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Challenges in Modelling and Control of Offshore De-oiling Hydrocyclone Systems

Petar Durdevic, Simon Pedersen and Zhenyu Yang

Aalborg University, Esbjerg Campus, Niels Bohrs Vej 8, 6700 Esbjerg, Denmark

E-mail: pdl@et.aau.dk, spe@et.aau.dk, yang@et.aau.dk

Abstract. Offshore de-oiling installations are facing an increasing challenge with regards to removing oil residuals from produced water prior to discharge into the ocean. The de-oiling of produced water is initially achieved in the primary separation processes using gravity-based multi-phase separators, which can effectively handle large amounts of oil-well fluids but may struggle with the efficient separation of small dispersed oil particles. Thereby hydrocyclone systems are commonly employed in the downstream Produced Water Treatment (PWT) process for further reducing the oil concentration in the produced water before it can be discharged into the ocean. The popularity of hydrocyclone technology in the offshore oil and gas industry is mainly due to its rugged design and low maintenance requirements. However, to operate and control this type of system in an efficient way is far less simple, and alternatively this task imposes a number of key control challenges. Specifically, there is much research to be performed in the direction of dynamic modelling and control of de-oiling hydrocyclone systems. The current solutions rely heavily on empirical trial-and-error approaches. This paper gives a brief review of current hydrocyclone control solutions and the remaining challenges and includes some of our recent work in this topic and ends with a motivation for future work.

1. Introduction

Many matured offshore oilfields have a high water content and the pumped well-fluids in some cases contain more than 90 % water, and this water is referred to as *produced water*. It has been surveyed that globally around 250 million barrels of produced water along with 80 million barrels of oil is produced each day [1]. This high water-cut situation requires effective Produced Water Treatment (PWT) to achieve pure oil product on the platforms, but also to fulfil governmental effluent discharge regulations. For instance, the current limitation for hydrocarbon discharge in North Sea is set at 30 mg/l (30ppm) [2]. It has been shown that the discharged hydrocarbons could have a negative effect on the surrounding marine life, for example a small concentration of Polycyclic Aromatic Hydrocarbons (PAH) as low as 100 parts per billion (PPB) can affect fish development [3]. Produced water can also contain different harmful materials, such as metals (barium and zinc), benzene, toulene, ethylbenzene xylene (BTEX), naphthalene, phenanthrene, dibenzothiophene (NPD), polyaromatic hydrocarbons (PAHs) and phenols etc. [4], and hence direct discharge of the produced water is strictly prohibited in order to protect the marine life and environment.

In offshore installations, on-site cleaning of produced water, which is referred to as PWT, is needed as it is expensive to send such large quantities of water to the onshore separation facilities [5]. However, due to the space and weight restrictions on offshore installations, the

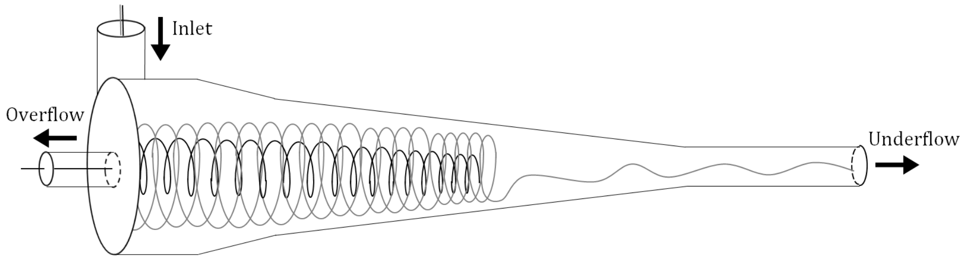

Figure 1: Hydrocyclone Separation principle - the grey/black line indicates the water/oil flow

installation and operation of offshore PWT must be very cost-effective while providing sufficient capability and quality. Moreover, due to the harsh weather and marine conditions, especially in the North Sea, the PWT requires robust installations and instrumentation. Even though almost all PWT of the current offshore installations perform to an acceptable level, the consistent increase in water-cut will sooner or later bring extra difficulties and challenges to the current PWT technologies and systems.

To achieve the required effluent discharge concentrations for oil in the produced water, the separation of water and hydrocarbon products is generally achieved in two stages. The initial separation processes uses gravity-based multi-phase separators, which can effectively handle large amounts of well-fluids, but cannot efficiently separate small dispersed oil droplets. The next stage in separation is by the hydrocyclones that reduce the dispersed oil content to the required levels before the effluent is discharged into the ocean.

It is common knowledge that the hydrocyclone's de-oiling performance is very sensitive to fluctuating inflow rates [6], [7]. The efficient operation and control of this type of system imposes a number of key control challenges. The current modelling and analysis heavily rely on CFD-based approaches, and the control development heavily relies on empirical trial-and-error approaches. We found that there is lack of research in cost-effective modelling and control of de-oiling hydrocyclone dynamic systems. In 2013 Aalborg University in collaboration with one of the Danish oil operators and an oil service company, launched a research project - PDPWAC - with one of the research objectives being the optimization of the hydrocyclone-based PWT using plant-wide control strategy. This paper gives a brief review of modelling and control of offshore de-oiling hydrocyclone systems, presents some of our work in this direction and points out some remaining challenges.

The rest of this paper is organized as follows: Section 2 introduces the basic configuration and operating principle of typical de-oiling hydrocyclone systems; section 3 gives a brief overview of hydrocyclone modelling methods and the challenges that lie within; section 4 presents some key challenges in the control of hydrocyclone systems, along with some latest solutions from our work; finally section 5 concludes this work.

2. Hydrocyclone Principle and Control

Hydrocyclone technology emerged in the oil industry in the 1980's and has been increasingly used since then. Hydrocyclone systems represent more than 90% of current de-oiling facilities in the offshore oil and gas installations [8], and this popularity is mainly due to its simplicity and ruggedness [9].

2.1. Hydrocyclone Configuration & Principle

A typical de-oiling hydrocyclone consists of one or more tangential inlets, where the produced water flowing out of the separator stack enters the hydrocyclone facilities. The mixed water and oil are accelerated in a circular movement inside the cylindrical chamber as shown in Figure 1. As the mixture rotates, the centripetal force separates these two phases with the heavier phase (water) moving towards the walls while the lighter phase (dispersed oil) moves to the cylinder's centre, where eventually an oil core is generated. Besides the cylindrical chamber segment, a hydrocyclone also consists of two conical sections and two outlets, namely *overflow* and *underflow* outlets. Ideally, the oil trapped in the oil core will gradually exit through the overflow outlet, while the water will go through the underflow outlet [7]. In practical applications, especially for the offshore situations, a number of hydrocyclone liners are need to be stacked in parallel inside one holding vessel, so that the handling capability of produced water can be significantly increased without requiring a lot of installation space [9].

2.2. Hydrocyclone control

An offshore installation relevant to PWT is sketched in Figure 2, where the separator and the hydrocyclone are directly connected. Normally, the underflow control valve located at the hydrocyclone's underflow outlet is used for the purpose of separator water level control ("LC" in Figure 2). The hydrocyclone separation performance is controlled via the *PDR control* ("PDR" in Figure 2) loop by manipulating the overflow control valve located at the hydrocyclone's overflow outlet, where PDR is the Pressure Drop Ratio over the hydrocyclone's outlets and inlet, i.e.,

$$PDR = \frac{P_i - P_o}{P_i - P_u} \tag{1}$$

Where P_i is the measured inlet pressure, and P_u/P_o is the the underflow/overflow pressure measurement. It has been experimentally discovered that the PDR and the flow-split inside the hydrocyclone are closely linearly-dependent [10]. The flow-split directly determines the amounts of flow going through the underflow and the overflow outlets, respectively. To maintain a satisfactory separation efficiency, the flow-split is crucial for hydrocyclone's operation, as it will determine how much oil and water will be able to escape through the under- and over-flow respectively.

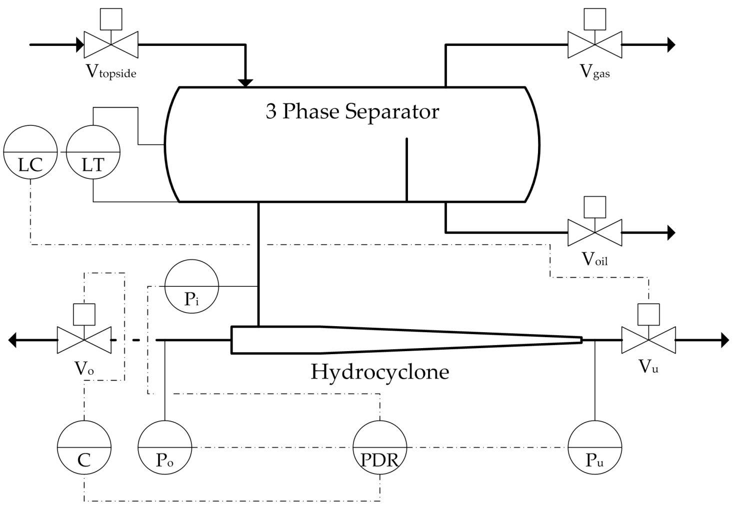

Figure 2: Two control loops in a typical control structure.

It can be observed that the dynamics of the hydrocyclone's PDR and the separator's level are physically coupled and thereby may affect each other's performance. Furthermore, the separator level control is often disturbed by the varying inflow rate to the separator system. A typical influence to the separator is slugging inflow which could be caused by the riser configuration or hydrodynamics [11], [12], [13] and [14]. A measured severe slug that occurred at one installation in North Sea is illustrated in Figure 3, where the severe slug is indicted by large oscillating pressure measurements at the riser top. All these issues lay out many challenges to the efficient and reliable control of the hydrocyclone .

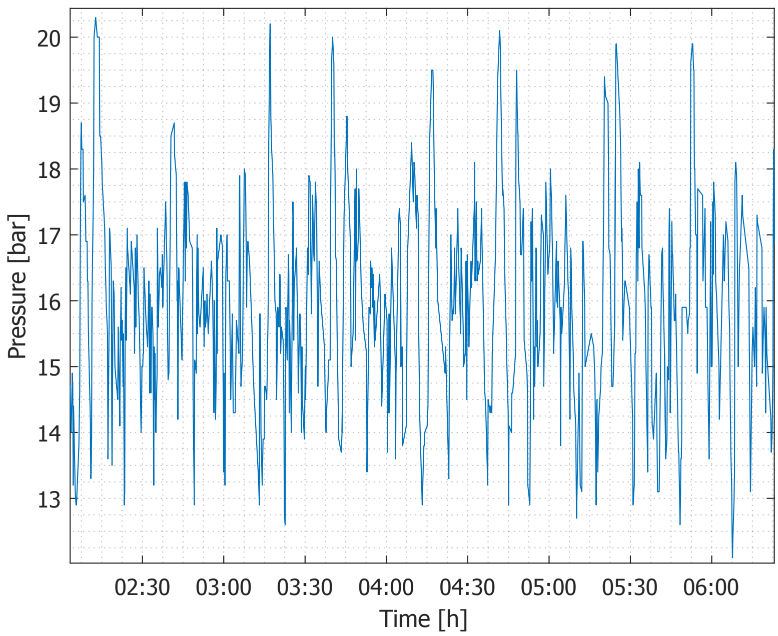

Figure 3: One example of riser-induced slugging flow indicated by topside pressure fluctuations

3. Modeling De-oiling Hydrocyclone Operation

It has been observed that there has been little work done focusing on the control-oriented modelling of de-oiling hydrocyclone systems, instead, there are plenty of different models and analysis based on Computational Fluid Dynamics (CFD) technology [15, 16, 17]. Although CFD-based models have a sophisticated capability and power in illustrating detailed information, they are not oriented or suited for the purpose of control design due to their complexity. For dynamic control purposes simple dynamic models, which can express the key dynamic characteristics between the system's inputs and outputs, are preferred instead.

The first-principle-based modelling is investigated in [18] for a solid-liquid hydrocyclone setup, and this work is further extended in [19]. [20] described a solid-liquid hydrocyclone with a simple dynamic model by using transport balance by considering the slip velocity and turbulent particle diffusivity, based on the $k - \eta$ model developed in [21] and [22]. However, the extension of these models to handling liquid-liquid de-oiling hydrocyclone is not clear. Similar situation exists regarding the work done in [20], which only focused on the solid-liquid hydrocyclone and also assumed that the inlet flow is fed through the entire top section of the hydrocyclone. As many of these relatively simple models (when compared to CFD-based models) are regarding solid-liquid separating cyclones, the correlation between solid-liquid cyclone separation and liquid-liquid hydrocyclone separation needs further investigations before we can answer whether some models developed for one type of cyclone system could be applied or extended to another type of cyclone system.

In our previous work a black-box modelling method was used for a de-oiling hydrocyclone setup in [23] by regarding the PDR as the controlled variable (output). The opening degrees of two controllable valves, i.e., the underflow valve V_u and overflow valve V_o, were regarded as the manipulated variables (controllable inputs). Based on experimental data, a set of linear models were identified by using PE system identification method. However, due to the heavy nonlinearity of cyclone's separation dynamics, it was noticed that some nonlinear model(s) should be developed if a relatively large operating range and different operating conditions need to be considered. An extension of this work to employ the Hammerstein-Weiner nonlinear model is currently underway as part of our work, and some of the preliminary results have showed a huge potential for this type of model to explain the nonlinearity in the de-oiling hydrocyclone system.

4. Challenges in de-oiling hydrocyclone control

There is little literature to be found in the systematic design of de-oiling hydrocyclone control solutions, including the standardized PID-based PDR control described in section 2 where there is no systematic approach described to tune these controllers except extensive empirical tunings, though some control designs can be found for solid-liquid cyclone separation.

4.1. Solid-liquid hydrocyclone control

The volume-split regulation has been developed in [24] by controlling the overflow valve for solid-liquid cyclone systems, which is quite similar to the PDR control for de-oiling hydrocyclones. The measured signals are the inlet pressure, the overflow pressure and an underflow discharge pattern recognition sensor, the manipulated variables are the speed of the feeding pump and the opening degree of the overflow valve. The control systems balance the underflow output between the rope discharge and spray discharge, so that the clogging problem can be avoided at the bottom of the hydrocyclone [25], [24], [26]. However, any direct application of these solid-liquid control solutions for liquid-liquid hydrocyclone separation is still very open and challenging.

The control of the inflow rate is not possible in offshore de-oiling hydrocyclone situations, as the inflow rate is determined by the separator level control loop, as shown in figure 5. Furthermore, the usage of monitoring spray rope discharge pattern for control purposes is not possible for de-oiling hydrocyclones. Moreover, the de-oiling hydrocyclones are not subjected to clogging problem, instead, water has a low viscosity compared to the infinite viscosity of solid materials. A thorough investigation of the likeness between these two types of separations needs to be done before the control techniques used for solid-liquid cyclones can be applied for liquid-liquid de-oiling hydrocyclones.

4.2. Coordinated separator and cyclone controls

The (water) level controller is designed to keep the water level inside the separator at a certain level based on a pre-determined set-point. From a practical perspective, the water level set-point is not crucial as long as the water level can be maintained within a safety range. Maintaining the level within a specified range is important to ensure a correct residence time which is directly related to the separator's efficiency. According to [27] the normal residence time for oil production separators is about $2-4$ minutes. Residence time is an optimization or trade-off problem, as a longer residence time ensures a better separation, and a lower residence time ensures faster process flow. The problem with longer residence times is that if the mass flow rate is to be kept high the equipment will correspondingly grow in size. In our investigations we have discovered a coupling effect of V_u and V_o functionalities, [28]. However, the opening cross-section area of V_u is about 25 times larger than that of V_o, thereby V_u acts as the dominant influence. Figure 4 illustrates a scenario where PID controllers are applied on both the level and PDR control loops, and a severe oscillating inflow rate F_{in} was generated to emulate a severe

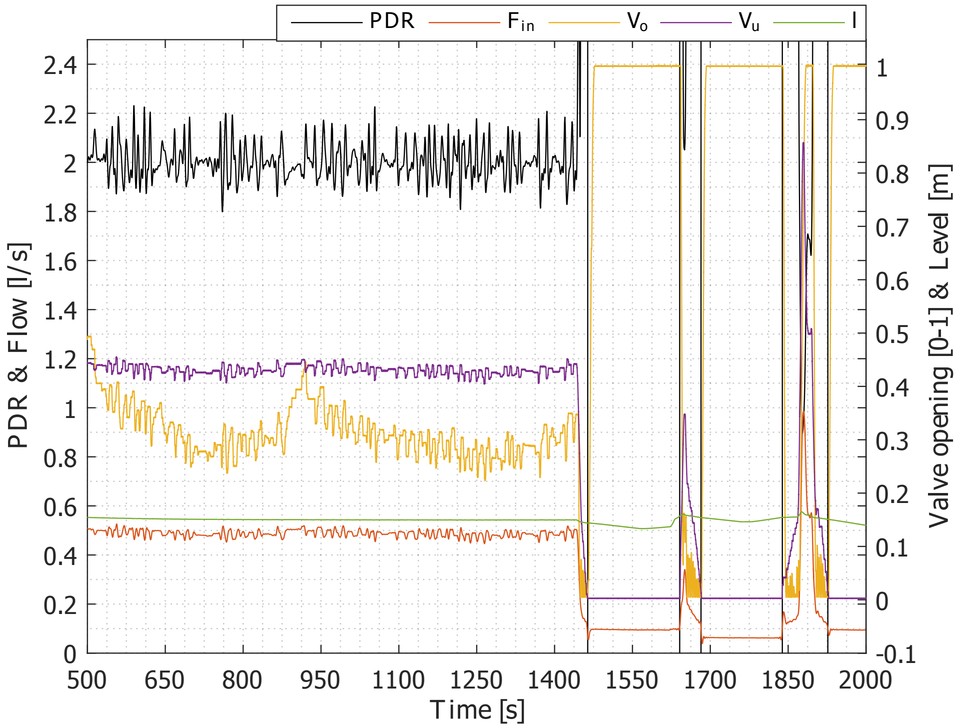

Figure 4: Test illustrating the coupling phenomena in the separation system.

condition. This test illustrates the impact of a sudden reduction in F_{in} (which happens at 1420s) on the controlled level and PDR performances. The halt of F_{in} caused the level in the separator to quickly decrease, which directly resulted in shutting of V_u due to the level controller. This action consequently increased the pressure over V_u, and then the PDR controller was forced to open V_o further. This scenario results in an unnecessary change of system efficiency ϵ, where $\epsilon = 1 - \frac{C_u}{C_i}$ and C_i & C_u are the inlet and outlet oil concentrations respectively. In addition, the dominance of V_u is evident from $500 - 1420$s, where small changes in V_u are equal to relatively larger fluctuations in V_o.

A block diagram of the combined level control and hydrocyclone PDR control is illustrated in Figure 5, the coupling effect is illustrated by the dotted lines. The current control consists in most cases of individually tuned and implemented PID controller on the level and the PDR, respectively. But a solution could lie in extending this with a controller structure which takes both the objectives into consideration. This control design problem can be formulated as a typical MIMO control problem, as long as we have the dynamic models describing the separator level dynamics as well as PDR dynamics.

In this case a MIMO feedback solution could be proposed to introduce a systematic design paradigm to the system which will help avoid the struggle of the two individual systems, and instead link them together into a cooperative control scheme.

4.3. Cyclone performance's sensitivity

Even with a good control solution, the hydrocyclone performance can still be very sensitive to fluctuations of inflow rates, which could be caused by the upstream separation processes (e.g., three-phase separators). The flow rate is equally important to the hydrocyclone's separation performance. If the flow through the hydrocyclone is insufficient, the swirl motion inside the hydrocyclone will not be formed or the velocity will be insufficient [30]. If this occurs, there

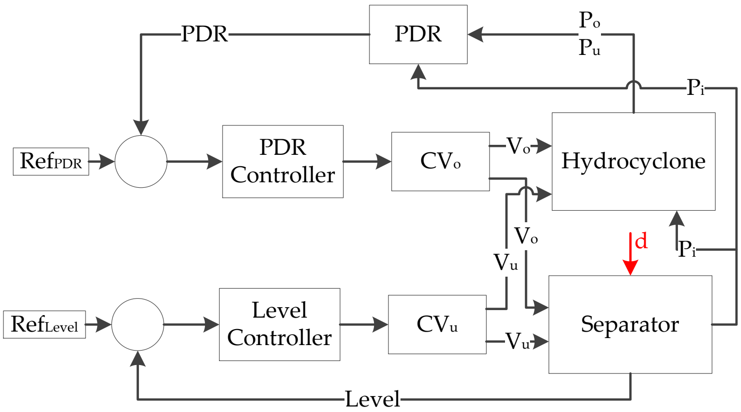

Figure 5: Control formulation of combined separator and cyclone controls [29]

will not be enough centripetal force to split the heavier liquid from the lighter one and push it towards the wall of the liner.

The plot in figure 6 shows a test performed on our pilot plant set-up, where F_{in} was increased from 0.2l/s to 0.68l/s, with 9 steps. During these increases ϵ was measured by measuring the Oil-in-Water (OiW) concentration in the inlet and the underflow of the hydrocyclone using the TD4100 equipment described in [31]. As F_{in} increases the ϵ increases, due to the fact that the centripetal force is being increased.

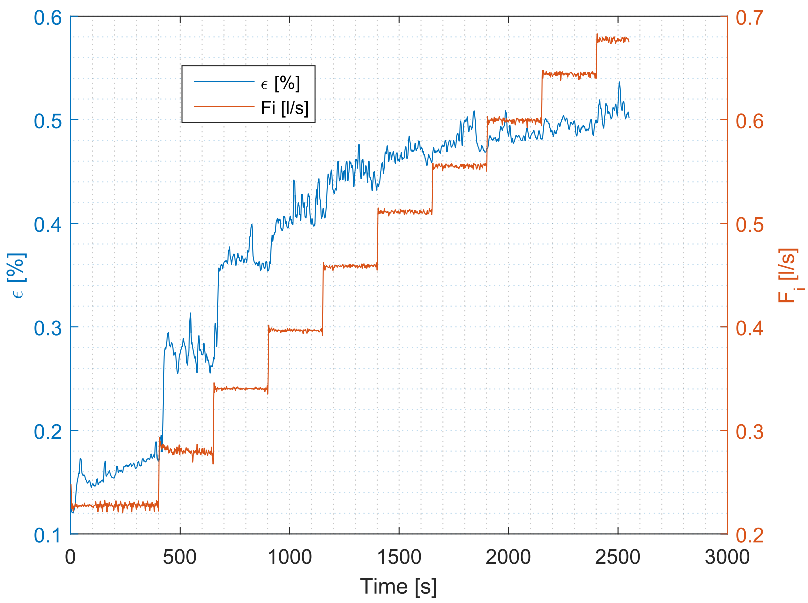

Figure 6: Dependency of ϵ on F_{in} at a controlled PDR

4.4. Efficiency real-time measurement

One of the important factors with regard to hydrocyclone operation is its efficiency measurement and prediction, which relates to the OiW concentration measurement. For the purpose of real-time applications, the OiW technology is not yet matured and the existing solutions are quite methodology dependent. Extensive investigations and development are needed in this area. A mathematical model of the liquid-liquid hydrocyclone's efficiency was introduced in [32] by modelling the dispersed droplet trajectories. This model can be very efficient in predicting the d_{100} value for a Coleman Thew type of hydrocyclone, however, it did not take into account the coalescence and breakup of droplets, and this can limit the prediction accuracy due to the fact that some high inflow rates often create a high shear stress which can break up droplets. d_{100} classifies the smallest droplet size which can be separated with an 100% efficiency, equally d_{50} would correspond to a separation efficiency of 50% [32]. One possibility is to measure droplet sizes at different stages in the separation system to investigate how the separation is affected by different droplet sizes, and if any improvement can be done during different operating conditions.

[31] investigated different OiW measurement technologies in terms of their precision and real-time measurement capabilities. The oil droplet size measurement was done with high precision using a microscopy based measurement instrument. However, due to the specific measurement principle, consistent online OiW concentration measurements have not yet been achieved, which casts a doubt about the instrument's capability for reliable real-time OiW measurement. Still, this does enable for steady state analysis of system performance at different particle sizes, which was performed in [33], but it does not assist in the possible design of control based models. Alternative measurement equipment using the same measuring principle is presented in [34] and their results seem quite promising.

In addition [31] evaluated another OiW instrument, which measures the concentration of OiW based on fluorescence principle. This method yielded far better OiW concentration results and has also be able to provide data in real-time. One result is illustrated in Figure 7. In this experiment, mixtures with different OiW concentrations were injected into the view-cell of this instrument with 10s intervals. The right plot illustrates a zoomed-in view of a step from 5 to 10 PPM. However, due to the extreme low concentrations, some measurements drift slightly. Regarding the OiW concentration measurement, this measuring instrument yields us some promising results, but further research is still needed to evaluate the reliability and repeatability of this method if it is to be used for dynamic model development and system dynamic performance evaluation.

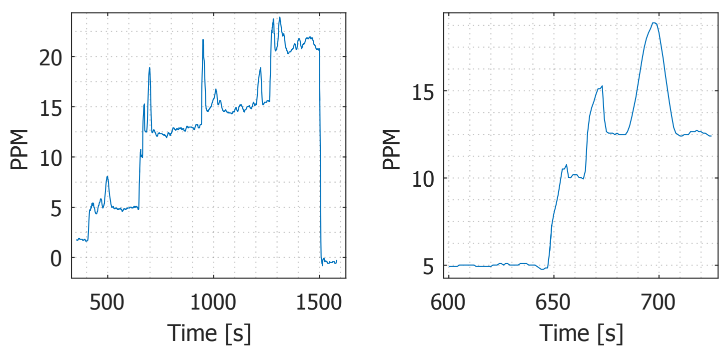

Figure 7: OiW measurement performed using a fluorescence based instrument Turner Design TD4100, [31]

5. Conclusions

The systematic solutions for de-oiling hydrocyclone control are still quite open with respect to its inherent complexity and heavy coupling with its upstream and downstream facilities. However, the real-time performance of the de-oiling hydrocyclone is crucial in determining the discharged water quality, and thereby the reduction of the environmental footprint caused by the offshore oil and gas production.

The current control solutions for hydrocyclones are PID-type solutions which lack systematic tuning strategies. Some advanced control solutions can be found in handling solid-liquid cyclone systems. However, the extension of these solutions to liquid-liquid de-oiling hydrocyclones is not straightforward. One of the key issues which blocks the application of advanced control methods in de-oiling hydrocyclone systems, lies in the lack of a deep understanding of the hydrocyclone's separation dynamics from the control point of view. This is reflected in reality, as there are no control-oriented modelling methods, nor models available for de-oiling hydrocyclone systems at this moment. Here CFD-based models and methods can play a very powerful role in emulating and analysing hydrocyclone separation processes, but they cannot yet be applied for control purposes. Instead a less detailed model strategy based on simple ODE models is preferred that describes the system from the control perspective, which is the PDR, with an extension of efficiency measurements.

For offshore de-oiling, the hydrocyclone performance is heavily coupled with the upstream separator's dynamics due to a lack of buffer vessels between them. Thereby, a coordination of the separator's (water) level control and hydrocyclone's PDR control is recommended. A MIMO control strategy can be applied to handle this control design problem, as long as some mathematical models of both parts are available. If the hydrocyclone's efficiency can be measured in a real-time and reliable manner, the hydrocyclone's PDR control strategy can be extended to be a direct-efficiency-based feedback solution. However, at this moment, the OiW real-time measurement technology, which fundamentally detects the hydrocyclone's efficiency, is still quite open and not yet matured.

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