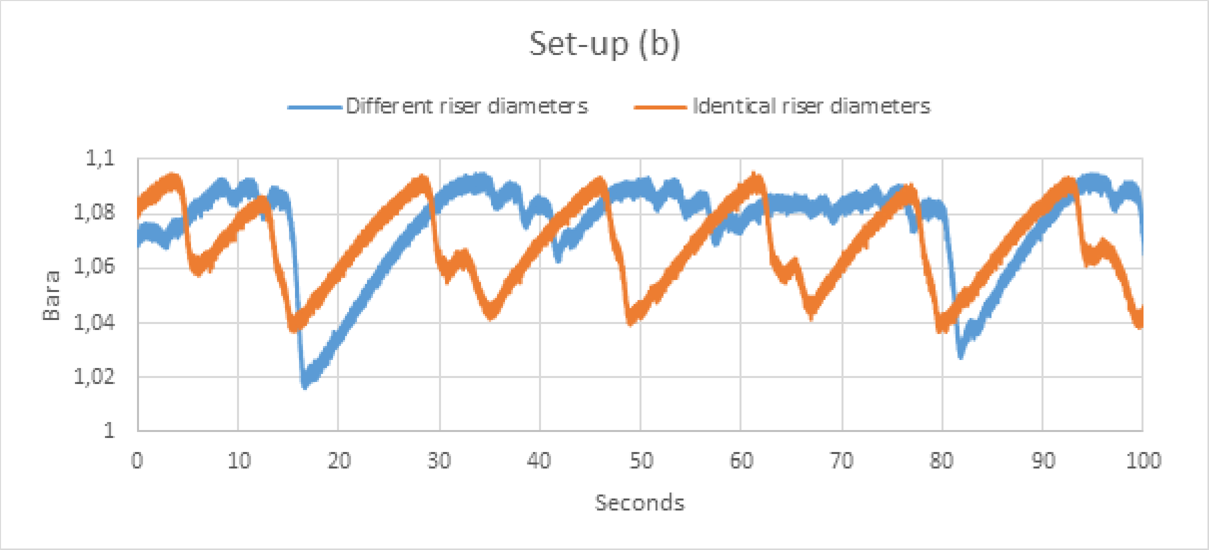

**Figure 6-15: Pressure recordings at setup (b) and corresponding original setup. $Q_L$=0,08 $Q_G$=0,12.**

### 6.3.3 Setup (c)

Here, the thin riser is set as riser 2 (run-arm). With this setup, all production occurred in riser 1, as a severe slug flow. When the setup with equal riser diameters resulted in a two-stage blowout, this behaviour is now eliminated, as the liquid occupying the thin riser is of such a low volume that the blowout can take place in one single go. Now, the pressure recordings approximate what you would expect of a single riser system, and are highly cyclic.

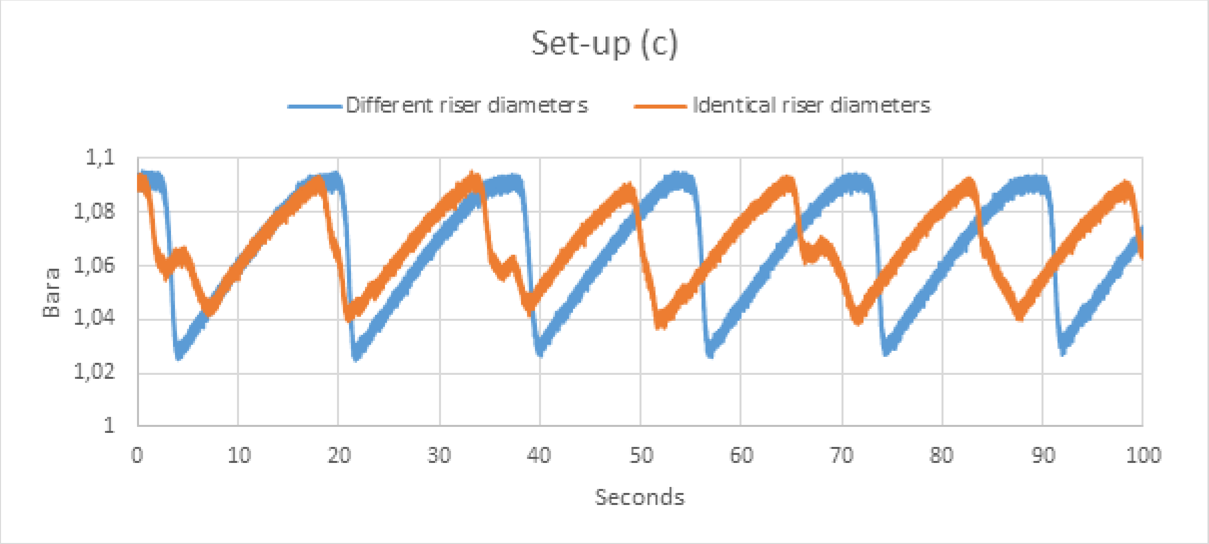

**Figure 6-16: Pressure recordings at setup (c) and corresponding original setup. $Q_L$=0,08 $Q_G$=0,12.**

# 7 DISCUSSION

If symmetrical, dual risers can give an equal phase split, visualized by the symmetrical blowout that occurs at severe slugging conditions. However, ensuring equal phase split can be difficult, as the gas phase in particular is highly sensitive to anomalies in said symmetry. Additionally, the low flow rates applied here gives a small momentum of the phases. Higher flow rates, particularly for liquid, leads to a higher momentum. With an impacting T, higher flow rates were shown by Prickaerts et.al to overcome some asymmetries (19). A typical field case will, as previously mentioned, have much higher flow rates and significantly lower liquid-to-gas ratios. However, the indications provided in these experiments make it seem unlikely that momentum forces will influence the gas phase, as the observations prove how easily the gas phase is affected by asymmetries. Rather than increased gas rates, choking should be the go to initiative towards manipulating the split over a non-symmetrical junction, as illustrated in the second study from STC/DUT (19).

The experiments does suggest that a single riser system exposed to severe slugging conditions could be stabilized by adding a thin riser connected through a side-arm branch of the run line. Setup (b) in chapter 6.3.2 showed some promising results in terms of flow regimes and pressure fluctuation. Flow rates that previously resulted in severe slugging in the asymmetrical setup now gave a stable slug flow, albeit with certain irregularities. The gas phase prefers the easiest route, shown in the original setup to be riser 1. The transition from the main pipeline to the now thinner riser means that there is a constriction in the preferred gas path that does not let the same amount of gas through as earlier. Effectively, this shows that a thin riser can act in the same manner a choke would, the latter shown in the experiments done by Haandrikman et.al (18, 19), where choking was shown to alter the initial phase split of the system. However, there are occasional major pressure drops caused by complete blowouts. This can be problematic in an actual field case, so this particular geometry should be investigated further in order to eliminate this behaviour, for instance by utilizing an even smaller side-arm riser (relative to the main riser) or by conducting experiments in a system that allows for higher total flow rates.

For the impacting T-junction, a thin riser does not help in stabilizing severe slugging. Instead, production only happens through the big riser, but still as severe slugging. While it does limit a potential slug control system to one instead of two risers, this would be an unnecessary addition to a system that has only one riser in the first place.

Initially, both systems were to a certain extend rigid in their setup. The risers were of equal height, the splitter base was levelled and the system was not exposed to any outside disturbances during an experiment. However, for an actual flexible riser system, one cannot expect a system like this to stay completely symmetrical subsea. Waves and currents, as well as potential slugging, will influence the position of the risers relative to each other. Hence, complete symmetry will be impossible to maintain even if a system is symmetric initially. Even the mini-loop used in these experiments was affected by the severe slugging. The sheer force of the blowout causes ripple effects in the separator, which again leads the risers to momentarily displace.

Hence, when evaluating the results, fluctuations in the physical setup should be considered. The loop itself is a mobile, changeable setup – which is a big advantage when wanting to investigate different geometries – however; its flexibility can compromise its accuracy. Junctions and hose connectors may not be entirely sealed, and while water leakage is easy to discover, air leakage is not. These, and other sources of error will cause some diversification and must be taken into consideration when handling the results.

Such leakage proved to be an issue that arose some time into the experimental period. Initially, an air safety tank was present between the air meter and inlet mixer. For low airflow, some backflow of water to the air supply line had previously occurred, so the tank was placed here to ensure no water entered the high-pressure tank or compressor. After several experiments had been executed, logged and processed, it was discovered that this tank was leaking. Hence, the experiments had to be redone, as the leakage opposed pressure build-up in the system.

Certain parts of the loop were shared with individuals working on other research projects. In principle, this should not be an issue, but being mobile and adjustable, the geometry of the loop would at times be altered as a consequence of this. When parts of the loop were used for other experiments, it had to be reassembled the next day. Assuring that the geometry was identical from one day to the next proved impossible, and the results are most likely affected by this.

Issues with instrumentation were also present. The liquid flow meter has a high resolution, and paired with a manual valve, ensuring constant and accurate liquid flow was difficult. This meter does not allow for direct recording of flow rates either. Additionally, the valve itself has been worn out in the course of this work, as it started leaking sometime during the final experiments.

The pressure transmitter, data acquisition card or some other devices used for recording is not resistant towards outside disturbances. It became clear at one incident where a different experimental facility was starting while the mini-loop was running. The records showed several inexplicable pressure drops during a highly cyclic slugging regime. An example of this erratic behaviour can be seen in Appendix E, figure (h).

# 8 CONCLUSION

This study has experimentally investigated dual riser systems in a small-scale facility, with particular focus on severe slugging in said systems. Several setups and geometries have been tested, with the aim to investigate the pressure fluctuations during a severe slugging cycle or towards stabilizing a system exposed to conditions known to cause severe slugging.

Visual observations as well as pressure recordings show that a symmetrical phase split during severe slugging is possible if a system is symmetrical. Although actual phase split measurements were not taken, the flow pattern observed for an impacting (and symmetrical) T-junction show identical flow propagation in the two risers, given that the incoming flow is stratified. This differs from other studies done on dual riser systems, where the intended symmetrical system was subject to asymmetries regarding riser heights and backpressure in the risers (19). Haandrikman et.al could only reach an equal phase split by choking, as their system was not symmetrical in its setup.

Further on, various flow phenomena for various flow rates have been observed and mapped for two particular systems. However, uncertainties regarding the liquid flow rates are present, and this should be taken into account when reading the regime maps.

Pressure recordings show highly unstable and chaotic behaviour for several variations of flow rates. For low liquid-to-gas ratios, severe slugging can exist in both symmetrical and non-symmetrical systems. In a symmetrical system, the gas phase is highly dependent on the symmetry of the split to be accurate (including height of the risers) in order to produce equal blowout in both risers. Should the intended symmetrical setup indeed be asymmetrical in terms of riser height, levelling of the splitter base or for other reasons, blowout will only occur in one of the risers. A system with a side-arm splitter with equal risers will only produce severe slugging in one riser regardless, namely the riser that the gas will meet first.

Using dual risers of different diameters have shown promises towards stable flow for the side-arm system. In particular, this was observed and recorded for the setup where the side-arm is replaced by a thinner riser. Instead of producing severe slugging in the first riser exclusively, production is now divided over both as a normal slug flow. While there are instances of larger pressure variations, as the occasional severe slug is allowed to grow, this setup show that different riser diameters can be used to force the phase split in the same way a choke can, illustrated by Prickaerts, Haandrikman and Henkes in their study on a non-symmetric splitter to dual risers (18).

## 8.1 Recommendations for further work

The mini-loop is a very versatile facility, allowing flow systems with geometries only limited by imagination. It is easy and quick to change between geometries, and in this sense it is a very useful device in getting preliminary indications of flow phenomena. These are indications that can be used towards deciding whether a certain system would be interesting to investigate in a larger scale.

As of today however, the loop is slightly limited in its scientific accuracy. Due to issues mentioned previously, the results obtained in these experiments cannot be used to gain empirical correlations for flow regimes, period times or amplitudes. There are simply too many uncertainties regarding flow rates, symmetry and pressures.

In potential further work it would be interesting to look at the phase split quantitatively by diverting the risers to separate containers to measure the mass fractions. Such measurements can make it possible to confirm that the split is indeed equal, as the observations indicate. Focusing on utilizing different riser diameters towards stabilizing the flow can also prove to be worthwhile, as one of the setups showed some promising results in this sense. Experimenting with positioning and different diameters of this thin riser is recommended. An example could be inserting the thin riser into the larger one. Such a setup can, if designed properly, allow for total separation upstream of a riser, where gas flows in the smaller tube inside the liquid filled main riser. This should be possible to design for the mini-loop.

If it is deemed worthwhile to continue work on the mini-loop, parts of it will need to be improved. In particular, this involves a new liquid flow meter, as the one mounted on the loop now is highly inaccurate and the valve has been worn out during the experiments. A digital liquid meter could be wired to a data acquisition system along with the gas meter so that accurate flow rates can be recorded together with the pressure.

Further work on multiple risers can also include an up-scaled experimental facility. This will require more resources and planning, and a larger facility will not be as flexible in designs/setups as the mini-loop is. However, a larger loop can allow for higher flow rates and pressures, approaching an actual field case if necessary. Shell Technology Centre and Delft Technical University stated that their facility was to be improved towards better symmetry for further research. If possible, extended cooperation with Shell on the subject of dual risers can be valuable, given their knowledge on the issue.

Computer simulations should be possible, and a prototype was initiated in LedaFlow, a multiphase flow software that includes a branching option. However, as time was restricted due to problems mentioned earlier, this was not developed to a successful compilation. A continuation of this approach is advisable, as simulation results can be compared to the experimental results. Additionally, a simulation model can easily be up-scaled to match conditions for different field cases.

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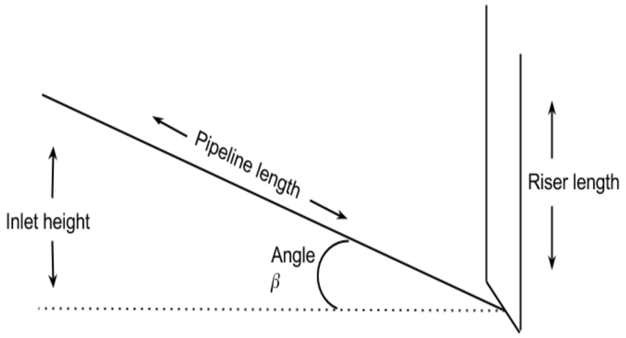
# APPENDIX A – EXPERIMENTAL FACILITY

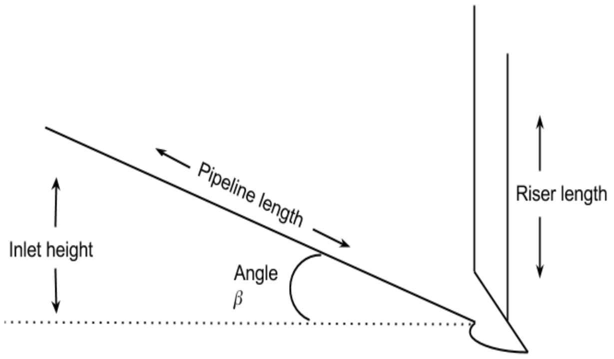
Detailed information on the loop and its dimensions are included here, as well as pictures of the facility.

## Symmetrical setup



| DATA | |
|---|---|
| **Pipeline length** | 230 cm |
| **Inlet height** | 68 cm |
| **Angle** | 17,2 ° |
| **Riser length** | 92 cm |
| **Distance between risers** | 21 cm |
| **Pipe internal diameter** | 16 mm |

## Non-symmetrical setup

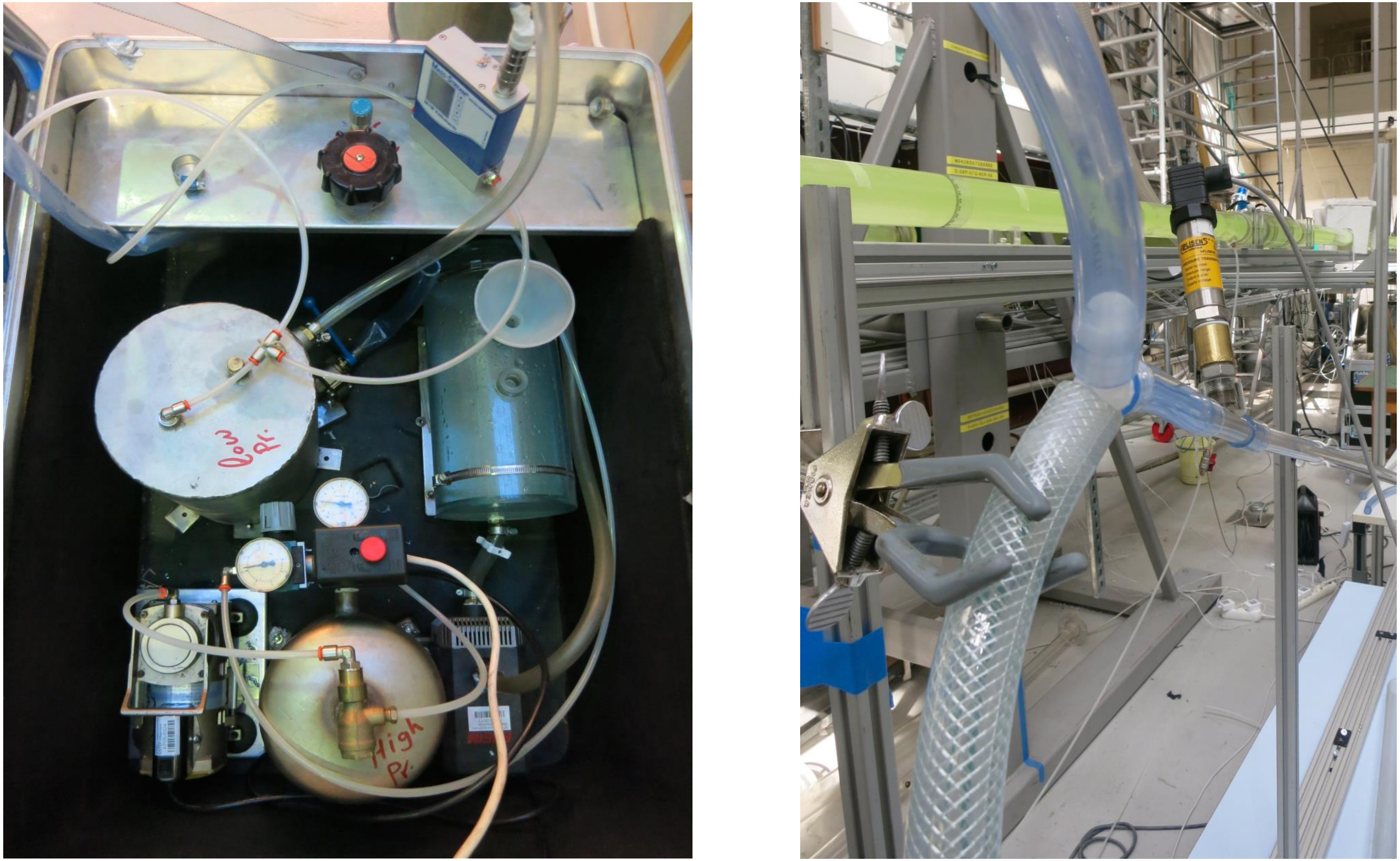


| DATA | |
|---|---|
| **Pipeline length** | 210 cm |
| **Inlet height** | 68 cm |
| **Angle** | 18,9 ° |
| **Riser length** | 92 cm |
| **Distance between risers** | 21 cm |
| **Pipe internal diameter** | 16 mm |

The dimensions remains unchanged when the systems consists of risers with different internal diameters.

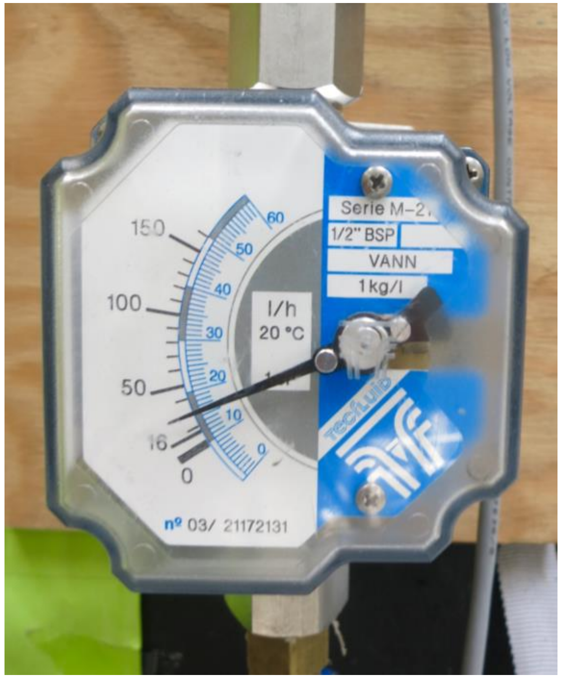
Left: Symmetrical splitter configuration

Right: Non-symmetrical (side-arm) splitter configuration



Left: Two-phase flow simulator with water and air tanks, pump, compressor and gas flow meter

Right: Inlet mixer. Gas inlet at the top, pressure transmitter after mixer.



Left: Riser inlet to separator

Middle: Liquid flow meter

Right: Gas flow meter

# APPENDIX B – CALCULATION OF FLOW RATES AND SUPERFICIAL VELOCITIES

The meters for liquid and gas connected to the loop gives flow rates in different units. For liquid, the meter displays litres per hour, L/hr, and the gas displays normal litres per minute, Ln/min. Volumetric flow rates and corresponding superficial velocities are therefore calculated in the following manner.

## Gas flow rates

The gas flow meter displays flow in normal litres per minute. Data for air at normal conditions, that is 0° C and atmospheric pressure, is listed in the table below.

| **Data, air** | **@0˚C 1,013bar** | |
|---|---|---|
| **Density** | 1,2922 | kg/m$^3$ |
| **V$_m$** | 22,414 | L$_n$/mole |
| **MW** | 28,97 | g/mole |

Conversion from normal litres per minute to normal cubic metres per hour, Nm$^3$/hr, is then given by the following equation:

$$Q_G\left[\frac{Nm^3}{hr}\right]=\frac{[\frac{L_n}{min}]}{V_m[\frac{L_n}{mole}]}*\frac{MW\left[\frac{g}{mole}\right]*\frac{1\,[kg]}{1000\,[g]}}{\rho\left[\frac{kg}{m^3}\right]}*\frac{60\,[min]}{1\,[hr]}$$

## Liquid flow rates

The liquid flow meter gives values in litres per hour. Conversion to cubic meter per hour, m$^3$/hr, is given by the following correlation.

$$Q_L\left[\frac{m^3}{hr}\right]=\left[\frac{L}{hr}\right]*\frac{1\,[m^3]}{1000\,[L]}$$

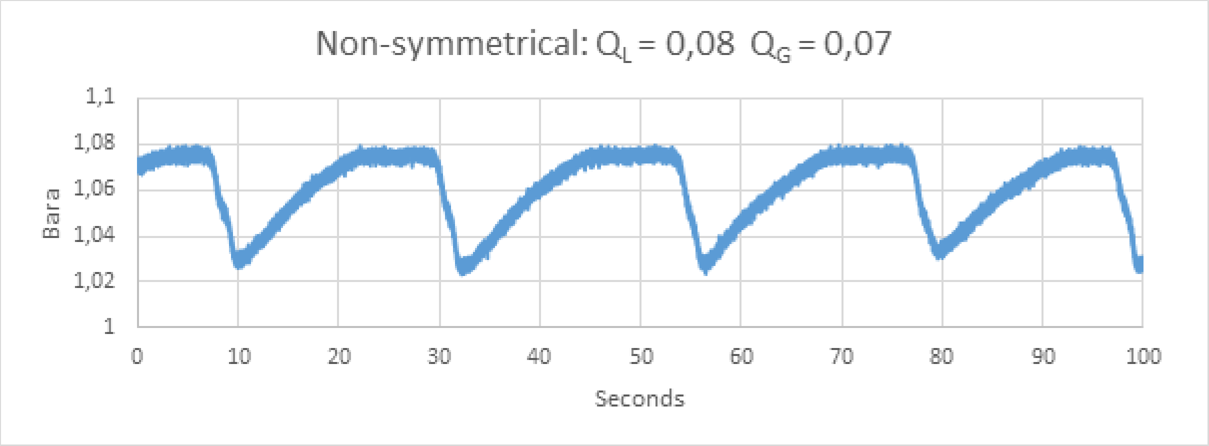
The total range of gas and liquid flow rates were calculated in Excel. These are shown in the table below, accompanied by corresponding superficial velocities. The latter is calculated by the equation given in the main report. The flow rates gives a possible LGR range from *0.028* to *2.33*.

| Gas flow rate | | |
|---|---|---|
| $L_n$/min | Nm$^3$/hr | $U_{SG}$ m/s |
| 1 | 0,0600 | 0,0829 |
| 1,5 | 0,0900 | 0,1244 |
| 2 | 0,1200 | 0,1658 |
| 2,5 | 0,1500 | 0,2073 |
| 3 | 0,1800 | 0,2487 |
| 3,5 | 0,2100 | 0,2902 |
| 4 | 0,2401 | 0,3316 |
| 4,5 | 0,2701 | 0,3731 |
| 5 | 0,3001 | 0,4146 |
| 5,5 | 0,3301 | 0,4560 |
| 6 | 0,3601 | 0,4975 |
| 6,5 | 0,3901 | 0,5389 |
| 7 | 0,4201 | 0,5804 |
| 7,5 | 0,4501 | 0,6218 |
| 8 | 0,4801 | 0,6633 |
| 8,5 | 0,5101 | 0,7048 |
| 9 | 0,5401 | 0,7462 |
| 9,5 | 0,5701 | 0,7877 |
| 10 | 0,6001 | 0,8291 |
| 10,5 | 0,6301 | 0,8706 |
| 11 | 0,6602 | 0,9120 |
| 11,5 | 0,6902 | 0,9535 |
| 12 | 0,7202 | 0,9949 |

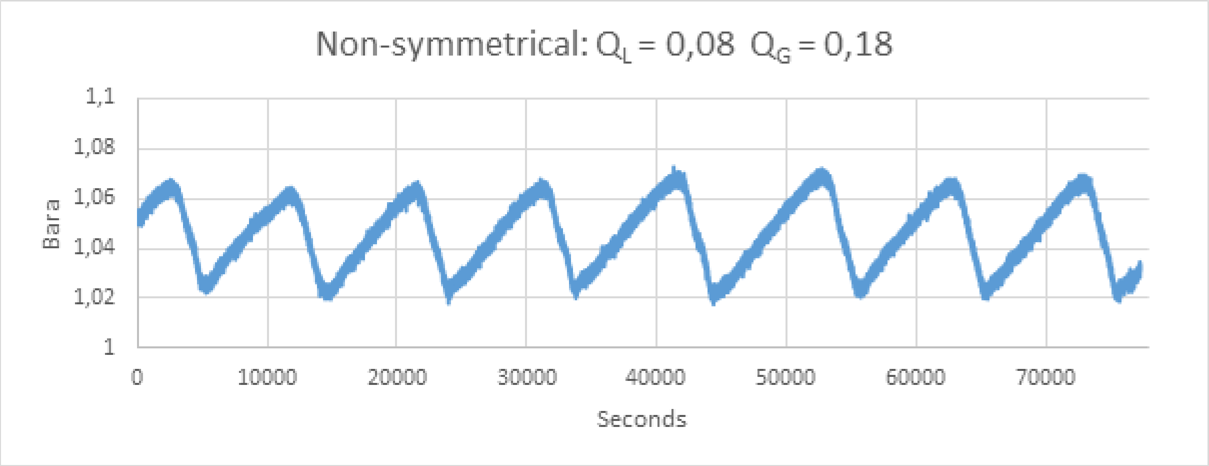
| Liquid flow rate | | |
|---|---|---|
| L/hr | m$^3$/hr | $U_{SL}$ m/s |
| 20 | 0,0200 | 0,0276 |
| 25 | 0,0250 | 0,0345 |
| 30 | 0,0300 | 0,0414 |
| 35 | 0,0350 | 0,0484 |
| 40 | 0,0400 | 0,0553 |
| 45 | 0,0450 | 0,0622 |
| 50 | 0,0500 | 0,0691 |
| 55 | 0,0550 | 0,0760 |
| 60 | 0,0600 | 0,0829 |
| 65 | 0,0650 | 0,0898 |
| 70 | 0,0700 | 0,0967 |
| 75 | 0,0750 | 0,1036 |
| 80 | 0,0800 | 0,1105 |
| 85 | 0,0850 | 0,1174 |
| 90 | 0,0900 | 0,1243 |
| 95 | 0,0950 | 0,1312 |
| 100 | 0,1000 | 0,1382 |
| 105 | 0,1050 | 0,1451 |
| 110 | 0,1100 | 0,1520 |
| 115 | 0,1150 | 0,1589 |
| 120 | 0,1200 | 0,1658 |
| 125 | 0,1250 | 0,1727 |
| 130 | 0,1300 | 0,1796 |
| 135 | 0,1350 | 0,1865 |
| 140 | 0,1400 | 0,1934 |

# APPENDIX C – PRESSURE GRAPHS

## Non-symmetrical setup, identical risers



(a)



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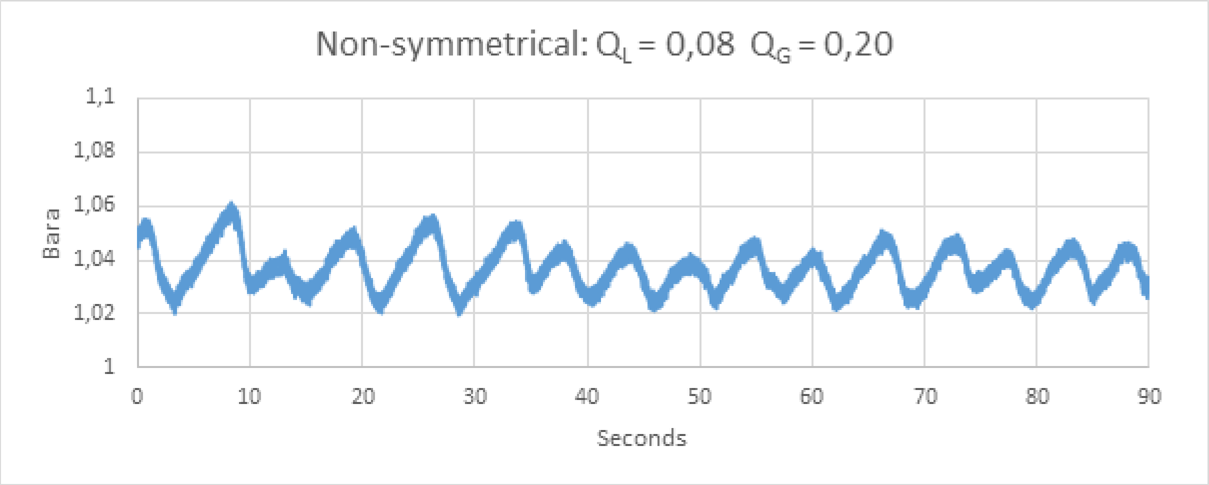
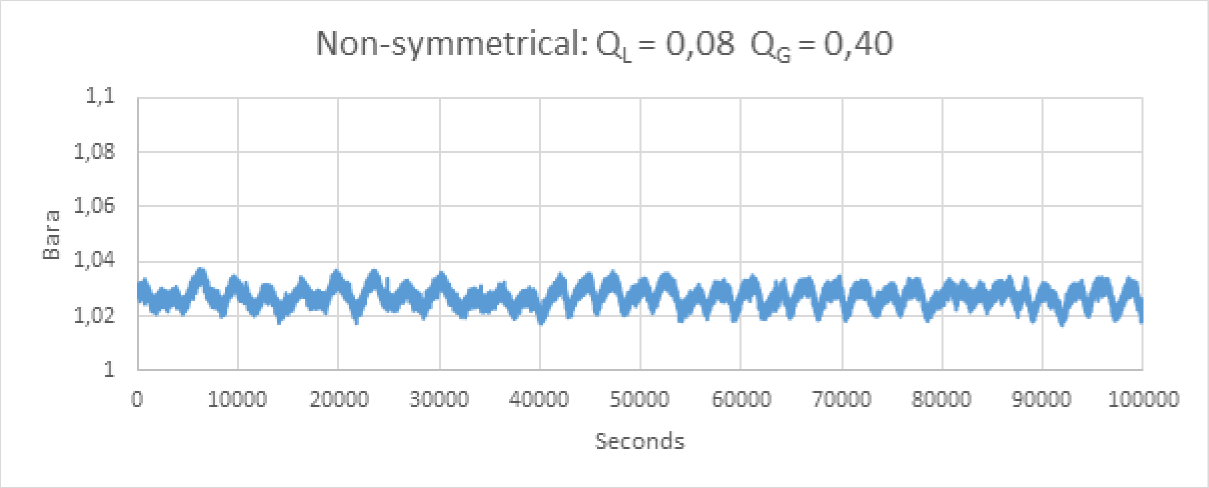
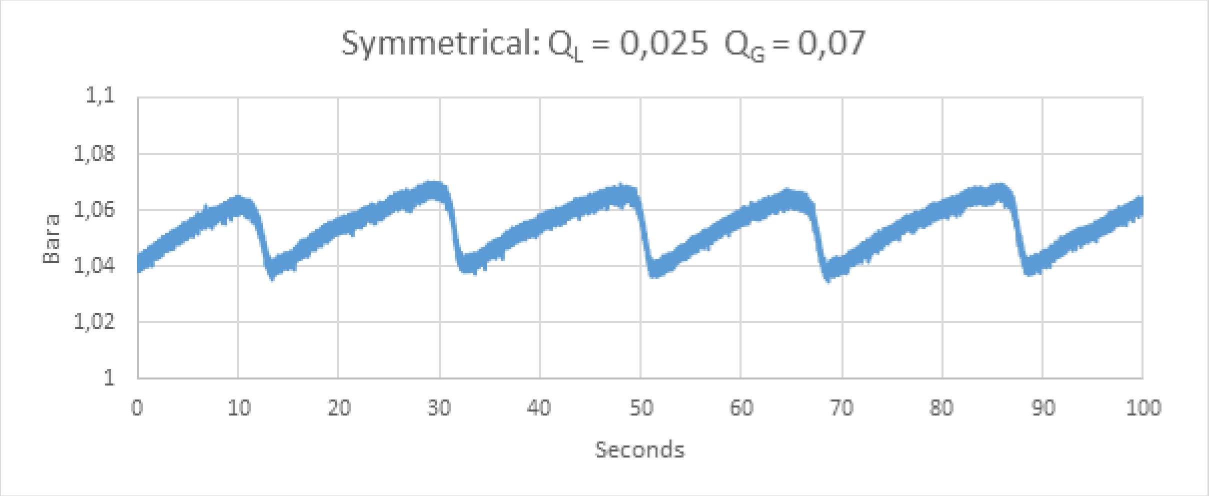


(c)

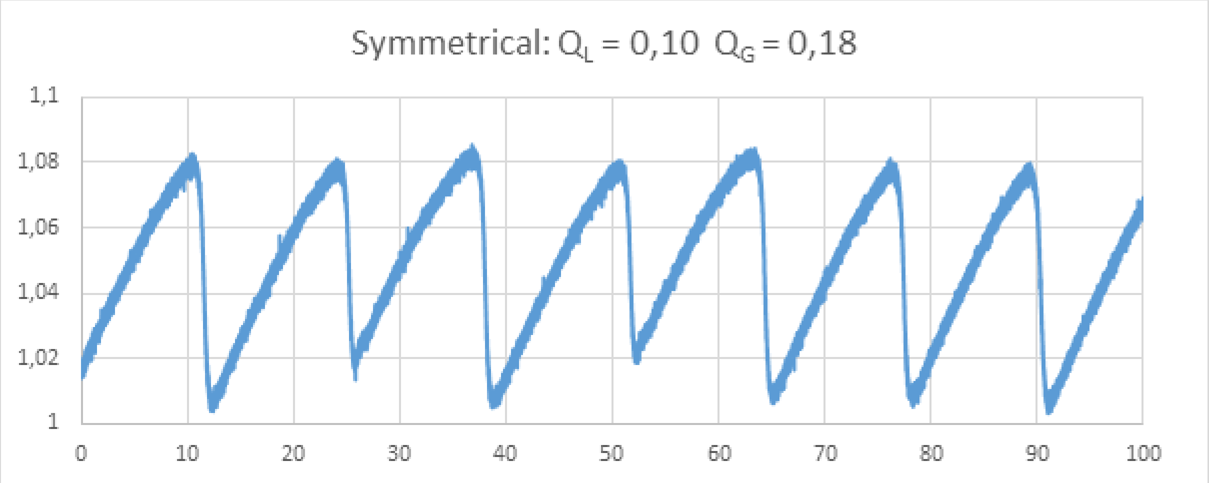


(d)

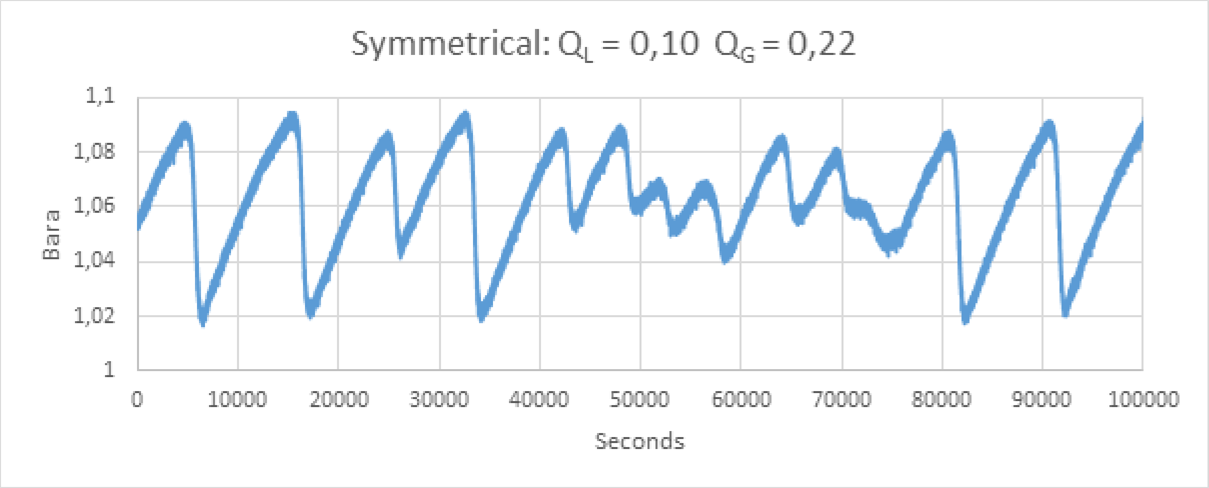
## Symmetrical setup, identical risers



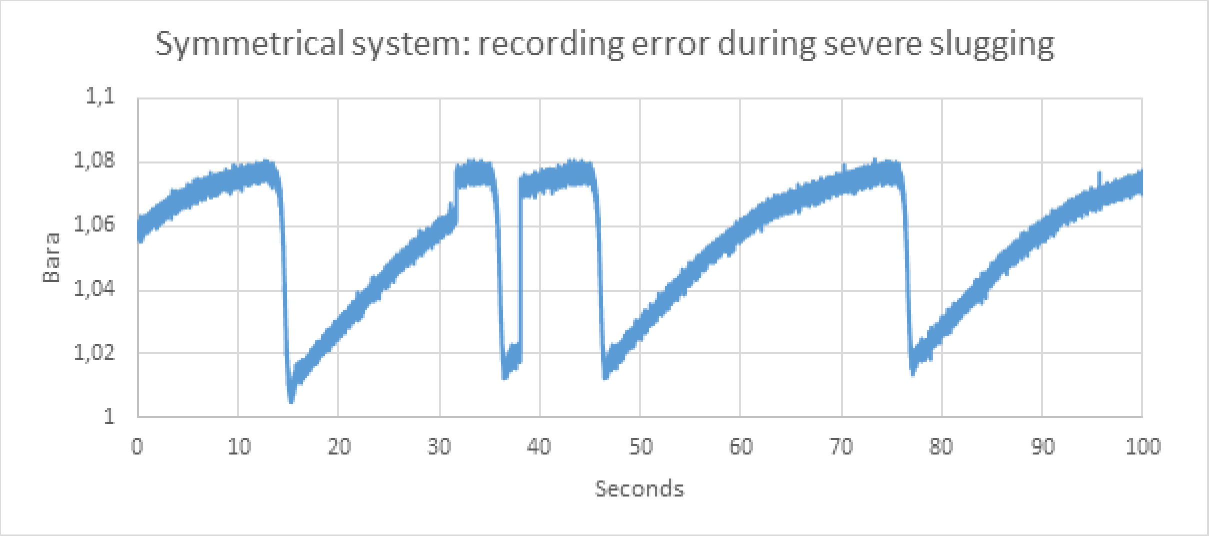
(e)



(f)


Symmetrical: $Q_L$ = 0,10 $Q_G$ = 0,22
Bara
1,1
1,08
1,06
1,04
1,02
1
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
Seconds

(g)


Symmetrical system: recording error during severe slugging
Bara
1,1
1,08
1,06
1,04
1,02
1
0
10
20
30
40
50
60
70
80
90
100
Seconds

(h)

# APPENDIX D – DATA TABLES

All pressures in bars and periods in seconds.

## Non-symmetrical, identical risers

| $Q_L$ | $U_{SL}$ | $Q_G$ | $U_{SG}$ | $P_{max}$ | $P_{min}$ | $\Delta P$ | $P_{avg}$ | Period* |
|---|---|---|---|---|---|---|---|---|
| 0,080 | 0,111 | 0,073 | 0,100 | 1,0800 | 1,0232 | 0,0568 | 1,0604 | 22,3548 |
| | | 0,108 | 0,149 | 1,0811 | 1,0242 | 0,0569 | 1,0564 | 15,7706 |
| | | 0,120 | 0,166 | 1,0952 | 1,0326 | 0,0626 | 1,0675 | 16,7277 |
| | | 0,150 | 0,207 | 1,0771 | 1,0181 | 0,0589 | 1,0483 | 11,6387 |
| | | 0,180 | 0,249 | 1,0728 | 1,0175 | 0,0553 | 1,0459 | 10,0646 |
| | | 0,198 | 0,274 | 1,0613 | 1,0197 | 0,0417 | 1,0369 | 5,8384 |
| | | 0,254 | 0,351 | 1,0596 | 1,0190 | 0,0406 | 1,0380 | 7,0708 |
| | | 0,290 | 0,400 | 1,0496 | 1,0197 | 0,0299 | 1,0344 | 5,0983 |
| | | 0,306 | 0,423 | 1,0420 | 1,0189 | 0,0231 | 1,0297 | 4,3861 |
| | | 0,327 | 0,452 | 1,0405 | 1,0197 | 0,0208 | 1,0303 | 3,4735 |
| | | 0,366 | 0,506 | 1,0420 | 1,0217 | 0,0204 | 1,0296 | 3,2623 |
| | | 0,409 | 0,565 | 1,0374 | 1,0173 | 0,0202 | 1,0270 | 2,7418 |

*Average

## Symmetrical, identical risers

| $Q_L$ | $U_{SL}$ | $Q_G$ | $U_{SG}$ | $P_{max}$ | $P_{min}$ | $\Delta P$ | $P_{avg}$ | Period* |
|---|---|---|---|---|---|---|---|---|
| 0,025 | 0,034 | 0,073 | 0,100 | 1,0790 | 1,0335 | 0,0455 | 1,0544 | |
| 0,070 | 0,097 | 0,180 | 0,249 | 1,0656 | 1,0130 | 0,0526 | 1,0437 | |
| 0,080 | 0,110 | 0,073 | 0,100 | 1,0818 | 1,0038 | 0,0780 | 1,0560 | |
| | | 0,108 | 0,149 | 1,0828 | 0,9999 | 0,0829 | 1,0486 | 22,6653 |
| | | 0,120 | 0,166 | 1,0945 | 1,0133 | 0,0812 | 1,0595 | 19,4935 |
| | | 0,150 | 0,207 | 1,0824 | 0,9997 | 0,0827 | 1,0458 | 16,1007 |
| | | 0,180 | 0,249 | 1,0823 | 1,0006 | 0,0816 | 1,0458 | 13,4352 |
| | | 0,204 | 0,282 | 1,0817 | 0,9996 | 0,0821 | 1,0457 | 7,7550 |
| | | 0,222 | 0,307 | 1,0815 | 1,0022 | 0,0793 | 1,0480 | 7,3827 |
| | | 0,254 | 0,351 | 1,0782 | 1,0019 | 0,0763 | 1,0433 | 6,1666 |
| | | 0,290 | 0,400 | 1,0728 | 1,0023 | 0,0706 | 1,0415 | 4,9595 |
| | | 0,306 | 0,423 | 1,0635 | 1,0140 | 0,0496 | 1,0344 | 3,9837 |
| | | 0,327 | 0,452 | 1,0612 | 1,0197 | 0,0414 | 1,0347 | 4,0467 |
| | | 0,366 | 0,506 | 1,0461 | 1,0190 | 0,0272 | 1,0315 | 3,1339 |
| 0,100 | 0,138 | 0,180 | 0,249 | 1,0855 | 1,0028 | 0,0827 | 1,0485 | |
| | | 0,222 | 0,307 | 1,0961 | 1,0165 | 0,0796 | 1,0631 | |

*Average

# APPENDIX E – RISK ASSESSMENT REPORT

A risk assessment for the laboratory work was carried out and approved according to the departments' procedures. As it is an extensive document, only an excerpt of the risk assessment is included here. The full report is available in the laboratory as well as a digital version submitted to supervisor Ole Jørgen Nydal.

The experiment involves the small-scale flow loop in the multiphase flow laboratory at NTNU. The loop is fed water and air to create a two-phase flow in a setup of plexiglass pipes with internal diameter of 16 mm.

The pressures and flow rates the equipment is capable of producing are relatively small. Hence, it is not expected that any incidents connected to the experiment will require evacuation of the laboratory or building. However, emergency shut-down procedure is included for alarms caused by other unrelated lab activity.

The conclusion on the risk assessment states that there are no intolerable risks connected to the experiments or the facility. Operational procedures are clear, however, misinterpretation of these will not lead to unacceptable hazardous situations. Besides following start-up and shutdown procedure, operators must wear safety glasses and be sure to keep the area around the rig tidy to avoid personal injury.