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INVESTIGATION OF FLOW PULSATION TO MITIGATE CRUDE OIL FOULING

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ABSTRACT

The EU Horizon 2020 project "FlowEnhancer" aimed to reduce crude oil fouling in the tube side of shell and tube heat exchangers by investigating maldistribution of tubeside velocity. As part of the project, a test sequence was performed in a pilot-plant fouling rig to investigate how crude oil fouling is affected by pulsating flow.

Previous studies, mainly from the dairy and water processing industries, have used pulsating flows with frequencies from 0.2 to 20 Hz, with 1 - 2 Hz usually identified as optimum, and velocity amplitudes of ± 0.1 to 5 of the steady-state flow velocity. The pulsation led to a reduced build-up or, depending on the application, to a continuous removal of the deposit layer by continuously increasing and decreasing (up to partial flow reversal) the flow velocity and thus the wall shear stress.

The results of these tests, carried out in two parallel test sections of 3 m length and consisting of double pipe heat exchangers with 19 mm ID tubes, are presented here. The pulsation (periodically fluctuating flow velocity) was induced by opening and closing control valves to these two parallel test sections. The test conditions were 200 °C inlet temperature on the tube side (crude) and 320 °C on the shell side (hot heat transfer fluid), with velocity fluctuations around a mean of 1.2 m/s in one test-section and 0.8 m/s in the second test section.

The tests showed lower fouling rates with pulsation, but also lower average heat transfer coefficients.

INTRODUCTION

Fouling is a widespread and costly problem in diverse industrial processes, causing reduced efficiency, increased maintenance and costs, and lower product quality. Innovative solutions to overcome fouling have been explored by researchers and engineers in recent years and decades, of which one is the application of flow pulsation. This technique involves the application of periodic fluctuations in fluid flow that can potentially have a significant impact on fouling behavior. In this paper, the effectiveness and potential applications of using flow pulsation to reduce crude oil fouling inside heat exchanger tubes is investigated.

Fouling in industrial processes occurs when unwanted deposits accumulate on the surface of heat exchangers, pipelines, and other equipment, leading to a reduction in heat transfer efficiency, increased pressure drop, and higher energy consumption. This paper is particularly concerned with crude oil fouling, a challenging and widespread problem in the oil and gas industry. This type of fouling involves the deposition of heavy organic compounds and contaminants found in crude oil on heat exchangers and other equipment surfaces. This process results in lowered efficiency of heat transfer and increased maintenance requirements.

Traditionally, strategies for mitigating crude oil fouling include chemical treatments, mechanical cleaning, or the selection of fouling-resistant surfaces. Although these methods can be effective, they can also have negative safety, environmental and economic consequences. Chemical treatments may introduce pollutants or necessitate extensive disposal procedures, while mechanical cleaning is labour-intensive, involves safety risks and has the potential to disrupt operations [1]. Additionally, fouling-resistant surfaces can be expensive, difficult to apply, and not always suitable for specific process conditions
[2–4].

Recently, increased interest in alternative methods to reduce crude oil fouling, has led to a potential method, which involves implementing flow pulsation. Intentional flow pulsation, as the term suggests, involves the creation of oscillations or periodic fluctuations in the flow rate of a fluid. This dynamic flow behavior may influence fouling behavior in several ways, including enhanced mass transfer, enhanced turbulence, and modified boundary layer characteristics. Typical flow pulsation methods are piston pulsators [5–9], valve interrupters [10–12], and gas pulsation techniques [13].

To highlight the potential benefits and applications of flow pulsation against crude oil fouling, some additional references are presented below.

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Pulsation

One of the earliest studies in investigation of pulsating flows in the context of heat exchangers was done by Keil and Baird [14]. The objective was to improve the heat transfer in a water/steam shell-and-tube heat exchanger with pulsating flow on the waterside. The authors concluded that flow pulsation can profoundly improve the heat exchange process. The use of pulsations promotes efficient mixing of the heat transfer medium, resulting in increased heat transfer. This is specifically relevant for heat exchangers, as flow pulsations can help to prevent deposits or thermal insulation barriers on the exchanger surfaces.

Gillham et al. [9] studied the effects of flow pulsation on the removal of whey protein deposits. Pulsating flows were generated by imposing a time-dependent flow profile with specific frequencies of ≤ 2 Hz and amplitudes of about ±10 % of the steady flow rate, which was at Re = 580. These conditions allowed the researchers to isolate the effects of flow pulsation on cleaning efficiency while maintaining a consistent operating environment. The authors observed that the cleaning efficiency was affected by the difference in pulse, the steady flow velocity, and the presence of reverse flow.

Augustin and Bohnet [7] investigated the impact of pulsation on the formation of crystallization fouling of an aqueous $CaSO_4$ solution using a piston pulsator with variable piston stroke and amplitude. A slightly higher heat exchange was observed, which was associated with the extended induction phase due to the pulsation and the resulting higher turbulence. In order to minimize the energy required for a steady pulsation and for technical reasons, in additional tests the stroke frequency (10 seconds to 30 minutes) and the number of strokes per cycle (1-10 strokes) were varied. All unsteady pulsation tests result in lower fouling resistances over time compared to steady flow at 0.5 m/s, but also higher fouling resistances compared to steady pulsation with a maximum of 0.5 m/s pulsed flow velocity.

The report of Boxler et al. [8] is derived from Augustin and Bohnet's work [7] and offers a survey of flow pulsation to improve fouling behavior, particularly in the context of the dairy industry. They utilized a similar pulsation configuration with a much more milk like model solution of whey protein isolate and simulated milk ultrafiltrate. Furthermore, they employed a plate heat exchanger instead of a tubular heat exchanger and varied the amplitude and frequency. In conclusion, there was a decreased fouling behavior and an increased heat transfer at higher values of waviness (W > 1). Waviness is a measure used to evaluate the pulsation flow characteristics into a channel. It was introduced by Dettmann as the ratio of the maximum pulse velocity $w_{pulse,max}$ to the average steady flow velocity $\overline{w}_0$, as follows:

$$W = \frac{w_{pulse,max}}{\overline{w}_0} \qquad (1)$$

Eq. (1) indicates that if an amplitude of ±10 % is applied around the average steady flow velocity, the waviness is W = 1.1.

The current pulsation flow velocity for each point in time t can be derived from two components [7]. On the one hand, from the steady flow velocity w_{steady} and on the other hand from the superimposed pulsation velocity, see Eq. (2).

$$w(t) = w_{steady} + w_{pulse,max} \cdot \sin(\omega t) \qquad (2)$$

The average steady flow velocity can then be described by Eq. (3):

$$\overline{w}_0 = \frac{1}{t_{pulse}} \int_0^{t_{pulse}} w(t)dt \qquad (3)$$

Moving beyond the experimental studies, also numerical studies have been done to predict beneficial effects on fouling [15] and cleaning [16] behavior using pulsating flows.

Saghatoleslami et al. [15] used numerical simulations (two-dimensional) to predict fouling rates and thicknesses in heat exchangers under pulsating flow conditions. A $CaSO_4$ fouling model was added as a user defined function in Ansys Fluent. Consequently, different pulsation parameters were varied and their influence on the fouling behavior was studied. Since they obtained conflicting results regarding the fouling resistance at different amplitude and frequency values, it was recommended to study the fouling behavior in more detail and in a three-dimensional setup.

In conclusion, flow pulsation is potentially a promising technique for the mitigation of crude oil fouling and offers significant potential for improving the efficiency and sustainability of oil and gas processes while reducing maintenance costs. The papers discussed provide an assessment of the effectiveness of using flow pulsation to reduce fouling and provide the basis for further research and innovation in this area, specifically tailored to the challenges of crude oil fouling.

On the other hand, pulsation techniques, especially piston pulsators, have a significant impact on energy consumption and other process conditions that must be weighed against the energy savings achieved by using these pulsation techniques.

PULSATION TEST

Experimental Setup

The pilot-scale fouling test unit used for these experiments is designed to duplicate the flow and temperature conditions found in actual crude oil preheat trains. This includes crude oil and heating medium temperatures, velocities, and tube geometry.

Figure 1 shows a schematic of the flow arrangement. The test sections, two in parallel, are

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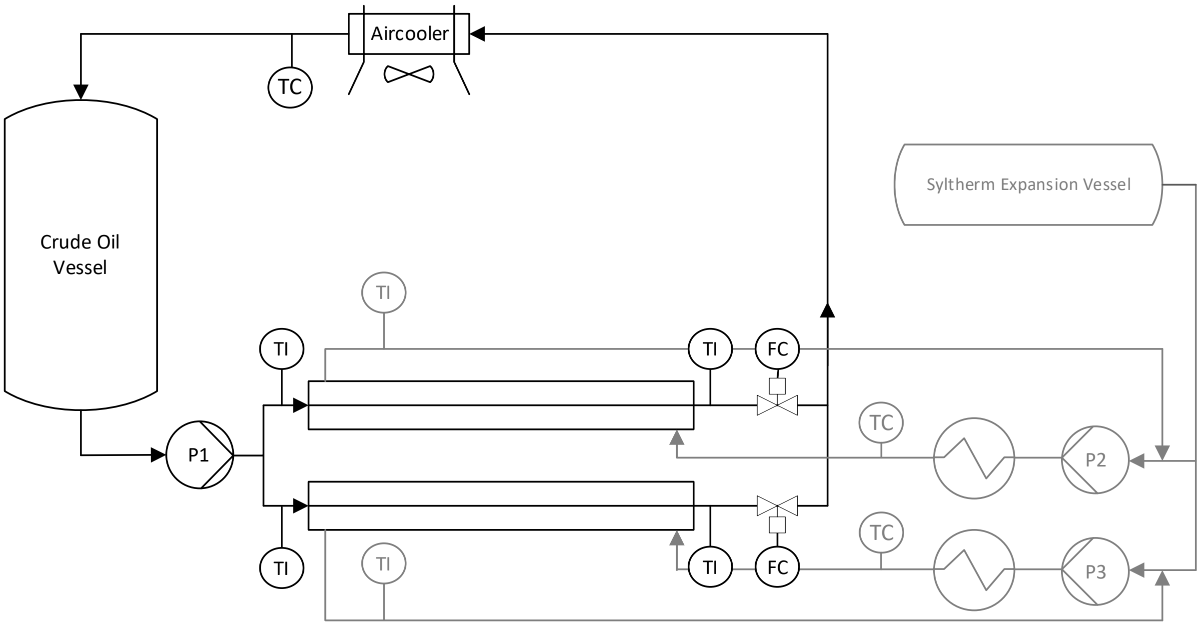

Figure 1 Test Unit Flow Schematic

double pipe heat exchangers with a standard 25 mm OD (1”) heat exchanger tube in each, 3 m in length. Crude oil, shown in black, flows on the tubeside and the heating medium Syltherm 800, shown in grey, flows on the shellside. The flow rates are set for both sides at the start of a test. The crude flow is set to match the desired velocity and the hot flow is set to the maximum possible to minimize the hot side heat transfer resistance and its impact on the result. The hot fluid is heated by electric heaters, which also allow temperature control. The crude is heated in the test sections and recirculated through a controlled air-cooled heat exchanger to maintain the inlet temperature to the test sections.

Both flow rates and the hot side inlet temperature can be controlled independently for the two parallel test sections. Thus, it is possible to obtain two data points, at two crude side velocities, from each test. As shown in Figure 1, the crude flow enters the tubeside from the left, while the Syltherm flow enters from the bottom right in a counter flow configuration. Of importance are the flow control valves (FC) and the temperature measurements (TI) at the inlet and outlet of each side. Temperature is measured by four resistance temperature detectors (RTDs) each for the inlet and outlet on the crude and Syltherm sides.

The crude side flow control valves (FC) located downstream of each test section, are used to adjust the flow to obtain the desired velocity or pulsation. For the baseline tests, the valve positions were set at the start of the test and remained there for the duration of the tests.

For pulsation, the valves are set to the base velocity positions at the start of the test, but when pulsation is initiated, the opening is increased to provide 50 % higher flow for one minute and is then decreased to provide 50 % lower flow for the next minute. This cycle is repeated until the test is stopped. The two test sections, FT-1 and FT-2, were pulsed in opposite directions so that when FT-1 was at +50 % flow, FT-2 was at -50 % and vice versa.

The valve opening takes 4-5 seconds to stabilize the flow at the desired level, so in reality the maximum and minimum flows are obtained for approximately 55 seconds per minute (see Figure 2).

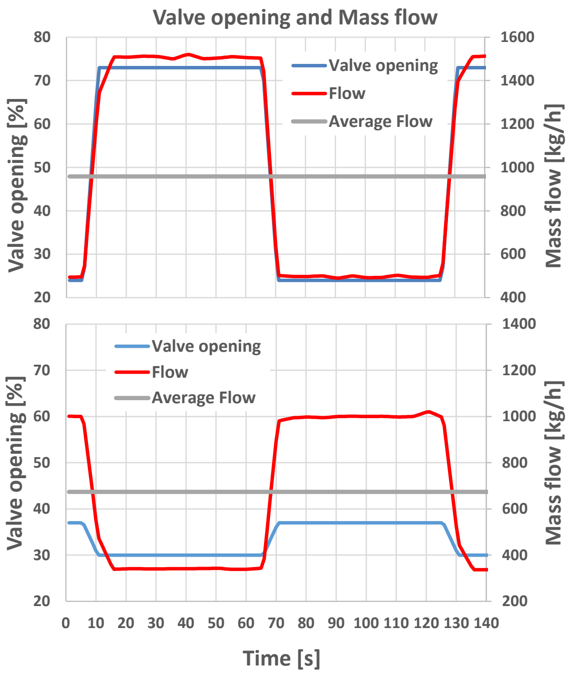

Figure 2 Pulse interval and corresponding mass flow at top: FT-1 and bottom: FT-2
(Note different mass flow scales)

The test conditions were 200 °C inlet temperature on the tube side (crude) and 320 °C on the shell side (hot heat transfer fluid), with tube side velocity fluctuations around an average of 1.2 m/s in one test section and 0.8 m/s in the second test section, corresponding to Reynolds numbers of $Re_{1,2} \approx 22{,}000$ and $Re_{0,8} \approx 15{,}000$. Typical

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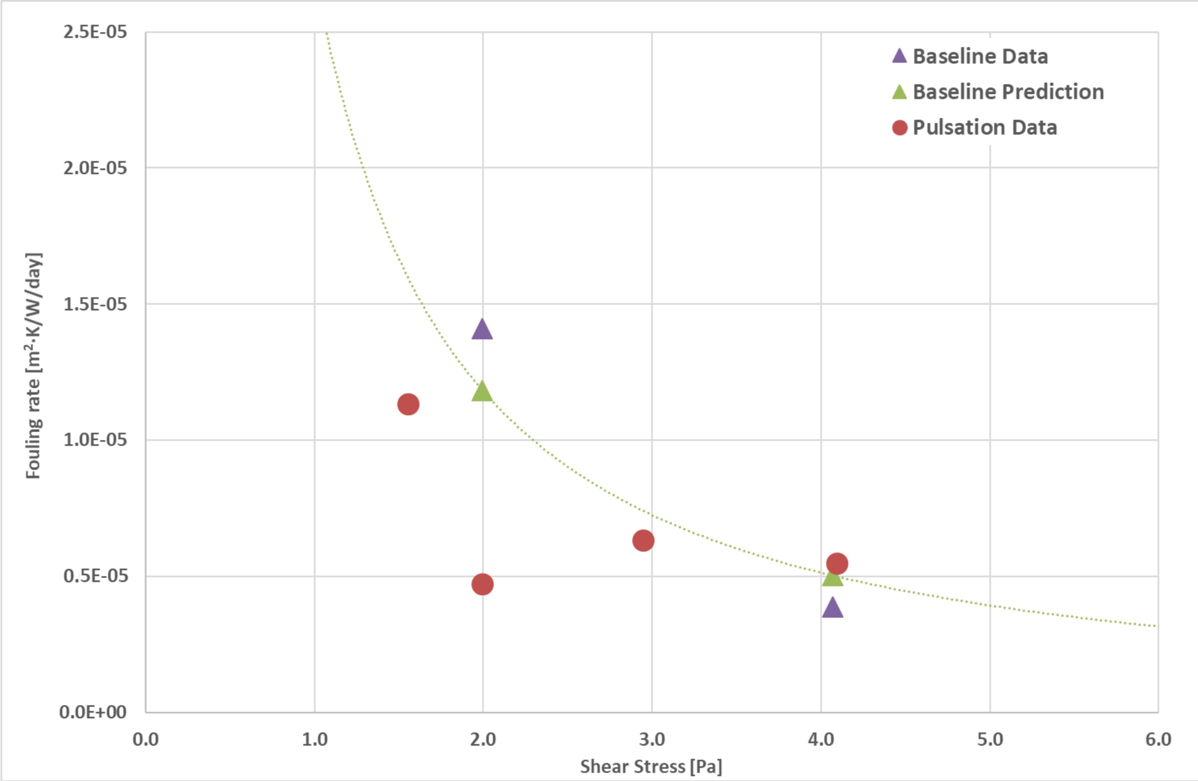

Figure 3 Comparison of Fouling Resistance with and without Pulsation

design flow velocities are between 1.5 and 2.5 m/s. Unfortunately, typical operating velocities are reduced to half of the design velocity as partial loads cannot be avoided. The properties of the crude oil used were derived for each time step as an average between the in- and outlet temperatures. Averaged values can be found in Table 1.

Table 1 Crude oil properties

Properties	FT1	FT2
Density (kg/m³)	732.2	730.3
Viscosity (mPas)	0.8031	0.7878
Specific heat (kJ/kg/K)	2.494	2.446
Thermal Cond. (W/m/K)	0.0782	0.078

In total, three tests were performed, each providing two data points. The first was a baseline test (without pulsation) to establish fouling rates against which the pulsation test results could be compared. The next two tests started at a set velocity, which was then pulsed to +50 % for one minute and -50 % for the next minute. The waviness for both sections then is $W = 1.5$. In terms of the changeover times, the measured average velocity was slightly different from the theoretical values so the real waviness was about $W \approx 1.45$. Data were recorded every second, and the fouling rates were determined using hourly averages of the second-by-second data.

RESULTS

All analyses are performed using hourly averaged second-by-second data:

1. Crude and Syltherm properties are known.
   a. Crude properties, as a function of temperature, are calculated using a simulation based on assay data.
   b. Syltherm properties are as provided by the manufacturer.
2. Test section geometry (flow areas, surface area, tube diameter and thickness) are known.
3. Fluid flows and bulk temperatures (inlet, outlet) are measured on both sides
4. Heat duty ($\dot{Q}$, kW), which here equals to the enthalpy flux difference $\Delta\dot{H}$, is calculated for the crude oil side using Eq. (4).

$$\dot{Q} = \dot{m} \cdot c_p \cdot (T_{c,out} - T_{c,in}) \quad (4)$$

5. Log Mean Temperature Difference ($\Delta\theta_m$, K) is calculated using Eq. (5).

$$\Delta\theta_m = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\ln\left(\frac{T_{h,in} - T_{c,out}}{T_{h,out} - T_{c,in}}\right)} \quad (5)$$

6. OHTC (U, W/m²/K) is calculated using Eq. (6)
   a. Fouling may take some time to start after steady state flow and temperature conditions are reached. This is known as the induction period (see Figure 4).
   b. The first hourly point at the end of induction, when fouling starts, is the clean value U_{clean}.

$$U = \frac{\dot{Q}}{A \cdot \Delta\theta_m} \quad (6)$$

7. Fouling resistance (R_f, m²·K/W) is calculated using Eq. (7). The first point, when $U = U_{clean}$, $R_f = 0$ by definition.

$$R_f = \frac{1}{U} - \frac{1}{U_{clean}} \quad (7)$$

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R_f is smoothed using an exponential moving average, giving more weightage to the previous hour relative to the current hour. It is then plotted vs time (see Figure 5) and the slope of this line is the fouling rate (dR_f/dt, m²·K/W/day). Compared to Figure 4, Figure 5 only shows the post induction time/fouling period. Furthermore, Figure 5 assumes a linear fouling rate, as the linear trend fits the curve best, even though the curve shows a more dynamic behaviour. These non-linearities can be described by fouling layers falling off the wall or non-symmetric growth of the layers.

Figure 3 is a plot of the fouling rate (increase in fouling resistance per day) versus tubeside shear stress. Shear stress is a critical variable in fouling propensity. It affects the deposition and removal of material on the tube wall and thus influences the fouling rate and is a function of velocity but is a more fundamental parameter.

In Figure 3, the points and curve shown for "Baseline Prediction" represent the expected fouling rate calculated using a correlation developed by Shell [17]. It is used here for two purposes: (1) to confirm that the two baseline data points are within the expected range compared to the prediction, and (2) to quantify the fouling reduction for the pulsation tests.

Table 2 Fouling Rate Values

Data Point	Shear Stress	Velocity	Pulsed Fouling Rate	Steady Fouling Rate (*)	Improvement (*)
	Pa	m/s	m²·K/W/day	m²·K/W/day	%
1	1.56	0.70	1.13E-05	1.59E-05	-29.0%
2	2.00	0.80	4.70E-06	1.18E-05	-60.1%
3	2.95	1.03	6.31E-06	7.40E-06	-14.8%
4	4.10	1.22	5.44E-06	4.98E-06	9.2%

(* The rate and improvement correspond to the Baseline prediction curve in Figure 3)

It can be seen in Table 2, a 29 % and 60 % reduction in fouling was achieved at the two lower velocities, but no significant improvement was observed at the two higher velocities. The -14 % and +9 % values are within the accuracy of the correlation and are therefore interpreted as zero improvement.

Table 3 shows detailed results for each of the six data points - two baseline and four pulsation tests. In addition to the information in Table 2, Table 3 includes temperatures, heat duties, measured clean overall heat transfer coefficients, and valve openings.

The major conclusion from the tests is that pulsation was able to reduce the fouling rate at the two lower velocities but showed no effect at the two higher velocities. Note that the tests cover only one pulsation amplitude for velocity (±50 %) and one frequency (1 minute). Further testing and theoretical work will be required to explain the results and to optimize the amplitude and frequency.

In addition to the differences in the measured fouling rates, the most important conclusion from

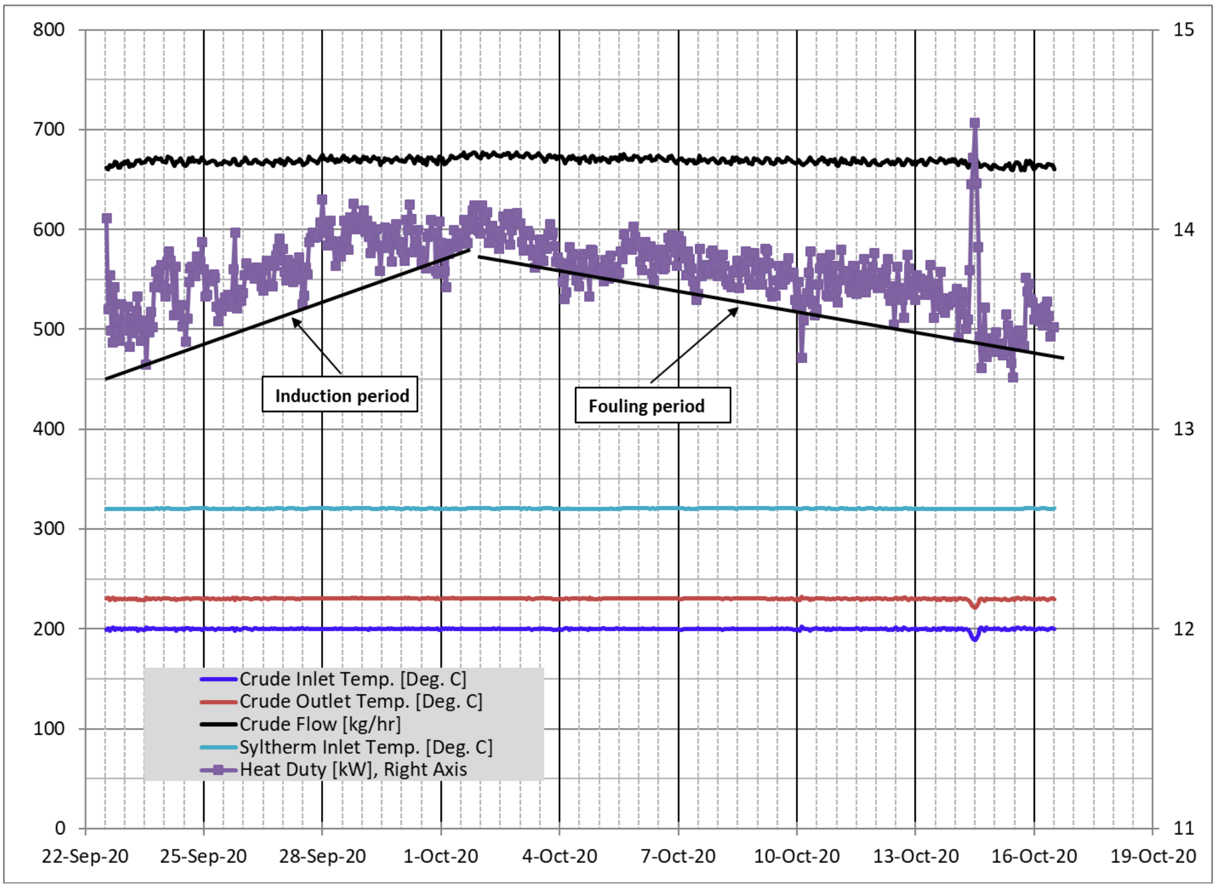

Figure 4 Illustration of Test Data (Flow, Temperatures, Heat Duty)

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Table 3 Test Data

Data Point	Shear Stress	Base Velocity	Pulsed Fouling Rate	Steady Fouling Rate	Improve-ment	Clean Heat Duty	Crude T_{in}	Syltherm T_{in}	Average Valve Opening	OHTC Measured, clean
	Pa	m/s	m²·K/W/day	m²·K/W/day	%	kW	°C	°C	%	m²·K/W
1 - baseline	2.00	0.83	--	1.18E-05	--	18.5	200	328	35.8	738
2 - baseline	4.07	1.23	--	4.98E-06	--	23.0	200	323	51.4	937
3 - pulsation	1.56	0.71	1.13E-05	1.59E-05	-29.0%	13.0	200	328	21.5	497
4 - pulsation	1.96	0.81	4.70E-06	1.18E-05	-60.1%	13.6	201	321	33.5	559
5 - pulsation	2.95	1.02	6.31E-06	7.40E-06	-14.8%	17.0	200	328	31.5	645
6 - pulsation	3.97	1.21	5.44E-06	4.98E-06	9.2%	17.5	201	321	48.5	703

Table 2 is that the pulsation tests have lower clean overall heat transfer coefficients (OHTC) and lower clean heat duties compared to the baseline test. Comparing the tests at the same nominal conditions – test 1 vs 4 and test 2 vs 6 – it could be seen that the corresponding OHTCs are 738 vs 559, and 937 vs 703, a decrease of 25% at each condition. A possible explanation is that the decrease in heat transfer at the -50 % pulse more than offsets the increase at the +50 % pulse. In addition, the average valve opening for the pulsation tests is lower than for the baseline tests, as shown in Table 3.

CONCLUSIONS

The tests showed lower fouling rates with pulsation, but also lower average heat transfer coefficients. This is possibly due to the lower average mass flow rate resulting from the opening and closing of the control valves.

These tests indicate that the pulsation technique can reduce fouling, at least at lower velocities. Since fouling is higher at low velocities and decreases exponentially with increasing velocity, the good effect of pulsation at low velocities has the potential to be beneficial in practice.

However, this proof of concept was in a pilot plant setting with single tube heat exchangers and with only a small amount of data. Further work is needed to apply this technique to operating crude oil heat exchangers. Ideas and future steps needed to make this technology commercially viable are listed below:

Develop a method to simulate the data obtained from these single tube tests. This will help to understand the positive and negative effects of pulsation and allow reliable simulations at different amplitudes and frequencies. More focused tests can be designed based on such simulations.

The limited testing done so far shows no effectiveness at higher velocities, and no clear trend with velocity. An understanding developed with simulations may be able to explain the variations in the data and allow for optimization of the pulsation amplitude and frequency, as well as to determine if there is in fact a maximum threshold velocity for application.

1. Using the above understanding, develop methods to simulate real-size heat exchangers. When several hundred tubes are involved, the pulse in each tube will vary, so a straightforward

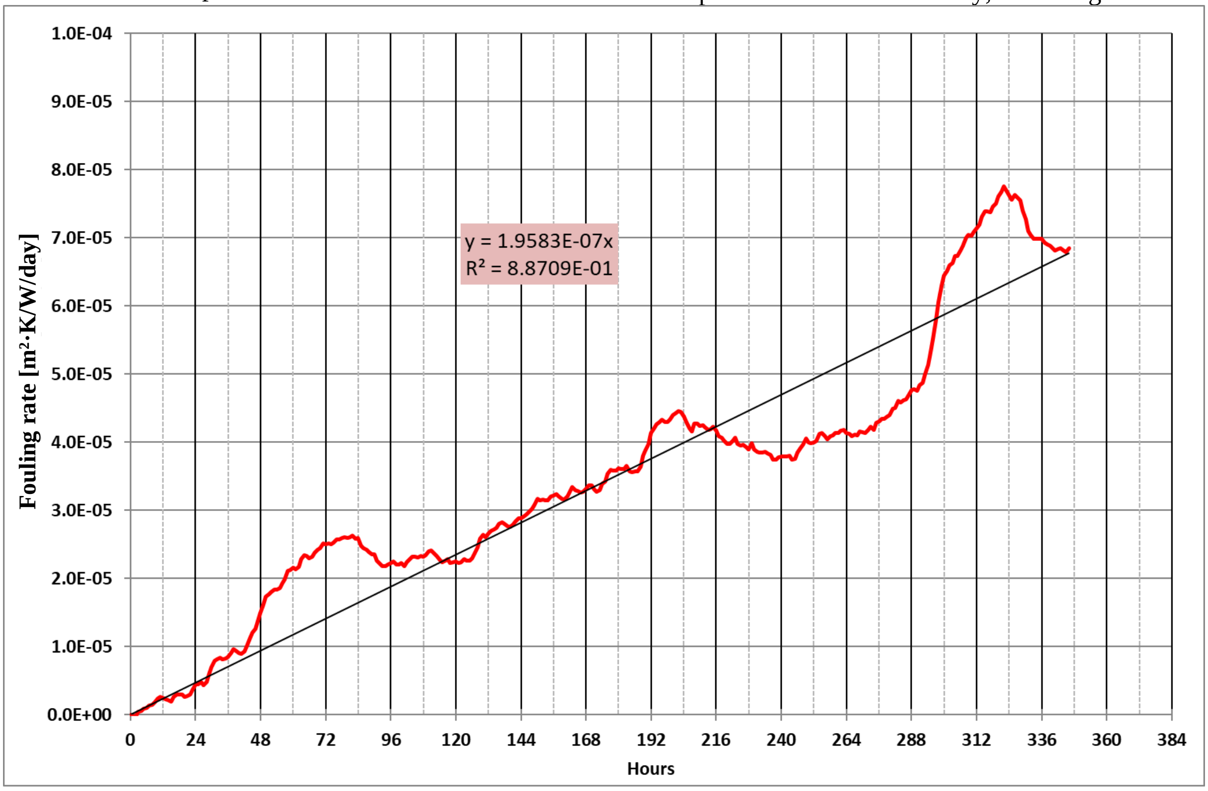

Figure 5 Illustration of Test Data (Fouling Resistance and Rate for fouling period)

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extrapolation of single tube data will not result in a correct quantification of the benefits for large heat exchangers.
2. If the quantified benefits are high enough (e.g., 50 % reduction in fouling), plan to test pulsation in the field. This will require designing a flow pulsation system that can be easily adapted to existing heat exchangers and piping.

In addition, a pulsation test rig as described in [8] with a piston or membrane pulsator may provide more reliable testing. This will result in a more continuous flow pulsation without several seconds of changeover time followed by several seconds of steady flow conditions. On the other hand, the test facility used here generates much lower acquisition and operating costs. Therefore, possible pulsation techniques should be considered as a whole and weighed against each other.

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NOMENCLATURE

A Surface area tube based on outside diameter, m^2
c_p Specific heat coefficient, kJ/kg/K
$\dot{H}$ Enthalpy flux, W
$\dot{m}$ Mass flow rate, kg/s
$\dot{Q}$ Heat duty, W
R Thermal resistance, $m^2 \cdot K/W$
U Overall heat transfer coefficient, $W/m^2/K$
T Temperature, K
t Time, day

η Dynamic viscosity, Pa·s
λ Thermal conductivity, W/m/K
$\Delta\theta_m$ Logarithmic mean temperature difference, K

Subscript

c crude (side)
f fouling
h hot side
in condition at the entrance
out condition at the outlet

REFERENCES

[1] Mancin S., and Coletti F., ANTI-FOULING COATING TECHNOLOGIES A CRITICAL REVIEW AND DEVELOPMENT ROADMAP, *Proceedings of Heat Exchanger Fouling and Cleaning 2022*, Heat Exchanger Fouling and Cleaning 2022, ed.

[2] Geddert T., Albert F., Bialuch I., Augustin W., and Scholl S., 2009,"Verringerung der Belagbildung durch beschichtete Oberflächen," Vakuum in Forschung und Praxis, **21**(3), pp. 14–17.

[3] Zettler H. U., Wei M., Zhao Q., and Müller-Steinhagen H., 2005,"Influence of surface properties and characteristics on fouling in plate heat exchangers," Heat Transfer Engineering, **26**(2), pp. 3–17.

[4] Krauss L., Schab R., Unz S., Beckmann M., Krug M., Puettmann J., Nizard H., and Gloess D., 2023,"Investigation of the Chemical Durability and Thermal Impact on Functional Coated Surfaces," Heat Transfer Engineering, pp. 1–11.

[5] West F. B., and Taylor A. T., 1952,"The effect of pulsations on heat transfer-turbulent flow of water inside tubes," Chem. Eng. Prog.(48), pp. 39–43.

[6] Linke W., and Hufschmidt W., 1958,"Wärmeübergang bei pulsierender Strömung," Chemie Ingenieur Technik, **30**(3), pp. 159–165.

[7] Augustin W., and Bohnet M., 2001,"Einfluss einer pulsierenden Strömung auf das Foulingverhalten an wärmeübertragenden Flächen," Chemie Ingenieur Technik, **73**(9), pp. 1139–1144.

[8] Boxler C., and Scholl S., 2011,"Einsatz pulsierender Strömung zur Verbesserung des Foulingverhaltens," Institut für Chemische und Thermische Verfahrenstechnik, Technische Universität Braunschweig.

[9] Gillham C., Fryer P., Hasting A., and Wilson D., 2000,"Enhanced cleaning of whey protein soils using pulsed flows," Journal of Food Engineering, **46**(3), pp. 199–209.

[10] Darling G. B., 1959,"Heat transfer to liquids in intermittent flow," Petroleum(22).

[11] Blel W., Le Gentil-Lelièvre C., Bénézech T., Legrand J., and Legentilhomme P., 2009,"Application of turbulent pulsating flows to the bacterial removal during a cleaning in place procedure. Part 1: Experimental analysis of wall shear stress in a cylindrical pipe," Journal of Food Engineering, **90**(4), pp. 422–432.

[12] Farries R., and Patel H., 1993,"The effect of flow reversal and pulsing on surface cleaning," University of Cambridge, UK.

[13] Milburn C. R., and Baird M. H. I., 1970,"Flow Pulsation Generator for Pilot-Scale Studies," Industrial & Engineering Chemistry Process Design and Development, **9**(4), pp. 629–635.

[14] Keil R. H., and Baird M. H. I., 1971,"Enhancement of Heat Transfer by Flow Pulsation," Industrial & Engineering Chemistry Process Design and Development, **10**(4), pp. 473–478.

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[15] Saghatoleslami N., Salooki M. K., and Armin M. A., 2010,“Prediction of thickness and fouling rate in pulsating flow heat exchangers, using FLUENT simulator,” Korean Journal of Chemical Engineering, **27**(1), pp. 96–103.

[16] Augustin W., Fuchs T., Föste H., Schöler M., Majschak J.-P., and Scholl S., 2010,“Pulsed flow for enhanced cleaning in food processing,” Food and Bioproducts Processing, **88**(4), pp. 384–391.

[17] Joshi H. M., Crude oil fouling field data and a model for pilot-plant scale data, *Proceedings of Heat Exchanger Fouling and Cleaning 2013*, Heat Exchanger Fouling and Cleaning 2013, ed., pp. 22–26.

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