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Experiment Analysis and Baseline Hydraulic Characterisation of HiPOR, a High Pressure Crude Oil Fouling Rig

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Crude oil fouling is one of the most common and challenging issue in refinery heat exchangers. It not only affects continuity and safety of operations but it also costs to a refinery several millions a year in maintenance, extra fuel and loss of production. To improve the understanding of fouling high quality primary measurements are needed at temperatures, pressures and flow conditions close to those in actual refining operations. To produce such critical data a high pressure oil rig (HiPOR) was developed at Imperial College London and licensed to Hexxcell Ltd. In parallel, a mathematical model for the rig has been developed. The model includes all the major equipment components in the process flow diagram and is capable of simulating the operations of HiPOR including start-up, heating and cooling.
In this paper, the measurements obtained from a set of experimental runs with a non-fouling oil and in cold conditions (i.e. at oil constant temperatures below 100 °C) are used to characterize the hydraulic performance of the rig. A baseline validation of the hydraulic performance of the model against those data is also presented.
Excellent reproducibility of all primary measurements at various operating conditions was demonstrated across repeated runs, providing excellent confidence on the reliability of the data for following analyses. The simulation results also show good agreement of the model with the experimental hydraulic data.

1. Introduction

Fouling, the deposition of unwanted material on heat transfer surfaces is a common problem that affects a large portion of heat transfer equipment in the process industry. Fouling is particularly severe in pre-heat trains of crude oil refineries where it has a tremendous impact on economics, operations, environmental emissions, maintenance and safety (Coletti et al. 2015). Understanding fouling has been a tough challenge for researchers in industry and academia alike as it involves a number of very complex phenomena which interact with each other (Müller-Steinhagen, 2011). Macchietto et al. (2011) have described a systematic and multi-pronged attach to crude oil fouling research involving the interaction of modelling and experimental activities at several scales of investigation. Although progress has been made over the years, several challenges are still confronting researches attempting to make progress in the understanding of this phenomenon. One of the major challenges is the lack of high quality primary measurement obtained in tightly controlled settings that would enable relating specific process conditions (e.g. temperature, pressure, shear stress) and composition to the fouling behaviour. A specific challenge in the past has been ensuring reproducibility of data in repeated experiments. A further issue is the extrapolation (scaling up) of results obtained in small scale batch experiments to actual refinery conditions.
This paper focuses on the characterisation of the hydraulic performance of a high pressure oil rig (HiPOR) designed at Imperial College London and licensed to Hexxcell Ltd. to produce and accurately measure fouling deposits at refinery conditions. The paper also illustrates the validation of the hydraulic part of a mathematical model of the rig against experimental measurements. For this purpose, experimental runs were carried out with Paratherm, a non-fouling oil. This provided reliable baseline data and validation, essential for the interpretation of experimental data produced with fouling fluids.

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Experimental set up and results are presented in sections 2 and 4, the mathematical model in section 3 and the validation procedure in section 4.3. The paper briefly discusses how such a reliable baseline reference data and model will be used for the interpretation of experimental crude oil fouling data generated with HIPOR.

2. Experimental set-up

A schematic flowsheet of the HiPOR facility is shown in Figure 1. The rig can be divided into a few sections (Pental 2011): storage tank, test sections, pumps, cooling loop and circulation pipework. The oil, stored in the 120 l tank, is circulated by the primary pump through two 2 m long main test sections (a tubular and an annulus flow section, or two tubular sections, etc.). Whilst a tubular section provides data on the same geometry found in refinery heat exchangers, an annulus section permits precise additional measurement of temperature profiles along the full axial direction and easy access to the fouling deposits for subsequent (off-line) characterization. For a precise control of test conditions, Joule heating is used to supply heat to the crude in the test sections where the oil reaches the desired, industrially relevant, conditions of temperature and pressure (i.e. up to 270 °C and 30 bar, with test wall temperatures of up to 370°C).

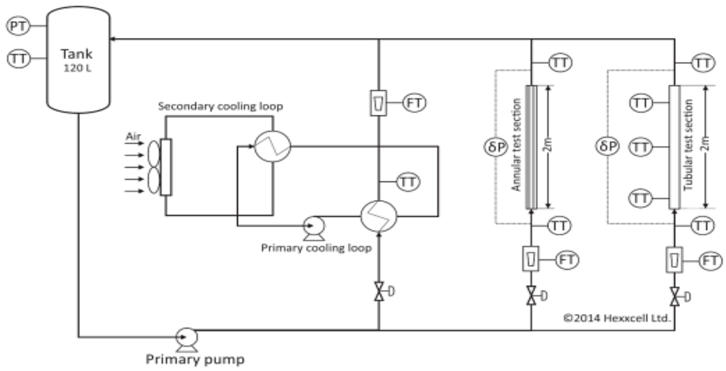

Figure 1: Schematic diagram of HiPOR (©Copyright 2015 Hexxcell Ltd)

Key temperature, pressure and flow sensors and control elements are installed at strategic points to measure and control all important variables. A metal short-stroke Rotameter flowmeter and differential pressure meter were calibrated for high precision with an estimated error of ±0.04 m^3/h and ± 2 mbar (see Section 4.1) and provided reliable primary measurements of these variables. An automated control system (LabView, 2013) was developed to monitor and precisely control key process conditions and log all results. Experiments were repeated to check the reproducibility of the measurements.

3. Model

A model for the rig was implemented using the Hexxcell Studio™ (Hexxcell ltd.) model libraries for the test sections. Hexxcell Studio™ runs on a commercial process simulation platform (PSE, 2014) and can also use its standard model libraries. Each individual rig component and section was modelled taking into account its specific hydraulic characteristics such as surface roughness, pipe section length, internal diameter, bends, pumps characteristic curves, valves stem position and flow coefficients (Martinez-Minuesa, 2014). Figure 2 shows all major equipment, valves and piping included in the model.

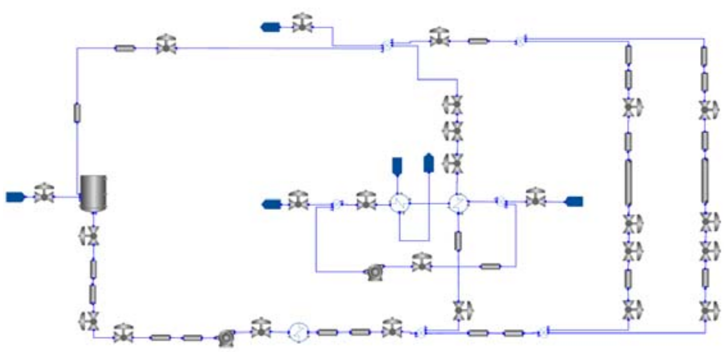

Figure 2: Snapshot of the HiPOR flowsheet model in the Hexxcell Studio™ simulation.

An ad-hoc physical property package was developed and interfaced with the model to calculate the necessary properties (density, viscosity, thermal conductivity and specific heat capacity) of the fluids involved as a function of temperature. The model is written in such a way that it allows to interface a number of other commercially available physical property packages as well as proprietary ones. This feature is particularity important as it allows the flexibility of using different physical property software packages depending on the information available for oils. Moreover, it allows highly specialised databases, developed over the years by individual oil companies, to be used with the model.

4. Result and discussion

4.1 Test runs

A number of test runs were carried out using Paratherm as the fluid. Paratherm is an oil that can be safely used even at high temperature without fouling, while presenting viscosity and density characteristics similar to typical oils. It is thus ideal to characterize baseline hydraulic (and thermal) features of the rig over the entire range of the planned application. In a typical run, the oil is preheat to 60 ºC and circulated through one or both the test sections. For the two test runs shown in Fig. 3 and Fig 4, during start-up valve V17 (at the inlet the test section) was opened in steps of 10 % until fully open, then flow maintained for 2 h. Then valve was then closed for shutdown in steps of 10 % of the opening at a time. The initial and final transients allowed establishing the valves characteristic, the steady state period to check the consistency of flowrate measurements.

4.2 Reproducibility

To test the reproducibility of the measurements, the results of two cold run experiments are examined in this section. The two runs were performed with the exact same schedule of inputs (given above) thus the values of the measured variables are expected to be close. The following shows data for a time slice of 100 min from the same starting time (minute 50) in the two runs. Figure 3 shows that the difference in measured flowrates at the inlet of the annulus (F1), tubular (F2) and cooling sections (F3) between the two runs is within ±0.04 m^3/h (2 %). Considering the scale and complexity of the equipment, this is an excellent result, indicating that repeated cold runs with non-fouling fluids are reproducible enough to allow the study of the phenomena of interest.

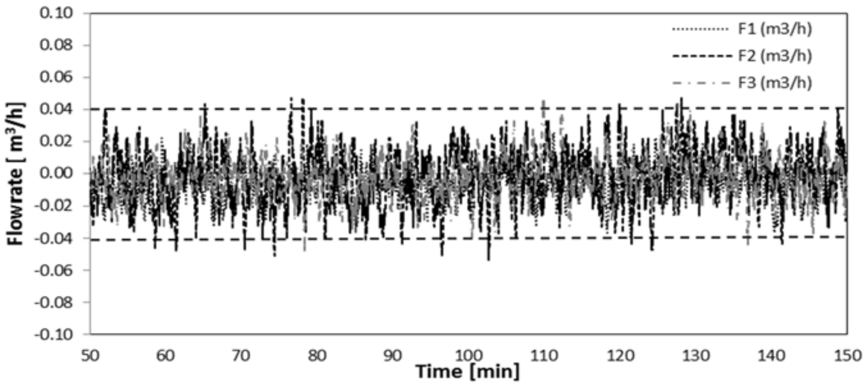

Figure 3: Flowrate measurement points are reproducible within an absolute difference of ±0.04 m^3/h

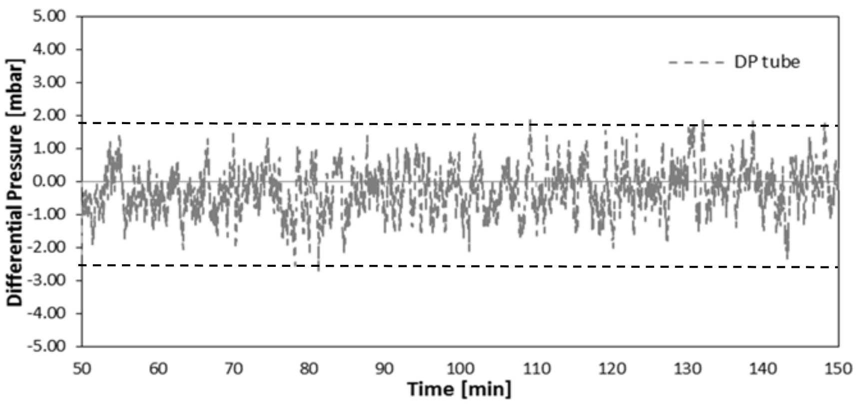

Figure 4: Differential pressure (δP) measurements in the tubular test section are reproducible within an absolute difference of ± 2 mbar

The differences in the differential pressure measurements at the tubular test section for the two experimental runs considered also show excellent agreement as shown in Figure 4. In this case, the difference within the two runs is ± 2 mbar. The results in Figure 3 and Figure 4 demonstrate that the control and instrumentation systems on the rig are capable of producing replicable results which can be used with confidence for baseline validation with non-fouling oil.

4.3 Model hydraulic validation

The experimental data from the runs shown above were used to validate the mathematical model of the rig described in section 3. Figure 5 shows an overlay plot of model calculations and experimental measurements of the flowrate at the inlet of the tubular test section (F2) over 200 min. For the first 30 min of the experiment the valve is closed thus there is no flow, the valve is then gradually opened and finally closed around time 165 min. The mathematical model, which accounts for pressure drops in the piping, valves and equipment with a good level of detail, follows pretty well the experimental data. The experiments respond a bit more slowly than the model to valve opening and closing, and there is a small steady state bias, most likely due to the fact that some pipe fittings (flanges, etc.) were not taken into account. To represent the hydraulic contribution (pressure drop) of all elements that were neglected, a fictitious pipe length was added to the circuit. Figure 6 shows that the addition of 5 m of equivalent length of pipe is sufficient to achieve an excellent agreement with the experimental data for the flowrate measurements.

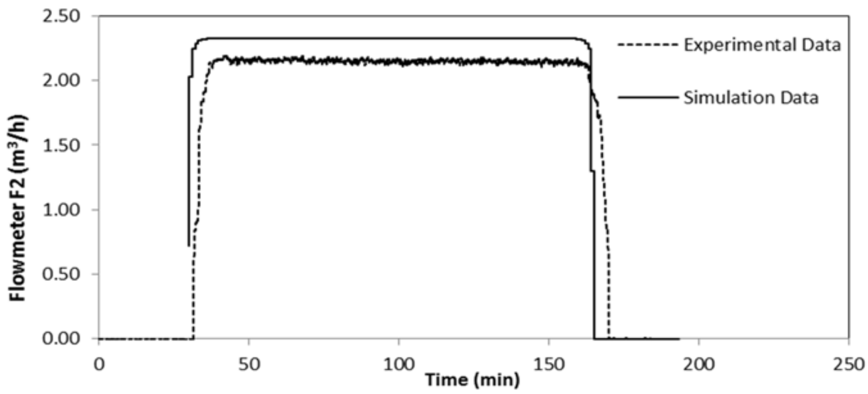

Figure 5: Flowrate in the tubular test section (F2): experimental and simulated

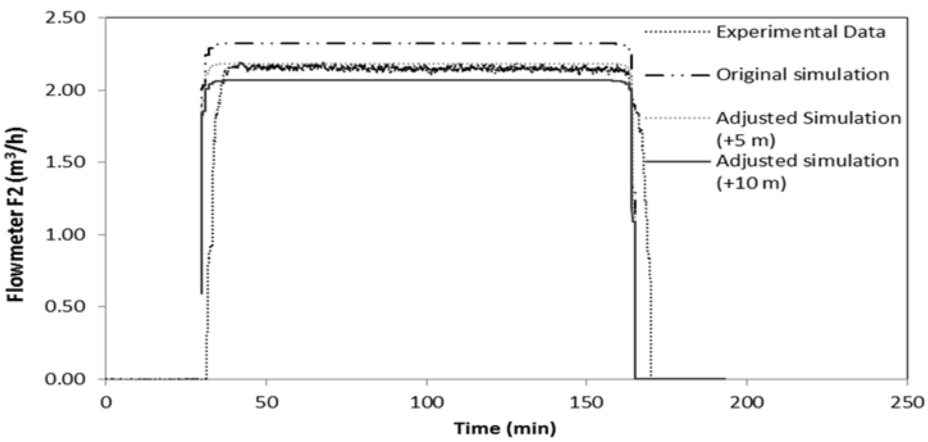

Figure 6: Flowrate in the tubular test section (F2): experiment, original and adjusted simulation data

When the adjusted value of the equivalent length is increased to 10 m, the simulation under predicts the experimental steady-state flowrate. Table 1 reports the relative error of the calculated flowrate, F2 without and with these corrections. The initial average error of 8.1 % is reduced to only 1.6 % when a 5 m equivalent length is added to the circuit. These good results will need to be confirmed at higher temperatures, due to density and viscosity changes, and with fouling in the test sections.

Table 1: Relative error of calculated flowrate for simulation data

	Original simulation	Adjusted simulation (+5 m)	Adjusted simulation (+10 m)
Average	8.1 %	1.6 %	4.0 %
max	10.4 %	3.6 %	5.7 %
min	6.2 %	0.0 %	2.0 %

One of the benefits of using the mathematical model thus developed is that it is possible to easily calculate the flow distribution between the two test sections and fluid velocities in the tubular and annular test sections as a function of the opening of the control valves (V17 and V13) at the inlet of the test section. Calculated velocities are presented in Table 2 and 3 and plotted in Figure 7 and 8, when using two parallel tubular test sections, with test section 1 a ¾“ diameter tube and test section 2 of 1” diameter.

These results show that the model could be used to predict flowrates in the main rig circuit and (comparing with primary flowrate measurements), in the test sections, accounting for fluid properties, pressure drops, pump performance and valve characteristics in the entire flow circuit. The calculated velocities in the test sections will be very useful for hydraulic analysis with crude oil fouling, as velocity is one of the key variables affecting the fouling resistance.

Table 2: Calculated velocity in 1” tubular test section for different valve opening positions. V13 is the control valve at the inlet of test section 1, V17 is the valve at the inlet of test section 2.

1” Tubular Test Section Velocity (m/s)		V13 opening (%)				
		100 %	75 %	25 %	5 %	0 %
V17 opening (%)	100%	0.61	0.61	0.64	0.84	1.15
	75%	0.61	0.61	0.64	0.84	1.14
	25%	0.59	0.59	0.61	0.82	1.12
	5%	0.37	0.37	0.38	0.55	0.81
	0%	0.00	0.00	0.00	0.00	-

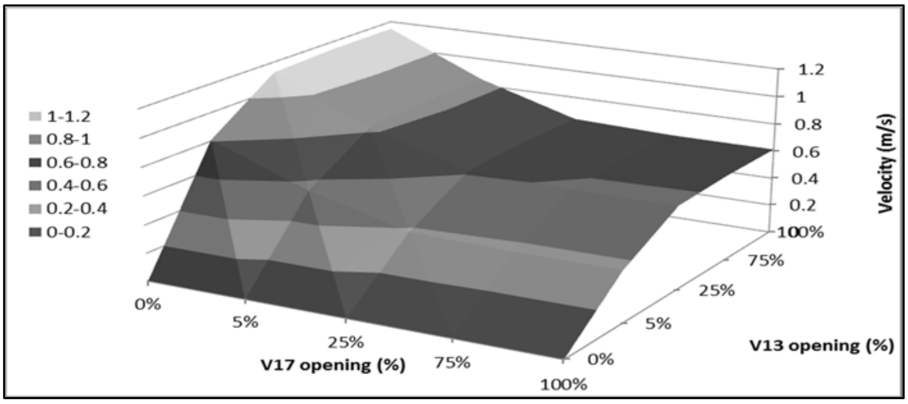

Figure 7: Calculated velocity in the 1” tubular test section as a function of the opening of control valves at the inlet of test section 1 (V13) and test section 2 (V17).

Table 3: Calculated velocity in the 3/4“test section for different valve opening positions. V13 is the control valve at the inlet of test section 1, V17 is the valve at the inlet of test section 2.

¾ “ Tubular Test Section Velocity (m/s)		V13 opening (%)				
		100 %	75 %	25 %	5 %	0 %
V17 opening (%)	100%	0.67	0.67	0.64	0.39	0.00
	75%	0.67	0.67	0.64	0.39	0.00
	25%	0.69	0.69	0.66	0.41	0.00
	5%	0.88	0.88	0.85	0.56	0.00
	0%	1.17	1.17	1.15	0.82	-

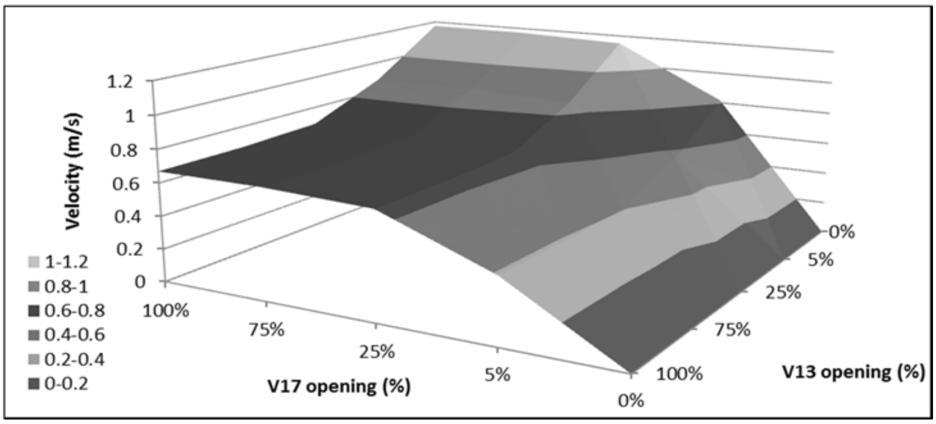

Figure 8: Calculated velocity in the ¾“ tubular test section as a function of the opening of control valves at the inlet of test section 1 (V13) and test section 2 (V17).

5. Conclusion

It is very important to characterise in detail the hydraulic behaviour of an experimental rig in clean conditions, as this gives the baseline for the evaluation of data obtained with fouling oils. In particular, accurate measurement of flow and calculation of velocity in the test sections is important, as velocities crucially affect fouling rate. It has been shown that for a non-fouling oil HIPOR can produce primary flow and pressure drop measurements with high reproducibility, and these could be used in hydraulic analysis. The validation of the hydraulic model shows a reasonable agreement with experimental data with quantified adjustments, leading to calculation of flows and velocities in the test sections when operated either individually or in parallel. Of course, accurate and reproducible measurement and control of the thermal aspects of the rig are equally important in providing quality data for measurement of crude oil fouling phenomena. Characterisation of such thermal characteristics of the rig, and discussion and validation of a full thermal hydraulic model of HiPOR will be presented in a separate paper.

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