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MASTER'S THESIS

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Abstract

The production of petroleum from well is always accompanied by water production, which causes several problems such as loss of pressure in the production line, environmental pollution, corrosion, and issues in transportation and storage facilities. The oil and water phases need to be separated after the production. However, separation of water and oil at seabed can provide the most efficient way of separating these two phases. An inclined pipe separator can do this job safely and efficiently. The design of the subsea separator and the flow regimes of oil-water are essential for the efficiency of the separator.

The test facility was built at the Subsea 7 mechanical base, Dusavik. It consists of a 4 m long 3-inch acrylic horizontal PVC pipe, upward inclinable the 2.5 m long 8-inch IPIP separator, flow rate metering manifold, and high capacity pumping system. The pumping system consists of two centrifugal pumps, both equipped with control systems to have desired rates. Tap water and Exxsol D60 are the working fluids. The tests are performed in three mixture flow rate: 0.3 m/s, 0.5 m/s, and 0.8 m/s. Three pressure transducers are installed in the IPIP separator. Signals from measurement sources are collected and digitized for storage, analysis, and presentation on a personal computer (PC) by the data acquisition system. Flow regimes are determined by visual observation with video recording, and a flow pattern map is made for each condition.

According to the experiments and literature study, the flow regimes of oil and water alter from stratified flow to dispersed flow pattern as pipe inclination shifts from horizontal to vertical. Besides, the oil-water flow pattern in pipe behaves as dispersed flow at high mixture velocity (more than 0.8 m/s). Based on the experiments, it is noticeable that the new design of IPIP separator separates more water at the condition of low (0.3 m/s) and medium (0.5 m/s) mixture velocity cases with 90 % water cut.

This study has shown that the stratified flow regime of the oil-water mixture in the inlet of IPIP separator has a reasonable effect on the efficiency of the separation.

Contents

List of Figures

List of Tables

Nomenclature

Abbreviations

FPSO	Floating Production, Storage and Offloading
IPIP	Inclined Pipe in Pipe
HPS	Horizontal Pipe Separator
PIPS	Pipe in Pipe Separator
UiS	University of Stavanger
ST	Stratified
SM	Stratified Mixing
SW	Stratified Wavy
PF	Plug Flow
DC	Dispersed Continuous
$D_{w/o}$	Dispersed Water in Oil
$D_{o/w}$	Dispersed Oil in Water
$D_{O/WW/O}$	Dispersed Oil in Water and Water in Oil
PE	Potential Energy
KE	Kinetic Energy
SE	Surface Energy
TE	Total Energy
P&ID	Piping and Instrumentation Diagram
IBC	Intermediate Bulk Container
RPM	Rotation per Minutes
PVC	Polyvinyl Chloride
ID	Internal Diameter
LED	Light-emitting Diode

Greek letters

ϵ_w	True water fraction
ϵ_o	True oil fraction
ρ	Fluid density$[kg/m^3]$
ρ_m	Mixture density$[kg/m^3]$
ρ_w	Density of water$[kg/m^3]$
ρ_o	Density of oil$[kg/m^3]$
μ	Fluid viscosity$[Ns/m^2]$
μ_m	Mixture viscosity$[Ns/m^2]$
μ_w	Viscosity of water$[Ns/m^2]$
μ_o	Viscosity of oil$[Ns/m^2]$
τ_o	Shear stress in oil$[N/m^2]$
τ_w	Shear stress in water$[N/m^2]$
σ	Surface tension$[N/m]$
β	Inclination angle$[°]$

Roman letters

S	Slip velocity
U_o	Velocity of oil$[m/s]$
U_w	Velocity of water$[m/s]$
U_{SW}	Superficial velocity of water$[m/s]$
U_{SO}	Superficial velocity of oil$[m/s]$
U	Flow velocity in pipe$[m/s]$
P	Pressure$[N/m^2]$
D	Pipe diameter$[m]$
A	Cross-sectional area of pipe$[m^2]$
h	Height$[m]$
g	Gravitational acceleration$[m/s^2]$
f	Friction factor
Re	Reynold number
We	Weber number
$\frac{dP}{dx}$	Pressure gradient$[N/m^3]$
q_o	Flow rate of oil$[m^3/s]$
q_w	Flow rate of water$[m^3/s]$

Chapter 1

Introduction

The amount of water produced in production flow steadily rise during an oil field's operational life. At a later time, the produced water becomes dominant over oil. The percentage of water produced gradually increases until the field is not economically efficient to continue production. Rising water rate is posing problems, and it disturbs both upstream and downstream processes. A wide variety of production treatments exists, and subsea separation is one of the techniques. It has been developed to deal with the mentioned problems. Although, in onshore, there are many alternatives to deal with these problems. Application of these processes in offshore is even more expensive and complicated. FPSO is one and advanced option that is used mostly for storing produced fluid, but at the depletion stage of the field with more than 90% water cuts, this method is not practical to apply. Therefore, subsea production treatment becomes a necessity, that is separation right on the seabed. Subsea production treatment is the most effective process to handle the production water in offshore.

1.1 Motivation

The Oil companies started to produce the deepwater oil fields such as the Norwegian Continental Shelf, Gulf of Mexico, Deepwater Caspian Sea and other areas on the depletion of production from shallow water and onshore oil fields. Production and transportation of petroleum from these fields are much more challenging and costly. Processing the production water is expensive and complicated in deep water environment.

As an alternative to FPSO technology, the fluids produced from well are routed to a Subsea separator where oil-water mixing is separated and transported apart.

The residual fluid from the separator which is high-quality water is released to sea or boosted back down to seabed for re-injection. Another area of the advantage of having subsea separation is its effect on enhancing oil recovery: While the field matures, reservoir pressure will decline, subsequently reducing the wellhead pressure. The amount of water is the most substantial component produced; reducing the amount of produced water in the liquid column in riser pipe will decrease the pressure loss allowing raised production rates and overall recovery [32].

From an environmental point of view, the oil pollution in world's ocean is not only because of the oil spill but also draining of less treated residual water from the oil fields to the sea. The advanced subsea separation system decreases the effect of pollution on seawater, and it makes subsea separation both economically and environmentally applicable for industry.

The thesis is a collaboration of Subsea 7 and the University of Stavanger. This research concentrates on investigating the subsea separation system by laboratory experiments and explains the data collected.

1.2 Objective

The main objective of the thesis is to build the IPIP separation system and investigate the oil-water flow regimes in a pipe by changing inclination angle, flow rates, and water cuts.

Several tasks of the project can be specified as follows:

1. Research oil water flow models and understand the dynamics of the fluids in pipes.

2. To study oil-water flow regimes in horizontal pipe;

3. To study oil-water flow regimes in an inclined pipe;

4. To investigate how oil-water proportions, fluid velocities, and inclination angles of pipe affect oil-water flow pattern in the pipe;

5. To develop test matrix;

6. To build the lab size set up of subsea separation and carry out several screen tests;

7. To take part in HAZOP meeting and work on its action plan (Appendices B)

8. To build the inclined pipe in pipe separator, designed by Subsea 7, and implement tests on it to observe how the separator work;

9. To analyze the droplet size using camera images.

1.3 Outline of thesis

The thesis is experimental and aims to investigate oil-water flow in an inclined pipe and find out the applicability of this study on subsea separation systems.

The experimental and theoretical concept of oil-water flow in the pipe is described in Chapter 2. Also, several mathematical flow regime models are briefly discussed.

The detailed description of the experimental setup and testing procedures is explicated in chapter 3. The tools and instruments used for data logging are put here as well.

Chapter 4 shows the result obtained through the experiments. The pictures of observed oil-water flow profiles in both HPS and inner pipe of IPIP separator are presented. The effect of oil-water mixing velocity and water cuts on pressure difference in IPIP separator is discussed too. The operation issue of IPIP separator and its applicability at the different flow velocities are analyzed in Chapter 4. Conclusion and further work are addressed in Chapter 5.

Chapter 2

Theoretical part

2.1 Multiphase Flow

It is widely known that multiphase flow is the simultaneous flow of several phases in one stream. It is a comprehensive subject, and in this master thesis, multiphase flow is referred to as two-phase oil-water flow in an inclined pipe. Oil-water flow characteristics, such as accurate prediction of flow pattern, water holdup, and pressure gradient, are significant in petroleum engineering applications. Various flow patterns are observed in two-phase flow in a pipe. It is different from single-phase flow because of the steady flow dynamic is dependent on fluid properties (density, viscosity), pipe inclination, flow rates of the phases (mixture velocity), and proportion of phases (water cut) [35].

2.1.1 Oil water flow regimes in pipe

Flow regimes in pipeline effect on pressure drop, flow-related mixing condition, proper functioning of mechanism such as valves, pumps, measuring tools, and also sustainable operation condition. Researchers have involved in the identification of oil-water flow profiles for ages. Oil-water flow patterns are sub-classified as segregated and dispersed flow. The gravity is the main force acting when the velocities of oil and water are low, which prevents interface interaction leading to a stratified flow. The increment on the flow rate leads to form waves between oil and water layers. Hence this flow regime is called wavy stratified. As well as, interfacial mixing of oil and water phases creates droplets at the interface, and those droplets can stay there until gravitational buoyancy forces over the turbulence forces, otherwise droplets would spread all areas of the cross-section. Dispersed oil-water flow can be classified as water dominated and oil dominated. Water dominated flow occurs at greater superficial velocities and high water cut, and it contains oil droplets inside. The oil-water mixture flow pattern is dispersed oil dominated flow at high mixture velocity with low water cut. Beside segregated and dispersed flow regimes, slug, plug, and annular flow patterns can be observed as variation inflow conditions [13].

2.1.2 Superficial velocities for oil and water flow in pipe

Water and oil flow with volumetric flow rates q_O, q_W , respectively, refer to the volume rate of fluid transported through the cross-section of the pipe. As we know volumetric flow rates for water and oil, we can calculate the superficial velocities that define the flow given by:

$$U_{SW} = q_W/A, U_{SO} = q_O/A \tag{2.1}$$

where, U_{SW}, U_{SO} are superficial velocities for water and oil, respectively, A is the cross-sectional area of the pipe [35].

2.1.3 Two phase fluid properties

In this section, calculation techniques of oil-water mixture flow density and viscosity are shown, and sometimes this method is called mixing rule [35]. The slip velocity is defined as

$$S = U_O/U_W \tag{2.2}$$

where U_O, U_W are oil and water velocities, respectively. Knowing slip velocity, water, and oil flow rates, we can calculate the true fractions at slip as

$$\varepsilon_W = \frac{q_W}{q_W + q_O/S} \tag{2.3}$$

$$\varepsilon_O = \frac{q_O}{q_O + q_W S} \tag{2.4}$$

where q_O, q_W are oil and water flow rate, respectively. From eq.(2.3) and (2.4), density can be calculated as

$$\rho_m = \rho_W \varepsilon_W + \rho_O \varepsilon_O \tag{2.5}$$

But mixture viscosity is not well defined, it is dependant on dynamical processes. There are various viscosity models, Dukler's model is reasonable for stratified flow case

$$\mu_m = \mu_W \varepsilon_W + \mu_O \varepsilon_O \tag{2.6}$$

but a small change in the system may make question this equation [34].

2.1.4 Dimensionless numbers in fluid dynamics

To make a flow model, dimensionless groups have to be defined first and hence try to find the relation between flow regimes and those numbers. The good example, to find dimensionless numbers, is Buckingham Π theorem [15].

Many dimensional groups such as Reynolds, Froude, and Weber's numbers are used to solve the fluid dynamic problems [11].

$$Re = \frac{\rho U D}{\mu} \tag{2.7}$$

The relation between inertia forces and viscous forces may be indicated by Reynold's number.

$$Fr = \frac{U^2}{gD} \tag{2.8}$$

Froude number gives the clue about the ratio between inertia and gravity-buoyancy forces.

$$We = \frac{\rho U^2 D}{\sigma} \tag{2.9}$$

The Weber number is often useful in analyzing fluid flows where there is an interface between two different fluids with strongly curved surfaces.

2.1.5 Pressure gradients in pipe

The pressure gradient for oil-water flow is dependent on fluid parameters (density and viscosity), pipe size (diameter and pipe inclination), and flow velocity. In this thesis, we look at the experimental relation between pressure difference and the pipe inclination [28]. Frictional pressure gradient, hydrostatic pressure gradient, and acceleration pressure gradient are calculated individually and sum up to find the total pressure gradient. The frictional pressure gradient is defined as below

$$(\frac{dP}{dx})_f = \frac{4}{D} f \frac{1}{2} \rho_m U_m^2 \tag{2.10}$$

$$Re_m = \frac{\rho_m U_m D}{\mu} \tag{2.11}$$

Where the m means mixture, f is a friction factor that can vary from laminar flow to turbulent flow regime. The hydrostatic pressure gradient is defined as almost the same as single-phase flow, but fluid mixture parameters should be taken into account [35].

$$(\frac{dP}{dx})_h = \rho_m g cos\beta \tag{2.12}$$

β is an inclination angle for the pipe.

The velocity of the mixture, oil, and water, is changing as the flow is passing through the varying diameter. Hence it affects the change in the pressure gradient as well. This process is called acceleration pressure drop. Acceleration pressure drop is defined as below, considering Bernoulli's equation [14].

$$(\frac{dP}{dx})_a = -\rho_m U_m \frac{dU_m}{dx} \tag{2.13}$$

2.2 Literature review

Despite their importance of oil-water flow characteristics in many engineering applications, liquid-liquid flow in the pipe has not been paid attention to the same wide as gas-liquid flow and even less on oil-water flow in the inclined pipe.

2.2.1 Existence of experimental investigation in the oil-water flow pattern in an inclined pipe

For the academic point of view, Kshanthi [25] did literature research for her Ph.D. dissertation and got the results on Table 2.1. It presents studies done in oil-water mixture flow regimes in the pipe with several inclination angles. Flow patterns are classified into two categories: segregated flow and dispersed flow [26].

Besides, there are a lot of experimental approaches to flow regime observation in an inclined pipe. One of them is summarized [17]: The experiments were carried out to find flow pattern maps, local phase fractions, and pressure gradient measurements with changing pipe inclination (from -5° to +5°), water cuts (from0% to100%) and mixing velocities (0.1 m/s to 1.0 m/s). The experimental set-up was performed in 16 m acrylic pipe test section with ID=60mm and using 61cP viscosity oil and tap water as a test fluid. The flow patterns were classified as below:

- ST- stratified flow-was observed only at low mixture velocities (less than 3 m/s);
- SM-stratified flow with mixing at the interface (0.3 m/s < Um < 0.7 m/s)-this kind of behavior has been found for all pipe inclination except +2.5° and

+5° where the flow was stratified or stratified wavy even at higher velocities (up to 0.8 m/s). For upward pipe inclination the water accumulation increases Uo>Uw, that is why at -2.5° and -5° cases flow tends to mix at intermediate velocities; Generally, they concluded that increasing angle of pipe stabilizes the interface and flow tends to stratify with smooth and wavy interface.

- Dw/o-dispersed water in oil at high mixture velocity Um>0.8 m/s and 10% water-cut (WC).
- Do/w-dispersed oil in water- at high mixture velocity Um>0.8 m/s and 90% water-cut. Distinct stratification is observed during high-velocity cases Um>0.8 m/s: Oil droplets occupied the upper part of pipe Do/w, more water droplets occupied the lower part of pipe Dw/o.

Table 2.1: Recent oil-water flow studies on positive and slightly inclined pipe flows for low viscous oil [25]

Study	μ (mPa.s) ρ (kg/m^3)	Flow conditions $U_{mix}(m/s)$; λ_W	Flow patterns
Alkaya [2] β :0 ° , 0.5° , 1° , 2° , 5° D:50.8 mm P:1.4 bar;T:35C°	$\mu_O = 12.9$ $\rho_O = 848$ $\mu_W = 0.72$ $\rho_W = 994$	U_{mix} 0.025-1.75 λ 0-1	ST, ST& MI, $D_{O/W\&\ W}, D_{W/O\&\ O}$, $D_{W/O}\& D_{W/O}$, $D_{W/O}, D_{O/W}$
Lum [20] β :0° , 5° D:38 mm	$\mu_O = 5.5$ $\rho_O = 828$ $\mu_W = 0.99$ $\rho_W = 998$	U_{mix} 0.7-2.5 λ 0.1-0.9	SW, Dual continuous , $D_{W/O}, D_{O/W}$
Lum [21] β :0° , 10° D:38 mm	$\mu_O = 5.5$ $\rho_O = 828$ $\mu_W = 0.99$ $\rho_W = 998$	U_{mix} 0.7-2.5 λ 0.1-0.9	SW, Dual continuous , $D_{W/O}, D_{O/W}$, Plug Flow
Rodriguez and Oliemans [29] β :0° ,1° ,2° , 5° D:82.5 mm	$\mu_O = 7.5$ $\rho_O = 830$ $\mu_W = 0.8$ $\rho_W = 1060$	U_{mix} 0.04-5.55 λ 0.1-0.9	ST, ST& MI, SW, $D_{W/O\&\ O}$, $D_{W/O}\& D_{W/O}$, $D_{W/O}, D_{O/W}$
Kumara [19] β :0° ,1° ,5° D:56.3 mm	$\mu_O = 5.5$ $\rho_O = 828$ $\mu_W = 0.99$ $\rho_W = 998$	U_{mix} 0.025-1.5 λ 0.025-0.975	ST, ST& MI, SW, $D_{W/O}\& D_{W/O}$, $D_{W/O\&\ O}, D_{W/O}$, $D_{O/W}, PlugFlow$

Another experiment was carried out by Kumara [18]. The experiment was performed in a 15 m long, 56 mm ID, and inclinable steel pipe. There were oil (density=790 kg/m3, viscosity=1.64 cP) and water (density=996kg/m3 and viscosity=1cP) used as test fluid. The tests were carried out by changing inclination (from -5° to +5°), mixture velocity (0.25m/s-1.5m/s) and water cuts (2.5%-97.5%). Characterization of flow patterns and their boundaries were obtained by visual observation and by analyzing local water volume fraction measurements:

- ST (stratified flow): Um=0.25m/s, WC=25% and 0° inclination from horizontal.
- SW (stratified wavy flow): Um=0.25m/s, WC=50%, and +5° inclination; the most important hydrodynamic feature of this flow pattern is the stable wavy structure of the interface.
- STMI (stratified flow with mixing at interface): Um=0.5m/s, WC=25% and 0° inclination. There is some droplet along the interface.

Dispersed flow: Dispersion of oil in water over the water layer, however, water may have small oil droplets at Um=0.5 m/s, WC=95%, and +5° inclination.

- Do/w (oil in water dispersed flow): Um=2.5m/s, WC=95% and +5° inclination.
- Dw/o (water in oil dispersed flow): Um=1.5m/s, WC=2.5% and +5° inclination.
- Do/ww/o (dispersion of oil in water and water in oil flow): Um=1m/s, WC=50% and +5° inclination.
- PF (plug flow): Um=0.25 m/s, WC=92.5% and +5 ° inclination.

2.2.2 Liquid-liquid flow regimes

Unlike the gas-liquid flow regime, the wetting properties, viscosity, and incompressibility characters of both phases are not negligible in liquid-liquid flow regimes. Flow patterns for liquid-liquid flow are dependant on the three primary parameters: flow velocity, pipe parameters, and fluid properties. Pipe diameter, pipe roughness, and inclination angle are considered as pipe parameters. The liquid densities, viscosity, surface tension, and wettability of both phases are fluid parameters. For liquid-liquid flow, the density ratios are close to unity compared to liquid-gas ratios, and the viscosity ratio is from 0.3 to 10000 [38]. Interfacial forces are the main forces because of wetting characteristics and surface tension between liquid-liquid phases. The parameters mentioned above and conditions make liquid-liquid flow a complex research topic and complicate the development of flow regime prediction. Two types of flow regime are typical in liquid-liquid. Here the flow properties and conditions are changing, and it causes dispersed and stratified flow regime. The changes in fluid parameters, velocity, and pipe parameters lead the several transitional flow profiles when the degree of dispersion or segregation of both phases alters. Dispersed oil in water, dispersed water in oil, stratified smooth, and stratified wavy flow regimes may be examples of transition flow profiles for oil and water flow in a pipe [23].

Several mechanical and experimental models for liquid-gas flow in pipe have been researched (Begs and Brill [8], Taitel and Dukler [34], Barnea [4], Mandhane [22]), which are applicable to use. In contrast, there is not enough investigation on liquid-liquid flow, and it has not been modeled as much as liquid-gas flow because of homogeneous mixture behaving of liquid-liquid flow [36]. Many experiments on liquid-liquid flow give an overview that the complex hydrodynamic profile can be observed in liquid-liquid flow, thus founding homogeneous model is only useful at the limited range of conditions.

Russell investigated one of the first studies about liquid-liquid flow in 1959 [30]. He observed the flow regimes in pipe: stratified flow, bubble flow, and dispersed flow. Furthermore he added those terms into liquid-liquid flow regime literature. After Russell, several types of research were carried out on liquid-liquid flow in a horizontal pipe. Limited experiment and research focused on liquid-liquid flow in an inclined pipe, Oddie [23], Lum [21], Rodriguez and Oliemans [29], Kumara [19].

2.2.3 Liquid-liquid flow pattern classification in an inclined pipe

Studies show that two immiscible liquid may flow as either segregated with layers or dispersed profiles. Oddie [23] conducted steady-state or transient experiments of oil-water multiphase flow on 11 m long and 15 cm diameter inclinable transparent pipe with kerosene (the viscosity of 1.5 cP and the density of 810 kg/m^3) and tap water. Consequently, 72 tests were conducted, and homogeneous/dispersed, mixed/semi-mixed, and segregated/semi-segregated flow profiles were observed for oil-water flow. The inclination angle of pipe in test section was varied with eight deviations: $+92^\circ$, $+90^\circ$, $+88^\circ$, $+80^\circ$, $+70^\circ$, $+45^\circ$, $+5^\circ$ and 0° . The increment in setting time of mixture was observed with inclination from 0° to $+70^\circ$ at the range of different flow rates. Oddie observed several flow regimes and found out that those flow profiles may show the various structure as small changes occur in flow conditions. Thus he tended to use traditional terms for describing flow regimes. Especially, water and oil flow as "milky" at the high flow rates, determination of interface between oil and water is not possible in these cases. The observed flow regimes were called according to the definitions of Oglesby [24]: segregated, semi-segregated, semi-mixed, mixed, dispersed, and homogeneous. If the oil-water mixture flows with separated layers in a pipe, flow pattern is called segregated flow. The width of the interface between oil and water is increasing at high mixture velocities. Thus it leads to flow with three layers: oil at the top of the pipe, water at the bottom of the pipe, and the mixture of both phases flows between oil and water layers. The flow profile is mixed when oil and water dispersion occupied more than half cross-section of pipe, and by this way flow regime changes from mixed to dispersed flow at a condition where oil and water are dispersed. The difference between phases is not apparent at the high velocities for homogeneous flow cases.

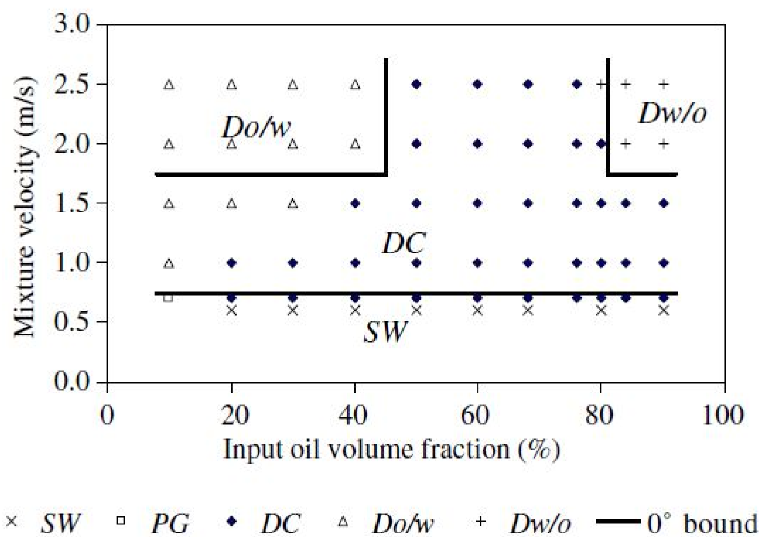

Figure 2.1: The flow pattern map for +5°inclination with the flow pattern boundaries at 0°[20]

Oddie concluded that oil and water tend to mix easily and shows only dispersed flow when pipe deviation is in the range of 0° and 45° . As the pipe deviated further, flow tries to form segregated flow till 70° . But overall, oil and water flow profiles in pipe tend to show dispersed flow regimes at high mixture velocities without depending on the deviation angle of the pipe.

J.Y. Lum has researched experimentally to see how oil and water flow regimes in pipe change at different pipe inclination, both in the direction of upward and downward. He used traditional terminology to call the flow regimes that he observed: separated flow where both oil and water phases retrain their continuity, and dispersed flow where droplets of one phase dispersed in another continuous phase [20]. The test was conducted in a 7 m long transparent acrylic pipe section with 18 mm inside diameter with deviation range from +10° to -5°. Oil Exxol D140 (828 kg/m^3 density and 5,5 mPas viscosity) and tap water were used as the test fluid. Although flow patterns are not visible at high mixture velocity, observed flow profiles are shown in Figure 2.1, where mixture velocity is up to 2.5 m/s. Lum concluded that stratified flow tends to form wavy and change to dispersed flow at more than +5°inclination angle despite lower velocities. Besides, stratified flow is more common in case of upward inclination than downward [21].

2.3 Subsea oil-water separation techniques

The oil-water separator, as referring to its name, is a tool that used to separate the mixture into the separate components. In industry, there are several separator types with different characteristics: gravitational plate separator, centrifugal oily water separator, hydro-cyclone oil-water separator, and inclined pipe-in-pipe separator. There is quite enough research on all separation types except inclined pipe in pipe separator. It is the contemporary separation system that increases the separation quality by varying inclination.

Being different from onshore, we have the additional difficulties with subsea to separate oil and water. Separation systems based on gravitational forces of fluid are well-known downstream of the petroleum industry. However, one of the primary insufficiency is time that allows us to let settle the water down as a result of density difference between water and oil. Considering the time limit at the seabed, that kind of separation is not efficient, and existing technology needs to be developed by taking into account all complication of offshore. In an offshore sector, pipe in pipe separators such as cyclonic and inline separation systems are used by many companies nowadays. They work on plurality of port that may allow to extract more liquid without disturbing stratified flow.

2.3.1 Inclined pipe in pipe oil-water separator

In the conventional gravitational separator, separation is usually achieved by allowing the fluid phase to have a few minutes of idle retention time under the influence of gravity alone. An alternative to gravitational tank separators inclined pipe in pipe separator is used to decrease retention time. The central design concept of IPIP separator is to have tap points for both oil outlets and water outlets, which separated phase flows through those. The total cross-section area of all outlets would be around not more than the cross-section of inner pipe (Figure 2.2).

At the concept of Schlumberger pipe in pipe separator [6], the angle of inclination to the horizontal line may range from 2 to 6 degrees. They found out that inclination beyond 6 degrees may harm a stratified flow pattern. The liquid cut may be measured

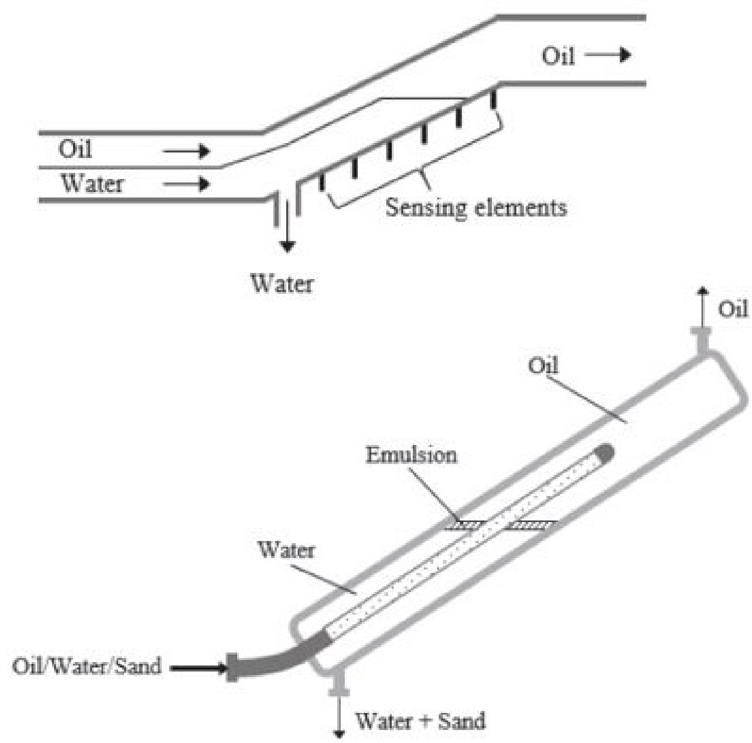

Figure 2.2: Inclined pipe in pipe separator [6]

by multiphase meter before the separator, and we can calibrate it to control the extraction of liquid from the separator. The Downhill section is more efficient for gas and liquid phase flow while the liquid-liquid phase flow separation is more efficient in uphill inclined pipe separator. Valve sensors work as considering the conductivity of oil and water: oil is not conductive. The separation system, as in Figure 2.2, is simple; there is not considerable obstacle to cause friction pressure loss, but one T junction for oil and water stream connection can cause pressure drop on fluid flow.

2.4 Oil and water emulsion

The temporarily stable mixture of immiscible fluids, such as oil and water, is called an emulsion and it achieved suspending tiny droplets of one phase into another phase or vice versa. There are plenty of common emulsion types such as oil suspended in water or aqueous phase (o/w) or water suspended in oil (w/o) [27]. In the schematic

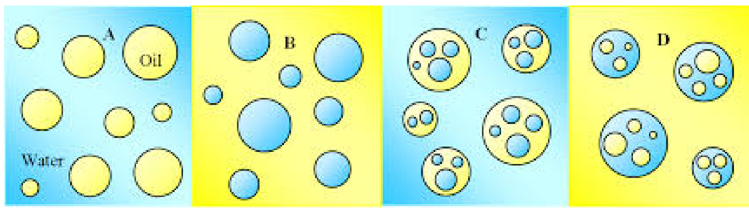

Figure 2.3: Water in oil in water emulsion [27]

diagram (Figure 2.3), there are four types of emulsion described.

- Oil-in-water (O/W) emulsions (A): The emulsion where oil dispersed as the form of small droplets into the water phase.
- Water-in-oil (W/O) emulsions (B): The emulsion where tiny water droplets dispersed into the oil phase as a dispersion medium.
- Water-in-oil-in-water (W/O/W) emulsions (C): The tiny water droplets are dispersed into the oil and forms a water in oil emulsion droplets, and this kind of droplets disperse in the water phase itself as well.
- Oil-in-water-in-oil (O/W/O) emulsions (D): Opposite to W/O/W emulsion, oil is dispersed within water droplets in water in oil emulsion.

2.4.1 Characteristics and Morphology of Emulsions

Emulsions can be characterized by its appearance, types, mixing properties, and phase inversion. Several factors affect emulsion character. For example, it may observe different characters in aged emulsion than a fresh sample due to oil contains many types of adsorbable materials itself.

Also, one of the fundamental characteristics of the emulsion is its morphology, which means emulsion can be present either water in oil, oil in water, or multiple version.

2.4.2 Droplet size and droplet size distribution

The droplet size of oilfield emulsion can be between the range of 0.1 µm and 100 µm or maybe larger. The distribution function shows the range of droplet size in emulsions.

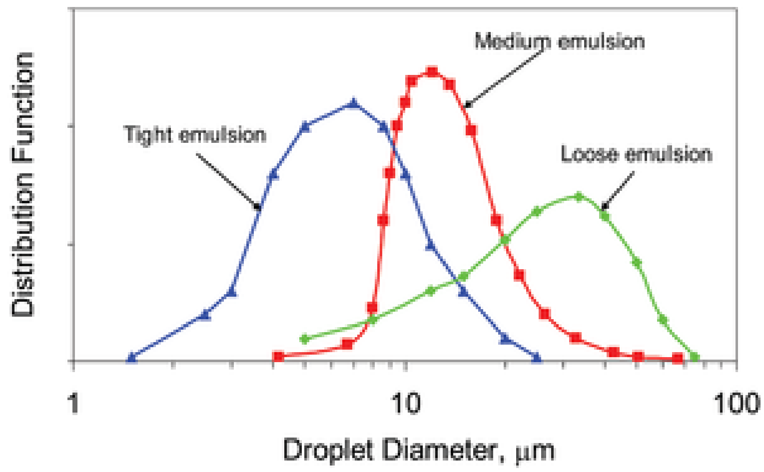

Figure 2.4: Droplet-size distribution of petroleum emulsions [5]

The droplet size distribution determines the stability of emulsion that is significant to consider when selecting the excellent separation technique. As a rule of thumb, the emulsion would be tighter if the average size of the oil droplet is smaller, which leads to the requirement of longer residence time in the separator [33].

2.5 Mathematical flow regime models

Flow in inclined pipe shows different flow regime profiles with changing pipe inclination from horizontal to vertical, and it shows the importance of geometrical condition on flow regimes. In this chapter, we will investigate several flow regime models in various states.

2.5.1 Near horizontal and vertical flow regime models

The classical model combined theory and experiment in itself was emerged by Taitel and Dukler in 1976. The model based on the relation of several forces between fluid-fluid and fluid-wall in a horizontal or near horizontal pipe [34] as the forces, buoyancy, turbulence, interfacial friction forces, and forces related to Bernoulli's effect were considered. Smooth stratified, stratified wavy, annular, disperse, and slug flows are possible to observe. The model based on that if we know superficial velocities, hence fluid fraction can be calculated with assuming near-horizontal stratified flow. Although real fractions are not possible to be found, it is a good starting point for flow regime investigation, knowing fluid fractions are flow regime dependant. Meanwhile, the model works on making an assumption (stratified flow) and checks if it is satisfied. This model predicts flow regimes profile for liquid-gas flow, however it is not efficient for liquid-liquid flow regimes.

Taitel, Barnea, and Dukler introduced the model for upward vertical flow patterns in 1980 [4]. This model is mathematically more straightforward than the horizontal flow regimes' model, only knowing superficial velocities allows us to determine the model for flow regime borders. Dispersed bubble flow (small bubble, medium-sized bubble), slug flow, churn flow, and annular flows are possible to be observed.

The Beggs and Brill model was designed based on the experimental investigation at the University of Tulsa [40]. 90 feet long pipe with inner diameter 1-1.5 inch pipe was used, and the experiment was carried out while changing pipe inclination from -90 ° to +90 ° . The dimensionless number [35] in this model is Froude number $N_{FR} = \frac{U_M^2}{gD}$. Flow regime profiles were subclassified into segregated: stratified, wavy, annular; intermittent: plug and slug flow; distributed: bubble and mist flow. The total pressure gradient can be defined as applying Beggs and Brill model for oil and gas flow [8]. Although, this model will not show the appropriate result if we use for liquid-liquid flow instead of liquid-gas flow patterns, it is a good starting point to use for modeling oil-water flow in inclined pipe with rough assumptions interest.

The Lockhart-Martinelli model [10] is the simplified model with the assumption that two-phase flow is characterized as a separated flow. It leads to calculating total frictional pressure as summing of the superficial pressure drops for liquid and gas, respectively.

$$(\frac{dP}{dx})_f = (\frac{dP}{dx})_{GS} + C\sqrt{(\frac{dP}{dx})_{GS}(\frac{dP}{dx})_{LS}} + (\frac{dP}{dx})_{LS} \tag{2.14}$$

2.5.2 Homogeneous dispersed flow model

In this model, two-phase flow either dispersed fully with oil or water and flowing as a single-phase flow. We can calculate the total pressure gradient in an inclined pipe as the sum of the frictional and the gravitational pressure gradients.

$$\frac{dP}{dx} = (\frac{dP}{dx})_f + (\frac{dP}{dx})_h \tag{2.15}$$

Equation (2.10) and (2.12) defined frictional, and gravitational pressure drops, respectively. For laminar flow regime, the friction factor is f=64/Re, but turbulent friction factors are dependent on pipe roughness, which can be calculated by several methods. Drew, Koo, and McAdams smooth pipe friction factor can be assumed for calculating pressure drop in this case [12].

$$f = 0.0056 + 0.5Re^{-0.32}, \tag{2.16}$$

This equation is only valid for the range of Reynolds number 3000 and $3x10^6$. Both mixture viscosity and friction factor can be defined by different models depending on the dynamical processes in various flow regimes.

2.5.3 One-dimensional analysis for oil-water flow

In this section, a numerical solution of a one dimensional (1D), stratified two-phase flow analysis in inclined or nearly horizontal pipes is proposed. Flow pattern transitions have been computed numerically and compared with data from theoretical transition boundaries and experimental observations [7].

Furthermore, the model will be simplified to lead a computational-numerical resolution. Here, a simplified version of the one-dimensional two-fluid flow model is used for the derivation of the model. The total mass conservation equation and the combined momentum equation for the stratified flow regime are used to define the model.

$$\tau_O \frac{S_O}{A_O} - \tau_W \frac{S_W}{A_W} + \tau_i S_i \left(\frac{1}{\alpha_W A_W} + \frac{1}{\alpha_O A_O}\right) - (\rho_W - \rho_O) g sin\beta = 0 \tag{2.17}$$

$$\frac{\partial(\rho_W U_W - \rho_O U_O)}{\partial(t)} + \frac{\partial(\frac{1}{2}\rho_W U_W^2 - \frac{1}{2}\rho_O U_O^2 + (\rho_W - \rho_O) h g cos\beta)}{\partial(x)} = 0 \tag{2.18}$$

The governing equation are completed by two algebraic relations:

$$\alpha_W + \alpha_O = 1 \tag{2.19}$$

(2.19) shows the volume fraction constraint. Mixture velocity

$$U_m(t) = U_{SO} + U_{SW} \tag{2.20}$$

the mixture velocity is an input parameter, which is a function of time, and it is constant as we consider both fluids are incompressible.

2.5.4 Modelling of oil-water flow using energy minimization concept

For the inclined case, the combined momentum equation for fully developed stratified flow for oil and water can be written as eq.(2.18), here we eliminate pressure drop assuming it is the same for oil and water layered flow profile. The new model is developed to predict flow behavior, including flow pattern, pressure gradient, and hold up for oil and water flow in horizontal or slightly inclined pipe. The model based on that system stabilizes to its minimum total energy [31]. Brauner and Moalem Maron (1989) and then Trallero (1995) worked on pressure drop prediction by the mean of two fluid modeling approaches. They assumed smooth pipe and smooth interface, homogeneous dispersion, steady-state flow, and negligible surface energy between the fluid and pipe wall for the model [39].

The model considers stratified smooth, dispersion of oil in water and oil layer, the diffusion of water in oil and water layer, dual dispersion flow patterns. Moreover, for the stratified flow pattern, the continuity and combined momentum balance equation are solved. The model prediction about pressure drop was compared with experimental data from Alkaya [2], Abduvayt [1], Atmaca [3], and Trallero [37]. Hence it has resulted in that model fulfilled more or less with all experimental data.

The mixture assumed to consist of two continuous phases, oil continuous layer, and continuous water layer, respectively. Anoop Sharma considered those layers during calculation potential, kinetic and surface energies [31].

$$PE = A_1\rho_1\ gh_1 + A_2\rho_2\ gh_2 \tag{2.21}$$

$$KE = \frac{1}{2}A_1\rho_1\ v_1^2 + \frac{1}{2}A_2\rho_2\ v_2^2 \tag{2.22}$$

$$SE = \sigma[dsin(\beta/2) + \frac{6A_1H_{D1}}{d_{SM1}} + \frac{6A_2H_{D2}}{d_{SM2}}] \tag{2.23}$$

Where, d_{SM1}, d_{SM2} are Sauter mean diameter for oil and water [9], respectively. It shows the total volume of the measured droplet population divided by the total surface area of the population.

Hence, the equation below represents the total energy of the system as:

$$TE = PE + KE + SE \tag{2.24}$$

The solution for this model is where the total energy is minimum, and the combined momentum equation is near zero.

Chapter 3

Experimental part

3.1 Experimental Methodology

The motivation of the following experiment is based on both observing oil-water flow patterns in both horizontal pipe separator, and pipe in pipe separator. And the samples will be taken from outlets of PIPS sampling points to measure the droplet size.

3.2 Test fluids

Samples, tap water and Exxsol D60 oil, were taken from Subsea7 Dusavik base. The test fluids and their properties are shown as below:

Table 3.1: Physical properties of test fluids at 15 °C and 1 atm.

Property	Tap Water	Exxsol D60 Oil
Density, g/cm^3	0.9997	0.7976
Viscosity, mPa s	1.686	2.002
Shear Stress,Pa	0.118	0.1402
Torque, μNm	6.268	7.45

Properties of oil and water used in both testing and analysis have been taken from existing literature such as data-sheets and engineering tables (Appendix C). To get more accurate results testing of the liquids have been performed at the University of Stavanger. Anton Paar DMA 4100 densitometer (Figure3.1) was used to measure the density of tap water and Exxsol D60 Oil at UiS lab. The testing temperature was set 20°C and 2 ml sample was used to measure, within about 2 minutes density results displayed on screen.

Figure 3.1: Anton Paar DMA 4100 densitometer

Figure 3.2: Anton Paar MCR 302 rheometer

As for the rheology analysis, Anton Paar MCR 302 rheometer (Figure 3.2) was used to measure share rate, share stress and viscosity. Calibration of test equipment was performed on March 13th 2019.

Both oil and water viscosity is measured at the temperature of 4°C. This temperature was selected considering average sea temperature as the separator set-up designed for subsea. 20 ml of each liquid was taken as the representative sample for analysing. The test was run to see how the viscosity of fluid (oil) change at the range of 1^{-s} and 100^{-s} share rate to characterise the rheological behaviour of the fluid (Appendix C).

3.3 Experimental set-up: installed equipment

The experiments were performed by using the the two phase flow in inclined pipe-in-pipe separator facility at Subsea7's Dusavik base. The sketch of flow facility is represented in Figure 3.3. This section will give information about all parts of the

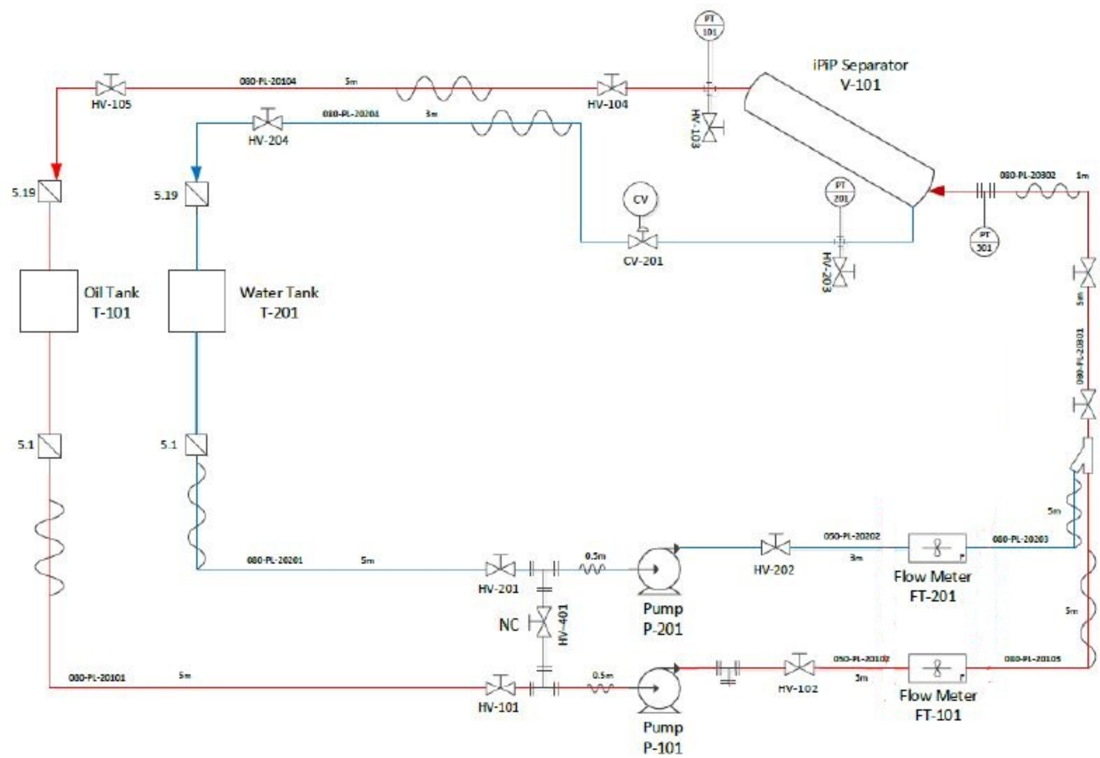

Figure 3.3: P&ID for small-scale separation flow loop (Subsea7)

set-up that forms the flow loop (Appendix A).

The interpretation of the piping and instrumentation diagram shows that oil from the T-101 tank and water from T-201 tank flow through the filters, 5.1, to pumps P-101 and P-201, respectively (Figure 3.4). There are flow meters and valves installed after the pumps to control the flow rate while running the system. Y-joint is inserted to join both oil and water lines to lead into the horizontal separator. The horizontal separator is a transparent acrylic pipe and it was placed after the Y-joint. The two-phase flow pattern can be observed in it. As the flow got the form of stratified oil-water pattern in horizontal pipe separator, it was directed to IPIP separator, V-101, IPIP separator has been designed by Subsea7 and short information about it will be given at the next section. Also, valves and pressure transducers were involved in the test set-up.

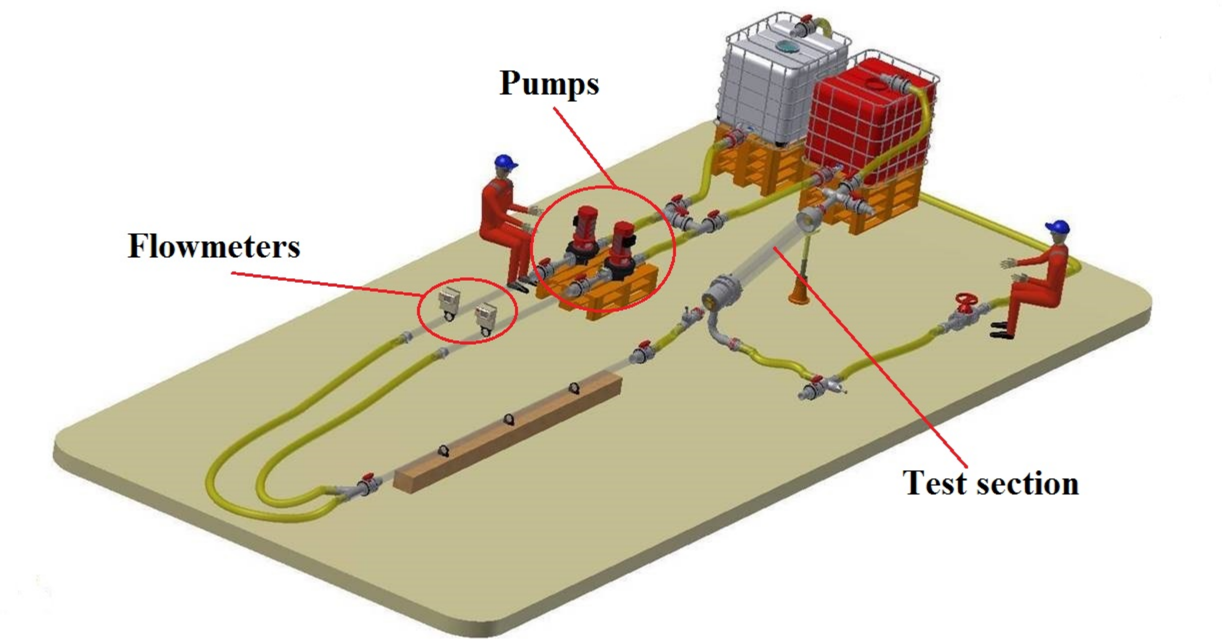

Figure 3.4: General view of small-scale separation flow loop (Subsea7)

3.3.1 Pump and controller

Oil was pumped from the oil storage tank T-101 by P-101, and P-201 was used to pump water from water tank T-201 to get planned mixture velocity and water cut at the inlet point of IPIP separator. Both T-101 and T-201 are IBC type plastic tank with 1000 l capacity.

"Grundfos TP 2000 series" type of centrifugal pump was used, and it pumps the fluids by exchanging rotational kinetic energy to hydrodynamic energy of flow, and it is widely common to use for fluid circulation issue. It can pump 29 m^3/h at maximum head 24 m. The pressure test for the pump has been made with water containing anti-corrosive additives at a temperature of 20 °C.

Figure 3.5: Single stage vertical inline centrifugal pump with control panel

Having the automatic controlling system allows us to change the RPM of pump gear, and it gives expected flow rate, but in case of controlling issues after the flow meters, HV-106 and HV-204 ball valves may be used to get an accurate water cuts.

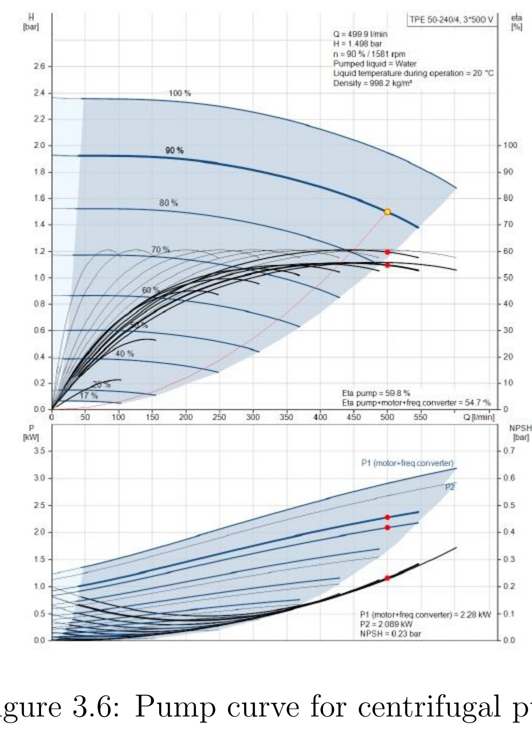

Figure 3.6: Pump curve for centrifugal pump

The graphical representation of the performance characteristics of a pump is as Figure 3.6. It is plotted on an x-y graph with units of head and in units of flow rate, respectively. The information from the curve allows being sure that this kind of pump is suitable for testing goals. The maximum expected flow rate is 2.8 l/s, and the applied maximum pressure for leak test is 2.4 bar.

3.3.2 Transit-time ultrasonic flow meters

The wall-mounted transit time ultrasonic flow meters measure the flow-rate at three points, oil line after P-101 and water line after P-201 to control the water cut. TUF-2000SW series (Figure 3.7) and TS-1 clamp-on type transducer are the combinations of tools used to measure flow rates.

The ultrasonic flow meter is designed to measure the fluid viscosity of liquid within a closed conduit and to have a non-contacting, clamp-on type, which will provide benefits of non-fouling operation and easy installation. The transducer was mounted in V-method (Figure 3.8), where the sound transverses the pipe twice. V-method installation is the most extensive mode for daily measurement with inner pipe diameter ranging from 11 mm to 200mm.(Yantai Auto Instrument Making Co., Ltd)

The steps to the installation of transducers and set flow meter:

- Transducers were located in an optimum position where the straight pipe length is sufficient, and the pipe is in a favorable condition;

- Although PVC pipe does not have any rust problem, the pipe was cleaned from any dust before installing transducers;

- The adequate coupler applied to the spot where the transducers were to be installed to ensure there is no gap between the pipe surface and the transducers;

- To run the flow meter, the standard pipe material, standard liquid, and installation space for transducers entered into the system by the keyboard of flow-meter (Figure3.7).

The accuracy of the tool is ±1 percent. All flow-meter were synchronized to check if they measure the correct flow rate. The transducers were placed on the same pipe as Figure 3.9. Water pumped through the pipe where transducers placed on, the flow rates were checked on screen with several pump rates. We accepted that all flow meter was working synchronized when the same data presented on the screen for all flow meter.

Figure 3.7: Transit-time ultrasonic flow meter and clamp on type transducer

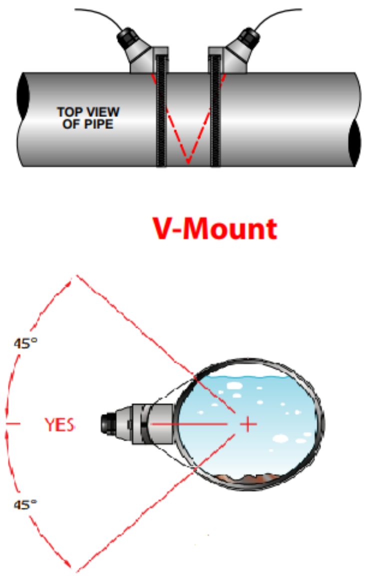

Figure 3.8: V-method Installation

Figure 3.9: Flow meter synchronisation

3.3.3 Mixing and horizontal separation unit

Oil and water streams, passing through the flow meter and valves, combine by Y-junction (Figure 3.10) to have a small interfacial mixing before entering the test section. 4m and 3-inch ID horizontal pipe, separation part (Figure 3.16), is used to get a stratified flow pattern into the inclined pipe section after Y-joint.

Figure 3.10: Y-joint for mixing oil and water

3.3.4 The Inclined Pipe in Pipe Separator and Test Section

The test section consists of two parts. The first one is the horizontal pipe separator with a 4 m long 3-inch acrylic pipe that helps stratified oil-water flow before the second section, IPIP. IPIP separator is the upward inclinable 8 inch and 2,5 m long acrylic pipe. From the Figure 3.11, 3 inch and 2,5 m long acrylic inner pipe passes through the 8-inch outer pipe. A 3-inch inner pipe has some tapping points (10 holes) near the water outlet to flash water from the inner pipe into the outer pipe. Based on the physics, the number of holes should be chosen by considering the total cross-section area of all tapping points should be more than the cross-section area of the oil and water inlet 3-inch line (Figure 3.11). There is one more tapping point on top of the inner 3-inch pipe, near the oil outlet, the idea of having that tapping point is to lead the oil, which assembles inside the 8-inch outer pipe, into the inner pipe.

The thread connection is considered to fit the inner pipe into the outer pipe. It will allow us to easily change the design of the inner pipe and set new designed inner pipe for further testing. Variation in an inclination angle of IPIP separator is obtained by inserted screw-jack (Appendix E).

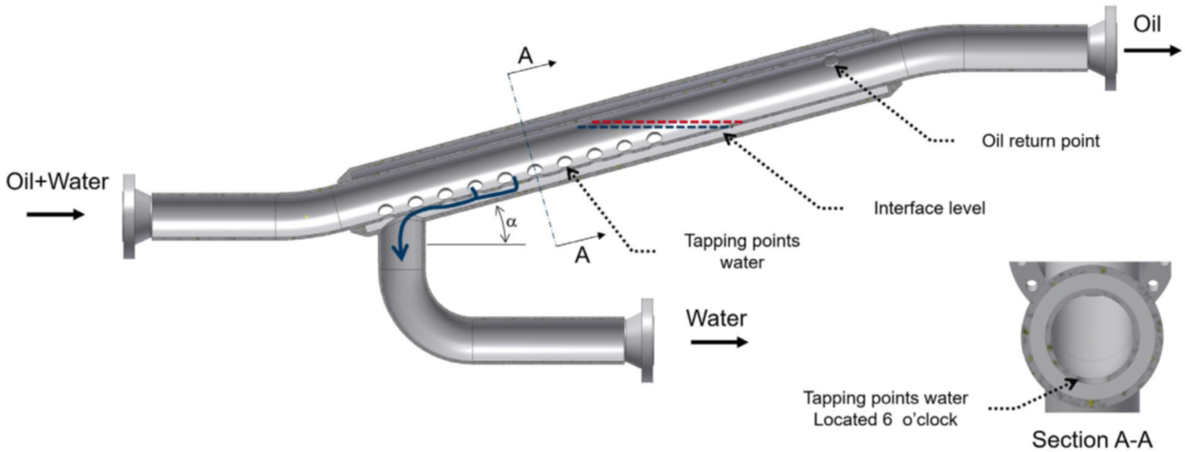

Figure 3.11: Inclined Pipe in Pipe Separator (Subsea7)

3.3.5 Connections in the flow loop

The transparent acrylic PVC 3-inch pipe and 3-inch flexible hose were used to close the loop. 3-inch PVC pipe glued into the fittings by PVC super-glue, and the connection between fittings and hose was sealed by glue and tape as well. The temperature range for PVC is 0-60°C.

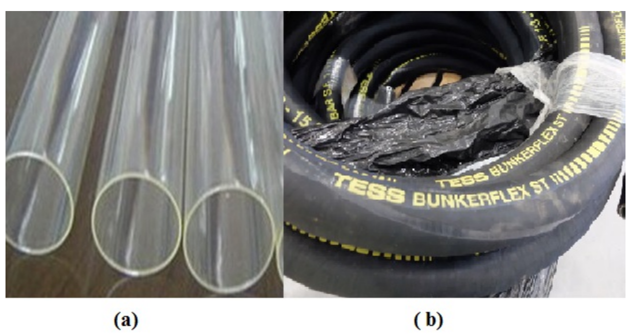

Figure 3.12: (a)Transparent acrylic PVC pipe, (b)Flexible hose

The 3-inch ball valve (Figure 3.13) is used to shutoff and flow rate control in system during experiments. The goal of ball valve is to control flow line through it, with rotating perforated ball by quarter-turn handle. When the ball's perforated side is in flow direction valve is open, otherwise it is close.

Figure 3.13: Three Inch Ball valve.

3.3.6 Data logging and measured parameters

There are three APCE-200PD type pressure transmitters are installed on the test-inclined pipe section: oil-water inlet, water outlet, and oil outlet. Those allow measuring differential pressure where mixture fluid, oil, and water, flow through it.

Figure 3.14: Smart pressure transmitter APCE-2000PD.

The simplicity, low weight, 0.1% high accuracy and easy edibility characters are considered, and it leads to choosing smart APCE-200PD type pressure transmitter (pressure range: 1...3 bar) (Figure 3.14).

LabView 2015 is used to collect data for all the tests. LabView enables us to log, analyze, and present data from measurement devices without programming. LabView is an interactive measurement and data-logging software for quickly acquiring, analyzing, and presenting data from hundreds of data acquisition instruments and devices without programming. Signals can be processed and analyzed, and resulting signals can be sent to hardware devices where applications can be scaled with automatic LabView code generation. Custom reports can be easily created and exported to LabView, DIAdem, or Microsoft Excel (National instrument).

3.3.7 The measurement method for droplet-size

Two sampling points, in oil outlet and water outlet of IPIP separator, are considered to take a sample for droplet size measurement. The procedures for sampling are as below:

- Take samples (volume of petri dish) from both water and oil outlets by varying water cuts in the inlet line.
- Take a picture of emulsion (what is in a petri dish) by a smart camera. Four types of emulsion are expected: (W/O, O/W, W/O/W, O/W/O).
- Zoom out the picture to see the droplet size.
- Repeat the test at both several water cuts and different inclination angles, flow rate as well.
- Analyze the results of how droplet size changes within different tests.

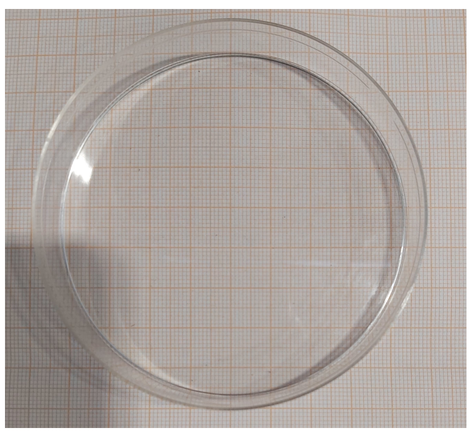

Figure 3.15: Petri dish with reference scale

The reference scale (millimeter paper) taped under the petri dish (Figure 3.15) to say at least approximate size of droplets.

3.3.8 High-speed camera imaging

The android type of smartphone was used to collect photographs and videos in both horizontal pipe separator and IPIP separator section to observe the flow regime

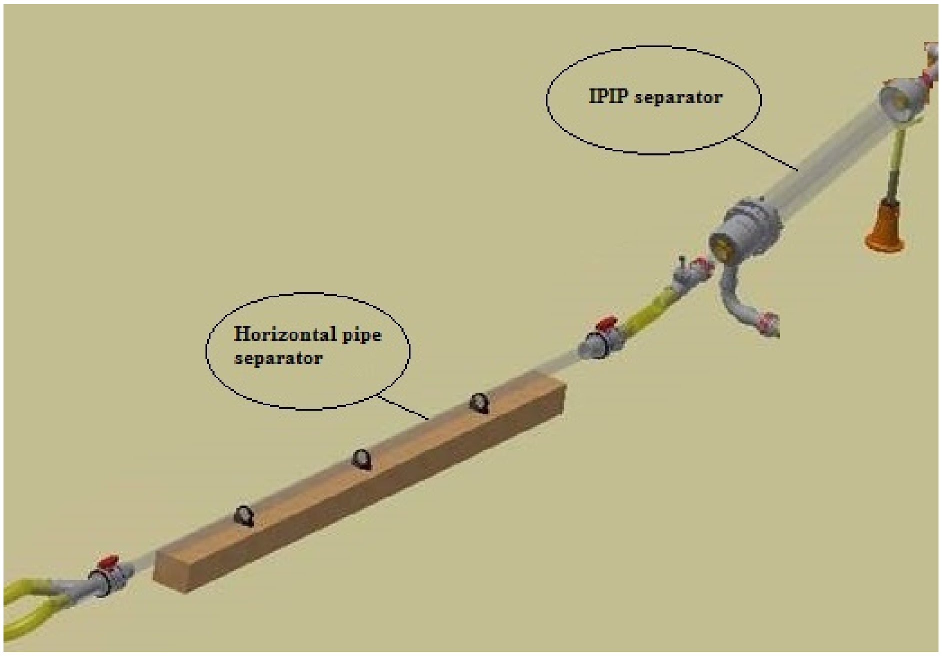

Figure 3.16: The observation sections for cameras' objective

profile at all tests (Figure 3.16). Having a triple camera availability allows to have high quality pictures and videos at even high flow velocities. The primary camera is a 32MP (f/1.7 snapper), joined by a familiar 8MP wide angle shooter (f/2.2 ultra-wide), and a 5MP depth sensor. There is also a single LED flash around (Samsung A70).

3.4 Experimental procedures.

In the test section, the pipe inclination was aligned by level-meter at the beginning of the experiment. Pressure transducers were inserted into the test section, and they need to be aligned as well. The experimental procedures are followed as below:

- Both test section and instruments were aligned;
- Installed pumps and measurement tools should be calibrated before initiating tests if needed. Synchronization was used for flow meters instead of calibration;
- Leak and electric safety tests have to be carried out. Initially, toolbox talk [16] carried out at the beginning of every test.

The leak test was implemented according to the procedures below:

- Checked that water tank T-201 was filled enough, around more than 400l, to fill all systems.
- Opened all valves except HV-101, HV-103, HV-104, and HV203.
- Firstly, let water flow through the system as possible. One bar pressure was expected in the test setup, considering the level of water in the tank.
- Secondly, the test system was observed visually and tried to put sign all the leak.
- Closed HV-201, open any tread connection after the pumps, HV-202, to drain water from the system.

It was the low-pressure leak test, the leak was found at 22 points in the system. Most of them were found in the connection between pipe and hose, thread connection, and some glued parts. Epoxy was used to seal on all leaking points. It needed to dry at least 24 hours.

The high pressure, 2.4bar, leak test was implemented according to procedures below:

- The low-pressure leak test was repeated to check the leakage points again.
- As no leak founded, pumps P-201 and P-101 were set to run, respectively. Pumps could create a maximum of 4 bar pressure, and it was easily controlled.
- Test system was observed visually and tried to put sign to all of the leakage pints.
- Both pumps turned off.
- Closed HV-201, opened any thread connection after the pumps, HV-202, to drain water from the system.

There was no leak after the high-pressure leak test.

Considering no leak in the system, we started to run the real tests according to the testing procedures and test matrix (Table 3.2).

Table 3.2: Test Matrix

No	Test	Mix velocity (m/s)	Water cut%	Oil Flow rate (l/m)	Water flow rate (l/m)	Inclination	Description
1.	1.1	0.3	10	84.3	9.4	15°	Low velocity test
2.	1.2	0.3	25	70.3	23.4	15°	Low velocity test
3.	1.3	0.3	50	46.8	46.8	15°	Low velocity test
4.	1.4	0.3	75	23.4	70.3	15°	Low velocity test
5.	1.5	0.3	90	9.4	84.3	15°	Low velocity test
6.	2.1	0.5	10	140.5	15.6	15°	Medium velocity test
7.	2.2	0.5	25	117.1	39.0	15°	Medium velocity test
8.	2.3	0.5	50	78.1	78.1	15°	Medium velocity test
9.	2.4	0.5	75	39.0	117.1	15°	Medium velocity test
10.	2.5	0.5	90	15.6	140.5	15°	Medium velocity test
11.	3.1	0.8	10	224.8	25.0	15°	High velocity test
12.	3.2	0.8	25	187.3	62.4	15°	High velocity test
13.	3.3	0.8	50	124.9	124.9	15°	High velocity test
14.	4.1	0.3	50	46.8	46.8	10°	Inclination test
15.	4.2	0.5	50	78.1	78.1	10°	Inclination test
16.	4.3	0.8	50	124.9	124.9	10°	Inclination test

This matrix was the screening test and the next phase was to perform detail testing based on the results from the screening test.

The tests were conducted to see the flow regime changes of oil-water flow in an inclined pipe with varying water cut and inclination angle at the different mixture velocities. The idea of testing was to observe the flow profiles in an inclined pipe with efficient angles variants that would give a great initiation to say something about efficiencies of subsea inclined pipe separation.

3.4.1 Testing procedures

Before starting each test, the checked levels of water in T-201 and oil in T-101 were enough to implement tests. Sometimes because of poor separation by IPIP separator, we observed oil in the water tank, then the oil in water tank T-201 transferred manually to T-101 every day before starting tests. As considering water is heavier than oil, we checked that there was no migration between oil and water tanks. The levels of fluid in tanks were always more than around 400l. The testing procedures were carried out as below:

- Opened all valves except HV-401, HV-103 and Hv203;
- Oil and water flow through the filters after tanks was observed visually;
- Closed CV-201 (ball valve due to purchase delay, water outlet valve);
- Commenced running pumps P-201 and P-101, respectively. The desired flow rate in the test matrix was adjusted by changing RPM of the pump and controlling flow by proportional open-close of HV-202, HV-102 valves;
- Opened CV-201 when the fluid level reached the oil outlet in the IPIP separator. CV-201 was adjusted to have a stable interface level in IPIP separator. And the new adjustment implemented for HV-102 and HV-202 to stabilize the mixture velocity according to the test matrix;
- Followed the experimental investigation and sampling procedures;
- After the testing was done, the HV-103 was closed and the HV-401 was opened at the same time. Both pumps run to create only water flow in the system;
- Observed rising interface in the IPIP separator. As there was no observed oil in the system, HV-104 was closed;
- Turned off the pumps and closed HV-201. After opened HV-202, thread connections were checked and opened to drain water from the system.

3.4.2 Experimental investigation and sampling procedures

We observed how mixture, oil-water flow regime changes through the horizontal pipe separator section. The pictures were taken at the start point of the horizontal pipe separator, after the Y-joint, and its end.

As for the IPIP separator, we observed the flow regime in an inner pipe and flow pattern through the tap points into the outer pipe. We recorded all the pictures and videos at each test. Pressures were measured individually at three points in an IPIP separator for each test: oil and water mixture inlet, water outlet, and oil outlet.

Followed the measurement method for droplet size (section 3.3.7) and took samples from both water and oil outlet (Figure3.17). Detailed information about the results of the testing operation is inserted into Chapter 4.

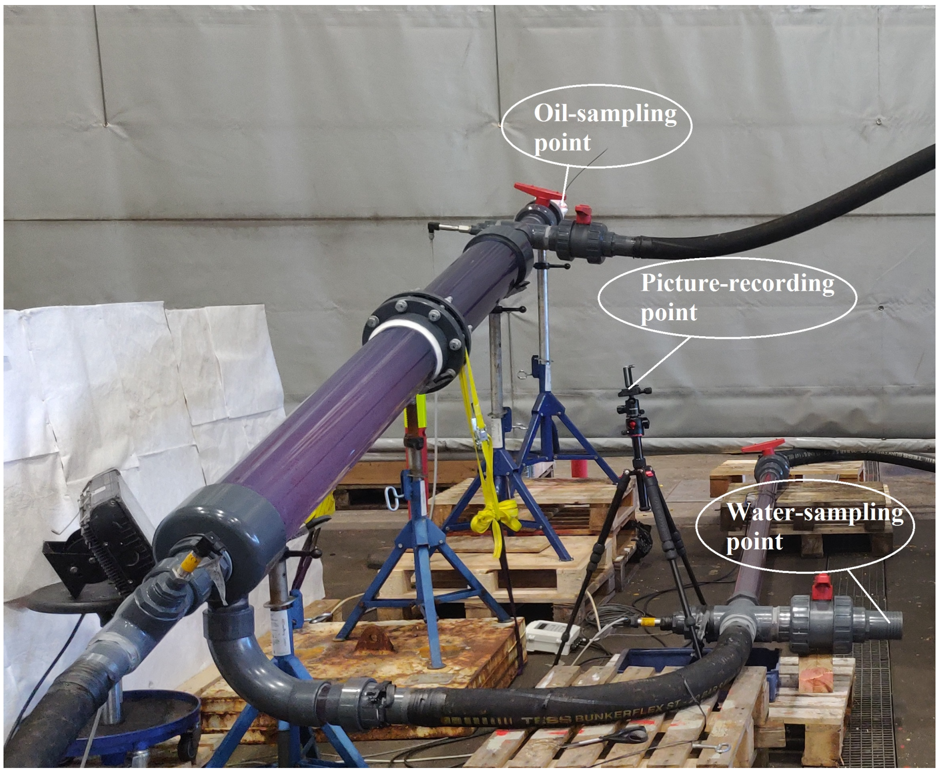

Figure 3.17: The sampling points in the IPIP separator

Chapter 4

Results and Discussion

4.1 Experimental investigation of oil-water flow in an horizontal pipe separator

There are overall 13 tests carried out to observe how oil and water mixture flow regime changes through the horizontal pipe separator. All those observations provide us with an answer to the question: Is the length of the horizontal pipe separator enough to get stratified flow before the inlet of the IPIP separator?

Low velocity tests

The flow starts with the semi-dispersed flow, water in oil, and there are no stratified flow observed in the HPS (test 1.1), but stratified flow with water droplet, Figure 4.1, is observed at the end of the HPS. As water cut rises from 10 % to 25%, the flow starts as the stratified wavy flow and gives its place to stratified flow at the end of the HPS (test 1.2). The stratified smooth flow profile is observed through the all

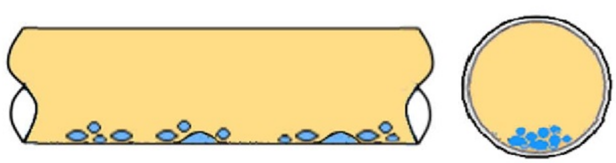

Figure 4.1: Stratified flow with water droplet

pipe section with a 50 % water cut (test 1.3). The same flow pattern (Figure 4.2) is observed in test 1.4 and test 1.5 as in test 1.3.

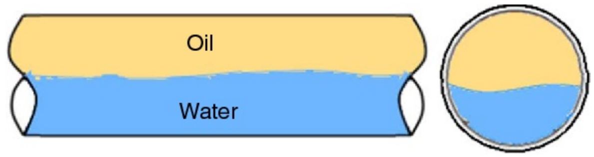

Figure 4.2: Stratified smooth flow pattern

Medium velocity tests

Semi-dispersed water in oil flow regime (Figure 4.3) is observed in a medium velocity 2.1 test compared with the low velocity 1.1 test. Depending on the water cuts, the observed flow pattern at the end of the HPS is smooth stratified flow with different level of interface for all the medium velocity tests. The mixing layer between interface

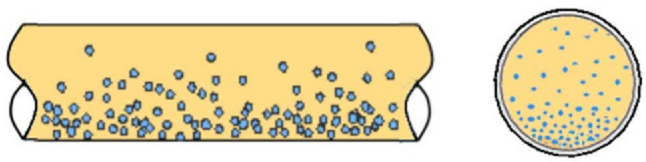

Figure 4.3: Semi-dispersed flow pattern

is more visible than low velocity tests. And generally, flow can be characterized as wavy stratified flow with mixing interface for medium velocity tests in which water cut is more than 10 %. Interestingly, we inspect semi-dispersed flow patterns only as

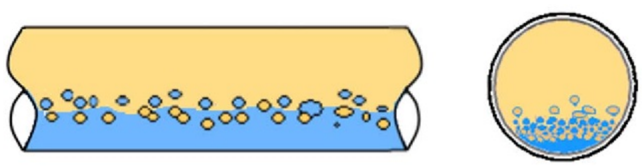

Figure 4.4: Stratified wavy flow pattern with mixing interface

the form of water droplets in continuous oil media for both low velocity and medium velocity tests at 10 % water cut. We obtained separated flow regimes with some mixing interface at the condition of more than 10 % water cut without depending on mixture velocity.

High velocity tests

Without depending on water cuts, the dispersed flow (Figure 4.5) is continuous at the start of the HPS. In detail, dispersed water in the oil flow pattern is typical for test 3.1, and as expected, it gives its place to dispersed oil in water with rising water cuts. Semi dispersed water in continuous oil media flow pattern (Figure 4.3)

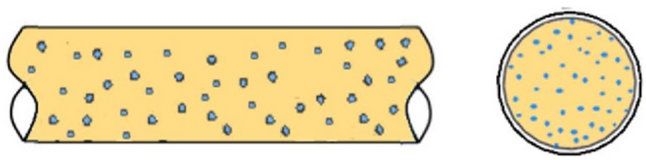

Figure 4.5: Full dispersed flow pattern

is witnessed at the end of the HPS for test 3.1, but a stratified wavy flow regime is the most inspected flow at the same search place for both test 3.2 and 3.3 (Figure 4.4). The thickness of the mixing interface is decreasing with rising water cuts at high-velocity tests.

4.2 Experimental investigation of oil-water flow in an inclined pipe in pipe separator

Low velocity tests

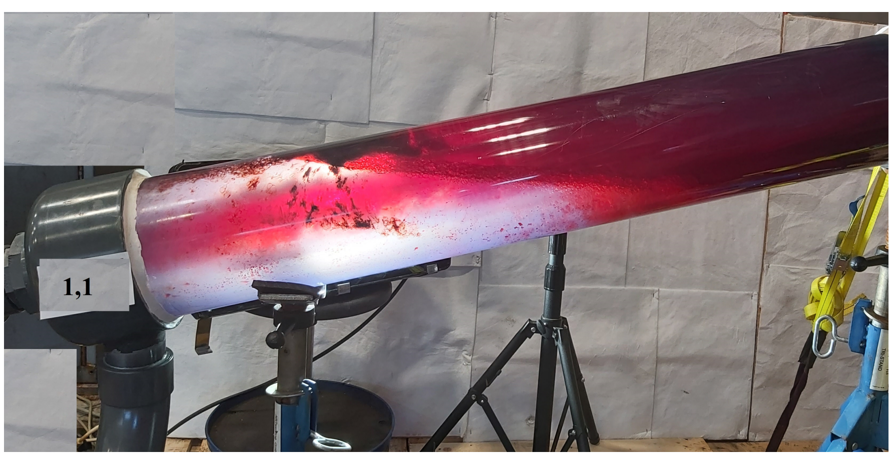

Figure 4.6: Test 1.1- OW flow in an IPIP separator

The dispersed water in oil mixture flows through the inner pipe in an IPIP separator as Figure 4.6. Although the flow is dispersed, separation of mixture in IPIP separator is quiet proportional by having stabilized interface level. The flow pattern turns to form a stratified wavy flow as increasing water cut (Figure 4.7). By combined the test data (test 1.3, test 1.4 and test 1.5), it is clear that with the high water cuts, flow regimes of oil and water mixture in an IPIP separator is stratified (Figure 4.8).

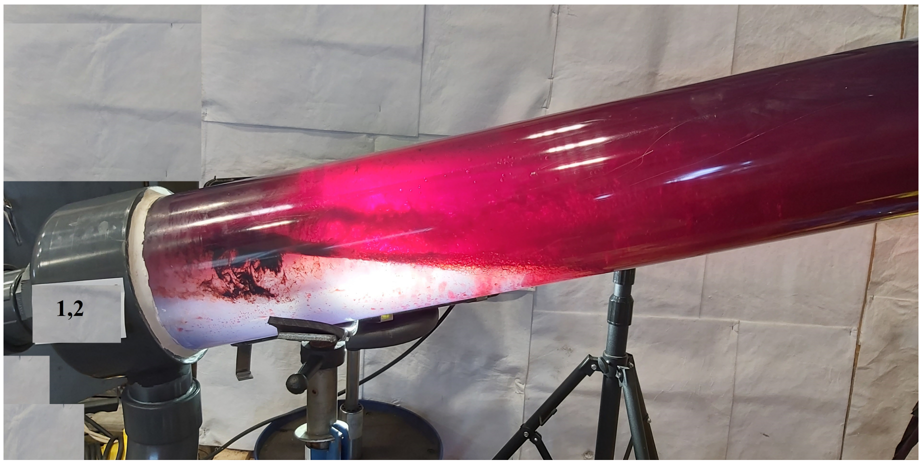

Figure 4.7: Test 1.2- OW flow in an IPIP separator

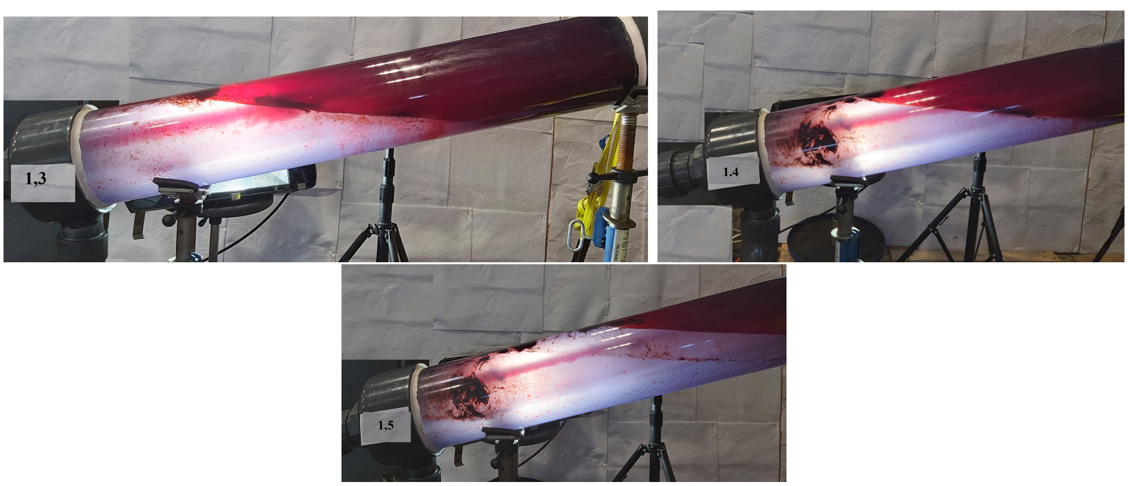

Figure 4.8: Stratified OW flow in an IPIP separator (test1.3; 1.4 and 1.5)

Medium velocity tests

The turbulence in the oil and water mixture flow increases at the high mixture velocity cases. Compared with the low-velocity tests, more turbulence and waviness are observed for the medium velocity tests. As a result, for the 2.1 test, having the

Figure 4.9: Test 2.1- OW flow in an IPIP separator

higher energy, oil holds water droplets itself and migrates together to the oil outlet, and it decreases the oil quality in the oil outlet of IPIP separator, but there are no observed oil droplets in water outlet.

In the higher water cut tests with 0.5 m/s mixture velocity, the stratified flow pattern is observed with some wavy interface similar to low-velocity tests in the inner pipe. Differing from the low-velocity tests, maintaining a stable interface is much more complicated for 0.5 m/s mixture velocity tests. The tap points in the 3-inch inner pipe are not enough to drain all separated water into the outer pipe of IPIP separator. Thus, the water through the tap points splash the oil-water interface and creates the water-oil-water dispersed system near the interface. Having that kind of interface requires extra residual time for separation. The pictures of flow regimes in the IPIP separator are presented in Figure 4.10, 4.11, and 4.12.

High velocity tests

The dispersed oil in water and dispersed water in oil are observed at the high water cuts and the low water cuts, respectively. Also, the separation efficiency of the IPIP separator is reduced because of the dispersed flow in the inner pipe. From visual observation, a minimum of 10 % water in oil outlet and 10 % oil in water outlet are inspected for the 50 % water cut (Figure 4.13).

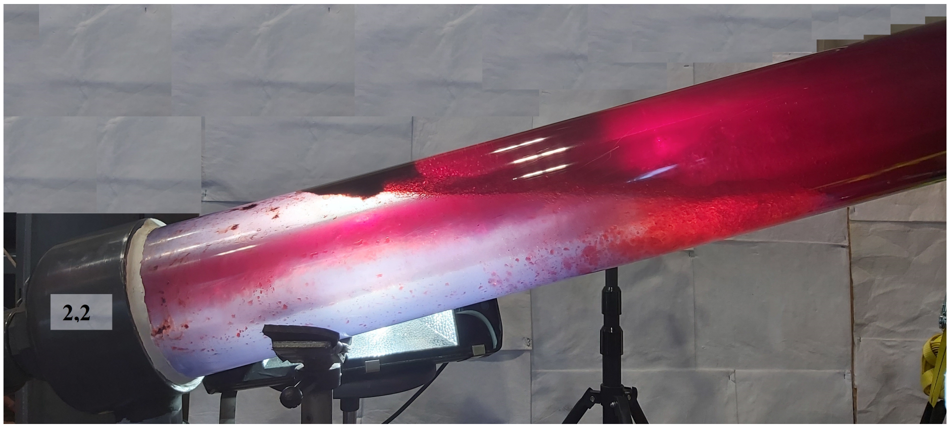

Figure 4.10: Test 2.2- OW flow in an IPIP separator

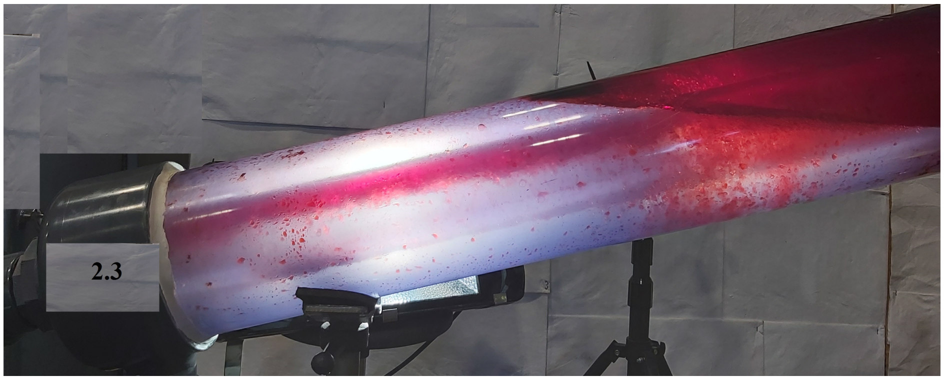

Figure 4.11: Test 2.3- OW flow in an IPIP separator

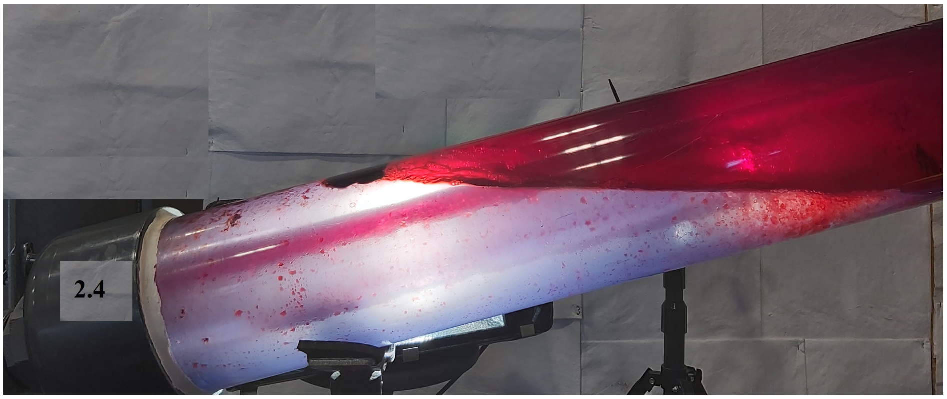

Figure 4.12: Test 2.4- OW flow in an IPIP separator

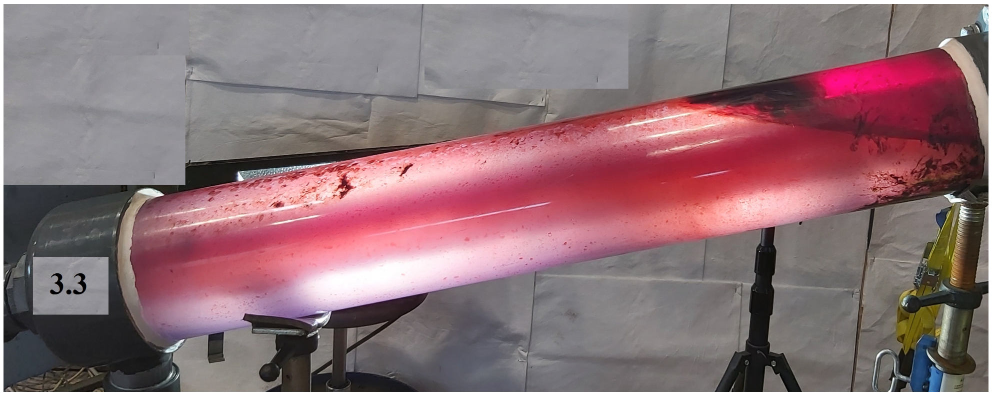

Figure 4.13: Test 3.3- OW flow in an IPIP separator

In general, the oil and water mixture flow regime changes from a smooth stratified flow pattern to a dispersed flow pattern with rising mixture velocity.

4.3 Droplet size measurement

In the experiment, the dispersed phase was present as the different sizes of droplets. It was challenging to measure their sizes because of the limited capacity of camera, and microscopic measurement was the only available option to easily see the ranges of droplets.

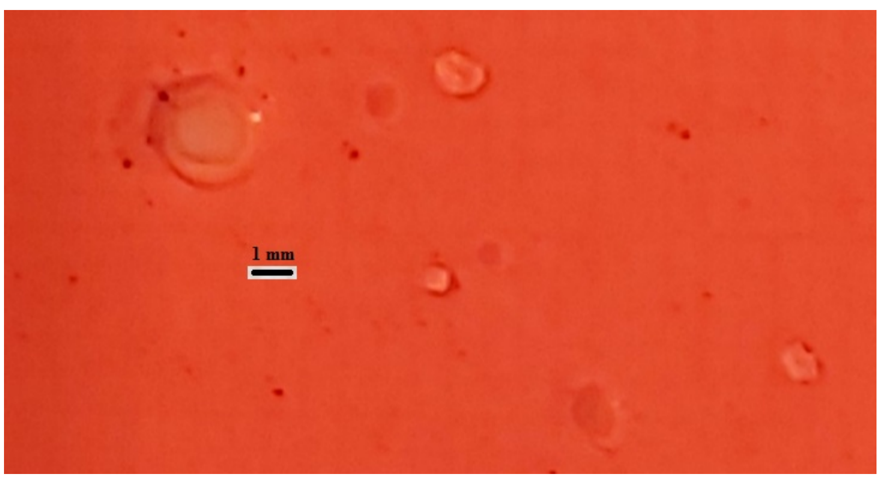

Figure 4.14: Images of the sample in oil outlet (50% water cuts and low velocity test)

Also, the sampling is not well designed to sample all droplets to be seen. Ten attempts were tried, and droplet size measurements were possible in only two tests. From the smartphone's camera, we could measure only the big size droplets that at least would give an idea about the dispersion in an inclined pipe. Both two samples were taken from the oil outlet. It was the unusual observation that the maximum size of a water droplet in oil was around 2 mm for 50% water cut and low-velocity test (Figure 4.14), but in 90% water cut and medium velocity test (Figure 4.15) maximum droplet size was less than 1 mm. It can be explained which oil and water tend to mix more and create dispersed flow at high mixture velocity than low velocity without depending on water cuts.

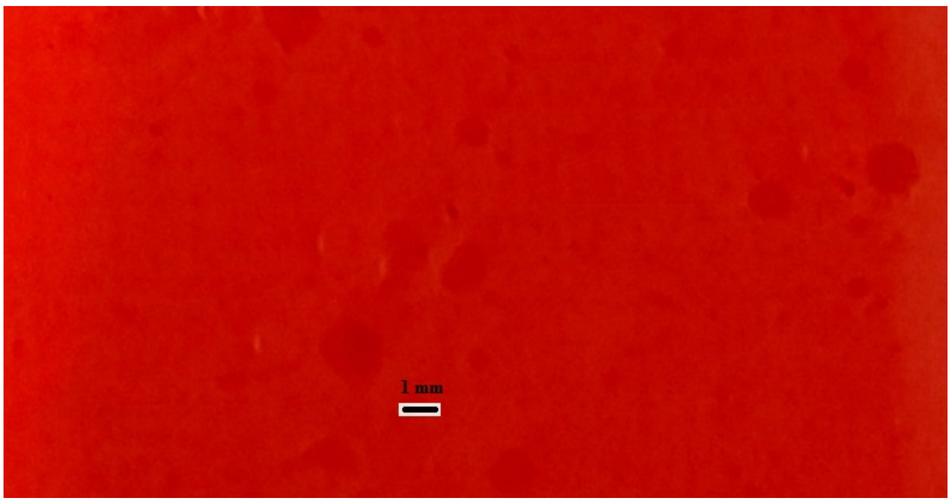

Figure 4.15: Images of the sample in oil outlet (90% water cuts and medium velocity test)

4.4 Pressure difference in the IPIP separator

The pressure differences were measured between the inlet and oil outlet of the IPIP separator, between the inlet and water outlet of the IPIP separator (Appendix A). There are spikes on pressure reading due to signal noises.

The testing set-up is a low pressurized system around 1 bar, so the pressure difference is the sum of friction and hydrostatic elevation. Because of the challenge of having an appropriate oil-water interface in IPIP separator, we adjusted both oil and water outlet individually until getting a balanced interface.

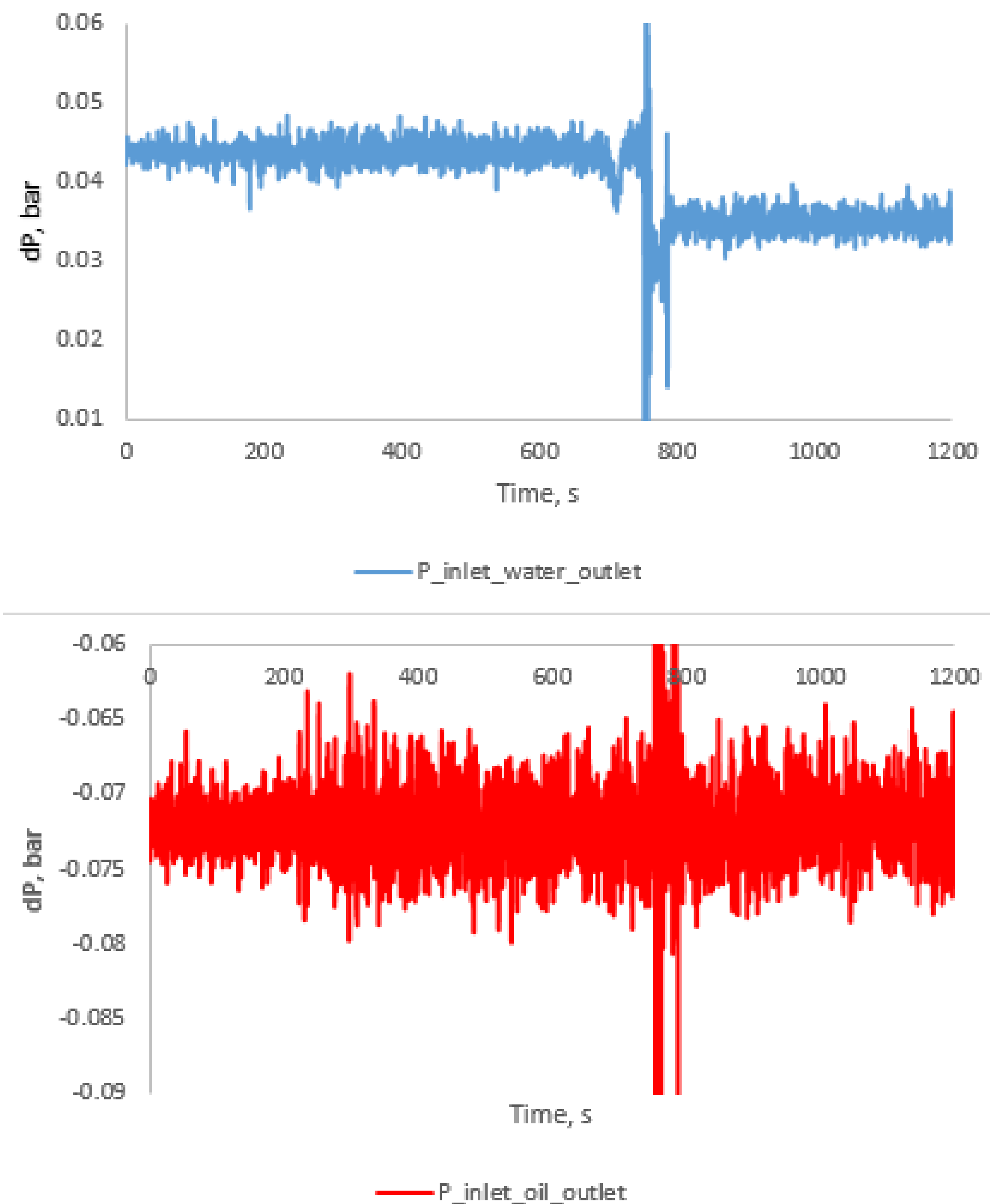

Figure 4.16: Pressure difference in the IPIP separator-Low velocity test 1.3

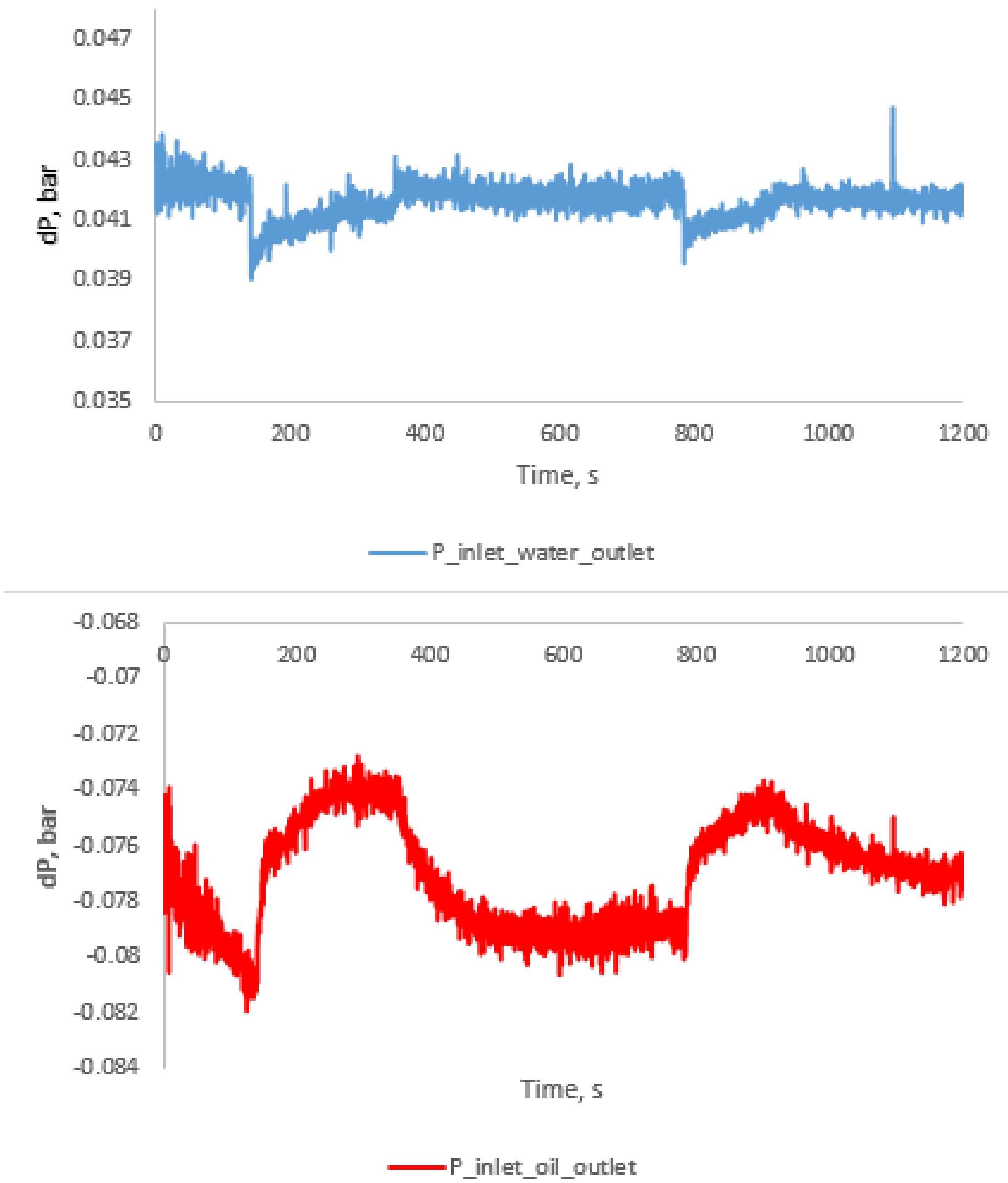

Figure 4.17: Pressure difference in the IPIP separator-Medium velocity test 2.3

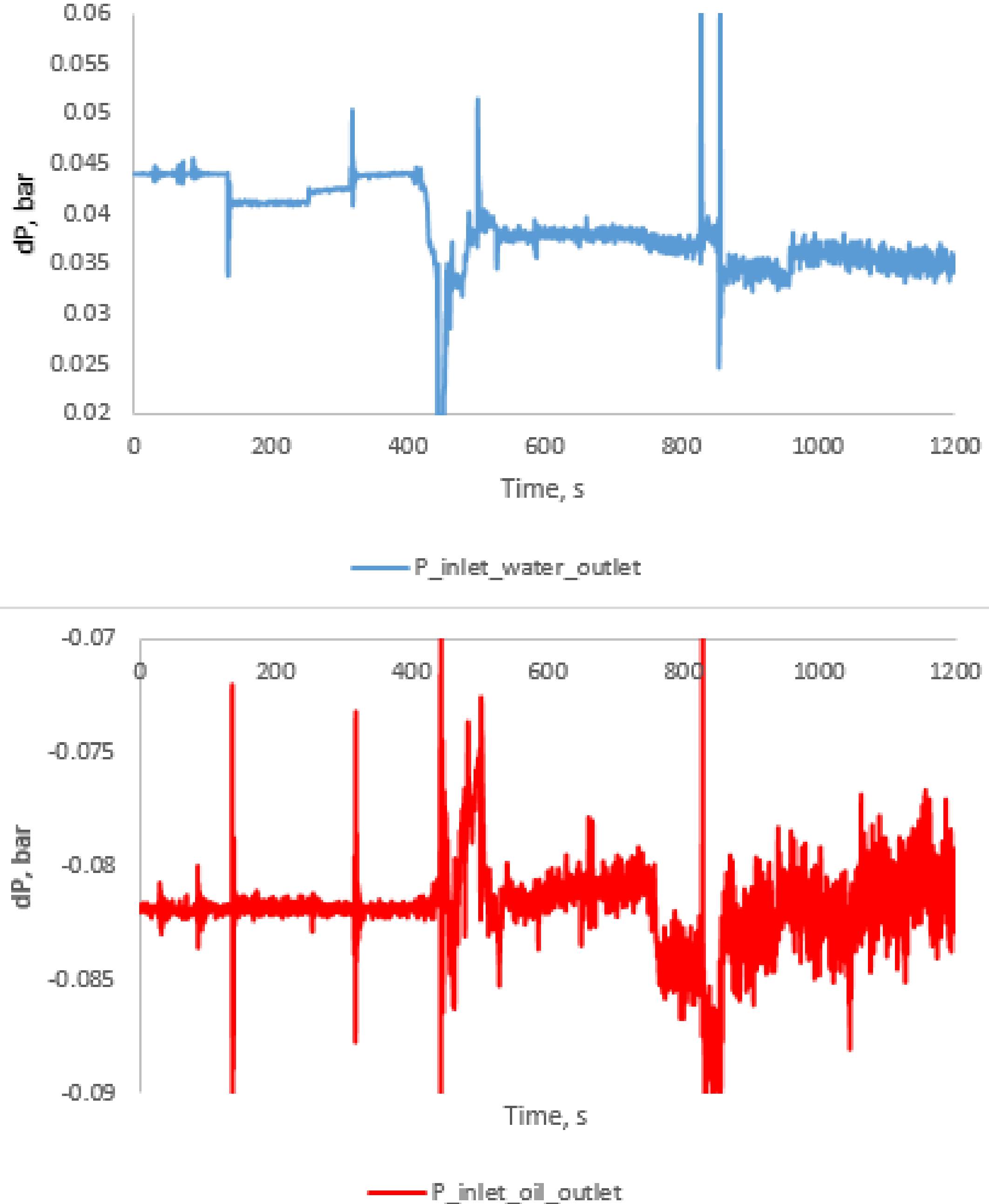

Figure 4.18: Pressure difference in the IPIP separator-High velocity test 3.3

Considering pressure difference data for each test, we can neglect the effect of different water cuts on the pressure difference and the level of the interface.

It is clear that the pressure difference is stable for low-velocity tests (Figure 4.16); it proves that the interface level is no issue for those cases. As for medium velocity tests (Figure 4.17), the number of attempts for adjustment in both water and oil outlet is higher than low-velocity tests. That is why we are observing some fluctuations in pressure differences in the IPIP separator. The controlling of oil-water interface and turbulence in the IPIP separator are not possible at the high mixture velocity of 0.8m/s by adjustments of oil and water outlets. Figure 4.18 shows that maximum stability happens only at 500s and 700s, around 3 minutes (Appendix D).

4.5 Inclination tests for the IPIP separator

Selected data sets of inclination tests are presented here. Figure 4.19, 4.20 and 4.21 make the characteristic effect of in inclination is clear. The water accumulation for 10°cases is higher than 15°cases at both low mixture velocity and medium velocity tests(0.3 m/s and 0.5 m/s). The main axial velocities for oil phase is higher than water phase, so flow pattern is more stratified in 10°inclined pipe than 15°inclined.

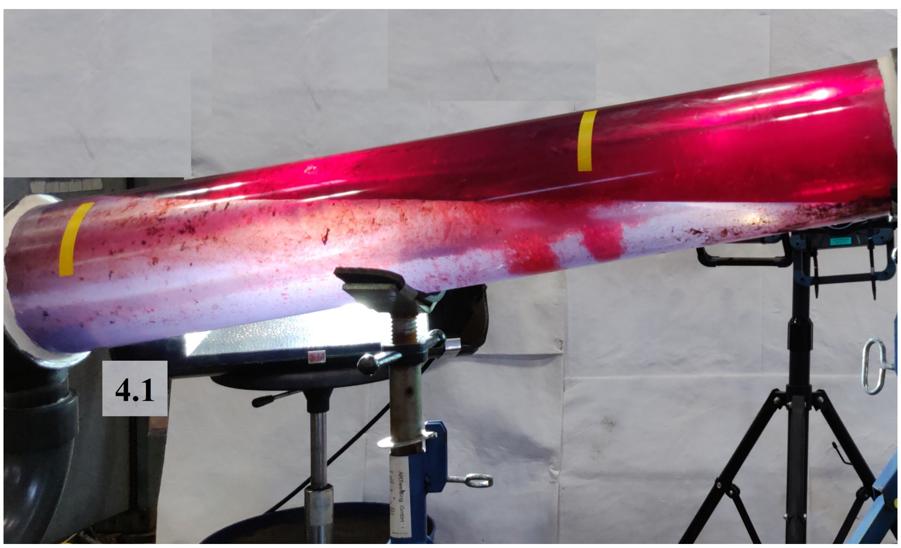

Figure 4.19: Test 4.1- OW flow in an IPIP separator

It is clearly observed that the oil-water flow pattern in inner pipe of IPIP separator is segregated at the position of 10 °with both low and medium mixture velocity tests

(Table 3.2: test 4.1 and test 4.2). And segregated flow pattern is continuous from inlet of IPIP separator to its oil outlet. As for the test 4.3, observed flow regime is dispersed flow in inner pipe and turbulence in the IPIP separator (Figure 4.21).

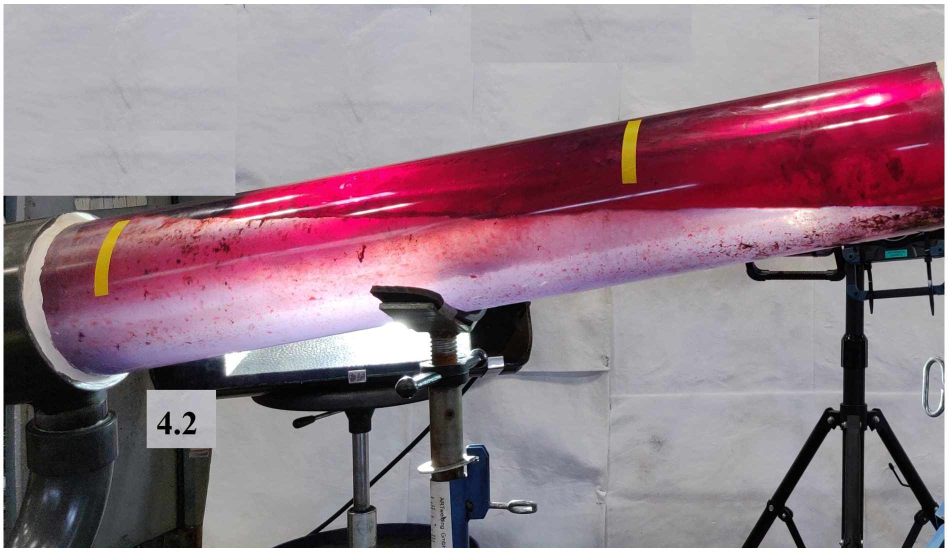

Figure 4.20: Test 4.2- OW flow in an IPIP separator

Figure 4.21: Test 4.3- OW flow in an IPIP separator

Chapter 5

Conclusions and Further work

This thesis investigated the building of IPIP separator test set-up and studied oil-water mixture flow through the IPIP separator. The theoretical background of oil-water flow in the pipe, separation systems, and existing experimental researches were described in detail. Several experiments were performed on the IPIP separation set-up at Subsea 7 base. The main goal of testing was to inspect how the IPIP separator works within various water-cuts and changing flow velocities. Tap water, and Exxsol D60 oil were used as test fluids. The red oil dye was applied to color Exxsol D60 oil, so it was easy to discern the oil-water mixing flow profile in the acrylic PVC pipe. Several challenges affected both building and testing procedures of IPIP separator set-up:

- Many leaks between hose and pipe connection despite application of enough glue. The main reason for the leaks was that the hose used is not applicable for laboratory size of testing. However the leak problem was solved by applying extra tape layers and supper glue.
- Considering the Covid-19 situation there were delays in purchase of parts as well as it affected the separator building and test plan.
- The oil tank had low oil outlet during the testing. If we had more water droplets in oil, it would have filled oil tank with water. Thus for the next test desired water cut was possible with a slightly different result.
- The level of water tank was high. The high level of water tank made the water coming from water outlet require much more pressure to push all water into the tank.

- There was air on the top of the IPIP separator that decreased the reliability of subsea system.

- The Centrifugal pump was not the best choice for maintaining the same flow rate during the test.

- The size and the number of tap points in IPIP separator were not enough to drain all water from the oil-water mixture especially at 10 °inclination tests.

- Substances like wax at the interface, behave as membrane or seals. And when the interface level was under the water tap points, the water bubbles splashed the wax and made turbulence around the inner pipe.

- The horizontal separator pipe length was not enough to have stratified flow at the high mixture velocity (0.8 m/s) with both 10% and 90% water cuts.

- It was not possible to inspect water droplet size in oil outlet and oil droplet size in water outlet with limited capacity of camera. The size of droplets was quite tiny that the objective of camera could not catch them.

Before starting test IPIP separator, inspection on the oil-water flow pattern in an inclined pipe was planned. It would give an idea about the new design of IPIP separator. That test was not possible to implement within the master thesis deadline considering the Covid-19 situation, but IPIP separator was designed with a thread connection that made it easy to take apart. For further work, the set-up is applicable to do many testings with a different alternative to IPIP separator.

Followings are the conclusion that can be obtained out of this study:

1. According to the literature study, the separation efficiency of the IPIP separator (Figure 3.11) is better at low mixture velocity tests (0.3 m/s and 0.5 m/s) than high mixture velocity tests (0.8 m/s).

2. The IPIP separator set-up was built according to P&ID, and it is applicable to do all tests in conformity with the test matrix.

3. The separation quality is not affected by various water cuts at low velocity tests.

4. The separation is dependant on interface level of oil and water in the IPIP separator with changing water cuts at both moderate and high mixture velocity tests.

5. Oil quantity in oil outlet is high at the condition where interface level is low. Similarly, water separated from the mixture has better quality when the interface level is high compare to lower interface level. (There is no lab test carried out within master thesis deadline regarding oil content in water outlet and water content in oil outlet. The quality of separation is based on visual observation only.)

6. The size of 4m and 3-inch horizontal pipe separator is enough to acquire separated flow patterns before the inlet of the IPIP separator, except in the condition of the high mixture velocity with 10% water cut.

7. More water is separated at higher water cuts. Thus the efficiency of IPIP separator is high.

8. The stratified oil-water flow regime is observed in 10°inclined pipe at 0.3 m/s and 0.5 m/s mixture velocity tests.

9. The separation quality with the inclination of 10 °is lower than 15°in this design of IPIP separator (Figure 3.11). The number of tapping points on the inner pipe is not enough to drain water from the oil-water mixture during 10°inclination tests.

10. Combining two tests for droplet size measurement (Figure 4.14 and 4.15), the size of water droplets in oil outlet is larger at low velocity test than at the high velocity test.

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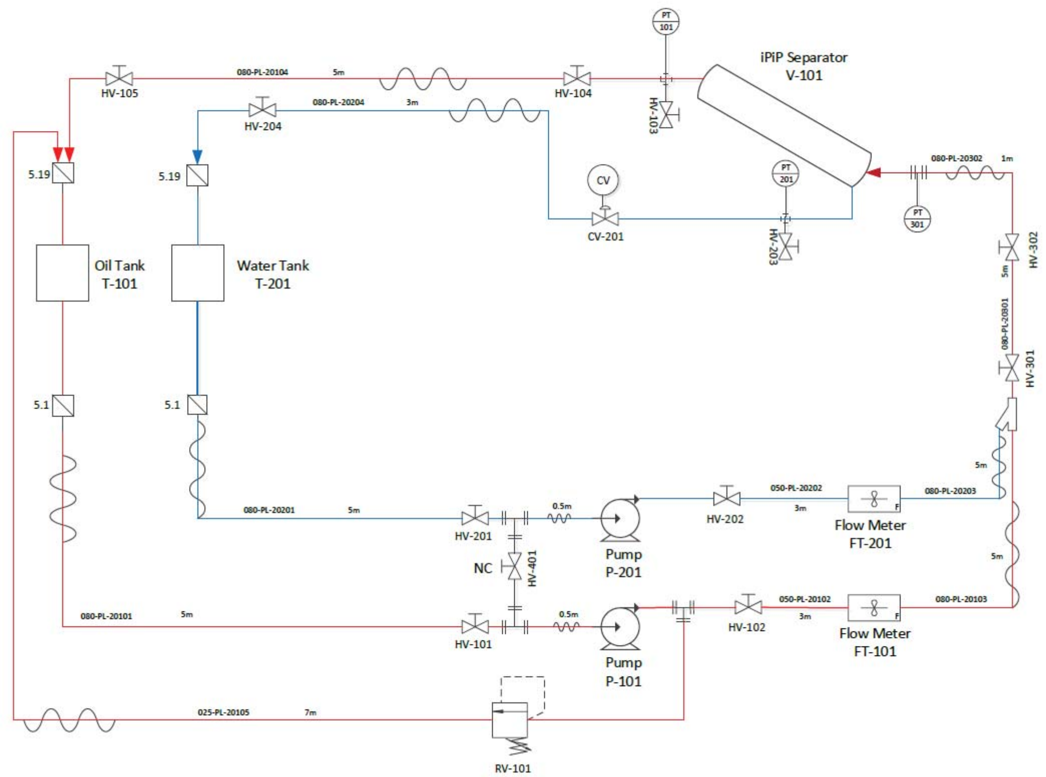
Appendix

A. P&ID



NOTES:

1). SEE SHEET 2 FOR MATERIAL TAKE-OFF
2) 5.1 AND 5.19 ARE FILTERS

OIL/WATER

OIL

WATER

LIST OF ABBREVIATIONS

CV : CONTROL VALVE
FT : FLOW METER
NC : NORMAL CLOSED
PT : PRESSURE TRANSMITTER
RV : RELIEF VALVE

P&ID used for HAZOP 4th June 2020

Rev	Date	Revision	Rev by	Chk'd Engr	App Project
01	17.04.2020	ISSUED FOR REVIEW	VAE	RJ	

Name of Client

subsea 7

Subsea 7 Engineering			Subsea 7 Approval		Client
Draughtsman	Checker	Originator/Engineer	Lead Engineer	Project Manager	Approval
-					
Date	Date	Date	Date	Date	Date
-					

Sheet Size	Drawing & Plotting Scale.

Project **TEC-18-0538**

Title

Overall P&ID –
Small Scale Separation Flow Loop

Dwg No. **TEC-18-0538-DWG-03** Rev **01**

Material Take-Off

Instrument List					
Displayed Text	**Description**	**Connection Size**	**Service**	**Manufacturer**	**Model**
FT-101	Ultrasonic Flow Meter	3"	Oil	Instrument Team	TUF-2000S+TS
FT-201	Ultrasonic Flow Meter	3"	Water	Instrument Team	TUF-2000S+TM
PT-101	Pressure Transmitter	1"	Oil	Aplisens	APRE-2000PD/-0.5..0.5bar/P (M20)
PT-201	Pressure Transmitter	1"	Water	Aplisens	APCE-2000PD/0..4barABS/CG1"
PT-301	Pressure Transmitter	1"	Oil/Water	Aplisens	APCE-2000PD/0..4barABS/CG1"

Equipment List				
Displayed Text	**Description**	**Manufacturer**	**Material**	**Model**
P-101	Centrifugal Pump	Grundfos	Cast Iron with Viton Rubber	TPE 50-240/4 A-F-A-BQQV-JD4 (0-500 l/min)
P-201	Centrifugal Pump	Grundfos	Cast Iron with Viton Rubber	TPE 50-240/4 A-F-A-BQQV-JD4 (0-500 l/min)
T-101	Oil Tank	Swire		THSK, 2300L
T-201	Water Tank	Swire		THSK, 2300L
V-101	Separator	Subsea 7	PVC	Pipe-in-Pipe

Valve List						
Displayed Text	**Description**	**Line Size**	**Valve Class**	**Material**	**Manufacturer**	**Model**
CV-201	PVC Control Valve	DN80	PN10	PVC	GPA	T4OU-E-090
HV-101	PVC Ball Valve	DN80	PN16	PVC	GPA	S6FU-V-R080
HV-102	PVC Ball Valve	DN80	PN16	PVC	GPA	S6FU-V-R080
HV-103	PVC Ball Valve	DN80	PN16	PVC	GPA	S6FU-V-R080
HV-104	PVC Ball Valve	DN80	PN16	PVC	GPA	S6FU-V-R080
HV-105	PVC Ball Valve	DN80	PN16	PVC	GPA	S6FU-V-R080
HV-201	PVC Ball Valve	DN80	PN16	PVC	GPA	S6FU-V-R080
HV-202	PVC Ball Valve	DN80	PN16	PVC	GPA	S6FU-V-R080
HV-203	PVC Ball Valve	DN80	PN16	PVC	GPA	S6FU-V-R080
HV-204	PVC Ball Valve	DN80	PN16	PVC	GPA	S6FU-V-R080
HV-301	PVC Ball Valve	DN80	PN16	PVC	GPA	S6FU-V-R080
HV-302	PVC Ball Valve	DN80	PN16	PVC	GPA	S6FU-V-R080
HV-401	PVC Ball Valve	DN80	PN16	PVC	GPA	S6FU-V-R080
RV-101	Relief Valve	DN15		Brass	Goetze	G618T 1/2" 2..12BAR

Pipeline List							
Displayed Text	**Description**	**Line Size**	**Design Pressure**	**Manufacturer**	**Material**	**Part.No.**	**Quantity**
080-PL-20101	Oil	DN80	PN10	Tess	PVC Hose	10201-48	5m
050-PL-20102	Oil	DN50	PN16	GPA	PVC Pipe	TRP16-063	3m
080-PL-20103	Oil	DN80	PN10	Tess	PVC Hose	10201-48	5m
080-PL-20104	Oil	DN80	PN10	Tess	PVC Hose	10201-48	5m
025-PL-20105	Oil	DN25	PN10	GPA	PVC Hose	135-25-050	7m
080-PL-20201	Water	DN80	PN10	Tess	PVC Hose	10201-48	5m
050-PL-20202	Water	DN50	PN16	GPA	PVC Pipe	TRP16-063	3m
080-PL-20203	Water	DN80	PN10	Tess	PVC Hose	10201-48	5m
080-PL-20204	Water	DN80	PN10	Tess	PVC Hose	10201-48	3m
080-PL-20301	Oil/Water	DN80	PN10	GPA	PVC Pipe	TRP10-090	5m
080-PL-20302	Oil/Water	DN80	PN10	Tess	PVC Hose	10201-48	1m

NOTES:

1). SEE SHEET 01 FOR P&ID

OIL/WATER

OIL

WATER

LIST OF ABBREVIATIONS

CV : CONTROL VALVE
FT : FLOW METER
NC : NORMAL CLOSED
PT : PRESSURE TRANSMITTER
RV : RELIEF VALVE

Rev	Date	Revision	Rev by	Chk'd Engr.	App Project
01	17.04.2020	ISSUED FOR REVIEW	VAE	RJ	

Name of Client

Subsea 7 Engineering			Subsea 7 Approval		Client
Draughtsman	Checker	Originator/Engineer	Lead Engineer	Project Manager	Approval
-					
Date	Date	Date	Date	Date	Date
-					

Sheet Size | Drawing & Plotting Scale.

Project **TEC-18-0538**

Title

**Overall P&ID –
Small Scale Separation Flow Loop**

Dwg No. **TEC-18-0538-DWG-03** Rev **01**

B. HAZOP Worksheets

Node Description

Node 1. OIL - Intent of node is to provide oil, via a centrifugal pump, at an adjustable flowrate to the wye piece (to allow mixing) and on the outlet of the inclined separator allow the separated oil to return to the tank. Node includes a flowmeter, pressure sensor, sampling point and filters on the inlet and outlet of the oil storage tank. A relief valve is included on the pump discharge connecting back to the oil storage tank. Sections are constructed with a combination of rigid PVC pipework (3") and hose with threaded and glued connections. The system is leak tested (1.5barg) with water before operation. Monitored data is logged and samples taken to be tested (off-site) to assess separator efficiency.

Oil: Exxsol D60 Oil (flash point 64degC) coloured with dye

P&ID: TEC-18-0538-DWG-03

Design and Operating Conditions

Node	Flowrate	Operating Pressure	Design Pressure	Operating Temperature	Design Temperature
1	Varying from approximately 80 to 230 litres/min	Ambient pressure with a slight positive on discharge of pump. The maximum pump delivery pressure is 2.5bar	10bar (PN10 limiting PVC pipework) On basis glued/threaded connections are made up correctly they are also rated PN10. Pressure rating of connections will be leak tested, as part of the system leak test, to 1.5barg.	Ambient	Manufacturer recommendation to discuss with them if pipework/hose is planned for use at temperatures above 20degC. The epoxy used for glued connections is suitable up to 60degC

HAZOP Worksheet

Parameter	Deviation	Causes	Consequences	Mitigations	Action	Owner
FLOW	No/Less	Closed or partially closed valves at pump outlet HV-102 or other valves on iPiP outlet HV104 & 105	Dead-head pump (2.4+head of oil ~0.17barg) if valve(s) on discharge side are closed – pressure increase	Valve position checks in procedure Relief valve (set 1.5barg) vents back to oil tank		
			If valve closed on inlet pump will run dry, cavitation – potential damage	Valve position checks in procedure	1. Clarify consequences of pump running dry and any internal mechanism and highlight inlet valves to be pen	Venki
		Pump trips or stops	System stops flowing – delay to test	Operator in place monitoring flowmeter		

Parameter	Deviation	Causes	Consequences	Mitigations	Action	Owner
FLOW		Blockage in line or in filter	As per closed valve above	Clean system / fluid. Filter visible for Operator to check.	2. Include step to inspect filter in procedural steps	Venki
	More	Incorrect setting of pump (or outlet valve)	Effect on test results	Operator following test matrix for different flowrates and monitoring flowmeter as part of pump flowrate setting		
	Reverse	Valve downstream of wye closed and water pump P-201 running with oil pump P-101 switched off	Increased level in oil tank (from pumped water) – potential for overfilling Pump - potential for damage	Valve position checks in procedure Combined fluid volume (~2000litre) less than oil tank capacity (2300litre)	3. Confirm whether reverse flow through pump creates any issue for the pump itself	Venki

Parameter	Deviation	Causes	Consequences	Mitigations	Action	Owner
FLOW	Misdirected	Valve HV-401 (connecting water to oil sections) left in open position	Effect on test results	Valve position checks in procedure (HV-401 and HV-101 opened at end of each day to allow water flush)		
		Flushing operation – valve HV101 is left open	Water could be flushed back into oil tank – see above for increased level in tank	Valve position checks in procedure		
		Valves HV-104 and 105 left in closed position	Effect on test results all flow passes through water outlet to water tank. Increase in water tank, reduction in oil tank	Valve position checks in procedure	4. Clarify valve numbering in the procedure to reduce risk of valve positioning error	
	Fluctuating	Change in pump speed	Effect on test results	Operator sets pump speed using VSD pump control / interface Operator in position confirming flow with flow meter		

Parameter	Deviation	Causes	Consequences	Mitigations	Action	Owner
PRESSURE	More	Closed valve (or blockage) on pump discharge	Dead-head pump (2.4+head of oil ~0.17barg) if valve(s) on discharge side is closed – pressure increase	Valve position checks in procedure Relief valve (set 1.5barg) vents back to oil tank		
	Less	Open system (tank) – no credible Pressure Less scenarios identified				
TEMPERATURE	More	Note: operated in ambient temperature typically 15degC, controlled for the workshop. Pump dead-head leading to overheating	Local heating of PVC pipework/connections. Potential issue with integrity	Valve position checks Operator in place monitoring pump and flowmeter	5. Check with manufacturer regarding temperatures above 20degC	Venki

Parameter	Deviation	Causes	Consequences	Mitigations	Action	Owner
TEMPERATURE	Less	Operated in ambient temperature typically 15degC, controlled for workshop. No temperature less scenarios identified.				
LEVEL	High/More	Operator error during tank filling Also refer to Flow misdirected above.	Overfilling of oil tank, oil spillage	Tank is filled from a limited number of 205l barrels, only 4 available (total volume < tank volume) Workshop floor area arranged so that any overspill goes to oil separator rather than discharged.		

Parameter	Deviation	Causes	Consequences	Mitigations	Action	Owner
LEVEL	Low/Less	Pipe separator not functioning Also see above for Flow mis-directed.	Minor level change in oil tank. Cavitation of pump – see action 1 above for Flow/No.	Operator in position during tests. Level indication in place on tank.	6. Include in procedure points to check tank levels with respect to minimum level for pump requirements	Venki
		Damage to tank or pipework	Leakage – oil spillage, reduction in tank level	Workshop floor area arranged so that any overspill goes to oil separator rather than discharged.		
COMPOSITION	Part of	Incorrect flowmeter readings	Effect on test results	Manufacturer calibration of flowmeter. Flowmeter signal will be calibrated prior to starting tests.	7. Confirm manufacturer provision of calibration certificate and measurement method relating to the composition (i.e. if some oil in water flow or vice versa)	Venki

Parameter	Deviation	Causes	Consequences	Mitigations	Action	Owner
COMPOSITION	As Well As	Water build up in oil tank due to inefficient separation	Effect on test results	Level checks for potential build-up of water at bottom of oil tank	See action 6 above - including checks on tank levels in procedure	
	Other than	Air in system due to pump cavitation	Effect on flowmeter readings Cavitation of pump – see action 1 above for Flow/No.			
VISCOSITY	High (thick)	Emulsion being created	Effect on test results	Use of the same oil in previous tests did not generate emulsion to a level of concern. Pipework sections are transparent allowing the Operator to monitor if any emulsion being created.		
	Low (thin)	None identified				

Parameter	Deviation	Causes	Consequences	Mitigations	Action	Owner
OTHER	Instrumentation	Pressure sensor on outlet of iPiP No deviations identified				
	Sampling	Sample point at HV-103; location of sampling.			8. Consider the most appropriate position for the sample location to achieve best representative sample	Venki
	Corrosion, Erosion or Fatigue	Degradation of valve sealing material No other deviations identified	Potential leakage	Cross-check with the valve seal materials against the oil to be used in test has been performed and material shown to be compatible		
	Service Failures	Loss of power	Delay to test	Back-up generator is an option if considered necessary		

Parameter	Deviation	Causes	Consequences	Mitigations	Action	Owner
	Maintenance	None identified				
	Static	None identified				
	Outside conditions	None identified				
	Operating mode	None identified				
	Layout	None identified				
	OTHER	SIMOPS e.g. hot work	Other work in vicinity interacting with flow loop testing		9. Consider barrier restrictions for flow loop testing area and awareness / TBT to be performed for other workshop personnel	Roar / Venki

Node 2. WATER - Intent of node is to provide water, via a centrifugal pump, at an adjustable flowrate to the wye piece (to allow mixing) and on the outlet of the inclined separator allow the separated water to return to the tank. Node includes a flowmeter, pressure sensor, sampling point, control valve and filters on the inlet and outlet of the water storage tank. Section is constructed with a combination of rigid PVC pipework (3"), valves, fittings and hose with threaded and glued connections. System is leak tested with water before operation.

Fluid – standard water supply

P&ID - TEC-18-0538-DWG-03

Design and Operating Conditions

Node	Flowrate	Operating Pressure	Design Pressure	Operating Temperature	Design Temperature
2	Varying from approximately 9 to 230 litres/min	Ambient pressure with a slight positive on discharge of pump. The maximum pump delivery pressure is 2.5bar	10bar (PN10 limiting PVC pipework) On basis glued/threaded connections are made up correctly they are also rated PN10. Pressure rating of connections will be leak tested, as part of the system leak test, to 1.5barg.	Ambient	Manufacturer recommendation to discuss with them if pipework/hose is planned for use at temperatures above 20degC. The epoxy used for glued connections is suitable up to 60degC

HAZOP Worksheet

Parameter	Deviation	Causes	Consequences	Mitigations	Action	Owner
FLOW	No/Less	Closed or partially closed valves at pump outlet or other valves on iPiP outlet	If HV-202 closed on pump discharge – deadhead of pump to (2.4barg + hydrostatic head) – increase in pressure. Potential leakage at connections	Valve position checks by Operator (note no relief valve in water node)	10. Leak test pressure – increase test pressure to that of pump max to ensure no leakage in the event of a closed valve or blockage and pump deadhead	Venki
		Blockage	As per closed valve	Note action 2 to check filters		
		Low level in water tank	Pump cavitation – possible damage	Note action 1 to clarify any detriment to pump due to cavitation		
		Pump stops / trips	Delay to the test	Operator in place monitoring flowmeter		

Parameter	Deviation	Causes	Consequences	Mitigations	Action	Owner
FLOW	More	Incorrect setting of pump (or outlet valve)	Effect on test results	Operator following test matrix for different flowrates and monitoring flowmeter as part of pump flowrate setting		
	Reverse	Valve downstream of wye closed and water pump P-201 switched off and oil pump P-101 running	Increased level in water tank (from pumped oil) – potential for overfilling Pump - potential for damage – see action 3	Valve position checks in procedure Combined fluid volume (~2000litre) less than water tank capacity (2300litre) Level monitoring/ check possible on water tank		
	Misdirected	Valve HV-401 (connecting water to oil sections) left in open position	Effect on test results	Valve position checks in procedure (HV-401 and HV-101 opened at end of each day to allow water flush)		

Parameter	Deviation	Causes	Consequences	Mitigations	Action	Owner
FLOW						
	Misdirected	Flushing operation – valve HV101 is left open	Oil could be flushed back into water tank – see above for increased level in tank	Valve position checks in procedure		
		Valves HV-204 left in closed position	Effect on test results all flow passes through oil outlet to oil tank. Increase in oil tank, reduction in water tank level	Valve position checks in procedure		
	Fluctuating	Change in pump speed	Effect on test results	Operator sets pump speed using VSD pump control / interface Operator in position confirming flow with flow meter		
PRESSURE	More	Closed valve (or blockage) on pump discharge	Dead-head pump (2.4+head of oil ~0.17barg) if valve(s) on discharge side is closed – pressure increase	Valve position checks in procedure Relief valve (set 1.5barg) vents back to oil tank		

Parameter	Deviation	Causes	Consequences	Mitigations	Action	Owner
PRESSURE	Less	Open system (tank) – no credible Pressure Less scenarios identified				
TEMPERATURE	More	Note: operated in ambient temperature typically 15degC, controlled for the workshop. Pump dead-head leading to overheating	Local heating of PVC pipework/connections. Potential issue with integrity	Valve position checks Operator in place monitoring pump and flowmeter	See action 5 to check with manufacturer regarding temperatures above 20degC	
	Less	Operated in ambient temperature typically 15degC, controlled for workshop.	No temperature less scenarios identified.			

Parameter	Deviation	Causes	Consequences	Mitigations	Action	Owner
LEVEL	High/More	Operator error in filling from water supply	Overfill leading to water spillage	Operator monitoring during tank filling Spillage contained in oil separator system		
	Low/Less	Pipe separator not functioning Also see above for Flow mis-directed.	Minor level change in oil tank. Cavitation of pump – see action 1 above for Flow/No.	Operator in position during tests. Level indication in place on tank.		
		Damage to tank or pipework	Leakage – oil spillage, reduction in tank level	Workshop floor area arranged so that any overspill goes to oil separator rather than discharged.		
COMPOSITION	Part of	Incorrect flowmeter readings	Effect on test results	Manufacturer calibration of flowmeter (see action 7). Flowmeter signal will be calibrated prior to starting tests.		

Parameter	Deviation	Causes	Consequences	Mitigations	Action	Owner
	As Well As	Oil build up in water tank due to inefficient separation	Effect on test results	Level checks for potential build-up of oil at top of water tank		
	Other than	Air in system due to pump cavitation	Effect on flowmeter readings Cavitation of pump – see action 1 above for Flow/No.			
VISCOSITY	High (thick)	None identified				
	Low (thin)	None identified				
OTHER	Instrumentation	Pressure sensor on outlet of iPiP No deviations identified				
		CV-201 (membrane valve)- Incorrect CV setting	Change in interface level – potential for water overflow to oil outlet (or vice versa)	iPiP pipework is transparent; Operator monitoring interface level during tests	11. Add additional flowmeter on iPiP water outlet to P&ID	Venki

Parameter	Deviation	Causes	Consequences	Mitigations	Action	Owner
OTHER	Sampling	Sample point at HV-203; location of sampling.			See action 8 regarding orientation of sampling point	
	Corrosion, Erosion or Fatigue	Degradation of valve sealing material No other deviations identified	Potential leakage	Cross-check with the valve seal materials against the oil to be used in test has been performed and material shown to be compatible		
	Service Failures	Loss of power	Delay to test	Back-up generator is an option if considered necessary		
	Maintenance	None identified				
	Static	None identified				
	Outside conditions	None identified				
	Operating mode	None identified				
	Layout	None identified				
	OTHER	SIMOPS e.g. hot work	Other work in vicinity interacting with flow loop testing		See action 9 regarding barriers	

Node 3. Oil & Water – intent of node is to allow both oil and water flows to mix and then separate via a horizontal pipe separator and an inclined pipe in pipe separator (with adjustable angle), a pressure sensor is in place at the inlet to the pipe in pipe separator. Section is constructed with a combination of rigid PVC pipework (3”), valves, fittings and hose with threaded and glued connections. System is leak tested with water before operation.

Fluid – Exxsol D60 Oil coloured with dye and fresh water

P&ID - TEC-18-0538-DWG-03

Design and Operating Conditions

Node	Flowrate	Operating Pressure	Design Pressure	Operating Temperature	Design Temperature
3	Varying from approximately 95 to 480 litres/min	Ambient, slight positive on inlet to inclined separator The maximum pump delivery pressure is 2.5bar	10bar (PN10 limiting PVC pipework) On basis glued/threaded connections are made up correctly they are also rated PN10. Pressure rating of connections will be leak tested, as part of the system leak test, to 1.5barg.	Ambient	Manufacturer recommendation to discuss with them if pipework/hose is planned for use at temperatures above 20degC. The epoxy used for glued connections is suitable up to 60degC

HAZOP Worksheet

Parameter	Deviation	Causes	Consequences	Mitigations	Action	Owner
FLOW	No/Less	Closed or partially closed valves HV-301 and/or HV-302 Blockage	Dead-head pump (2.4+head of oil ~0.17barg) – pressure increase Potential for miss directed flow -water into oil or vice versa should one pump be running and one off	Valve position checks in procedure Relief valve (set 1.5barg) vents back to oil tank See action 10 regarding Leak test for maximum pressure		
		Low level in tank(s)	Pump cavitation – – potential damage (see action 1)	Valve position checks in procedure and action to include tank level checks (see action 2)		
		Pump trips or stops	System stops flowing – delay to test	Operator in place monitoring flowmeter		

Parameter	Deviation	Causes	Consequences	Mitigations	Action	Owner
FLOW	More	Incorrect setting of pump (or outlet valve)	Effect on test results	Operator following test matrix for different flowrates and monitoring flowmeter as part of pump flowrate setting		
	Reverse	Minor reverse flow expected when pumps stopped until system levels balance No other scenarios identified				
	Misdirected	None identified				
	Fluctuating	Change in pump speed	Effect on test results	Operator sets pump speed using VSD pump control / interface Operator in position confirming flow with flow meter		

Parameter	Deviation	Causes	Consequences	Mitigations	Action	Owner
PRESSURE	More	Closed valve (or blockage) on pump discharge	Dead-head pump (2.4+head of oil ~0.17barg) if valve(s) on discharge side is closed – pressure increase	Valve position checks in procedure Relief valve (set 1.5barg) vents back to oil tank		
	Less	Open system (tank) – no credible Pressure Less scenarios identified				
TEMPERATURE	More	Note: operated in ambient temperature typically 15degC, controlled for the workshop. Pump dead-head leading to overheating	Local heating of PVC pipework/connections. Potential issue with integrity	Valve position checks Operator in place monitoring pump and flowmeter	See action 5 to check with manufacturer regarding temperatures above 20degC	

Parameter	Deviation	Causes	Consequences	Mitigations	Action	Owner
TEMPERATURE	Less	Operated in ambient temperature typically 15degC, controlled for workshop.	No temperature less scenarios identified.			
LEVEL	High/More	Operator error in filling from water supply	Overfill leading to water spillage	Operator monitoring during tank filling Spillage contained in oil separator system		
	Low/Less	Pipe separator not functioning Also see above for Flow mis-directed.	Minor level change in oil tank. Cavitation of pump – see action 1 above for Flow/No.	Operator in position during tests. Level indication in place on tank.		
		Damage to pipework	Leakage – oil spillage, reduction in tank level	Workshop floor area arranged so that any overspill goes to oil separator rather than discharged.		
	Angle	Effect of holes in iPiP at different angles discussed	No hazard or operability issues identified			

Parameter	Deviation	Causes	Consequences	Mitigations	Action	Owner
COMPOSITION	Part of	Incorrect flowmeter readings	Effect on test results	Manufacturer calibration of flowmeter (see action 7). Flowmeter signal will be calibrated prior to starting tests.		
	As Well As	None identified				
	Other than	None identified				
VISCOSITY	High (thick)	Emulsion being created	Effect on test results	Use of the same oil in previous tests did not generate emulsion to a level of concern. Pipework sections are transparent allowing the Operator to monitor if any emulsion being created.		
	Low (thin)	None identified				
OTHER	Instrumentation	PT on inlet to iPiP None identified				
	Sampling	n/a in this node				

Parameter	Deviation	Causes	Consequences	Mitigations	Action	Owner
	Corrosion, Erosion or Fatigue	None identified				
	Service Failures	Loss of power	Delay to test	Back-up generator is an option if considered necessary		
	Maintenance	Option to dis-assemble iPiP as part of test to change the inner pipe and then re-instate	New connections made	Leak test will be repeated following re-instatement of iPiP		
	Static	None identified				
	Outside conditions	None identified				
	Operating mode	None identified				
	Layout	None identified				
	OTHER	Dye – consideration for PPE Oil – consideration for PPE	Injury to personnel Injury to personnel	SDS assessed awareness of correct PPE (standard) SDS assessed awareness of correct PPE (standard), chemical gloves selected for oil filling operation		

C. Data from measurements

APPENDIX – DATA FROM MEASUREMENTS

Water

Meas. Pts.	Shear Rate [1/s]	Shear Stress [Pa]	Viscosity [mPa·s]	Temperature [°C]	Time [s]
1	1	0,000603	0,603	4	30
2	6,21	0,00958	1,54	4	60
3	11,4	0,0178	1,56	4	90
4	16,6	0,026	1,56	4,01	120
5	21,8	0,0345	1,58	4,01	150
6	27,1	0,043	1,59	4	180
7	32,3	0,0518	1,61	4	210
8	37,5	0,0606	1,62	4	240
9	42,7	0,0695	1,63	4	270
10	47,9	0,0786	1,64	4	300
11	53,1	0,0877	1,65	4	330
12	58,3	0,097	1,66	4	360
13	63,5	0,106	1,67	4	390
14	68,7	0,116	1,68	4	420
15	73,9	0,125	1,69	4	450
16	79,2	0,135	1,7	4	480
17	84,4	0,144	1,71	4	510
18	89,6	0,154	1,72	4	540
19	94,8	0,164	1,73	4	570
20	100	0,173	1,73	4	600

Meas. Pts.	Time [s]	Torque [µNm]	Shear Rate [1/s]	Shear Stress [Pa]	Viscosity [mPa·s]
1	60	6,261	70	0,1179	1,684
2	120	6,266	70	0,118	1,685
3	180	6,268	70	0,118	1,686
4	240	6,269	70	0,118	1,686
5	300	6,271	70	0,118	1,686
6	360	6,27	70	0,118	1,686
7	420	6,269	70	0,118	1,686
8	480	6,268	70	0,118	1,686
9	540	6,27	70	0,118	1,686
10	600	6,27	70	0,118	1,686

Oil

Meas. Pts.	Shear Rate [1/s]	Shear Stress [Pa]	Viscosity [mPa·s]	Speed [1/min]	Torque [mNm]
1	1	0,00237	2,37	0,774	0,000126
2	6,21	0,0115	1,85	4,81	0,00061
3	11,4	0,0216	1,89	8,85	0,00115
4	16,6	0,0315	1,89	12,9	0,00167
5	21,8	0,0416	1,91	16,9	0,00221
6	27,1	0,0518	1,92	21	0,00275
7	32,3	0,0622	1,93	25	0,00331
8	37,5	0,0727	1,94	29	0,00386
9	42,7	0,0832	1,95	33,1	0,00442
10	47,9	0,0939	1,96	37,1	0,00499
11	53,1	0,105	1,97	41,1	0,00556
12	58,3	0,116	1,98	45,2	0,00614
13	63,5	0,126	1,99	49,2	0,00671
14	68,7	0,137	2	53,2	0,0073
15	73,9	0,149	2,01	57,3	0,0079
16	79,2	0,16	2,02	61,3	0,00848
17	84,4	0,171	2,03	65,4	0,00908
18	89,6	0,182	2,03	69,4	0,00968
19	94,8	0,193	2,04	73,4	0,0103
20	100	0,204	2,04	77,5	0,0108

Meas. Pts.	Time [s]	Viscosity [mPa·s]	Shear Rate [1/s]	Shear Stress [Pa]	Temperature [°C]	Torque [µNm]
1	60	2,002	70	0,1401	4	7,44
2	120	2,002	70	0,1401	4	7,44
3	180	2,002	70	0,1402	3,99	7,45
4	240	2,002	70	0,1402	3,99	7,45
5	300	2,002	70	0,1402	4	7,45
6	360	2,003	70	0,1402	4	7,45
7	420	2,003	70	0,1402	4	7,45
8	480	2,003	70	0,1402	4	7,45
9	540	2,002	70	0,1402	4	7,45
10	600	2,002	70	0,1402	4	7,45

D. Pressure difference in IPIP separator

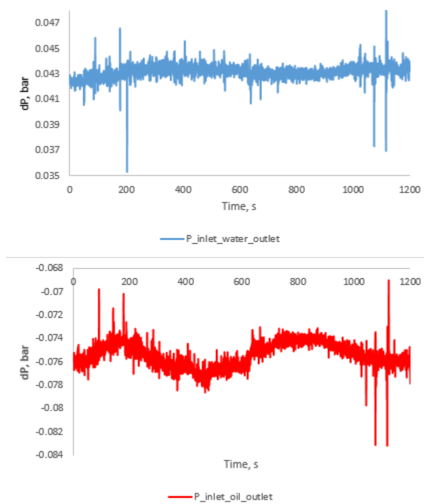


Figure 5.1: Low velocity test 1.1

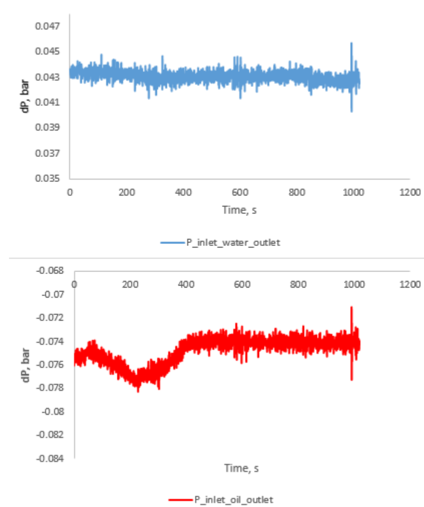


Figure 5.2: Low velocity test 1.2

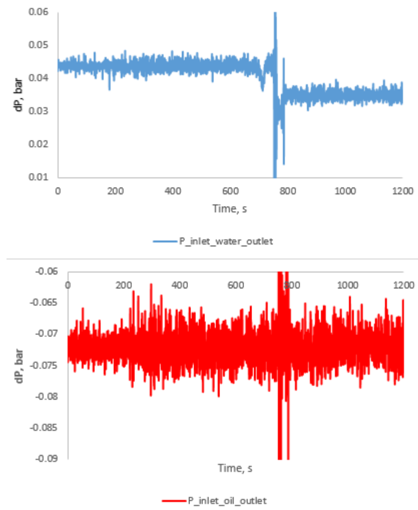


Figure 5.3: Low velocity test 1.3

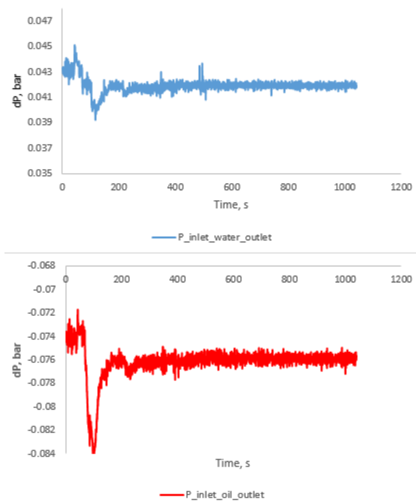


Figure 5.4: Low velocity test 1.4

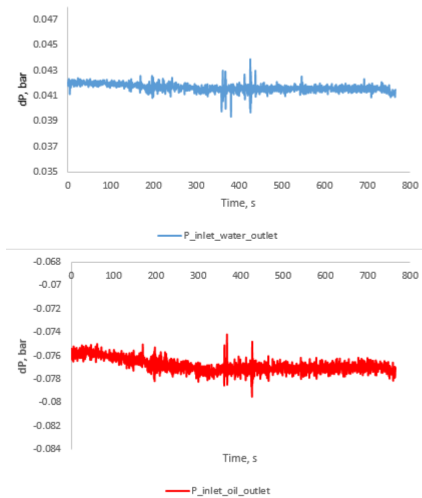


Figure 5.5: Low velocity test 1.5

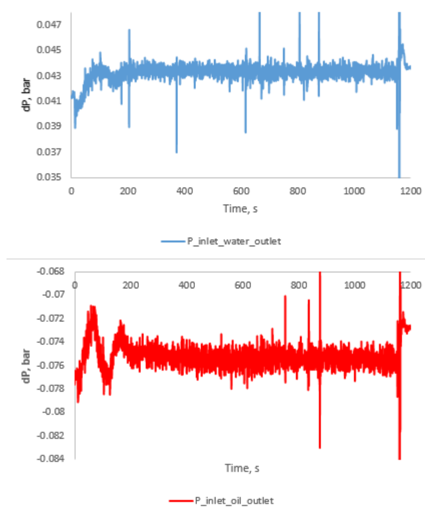


Figure 5.6: Medium velocity test 2.1

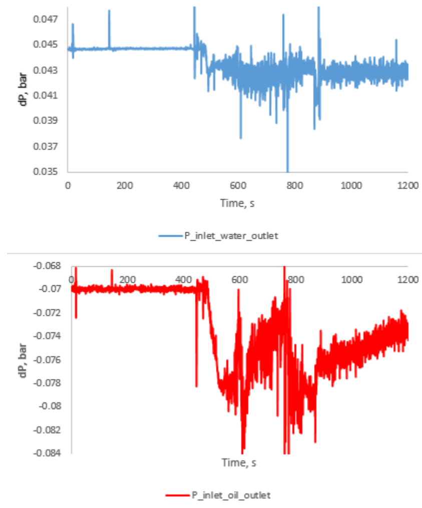


Figure 5.7: Medium velocity test 2.2

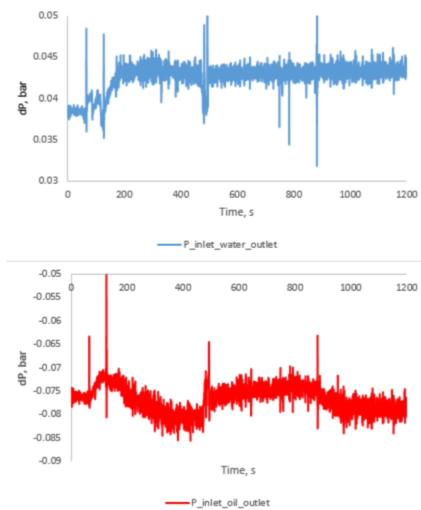


Figure 5.8: Medium velocity test 2.4

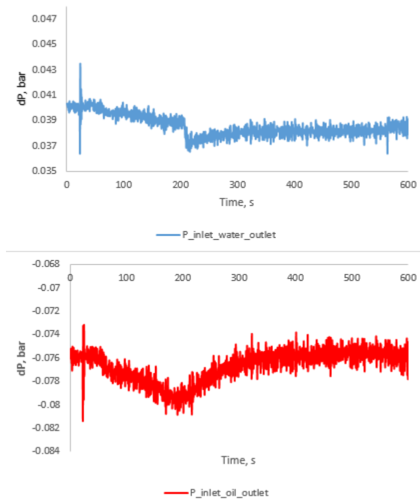


Figure 5.9: Medium velocity test 2.5

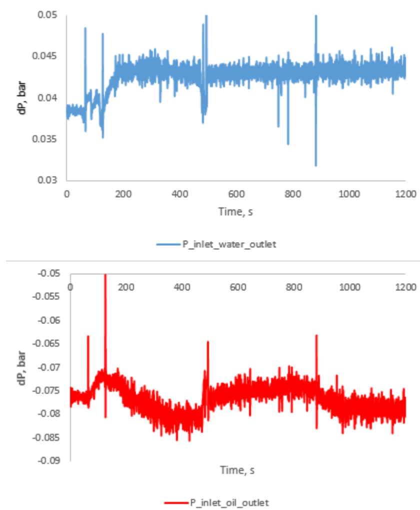


Figure 5.10: High velocity test 3.1

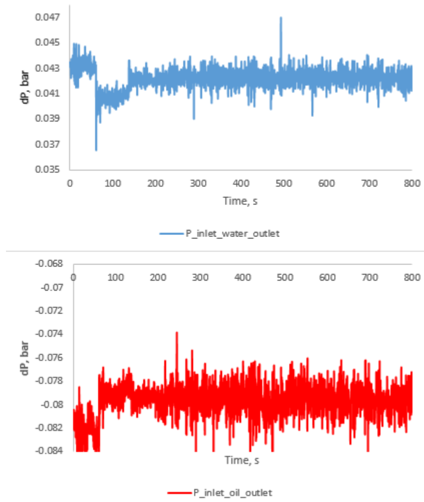


Figure 5.11: High velocity test 3.2

E. Illustrations

Figure 5.12: IPIP separator flow loop

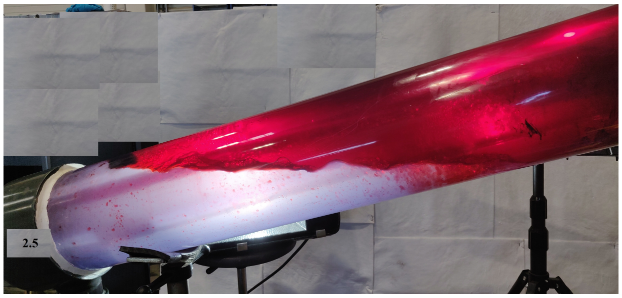


Figure 5.13: Test 2.5- OW flow in an IPIP separator

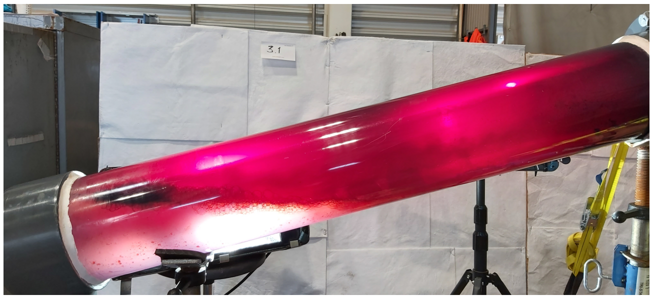


Figure 5.14: Test 3.1- OW flow in an IPIP separator

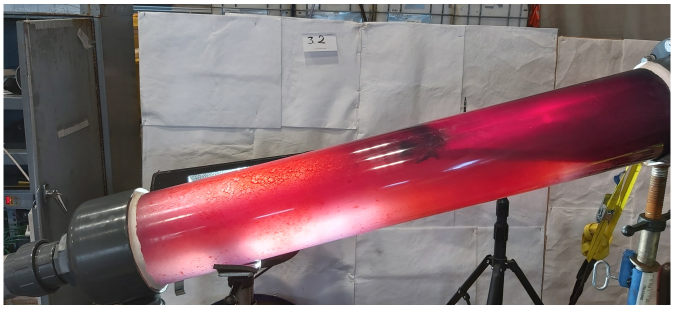


Figure 5.15: Test 3.2- OW flow in an IPIP separator