FOULING MANAGEMENT THROUGH DIGITAL TRANSFORMATION

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ABSTRACT

Energy intensive industries are continuously adapting to the combined effect of tight regulations, growing need for social and environmental reputation and technology advances. In addition to the current challenges of optimizing energy efficiency, maintaining throughput, product quality and safety, industry has to now comply with strict environmental registries aimed at reducing emissions in line with the 2021 United Nations Climate Change Conference (COP26) pledge. This paper discusses how successful digital transformation are helping process industries perform timely and crucial analysis via identifying and eliminating waste through standardization of tools, eliminating lost time in data processing and facilitating collaboration between different work groups throughout the organization.

Three case studies are provided to highlight (1) successful digital transformation at ENEOS group refineries on their endeavors in management and mitigating fouling in crude preheat trains; (2) identifying and preventing fouling related vibration problem in the system before the problem occurring; and, (3) rigorous furnace performance monitoring and prediction to avoid operations that can result in structural safety concerns. Commercial software tools HTRI SmartPM™, Xfh® Ultra and Xist® were used in the study.

INTRODUCTION

Digitalization of plant data is a key component in operating a process plant, however, how the plant data is handled plays an important role in the Industry 4.0 initiative. 'Digital transformation (DX)' is totally different from 'digitalization', as DX is an organization wide effort to radically change the work process by implementing a system that:

- fits within the existing work flow
- promoting collaboration, and,
- providing agility

Fig. 1 is an illustration of how several HTRI software tools connect within each other, with plant data and with end users through a digital platform.

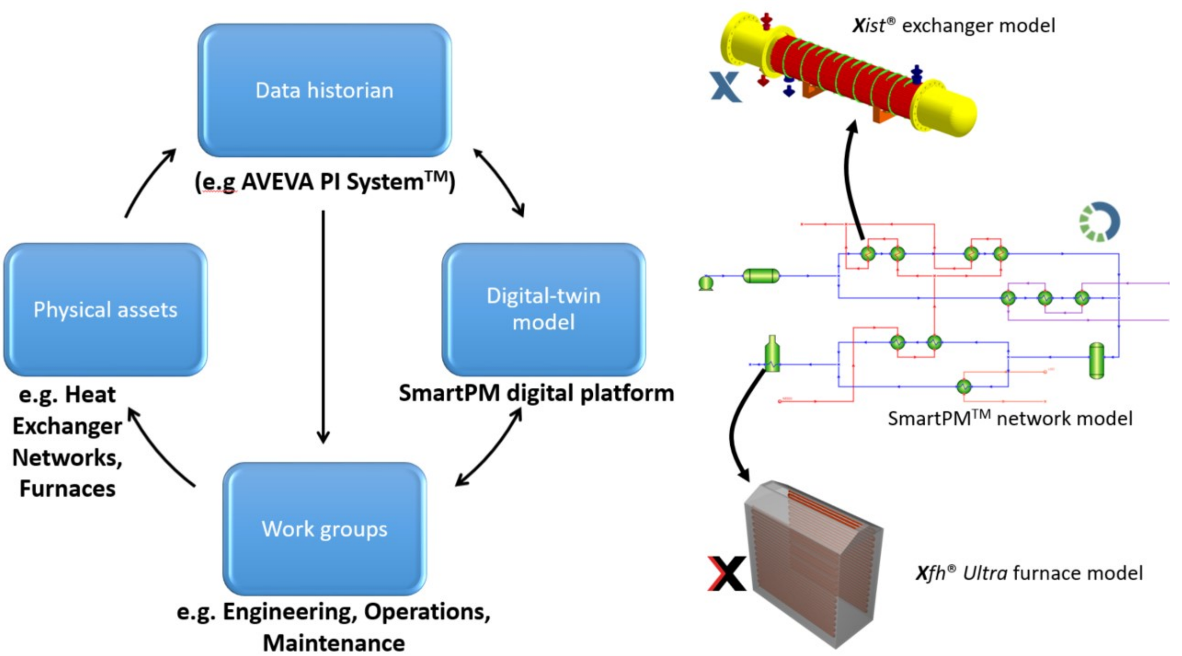

Fig. 1: Schematic workflow connecting physical assets to equivalent digital twin models *via* HTRI technology.

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A 'physical asset' (in Fig. 1) can be a single heat exchanger, network of heat exchangers, furnaces, connected pumps, valves, etc. A digital equivalent of the asset is created using HTRI software tools (e.g. HTRI SmartPM^{TM}, Xist®, Xfh® Ultra). Having a standard set of tools facilitates 'Work groups' (individuals, groups or departments), geographically located anywhere, to collaboratively interact with the digital twin models to make operational, engineering, financial and environmental decisions. E.g. operators looking at real time optimization and fouling mitigation may work in collaborative projects at the same time with maintenance group who are looking into heat exchanger restoration and, with the engineering group who are looking into OPEX and CAPEX projects.

Three case studies are highlighted here which are results of a successful digital transformation:

Case study 1 is a high-level summary of a successful digital transformation application at ENEOS refinery group in Japan.
Case study 2 highlights the use of digital twin models to identify possible equipment vibration problem caused by fouling several months before the actual problem is likely to occur.
Case study 3 a digital twin of a combined crude preheat train and furnace used to monitor the furnace performance and predict impact on the furnace with cleaning certain heat exchangers in the preheat train.

Case study 1 – Digital transformation at ENEOS refineries, Japan

The use of HTRI SmartPM^{TM} tool at ENEOS group refineries for refinery wide digital transformation was presented at the 2021 HTRI Global Conference [1] and at the 46th refinery panel discussion held by the Japan Petroleum Institute in Feb. 2022 [2]; a summary of the content is discussed here. ENEOS refinery is the biggest crude oil refining group in Japan with 11 refineries located across the country Fig. 2. SmartPM^{TM} has been used to construct 13 heat exchanger network models for their refineries, 11 of them being the crude preheat train. Over 30 SmartPM^{TM} model users across the company utilize the tool for performance monitoring and process optimization including:

- Monitoring fouling
- Fouling prediction
- Flow split and cleaning schedule optimization
- Evaluation of anti-foulant usage
- Evaluation of retrofit and revamp projects

Evaluation of different cleaning scenarios at ENEOS Negishi refinery

Before utilizing SmartPM^{TM} the refinery had a cleaning plan (Case 1). Using SmartPM^{TM} it was possible to generate a list of heat exchangers and combinations of heat exchangers to clean on a specific date in the descending order of the energy benefit incorporating network interactions of cleaning one unit on another. The cleaning plan at the refinery was re-evaluated using SmartPM^{TM} which is called 'Case 2'. Ultimately Case 2 was followed at the refinery and monitoring was done to validate if they actually got the performance predicted by the digital model.

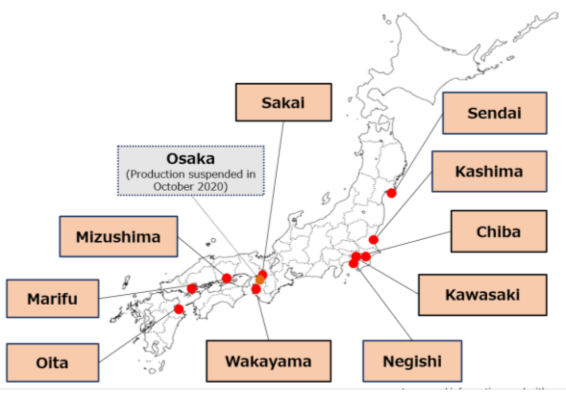

Fig. 2: Illustration of ENEOS group refineries location across Japan utilizing SmartPM^{TM} digital twin model.

Fig. 3 is a plot of change in furnace inlet temperature (FIT) over time including 4 sets of data; the first set of data given by the dashed line marked 'No cleaning' is the FIT profile that would be obtained when no cleaning actions were performed. Above this, marked 'Case 1: Original expected trend' shows about 10 °C increase in FIT when following the cleaning actions initially proposed at the plant. The SmartPM^{TM} proposed cleaning sequence given by Case 2 shows a further 5 °C increase compared to Case 1. Once the plant actually followed the cleaning schedule given by Case 2, the FIT profile obtained is shown in the scattered data marked 'Plant data after cleaning'. Once the plant operation has reached steady state following the disturbance after cleaning, it was possible to observe that the actual FIT trend followed the SmartPM^{TM} prediction.

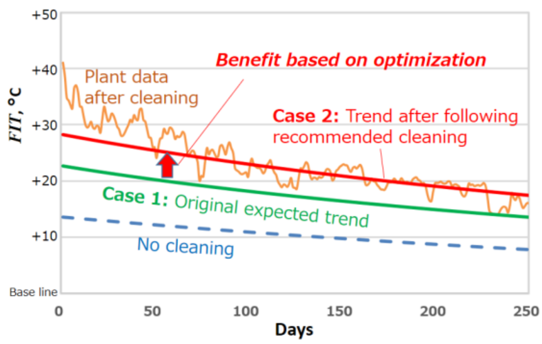

Fig. 3: Comparison of FIT at Negishi refinery preheat train for different cleaning strategies.

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Optimizing cleaning actions at ENEOS Marifu refinery

Marifu refinery have identified that SmartPM enabled to significantly reduce the associated workload for cleaning optimization. One analysis indicated that following the conventional method, which included a combination of chemical and mechanical cleaning over 3 cleaning events involving cleaning of 20 shells resulted in less benefit than the SmartPM proposed cleaning schedule which included mechanical cleaning of 10 shells over 4 cleaning events. When cleaning occurs, there is a temporal drop in FIT when the unit is isolated from the network, hence, Figure 4 shows data below the no cleaning line for the periods where cleaning events occur. The benefit achieved was both in terms of improved energy recovery as shown in the area plot comparison of FIT over time and the reduced number of total shells cleaned over the events (10 shells cleaned over 20 shells) (Fig. 4).

	Cleaning method	Cleaning events	Number of shells cleaned
Conventional method	Chemical and mechanical	3	20
Optimized	Mechanical cleaning	4	10

Fig. 4: FIT profile illustrating the comparison between the conventional and optimized cleaning process at Marifu refinery. Labels 1, 2 and 3 denote the cleaning events associated with the conventional cleaning method. Area B denotes the benefit of using the conventional cleaning method and Area A denotes the benefit of switching to the optimized method. The difference in Areas A and B provides the benefit of switching to the optimized method.

Flow split optimization at ENEOS Osaka Refinery

Fig. 5 is a simple illustration of a section of the preheat train at the Osaka refinery. The crude preheat train divides to three parallel branches following a preflash. The original operation was to maintain the outlet temperatures of the three parallel branches equal by adjusting the flow splits (which were 63, 19 and 19 %).

The SmartPM optimization study identified the best flow split to maximize the mixed FIT temperature resulting in a 44, 27, 29 % flow split. The result is plotted in Fig. 6 showing the FIT variation over time. The bottom line shows the FIT trend under conventional operation. The optimized line which is 1.5 °C above the conventional line shows the optimized performance. It is also observed that the monitoring data obtained following the flow split optimization followed the SmartPM prediction.

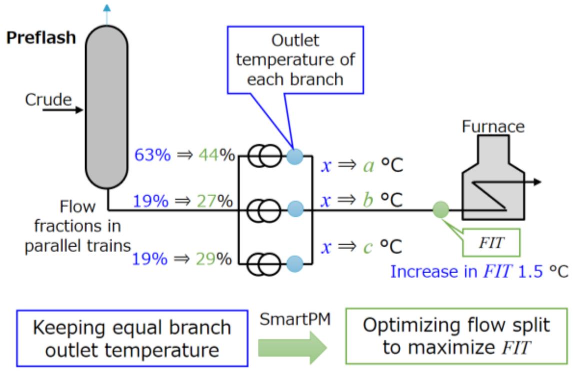

Fig. 5: Schematic of the post preflash section of a preheat train with 3 parallel branches. Flow splits marked 63 %, 19 % and 19 % shows the original flow split, while 44 %, 27 % and 29 % show the optimized flow split.

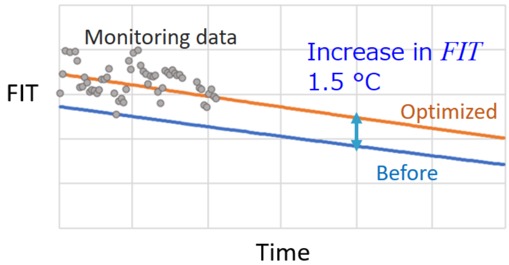

Fig. 6: FIT profile before and after monitoring flow split optimization.

Anti-foulant usage optimization at ENEOS Osaka refinery

At Osaka refinery, anti-foulants are used on a daily basis. Different anti-foulants were used over specific periods; it was not straight forward to evaluate the impact of anti-foulants given the dynamic variation in operating conditions. The changes in operating conditions are not limited to changes in flow rates and temperature but also changes in valve openings, exchanger bypasses, exchangers being offline, etc. SmartPM™ was used to perform data reconciliation and fit 'dynamic fouling models' for the crudes for different periods where different anti-foulants were used. Dynamic fouling models are used to predict fouling under changing operating conditions. The fouling model is defined for a stream. Fouling is a function of the stream chemistry which is the type of crude/anti-foulant blend, operating conditions that represents the changing surface temperatures and flow parameters within units and the metallurgy of the surface such as if the unit is CS, SS, special alloy, etc. Detailed description of the dynamic fouling models are presented elsewhere [3,4].

For each anti-foulant/crude blend a fouling propensity factor is identified through fouling model fitting for historical data. Such fouling model fits are validated through re-simulation of the past performance. The result is the fouling prediction superimposed on top of the historical fouling resistances for all exchangers. Two examples are shown in Fig. 7 for periods where two different anti foulants were used. These are plots of fouling resistances changing over time, and it is visible on the FIT plot that the different anti-foulants have an impact on how fast the FIT drop which is related to the fouling resistance changes for each units.

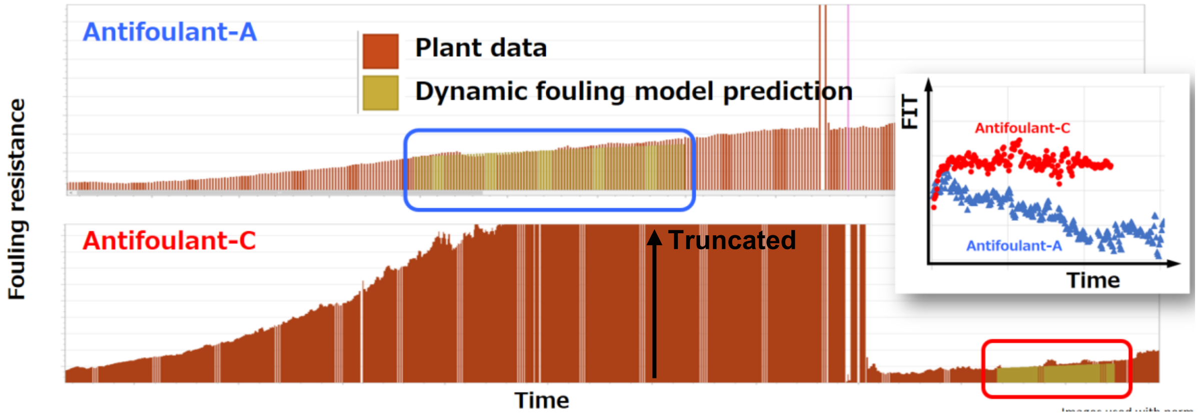

Fig. 7: Predicted fouling profile superimposed on monitored fouling resistance profile for two exchangers and two periods where two different anti-foulants (antifoulant A and antifoulant B) were used. For the plot in the usage of antifoulant B the data is truncated in the fouling resistance, marked in the plot). Region marked by rectangle indicates comparison of dynamic fouling prediction and monitored plant data.

Table 1 shows the summary performances of 3 different anti-foulants based on the drop in FIT over a specified time scale, A, B and C. Fig. 8 shows the FIT variation over time for 3 sets of data. The steepest line marked NFIT per Antifoulant-A is the prediction of FIT under a normalized condition (i.e. a simulation study at a fixed stream temperature and flow inlet conditions to the network). The NFIT per Antifoulant-C indicates the prediction of the FIT drop using anti-foulant C under the same normalized condition as anti-foulant-A. The plant data shows the actual FIT drop using antifoulant-C which follows the prediction. The difference in FIT drop, in this case, using anti-foulant C has only a drop of 7.8 °C compared to 19.1 deg C, giving a difference in drop of 11.3 °C over a specified cycle period. This change in drop can be converted to economic parameters to quantify the efficacy of using one anti-foulant over another leading to analysis such as what is the maximum viable cost that can be paid for using a certain anti-foulant compared to another.

At ENEOS, conventionally many of the studies involving cleaning, use of additives such as anti-foulants, optimizing operations such as flow splits and CAPEX heavy projects had to be done separately and independent of each other. SmartPM™ is seen as a tool that opens new possibilities to perform a systematic combined optimization analyses identifying overall impact on the network level while incorporating individual operational strategies and technical constraints (Fig. 9).

Table 1: Summary of 3 different anti-foulants and evaluated drop in FIT over a specified period.

Anti-foulant	Drop in FIT (°C)
Anti-foulant A	19.1
Anti-foulant B	17.3
Anti-foulant C	7.8

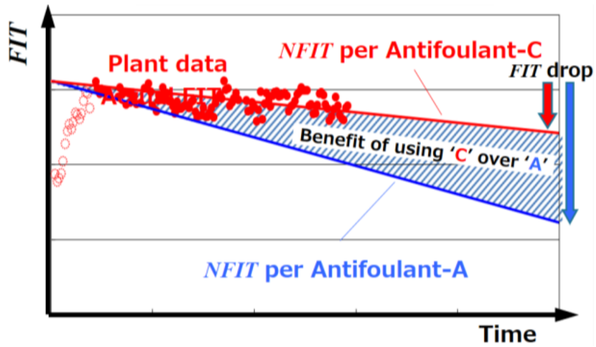

Fig. 8: Comparison of FIT for different anti-foulant usage.

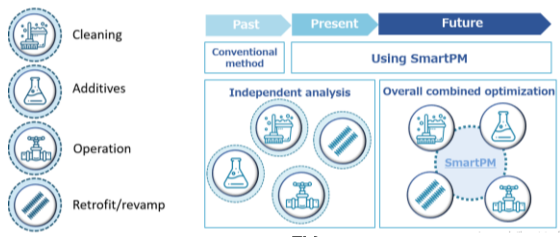

Fig. 9: Future of SmartPM™ usage at ENEOS.

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CASE STUDY 2 – FOULING RELATED VIBRATION PROBLEM

Any equipment with fluid flow will experience vibration. Depending on the degree of vibration, the equipment can result in a mechanical failure caused by mechanical wear, fretting corrosion and fatigue cracking [5,6]. In this case study we revisit the thermo-hydraulic channeling phenomenon presented by Ishiyama *et al*. [7,8] and illustrate a possibility of the exchangers reaching a safety limit imposed by vibration constraint based on a digital twin model of two parallel heat exchangers at a section of a crude preheat train (Fig. 10). The safety limit is separate from the degradation of the thermal or hydraulic performance analysis previously discussed.

EX1A has the crude on the tube-side and EX2C has the crude on the shell-side. The crude stream splits to branches A and B before passing through the exchangers; there are no flow controls associated with the split and the flow will spontaneously adjust to equalize pressure drop across the branches. The operating condition of EX1A imposes severe crude-side (tube-side) fouling, compared to EX2C where there is almost no fouling based on the operating conditions. This is evident with the observed flow divergence (Fig. 11). By performing a thermo-hydraulic prediction of the network (e.g. such described by [7]) it is possible to predict the further divergence of the flow in the system.

The impact of the flow divergence can result in flow induced vibration problem in EX2C. Fluidelastic instability ratio (FIR) is used to quantify the degree of structure vibration. In this example this term is evaluated for the longest unsupported structure of the heat exchanger (for EX2C, this is the tube section corresponding to the entrance and exit of the shell marked A and B in Fig. 13). The predictive results indicate that vibration problem is possible in 6 months in the future (Fig. 12, FIR > 0.8) and this will become a most probably issue if continued for a prolonged period (as FIR moves towards 1).

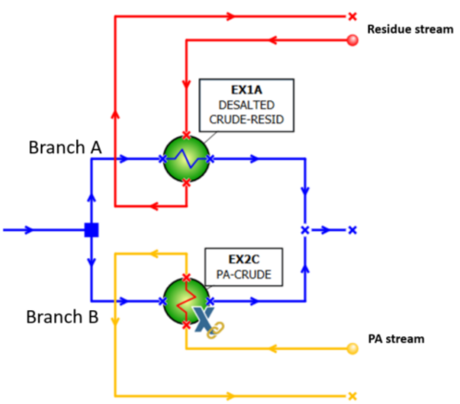

Fig. 10: Example two heat exchangers in parallel. Flow splits across branches A and B are uncontrolled.

The identification of possible vibration problem enables to take proactive measures including fouling mitigation actions to EX1A (e.g. installation of tube-inserts), flow control, installation of support plates in the unsupported length of EX2C, *etc*.

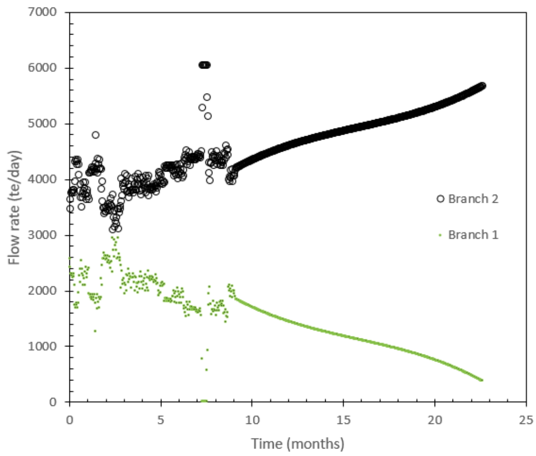

Fig. 11: Monitored and predicted flowrates across Branches A and B.

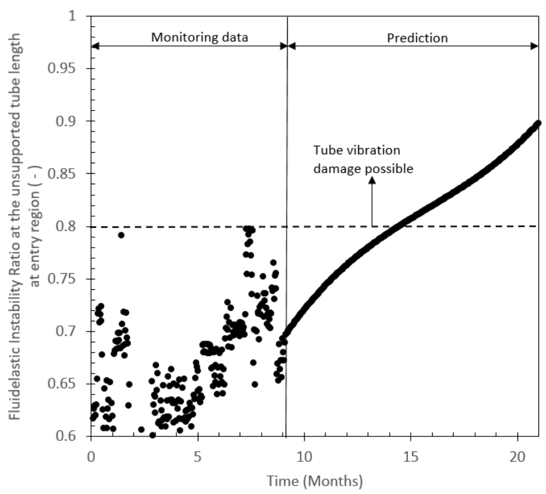

Fig. 12: Fluidelastic instability ratio for the entrance region of EX2C.

CASE STUDY 3

The impact of crude fouling on the preheat train is a combination of thermal, hydraulic and safety concerns (e.g. [4,9,10]). Thermal penalties results in increased fuel consumption, emissions, and increased maintenance events. Hydraulic penalties results in reduction in realized opportunity cost [4,8,11]. Increased maintenance events and reaching fired heater limits increases operational safety concerns in both operational safety and equipment integrity.

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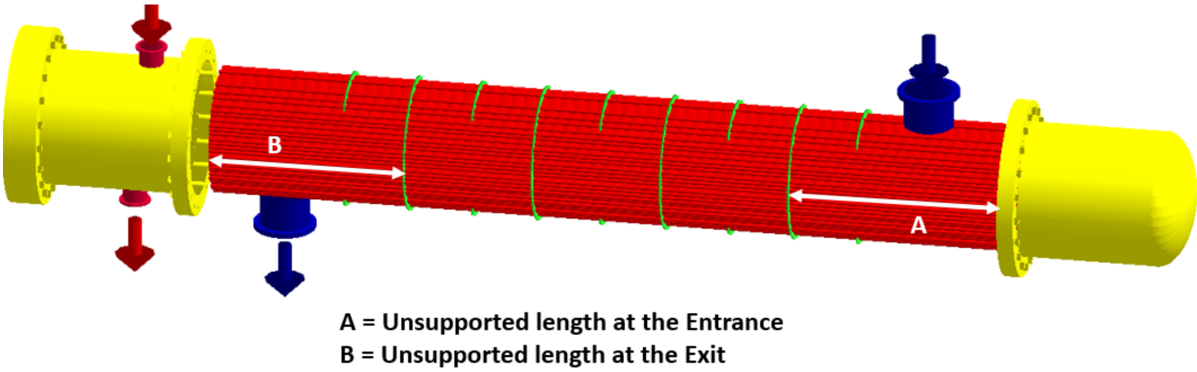

Fig. 13: 3-dimensional representation of EX2C with the longest unsupported tube length at the entrance and exit sections denoted by A and B.

The Furnace Outlet Temperature (FOT) is critical to operating the distillation column. 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 [12] or to reduce FOT, keeping throughput constant). For operations where FOT is fixed, any reduction of the CPHT heat duty needs to be compensated for in the furnace by firing more fuel. Although it is the heat exchangers which foul and resources might be spent in cleaning them, the largest impact in terms of both economics and operation is seen in the furnace.

Some critical safety concern relates to a series of furnace operating parameters which can be evaluated through a rigorous digital model of the furnace. Maximum peak wall temperature (outside) of the tube is an example. The peak wall temperature increases with increased fired duty and usually limits the furnace capacity due to safety concerns. The consequence of reaching the safety limit is that the crude rate must be cut back to maintain the FOT [13,14]. Usually this is a far larger economic loss than the increased fuel firing. An extreme case of reduction in FIT was reported by Ishiyama *et al*. [12] where a reduction of 30 °C in 6 months was observed.

In this section a case study is illustrated where the fired heater performance is monitored and the impact on furnace performance with cleaning actions in the preheat train is evaluated. A rigorous furnace model was constructed using Xfh® Ultra and connected to an example crude preheat train model constructed in SmartPM™ (Fig. 15). The monitoring data is obtained through the SmartPM digital platform and used to generate the furnace performance profiles. Fig. 14 are selected results showing the variation in FIT, furnace duty and maximum peak outside wall temperature over a period of two years.

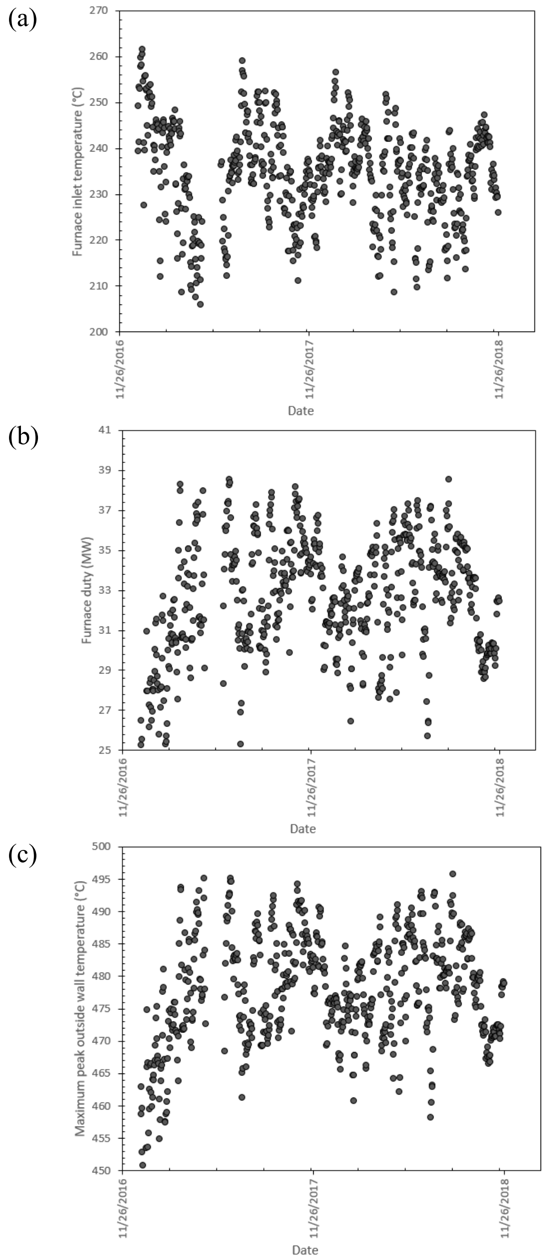

Fig. 14: Example of a monitored fired heater performance. Profiles for (a) FIT, (b) furnace duty and (c) maximum peak outside wall temperature.

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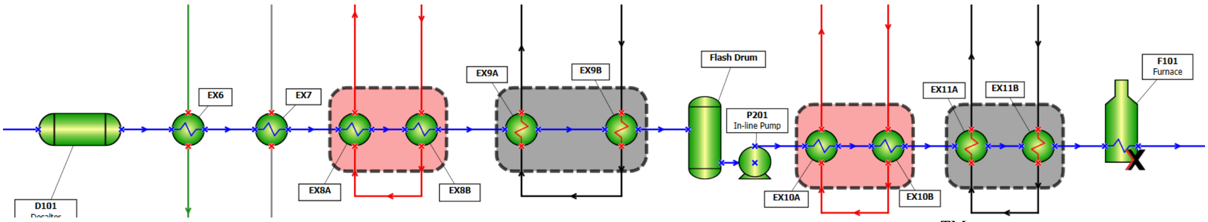

Fig. 15: Post desalter section of an example crude preheat train constructed in SmartPM™. The furnace model is constructed using Xfh® Ultra.

With the drop in FIT it is observed that both the furnace duty and the maximum peak outside wall temperature also increases (Fig. 14). If no control is performed to maintain the maximum peak outlet wall temperature, this can have an irreversible impact on the structural safety. Taking the reconciled result for the latest date, prediction studies were performed to evaluate how the impact in the drop of FIT will impact the future furnace operation if no cleaning actions were performed (Fig. 16(i)(a) marked 'No cleaning'). As an illustration the horizontal line marked 'Maximum safety limit' denote the manufacturers' specification of the maximum tube temperature limit. If no constraints are incorporated, the cleaning actions can temporarily result in exceeding the tube wall temperature above the maximum safety limit (marked as 'x' in Fig. 16(i)(a)) when the furnace duty temporarily increases when an exchanger is offline for cleaning (Fig. 16(ii)(a)). In Fig. 16(b), the cleaning schedule is generated considering the maximum safety limit as a constraint in the cleaning selection (Fig. 17, exchangers specified within the dashed enclosure). In this scenario the selection of the exchanger is performed to minimize lost production while maintaining the maximum safety limit of the tube throughout the operating cycle. Including furnace coking models to improve the estimate of TMT is an important topic to incorporate in future discussions.

CONCLUSIONS

Successful digital transformation using HTRI software tools were demonstrated *via* three case studies including:

- Companywide adoption of the tool for collaborative projects to maximize productivity and energy recovery
- Illustration of identifying vibration related problem at an early stage to prevent mechanical failure
- Combined preheat train and furnace simulation to obtain a technically viable cleaning schedule considering furnace safety constraints

NOMENCLATURE

CPHT Crude preheat train
COP26 2021 United Nations Climate Change Conference
FIT Furnace inlet temperature
FOT Furnace outlet temperature
Industry 4.0 4^{th} Industrial revolution

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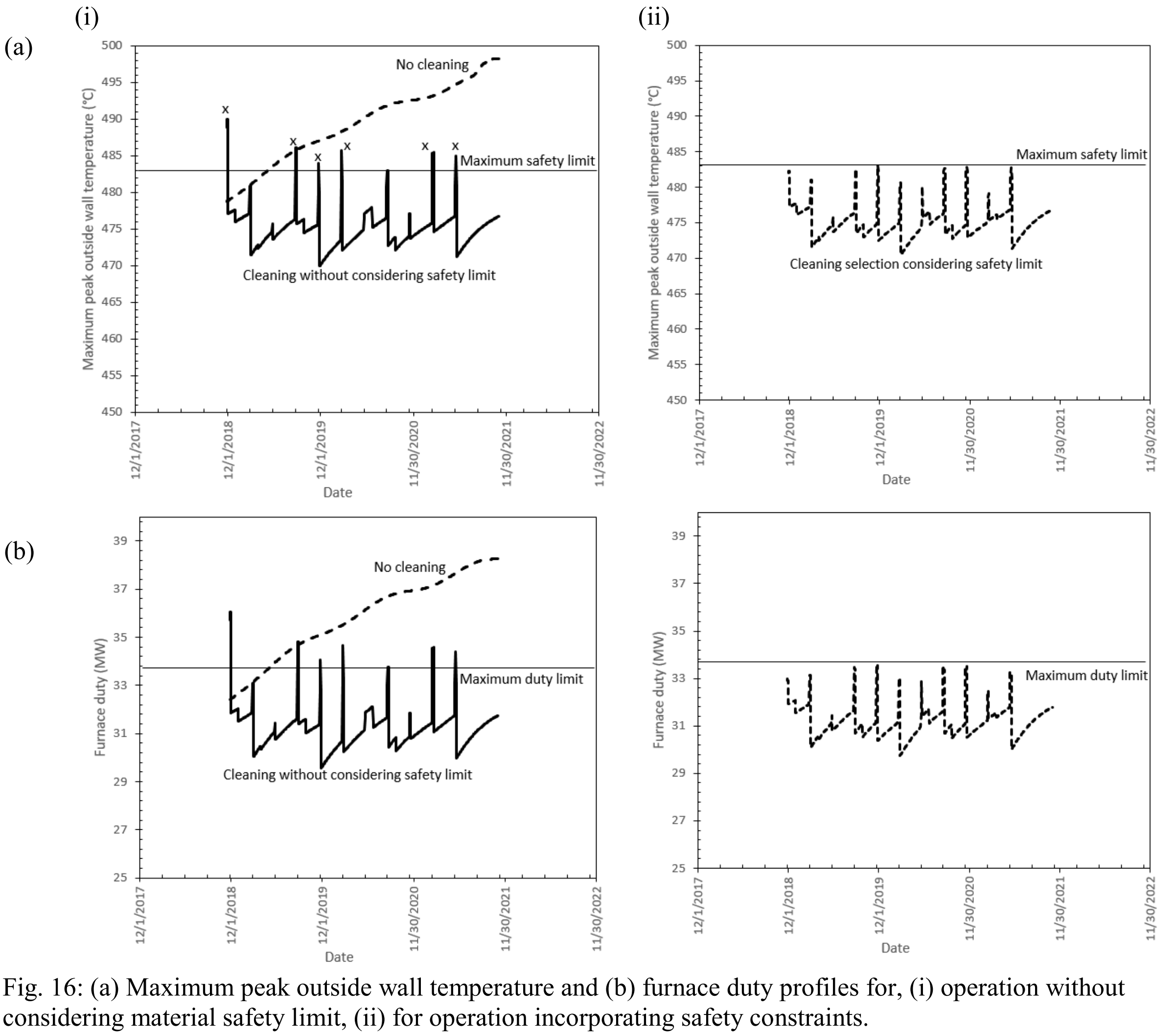

Fig. 16: (a) Maximum peak outside wall temperature and (b) furnace duty profiles for, (i) operation without considering material safety limit, (ii) for operation incorporating safety constraints.

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	2018		2019					2020					2021		
	November	...	February	May	August	November	...	February	May	August	November	...	February	May	...
EX3			10K				...						10K		...
EX6				10K			...								
Group EX10AB						20K	...								
Group EX11AB			60K		60K		...	60K		60K		...		60K	...
Group EX4AB	20K	...			20K		...		20K	20K		...			
Group EX5AB						20K	...		20K		20K	...	20K	20K	...
Group EX9AB	20K	...									20K	...			
Grand Total	40K	...	70K	10K	80K	40K	...	60K	40K	80K	40K	...	30K	80K	...

Fig. 17: Generated cleaning schedule incorporating limit on maximum peak outside wall temperature.

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