ECONOMIC AND ENVIRONMENTAL IMPLICATIONS OF FOULING IN CRUDE PREHEAT TRAINS

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ABSTRACT

The economic, environmental and safety consequences of fouling are the key reasons for industrial and research interest in heat exchanger fouling and cleaning. The implication of fouling in crude oil refineries has changed in the recent decades due to better monitoring tools, use of fouling mitigation devices, optimization of the use of antifoulants, optimization of process conditions, better blending of crudes, better design of heat exchangers and selection of exchanger tube materials. This brings a need for the economic impact of fouling in crude refinery preheat train to be revisited.

The estimation of the cost of fouling in crude preheat train by Van Nostrand *et al*. [1] is revisited by updating their original assumptions. The updated fouling cost estimate for the crude preheat train in the US refining sector is likely to be in the range of 1 - 1.2 B US$ per year for 2019. It is shown that the cost of fouling needs to be associated with a relevant refining profit or a crude refining margin as it is possible for the refinery to processes crudes with higher fouling problems after compensating the fouling cost with the price of the crude.

INTRODUCTION

Crude preheat train (PHT) is a network of heat exchangers used to preheat the crude before entering the fired heater and subsequently the distillation column for product separation. Configuration of a crude preheat train varies significantly based on when and where it was built, the capacity of the plant, budget and design philosophies followed during its construction. Fig. 1 is an example illustration of a simplified PHT. The crude enters the PHT via a feed pump to the cold train and heated till it reaches the desalter. The desalter inlet temperature is limited by the cold train performance and any associated controls. The desalter inlet temperature can exhibit a wide range of values among different PHTs (e.g. range of 90 to 150 °C). Inorganics, sand and other particulates are removed from the desalter. Following the desalter, the crude enters the middle train; some PHT consist of a pre-flash which removes lighter components of the crude. Depending on the location of the preflash, the preflash inlet temperature vary significantly among plants (160 – 220 °C); several preflashes can also be present on the same PHT. The crude is further preheated in the hot train before entering the furnace. The furnace provides the residual heat required for the crude to enter the column conditions. The product and pump-around streams from the columns recycles heat to the PHT.

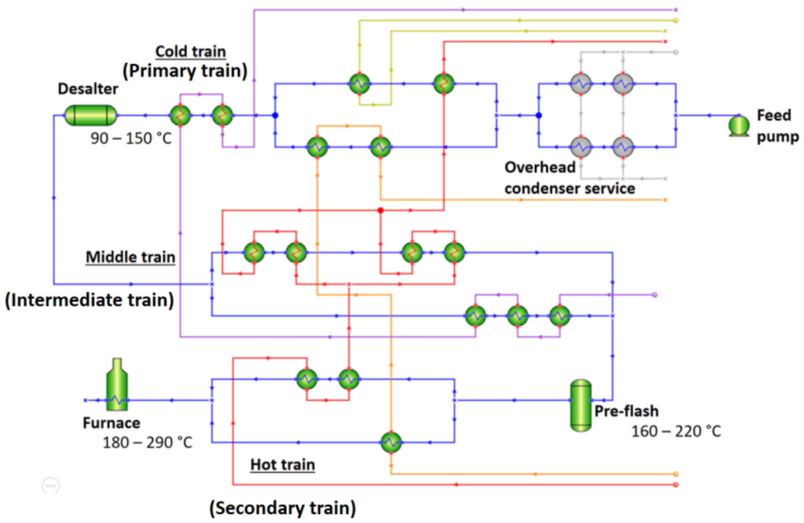

Fig. 1 An example schematic of a crude Preheat Train Configuration.

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The choice of allocation of crude and product stream on either the tube-side or the shell-side varies between refineries. Some notes on the stream allocations are summarized in Table 1. The fluid allocation is further influenced with the combined usage of fouling mitigation devices.

FOULING IN PHT

Fouling in the preheat train could be categorized as acute or chronic fouling. Acute fouling are events such as crude incompatibilities and malfunction of certain equipment such as the desalter. Experience on crude incompatibility has led to a significant improvement in handling crude incompatibilities on site, with a variety of methods to replace time consuming laboratory experiments to faster techniques to obtain compatibility results in several minutes (e.g. [2–4]).

When considering chronic fouling, different type of fouling are observed in different sections of the crude preheat train (e.g. [5–7]). For crude-side fouling, this includes both deposition of inorganic and organic material. After a prolonged exposure to heat, the deposits 'age' to a material which are usually harder to remove [8]. The overall fouling is likely to be a result of a combination of effects including corrosion depending of the exchanger metallurgy [9].

Inspection of the deposits would help trace the root cause of fouling [10,11]. Deposits from the field vary in a wide range of composition which may depend on the fluid type, length of operation, past cleaning methods, how the exchanger was dismantled before the deposits were collected and how the deposits were analyzed. A broader categorization of the deposits was discussed by Shank and McCartney [12] where the deposits were categorized as Asphaltic, Sulfurous, Silicate and Carbonaceous, though deposits may not fall exclusively into a single category, and is a complex mixture of several categories simultaneously.

Heavy product stream fouling can also be a dominant problem in the PHT. Quality of the residue stream is one of the key performance indicator of the distillation process (heavier residue stream implies increased separation of valuable products). Residue streams that have already undergone a phase separation while cooling down are known to foul the heat exchangers [13].

The thermal fouling resistance is calculated based on the operating conditions of the heat exchanger (e.g. using measured stream flow rates, temperatures and pressures) to reflect the thermal resistance given by

$$\frac{1}{U_o} = \frac{1}{h_o} + R_{f,od} + \frac{d_o \ln\left|\frac{d_o}{d_i}\right|}{2k_w} + \frac{d_o}{d_i} \times R_{f,id} + \frac{d_o}{d_i} \times \frac{1}{h_i} \quad (1)$$

$$R_f = R_{f,od}\frac{d_o}{d_i} + R_{f,id} \quad (2)$$

Here, U_o is the overall coefficient based on outside area, h_o is the shell-side fluid film coefficient, h_i is the tube-side fluid film coefficient, k_w is the thermal conductivity of the tube material, d_i is the tube internal diameter, d_o is the tube external diameter, $R_{f,id}$ is the tube-side fouling resistance, $R_{f,od}$ is the shell-side fouling resistance.

The overall thermal resistance, R_f, calculated (as a combination of tube-side and shell-side fouling resistance) can be further segregated for tube and shell sides based on known fouling mechanisms of the streams and/or availability of pressure drop measurements. Information on the pressure measurements, if available, are likely to improve the analysis, however is rarely available from field data [8].

TECHNICAL IMPLICATIONS OF CRUDE PREHEAT TRAIN FOULING

The impact of crude fouling on the preheat train is a combination of thermal, hydraulic and safety concerns (e.g. [6,11,12]). Thermal penalties results in increased fuel consumption, emissions, and increased maintenance events. Hydraulic penalties results in reduction in realized opportunity cost [6,13,14]. Increased maintenance events and reaching fired heater limits increases operational safety concerns in both operator safety and equipment integrity. Impact of fouling on uncontrolled flow splits can also result in equipment vibration problems [14].

Table 1: Some factors influencing fluid allocation in a crude preheat train

Service	Example allocation	Possible reason
Crude/Overhead	Condensing stream is commonly observed on the shell-side but sometimes on the tube-side	If corrosion is a problem, tube replacement or use of special alloys is cheaper when limited on the tube-side.
Crude/Light Product Stream	Crude on the tube-side Crude on the shell-side	Better control of flow velocity / easier to clean tube-side fouling Improvements in heat transfer
Crude/Heavy Product Stream	Crude on the tube-side Crude on the shell-side	Better control of flow velocity / easier to clean tube-side fouling Improvements in heat transfer
Crude/Residue Stream	Crude on the tube-side Residue on the tube-side	Control fouling of crude-side / enhance heat transfer on residue Control fouling of residue / enhance heat transfer on crude side

Implications to the integrated furnace crude preheat operation

Reduction in crude preheat results in a reduction in furnace inlet temperature (FIT). The Furnace Outlet Temperature (FOT) is a key parameter in the operation of the distillation column and the furnace duty needs to adjust where possible to accommodate the reduced FIT. It is common to operate at a target FOT, though, not necessarily fixed depending on certain operating strategies (e.g. when a furnace firing limit is reached, to reduce throughput keeping FOT constant [14] or to reduce FOT, keeping throughput constant). Fouling in pump-around heat exchangers can also result in operational constraints that impact the production.

In addition to the furnace firing capacity limits, operating constraints based on safety need consideration. This includes the maximum tube metal temperature (TMT) of the furnace tubes. As TMT would vary significantly along the tube length and also with coking in the furnace [15–18], direct monitoring of TMT is not always available. If limits on either the TMT or fuel firing is reached, production needs to reduce to maintain the FOT [19,20]. The reduction in throughput will result in a much greater economic loss to the plant.

An extreme case of reduction in FIT was reported by Ishiyama *et al*. [14] for a UK refinery, showing a reduction of 30 °C in 6 months.

Implications on network hydraulics

The network may face further hydraulic penalties leading to throughput reduction based on several reasons including:

- Unable to obtain the target desalter inlet temperature or flash inlet temperature
- Product streams not undergoing sufficient cooling
- Pumping capacity limit being reached
- Exchanger erosion and vibration concerns
- Limits imposed due to furnace operation and safety

Implications on safety

Safety concerns can be related to:

- Increased number of cleaning actions
- Material safety limits (e.g. sulfidation corrosion which is largely dependent on the surface temperature, fluid sulfur content and the sulfur species [21])

FOULING MITIGATION METHODS

Some fouling mitigation methods may be less popular than others in a refinery due to the lack of experience they have had on the application of the method over a prolonged period. A summary of fouling mitigation options used within PHT was listed by Ishiyama *et al*. [6,19]; these include:

(i) modification of the stream chemistry (e.g. *via* addition of anti-foulants);
(ii) modification of the operating condition (e.g. changes to shear stress and interaction of the change to other operating conditions);
(iii) modification to the surface;
(iv) systematic cleaning

The interaction of the change in one operating condition to another needs to be assessed on the selection of the fouling mitigation option [22].

ECONOMIC IMPACT OF CRUDE PREHEAT TRAIN FOULING

Earlier work by Van Nostrand *et al*. [23] provided an estimated cost of fouling in a crude oil refinery including the crude preheat train. This estimate (accounting for inflation) is a popular reference by many researchers in explaining the impact of fouling (e.g. [24–26]). Van Nostrand *et al*. analysis included the following assumptions:

- A hypothetical crude preheat train with a refining capacity of 100,000 bbl/day was assumed as a typical crude preheat train
- A typical run cycle was defined by 18 months operation followed by a 4 week shutdown
- Exchanger cleaning were performed during the shutdown
- A constant drop in network duty of 5.1 MM btu/hr per month (1.5 MW per month)
- Furnace efficiency was not mentioned
- The 4 week shutdown period was taken to estimate the lost opportunity

In this manuscript, the cost estimate for crude preheat train fouling is revisited. Since 2020, there has been significant volatility in the crude market due to the pandemic and the unsettled political atmosphere; 2019 was taken as the basis for estimating and comparison of the fouling related costs. An inflation calculator [27] was used to convert the cost estimates in Van Nostrand *et al*. [23], to values associated in 2019.

Shutdown

Shutdown can be either a planned event (e.g. to perform required infrastructure projects, equipment inspection and maintenance) or a unplanned event (e.g. due to extreme weather [28]). If the shutdown is planned this may usually follow an operating cycle of 3 to 6 years [29] in contrast to the 18 months run cycle used by Van Nostrand *et al*. [23]. Period of plant shutdown would also vary significantly based on the complexity of the plant and planned projects during the shutdown period in addition to the scheduled maintenance activities.

Lost opportunity

The throughput constraint significantly differs within different crude preheat trains, it is not straight forward to make a generalization on a single crude preheat train and scale it to represent the total average. Instead, an approach to compare the actual amount of crude processed at the plant and the calendar-day capacity was used to estimate the lost opportunity cost. Calendar-day (cd) capacity is the operator's estimate of the input that a distillation unit can process in a 24-hour period under usual operating conditions, taking into account the effects of both planned and unplanned maintenance [30]. Table 2 and Fig. 2 is a summary of the US refining capacity for 1980 and 2019. Fig. 2 shows the reduction in the number of US refineries together with a gradual increase in the operable utilization rate indicating the improvement in refinery efficiency.

Table 2: US refining capacity [31]

	1980	2019
Calendar-day capacity	18 MM bbl/day	18.8 MM bbl/day
Actual amount processed	13.8 MM bbl/day	17 MM bbl/day
Operable utilization rate (%)	77.7	90.4

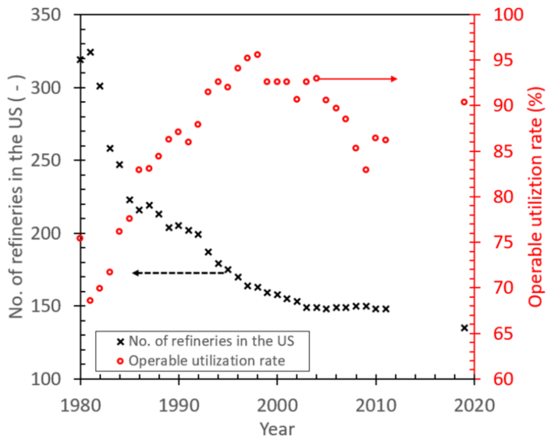

Fig. 2. Number of US refineries and the average operable utilization rate based on data in [31]

For 2019 the operable utilization rate (actual crude processed over calendar-day capacity) is 90.4 %. Taking this as the total lost opportunity (including non-fouling related throughput reductions), a lost opportunity of 1.8 MM bbl per day is obtained. This loss is not only based on fouling alone but also with other process and logistic factors, however, will provide an upper bound for the lost opportunity. Based on a lost opportunity cost of 3.5 US$/bbl [32], this will amount to 1.9 billion US$/year. Based on the authors experience about half of the cases where reduction in throughput was experienced is not directly linked to fouling and it is likely that the lost opportunity cost associated with fouling may be in the region of 0.95 billion US$/year.

Energy impact

Assuming a crude API of 30°, 1.5 MW drop (Van Nostrand *et al.* [23]) corresponds to approximately a drop in FIT of 4 °C per month for the 100,000 bbl/sd train. A refinery in Argentina reported a drop in FIT of 0.56 °C per month [7,33]. An extreme case where processing extremely fouling crude blend reported a drop in FIT of 5 °C per month [14]. Taking an energy cost of 5 US$/ MM btu [34] and assuming a furnace efficiency of 90% [35], the associated energy cost per year averages to approximately 195.5 MM US$ per year (bounded between limits of 41.4 to 349.7 MM US$ per year).

Emissions

The additional CO_2 emission related to the energy penalty can be estimated assuming complete oxidation of the fuel. CO_2 emission rate, $[CO_2]_{Emiss}$ is given by [36]:

$$[CO_2]_{Emiss} = \left(\frac{Q_{fuel}}{NHV}\right)\left(\frac{C\%}{100}\right)\alpha \qquad (3)$$

Here, a is the ratio of molar masses of CO_2 and C (=3.67), Q_{fuel} is the duty from fuel burnt, NHV (based on low heating value, LHV) is the net heating value, C% is the carbon content in the fuel. Using equation (3) and integrating over 1 year period, the emission estimates based on Van Nostrand *et al.* and 2019 are plotted in Fig. 3(2).

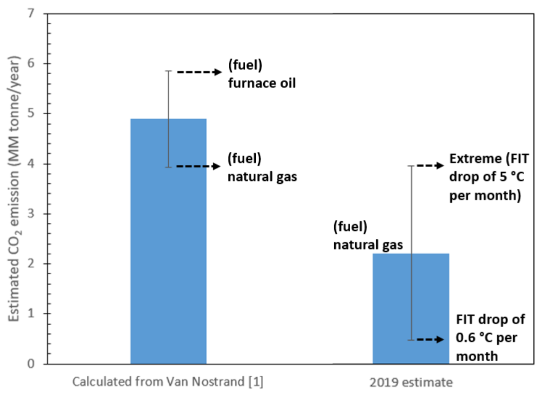

Fig. 3. CO_2 emission estimate based on fouling in crude preheat train for the US refinery.

A separate estimation of CO_2 emission by crude preheat train fouling was done in 2009 by Muller-Steinhagen *et al.* [37] who reported a value of 88 MM t CO_2 per year (globally). The estimation was done based on the assumptions that the global refining capacity was 87 MM bbl/day, energy consumption of the whole refinery accounts to around 6-7% of oil throughput and crude oil fouling accounts for around 10% of their total CO_2 footprint.

Antifoulant usage

There are a variety of antifoulants available from the market including dispersants, corrosion inhibitors, metal coordinators, polymerization inhibitors. The choice of antifoulant selection includes a series of criteria such as the fouling mechanism itself, the environment it would be used (acidic or basic), cost, dosage and its life-cycle downstream of the train. Successful case studies on the optimization of the use of Antifoulants have been recently reported by ENEOS refinery group [38,39]. The global antifoulant market for the crude preheat train was valued at 160.3 MM US$ in 2021 [40]. Approximately US covers about 19% of the world crude refining capacity [41] and the estimated antifoulant market for the crude preheat section in the US is estimated to be 32 MM US$. Even though the cost implications of antifoulant usage was discussed by Van Nostrand *et al*. the cost was not generalized by the authors to represent the total US refining industry.

Cleaning

Cost of cleaning depends on many parameters including the exchanger service, size, location of the unit, type of cleaning method and the availability of the cleaning contractors. Cost for a mechanical cleaning can be as high as 70,000 US$ (corrected to 2019 based on a reported value of 50,000 US$ in 2003 [42]). There are variety of cleaning methods available today (e.g. [43–46]) compared to the 1980's implying the refinery has a range of options to choose from based on associated costs, duration, vendor availability and past experience and possibly the degree of cleaning which is likely to vary among the methods.

The choice of cleaning heat exchangers during operation or at a shutdown or both, depends on the refinery operating philosophy and the operational constraints. Usually the cost of cleaning during a shutdown would be significantly high compared to cleaning during operation (via isolation); one reason can be attributed to priorities in resources allocation. Tools to make choices on selecting which heat exchangers to clean (or not to clean) has improved significantly enabling refineries to make better choices such as reduced number of cleaning events yielding higher cleaning benefits (e.g. [38,39]). An example at ENEOS Sakai refinery in Japan reported a reduction in number of cleaning events from 20 to 10 with an increased energy recovery benefit [39]. This example may provide an optimistic bound for the cost reduction related to cleaning and maintenance. i.e. Van Nostrand *et al*. [23] reported a value of 20 MM US$ (adjusted to 2019 value). The current estimate would likely to be between 10 to 20 MM US$.

Other factors such as distillate yield, high Sulphur crude processed, refinery age and refinery structure does impact the energy consumption [47] and introduces complexity in segregating the impact of fouling associated costs; this complication is not accounted in this analysis.

Table 3 is a summary of the comparison of the total US crude preheat train performance analysis between Van Nostrand *et al*. and this work based on figures corrected for 2019. An optimistic estimate shows that the cost of fouling have reduced to 1 – 1.2 B US$ per year (it is unlikely to be more than 2.2 B US$).

Table 3: Comparison of US crude preheat train operation between Van Nostrand et al. and estimate for 2019.

	Van Nostrand *et al*. [1]	2019
Total US refining capacity (MM bbl/cd)	18	18.8
Typical drop in FIT (°C/month, in the absence of mitigation technology or online cleaning)	4	(low fouling) 0.6 (average) 2.3 (worst case) 5
Cost associated to drop in FIT	183.6 MMUS$ (1980) 569.64 MM US$ (adjusted to 2019)	(based on average drop) 195.5 MM US$ (minimum and maximum bound) 41.4 to 349.7 MM US$
Lost opportunity	671.4 MM US$ (1980) 2.1 B US$ (adjusted to 2019)	(Upper bound) 1.9 B US$ (Associated with fouling) 950 MM US$
Cleaning + Maintenance	6.3 MM US$ (1980) 20 MM US$ (adjusted to 2019)	10 to 20 MM US$
Cycle	18 months	3 to 6 years
Cost of antifoulants	-	32 MM US$

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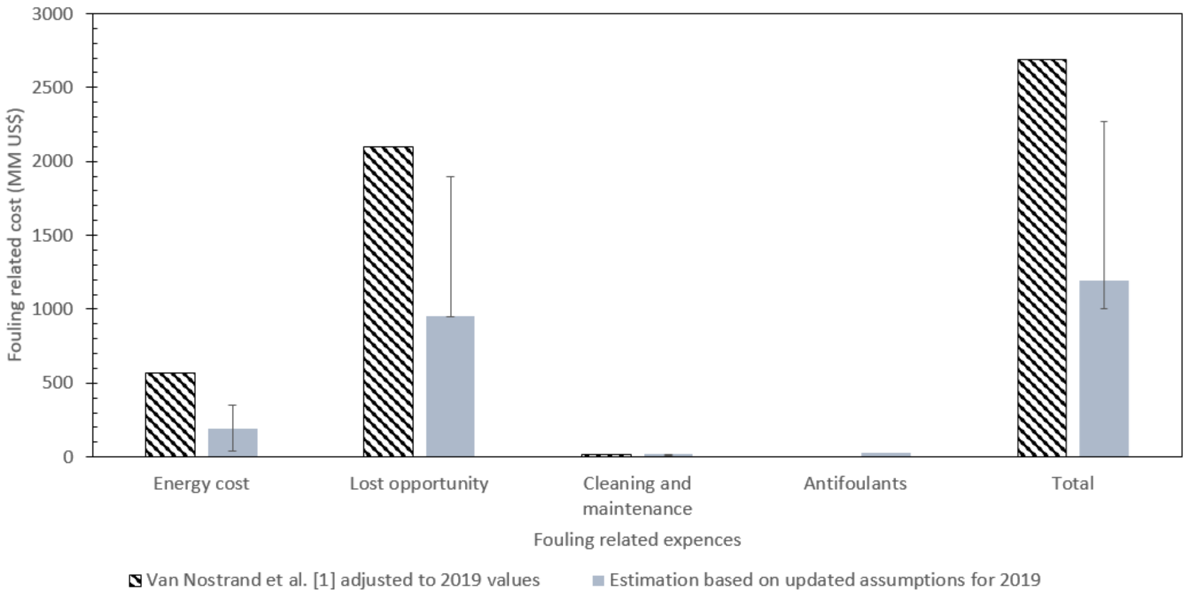

Fig. 4. Summary of fouling related cost comparison for the total US crude preheat trains.

RELATIONSHIP BETWEEN COST OF FOULING AND REFINERY MARGIN

The definition of a refinery margin varies significantly among refineries and also for the same refinery when processing different crude blends. In this manuscript, the margin is simply defined as the refinery profit per barrel of crude oil processed, where the refinery profit, P, is given by

$$P = F - R - C \tag{4}$$

Here F is the final product value, R is the cost for raw materials and C is the cost of operation.

Final product value F is based on the quantity and types of finished products that are derived from crude oil; these can be classified in four categories, light (e.g. diesel, kerosene, naphtha, etc.), heavy (e.g. fuel oil, bunker fuel), speciality (e.g. lube oil, solvents) and by-products (e.g. LPG, sulfur). The key raw material to the plant is crude oil, however, other raw materials are also purchased which includes semi-finished oils (e.g. blending components) and materials not derived from crude oil (e.g. MTBE, alcohols).

The cost of operation, C, is the actual cost associated with running the plant including the cost of energy, equipment maintenance, cleaning and labor.

A refinery can increase P by increasing F or reducing R and/or C or increasing the lumped value of $F - R - C$.

Table 4 is a hypothetical illustration of the use of equation (4). The current crude blend processed at the refinery is assumed to cost 80 US$/bbl. For a 100,000 bbl/cd refinery, this will amount to 2920 MMUS$ per year. A rule of thumb is taken that the cost of crude amounts 80% of the total refinery cost (based on [4]). 15% of the costs (438 MM US$) are associated to other feedstock and the remaining cost being the total cost of operation (18.25 MM US$). Assuming the value of the total product realized is 3412.75 MM US$, using equation (4) the refinery profit will be 36.5 MM US$ and the crude margin 1 US$/bbl. If a new crude blend was processed which would cause worse fouling problems the cost of operation may increase further (e.g. increased cleaning events and furnace energy under constant throughput); denoted here as Analysis 1, the new cost of operation is now increased to 21.08 MM US$. It is assumed that this crude blend having a worse fouling performance is cheaper (71 US$/bbl), however the value of the realized product (F) is lower (3105.60 MM US$) and use of other feedstock has also increased (442.38 MM US$). The refinery will have a larger profit (50.65 MM US$), even with worse fouling and reduced product value due to the reduced crude price. One way of understanding the fouling cost relation is to add the additional fouling cost related to operation to the crude price giving a crude price of 71.08 US$/bbl. The increase in crude price will be reflected in the product margin (e.g. 71.39 US$/bbl will result in a margin of 1.00 US$/bbl). If the crude price increases further to 72.39 US$/bbl, the margin reduces to zero and the process no longer profitable.

CONCLUSION

Estimation of the economic impact of crude preheat train fouling by Van Nostrand [23] was revisited and the underlying assumptions updated. An optimistic estimate on the cost of fouling in the crude preheat train is estimated to have reduced significantly over the last several decades; for a US crude refining capacity, the author estimates the cost of fouling in crude preheat train may have reduced to 1 – 1.2 B US$ (from 2.6 B US$). The total additional CO_2 emission due to fouling in the crude preheat train is estimated to have reduced from 4.9 MM tonne/year (in 1980) to 2.2 MM tonne/year (in 2019). The cost of crude preheat train fouling is only one of the many inputs that decides on the profitable operation of the refinery; there could be situations where the refinery would choose to process a worse fouler based on the net refinery profit accounting crude cost, product realized, feedstock cost and operating cost.

Table 4: Economics implication of crude oil fouling (assuming 100,000 bbld/sd)

		Margin US$/bbl	Crude price US$/bbl	Annual summary: Refinery profit (*P*) MM US$	Product realization (*F*) MM US$	Cost of raw materials (*R*): Cost of crude MM US$	Other feedstock MM US$	Cost of operation (*C*) MM US$
Current blend		1.00	80.00	36.50	3412.75	2920.00	438.00	18.25
New blend	Analysis 1	1.39	71.00	50.65	3105.60	2591.50	442.38	**21.08**
	Analysis 2	1.39	**71.08**	50.55	3105.60	2594.42	442.38	18.25
	Analysis 3	1.00	**71.39**	36.41	3105.60	2605.74	442.38	21.08
	Analysis 4	0.00	**72.39**	-0.09	3105.60	2642.24	442.38	21.08

NOMENCLATURE

C cost of operation, US$
$[CO_2]$emiss CO_2 emission rate, kg/s
C% carbon percentage in fuel, -
d_i tube internal diameter, m
d_o tube external diameter, m
k_w thermal conductivity of the tube, W/m K
F final product value, US$
h_i tube-side fluid film coefficient, W/m^2 K
h_o shell-side fluid film coefficient, W/m^2 K
NHV net heating value, J/kg
P refinery profit, US$
PHT preheat train
Q_{fuel} heat duty supplied by fuel combustion, W
R raw material cost, US$
R_f overall fouling resistance, m^2 K/W
$R_{f,id}$ tube-side fouling resistance, m^2 K/W
$R_{f,od}$ shell-side fouling resistance, m^2 K/W
t time, s or day
U_o Overall coefficient, W/m^2 K

Symbols

α ratio of molar masses of CO_2 and C, -

REFERENCES

[1] Van Nostrand, W. L., Leach, S. H., and Haluska, J. L., Economic Penalties Associated with the Fouling of Refinery Heat Transfer Equipment., *Fouling of Heat Transfer Equipment*, E.F.C. Somerscales, and J.G. Knudsen, eds., Hemisphere, Washington, pp. 619–643, 1981.

[2] Wiehe, I. A., Are You Processing Incompatible Crude Oils?, *World Refining*, vol. 11, no. 8, p. 24, 2001.

[3] Kumar, R., Voolapalli, R. K., and Upadhyayula, S., Prediction of Crude Oil Blends Compatibility and Blend Optimization for Increasing Heavy Oil Processing, *Fuel Processing Technology*, vol. 177, , pp. 309–327, 2018.

[4] Van den Berg, F. G. A., Kapusta, S. D., Ooms, A. C., and Smith, A. J., Fouling and Compatibility of Crudes as Basis for a New Crude Selection Strategy, *Petroleum Science and Technology*, vol. 21, no. 3–4, pp. 557–568, 2003.

[5] Lemke, H. K., Fouling in Refinery Equipment – an Overview., *Heat Transfer Equipment in the Process Industries*, C.B. Panchal, and A.E. Jones, eds., AIChE, New York, pp. 275–282, 1999.

[6] Ishiyama, E. M., Juhel, C., Aquino, B., Hagi, H., Pugh, S. J., Gomez Suarez, E., Kennedy, J., and Zettler, H. U., Advanced Fouling Management through Use of HTRI SmartPM: Case Studies from Total Refinery CDU Preheat Trains, *Heat Transfer Engineering*, vol. 0, no. 0, pp. 1–13, 2021.

[7] Ishiyama, E. M., Heins, A. V., Paterson, W. R., Spinelli, L., and Wilson, D. I., Scheduling Cleaning in a Crude Oil Preheat Train Subject to Fouling: Incorporating Desalter Control, *Applied Thermal Engineering*, vol. 30, no. 13, pp. 1852–1862, 2010.

[8] Ishiyama, E. M., Falkeman, E., Wilson, D. I., and Pugh, S. J., Quantifying Implications of Deposit Aging from Crude Refinery Preheat Train Data, *Heat Transfer Engineering*, vol. 41, no. 2, pp. 115–126, 2020.

[9] Hazelton, M., Stephenson, T., Lepore, J., Subramani, V., and Mitlin, D., Sulfide Promoted Chronic Fouling in a Refinery: A Broad Phenomenon Spanning a Range of Heat Transfer Surfaces and Oil Types, *Fuel*, vol. 160, , pp. 479–489, 2015.

[10] Brons, G. B., Brown, L. D., Joshi, H., Kennedy, R. J., Bruno, T., and Rudy, T. M., *A Method for Refinery Foulant Deposit Characterization*, Patent CA2573620A1, Canada, 2006.

ISBN: 978-0-9984188-2-7; Published online www.heatexchanger-fouling.com

[11] Chew, J., Joshi, H. M., Kazarian, S. G., Millan-Agorio, M., Tay, F. H., and Venditti, S., Chapter Four - Deposit Characterization and Measurements, *Crude Oil Fouling*, F. Coletti, and G.F. Hewitt, eds., Gulf Professional Publishing, Boston, pp. 95–178, 2015.

[12] Shank, R. A., and McCartney, T. R., Characterization of Crude Oil Fouling: Defining the Coke Spectrum, *13th International Conference on Heat Exchanger Fouling and Cleaning*, Warsaw, Poland, 2019.

[13] Ishiyama, E. M., Kennedy, J., and Pugh, S. J., Fouling Management of Thermal Cracking Units, *Heat Exchanger Fouling and Cleaning*, Enfield, Dublin, 2015.

[14] Ishiyama, E. M., Pugh, S. J., Polley, G. T., Kennedy, J., Wilson, D. I., Ogden-Quin, A., and Birch, G., How to Get the Best from Your Preheat Train - An UK Refinery Based Case Study, 2013.

[15] Morales-Fuentes, A., Rodriguez, G. M., Polley, G. T., Picon-Nunez, M., and Ishiyama, E. M., Simplified Analysis of Influence of Preheat Train Performance and Fired Heater Design on Fuel Efficiency of Fired Heaters, *9th International Conference on Heat Exchanger Fouling and Cleaning*, Crete, Greece, pp. 50–56, 2011.

[16] Morales-Fuentes, A., Picón-Núñez, M., Polley, G. T., and Méndez-Díaz, S., Analysis of the Influence of Operating Conditions on Fouling Rates in Fired Heaters, *Applied Thermal Engineering*, vol. 62, no. 2, pp. 777–784, 2014.

[17] Morales-Fuentes, A., Polley, G. T., Picón-Núñez, M., and Martínez-Martínez, S., Modeling the Thermo-Hydraulic Performance of Direct Fired Heaters for Crude Processing, *Applied Thermal Engineering*, vol. 39, , pp. 157–162, 2012.

[18] Morales-Fuentes, A., Polley, G. T., and Nunez, M. P., Influence of Pre-Heat Train Performance and Fired Heater Design on Fuel Efficiency of Crude Distillation Units, 2011.

[19] Ishiyama, E. M., Pugh, S. J., Kennedy, J., and Wilson, D. I., Effect of Scheduling Cleaning of Crude Preheat Train Exchangers on the Operation of Fired Heaters, *11th HEFC Conference*, Enfield, Dublin, 2015.

[20] Ishiyama, E. M., Pugh, S. J., Kennedy, J., and Wilson, D. I., Optimizing Operations of Crude Preheat Train and Furnace: Influence of Preheat Train Management on Furnace Operation, *3rd Sustainable Thermal Energy Conference*, Newcastle, UK, 2015.

[21] Jackowski, L., Risse, P., and Smith, R., Impact of Nonuniform Fouling on Operating Temperatures in Heat Exchanger Networks, *Heat Transfer Engineering*, vol. 38, no. 7–8, pp. 753–761, 2017.

[22] Ishiyama, E. M., Pugh, S. J., and Watkinson, A. P., Interaction of Heat Transfer Enhancement and Fouling in Operating Heat Exchangers, *14th International Conference on Heat Exchanger Fouling and Cleaning*, Wagrain, Austria, 2022.

[23] Van Nostrand, W. L., Leach, S. H., and Garcia, E., Heat Exchanger Monitoring and Its Application to Cleaning and Antifoulant Use, 1983.

[24] Steinhagen, R., Steinhagen, H. M., and Maani, K., Problems and Costs Due to Heat Exchanger Fouling in New Zealand Industries, *Heat Transfer Engineering*, vol. 14, no. 1, pp. 19–30, 1993.

[25] Coletti, F., and MacChietto, S., A Dynamic, Distributed Model of Shell-and-Tube Heat Exchangers Undergoing Crude Oil Fouling, *Industrial and Engineering Chemistry Research*, vol. 50, no. 8, pp. 4515–4533, 2011.

[26] Macchietto, S., Hewitt, G. F., Coletti, F., Crittenden, B. D., Dugwell, D. R., Galindo, A., Jackson, G., Kandiyoti, R., Kazarian, S. G., Luckham, P. F., Matar, O. K., Millan-Agorio, M., Müller, E. A., Paterson, W., Pugh, S. J., Richardson, S. M., and Wilson, D. I., Fouling in Crude Oil Preheat Trains: A Systematic Solution to an Old Problem, *Heat Transfer Engineering*, vol. 32, no. 3–4, pp. 197–215, 2011.

[27] Inflation Calculator | Find US Dollar's Value from 1913-2022 [Online]. Available: https://www.usinflationcalculator.com/. [Accessed: 18-Apr-2022].

[28] Motiva Port Arthur Refinery Shuts down amid "unprecedented" Freezing Temperatures, *12newsnow.com* [Online]. Available: https://www.12newsnow.com/article/news/local/power-city/motiva-shuts-down-due-to-freezing-temperatures/502-9caa8199-1238-492c-8c07-c9b294047da9. [Accessed: 12-Apr-2022], 2021.

[29] Editor, O. & G. I., What Are Shutdowns and Turnarounds?, *Oil & Gas IQ* [Online]. Available: https://www.oilandgasiq.com/integrity-hse-maintenance/news/what-are-shutdowns-and-turnarounds. [Accessed: 12-Apr-2022], 2018.

[30] EIA: U.S. Refinery Capacity Decreased During 2020, *Fuels Market News* [Online]. Available: https://fuelsmarketnews.com/eia-decreased-u-s-refinery-capacity-during-2020/. [Accessed: 11-Apr-2022], 2021.

[31] U.S. Energy Information Administration - EIA - Independent Statistics and Analysis [Online]. Available: https://www.eia.gov/totalenergy/data/annual/showtext.php?t=ptb0509. [Accessed: 23-Apr-2022].

[32] ARA Refining Margin by Oil Type 2021, *Statista* [Online]. Available: https://www.statista.com/statistics/1189456/ara-refining-margin-by-oil-type/. [Accessed: 18-Apr-2022].

[33] Ishiyama, E. M., Paterson, W. R., Wilson, D. I., Heins, A. V., and Spinelli, L., The Importance

of Scheduling and Desalter Control of Preheat Trains of Crude Distillation Units: A Case Study, Schladming, Austria, pp. 52–60, 2009.
[34] Natural Gas Price Per Million Btu - Natural Gas Prices Today [Online]. Available: https://www.oilcrudeprice.com/natural-gas-price/. [Accessed: 22-Apr-2022].
[35] Ishiyama, E. M., An Application of Fouling Models in Crude Preheat Train Operation, *HTRI Global Conference*, Navasota, Texas, 2020.
[36] Gadalla, M., Olujić, Ž., Jobson, M., and Smith, R., Estimation and Reduction of CO2 Emissions from Crude Oil Distillation Units, *Energy*, vol. 31, no. 13, pp. 2398–2408, 2006.
[37] Müller-Steinhagen, H., Malayeri, M. R., and Watkinson, A. P., Heat Exchanger Fouling: Environmental Impacts, *Heat Transfer Engineering*, vol. 30, no. 10–11, pp. 773–776, 2009.
[38] Okada, T., Digital Transformation of Crude Preheat Train Fouling Management through SmartPM, *46th Refining Panel Discussion Meeting*, Japan, 2022.
[39] Ishiyama, E. M., Digital Transformation Using HTRI SmartPM^{TM}: Case Studies at ENEOS Group Refineries, *HTRI Virtual Global Conference*, Navasota, Texas, 2021.
[40] CDU Heat Exchanger Antifoulants Market [Online]. Available: https://www.futuremarketinsights.com/reports/cdu-heat-exchanger-antifoulants-market. [Accessed: 24-Apr-2022].
[41] Ruble, I., The U.S. Crude Oil Refining Industry: Recent Developments, Upcoming Challenges and Prospects for Exports, *The Journal of Economic Asymmetries*, vol. 20, , p. e00132, 2019.
[42] Joshi, H., and Brons, G., Chemical Cleaning of Oil Refinery Heat Exchangers -- The Need for a Joint Effort, *Heat Exchanger Fouling and Cleaning: Fundamentals and Applications*, p. 219, 2003.
[43] Mol, R. A., Thermal Cleaning of Heat Exchangers, No Alternative but a Better Way to Clean, *13th International Conference on Heat Exchanger Fouling and Cleaning*, 2019.
[44] Kieser, B., and Stang, D., Taking Safety to the Max : Eliminating Hydroblasting Risk through Innovative Design, Automation and Process, *13th International Conference on Heat Exchanger Fouling and Cleaning*, Warsaw, Poland, 2019.
[45] Gazizullin, I. F., Bazanov, D. R., Semenikhin, V. I., and Rodin, I. Y., New Peroxide-Based Technology of Heat Exchangers Cleaning, *13th International Conference on Heat Exchanger Fouling and Cleaning*, 2019.
[46] Sumsion, D., Shell Side Jet a Next-Generation Solution to Revolutionise the Treatment of External Heat Transfer Surface Fouling, *13th International Conference on Heat Exchanger Fouling and Cleaning*, Warsaw, Poland, 2019.
[47] Joshi, J. M., Dalei, N. N., and Mehta, P., Estimating the Energy Consumption of Indian Refineries: An Empirical Analysis Based on Panel Data Econometrics, *International Journal of Energy Technology and Policy*, vol. 17, no. 3, pp. 275–298, 2021.

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