Produced Water Workshop
7-8 June 2016

Technical Paper

Optimization of Offshore De-oiling Hydrocyclone Performance: Plant-wide Control and Real-time OiW Measurement

Zhenyu Yang, Department of Energy Technology, Aalborg University
Petar Durdevic, Department of Energy Technology, Aalborg University
Simon Pedersen, Department of Energy Technology, Aalborg University

---

1 INTRODUCTION

One of the biggest environmental concerns in offshore oil & gas production is the quality of tremendous amounts of produced water discharged into the oceans. Today, in average three barrels of water are produced along with each barrel of oil [9]. This concern will become more severe in the future, along with the facts that the global oil demand will continuously grow by 7 mb/d to 2020 and exceed 99 mb/d in 2035, meanwhile, many production fields turn to be matured and thereby the water flooding technology is more and more employed as a key enhanced oil recovery solution for these fields [9].

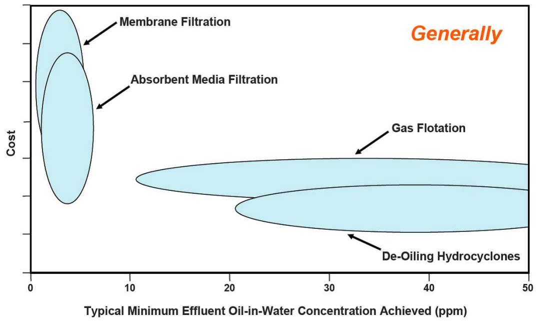

Fig.1 Classification of typical offshore PWT technologies in terms of performance vs. cost [12]

As shown in Fig.1, the offshore PWT technologies are classified into four categories according to their purification performance and relevant expenses [12]. Apparently, almost 90% of offshore PWT facilities are based on the hydrocyclone technology, due to the fact that it is one of the cheapest and most reliable solution with a best performance to 20 ppm (mg/l) [9,13]. In 2013, under the partial support from the Danish Advanced Technology Fund (now called Innovation Fund), the AAU together with two Danish OG companies, Maersk Oil and Ramboll Oil & Gas A/S, launched a research project HTF-PDPWAC with total budget of 10 million dkk. One of the focuses of this project is to optimization of the de-oiling hydrocyclone performance in order to improve the produced water treatment quality without sacrificing the capacity [14].

2 AAU TESTING FACILITIES

The testing facilities at AAU, Denmark, are mainly constructed under the support from two undergoing research projects, namely, HTF-PDPWAC project [14] and CWO-GreenOil-Lab project. The functionalities of these facilities are illustrated by the following diagram shown in Fig.2.

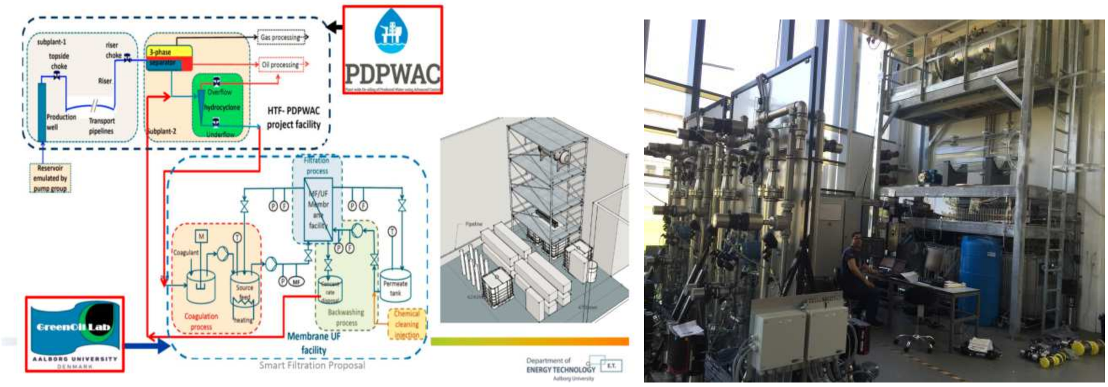

Fig.2 Skematic diagram of AAU testing facilities (left) and a photo of the standing rig system (right)

The **separation testing facility** (noted as "PDPWAC" block in Fig.2) consists of the following main subsystems:

- **Topside three-phase separation facility** consists of a pressurized steel API separator and a transparent one with their relevant control valves and transmitters.
- **De-oiling hydrocyclone facility** consists of two industrial liners provided by the cooperated industrial partner, one is lightly used and the other is discarded, and they can indicate different inner surface conditions and different life durations. There is also one transparent hydrocylone which is developed to visualize the separation patterns which occur inside the cyclone. The flow dynamics inside the cyclone can also be recorded by a high-speed industrial-standard camera. All cyclones are equipped with relevant control valves (underflow and overflow valves) and flow measurements.
- **Pipeline and riser system** consists of a 6-meter 2-in transparent PVC vertical pipeline and a 30-meter horizontal pipeline. The riser pipeline is equipped with controlled water, oil and gas (air) injection valves, which can emulate a riser [1] or a production well [8] using a gas-lifting mechanism. A set of temperature, pressure and flow transmitters are installed along the pipelines, which can provide necessary information about the flow condition and regimes as well as for safety purpose.
- **Flow circulation and injection facility** consists of a set of water, oil tanks and air compressor, a set of centrifugal water pumps, and a special oil injection pump as well as a oil and water homogenizer. All systems are equipped with necessary local control and monitoring system with flexible configurations.
- **Flow monitoring and measurement equipment** consists of a bunch of different flow-meters, such as EM, Ultro-sonic, Coriolis and ABB's nonradioactive VIS Multi-phase flow meters. Different Oil-in-Water (OiW) monitoring facilities, such as fluorescence-based OiW monitor (Turner TD-4100XD), Image-based OiW monitor (Jorin ViPA analyser), Tomography (ERT & ECT) sensors.
- **Communication and control system**. All data acquisition and control is performed using a standard PC running Simulink Real-time (xPC). The target PC is dedicated to run data capture and control experiment in real-time. A electrical distribution box is equipped with fuses, analog circuits (low-pass filters etc.) and power supplies.

The **filtration facility** (noted as "GreenOil-Lab" block in Fig.2) consists of four flexible filtration modules, each module is equipped with four steel membrane housing and each steel housing holds three Liqtech ceramic membrane lines. This platform provides a solid facility to study membrane filtration for PWT/IWT, optimization of filtration facility and operation, with the aim to promote this filtration technology to be the Best Available Technology (BAT) for future zero-pollutant discharge objective [13].

3 HYDROCYCLONE PRINCIPLE

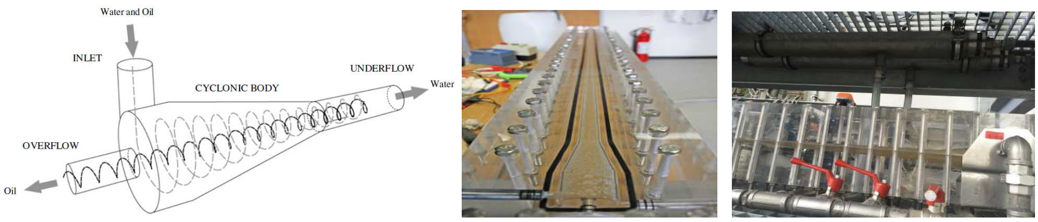

Fig.3 Principle of a typical hydrocyclone [3] (left) and our transparent cyclone equipment [4] (middle and right)

A hydrocyclone is a specifically designed facility following the enhanced gravity separation principle. A typical hydrocyclone can build up gravity fields of 2000-3000g. The key design parameters are often determined according to specific applications. In general, as shown in Fig.3, a typical de-oiling hydrocyclone consists of one or two tangential inlet(s), through which the pressurized liquid enters the cyclone's cylindrical chamber. Due to the centrifugal force, the liquid (oil and water) accelerates into a circular movement by following the cylinders wall. After passing the cylindrical segment, the liquid enters into a conical section designed with a proper cone angle. The centrifugal force causes the liquid to develop two vortex systems. The outer vortex, mainly containing the heavier liquid phase, i.e., water inside the de-oiling hydrocyclone, moves towards the *underflow* direction by following the conical wall. The inner vertex, mainly containing the lighter liquid phase, i.e., oil inside the de-oiling hydrocyclone, moves in the opposite direction, called *overflow direction*, by accumulating itself around the hydrocyclone's central axis.

The vortex flows inside the hydrocyclone follow the conservation of angular momentum [3], and the centrifugal force can be adjusted by altering the kinetic power input at the inlet, i.e., the injection velocity, or it can also be adjusted by choking the overflow and underflow control valves. The ultimate objective of using de-oiling hydrocyclone is to remove the oil content in the feeding liquid as much as possible, by pushing the oil phase out of the overflow outlet and the water phase out of the underflow outlet, respectively. This de-oiling separation performance can be generally evaluated using *hydrocyclone efficiency* [5,7]. The hydrocyclone efficiency usually is measured by oil mass recovery, i.e., it is defined as the ratio of the oil concentration in the underflow effluent over the oil concentration in the influent in terms of percentage [3].

4 CURRENT HYDROCYCLONE CONTROL

The control of hydrocyclones is critical in achieving high separation efficiency, and keeping a stable vortex flow in the presence of operational variations [13].

One typical hydrocyclone control structure for offshore de-oiling application is illustrated in Fig.4 [7]. The liquid feeding to hydrocyclone is directly from the water outlet of upstream three-phase separator without any buffer vessel in-between. A control valve *LCV*, installed at the underflow outlet, is manipulated by a separator level controller *LC01* by using the level transmitter *LT01* measurement, in order to maintain the separator water level at a proper Set-Point (SP). Three pressure transmitters *PT01, PT02, PT03*, are deployed in the system to measure the pressure at the hydrocyclone inlet, underflow and overflow, respectively. Two pressure differences, called *DP01, DP02*, are calculated according to $DP01 = PT01 - PT02$ and $DP02 = PT01 - PT03$, respectively. Both DP01 and DP02 signals feed to *PDY01* block, which calculates the Pressure Drop Ratio (PDR) by $PDR = DP02/DP01$ and feeds this to a controller *PDC01*. The PDC01 manipulates a control valve *PCV* which is installed after the hydrocyclone's overflow outlet, based on the transmitted PDR signal, to maintain the operational PDR at a pre-given set-point. This control loop is often referred to as the *PDR Control* [4,7,13].

In order to be sure that the hydrocyclone efficiency can be settled at the high level, in many cases, the level controller (LC01) needs to take care of the inflow rate as well, besides the separator water level control. The PDR set-point is normally empirically selected.

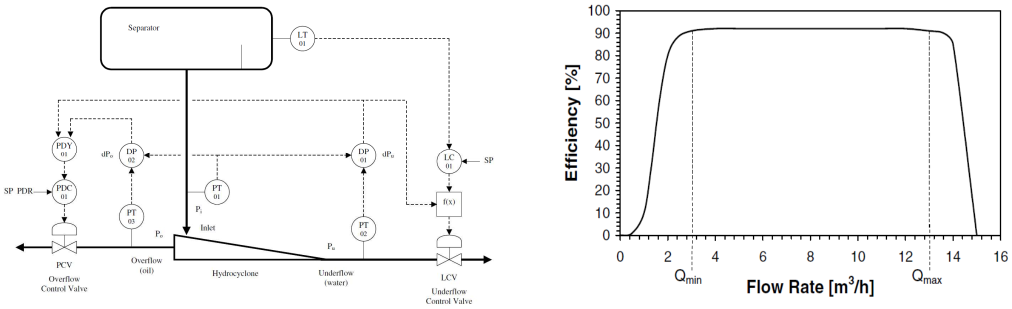

Fig.4 One typical hydrocyclone control structure and its efficiency-flow curve [7]

So far as we observed from literatures as well as experienced from practical production rigs, all the control solutions for hydrocyclone systems are some type of PID controllers. There is very little information about how these controllers were developed and what are the design criteria, neither is there any discussion of their potential optimization. In general, these open issues are mainly due to the following difficulties [13,14]:

- Lack of proper hydrocyclone models which have good orientations for supporting control design and analysis;
- The cost-effective and reliable sensing devices and methods for directly measuring the hydrocyclone efficiency in an real-time manner are still quite challenging;
- Lack of breakthrough ideas and thoughts of new control structures, criteria and corresponding design methods/methodology.

5 OPTIMIZATION OF HYDROCYCLONE CONTROL

The hydrocyclone control problem can be abstracted into a functional block-diagram as shown in Fig.5, where the concerned system is a three-input and two-output system, two manipulated variables are: the opening degrees of overflow and underflow control valves, and the third input, inflow rate to the separator, is regarded as the disturbance to the considered system. Two controlled variables are: the operational PDR and separator (water) level. From the process control point of view, the *plant* consists of functional models of hydrocyclone's PDR dynamic and the separator's water-level dynamic. There is a clear coupling between these two dynamic subsystems with respect to the physical principles, which is reflected by the *Pi* input to the hydrocyclone block. The optimal control problem turns to coordinately design both PDR controller and Level controller subject to given reference points.

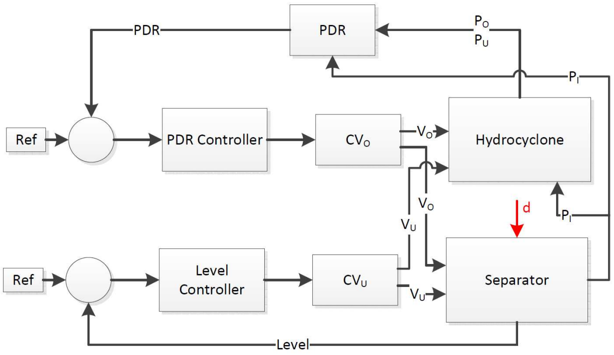

Fig.5 Block diagram formulation of plant-wide hydrocyclone control [13]

5.1 Mathematical Modeling

Mathematical modeling of the concerned system is the first fundamental step for optimal control design based on these Quantitative models. Modeling the separator level dynamics can be committed using mass and energy balance principles [15], while the modeling of cyclone dynamics can be much more complicated [2,4,7]. The precise and reliable way to study hydrocyclone dynamics is to use CFD technology [3], however, the CFD models are often too complicated for supporting control design purpose. Some of our recent development of control oriented models of hydrocyclones can be found in [2,4,13].

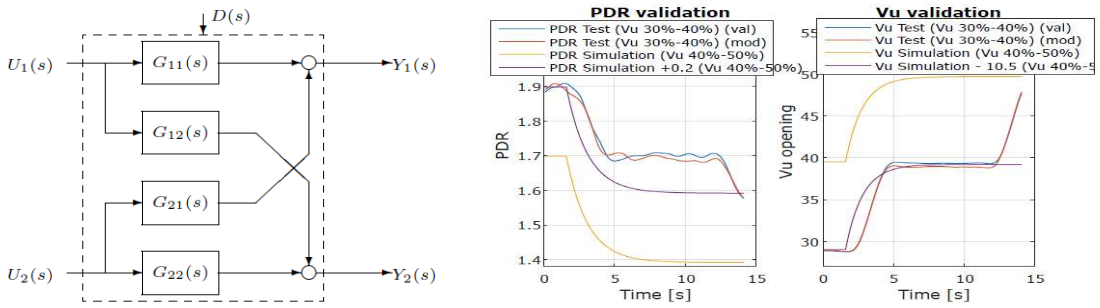

Fig.6 left: Diagram modeling the coupled dynamics between two MV and CVs [13]; Middle & Right: Model validations of underflow valve and system loop from underflow valve to PDR [4]

5.2 Real-time OiW Monitoring

It has been discovered that a good PDR control doesn't necessarily lead to high cyclone efficiency [5]. The PDR control has direct influence to flowsplit while the efficiency is also affected by the inflow rate, concentration of oil in the influent, dispersed oil droplet sizes etc. To be able to measure/monitor the hydrocyclone efficiency is very important for cyclone control design and evaluation. This leads to the issue of Oil-in-Water (OiW) measurement and monitoring. OSPAR has a recommended GC-FID based OiW measurement procedure, but it is an offline method [9]. Some real-time OiW measuring technologies have also been investgated by our recent research, including the fluorescence-based Turner Design TD-4100 XD Analyzer, an optical-image based Jorin VIPA Analyzer and Electrical Resistant Tomography (ERT) technology. Some of our results and observations can be found in [5,6,10].

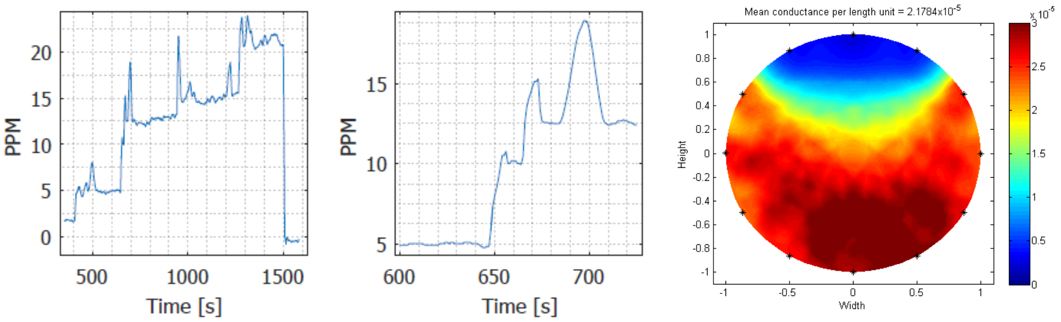

Fig.7 Left-two: TD4100 measurement with known oil concentrations diluted in Isopropyl alcohol, low concentrations shifts from 1 to 20 PPM. Left-1 plot illustrates all the concentration steps and the middle plot illustrates a zoom in on one of these steps [5]. Right: water-gas distribution constructed from an in-house designed ERT sensor [6]

5.3 Direct Efficiency Control

If the efficiency can be relaibly measured in a real-time manner, there is a huge opportunity to promote the hydrocyclone control into a brand new scope: direct efficiency control. Correspondingly, instead of building a set of models of control loops from control valves to PDR measurement, some models decribing the dynamic relationship from control valves to cyclone efficiency need to be identified. The optimal efficiency control aims to keep the system output (efficiency) as high as possible, subject to operation variations. This is one of our key undergoing investigations [2,4,11].

6 CONCLUSIONS

There is no doubt that any cost-effectively innovative PWT technology can lead to huge benefits for the oil & gas industry as well as protection of our global environment. This paper discussed some of our undergoing work and opportunities to optimize the existing hydrocyclone based de-oiling technology using the model-based plant-wide control strategy.

7 ACKNOWLEDGMENT

The authors would like to thank the support from the Danish National Advanced Technology Foundation (via PDPWAC Project (J.nr. 95-2012-3)). Thanks also go to colleagues J.P. Stigkær, A. Aillos, K. G. Nielsen and Yigen Crème from Mærsk Oil A/S, colleagues P. Sørensen, A. Andreasen, B. Løhndorf and Jakob Biltoft from Ramboll Oil & Gas A/S, for many valuable discussions and supports. Thanks also go to students: M. Bram, D. Hansen, A. Hassan and K. Panev for their contributions to this project.

8 REFERENCES

[1] J. Biltoft, L. Hansen, S. Pedersen and Z. Yang, "Recreating Riser Slugging Flow Based on an Economic Lab-sized Setup", Proc. *of* 5th IFAC Int. Workshop on Periodic Control Systems, Caen, France, July 3-5, 2013, pp.47-52.

[2] M. Bram, D. Hassan, D. Hansen, P. Durdevic, S. Pedersen and Z. Yang, "Experimental Modeling of a De-Oiling Hydrocyclone System", Proc. of the 20th Int. Conf. on Methods and Models in Automation and Robotics, Miedzyzdroje, Poland, 24-27 Aug. 2015. Pp.1080-1085.

[3] J.C. Cullivan, R.A. Williams and C.R. Cross, "Understanding the Hydrocyclone Separator through Computation Fluid Dynamics″, Trans IChemE, Vol.81, Part A, 2003, pp.455-466.

[4] P. Durdevic, S. Pedersen, M. Bram, D. Hansen, D. Hassan and Z. Yang, "Control Oriented Modeling of a De-Oiling Hydrocyclone", 17th IFAC Sym. on System Identification. IFAC-PapersOnLine, Vol.48, No.28, 2015, Pp.291–296.

[5] P. Durdevic, S. Pedersen and Z. Yang, "Evaluation of OiW Measurement Technologies for Deoiling Hydrocyclone Efficiency Estimation and Control**",** Proc. of IEEE OCEANS'16 Shanghai Conference, Shanghai, China, April 2016.

[6] P. Durdevic, L. Hansen, C. Mai, S. Pedersen and Z. Yang, "Cost-Effective ERT Technique for Oil-in-Water Measurement for Offshore Hydrocyclone Installations", 2nd IFAC Workshop on Automatic Control in Offshore Oil and Gas Production, Brazil. IFAC-PapersOnLine, Vol.48, No.6, Pp.147-153.

[7] T. Husveg, *Operational control of hydrocyclones and cyclones for petroleum flow control*, PHD Thesis, University of Stavanger, Norway, 2007.

[8] K. Jepsen, L. Hansen, C. Mai and Z. Yang, "Emulation and Control of Slugging Flows in a Gas-Lifted Offshore Oil Production Well Through a Lab-sized Facility", Proc. of *2013* IEEE Conf. on Control Applications**,** India, August 28-30, 2013, pp.906-911.

[9] OSPAR Commission 2013, "Background document concerning techniques for the management of produced water from offshore installations, 2013.

[10] S. Pedersen, C. Mai, L. Hansen, P. Durdevic and Z. Yang, "Online Slug Detection in Multi-phase Transportation Pipelines Using Electrical Tomography", *2nd IFAC Workshop on Automatic Control in Offshore Oil and Gas Production*, Brazil. IFAC-PapersOnLine, Vol.48, No.6, Pp.159-164.

[11] S. Pedersen, K. Stampe, S.L. Pedersen, P. Durdevic and Z. Yang, "Experimental Study of Stable Surfaces for Anti-Slug Control in Multi-phase Flow", Int. J. of Automation and Computing, Vol. 13, No.1, 2016, pp.81-88.

[12] A. Sinker, "Produced Water Treatment Using Hydrocyclones – Theory and practical application", 4th Int. Petroleum Environmental Conference, Houston, USA, 5-9 Nov 2007.

[13] Z. Yang, S. Pedersen and P. Durdevic, "Cleaning the Produced Water in Offshore Oil Production by Using Plant-wide Optimal Control Strategy"**,** in Proc. of IEEE OCEANS'14*,* St John's, Canada, 15-19 Oct 2014.

[14] Z. Yang, J.P. Stigkær, and B. Løhndorf, "Plant-wide control for better de-oiling of produced water in offshore oil & gas production", Proc. of 3rd IFAC Conf. on Intelligent Control and Automation Science, 2013, pp-45-50.

[15] Z. Yang, M. Juhl and B. Løhndorf, "*On the Innovation of Level Control of an Offshore Three-Phase Separator*", Proc. of 2010 IEEE Int. Conf. on Mechatronics and Automation, Xi'an, China, 4-7 Aug 2010, pp.1348-1353.