TRANSLATING CRUDE OIL FOULING TESTING RIG DATA TO THE FIELD: A ROAD MAP FOR FUTURE RESEARCH

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ABSTRACT

To obtain fundamental and applied knowledge of crude oil fouling, numerous researchers have conducted experiments in various fouling test rigs to study fouling in a controlled scientific manner. An ideal goal for applied research is to use data obtained from test rigs to accurately predict fouling in operating heat exchangers and associated networks. Despite significant efforts to design fouling equipment that better mimics the preheat train, direct translation of test rig data to the field is yet to be achieved.

Successful translation of fouling rig data to a field heat exchanger requires accounting both the impact of operating conditions and the context of the results obtained from the test rig. Although researchers have investigated many of the operating conditions and the nature of fouling data obtained from test rigs, which affect translation of fouling data, this manuscript revisits these fundamentals to identify avenues of research which are unanswered.

This paper organizes and discusses the key factors that must be understood and modeled to be able to translate test rig data to the field. The gaps in knowledge outline a roadmap for future research.

INTRODUCTION

The complexity of crude oil fouling has resulted in many types of fouling test rigs in different research groups (Kolaczkowski, 1977; Eaton and Lux, 1984; Asomaning, 1990; Shetty et al., 2016; Tajudin et al., 2015; Smith, 2013; Crittenden et al., 2015; Joshi, 2013). Currently, results of crude oil fouling experiments provide insights on fundamental behaviors and on the impact of different surfaces and crude types (e.g., Hazelton et al., 2015). They aid in the identification of dominant fouling mechanisms and help in evaluation of the efficacy of mitigation strategies (e.g., the use of antifoulants or coatings). They also provide useful comparative results (e.g., Crude B has an initial fouling rate twice that of Crude A), as well as evaluation of fouling of crude blends including crude incompatibility.

Although these applications are valuable, direct quantitative translation of the fouling rig data to the plant is not widely practiced. Translating fouling rig data to the field and quantitatively using fluid chemistry to predict crude oil fouling are two long-standing goals of crude oil fouling research. Refiners especially want to know how a crude (or blend) will foul and assess the fouling costs associated with operation of the preheat train, as well as costs associated with cleaning and modifications. These costs would then inform the crude price and purchasing decisions.

This paper looks at the differences between fouling rigs and preheat train exchangers and lays out the key factors that are required to be addressed to successfully translate test rig data to the field. From this, the fouling community can assess the gap in achieving this goal and the research required.

What we want to map

Translating rig data to the field requires models that account for the impact that operating conditions and the test rig have on fouling. As illustrated in Fig. 1,

1. Models need to fit fouling test rig data.
2. The translation process must update the models for their application to the crude preheat train (PHT) context.

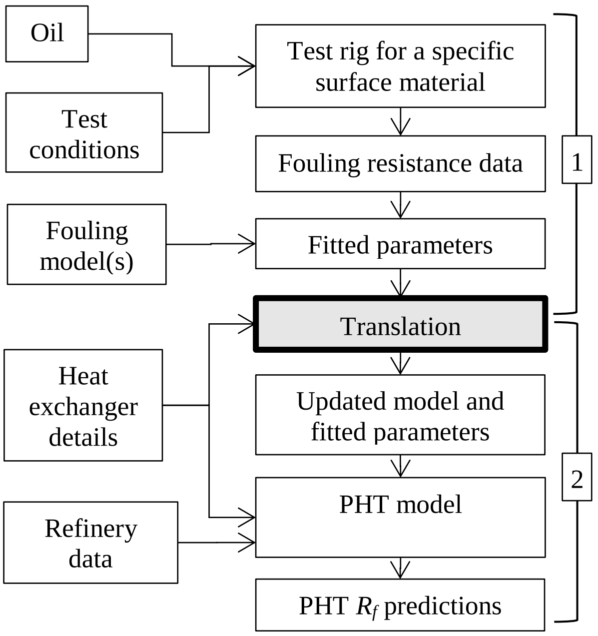

Fig. 1 Illustration of how test rig results would be used to predict refinery fouling.

How we can map rig data to field operations

Translation of fouling rig data to the field will rely on the development of fouling models that can account for both the fundamental impact of the operating conditions and for test rig specific behaviors. The model and parameters fit to fouling rig data would then be appropriately adjusted to predict field scenarios.

For example, consider an experiment with the fouling fluid recirculating through the fouling rig, assuming that precursor depletion is a factor that must be accounted for via a time-dependent expression (a term representing concentration decreasing with time). To apply the model to the context of the field (a quasi-constant precursor concentration), the starting concentration would be used as a constant and the time-dependent term eliminated.

Why we want to translate rig data to the field

Fouling test results will have applied value when demonstrated to reliably predict field experience. Thus, what is learned under scientifically controlled conditions can be translated in terms of what actually occurs in the preheat train.

If research can create models that use fluid chemistry and transport processes to predict fouling in the fouling rig, we are also capable of using chemistry to predict fouling in the field; thus achieving and linking the two key goals of crude oil fouling research.

Accurately translating fouling rig data to the field demonstrates that the dominating factors affecting fouling have been well understood. To improve on the existing fouling research we intend to identify further obstacles that requires attention to have a better translation of the rig fouling data with that observed from the field. A summary of challenges are summarized at the end of the manuscript (Table 5).

Fouling test rigs

The fouling test rigs of interest in this discussion are offline and are typically a batch-wise operation. Online slip-stream style test rigs are outside the scope of this discussion.

HTRI’s fouling rigs are designed to mimic as closely as possible the PHT operating conditions such as flow, temperatures, pressure, geometry, metallurgy, etc. (Bennett et al., 2009). For the purposes of scientific research, these rigs must have effective control of operating conditions, allow repeatable results, and support high confidence in measurement accuracy. However, not all industrial considerations can be accounted in scientific testing, resulting in differences, such as the fluid volume used, test duration, and inspection/collection of the deposit; the impact of these differences needs to be accounted when translating the rig result to industrial operations.

Key differences between a fouling test rig and a refinery PHT exchanger

Mode of operation. Due to their duration of operation, test rigs cannot typically operate in a continuous once-through fashion and have flowrates and tube diameters comparable to field PHTs. Virtually all fouling test rigs perform a batch-wise operation with recirculated test fluid, leading to concerns about precursor consumption and other reactions that may occur from maintaining the test fluid at elevated temperatures for sustained durations. In addition, because the PHT is once-through flow and not all oil is the same, the oil stream in a refinery is constantly changing in contrast to a batch test.

Purpose of equipment—science vs. production. Crude refinery operations are subject to real-world demands and circumstances, resulting in regularly changing operating conditions. Test rigs, however, are built for scientific research, which leads to exclusion/inclusion of factors that impact interpretation of test rig results. Test rigs operate under well-controlled operating conditions; however, the unpredictable nature of the refinery could contribute to fouling problems (e.g., desalter problems). Replicating this in a scientific manner is challenging. Fouling tests typically start with a clean surface, whereas a field exchanger (except when new) starts with some fouling layer even after cleaning (Joshi, 2013; Ishiyama et al., 2009). This condition difference impacts the initial fouling rate.

Heating method. For test rigs that use electrically heated test sections and operate with a constant flux/duty, the wall temperature increases and the surface temperature remains approximately constant as fouling occurs. In contrast, fouling in a heat exchanger decreases duty/flux, the wall temperature remains approximately constant, and the surface temperature decreases. Designs such as pilot-scale double-pipe test rigs better mimic actual plant behavior.

Fouling measurement. Some test rigs use the variation in the fouling surface wall temperature as a measure of fouling. In contrast, field fouling measurements are obtained from the reconciliation of bulk temperatures, pressures, and flows with thermal and hydraulic models (Ishiyama et al., 2013b). Thus, the fouling measurement is deduced based on available field data and the models used. Depending on the available shell-side data and the modeling techniques, fouling on the shell side may or may not be lumped together with the tube-side fouling.

Comparison of rig and field data

HTRI has tested crude oils for its membership and under proprietary contract. HTRI’s Crude Oil Fouling Task Force (COFTF) has directed the HTRI Fouling Program to primarily focus research efforts on the hot section of the crude PHT. The following generalized discussion is based by our experience testing in this operating space.

Quantitative comparison. Analysis and interpretation of refinery data can be very challenging due to the variable feedstock and operating conditions in a PHT. Although noisy data are observed, defined measurable trends can be obtained.

The fouling resistances observed in fouling rigs typically range from 10^{-6} – 10^{-4} m^2 K/W. Occasionally, resistances as high as 10^{-3} m^2 K/W can be observed, although these are often at very low flow rates and/or temperatures in excess of typical PHT conditions (Smith, 2013; Joshi, 2013; Srinivasan and Watkinson, 2015). Generally, maximum resistances observed for field exchangers are nominally 1 – 2 orders of magnitude greater lying in a range of 10^{-4} – 10^{-2} m^2 K/W (Joshi, 2013; Ishiyama et al., 2013).

Although fouling rates are the primary metric, the difference in absolute resistance affects the context of the fouling scenario that the rate is measured (fouling on metal vs. fouling on an aged deposit) and the dominating resistance, which is discussed below.

Based on HTRI's and COFTF members' experience, refinery heat exchangers tend to have higher fouling rates than fouling rigs operating at similar test conditions. The best direct assessment of this is shown in Table 1 that compares the average field conditions and overall rate vs. HTRI fouling tests for the same velocity and shear stress. The constant velocity scenario had a fouling rate an order of magnitude less than the field. The constant shear stress scenario resulted in negative fouling.

Table 1. Comparison of field and test rig data for HTRI Crude 20.

	Field exchanger	**Test rig** (matching field **velocity**)	**Test rig** (matching field **shear stress**)
Length of evaluation, days	100	5.5	5.5
Metallurgy	317L SS	317L SS	317L SS
Tube diameter, mm	21.18	11.78	11.78
T_b, °C	276.7 ± 6	275.9 ± 0.6	275.9± 0.6
$T_{w,0}$, °C	282 ± 6	283 ± 5	283 ± 5
V, m/s	2.65 ± 0.3	2.65 ± 0.01	1.98 ± 0.01
τ, Pa	5 – 10	12.43 ± 0.01	7.49 ± 0.01
dR_f/dt, m^2 K/W day	~2.1x10^{-5}	~1.6x10^{-6}	negative

Qualitative comparison. Qualitatively, fouling rigs are generally trusted to provide reliable trends, insights, and lessons learned to inform decision-making. It is for this reason their use perpetuates within the industry. For example, to compare two crudes, a fouling rig could evaluate each crude at a common set of conditions and determine which of the two oils fouled more. In 2013, Smith presented data from the HTRI fouling rig ranking eight different oils. The results compared very well with industry experience.

Regarding fouling behavior, testing in fouling rigs can result in trends in fouling resistance vs. time that are less commonly observed in field data:

- negative fouling resistances and rates at the beginning of a test
- induction periods dominating the duration of a fouling test (in field data, induction periods are insignificant compared to the operating period)
- asymptotic fouling trends (Asomaning, 1990, Hout, 1983; Smith, 2013; Fig. 5)

Such differences in fouling behavior/context discourages direct comparison of fouling rig data to field data (Crittenden et al., 2015).

The following sections highlight key factors that need to be quantitatively accounted for to successfully translate fouling rig data to the field.

ACCOUNTING FOR OPERATING CONDITION DIFFERENCES

Flow

For crude oil and other hydrocarbon systems, the general trend of fouling with flow has been discussed in literature (Crittenden et al., 1987; Epstein, 1994; Crittenden et al., 2007; Petkovic and Watkinson, 2014).

Fouling data reported by Crittenden (1987) and Crittenden et al. (2007) show for that, for both a styrene and a crude oil system (Maya crude oil), fouling increases with flow up to a maximum (transport limited flow region), and then fouling decreases as flow rate increases. However, the physical relationship of flow rate and fouling rate is less clear. At very low flows, there is little turbulence, and the fouling rate is diffusion limited. This is elaborated in Epstein's chemical reaction fouling model (Epstein, 1994). As transport limitations become negligible at higher flow rates, several theories could be discussed on the cause of the reduction in fouling with increased flow. Epstein proposed that it was the average residence time a parcel of fluid spent at the wall (chemical reaction perspective), however, the data used to fit this model had little to no data at much higher flow rates that would be necessary to support this hypothesis.

The authors have considered that fouling may be better modeled as catalysis reaction, given that fouling is a surface dependent phenomenon; thus, boundary layer thickness is the governing flow property, as previously visited by Paterson and Fryer (1988) for modeling milk fouling. To test this hypothesis, the term representing the residence-time-at-the-wall in Epstein's model was substituted for boundary layer thickness, and the revised model was fitted to Crittenden's (1987) data. Fig. 2 shows the comparison of these two model versions to predict Crittenden's data; both appear to fit equally well. Interestingly, the two versions have very different projections of fouling rate at much higher flow rates. If data were obtained at much high flowrates, it could help assess which model version is most accurate and provide a strong suggestion as to the physics of how flow impacts fouling for such system. Crude oil fouling can consist of a combination of fouling mechanisms (e.g. combination of autoxidation, polymerization and thermal decomposition). It is not yet understood if the influence of flow is universal or different for different fouling mechanisms. Quantification of individual mechanisms and the assessment of the impact of flow on each mechanism would be a long-term goal.

Ebert and Panchal (1996) and others have created a series of so called *threshold fouling models* (Wilson, 2014) in which fouling rate is the sum of deposition, typically governed by Reynolds number (turbulence), and removal or suppression, typically governed by shear stress or velocity.

The variety of flow expressions in the literature fouling models provide the impact of flow on fouling but not necessarily the fundamental insight.

How the impact of flow is modeled directly impacts how rig data are quantitatively translated to the field. Many fouling rigs have a different geometry than a field heat exchanger. Further, not all PHT exchangers have the same size tubes. The physics of how flow impacts fouling is necessary to accurately adjust the fouling rate obtained in a fouling unit to a scenario with a different (typically larger) flow path diameter.

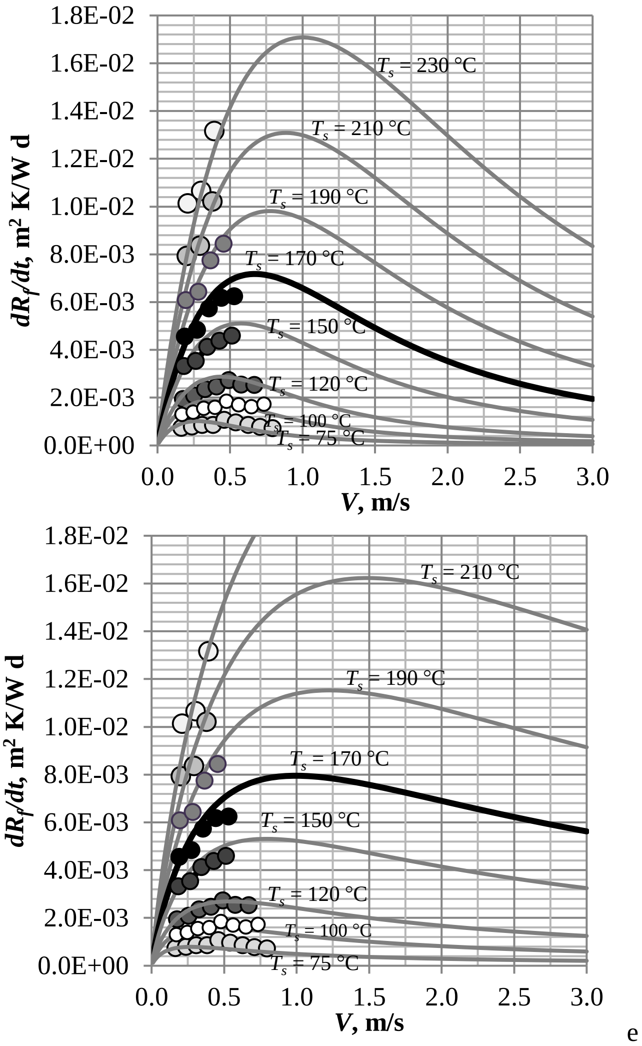

Fig. 2 Two versions of the Epstein (1994) model fit to styrene in kerosene data (Crittenden 1987). Top – Epstein's original model (fouling regulated by residence time at the surface). Bottom – fouling regulated by boundary layer thickness. The prediction line for T_s = 170 °C is bold to aid comparison.

Although the directional impact on fouling for the various proposed regulating flow parameters (velocity, shear stress, boundary layer thickness, retention time at the wall (boundary layer thickness divided by shear velocity), and Reynolds number) trend together, a change in diameter impacts each differently. Fig. 3 shows how four different flow parameters trend with velocity for two different diameters. It can be seen that the relative difference between the two tube diameters is different for each flow parameter. Thus, the amplitude of how a fouling prediction scales depends on the parameter that the fouling model uses. Future research needs to focus on understanding the physics of how flow impacts fouling rate for a variety of fouling mechanisms.

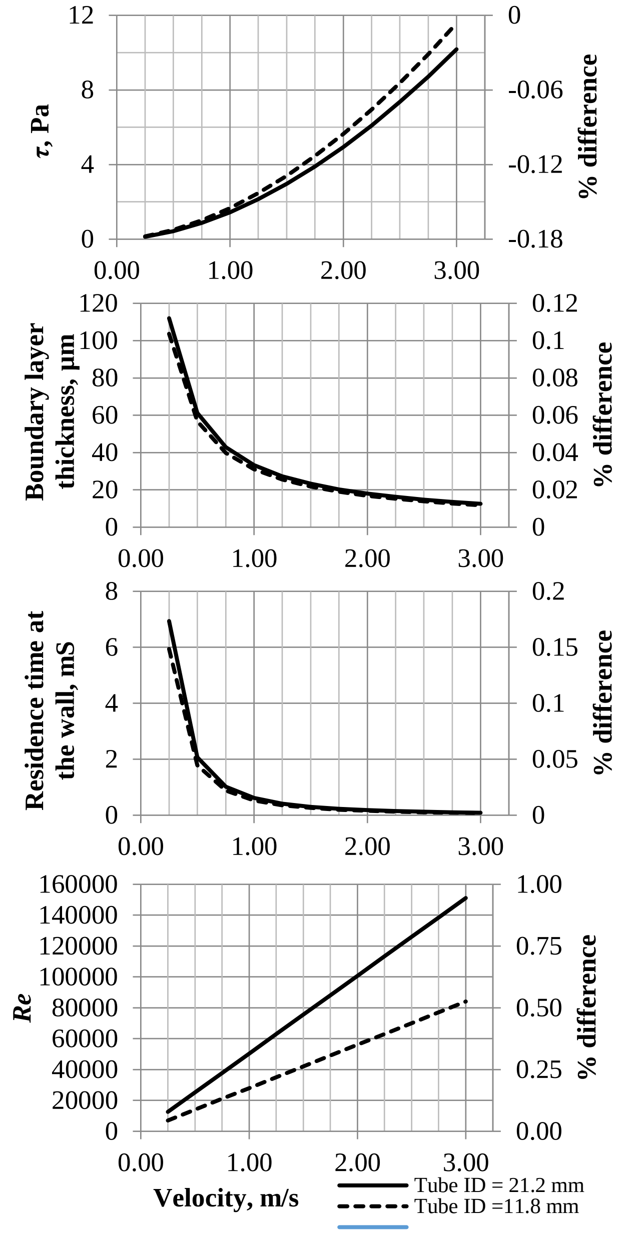

Fig. 3 Variation of four flow parameters with velocity for a 21.2-mm tube ID (PHT exchanger) and an 11.8-mm tube ID (HTRI fouling rig). Percent difference is relative to the 11.8-mm tube ID. Fluid properties are that of HTRI Crude 19 at T_b = 260 °C and T_s = 300 °C.

Temperatures

For fouling, two temperatures are in play: the bulk temperature of the fluid flowing through the system and the deposition temperature (the temperature regulating the attachment of material to the heat transfer surface).

Bulk temperature. Beyond its impact on physical properties, the explicit impact of bulk temperature on fouling is largely ignored in current crude oil fouling models (Wilson, 2014). Some models use film temperature, which is a combination of bulk and surface temperature (Watkinson, 2007). Given the complexity of crude oil fouling, this assumption is, at face value, reasonable given that the higher deposition temperature is considered a dominating factor. Although ignoring bulk temperature is convenient for model development, doing so overlooks the impact of bulk phase reactions and solubility, significant phenomena that are strongly affected by temperature and that can significantly affect the fouling behavior.

Some researchers have shown that increasing bulk temperature *decreased* fouling (Eaton and Lux, 1984; Asomaning, 1997; Kovo, 2006; Panchal et al., 1997) while others have shown the opposite (Srinivasan and Watkinson, 2015; Saleh et al., 2005, Oufer, 1997; Wang and Watkinson, 2015). These contradictory trends suggest competing mechanisms and/or a variance in the dominant mechanism from crude to crude. What can be concluded from these data is that bulk temperature does have a significant impact on fouling that should not be ignored.

With respect to temperature, fouling rig experiments either maintain the bulk temperature constant and vary the wall temperature (or vice versa) or maintain a constant wall-bulk temperature difference. In a heat exchanger, the bulk and wall/surface temperature (and therefore the wall-bulk temperature difference) vary along the length of the exchanger. Thus, experimental data never exactly matches the field scenario. If models are developed from test rig data obtained at a constant bulk temperature or a constant wall-bulk temperature difference, they may introduce large errors when the same models are used to predict fouling at a different bulk temperature if the impact of bulk temperature is not explicitly accounted for.

As further discussed by Shetty et al. (2016), bulk temperature clearly has an impact. Future work could include gathering more data to support/improve such bulk temperature relationships and use of such model approaches when modeling industrial heat exchanger performances.

Deposition temperature. Many researchers have defined the general trend with deposition temperature and demonstrated it to be modeled well by an Arrhenius type expression. If fouling rigs are operated with a constant duty, then when fouling progresses, the wall temperature (surface of the metal) increases and the surface or skin temperature (surface of the deposit that is touching the fluid) is maintained approximately constant. Film temperature is a temperature in between the wall and bulk temperature and is commonly assessed by interpolation (Equ. (1)). Ebert and Panchal (1996) proposed an α of 0.55. Depending on the fouling mechanism, the dominant temperature could vary between film and surface. This needs to be explored in the context of fouling experienced in the crude PHT.

$$T_f = \alpha \cdot (T_w - T_b) + T_b \tag{1}$$

In contrast, the duty of a heat exchanger decreases as fouling occurs; the operation is closer to having a constant wall temperature (compared to having a constant heat duty) and the surface temperature decreases. The temperature that drives deposition has been a matter of debate (skin vs. film temperature) (Wilson, 2014). The trend of wall, skin, or film temperature with increased fouling are important considerations as each has different implications on how a model interprets a rig and PHT scenario (Table 2). The trend with wall temperature does not correspond to most fouling rig rate trends. For this reason, most models do not use wall temperature, or, if they do, it is the initial wall temperature, which is approximately equal to the surface temperature for a test operating with a constant duty (Wilson, 2014). Although the trends shown in Table 2 for surface and film temperature are the same, film temperature implies that fouling rate *always* increases with increasing bulk temperature, which is not always the case. Surface temperature has logical trends, is independent of bulk temperature, and is the temperature of the surface exposed to the fluid. For these reasons, it is the most often used in fouling models (Wilson, 2014).

Table 2. Nominal fouling rate trends with respect to deposition temperature only as fouling resistance increases for a fouling rig and a PHT exchanger, given the same initial deposition temperature

Same initial temperature	**Rig fouling rate trend** (constant heat flux)	**PHT fouling rate trend** (~constant wall temp.)
Wall	Increases	~ Constant
Surface	~ Constant	Decreases
Film	~ Constant	Decreases

Pressure

Of all the operating conditions, pressure is the most dismissed and perhaps the least understood in testing. The impact of pressure on fouling in a test rig is complicated by not only what the pressure is, but how the pressurization is achieved, and whether the system has a headspace.

Preheat train heat exchangers operate at 140 – 500 psig, which is typically sufficient to prevent boiling. However boiling can occur in the PHT (Ishiyama and Pugh, 2013). In general, fouling tests are pressurized to maintain single-phase conditions. However, the accuracy of bubble point curves from the physical property generator software is unknown. Thus, if the system is not sufficiently over pressurized, boiling can occur, further convoluting fouling test results (Harris et al., 2017). As a conservative practice, HTRI and many others had used nitrogen to pressurize the fluid (Watkinson et al., 2000; Saleh et al., 2005; Yang et al., 2009). Since 2014-2015, HTRI has continued to challenge and improve its pressurization practices.

The actual pressure of the single-phase system may not affect fouling nearly as much as the method used to obtain the pressure in the experiment. For systems pressurized with nitrogen (Watkinson et al., 2000; Saleh et al., 2005; Yang et al., 2009), the fouling units are typically allowed to have some gas headspace. This headspace provides room for the fluid to expand when heated, but it also allows lighter gas components of the oil to accumulate as the fluid is heated. The pressure affects the solubility of those light components in the gas and can affect the solubility of fouling components in the fluid. Additionally, nitrogen dissolved in the gas may boil out of the solution at the surface (Hout, 1983; Fetissoff et al. 1982). Nitrogen may also impact the solubility of heavy oil components such as asphaltenes (Asomaning, 1997). Sometimes units are allowed to build pressure naturally, either through vapor pressure in the head space or through expansion of the fluid. When the temperature is stable, nitrogen may be added to achieve the final target pressure. The fluid expansion approach was used by Harris et al. (2017) because it eliminated the use of nitrogen. Additionally, the test section power was used to heat up the bulk fluid. However, it has recently been realized that this method results in the wall temperature crossing the bubble point curve during start-up which leads to fouling before the establishment of the references point ($t = 0$) as shown in Fig 4. Thus, the conclusion by Harris et al. (2017) may be more a reflection of the pressurization practice than it is of the pressure; however, new data have not been obtained to confirm this hypothesis.

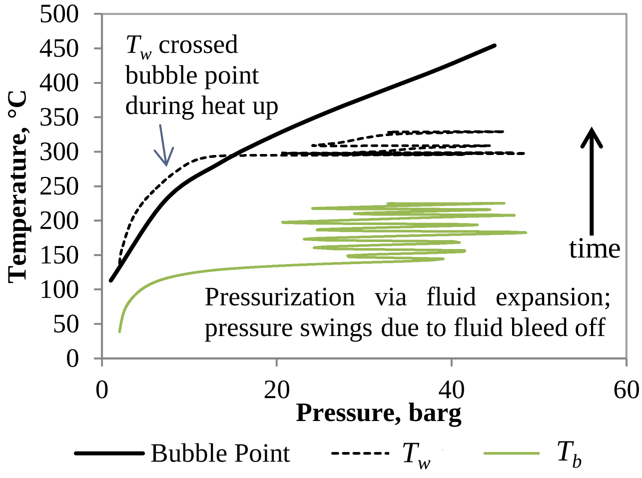

Fig. 4 Wall (T_w) and bulk (T_b) temperature vs pressure profiles for a fouling test during which the wall temperature crossed the bubble point during start-up.

Going forward, it is possible that pressure may impact fouling, for example by having impact on asphaltene solubility. To date, data from the literature have not been obtained that investigate the impact of pressure that do not also have caveats about the pressurization practice used. For the integrity of fouling rig data and conclusions, let alone the ability to translate that data to the field, pressurization practices need to be adopted that do not involve nitrogen, obtain pressures similar to the field, and avoid boiling (or close proximity to the bubble point), both during start-up and throughout the test.

ACCOUNTING FOR IMPACT OF DEPOSITION

Fouling deposition manifests differently in a PHT and a test rig. Fouling rigs often produce data with trends that are not as commonly observed in field data, which include asymptotic fouling, negative fouling, and induction periods. These trends can result from one or more of the issues discussed below.

Precursor Concentration, Consumption, and Generation

The identity of fouling precursors is often vague and may vary among different hydrocarbon streams. Precursors may be immediately present in the oil or created via reaction at elevated test temperatures (Panchal and Watkinson, 1993; Wilson, 2014). The concentration of precursors may both increase and decrease over the duration of a batch fouling test. In contrast, a refinery heat exchanger receives a continuous once-through stream of fluid with a precursor concentration that is more closely approximated as constant.

Precursor consumption during a fouling test is an often debated concern (Wilson, 2014). It has been argued that precursor depletion is responsible for asymptotic fouling trends, making initial fouling rate a key measurement for fouling rig data. The rationale is straightforward; batch fouling units contain a finite amount of test fluid, and as the test progresses and material is removed as a result of fouling, the fluid's precursor concentration is depleted, affecting the fouling rate. Counterarguments point to concentrations of presumed fouling precursors (often asphaltenes) and contend that significant depletion is unreasonable. For example, 4L of crude (860 kg/m^3) containing 0.5 w/w% asphaltenes would hold 17.2 g of asphaltenes. For a fouling unit with a heated area of ~40 cm^2, a deposit for $R_f = 10^{-4}$ m^2 K/W would have a mass of 0.1–0.2 g (~1% of the mass of the asphaltenes in the crude).

HTRI recently conducted a series of four successive tests where the oil from the previous test was reused for the next test. To evaluate concerns of precursor depletion, the fourth test had the same test conditions as the first ($V = 1.1$ m/s, $T_w = 361$ °C, $T_b = 260$ °C, $P = 2000$ kPa). As shown in Fig. 5, Run 4 showed much less fouling than Run 1. The reduction in fouling was suspected to be due to precursor depletion. Deposit analysis indicated that the Run 1 deposit contained much more iron and sulfur than that of Run 4 (Table 3). Oil analysis prior to Run 1 and after Run 4 (Table 4) also indicated that iron was depleted from the oil. In this example, iron was not the only fouling precursor but clearly played a significant role. This example clearly illustrates that fouling precursors can be depleted from batch testing and that precursors can exist in trace (ppm) concentrations. Accounting for precursor depletion in batch fouling tests is critical to translating data to the field; otherwise, measured rates may be underestimated.

Conversely, fouling precursors can be generated during a fouling test, for example, bulk phase precipitation of asphaltenes driven by bulk temperature (Wilson, 2014; Hout, 1983; Watkinson and Wilson, 1997). In a refinery, this reaction may be slower than the residence time in the heat exchanger and, thus, its impact is not experienced. If it does occur in the heat exchanger, it likely attains some pseudo steady-state, at which point the precursor concentration behaves as though it is constant. In a batch fouling system, the fluid is maintained at temperature for a much longer duration than the residence time of crude in the preheat train. As a result, intermediate reactions may proceed to a greater extent of conversion. It is even possible for the precursor concentration to decrease (immediate use of initial precursors), increase (generation of new precursors), and then decrease (consumption of new precursors when production has peaked). If methods do not properly account for the generation of precursors, field predictions could be overstated.

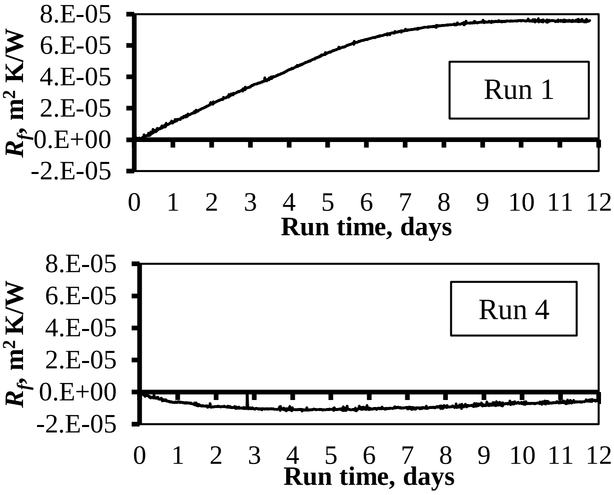

Fig. 5 Fouling resistance plots for Runs 1 (top) and 4 (bottom) of a four-test series using the same batch of crude. Runs 1 and 4 had the same test conditions.

Table 3 Deposit analysis of Runs 1 and 4.

Element	**Run 1** (w/w %)	**Run 4** (w/w %)
C	45.0	75.1
O	6.2	5.5
Si	0.4	0.1
S	**18.4**	**3.5**
Ca	1.0	–
Cr	1.8	4.0
Fe	**25.6**	**9.8**
Ni	1.0	–

Table 4 Oil analysis prior to Run 1 and after Run 4.

Element	**Prior to Run 1** (ppm)	**After Run 4** (ppm)
Fe	**747.5**	**114**
Ni	36.2	38.9
V	119	134

Future research needs to focus on identification of fouling precursors and methods to model transient concentrations during batch tests.

Influence of the Deposit

Dynamic variation in surface roughness, thickness, and thermo-physical properties of the foulant deposits can have a significant influence on quantifying the thermal and hydraulic impact of fouling. Laboratory experiments are typically conducted on clean surfaces, and PHT fouling occurs on fouled surfaces (with the exception of new equipment); the extent to which the deposit influences the fouling rate will be different.

Variation in surface roughness can result in heat transfer enhancements and have been observed experimentally (e.g., Albert et al., 2011; Crittenden and Alderman, 1988). Changes in deposit thickness and variation in surface roughness have been further accounted in data reduction methods used for interpreting laboratory data (Albert et al., 2011). Usually, obtaining information on surface roughness variation in industrial exchangers is impractical. Not all industrial exchangers have pressure drop measurements. In cases where pressure drop measurements for industrial exchangers are available, it is possible to obtain information relating to the deposit thickness and deposit thermal conductivity (Ishiyama et al., 2017), which assists in interpretation of exchanger thermo-hydraulics. Fouling rig tests often result in low fouling resistances (circa 10^{-5} m^2 K/W) with small fouling layer thicknesses (< 25 μm) so that pressure drop changes may not be detectable. Thus, obtaining useful deposit property data is more challenging and relies on additional equipment such as confocal laser scanning microscopes to measure the deposit thickness.

Both industrial and laboratory fouling deposits can be subject to deposit *aging* (the changes in thermo-physical properties of the foulant deposit with time). Aging affects fouling measurement, prediction, and comparison of test rig data to PHT data. Aging is likely to occur in industrial exchangers when the foulant deposit is exposed to a heated surface for a prolonged period of time (Ishiyama et al, 2010; Ishiyama, 2010). However, the aging effects could be masked with deposition of fresh foulants. Future research should consider development and validation of aging models through laboratory experiments where a fouling run is allowed to continue for a prolonged period even after the deposition process has ended (i.e., after depletion of the precursors).

Changing Heat Transfer Coefficient

Compared to data collected from a plant, fouling measurements in a test rig are collected for a shorter period of time, resulting in smaller values in fouling resistances, R_f, and a potential for higher errors based on how R_f is calculated.

Consider R_f measured as the difference between the overall heat transfer coefficient at a given time step (U) vs. at a reference time step (U_0) that is presumed to have no fouling at the same operating condition:

$$R_f = \frac{1}{U} - \frac{1}{U_0} \qquad (2)$$

For a fouling test rig that measures and monitors the metal surface temperature, the clean overall heat transfer coefficient is equal to the convective heat transfer coefficient, h_0:

$$\frac{1}{U_0} = \frac{1}{h_0} \tag{3}$$

Likewise, when fouling occurs, the overall heat transfer coefficient is the combined resistance of the deposit (R_d) and the convective heat transfer coefficient:

$$\frac{1}{U} = \frac{1}{h} + R_d \tag{4}$$

When operating conditions are held constant throughout the test, if it is assumed that the current and initial heat transfer coefficients are identical, then R_f is equal to R_d .

$$R_f = \left(\frac{1}{h} + R_d\right) - \frac{1}{h_0} \tag{4}$$

Although this logic seems reasonable, the convective heat transfer coefficient is unlikely to be constant. Material building up on the surface impacts the roughness and the surface temperature of the deposit, both of which have at least a small (< 5%) impact on the convective heat transfer coefficient. While even a 1% impact on the heat transfer coefficient does not seem sufficient for concern, it can have profound impact on R_f. Fig. 6 shows the percent difference between R_d and R_f as a result of a 1% change in the heat transfer coefficient as a function of R_f for a low and a high heat transfer coefficient. From the figure, for a fouling resistance of 10^{-5} m^2 K/W (typical rig fouling resistance), a 1% change in h creates a relative difference of 30 – 100% that directly impacts assessment of fouling rates; for a fouling resistance of 10^{-3} m^2 K/W, a 1% variation in h results in a relative difference of 1% or less (negligible).

Modeling of variations in h_0 have been discussed by Albert et al. (2011) and would need to be considered, where possible.

When applying or regressing a fouling model it is often assumed the heat transfer coefficient is constant as fouling occurs; thus, h is not a modeled variable. Small changes in h can have such a profound impact on R_f, so fitting R_d models to R_f data results in an inherently error prone model because the impact of changing h is not independently accounted for. Without the ability to segregate the contribution of h and R_d, trends such as asymptotic fouling, negative fouling, and induction periods are difficult to interpret and model.

To resolve this concern, future research should develop methods to segregate and individually model the impact of R_d and h by collecting and using both thermal and hydraulic data to reconcile fouling rig measurements. For example, the Gnielinski and Churchill correlations could be used to segregate R_d and h (Bennett and Huang, 2009). Although surface roughness has long been acknowledged to impact heat transfer and pressure drop, additional research is needed to identify which surface roughness parameters (Keyence, 2015) best correlate with heat transfer, pressure drop, and fouling. To achieve this, surface roughness measurement needs to be incorporated in fouling research using advanced tools such as laser confocal microscopes that can provide the surface topography data and quantify more than 50 different surface roughness parameters. For example, Fig. 7 shows 3D images for a clean and negatively fouled surface from which qualitative roughness differences are obvious, and quantitative differences may be measured using software.

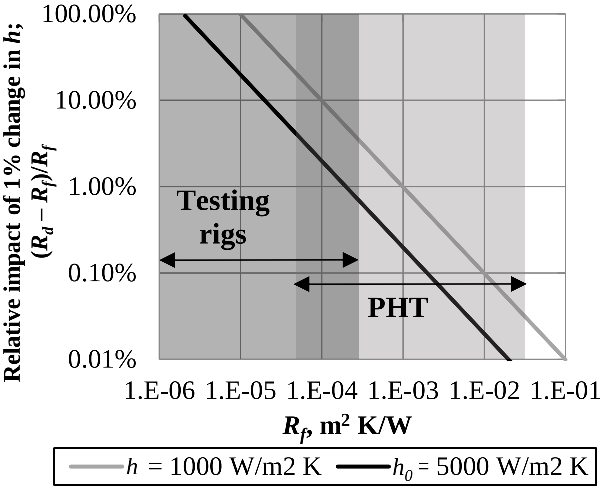

Fig. 6 Relative difference between R_d and R_f as function of R_f for a high and low tube-side heat transfer coefficient.

Surface Transition

Except for new heat exchanger bundles, fouling in a refinery heat exchanger begins with some deposit left on the surface, even after cleaning (Joshi, 2013; Ishiyama et al., 2009). Thus, fouling in an exchanger is deposition on an existing deposit. In contrast, the test section surface of a test rig is often rigorously cleaned or possibly replaced prior to each test. Thus, fouling in a test rig must undergo a transition of fouling to bare metal to fouling on deposit. The properties of the surface (composition, texture, etc.) affect the rate of attachment. Unless the bare metal surface and the deposit have an equal (or similar) impact on deposition rate, the transition impacts initial fouling trends. As illustrated in Fig. 8, a high initial fouling rate can be observed if the rate on the metal is greater than that on the deposit. Conversely, if the rate on metal is much slower than that on deposit, an induction period or initially accelerating rate may be observed.

Induction periods in fouling experiments have been investigated and modeled, with good agreement to test rig data (Young et al., 2009) Because the induction period for a field exchanger is much shorter than its run duration, what is of most use for predicting field exchanger fouling is the rate of fouling on existing deposit. Thus, accounting for the difference in the rate of fouling on bare metal vs. deposit is essential to accurately predicting field fouling behavior.

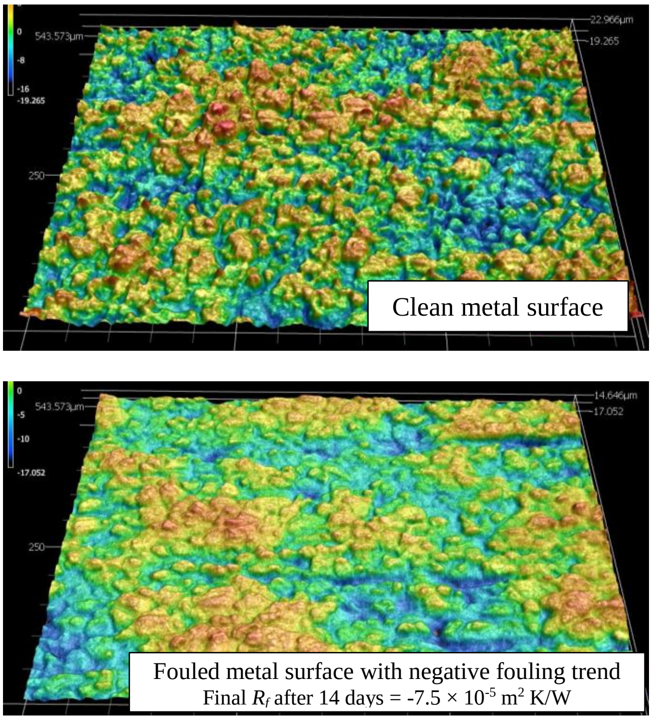

Fig. 7 3D images of clean bare metal and a fouled surface that had a negative fouling trend (color indicates height).

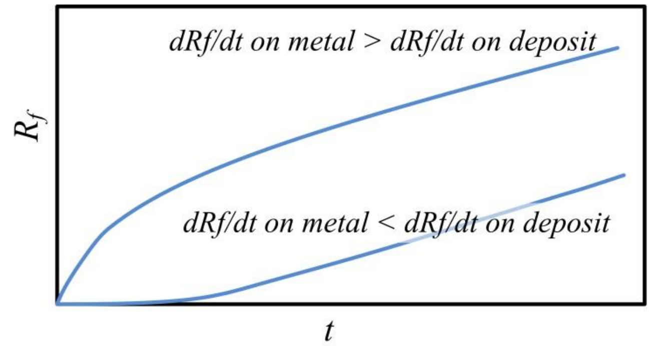

Fig. 8 Illustration of fouling trends that may result from a difference in fouling rate on bare metal and deposit.

SUMMARY

While the goal of translating test rig data to the field is non-trivial, review of the information required provides a useful roadmap for future research. This also leads to other goals such as mitigating fouling or predicting PHT fouling from crude chemistry.

The task of accounting for ‘seemingly everything’ needed for such translation is challenging. Individual design of experiments to build the understanding of the fundamentals of each contributing factor can gain the knowledge to better model/predict fouling. With the use of modern advanced computing strategies, it is possible for more complex fouling models to be used and implemented in a practical and meaningful manner. Models for use with experimental data may be more complicated due to additional accounting that is needed; whereas, models for field application will be simpler. For example, parameter lumping can be performed to make models more manageable. Table 5 summarizes the factors discussed with key points on where future research should focus.

Table 5 Summary for each key factor affecting translation of testing rig data to the field.

Factor	Summary
Flow	• Existing models predict the impact of flow on fouling. • The physical insight on how flow impacts fouling needs to be further understood. Investigation of the influence of both velocity and surface shear stress will enlighten the role of residence time and boundary layer thickness in fouling rates obtained from fouling rig data which will enable the translation of data to different geometries
Bulk temperature	• Literature data are contradictory, reporting competing influences of bulk temperature. • Experimental and modeling techniques are required to understand the influence of bulk temperature on fouling.
Surface temperature	• The impact of surface temperature is well captured in existing models for chemical reaction fouling.
Pressure	• The impact of pressure is not well supported by data; current literature data are often biased by experimental techniques. • Improved testing methods/equipment are required to investigate the influence of pressure on fouling.
Precursor concentration, consumption, and generation	• Limited discussions and models exist in the literature. • Additional research is required to provide supporting data and chemically identify fouling precursors.
Influence of the deposit	• Basic ideas of deposit impact are understood, and models have been developed that capture behavior.
Changing heat transfer coefficient	• Changing values of h significantly impact the accuracy of fouling measurements when R_f is small ($<10^{-4}$ m^2 K/W). • Methods need to be developed and validated to segregate the impact of h and R_d so that their contributions may be better understood and modeled separately. • Impact of roughness on fouling needs to be further investigated.

Factor	Summary
Surface transition	• Initial surface transition models are available in literature. Additional data are required to support and further develop surface transition models.

CONCLUSIONS

1. Interpretation of fouling rig experiment data were discussed to highlight the differences between data obtained from a heat exchanger in a crude refinery preheat train and data obtained from fouling rig experiments.
2. Flow rate (velocity and shear), bulk temperature, surface temperature, pressure, precursor concentration, presence of deposit, and calculation method of heat transfer coefficients are factors that need to be addressed when translating fouling rig data to operating exchangers. Future research should focus on these topics (Table 5).
3. Intrinsic differences such as the length of operation and condition of the heat exchanger surface (usually starts clean for a fouling experiment, but not necessarily for an operating exchanger) are usually not accounted for in fouling rig experiments. Tackling such obstacles are currently pursued at HTRI's research facility in Navasota, TX USA.

NOMENCLATURE

h	convective heat transfer coefficient, W/m^2 K
h_0	clean convective heat transfer coefficient, W/m^2 K
P	pressure, kPa
R_d	thermal resistance of the deposit, m^2 K/W
R_f	measured fouling resistance, m^2 K/W
Re	Reynolds number, dimensionless
t	time, day
T_b	bulk temperature, °C
T_s	surface temperature, °C
T_w	wall temperature, °C
$T_{w,0}$	initial wall temperature, °C
U	overall heat transfer coefficient, W/m^2 K
U_0	clean overall heat transfer coefficient, W/m^2 K
V	velocity, m/s
τ	shear stress, Pa

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