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Transiente olje-vann strømningsforsøk

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Master i produktutvikling og produksjon
Oppgaven levert: Juli 2009
Hovedveileder: Ole Jørgen Nydal, EPT

Norges teknisk-naturvitenskapelige universitet
Institutt for energi og prosessteknikk

Oppgavetekst

Det skal utføres sammenligninger mellom forsøksdata og numeriske beregninger for utblåsning av vann med en oljestrøm

Oppgaven gitt: 10. februar 2009
Hovedveileder: Ole Jørgen Nydal, EPT

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Science and Technology

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Norges Teknisk-Naturvitenskapelige Universitet

Report no:

Classification:

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Title of report Transient two phase flow experiments with oil and water	Date 06.07.2009 No. of pages/appendices 58/24
Author Pål Idar Ingebo	Project manager
Division Faculty of Engineering Science and technology Department of Energy and Process Technology	Project no.
ISBN no.	Price group

Client/Sponsor of project Chevron	Client's ref.

Abstract

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Flushing times, OLGA 6.0 predictions and the oil front, being an important parameter, are discussed in the analysis section. The foundation of the discussion is the water holdup vs. time plots collected from the experiments. These are attached to Appendices A to C, and shows data for oil superficial velocities between 0.02m/s - 0.8m/s for a .5-degree inclined, declined and horizontal test rig setup. As additional support, picture collages of the development of oil front shape and plots of oil front velocities along the pipeline are also presented. All raw data is handed over to the Department of Energy and Process Technology.

Relevant theory on liquid-liquid flows is presented in the literature review section together with a general description of OLGA 6.0. The Two-Fluid Model will also be addressed being the model of choice for the simulator engine.
The experimental laboratory is described in detail to enable an accurate reconstruction or continuing of the experiments at a later point in time. It contains layouts of the test-loop and supporting sections, measurement devices, fluid data and procedures for running and calibration.

OLGA 6.0 shows good predictions to the oil-water flushing scenario for all oil superficial velocities above 0.14m/s. An oil Usl>0.3m/s was needed to fully flush the water from both the test section and flexible outlet. The fastest flushing times within the Chevron specified velocity interval; are 30s, 48s and 51s for .5-degree declined, horizontal and .5-degree inclined setup respectively. For holdup vs. time curves showing no water for velocities below 0.3m/s a considerable amount of water is usually still concentrated in the outlet section. For oil Usl<0.14m/s where water is not flushed, is when OLGA 6.0 shows the most deviance to experimental results. The differences in registered and predicted holdups here are generally around 20-40%.

	Indexing Terms: English	Norwegian
Group 1		
Group 2		
Selected by author		

Norges teknisk-
naturvitenskapelige universitet
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Institutt for energi- og prosessteknikk

EPT-M-2009-37

MASTER THESIS

for

Stud.techn. Pål Idar Ingebo

Vår 2009

Transiente olje-vann strømningsforsøk

Transient two phase flow experiments with oil and water

Bakgrunn

Undersjøiske oljebrønner og rørledninger kobles ofte sammen ved hjelp av et U-formet rør ("jumper"). Samtidig med olje og gass produseres det ofte også vann fra brønner. Etter en ukontrollert nedstengning kan det da akkumuleres vann i U-koblingen: Dersom vannet ikke er inhibert kan gasshydrater dannes ved oppstarten igjen, når vannet kommer i kontakt med gass.

Strømningsproblemet vi er interessert i er hvordan olje som pumpes inn i røret (eller en hydratinhibitor som f.eks. glykol) vil fortrenge vannet. Det vil avhenge av strømningsratene og geometrien.

Det er tidligere utført noen transiente strømningsforsøk der en oljestrøm pumpes inn i et vannfylt rør og utblåsningen måles ved hjelp av impedansringer (6 cm rør). Denne oppgaven er en videreføring med vekt på forsøk med større rørdiameter (9 cm) og på sammenligning med strømningsmodeller for lagdelt olje-vannstrøm..

Mål

Det skal utføres sammenligninger mellom forsøksdata og numeriske beregninger for utblåsning av vann med en oljestrøm..

Oppgaven bearbeides ut fra følgende punkter:

1. Kort oversikt over problemstillingen
2. Utføre strømningsforsøk der en olje strøm fortrenger en vannfase
3. Sammenligne forsøksdata med beregninger (f.eks. OLGA eller egenprogrammerte modeller)

-- " --

Senest 14 dager etter utlevering av oppgaven skal kandidaten levere/sende instituttet en detaljert fremdrift- og evt. forsøksplan for oppgaven til evaluering og evt. diskusjon med faglig ansvarlig/ veiledere. Detaljer ved evt. utførelse av dataprogrammer skal avtales nærmere i samråd med faglig ansvarlig.

Besvarelsen redigeres mest mulig som en forskningsrapport med et sammendrag både på norsk og engelsk, konklusjon, litteraturliste, innholdsfortegnelse etc. Ved utarbeidelsen av teksten skal kandidaten legge vekt på å gjøre teksten oversiktlig og velskrevet. Med henblikk på lesning av besvarelsen er det viktig at de nødvendige henvisninger for korresponderende steder i tekst, tabeller og figurer anføres på begge steder. Ved bedømmelsen legges det stor vekt på at resultatene er grundig bearbeidet, at de oppstilles tabellarisk og/eller grafisk på en oversiktlig måte, og at de er diskutert utførlig.

Alle benyttede kilder, også muntlige opplysninger, skal oppgis på fullstendig måte. (For tidsskrifter og bøker oppgis forfatter, tittel, årgang, sidetall og evt. figurnummer.)

Det forutsettes at kandidaten tar initiativ til og holder nødvendig kontakt med faglærer og veileder(e). Kandidaten skal rette seg etter de reglementer og retningslinjer som gjelder ved (Firmanavn? og) alle (andre) fagmiljøer som kandidaten har kontakt med gjennom sin utførelse av oppgaven, samt etter eventuelle pålegg fra Institutt for energi- og prosessteknikk.

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Til Instituttet innleveres to - 2 komplette, kopier av besvarelsen. Ytterligere kopier til evt. medveiledere/oppgavegivere skal avtales med, og evt. leveres direkte til, de respektive.
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Institutt for energi og prosessteknikk, 12. januar 2009

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Johan Hustad
Instituttleder

Ole Jørgen Nydal

Ole Jørgen Nydal
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Preface

I was initially invited into a project in the fall of 2008 to produce the foundation for a masters thesis, through calibration and familiarizing with the experimental rig. My contact was Prof. Ole Jørgen Nydal at the Department of Energy and Process Technology at NTNU Gløshaugen. Gandi Rahmawan Setyadi, a Ph.D student was later assigned as my supervisor and collaborator in extracting experimental results. Extraction experimental data rather than programming became the focus of the thesis. A commercial multiphase software, OLGA 6.0, was therefore chosen when trying to recreate the experimental results.

I want to give thanks to Gandi Rahmawan Setyadi for being of huge help in conducting my experimental work and as a mentor during both the project and masters thesis. I also want to thank Ole Jørgen Nydal for giving valuable inputs to the experimental results and laboratory work.

Abstract

This thesis has been focused around extracting data from experiments on liquid-liquid flushing with oil and water. OLGA 6.0, a commercial multiphase flow simulator, has then been used for simulations to evaluate whether it can be used for predicting the experimental scenario. The results will be handed over to Chevron, acting as input on how ethylene glycol or ethanol can be used to flush water from offshore jumpers. Raw data produced will later be used as reference in programming own multiphase models at the Department of Energy and Process Technology at NTNU Gløshaugen.

Relevant theory on liquid-liquid flows is presented in the literature review section together with a general description of OLGA 6.0. The Two-Fluid Model will also be addressed being the model of choice for the simulator engine. The experimental laboratory is described in detail to enable an accurate reconstruction or continuing of the experiments at a later point in time. It contains layouts of the test-loop and supporting sections, measurement devices, fluid data and procedures for running and calibration.

Flushing times, OLGA 6.0 predictions and the oil front, being an important parameter, are discussed in the analysis section. The foundation of the discussion is the water holdup vs. time plots collected from the experiments. These are attached to Appendices A to C, and shows data for oil superficial velocities between 0.02m/s - 0.8m/s for a .5-degree inclined, declined and horizontal test rig setup. As additional support, picture collages of the development of oil front shape and plots of oil front velocities along the pipeline are also presented. All raw data is handed over to the Department of Energy and Process Technology.

OLGA 6.0 shows good predictions to the oil-water flushing scenario for all oil superficial velocities above 0.14m/s. An oil $U_{sl} \geq 0.3 m/s$ was needed to fully flush the water from both the test section and flexible outlet. The fastest flushing times within the Chevron specified velocity interval; are 30s, 48s and 51s for .5-degree declined, horizontal and .5-degree inclined setup respectively. For holdup vs. time curves showing no water for velocities below 0.3m/s a considerable amount of water is usually still concentrated in the outlet section. For oil $U_{sl} < 0.14 m/s$ where water is not flushed, is when OLGA 6.0 shows the most deviance to experimental results. The differences in registered and predicted holdups here are generally around 20-40%.

Sammendrag

Denne masteoppgaven er i all hovedsak rettet mot å ekstrahere eksperimentelle data på olje-vann flushing, begge i væskefase. Det vil også gjøres en evaluering på hvor godt flerfasesimulatoren OLGA 6.0 klarer å reprodusere resultater fra eksperimentene. Utgangspunktet for oppgaven kommer av en forespørsel fra Chevron. De trenger forsøksdata for å kunne diskutere hvorvidt etylen-glykol eller etanol kan anvendes til å flushe vann ut av jumper rør offshore. I tillegg er ideen å produsere en stor nok mengde data til å kunne brukes som referanse senere ved Institutt for Energi-og Prosessteknikk, til å programmere egne flerfasesimulatorer.

For å få en komplett og enkeltstående oppgave, er teorien rundt to fluid modellen samt beskrivelsen av lab oppsettet hentet direkte fra forløperen til denne masteroppgaven [10]. OLGA 6.0 utgaven bruker to fluid modellen i sin beregningsalgoritme og lab oppsettet er beskrevet nøyaktig nok til at eksperimentene skal kunne reproduseres.

Analysen er bygget opp rundt plottene av vann holdup vs. tid plottene for forsøk og simuleringer, som er vedlagt i Appendiks A til C. Gjennom disse diskuteres flushetider, oljefronter og OLGA 6.0 prediksjoner for superficielle oljehastigheter fra 0.02m/s til 0.8m/s. Testene er kjørt for test loop innstillinger på en halv grad stigning og helning samt horisontalt. Resten av Appendiksene inneholder visuelle data på oljefrontens formutvikling mens den passerer gjennom test seksjonen, og trendplott på hvordan den forandrer hastighet fra innløp til utløp.

For å fullstendig tømme testseksjonen og det fleksible utløpet må det brukes superficielle oljehastigheter på minst 0.3m/s. Innenfor intervallet Chevron har spesifisert, er de raskesete flushetidene 30s, 48s og 51s for hhv. for en halv grad helning, horisontal og en halv grad stigning. OLGA 6.0 simulatoren er også funnet til å egne seg bra til å beregne olje-vann flushing så lenge ikke vannholdup ligger igjen i testseksjonen. For oljehastigheter under 0.14m/s klarer ikke oljen å spyle ut alt vannet og forskjeller mellom registrert og predikert holdup ligger generelt mellom 20-40% i dette området.

Introduction

This thesis continues the work initiated in the autumn of 2008, listed as [10]. Much of the introduction as well as the main body of the literature review and lab description are extracted from [10] and presented here to minimize reader effort and provide continuity. The assignment originates from a request made by Chevron to provide data on liquid-liquid flushing. Numerical and visual data collected will be used for evaluating removal of seawater from jumper pipelines at off-coast production facilities. Chevron is one of the world's largest integrated energy companies with history tracing back to 1879 and its main focus is within the oil and gas industry. Headquartered in San Ramon, California, they conduct business in more than 100 countries and have an estimated 60000 employees worldwide [11].

A jumper pipeline is the pipeline connecting the wellhead with the manifold. The manifold, which collects the flow from several jumpers, then transports the production flow from the seabed to the surface for refining. A vital characteristic with the jumper is its capability of being physically de-installed and moved from one wellhead to another within its reach from the manifold. It is common for an offshore platform to experience such a procedure at least once a year. During these procedures however, the pipe-inlet will be freely exposed to the surrounding seawater, which will intrude into the pipeline.

Water creates a potential operational hazard in oil and gas production being one of the main elements in hydrate creation. Hydrates is much like ice in physical appearance, one of the differences in properties being it is much more adhesive. Due to its sticky nature hydrate particles easily accumulate in bends and narrow-ins creating plugs that halt production thus making it a very costly issue indeed. It was industrially discovered in 1934 when it was found blocking North American natural gas pipelines and is created by water molecules merging with light hydrocarbons making a crystalline structure. When water and oil is present, the pressure-temperature relationship becomes important and hydrates have even been registered at temperatures up to 30 ^{o}C at sufficient pressure. Following installation of a jumper pipeline at a new wellhead, the accumulated seawater will have a low temperature. Combined with the pressure induced at production start-up, we get a low temperature/high-pressure situation somewhere within the hydrate creation area illustrated in Figure 1.

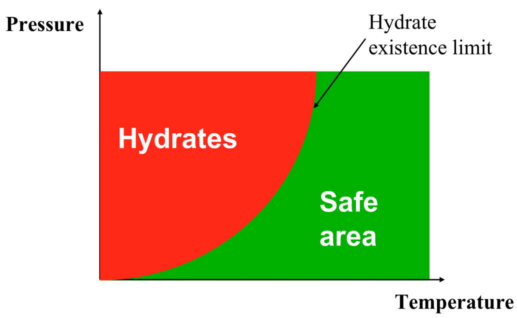


Figure 1 Left - Temperature – pressure relationship in hydrate creation.

With water, light hydrocarbons (methane, ethane, propane and butane), pressure and temperature being the four ingredients for creating hydrates, water and temperature are for the time being the easiest elements to manipulate in order to prevent hydrates from forming. I.e. electrical heating of pipelines, isolation, chemical inhibitors acting on the surface of the water molecules preventing them from accumulating, drying or water removal by flushing.

The scenario to which we are providing experimental data is where a 1km flexible jumper is being frequently installed/de-installed at one of Chevron's offshore sites outside the coast of Brazil. They wish to use flushing to completely remove the accumulated seawater before production start up and want to know the minimum injection flow rate required to remove the water and the time needed to complete the flushing. The procedure is conducted by attaching an injection line to the jumper pipeline at the connection point to the well using either ethylene glycol or ethanol as a flushing medium. With a maximum injection flow rate around 30gpm, this translates into an inlet speed of 0.67m/s and establishes a transient two-phase flow system where a static phase is displaced by a continuous phase. Due to the low injection flow rate the flow is most likely to be laminar in both phases. Also to be evaluated is the effect of the jumper geometry on the flow regimes during flushing.

The experimental and visual data on liquid-liquid phase displacement will be collected on a test rig in the multiphase laboratory at NTNU Gløshaugen; where the test rig is set up to mimic the jumper pipeline in question. For simulating, the choice fell upon the well-established OLGA multiphase flow simulator, thus enabling the collection of experimental data to be prioritized. In addition to [10], which conducted the necessary calibration and produced some initial experimental results for low flow rates. Other work of close relevance is [2] where three earlier versions of OLGA are reviewed. A summary of important findings from these reports will be presented in the Analysis section.

1 Litterature Review

In the following experiments oil will be flushing water out of a test pipeline in the lab. This will create a multiphase situation with a static liquid phase (water) being removed by a continuously flowing liquid-phase (oil).

Liquid-liquid flows have not been explored to the same extent as gas-liquid flows and many of the concepts related to the latter cannot readily be applied to liquid-liquid systems. The decisive differences being low density-differences in liquid-liquid flows and oil and oil-water emulsions sometimes show Newtonian or non-Newtonian rheological behaviour [1].

This chapter will give a short description of some general flow patterns in liquid-liquid flows, the two-fluid model and background for OLGA v6.0. The flow pattern and two-fluid model theory is mostly extracted from [2]. For further details on this subject the reader is encouraged to further exploring [2] and the references made there.

1.1 Flow patterns in horizontal Oil-Water flow

Knowledge of the flow patterns that occurs in a system is essential when it comes to deciding the right model of calculation. Flow pattern is the term used to describe the geometrical characteristics fluids may show during multiphase flow. Each of these patterns has a different influence on properties like the pressure gradient, in situ hold-up, heat transfer coefficient and corrosion of the pipe, which are implemented in the mathematical models. [2] Extracted from her references, Arnulf [2] has presented the following six patterns for horizontal oil-water flow:

1. **Stratified flow**
   a. Stratified smooth/wavy
   b. Stratified with mixing at the interface

2. **Dispersed flow**
   Water continous flow:
   a. Dispersed oil-in-water & water
   b. Oil-in-water emulsions
   Oil continous flow:
   c. Dispersed water-in-oil & oil-in-water
   d. Water-in-oil emulsions

1.1.1 Stratified flow

In stratified flow gravity is more dominant than the mixing forces and the fluids form layers in the pipe according to their density. This flow pattern exists only for horizontal or near horizontal flow. The two types of stratified flow are described as follows:

1-a Stratified smooth: In this flow pattern the interface is observed as smooth at low flow rates.

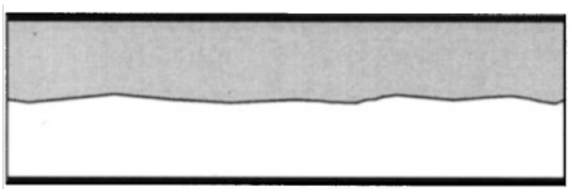


Figure 2: Stratified smooth oil-water flow, Fairuzov [3].

1-b Stratified with mixing at the interface: This is stratified flow with droplets of the opposing phases accumulating near the interface. As the flow rates increases, the relative movement between the phases will create small waves and initiate vortex motions around the interfacial area, which will cause droplets from each phase to tear off and venture a short distance into the opposing phase. By increasing the flow rates further, the flow disperses.

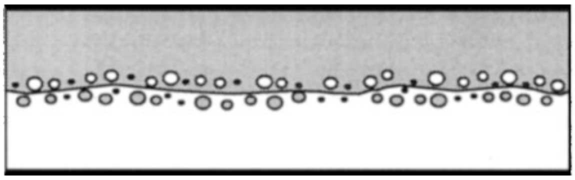


Figure 3: Stratified oil-water flow with mixing at the interface, water droplets in oil phase and oil droplets in water phase, Fairuzov [3].

1.1.2 Dispersed flow

In dispersed flow, the dynamic mixing forces are now dominating and with the relative phase fraction sufficiently high, this leads to one of the phases dispersing into the other across the pipe. Dispersed flows are divided into two mains; water continuous and oil continuous:

2-a Dispersed oil-in-water & water: When the water flow rate is sufficiently larger than that of the oil, the oil disperses into the water phase. Despite the increased influence from the mixing forces, gravity still play a little part as stratifying force and the oil will accumulate in the upper section of the pipe.

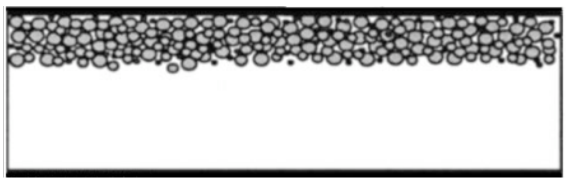


Figure 4: Dispersed oil-in-water & water, Fairuzov [3].

2-b Oil-in-water emulsions: If the water flow rate is increased further, this will decrease the separating effect of gravity relative to the dynamic mixing forces and the oil will therefore disperse more evenly over the pipe cross section.

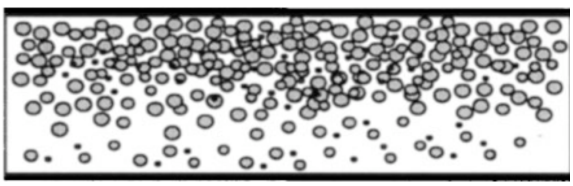


Figure 5: Oil-in-water emulsions, Fairuzov [3].

1.1.3 Oil continuous flow

2-c Dispersed water-in-oil & oil-in-water: With the oil flow rate sufficiently larger than that of water, droplets will be torn off both phases and dispersed into its opposing phase.

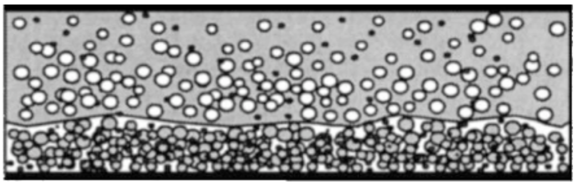


Figure 6: Dispersed water-in-oil & oil-in-water, Fairuzov [3].

2-d Water-in-oil emulsions: By further increasing the oil flow rate, the water will disperse as droplets into a continuous oil phase.

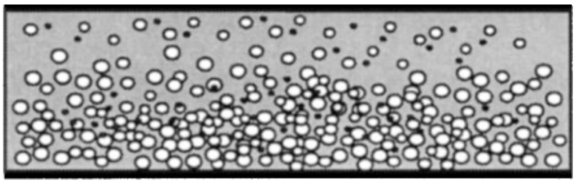


Figure 7: Water-in-oil emulsions, Fairuzov [3].

1.2 The Two-Fluid Model

This model is widely used to solve problems for two-phase separated flows and will be used to qualitatively evaluate the experimental results in this thesis. It is also the model the Olga 6.0 uses for its simulations. The general idea of the two-fluid model is to handle each phase isolated thus providing equations for conservation of mass and momentum for each separately. Special closure models for interferential shear stresses are then provided to ensure the dynamic effects between the phases are taken into account.

The situation for which the experiments conducted will be a transient liquid-liquid phase displacement as shown in Figure 8, with a possible back flow due to inclination and laminar flow rates. It is possible to split this system into a stratified section to where the two-fluid model can be applied and a bubble nose section which job is to penetrate the water. In the stratified section, displacement is mostly due to interfacial drag.

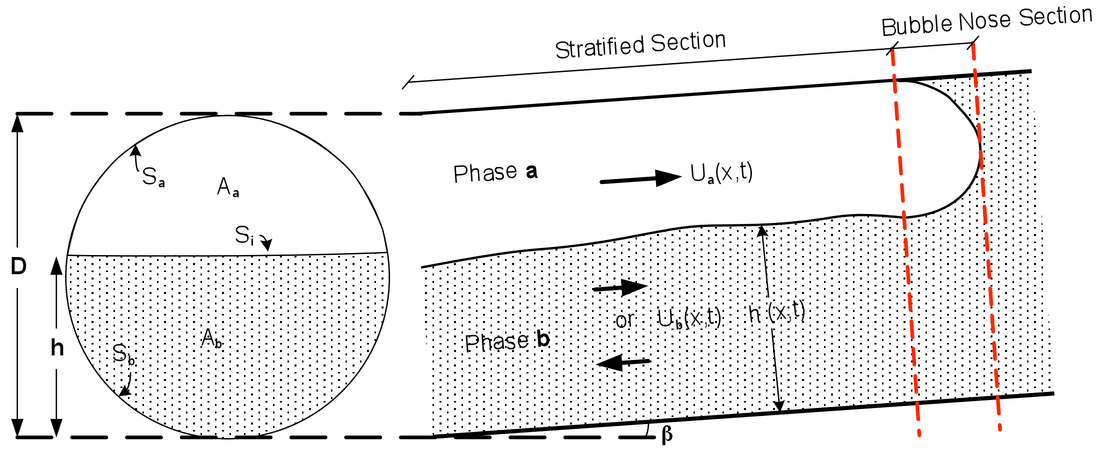


Figure 8 Transient liquid-liquid phase displacement in a near horizontal pipe.

In the following review, oil and water will be denoted as phases a and b respectively. Conservation of mass for each liquid:

$$\frac{\partial}{\partial t}(\rho_a A_a) + \frac{\partial}{\partial x}(\rho_a A_a U_a) = 0 \tag{1.2.1}$$

$$\frac{\partial}{\partial t}(\rho_b A_b) + \frac{\partial}{\partial x}(\rho_b A_b U_b) = 0 \tag{1.2.2}$$

Momentum equation for each liquid:

$$\frac{\partial}{\partial t}(\rho_a A_a U_a) + \frac{\partial}{\partial x}(\rho_a A_a U_a^2) = -\tau_a S_a - \tau_i S_i - \rho_a A_a g \sin\beta - A_a \frac{\partial P_{ia}}{\partial x} - \rho_a A_a g \sin\beta \frac{\partial h_w}{\partial x} \tag{1.2.3}$$

$$\frac{\partial}{\partial t}(\rho_b A_b U_b) + \frac{\partial}{\partial x}(\rho_b A_b U_b^2) = -\tau_b S_b - \tau_i S_i - \rho_b A_b g \sin\beta - A_b \frac{\partial P_{ib}}{\partial x} - \rho_b A_b g \sin\beta \frac{\partial h_w}{\partial x} \tag{1.2.4}$$

As Figure 8 indicates, S_a and S_b is the area of the cross section in each phase in contact with the pipe-walls, S_i being the area of the interface between the two liquids. Hence τ_a, τ_b and τ_i are the shear stresses related to the wall friction and friction at the interface.

In liquid-liquid system such as oil-water, the flow can be considered as incompressible, so the conservation of mass (1.1 and 1.2) can be rewritten as:

$$\frac{\partial A_a}{\partial t} + \frac{\partial}{\partial x}(A_a U_a) = 0 \tag{1.2.5}$$

$$\frac{\partial A_b}{\partial t} + \frac{\partial}{\partial x}(A_b U_b) = 0 \tag{1.2.6}$$

Then by adding equations 1.5 and 1.6:

$$\frac{\partial (A_b U_b)}{\partial x} + \frac{\partial (A_a U_a)}{\partial x} = 0 \tag{1.2.7}$$

Integration of 1.7 yields that the sum of the superficial velocities in the two phases is constant along the length of the pipeline:

$$U_b A_b + U_a A_a = U_m \tag{1.2.8}$$

U_m is called the mixture velocity of the two liquids and is defined as the total flow rate divided by the area of the pipeline cross-section.

The momentum equations 1.3 and 1.4 may also be combined into a single equation by eliminating the pressure drop and for steady flow conditions this gives:

$$F = -\tau_b \frac{S_b}{A_b} \pm \tau_i S_i \left(\frac{1}{A_a} - \frac{1}{A_b} \right) + \tau_a \frac{S_a}{A_a} + (\rho_b - \rho_a) A g \cos\beta \frac{\partial h_w}{\partial x} \tag{1.2.9}$$

The final touch to the model is now to apply the closure relations for the shear stresses. This may be provided by the use of friction factors for pipe flows and average velocities in the following expressions:

$$\tau_a = f_a \frac{\rho_a U_a |U_a|}{2} \tag{1.2.10}$$

$$\tau_b = f_b \frac{\rho_b U_b |U_b|}{2} \tag{1.2.11}$$

$$\tau_i = f_i \frac{\rho (U_a - U_b) |U_a - U_b|}{2} \tag{1.2.12}$$

The friction factors are given as:

$$f_a = C_a \left(\frac{\rho_a D_a |U_a|}{\mu_a} \right)^{-n_a} \tag{1.2.13}$$

$$f_b = C_b \left(\frac{\rho_b D_b |U_b|}{\mu_b} \right)^{-n_b} \tag{1.2.14}$$

The equivalent hydralic diameters for oil and water flows are often defined:

$$D_a = \frac{4A_a}{(S_a + S_i)}$$

$$D_b = \frac{4A_b}{S_b} \tag{1.2.15}$$

$$\rho = \rho_a; f_i = F_i f_a; for |U_a| > |U_b|$$

$$D_b = \frac{4A_b}{(S_b + S_i)}$$

$$D_a = \frac{4A_a}{S_a} \tag{1.2.16}$$

$$\rho = \rho_b; f_i = F_i f_b; for |U_b| > |U_a|$$

F_i is the waviness factor and is used to adjust the interfacial shear stress for influence of waves on the interface. $F_i \approx 1$ for smooth stratified flow, and $F_i > 1$ for wavy stratified flow and stratified flow with mixing at the interface.

1.3 General description of OLGA 6.0

OLGA is a commercial multiphase-flow simulator designed to calculate pressure gradients, liquid hold-up and flow pattern at user-specified sections of pipeline. It is developed and continually updated by the SPT-Group with its history of creation tracing back to the mid-eighties [7]. Compared to its predecessors Olga 6.0 has announced an improved ability to predict oil-water flows. Especially important is the implementation of an interfacial level gradient, which allows a more accurate handling of oil-water interaction.

1.3.1 Implementation of the Two-Fluid Model by OLGA 6.0

OLGA 6.0 implements a mechanistic two-fluid model with three momentum equations. This gives one for the gas field, one for the continuous hydrocarbon liquid field and one for the continuous water field. In addition there are corresponding equations for the conservation of mass (including liquid droplets) and one energy equation assuming homogenous temperature for all phases. The interaction between the phases is accounted for in the closure model for shear stresses and slip relation implemented in the equation system [6].

The water flushing experiments in consideration consists of the two phases, oil (Marcol 52) and water, making up an immiscible liquid-liquid two phase flow system. The equations below are the general expressions for momentum- and mass conservation used by OLGA 6.0 and is extracted from [12].

Conservation of mass:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \frac{\partial}{\partial z}(\alpha \rho_k U_k) = \sum_{k \neq l} \psi_{kl} + G_{Sk} \qquad (1.3.1)$$

$$k \in [g, o, do, od, w, dw, wd]$$

Where

α	: volume fraction
ρ	: density
A	: pipe cross section area
U	: mass velocity
ψ	: mass transfer between phases (equal to zero for the flushing case)
G_S	: external mass source (equal to zero for the flushing case)
k	: mass index (gas; oil : continuous, oil droplets in gas, oil dispersed in water; water : continuous, water droplets in gas, water dispersed in oil)

Momentum equation:

$$
\begin{aligned}
&\frac{\partial}{\partial t}\sum_{k\in kj}(\alpha_k\rho_k U_k)+\frac{\partial}{\partial z}\sum_{k\in kj}(\alpha_k\rho_k U_k U_k) \\
&\qquad = -\sum_{k\in kj}\left(\alpha_k\frac{\partial p}{\partial z}\right)+\sum_{k\in kj}\alpha_k\rho_k g\sin\beta+\Gamma_{ILG} \qquad (1.3.2)\\
&\qquad -f_j^w U_j-\sum_{l\notin j} f_{lj}^i U_{lj}-f_j^c-\sum_{l\notin j} f_{lj}^c U_l+\sum_{l\notin j}\Phi_{lj}+\sum_{k\in kj} G_{Sk}U_k
\end{aligned}
$$

Where,

p	: Interfacial pressure
β	: Pipe inclination angle
Γ_{ILG}	: Interfacial level gradient term (for horizontal and inclined pipe)
$f^{w/i/c}$	: Friction factor (the superscripts *w*, *i* and *c* indicate wall, interfacial and other flow regime other than segregated, respectively)
U_{lj}	: Slip velocity between phases
Φ	: Momentum contribution from deposition and entrainment of liquid droplet (equal to zero for the flushing case)
kj	: Set of masses contributing in phase, Gas, kj = g, do, dw (gas, oil droplets and water droplets) Oil, kj = oc, wd (oil continuous, water dispersed in oil) Water, kj = wc, od (water continuous, oil dispersed in water)
k,l,j	: Mass index

Additional governing equations typically solved in OLGA, i.e. pressure and energy equations are irrelevant to be discussed in isothermal-incompressible cases.

2 Description of the experimental rig and procedures

The continuous flow loop is generally outlined by Figure 9 and consists of a test section, a fluid supply section and a separation section dispatched over two floor levels. Three phases, air, water and oil can be circulated simultaneously in the loop.

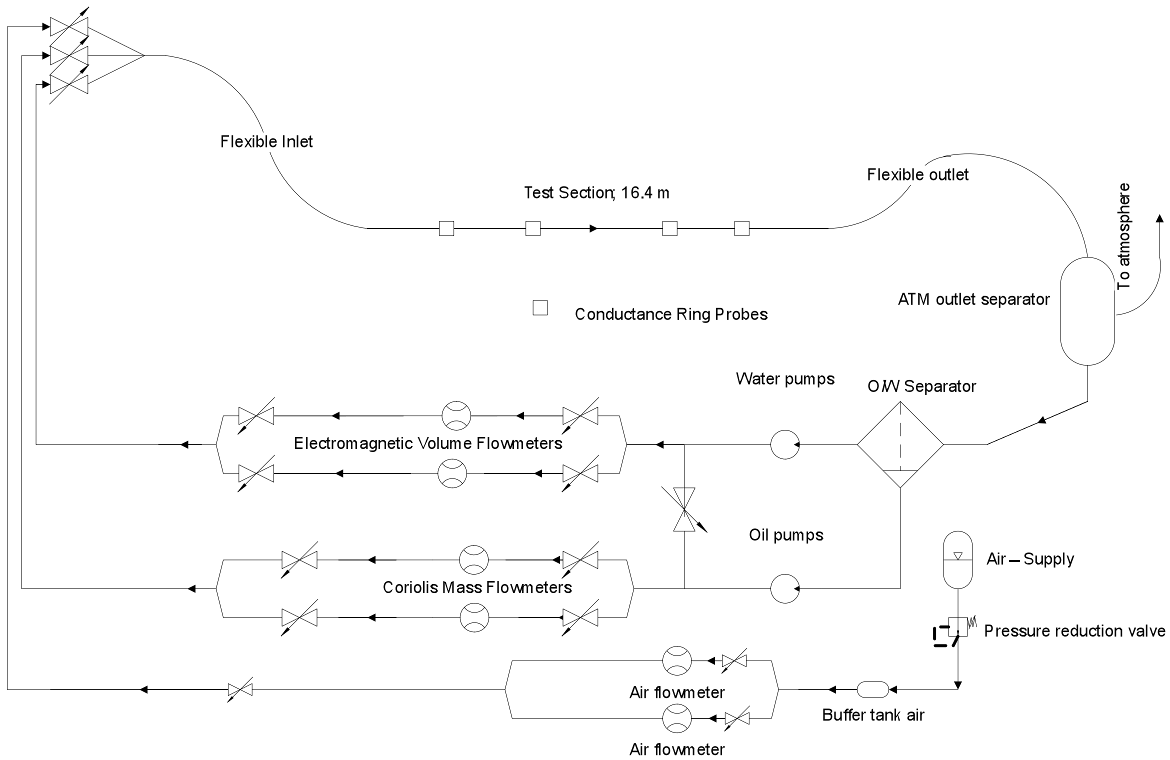


Figure 9 – Schematics showing the experimental loop.

2.1 The fluid supply section

The fluid supply section, schematics shown in Figure 10, contains a range of different pumps and pipelines to allow flexibility in adjusting the flow rate of the oil and water phases. The pump specifics are presented in Table 1 and Table 2. After passing through the pump the two phases, still separate, will be transported through either a D1 (21,3mm) or a D2 (60,3mm) pipeline. Here their volumetric flow rates can be measured before they continue towards the test section.

The air is supplied from a pressure tank at 7barg, which then transports the air through a pressure reduction valve to a buffer tank at 3barg before continuing to either a D3 (15mm) or a D4 (40mm) pipeline where volumetric flow is measured.

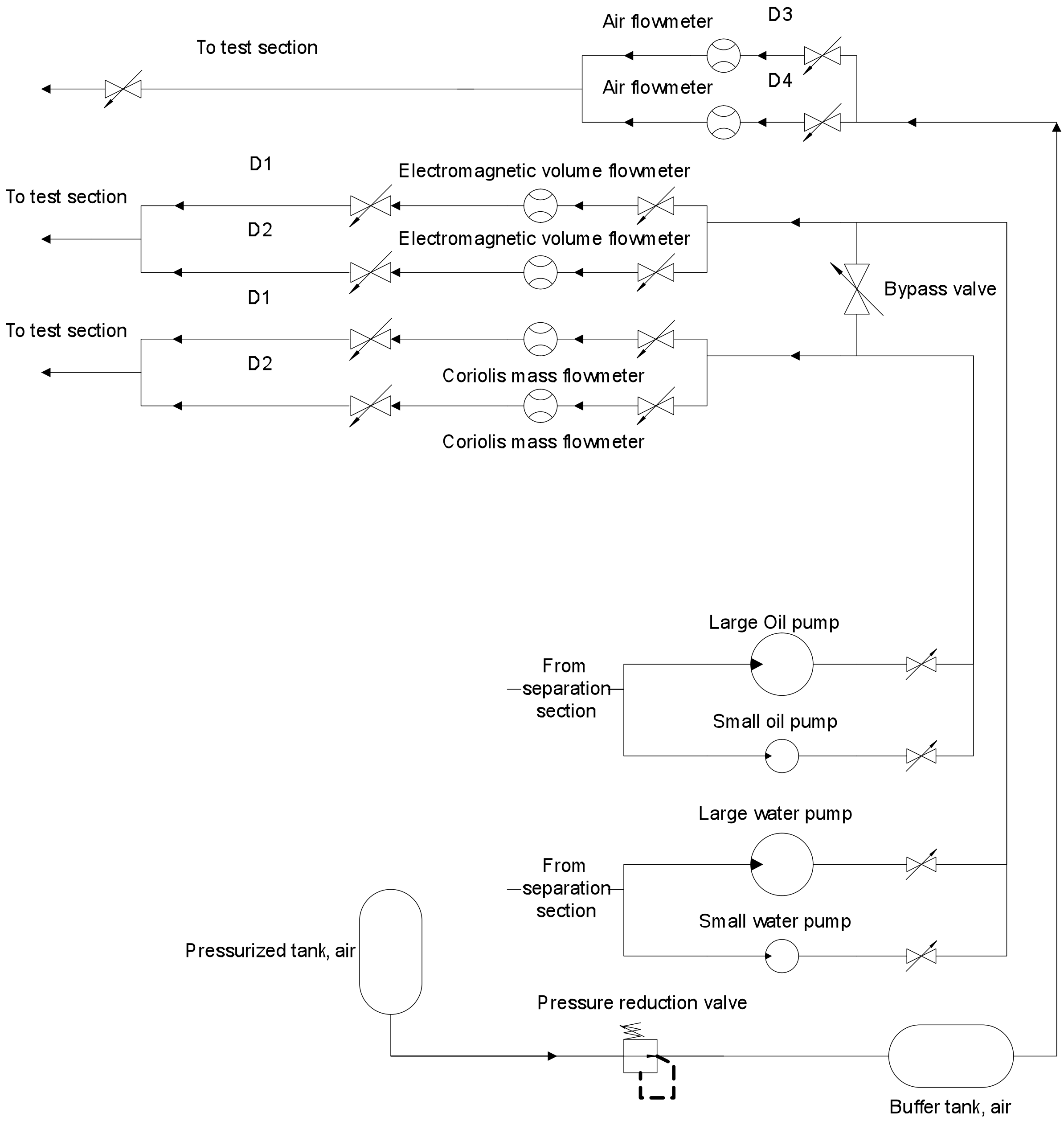


Figure 10 – Schematics showing the layout of the supply section of the experimental loop

	Small Water Pump	*Large Water Pump*	*Dosage Pump*
Name	Grundfoss	Gustavsberg C100-35	Prominent SIGMA 12090 PVT
Type	Centrifugal	Centrifugal	Displacement (Diaphragm)
Range (l/min)	Unknown	Unknown	0.048 – 1.661
U_{SW}	Unknown	Unknown	$0.3\cdot10^{-3} - 9.8\cdot10^{-3}$

Table 1. Manufacturing details on the water pumps, Chupin [4].

	Small Oil Pump	*Large Oil Pump*	*Dosage Pump*
Name	Grundfoss CR 8-30	Grundfoss CR 64-1	Displacement (Diaphragm)
Type	Centrifugal	Centrifugal	
Range (l/min)	99.7 – 199.5	498.7 – 1413.0	0.064 – 1.620
U_{SO} (m/s) [a]	0.59 – 1.18	2.94 – 8.34	$0.4 \cdot 10^{-3} - 9.5 \cdot 10^{-3}$

Table 2. Manufacturing details on the oil pumps Chupin [4].

2.2 The test section

The test section is set up to mimic the real jumper pipeline. The main part of the test section is the 15.11 meter straight made up of 17 acryl pipes mechanically linked together by bolts. Acryl was chosen to allow visual documentation of the flow. As illustrated by Figure 11, there are four conductance ring probes connected at the indicated positions for measuring real-time water holdup. The main straight is adjustable and is for this thesis being used for the three different elevations, .5-degree incline/decline and horizontal. At the flexible inlet Figure 12, three manual valves control the separate phases arriving from the fluid supply section. The outlet consists of a flexible pipeline, Figure 13, after which the flow continues to the separation section.

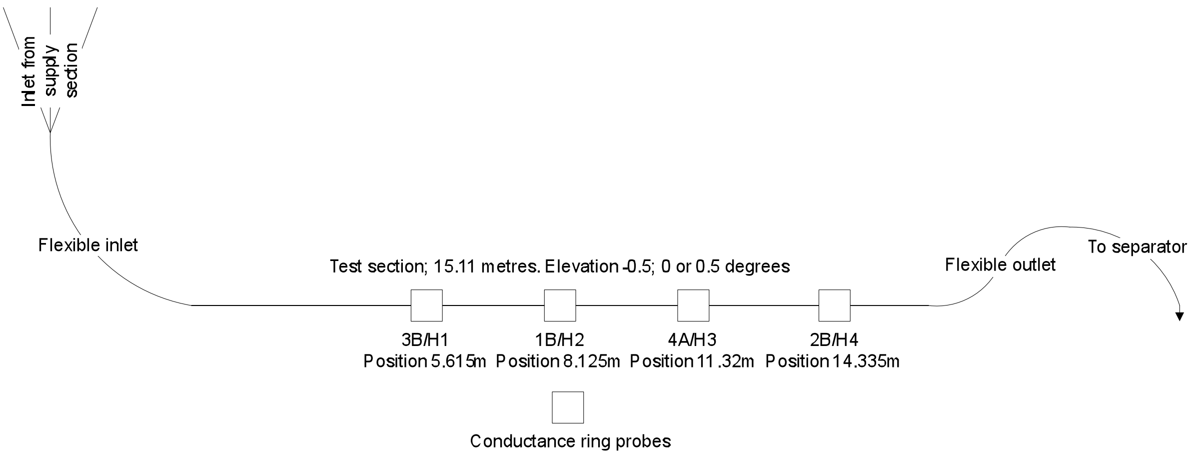


Figure 11 – Schematics showing the test section.


Figure 12. Flexible inlet configuration. **Figure 13 Flexible outlet configuration.**

2.3 The separation section

The separation section contains two separators. The first is placed at the end of the test section where air and oil fumes are separated from the liquids and vented into the atmosphere at 1bara and ambient temperature. From this tank, the remaining oil and water continues down one floor to a large separation tank where the two liquid phases get separated by gravity.

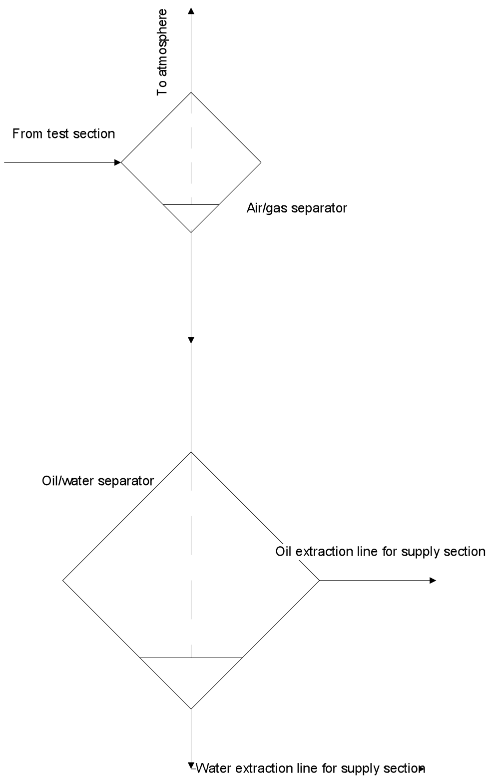


Figure 14 – Schematics showing the separation section.

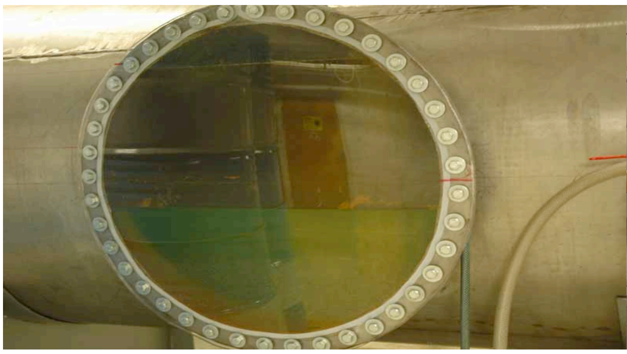


Figure 15. Oil/water separator. Water seen as green.

Figure 16 Air/gas separator.

2.4 Choice of fluids for the experimental runs

As mentioned in the introduction, ethylene glycol and ethanol are two very common flushing mediums and are therefore the ones in question. For practical reasons filtered tap water (green in colour) and a white mineral oil with production name Marcol 52 will be used instead, in this case to mimic ethanol. The difference in density between the water and the oil closely resembles that of seawater vs. ethanol.

Property	Density [Kg/ m^3]	Dynamic viscosity [$N \cdot \frac{s}{m^2}$]	Comment
Water	998.0	1.00 E-3	p = 1bara, T = 293K
Marcol 52	829.0	11.0 E-3	p = 1bara, T = 293K
Ethanol	789.0	1.20 E-3	p = 1bara, T = 293K

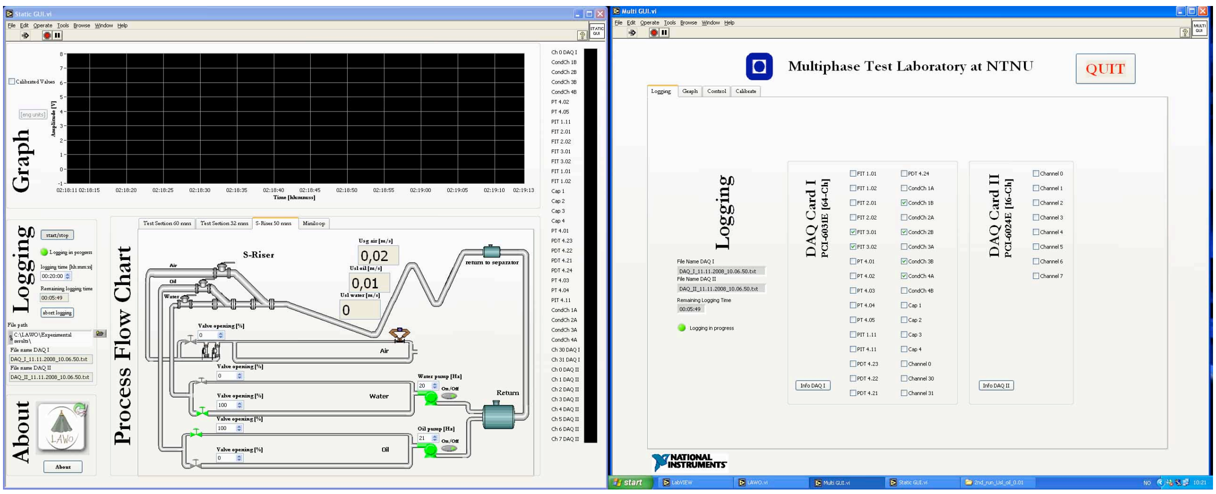
Table 3. Data for Marcol 52 and water.

2.5 Data acquisition by LAWO

The data recorded from an experimental run is as follows:

1. Water holdup in 6 cm test section.
2. Mass flow rate for the oil.

These values are logged real-time with a computer interface called lawo. Lawo is a program written in labview by a group of engineering students from HIST which translates the signals from the measurement devices in the experimental loop to numerical data and records it to a .txt-file on the computer. On the right side in Picture 1 is the list of measurement devices connected to the loop and from here they can be activated/deactivated by the checkboxes. On the left side is a rough outline of the experimental loop where it is possible to remotely activate the pumps and inlet valves to the test section while the logging values are shown as real-time graphs in the upper part of the screen.



Picture 1 – Screenshot of lawo interface.

Fluid	*Name*	*Type*	*Range*	*Usl*	*Accuracy*
Water	Endress & Hauser Promag 33	Elmag	0.053-0.987 l/s	0.02-0.35	0.5%
Water	Fisher – Porter COPA XM Series 3000	Elmag	0.83-10 l/s	0.29 – 3.53	0.5%
Oil	Micromotion F025	Coriolis	100-1000 kg/h	0.01-0.09	0.2%
Oil	Micromotion T150	Coriolis	1000-3600 kg/h	0.09-4.91	0.15%

Table 4 - Details on flowmeters used for oil and water phases, Chupin [4]. Usl = oil superficial velocity

2.6 Procedures for running of the experimental loop

The experiments conducted in the test loop are capturing steady state flow values. The procedures presented below are for ensuring steady state conditions when logging starts. Each experiment was also done twice to be able to cross-reference the registered data.

2.6.1 Start up procedure

1. Pressurize the air-supply section by opening valve from pressure tank
2. Activating the necessary supply pipelines for water and oil to reach the correct flow range.
3. Walk through the loop visually controlling the valves.
4. Continue the start up in LAWO
    a. Setting logging frequency to 50Hz.
    b. Activate the measurement devices attached to the selected supply lines and test section.

2.6.2 Experimental procedure

1. Fill test section with water and then close manual water valve at the flexible inlet.
2. Set %-opening on valve and pump frequency for the oil supply section, corresponding to Usl for the current experiment.
3. Choose time interval for data logging.
4. Name folder to where the data will be stored in .txt files for easy access later.
5. Wait for visual confirmation in direct-feed LAWO graphs for steady state on oil flow before opening manual oil valve at the flexible inlet to start the flushing.
6. Start logging interval.
7. When the logging interval has finished, start readying for next experimental run by:
    c. Flushing test section with water to rid of oil.
    d. Drying/flushing test section with air until the test section is completely free of oil and water.
    e. Repeat from 1.

2.6.3 Shutdown procedure:

1. Flushing the test section with water to remove oil leftovers on pipeline walls.
2. Flushing/drying the test section with air to until totally rid of oil and water.
3. Shutting down pumps and closing electrical valves through LAWO.
4. Closing all manual valves at the flexible inlet.
5. Closing valve from pressure tank connected to air-supply section.

2.7 Calibration

The calibration of the conductance rings and flow meters was conducted in [10]. With the only difference between the two setups being the fixed outlet being replaced with a flexible, no further calibrations were made.

3 Analysis

Numerical and visual data has been collected on water flushing for a .5-degree inclined, -declined and horizontal test rig setup, within an oil superficial velocity interval of 0.02m/s-0.8m/s. The water holdup vs. time plots collected through experiments and simulations (Appendix A to C) are the basis for the analysis and the main issues addressed will be flushing times, oil front properties and how simulations conducted in OLGA v.6.0 corresponds to these. Assumptions and boundary conditions for the simulations are also described in this section. All raw data collected will be handed over to the Department of Energy and Process Technology represented by Prof. Ole Jørgen Nydal to be available as reference in programming models on liquid-liquid flows.

In [10] it was concluded that in a .5-degree setup, water would not be fully flushed from the test section for oil superficial velocity$\in [0.012m/s, 0.11m/s]$. The experiments were done with a fixed outlet with a relative elevation of 3.9degrees. These results will be used together with a qualitative experiment to evaluate whether the outlet elevation influences the water holdup in the 15.11m test section. An important observation in the measurements was the tendency of the H4 holdup-curve to cross H3 and H2. Before the experimental runs this spring, laser measurements exposed local geometrical differences in the acryl pipelines around H4 as the possible reason. Mechanical adjustments to correct elevation were sufficient to eliminate the error.

In [2], three earlier versions of OLGA; OLGA, Opus and Opus2, were applied to an oil-water flushing scenario. The OLGA engine was based on the drift flux model, whereas the Opus and Opus2 were using the two-fluid model much like OLGA v6.0. It was concluded that the two-fluid model approach were the best suited for the simulations. In addition an explicit numerical solution was favoured to an implicit solution, in replicating the oil front shape.

3.1 OLGA 6.0 Simulation procedure

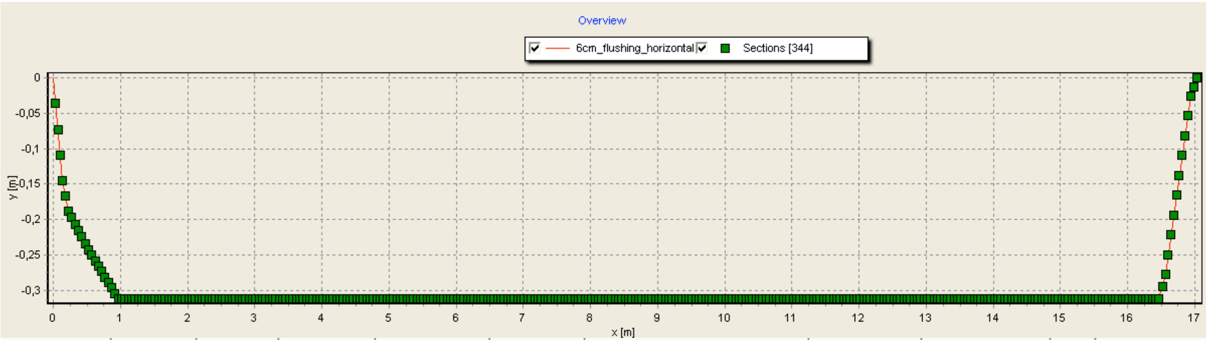
To mimic the experiments a source providing a constant mass flux of Marcol 52 was placed at calculation node 1 in “Inlet_1” (see tables in Figure 17 to Figure 19) in the case-defined geometries. The average mass flow was extracted from the logging in each experiment and used as the source-parameter in the corresponding simulation. A first-degree numerical explicit solution was chosen, after the conclusion in [2].

3.1.1 Fluid properties and phase equilibrium for Marcol 52 and Water

Temperature and pressure variations are assumed to have negligible effect on the fluid properties as well as there is also assumed to be no mass transfer between the phases. These assumptions are based upon a rather constant temperature around 293K with the pressure ranging from 1-1.5atm in the experimental runs. Calsep PVTSim v.18.0 is used to produce the fluid properties and phase equilibrium table as function of temperature and pressure to be utilized in the OLGA 6.0 simulations. The water-properties are set to pure H_2O while the data to represent Marcol 52 are created manually.

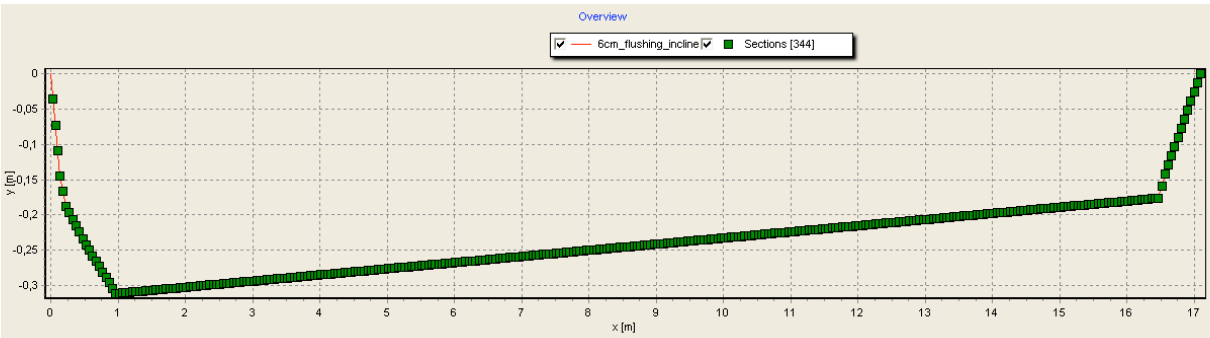
3.1.2 Geometries used; inclined, declined and horizontal

Simulations were run for the three geometries presented in Figure 17 through Figure 19 to predict the experimental results for the -0.5; 0; 0.5-degree setups. The green dots visualizes the calculation points for OLGA and whilst the corresponding tables shows the numerical details of the geometries.



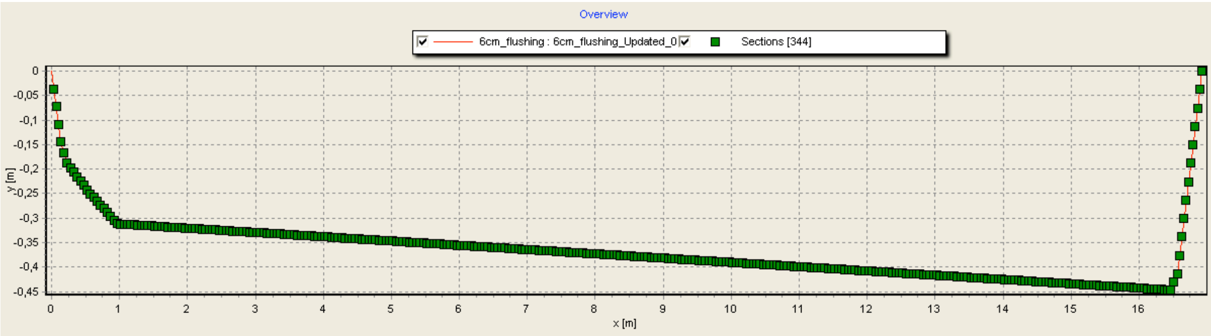
Pipe	x [m]	y [m]	Length [m]	Elevation [m]	# Sections	Length of sections (list [m])	Diameter [m]	Roughness [m]	Wall	# Equi. Pipes
Start Point	0	0								
Inlet_1	0,137671	-0,14507	0,199997	-0,14507	4	4:0,0499991	0,06	1e-005		
Inlet_2	0,227929	-0,18813	0,100003	-0,04306	2	2:0,0500017	0,06	1e-005		
Inlet_3	0,522906	-0,2428	0,3	-0,05467	6	6:0,0500001	0,06	1e-005		
Inlet_4	0,967609	-0,31164	0,45	-0,06884	9	9:0,05	0,06	1e-005		
Inlet_5	1,06761	-0,31164	0,100001	0	2	2:0,05	0,06	1e-005		
Test_section	16,0676	-0,31164	15	0	300	300:0,05	0,06	1e-005		
Outlet_1	16,4676	-0,31164	0,4	0	8	8:0,0500002	0,06	1e-005		
Outlet_2	16,5616	-0,27744	0,100028	0,0342	2	2:0,05	0,06	1e-005		
Outlet_3	16,9346	-0,0258	0,449946	0,25164	9	9:0,0499996	0,06	1e-005		
Outlet_4	17,0312	-8e-005	0,0999654	0,02572	2	2:0,0499827	0,06	1e-005		

Figure 17 Geometry with corresponding numerical values for horizontal setup



Pipe	x [m]	y [m]	Length [m]	Elevation [m]	# Sections	Length of sections (list [m])	Diameter [m]	Roughness [m]	Wall	# Equi. Pipes
Start Point	0	0								
Inlet_1	0,137671	-0,145075	0,2	-0,145075	4	4:0,05	0,06	1e-005		
Inlet_2	0,227929	-0,188126	0,0999995	-0,043051	2	2:0,05	0,06	1e-005		
Inlet_3	0,522906	-0,242797	0,300001	-0,054671	6	6:0,05	0,06	1e-005		
Inlet_4	0,967609	-0,31164	0,45	-0,068843	9	9:0,05	0,06	1e-005		
Inlet_5	1,06761	-0,31077	0,100005	0,00087	2	2:0,0500024	0,06	1e-005		
Test_section	16,067	-0,179868	15	0,130902	300	300:0,05	0,06	1e-005		
Outlet_1	16,467	-0,17638	0,400001	0,00348796	8	8:0,0500002	0,06	1e-005		
Outlet_2	16,561	-0,14218	0,1	0,0342	2	2:0,05	0,06	1e-005		
Outlet_3	16,9957	-0,02571	0,449994	0,11647	9	9:0,0499993	0,06	1e-005		
Outlet_4	17,0923	0,000174	0,100008	0,025884	2	2:0,0500039	0,06	1e-005		

Figure 18 Geometry with corresponding numerical values for .5-degree inclined setup



Pipe	x [m]	y [m]	Length [m]	Elevation [m]	# Sections	Length of sections (list [m])	Diameter [m]	Roughness [m]	Wall	# Equi. Pipes
Start Point	0	0								
Inlet_1	0,137671	-0,145075	0,2	-0,145075	4	4:0,05	0,06	1e-005		
Inlet_2	0,227929	-0,188126	0,0999995	-0,043051	2	2:0,05	0,06	1e-005		
Inlet_3	0,522906	-0,242797	0,300001	-0,054671	6	6:0,05	0,06	1e-005		
Inlet_4	0,967609	-0,31164	0,45	-0,068843	9	9:0,05	0,06	1e-005		
Inlet_5	1,0676	-0,31251	0,0999948	-0,00087	2	2:0,05	0,06	1e-005		
Test_section	16,177	-0,44436	15,11	-0,13185	302	302:0,0500331	0,06	1e-005		
Outlet_1	16,467	-0,4469	0,290011	-0,00254	6	6:0,0483311	0,06	1e-005		
Outlet_2	16,561	-0,4135	0,0997575	0,0334	2	2:0,0498788	0,06	1e-005		
Outlet_3	16,858	-0,07519	0,450181	0,33831	9	9:0,0500193	0,06	1e-005		
Outlet_4	16,9239	-9e-006	0,099975	0,075181	2	2:0,0499974	0,06	1e-005		

Figure 19 Geometry with corresponding numerical values for .5-degree declined setup

3.2 The oil front

The shape and velocity of the oil front are important parameter in determining the shape of the holdup vs. time curves. To illustrate, Figure 20 and 21 shows an oil front passing through the conductance rings at position H2 in the test rig with the corresponding excel-plot. The first steep fall is created when the front first breaches the cross section covered by the conductance ring, then the curve smoothes out as the water is gradually flushed. The oil front below has three bubble-like shapes in front, which is seen to create a zigzag pattern on the interface. In Figure 21, this is seen as the interference immediately after the first steep holdup-drop where the plot takes a sudden climb.

Figure 20. Oil front at Usl= 0.49m/s, .5-degree decline.

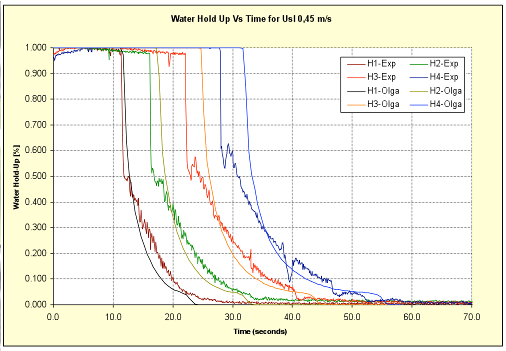


Figure 21. Holdup vs. Time curve corresponding to Figure 20.

Through visual observation, the oil front-shape is seen to develop through the whole 15.11m test section. Appendix F and G shows picture collages of oil fronts at four different velocities at .5-degree declined and .5 degree inclined setup. As the front travels down the pipeline it stretches out, being less steep at H4 than H1. This is also possible to view in the holdup vs. time plots, where the initial drop is larger for the H1-curve than the H4-curve indicating a larger front.

The oil front velocity is generally found to be decreasing on its way through the test section and the total drop increases continually with the increase in superficial oil velocity. To illustrate, Figure 22 shows oil front velocities at different experimental runs. Appendix D presents the plots for all setups and the OLGA 6.0 simulations. U1, U2 and U3 represent the local front velocity between measuring points H1-H2, H2-H3 and H3-H4 respectively. The velocities are given by $U = \Delta x / \Delta t$, where Δx is the distance between two adjacent conductance rings. Δt is extracted from the measurement files and is the time-difference between a chosen %-holdup at the first ring with the corresponding value at the second ring.

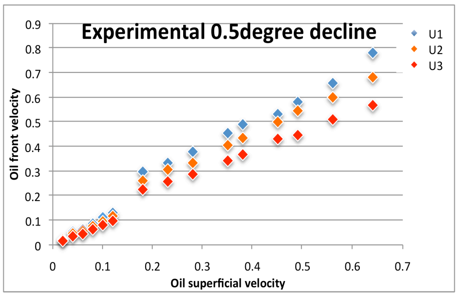


Figure 22. Oil front velocities in experimental runs for .5-degree declined setup.

The drop in oil front velocities through the test section might be related to changes in the velocity profile. As a qualitative assesment; the experimental situation is compared to a stationary system with Marcol 52 flowing through a d = 0.06m pipeline. From [13] it is given that the maximum development length for a velocity profile in a d = 0.06m pipeline is 8.28m (3.2.3). This indicates a possibility for L_e to be a deciding factor to the local velocities and through that influencing the velocity drop. It should nonetheless be investigated further to reach a definate conclusion.

$$\frac{L_e}{d} = d \cdot g(\text{Re}) \qquad \text{(Laminar)} \qquad (3.2.1)$$

$$L_e = 4{,}4 \cdot \text{Re}^{\frac{1}{6}} \qquad \text{(Turbulent)} \qquad (3.2.2)$$

$$L_{e,\max} = 138 \cdot d \qquad \text{(transition to turbulence, Re=2300 ,or } U_{sl}\text{=0.51m/s for Marcol 52)} \qquad (3.2.3)$$

Where,
d = diameter
L_e = distance from inlet to point where velocity profile is fully developed.

Another explanation of the oil front velocity drop could be that the oil pump frequency decreased during experimental runs, but no evidence of this was found. Figure 23 contains plots of voltage signals registered in flowmeters FIT 3.01 and 3.02, from two random logging sequences. These plots show a constant signal, thus eliminating the pumps as source for the velocity drops. The two pumps are not able to deliver an overlapping mass flow. As a result it causes what seems as a gap in the plot between $0.10m/s < U_{sl} < 0.20m/s$ for all test section setups. Removing information about the oil front velocity drop, the gap creates an impression of a suddenly increased loss.

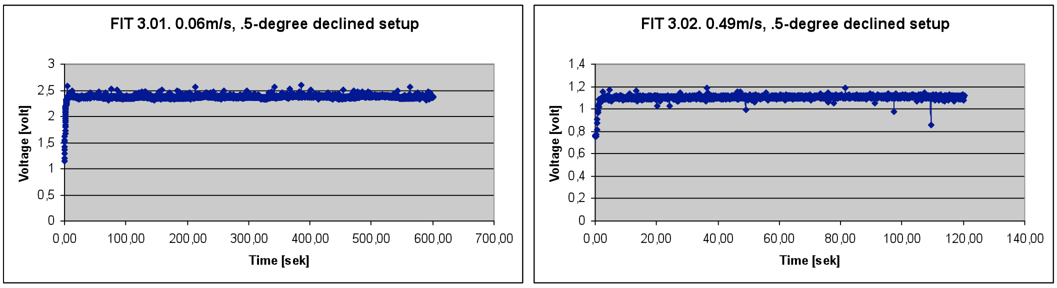


Figure 23. Voltage vs time plots for calculating mass flow measured in FIT 3.01 and FIT 3.02.

3.2.1 OLGA 6.0 predictions – oil front

OLGA 6.0 recaptures the trend in oil front velocity drop through the 15.11m test section for low flow rates. When velocity is increased the results become inconclusive, as can be seen in Figure 24. Since the specifics around the closure models used in OLGA is unknown, it is not possible to say how these would influence the results. Generally, simulations predict a lower oil front velocity than those found in corresponding experiments.

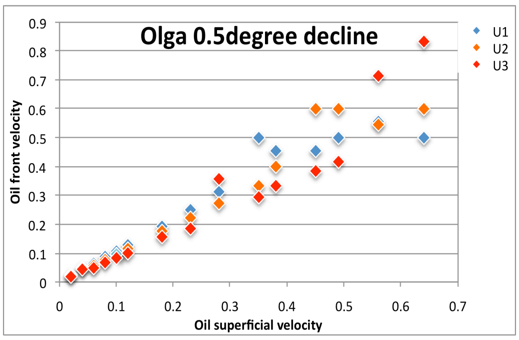


Figure 24. Oil front velocities in OLGA 6.0 simulations for .5-degree declined setup.

For the lower half of the velocity interval OLGA reproduces the shape of the front with good accuracy and around oil U_{sl}=0.4m/s the predicted front becomes larger than the experimental. A larger oil front means a steeper holdup curve which is causing the prediction of a shorter flushing time compared to simulations where the oil front is more correctly reproduced. See Figure 25 and 26 for illustration.

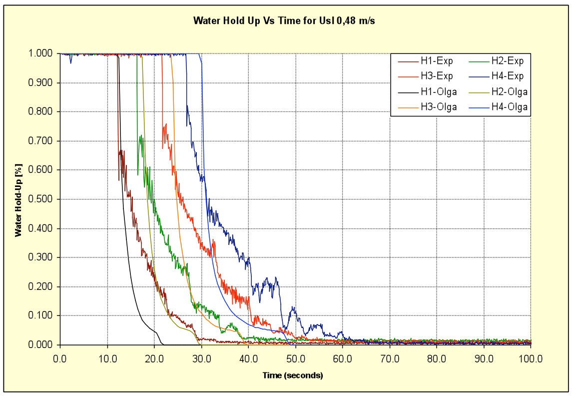


Figure 25. Holdup vs. time .5-degree inclined setup.

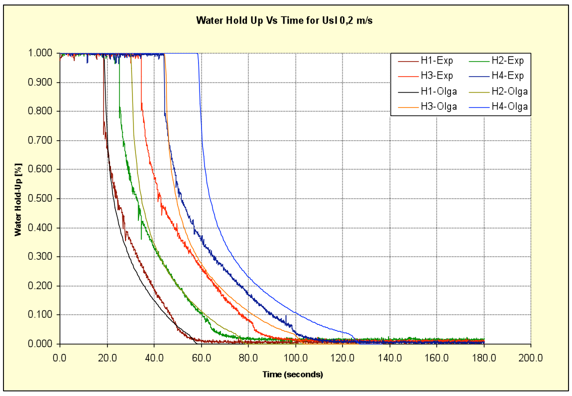


Figure 26. Holdup vs.time .5-degree inclined setup.

Generally, the difference between predicted and experienced oil front velocities is marginal for the three different test rig setups, one exception being for oil U_{sl}<0.14m/s. In this area the results for horizontal and .5-degree declined setup are closer to the experimental than the declined. Possibly indicating that a gravitational force counter acting to the direction of the flow can influence the results.

3.3 Flushing water from 15,11m test section

From the experiments it was found that the fastest flushing times within the interval defined by Chevron was around 30 seconds for U_{sl}= 0.64m/s with a .5-degree declined setup and the first oil superficial velocity to register a complete flushing from the 15.11 metres test section was at 0.1 m/s, also at .5-degree declined setup. Though the test section was fully flushed, water holdup was still present in the flexible outlet for all oil superficial velocities below 30m/s, independent of section elevation.

Table 5 contains selected flushing times for the horizontal and ±.5-degree experimental setups, starting with the first superficial velocities to fully flush the 15.11 metres straight section past the sensor at H4. The time is extracted from the “Adj. Time [s]” column in the experimental logging files when the holdup at H4 is 2%. Water level is registered with a three decimal accuracy and is never zero in any of the experiments. From just below 2% the holdup starts to decrease very slowly before settling around 0.8-0.1% at H4 and around 1.5-0.1% at H1-H3. 2% therefore acts as a calibrated zero avoiding these numerical areas. Visual data confirms the water to be flushed from the pipes, thus the trends might be instrumental.

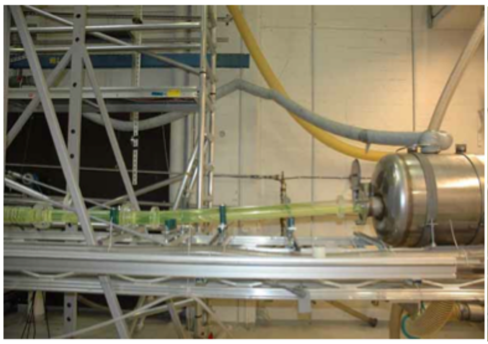
Setup	U_{sl}*[m/s]*	$\dot{m}$ *[kg/s]*	*Flushing time [sek]*	
			Experiments	OLGA 6.0
Horizontal	0.12	0.286	197	180
	0.15	0.356	110	136
	0.32	0.747	76	69
	0.4	0.955	65	55
	0.49	1.556	56	45
	0.61	1.443	***48***	***34***
.5-degree decline	0.10	0.235	177	180
	0.18	0.430	80	99
	0.35	0.817	65	59
	0.45	1.073	53	46
	0.56	1.328	49	38
	0.64	1.509	***30***	***33***
.5-degree incline	0.14	0.333	127	185
	0.15	0.344	127	179
	0.31	0.734	83	76
	0.41	0.962	68	56
	0.49	1.554	63	48
	0.62	1.165	***51***	***36***

Table 5 – Flushing times. Max and min registered times highlighted in red.

When oil superficial velocity was not sufficient to flush the pipeline, qualitative experiments found that the relative inclination angle of the flexible outlet would not affect the amount of water holdup left. Visual data from these experiments are presented in Appendix E. Another indication is the experimental results in [10] which are close to the results for the current .5-degree setup with a flexible outlet. Table 6 illustrates the interval in which the holdup measurements for H1-H4 are found. The mechanical difference on the experimental loop setup in where these results are extracted is the fixed outlet at a relative inclination of 3.9 degrees compared to the .5-degree inclined test section.

Usl [m/s]	*Flexible outlet [%holdup]*	*Usl [m/s]*	*Fixed outlet [%holdup]*
0.02	60-70%	0.012	67-77%
0.04	50-60%	0.04	50-60%
0.06	30-45%	0.07	30-50%
0.08	10-40%	0.11	25%
0.10	30%	x	x

Table 6. Shows holdup in %-cross section of pipeline for experimental runs on a .5-degree inclined test section with different outlet configurations.



Picture 2. Fixed outlet configuration. **Picture 3. Flexible outlet configuration.**

3.3.1 OLGA 6.0 predictions – flushing times

OLGA 6.0 shows good prediction to flushing times for oil superficial velocities where water is fully flushed from the test section during experiments, as seen in Table 5. For these velocities OLGA simulations generally expect a longer flushing time for oil U_{sl}<0.3m/s. After this value it changes to only expecting shorter flushing times. From [2] the OPUS model has the closest resemblance to OLGA 6.0 and this continually predicts a longer flushing time for the same velocity interval.

Experiments with the oil superficial velocity being insufficient to fully flush the water is found to be the most difficult to simulate. For these velocities the difference in actual and simulated water holdup can differ with as much as up to 40%, Table 7. The values are taken from the holdup vs. time plots in Appendix A-C. For test rig setups .5-degree incline, decline and horizontal, velocities insufficient for water flushing are U_{sl}<0.12m/s, 0.1m/s and 0.14m/s respectively. Despite this, the introduction of a level gradient to equation (1.3.2) allows OLGA 6.0 to show the difference in water holdup throughout the test section for elevated setups thus an improvement from the older versions in [2].

Usl [m/s]	*.5-degree incline*	*Horizontal*	*.5-degree decline*
0.02	0.19	0.21	0.23
0.04	0.28	0.33	0.29
0.06	0.44	0.33	0.2
0.08	0.4	0.28	0.07
0.10	0.29	0.11	X

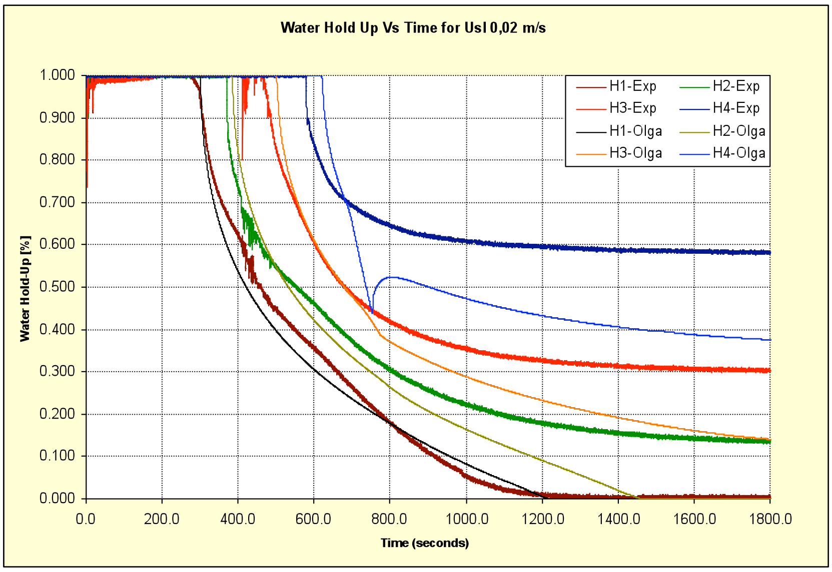
Table 7. Shows $\Delta h / D$ between simulations and experiments. h = holdup, D = pipeline diameter (0.06m)

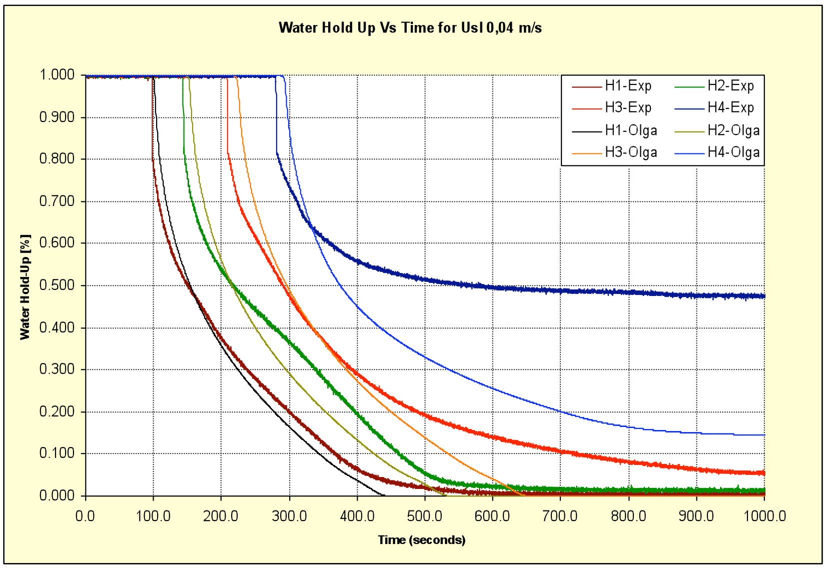
5 Conclusion

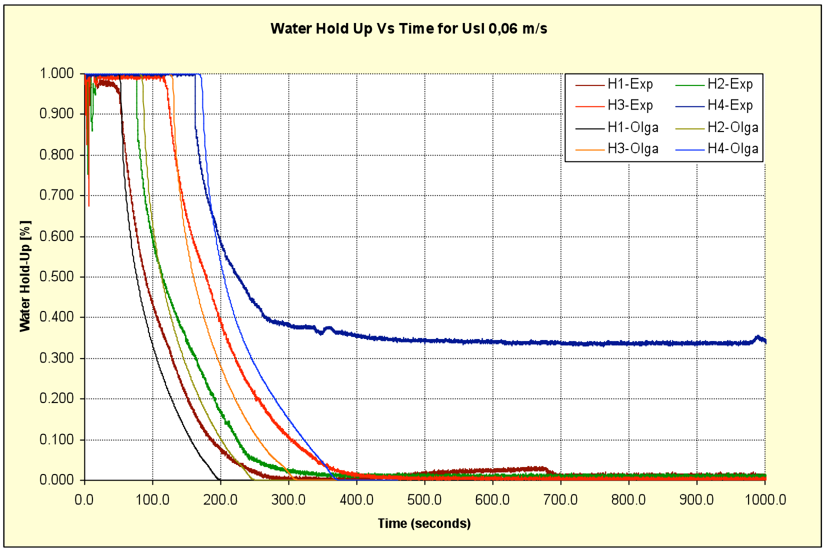
OLGA 6.0 shows good predictions to the oil-water flushing scenario for all oil superficial velocities above 0.14m/s. An oil $U_{sl} \geq 0.3m/s$ was needed to fully flush the water from both the test section and flexible outlet. The fastest flushing times within the Chevron specified velocity interval; are 30s, 48s and 51s for .5-degree declined, horizontal and .5-degree inclined setup respectively. For holdup vs. time curves showing no water for velocities below 0.3m/s a considerable amount of water is usually still concentrated in the outlet section. For oil $U_{sl} < 0.14m/s$ where water is not flushed, is when OLGA 6.0 shows the most deviance to experimental results. The differences in registered and predicted holdups here are generally around 20-40%.

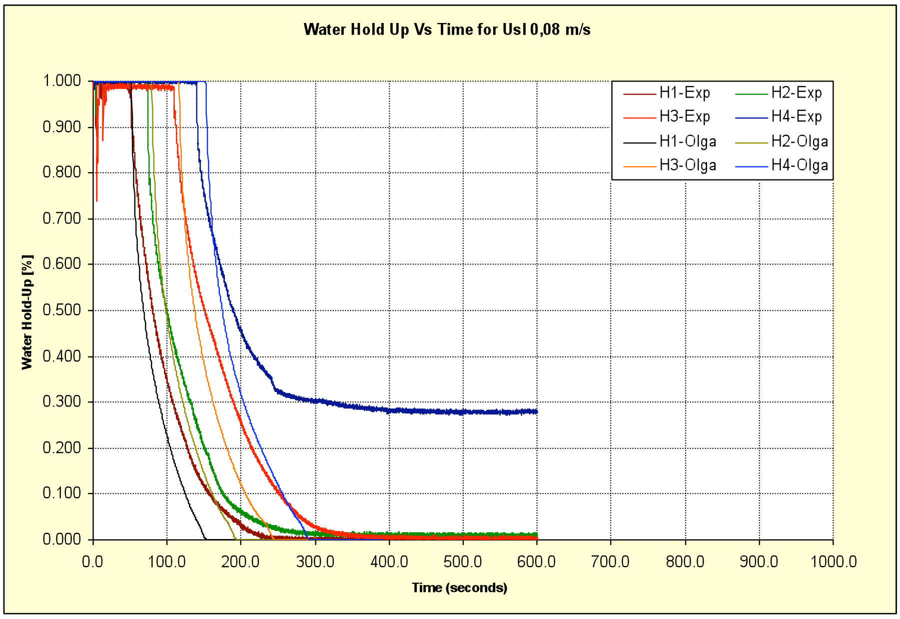
Compared to OPUS, OPUS 2 and an OLGA implementing a drift flux model [2], the OLGA 6.0 shows better liquid-liquid predictions. This is especially true when water is not flushed from the pipeline, and is likely due to the implementation of an interfacial level gradient.

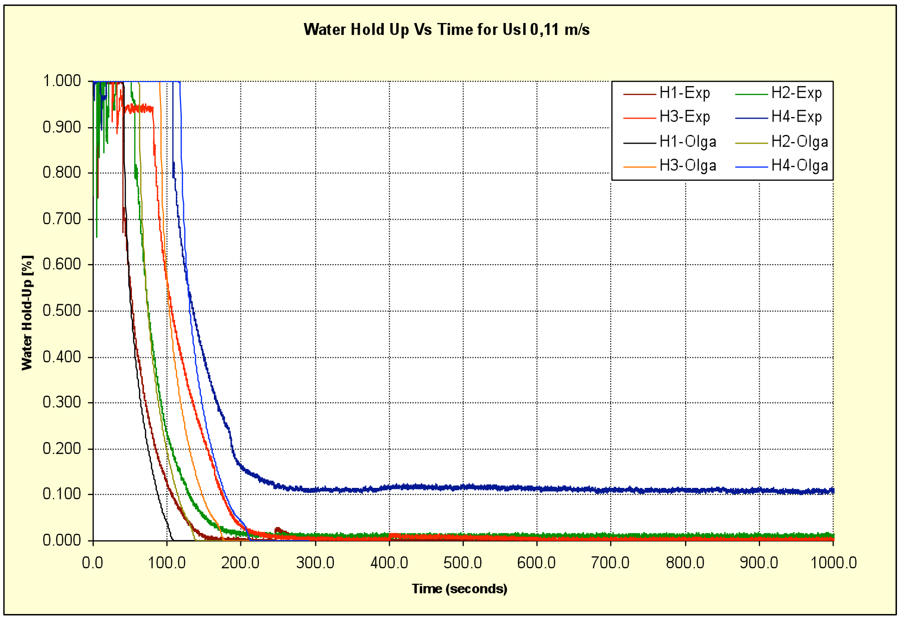
Appendix A Plots - Holdup vs. time horizontal

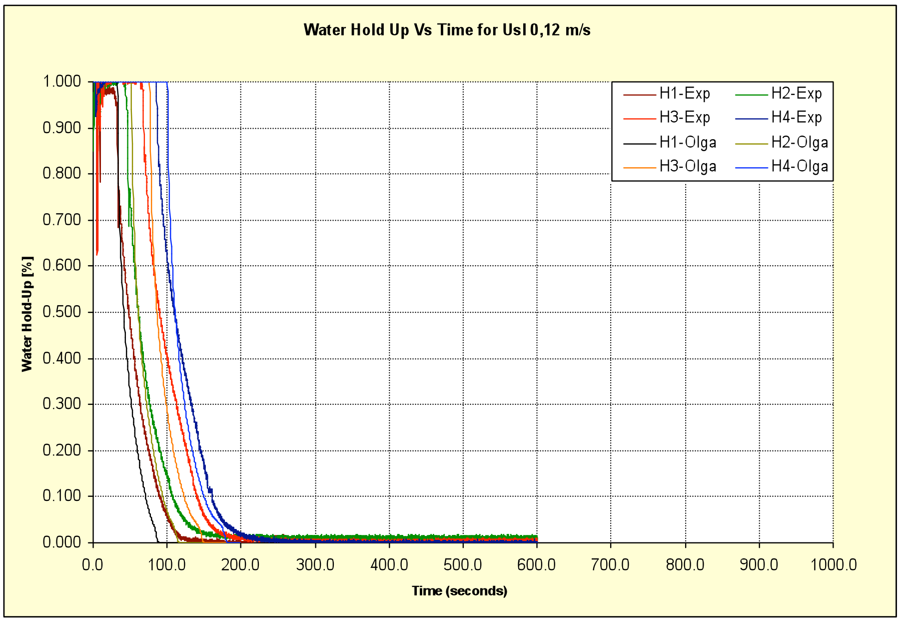


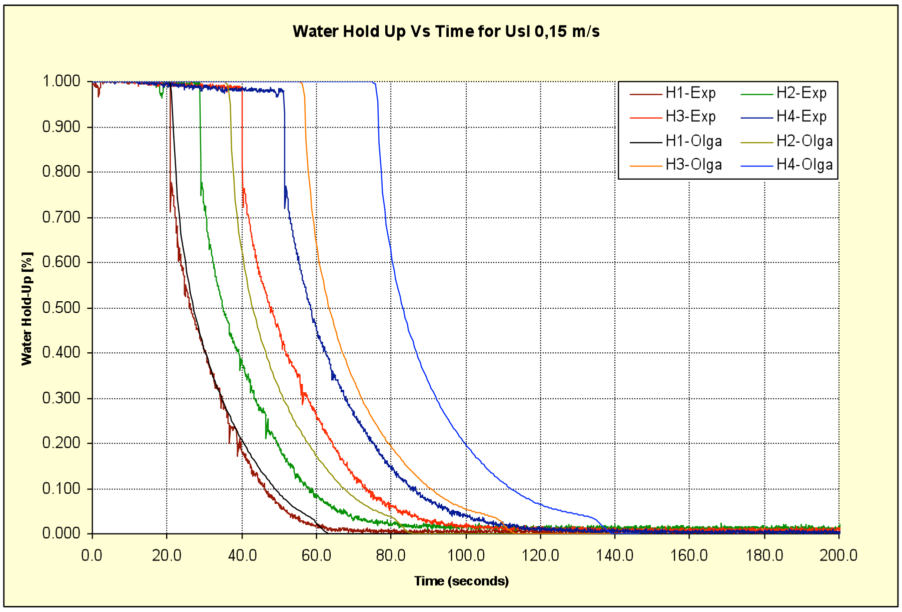


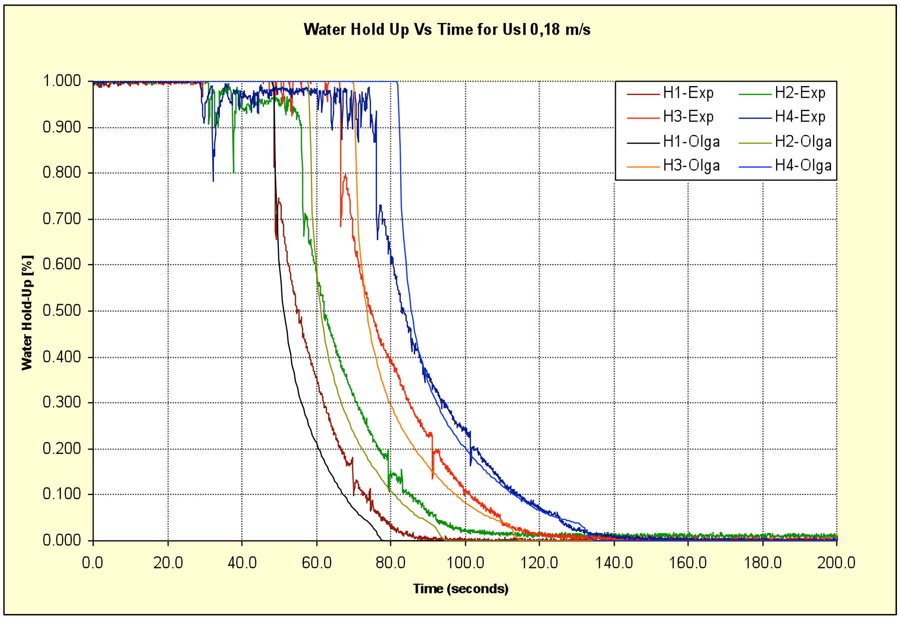


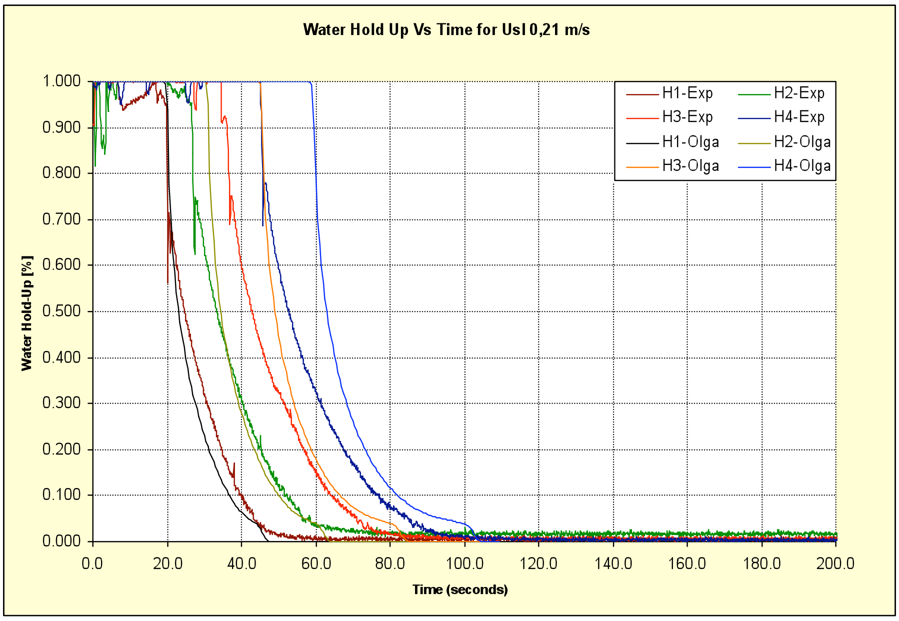

Water Hold Up Vs Time for Usl 0,08 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

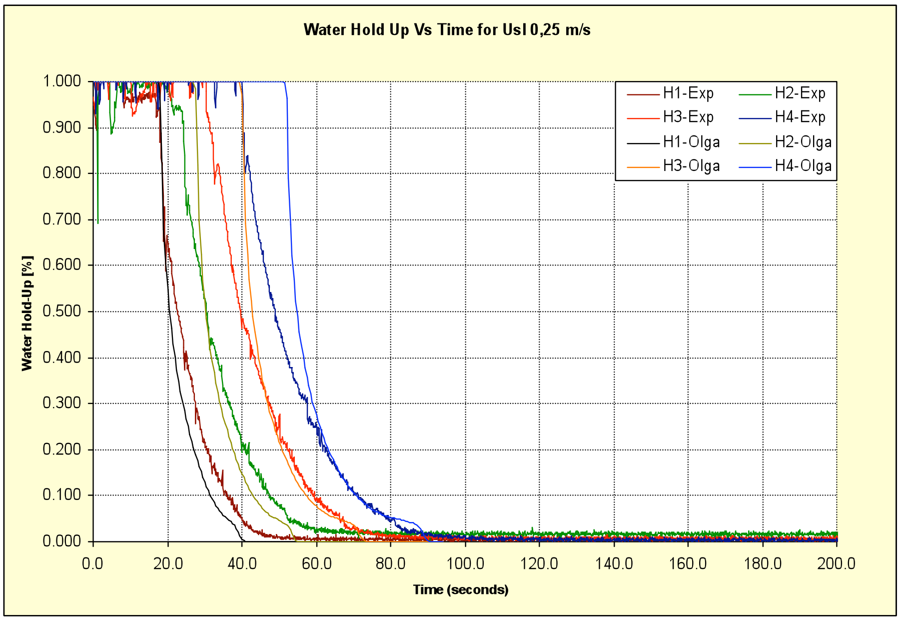

Water Hold Up Vs Time for Usl 0,11 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

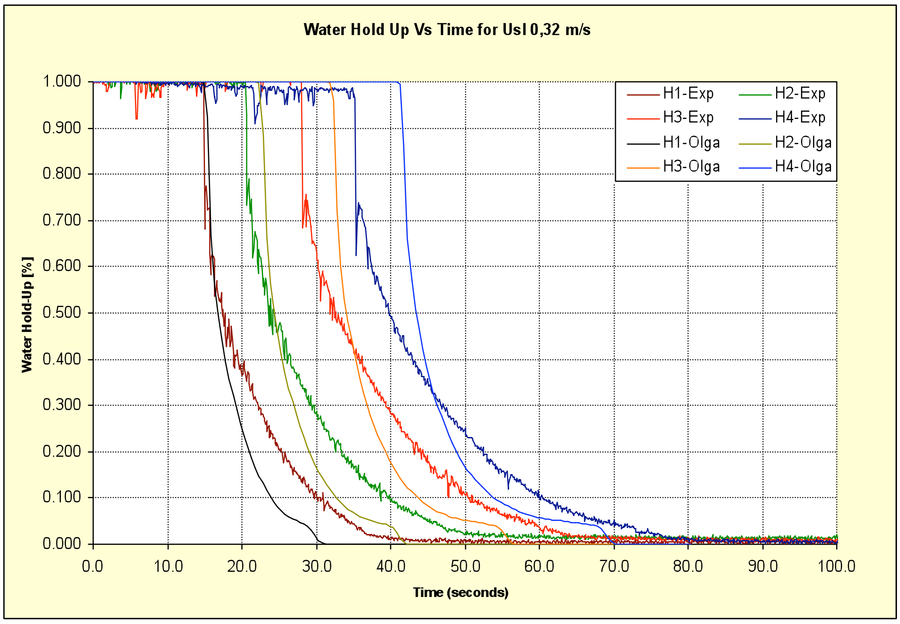

Water Hold Up Vs Time for Usl 0,12 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

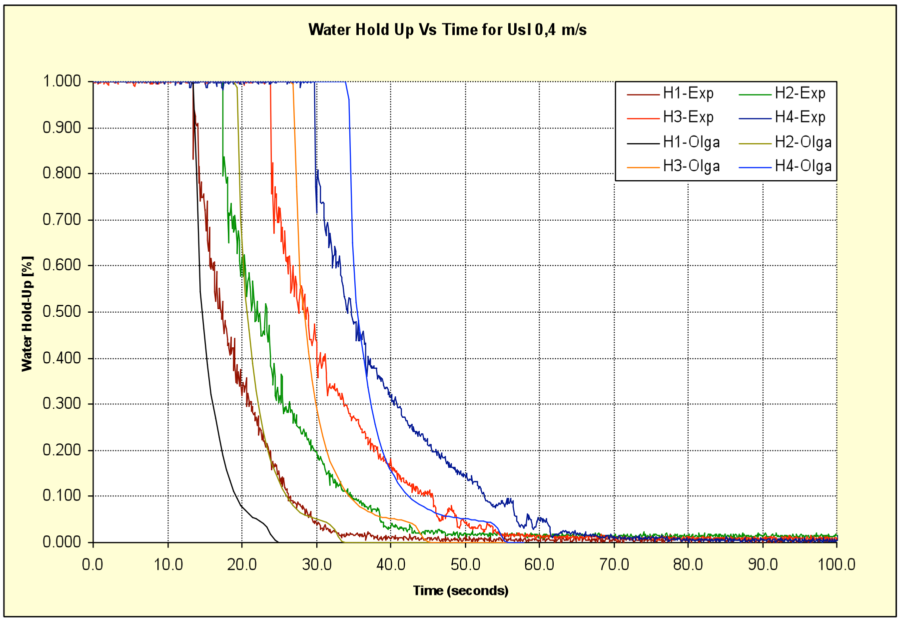

Water Hold Up Vs Time for Usl 0,15 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

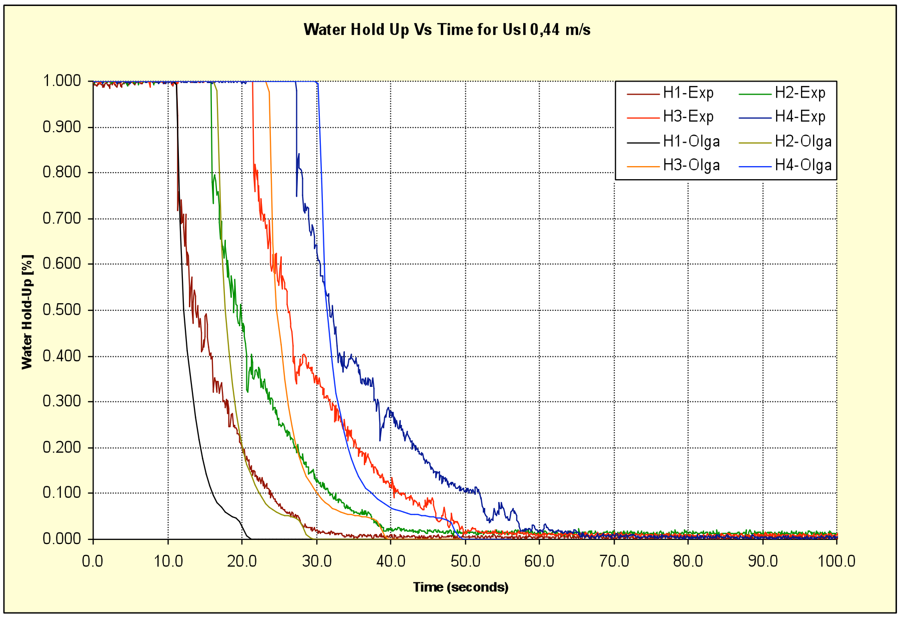

Water Hold Up Vs Time for Usl 0,18 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

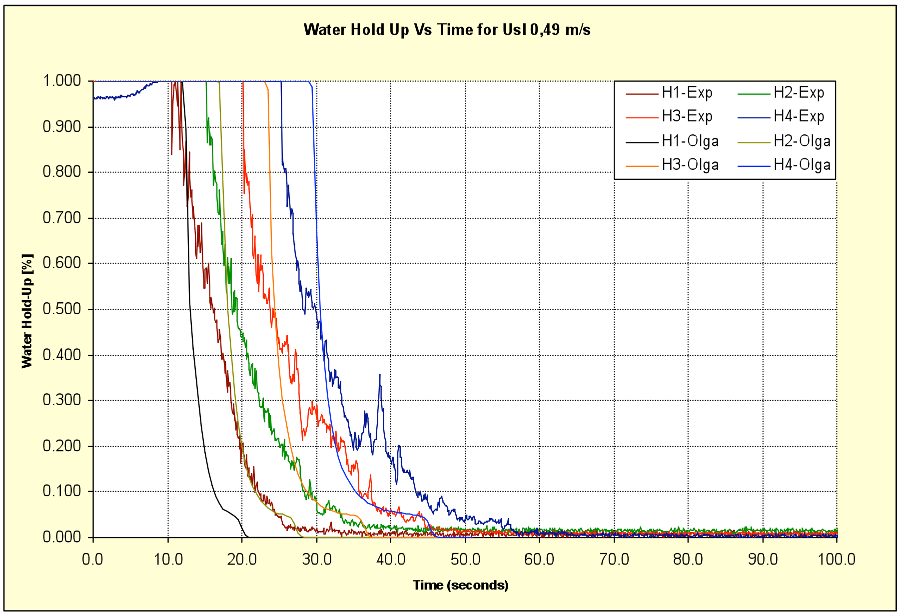

Water Hold Up Vs Time for Usl 0,21 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

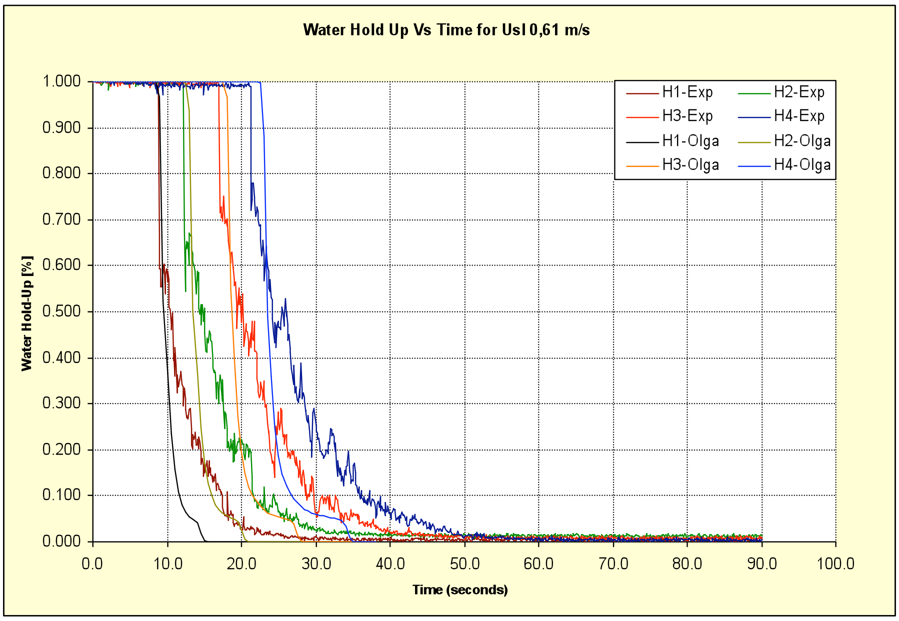

Water Hold Up Vs Time for Usl 0,25 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

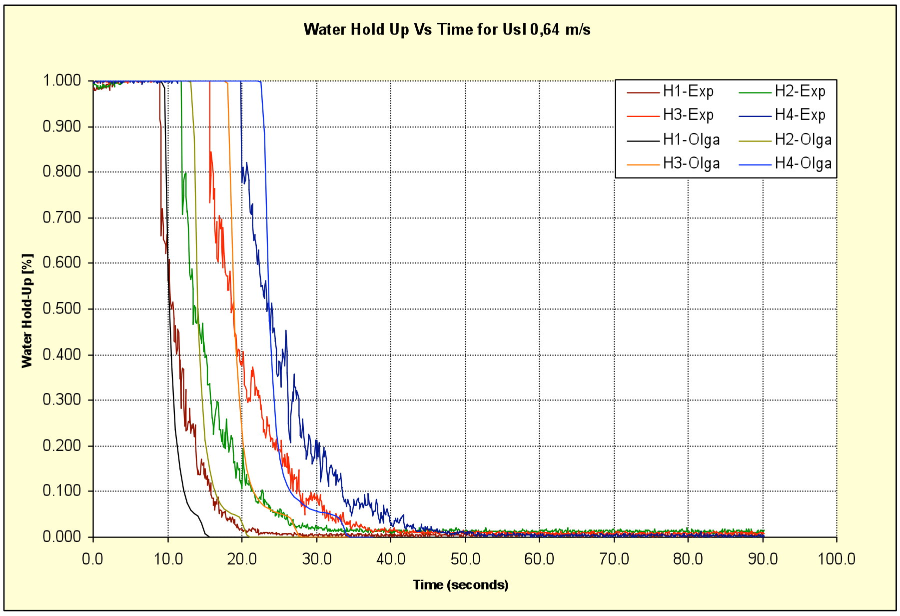

Water Hold Up Vs Time for Usl 0,32 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

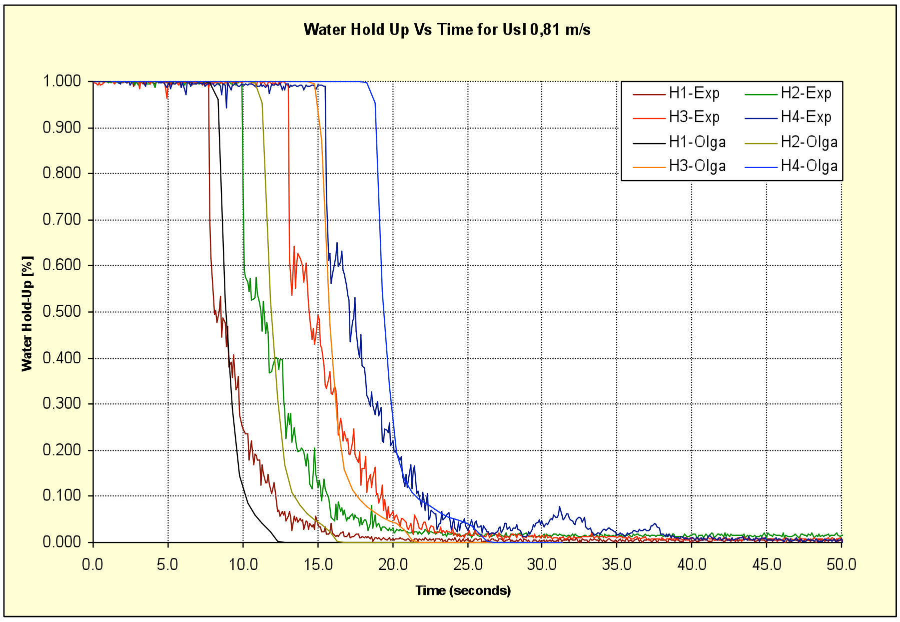

Water Hold Up Vs Time for Usl 0,4 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga


Water Hold Up Vs Time for Usl 0,44 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

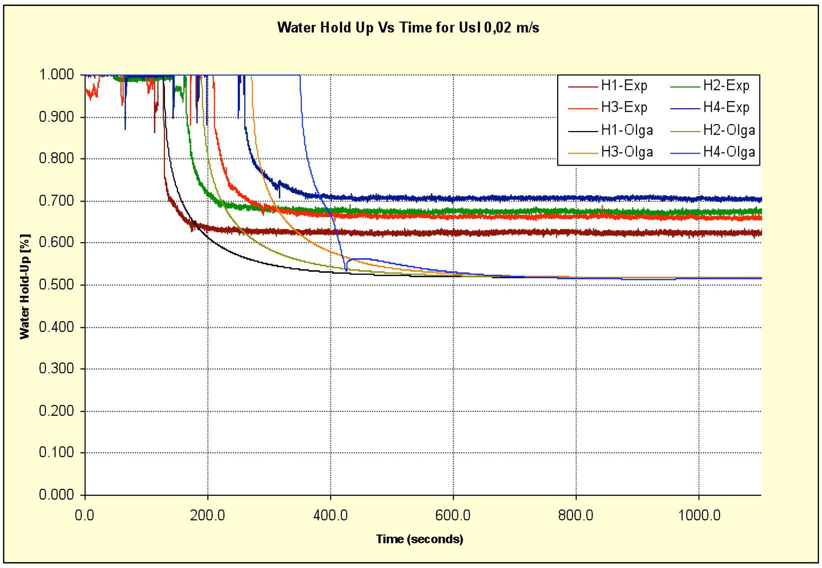

Water Hold Up Vs Time for Usl 0,49 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

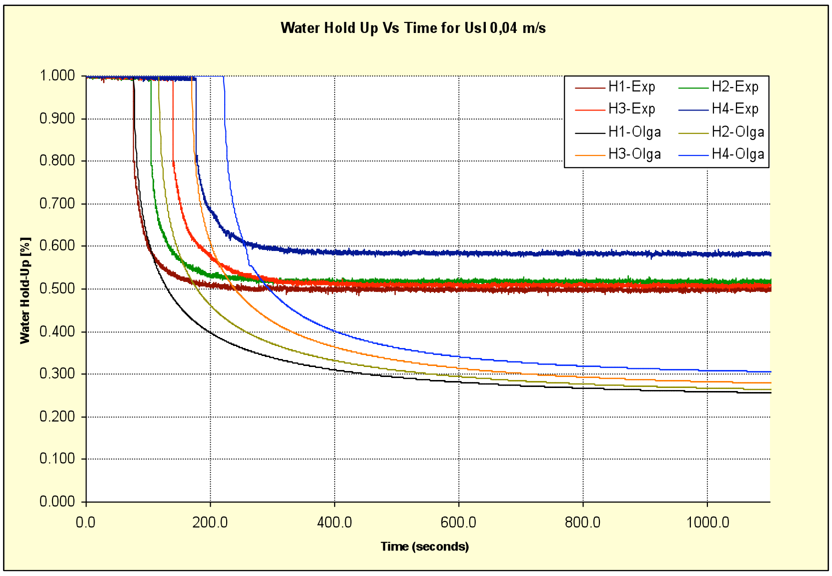

Water Hold Up Vs Time for Usl 0,61 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

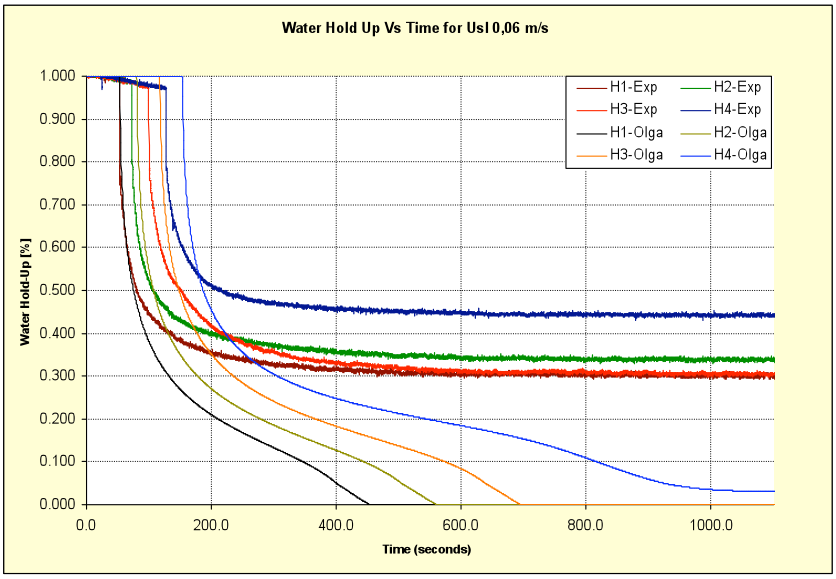

Water Hold Up Vs Time for Usl 0,64 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

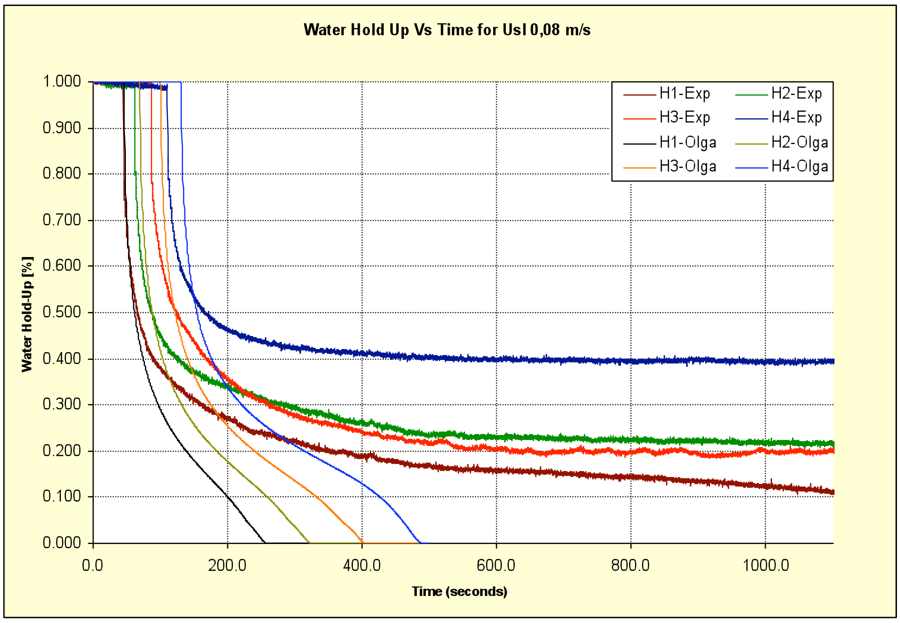

Water Hold Up Vs Time for Usl 0,81 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

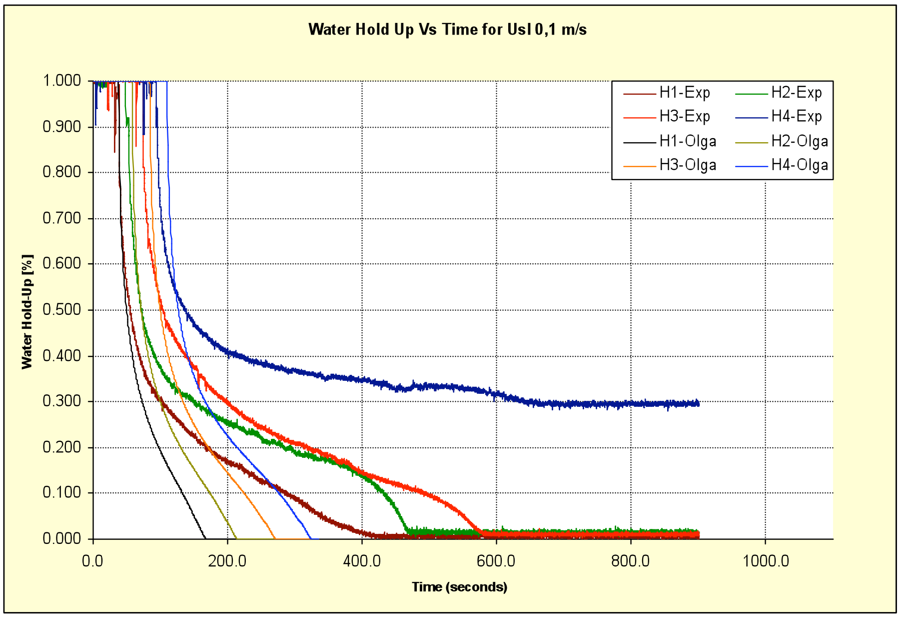
Appendix B Plots - Holdup vs. time .5-degree inclination

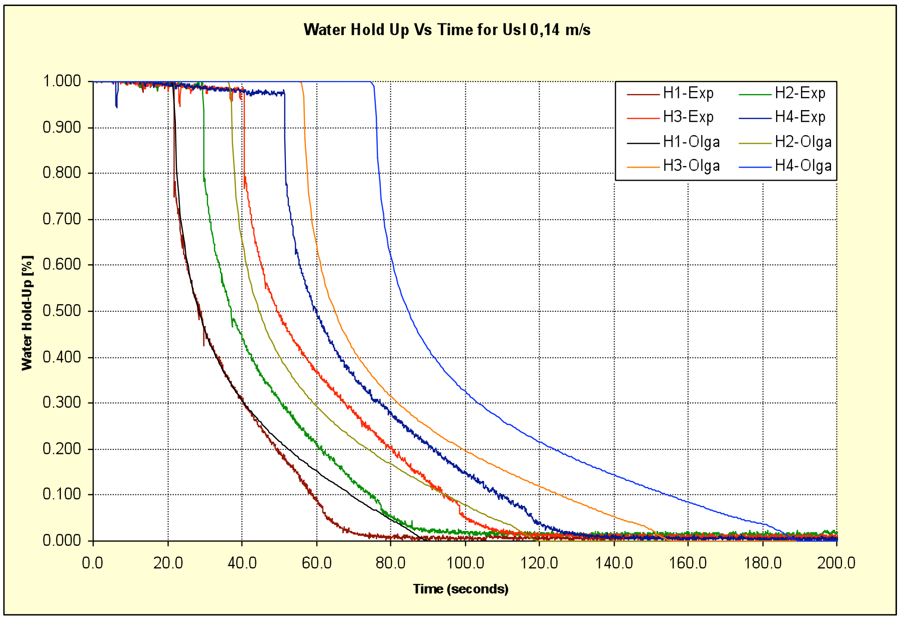


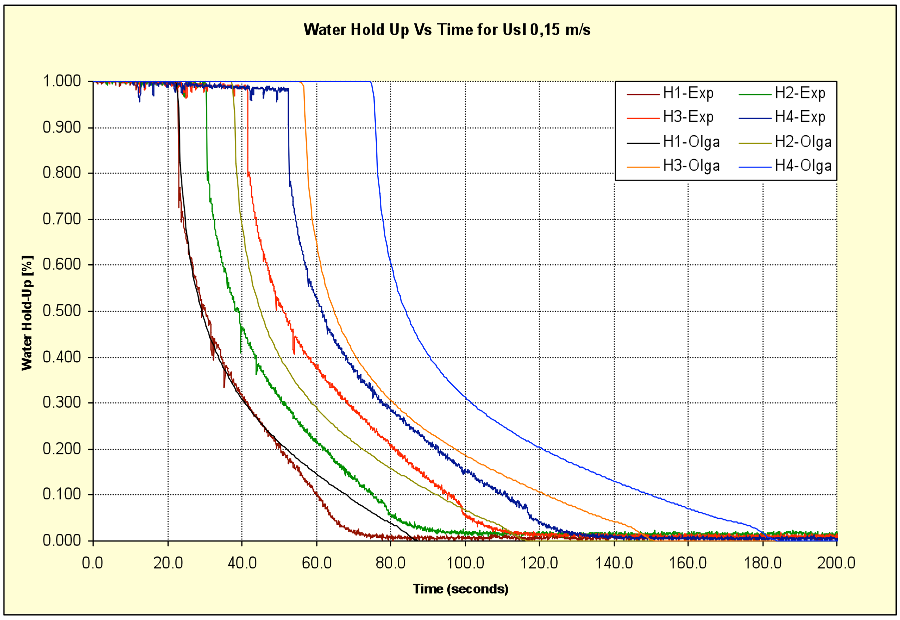


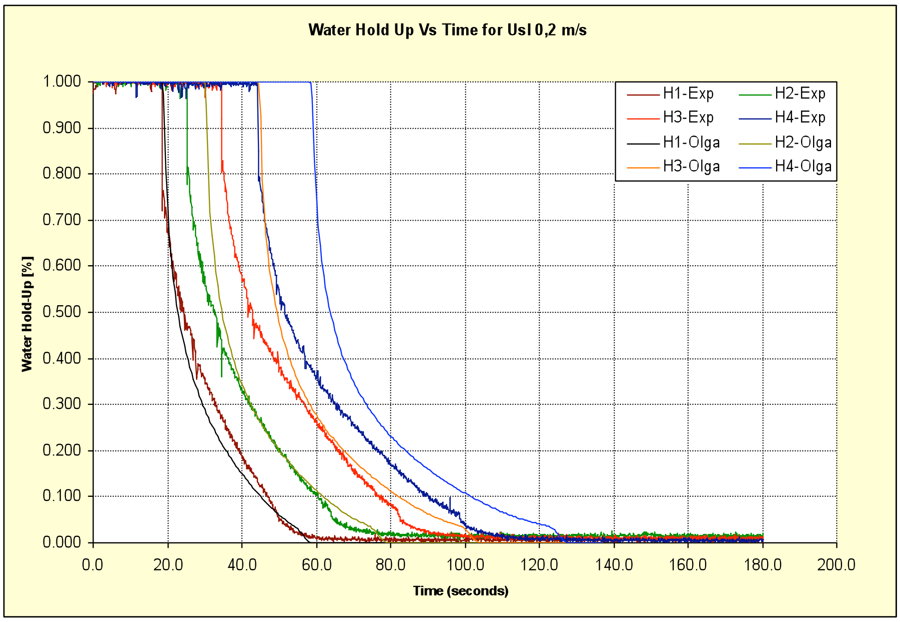


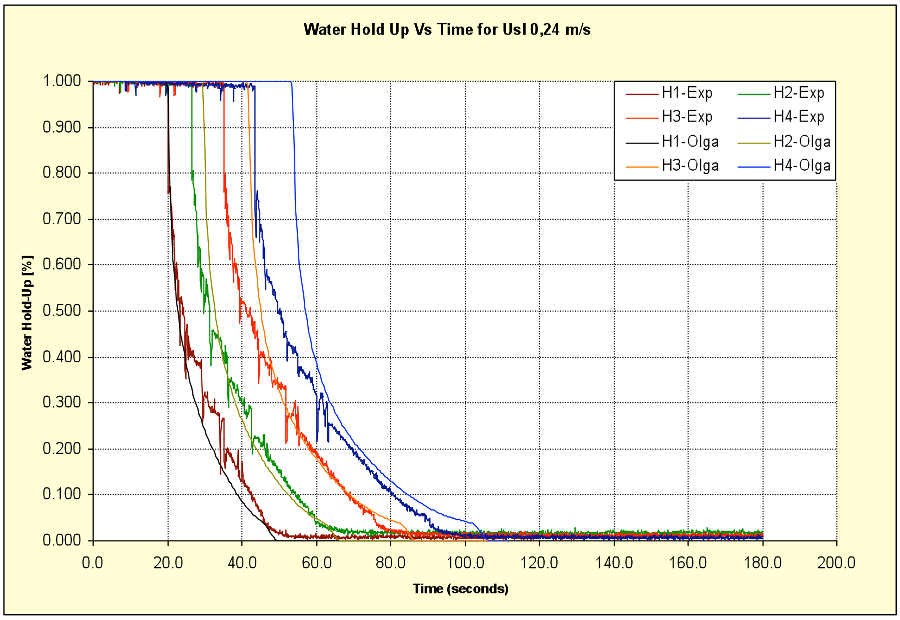

Water Hold Up Vs Time for Usl 0,08 m/s
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga
Water Hold-Up [%]
Time (seconds)

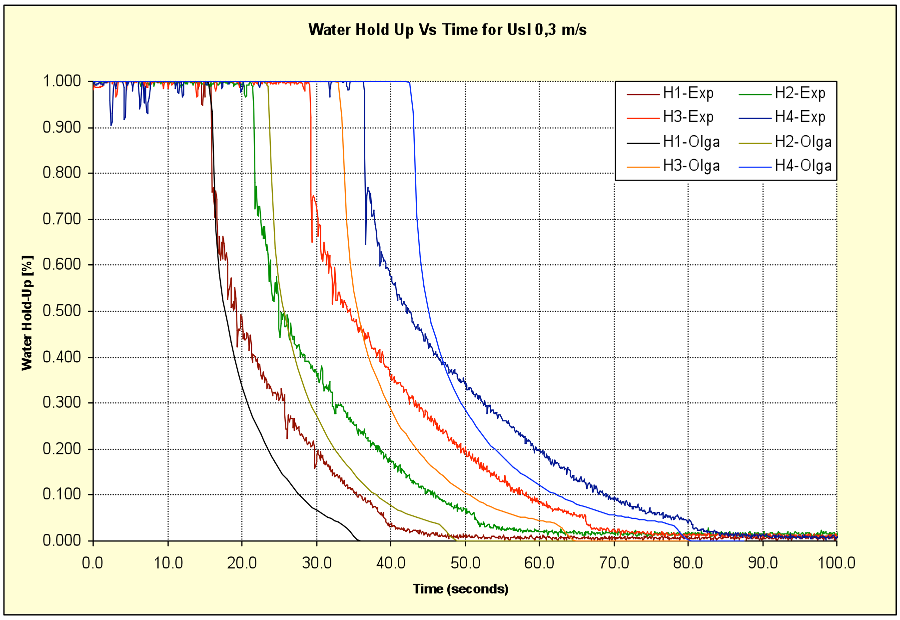

Water Hold Up Vs Time for Usl 0,1 m/s
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga
Water Hold-Up [%]
Time (seconds)

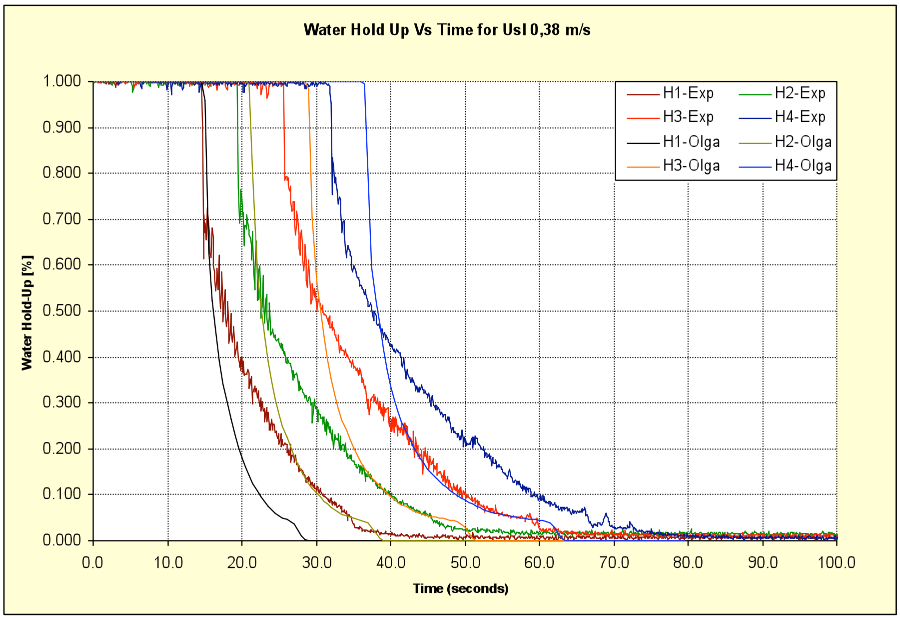

Water Hold Up Vs Time for Usl 0,14 m/s
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga
Water Hold-Up [%]
Time (seconds)

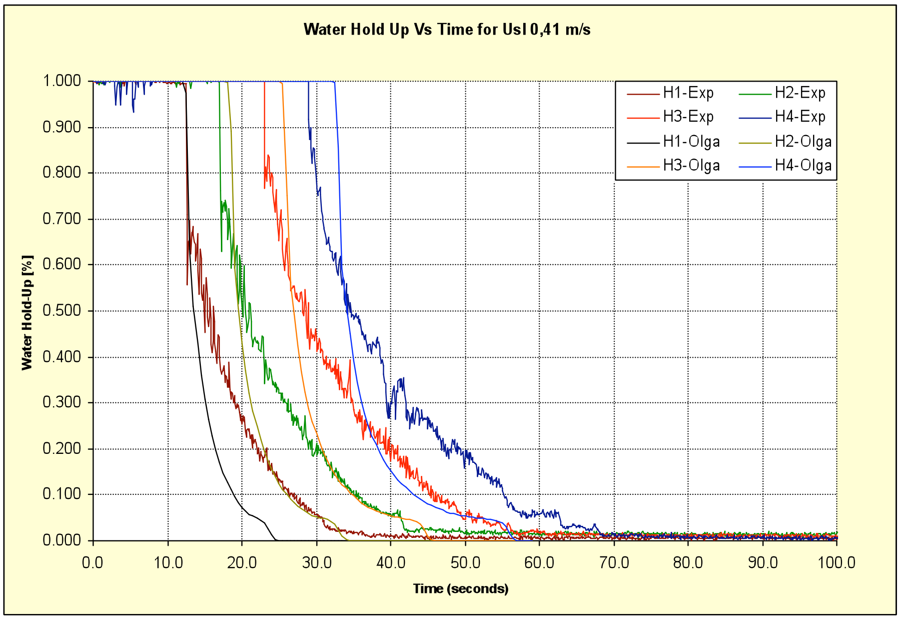

Water Hold Up Vs Time for Usl 0,15 m/s
Water Hold-Up [%]
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
200.0
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

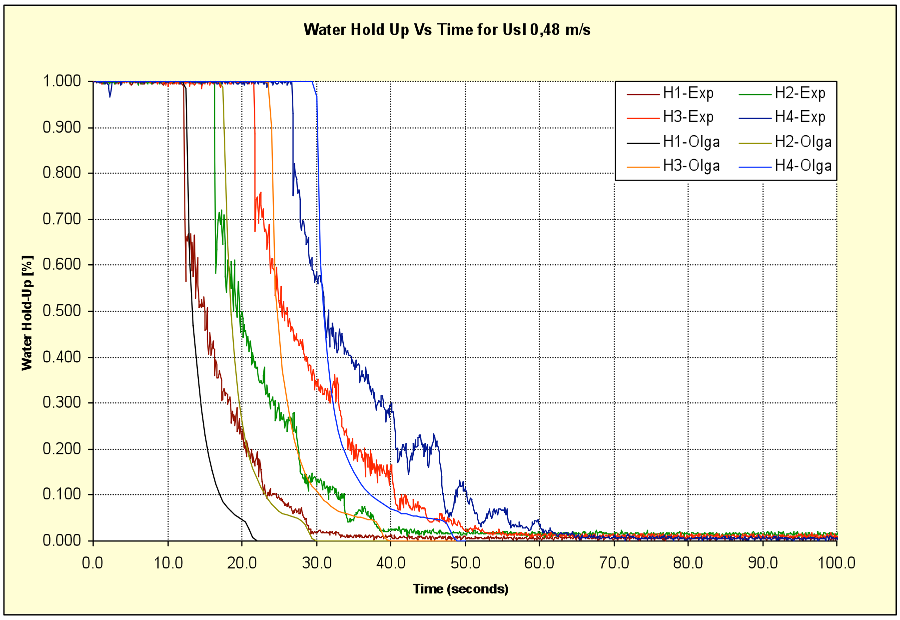

Water Hold Up Vs Time for Usl 0,2 m/s
Water Hold-Up [%]
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
200.0
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

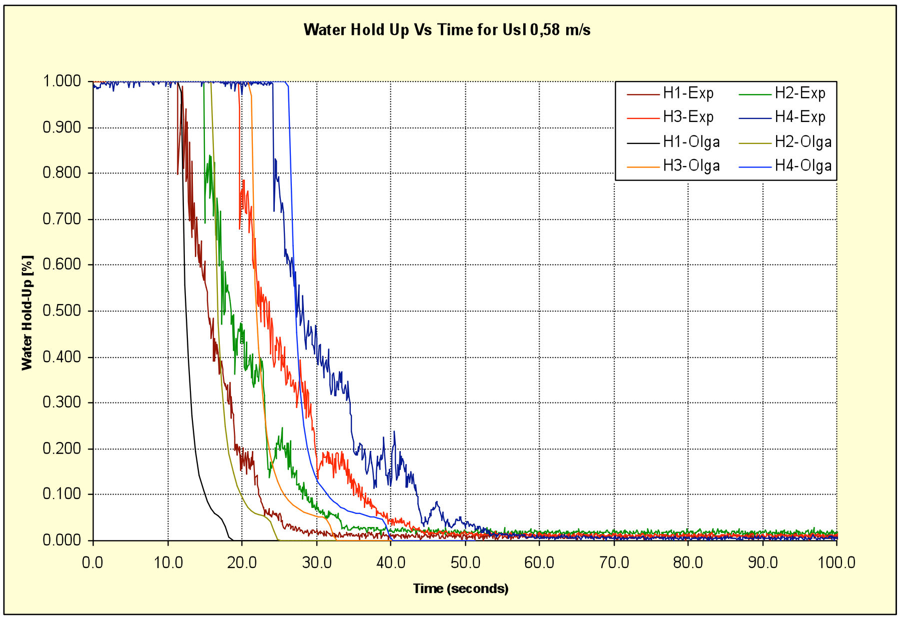

Water Hold Up Vs Time for Usl 0,24 m/s
Water Hold-Up [%]
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
200.0
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

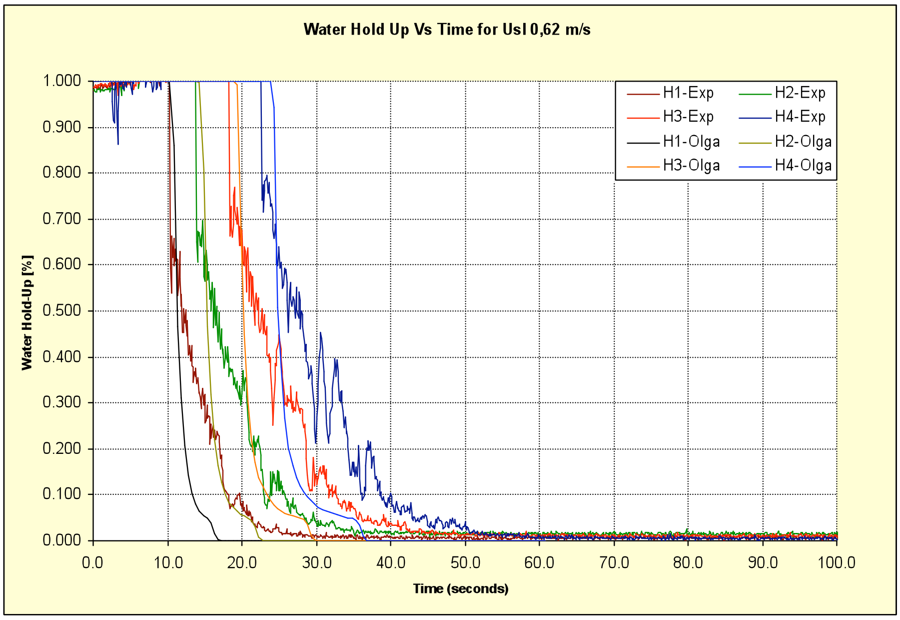

Water Hold Up Vs Time for Usl 0,3 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

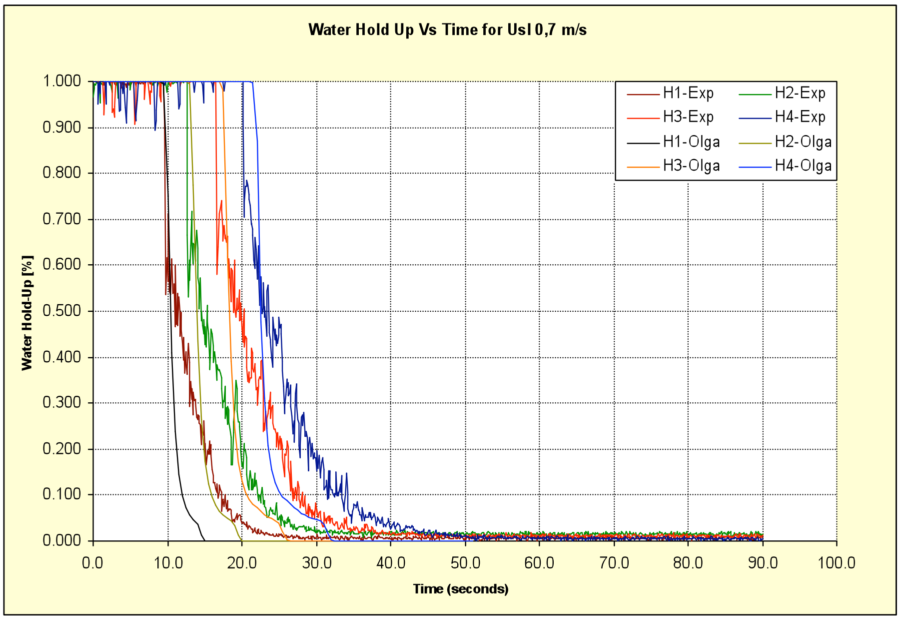

Water Hold Up Vs Time for Usl 0,38 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

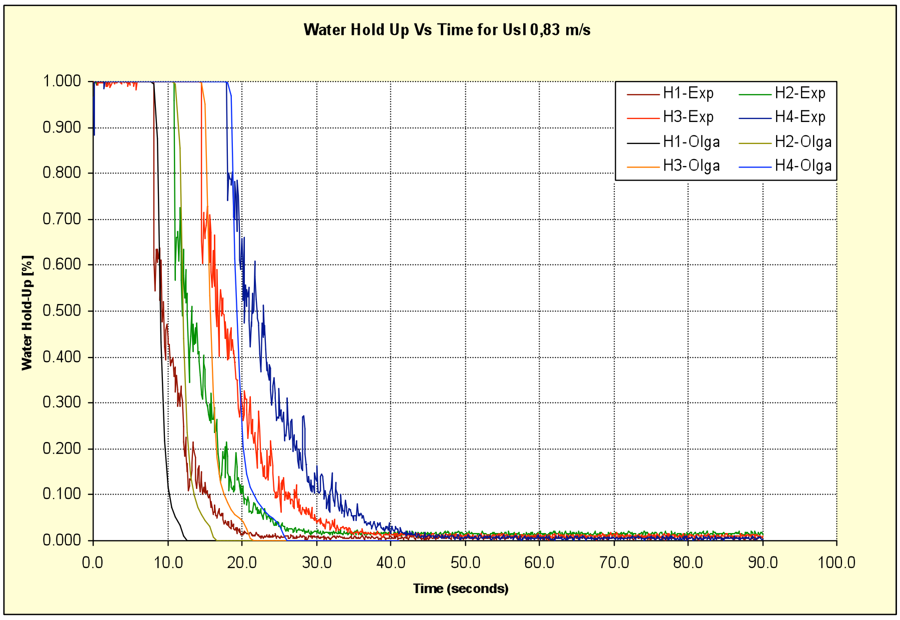

Water Hold Up Vs Time for Usl 0,41 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga


Water Hold Up Vs Time for Usl 0,48 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0

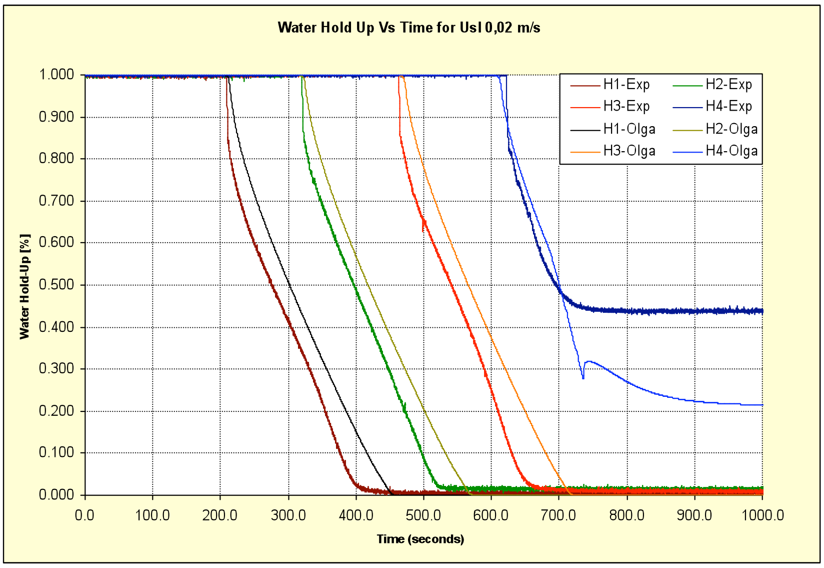

Water Hold Up Vs Time for Usl 0,58 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0

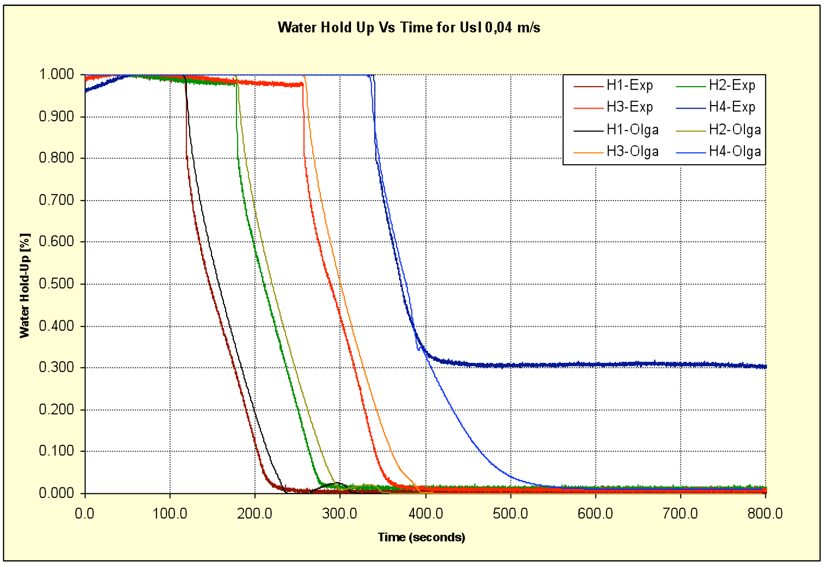

Water Hold Up Vs Time for Usl 0,62 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0

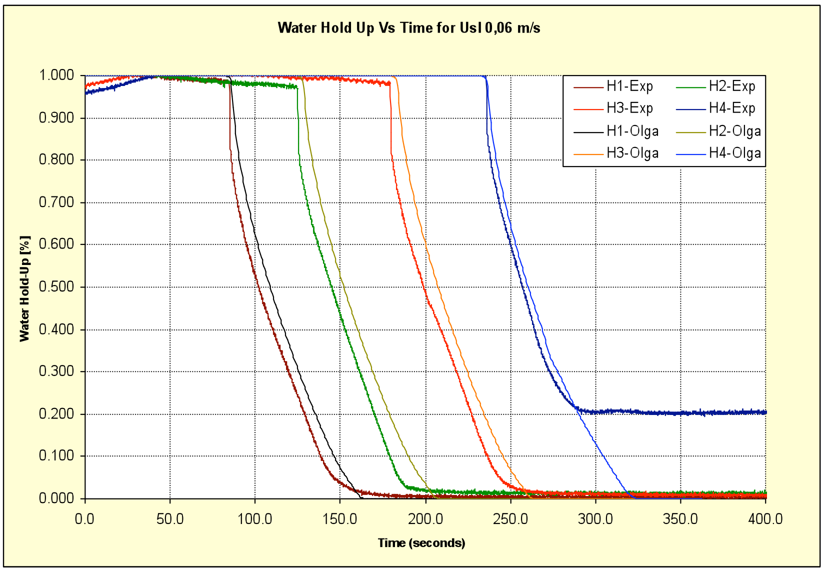

Water Hold Up Vs Time for Usl 0,7 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0

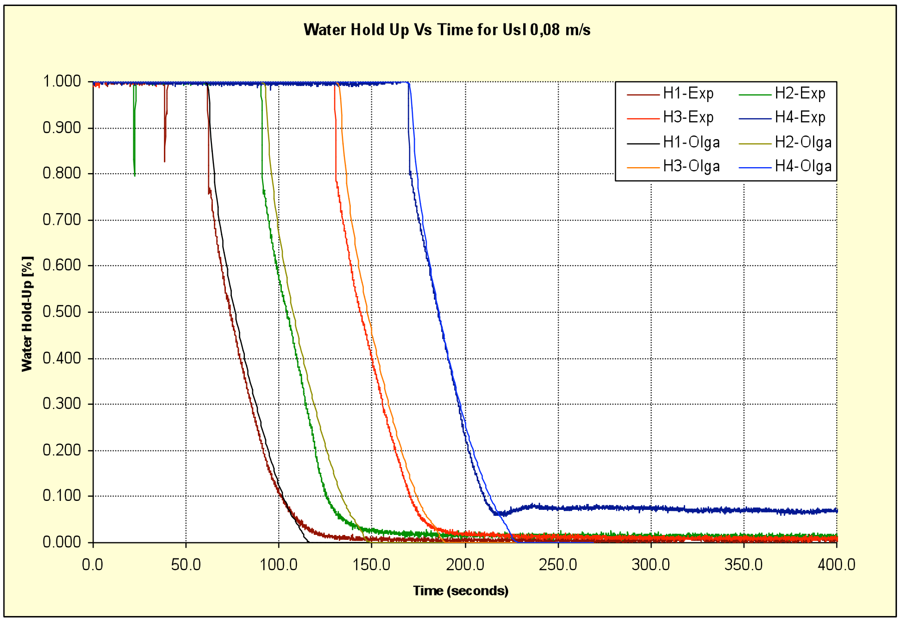

Water Hold Up Vs Time for Usl 0,83 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0

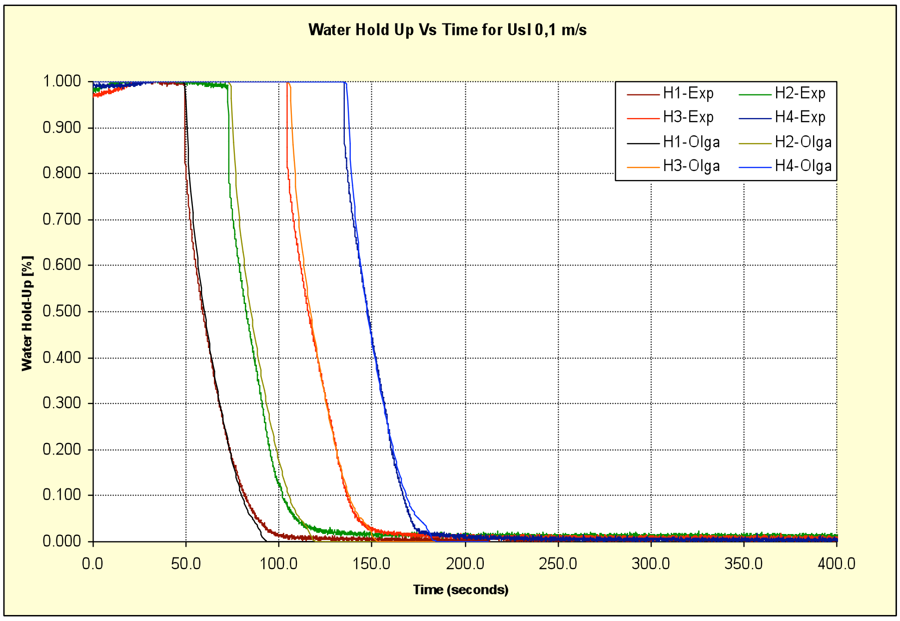
Appendix C Plots - Holdup vs. time .5-degree declination

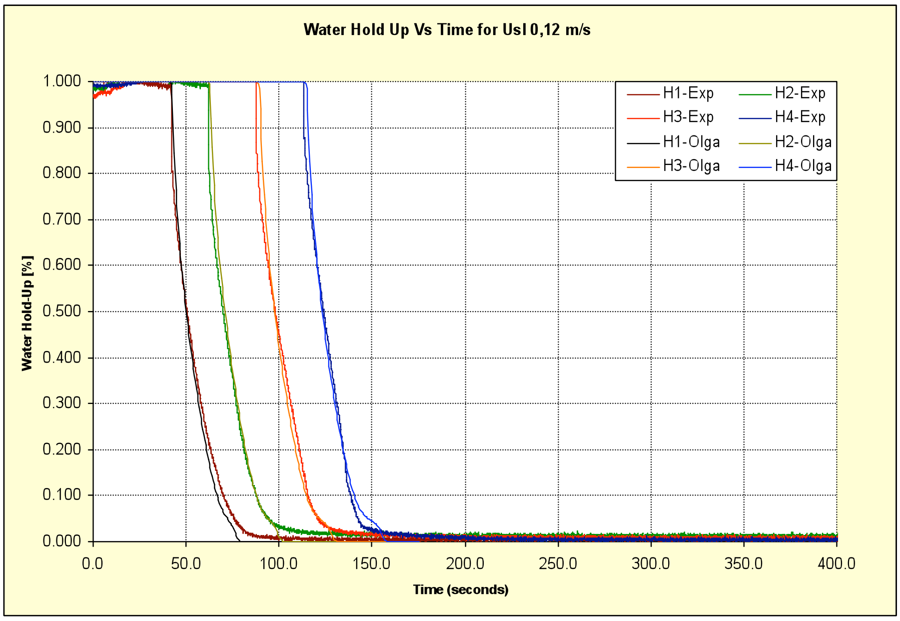


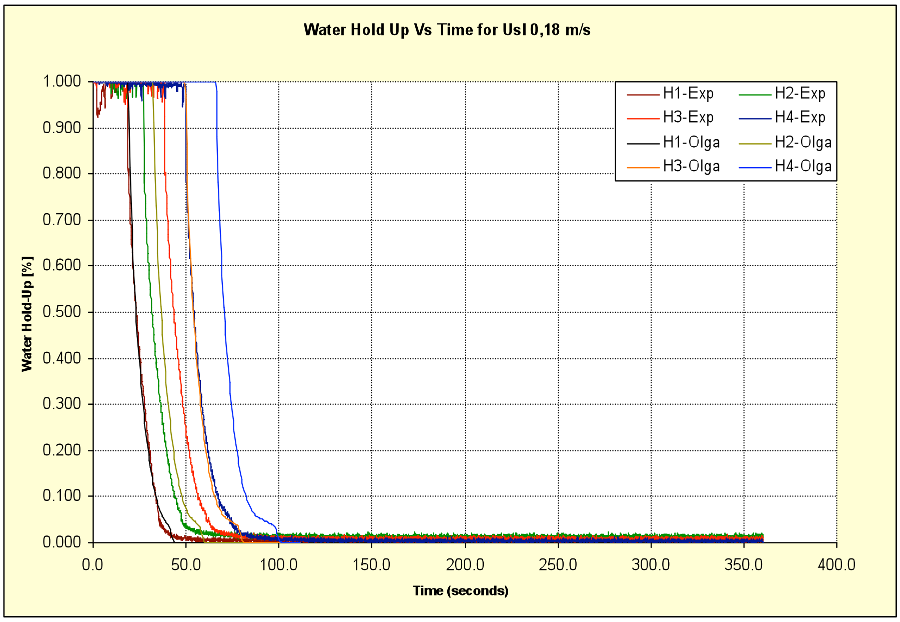


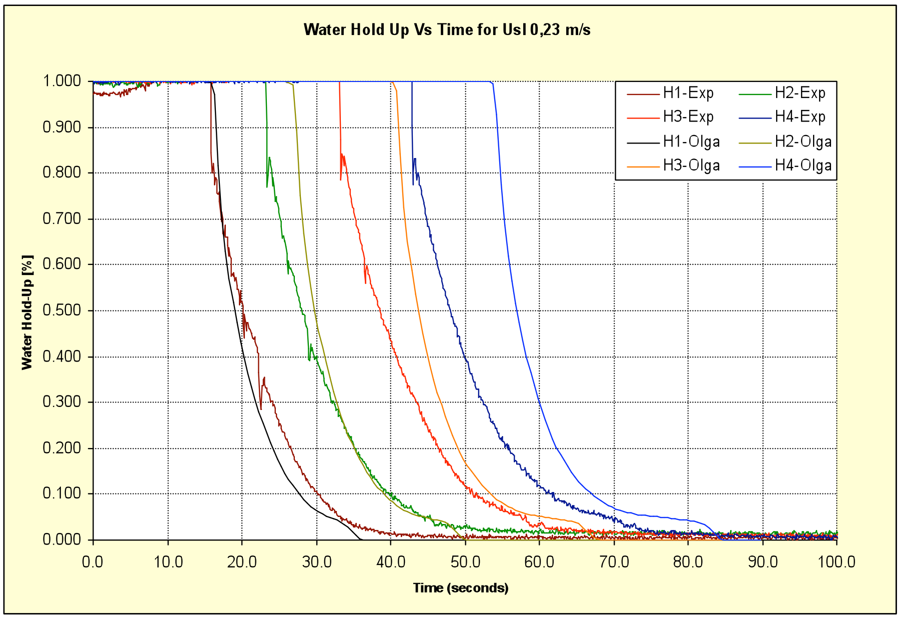


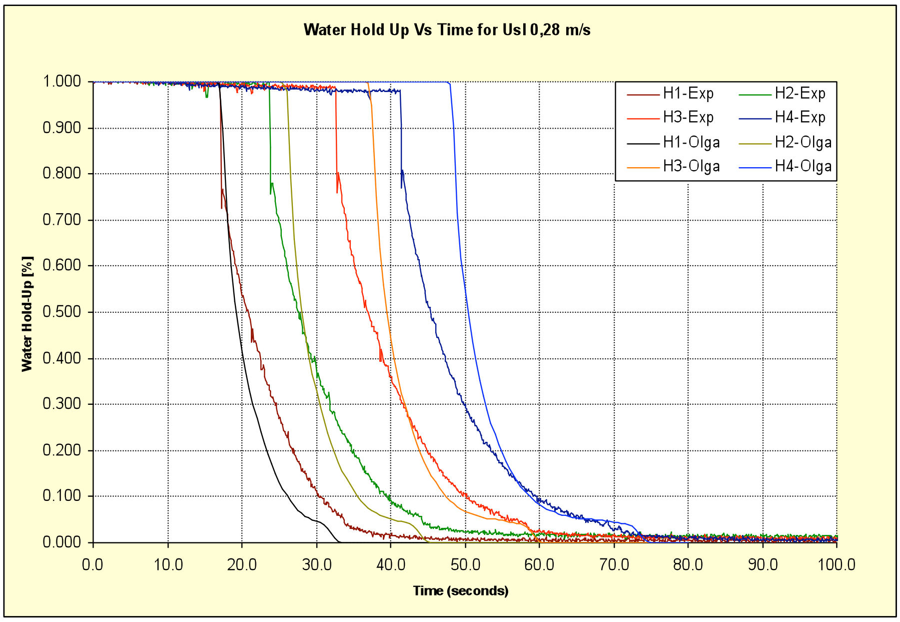

Water Hold Up Vs Time for Usl 0,08 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

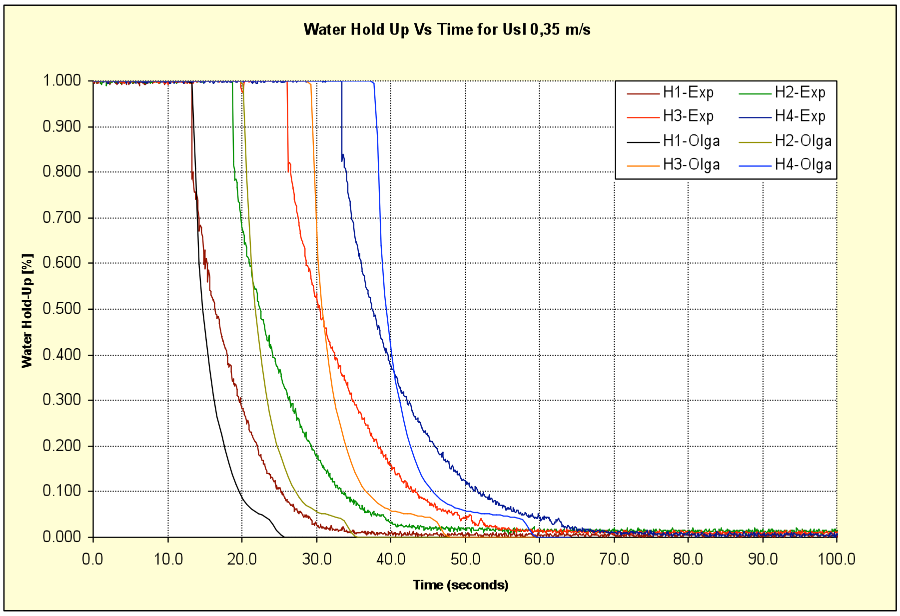

Water Hold Up Vs Time for Usl 0,1 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

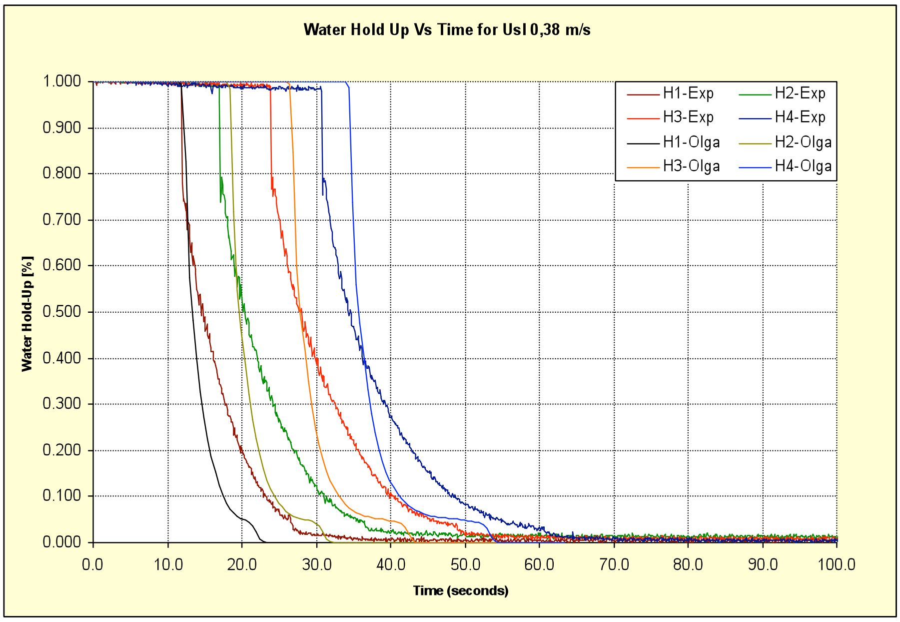

Water Hold Up Vs Time for Usl 0,12 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

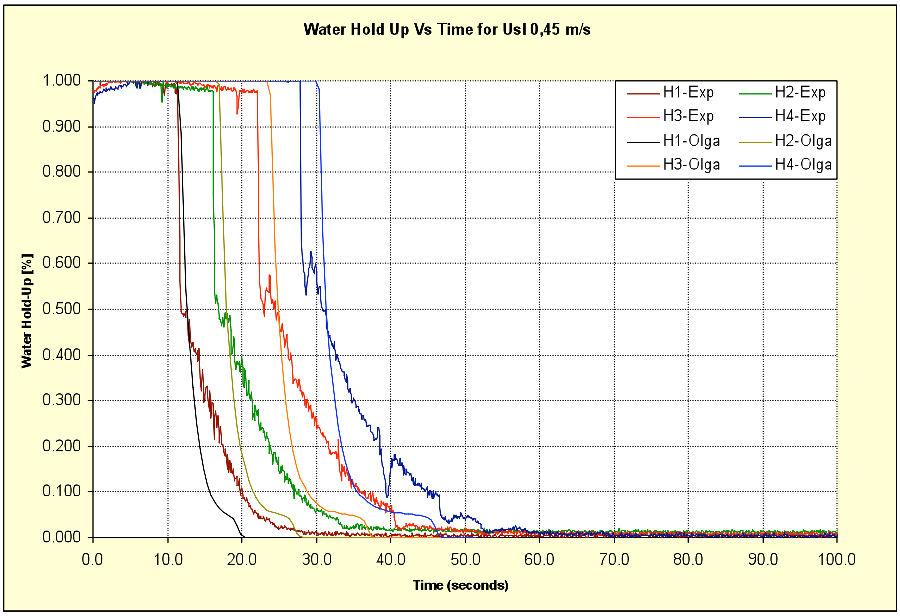

Water Hold Up Vs Time for Usl 0,18 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

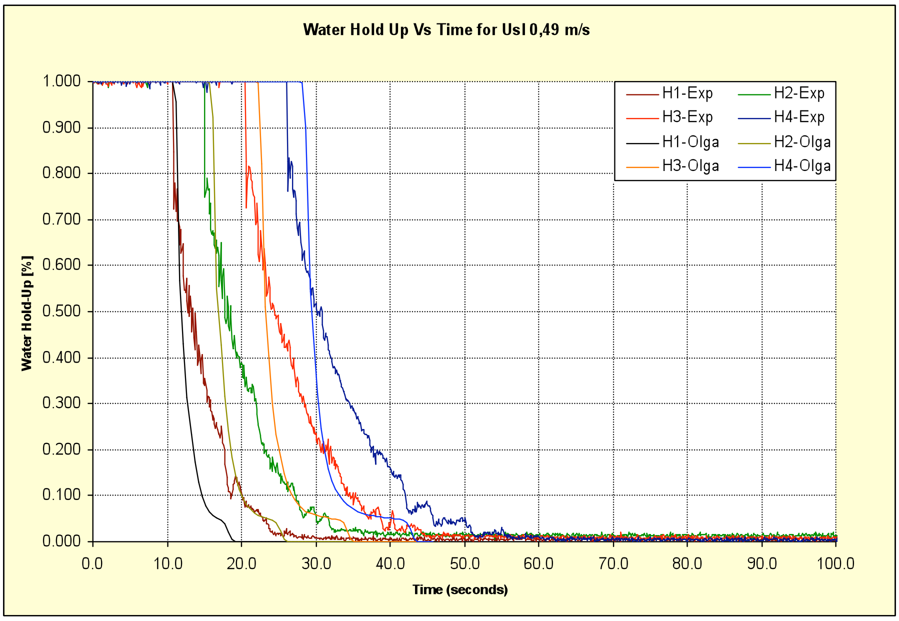

Water Hold Up Vs Time for Usl 0,23 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga


Water Hold Up Vs Time for Usl 0,28 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

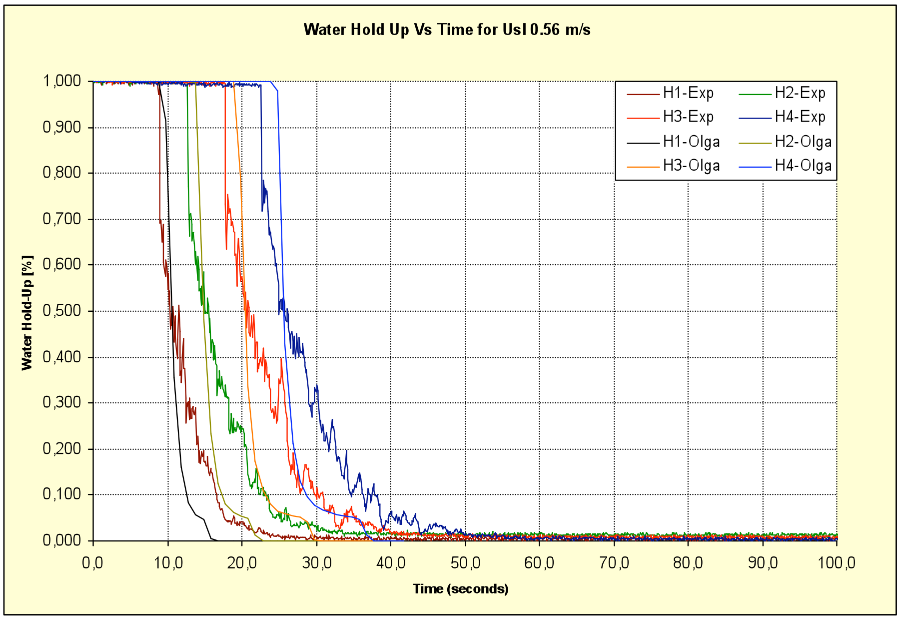

Water Hold Up Vs Time for Usl 0,35 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga


Water Hold Up Vs Time for Usl 0,38 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

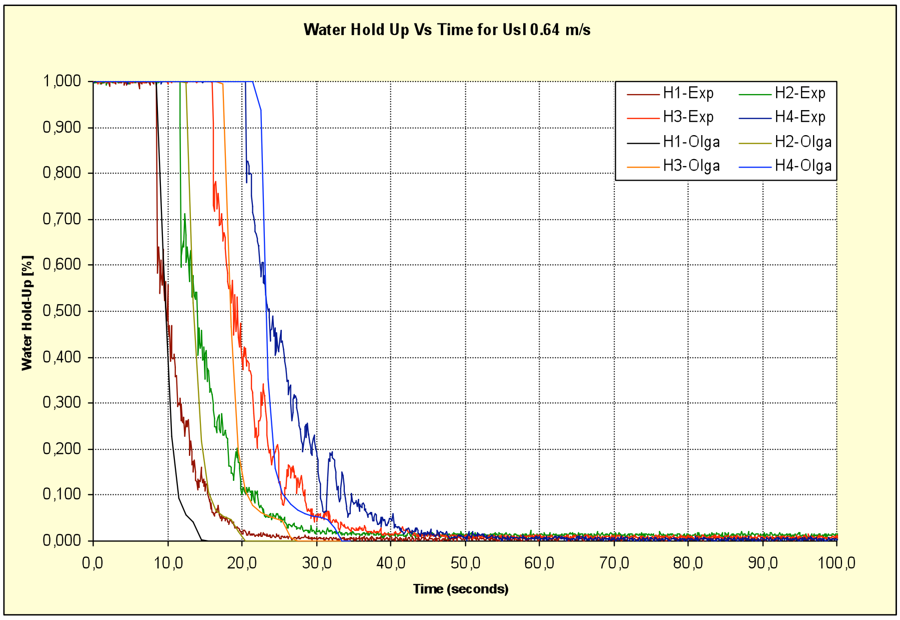

Water Hold Up Vs Time for Usl 0,45 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga



Water Hold Up Vs Time for Usl 0,49 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

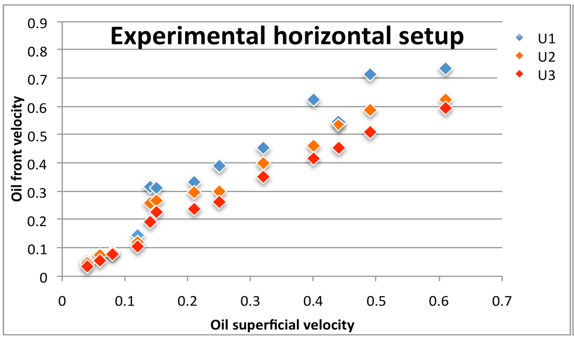


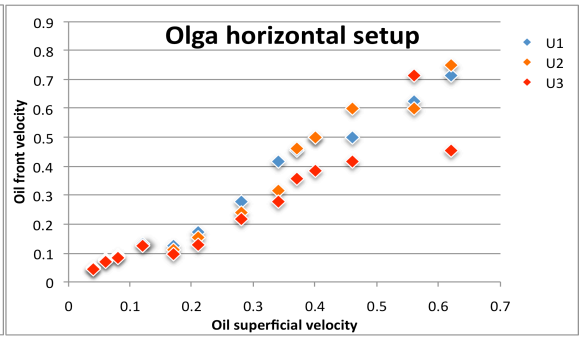
Water Hold Up Vs Time for Usl 0.56 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

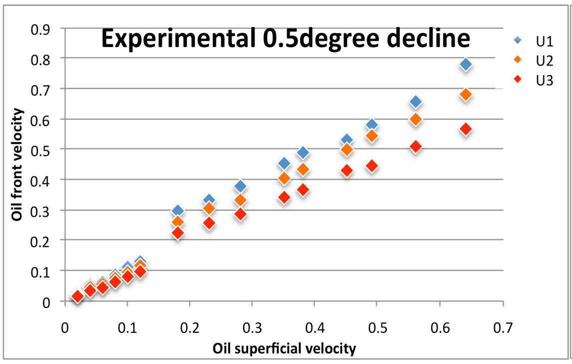


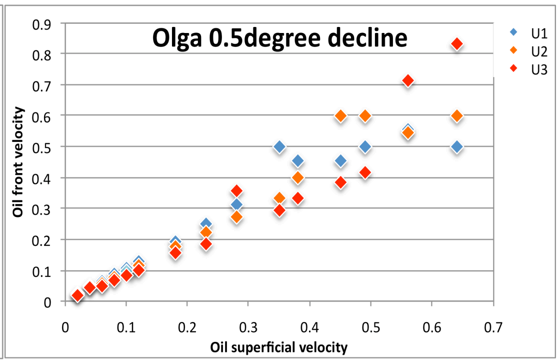
Water Hold Up Vs Time for Usl 0.64 m/s
Water Hold-Up [%]
Time (seconds)
H1-Exp
H2-Exp
H3-Exp
H4-Exp
H1-Olga
H2-Olga
H3-Olga
H4-Olga

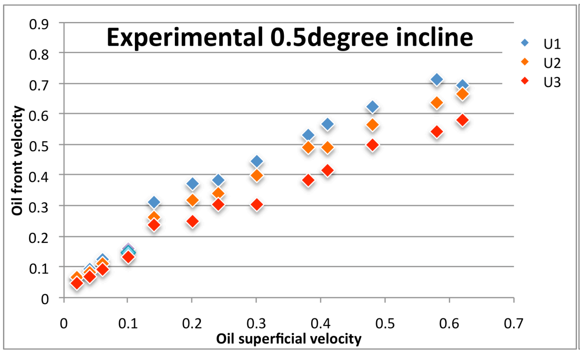
Appendix D Plots – Oil front velocities

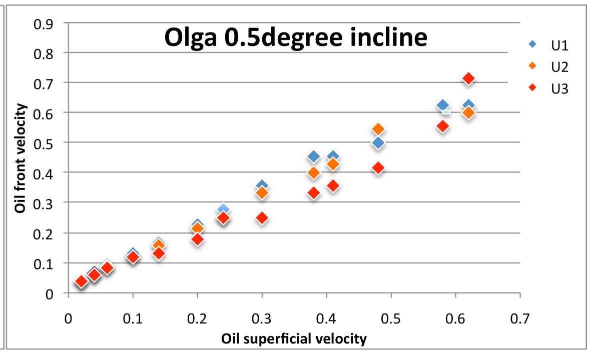












Appendix E Visual data - Water holdup in flexible outlet

These pictures illustrate how water holdup concentrated in the flexible outlet penetrates down into the test section depending on the angle of the outlet. On the right side are pictures of holdup taken at Area 1, see Figure C 1, and the left shows the corresponding angle of the outlet.

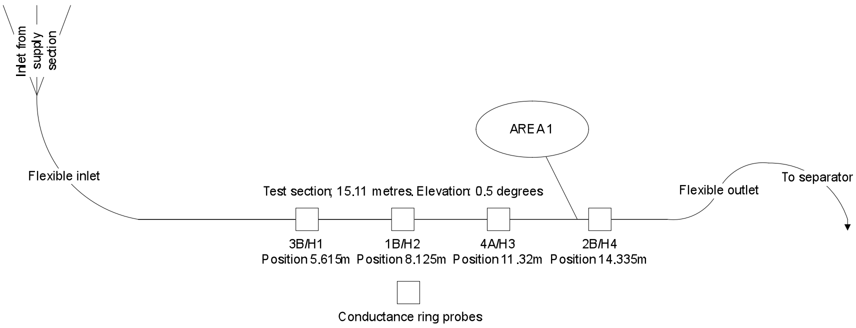
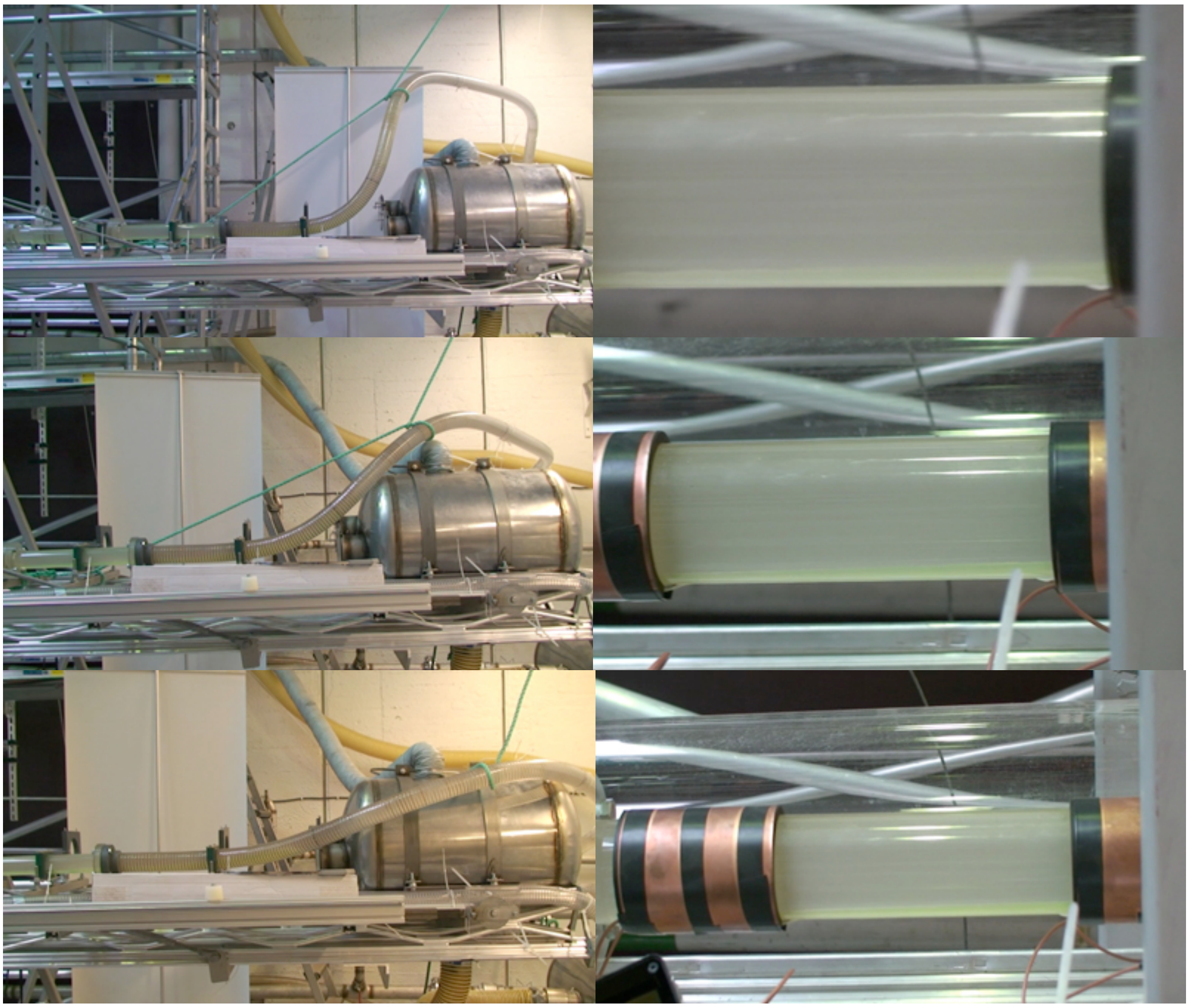
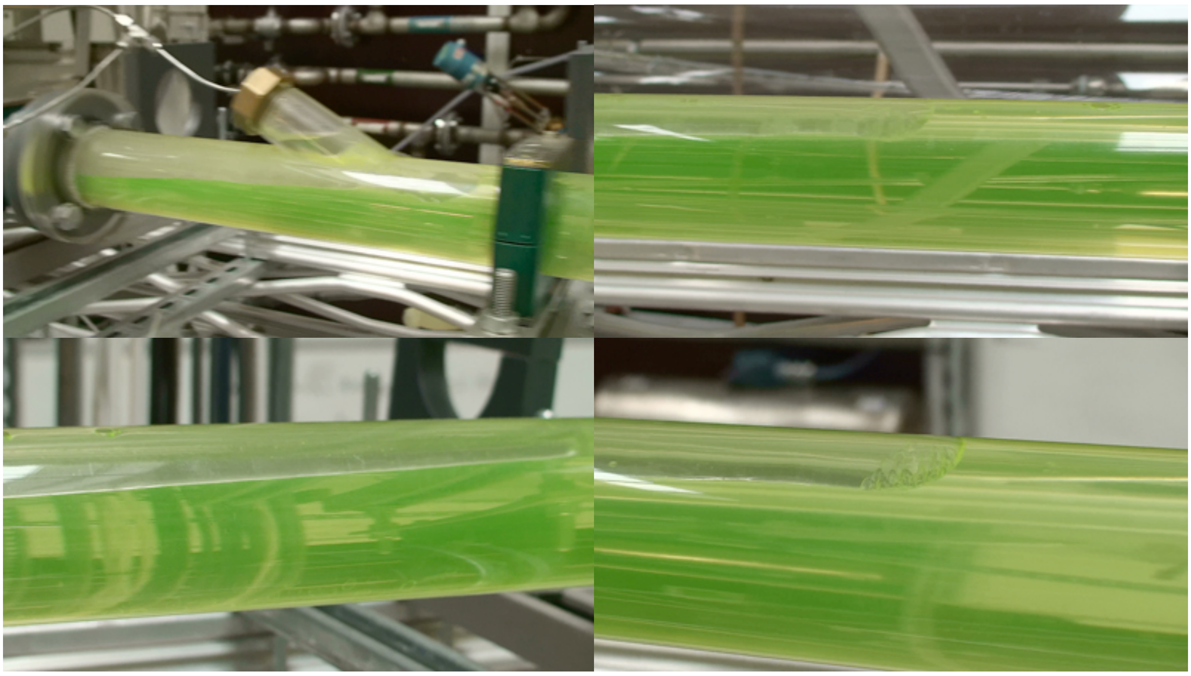


Figure C 1. Area 1 indicates the position for the pictures in the right column.



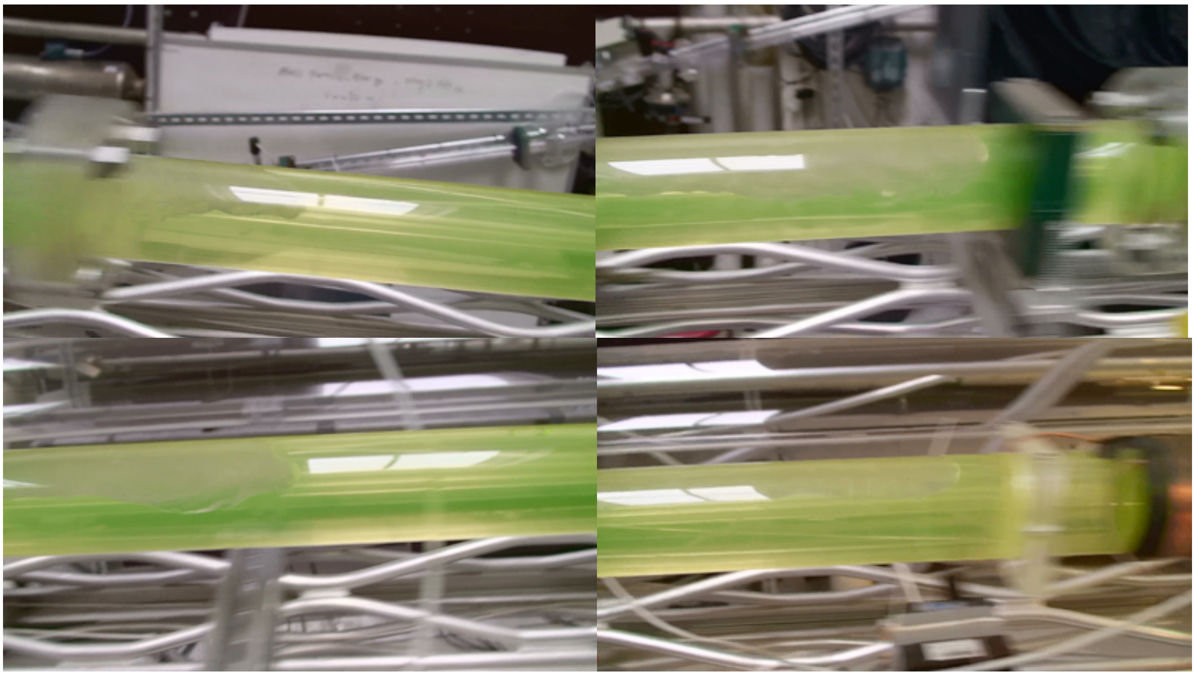
Appendix F Visual data – Oil front at .5-degree declination



Picture D 1. Usl = 0.10m/s, .5-degree declined. T-L: inlet; T-R: 3m; B-L: 5m; B-R: 6m.

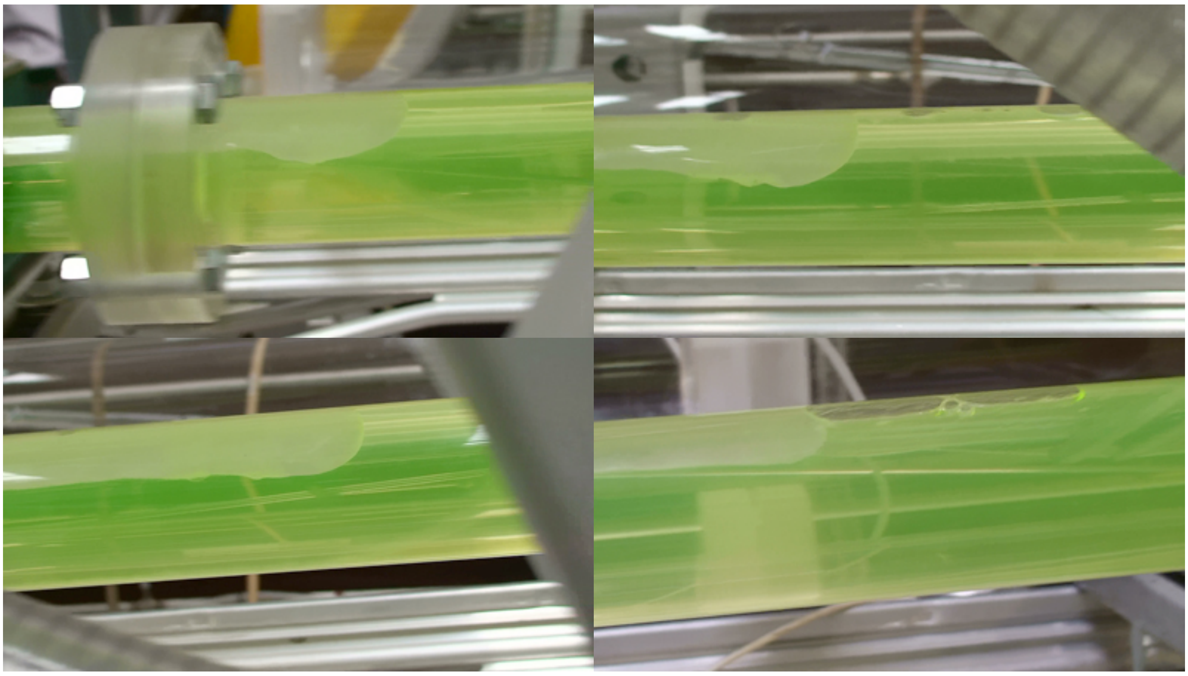
Picture D 2. Usl = 0.23m/s, .5-degree declined setup. T-L: inlet; T-R: 1m; B-L: 11m; B-R: 13m.

Picture D 3. Usl = 0.49m/s, .5-degree declined. T-L: 4m; T-R: 6m; B-L: 12m; B-R: 13m.



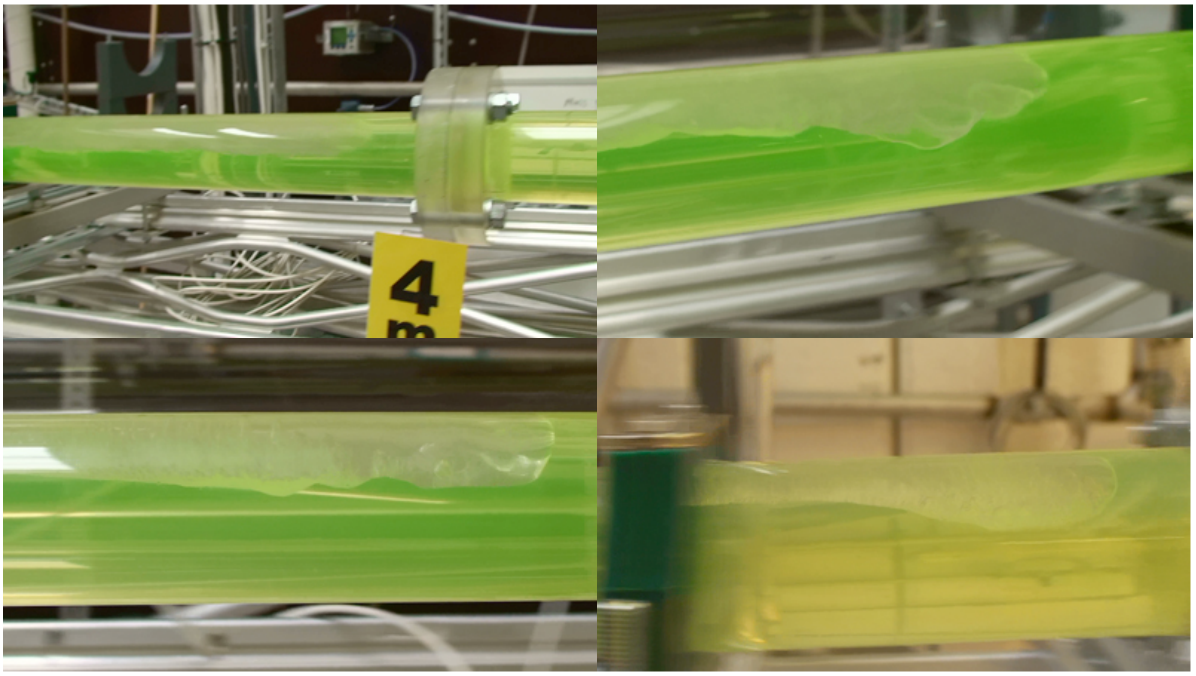
Picture D 4. Usl = 0.64m/s, .5-degree inclined. T-L: 4m; T-R: 6m; B-L: 11m; B-R: 13m.

Appendix G Visual data – Oil front at .5-degree inclination

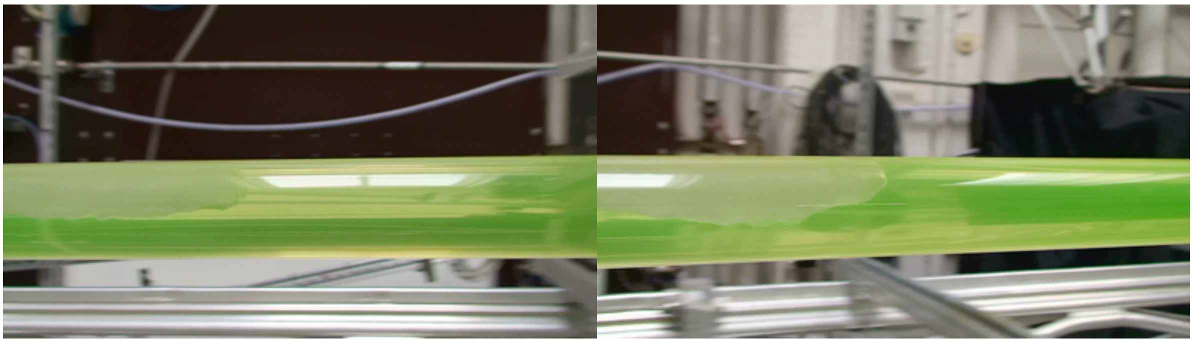


Picture E 1. Usl = 0.10m/s, .5-degree inclination. T-L: 3m; T-R: 7m; B-L: 10m; B-R: 12m.

Picture E 2. Usl = 0.30m/s, .5-degree inclination. T-L: inlet; T-R: 4m; B-L: 10m; B-R 12m.



Picture E 3. Usl = 0.58m/s, .5-degree inclination. T-L: 4m; T-R: 9m; B-L: 12m; B-R: 13m.


Picture E 4. Usl = 0.70m/s, .5-degree inclination. Left: 4m; Right: 6m.

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