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IMPACT OF FUEL SELECTION ON FLUE GAS-SIDE FOULING IN FIRED HEATERS: A TECHNO- ENVIRONMENTAL ANALYSIS

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ABSTRACT

Fired heaters are critical in the process industries, providing necessary heat to various processes. Their performance is closely linked to safety standards, particularly regarding the temperatures of the heater tubes and the maximum temperatures allowed during operation. Constant monitoring is essential to maintain the equipment's longevity, prevent unexpected shutdowns, and ensure safety. Two main challenges in operating these heaters efficiently and safely are fouling and slagging. Slagging refers to deposits forming on the outside of the heater's tubes.

This study introduces a method to assess the performance of fired heaters using digital twin models and commercial software tools. The method focuses on estimating fouling in the heater's convection section and slagging on the outside of the radiant tubes based on available monitoring data. It also considers how different fuel mixtures used in industrial plants affect these issues.

A case study looks at heaters in Hellenic Petroleum's Aspropyrgos Refinery crude preheat trains, showing how this assessment helps make better technical and economic decisions. It highlights the link between the type of fuel used (a mix of fuel gas, off gas, and fuel oil), the likelihood of heater slagging, and the need to shut down the heater due to reaching safety limits. These findings are crucial for choosing the right fuel, balancing cost with performance and maintenance needs. Additionally, "what if" scenarios are conducted to evaluate the performance of switching to 100% hydrogen fuel through digital experiments, exploring its implications on operations.

INTRODUCTION

The efficient functioning and long-term use of industrial heaters are crucial for ensuring the productivity, safety, environmental sustainability, and financial success of manufacturing plants. Unexpected shutdowns can cause significant losses in production, potentially costing millions. The lifespan of these heaters is often affected by issues like buildup of unwanted materials and excessive heat in heater tubes. Problems often arise from heaters being run too hot, compounded by fouling in upstream heat exchangers and the need to switch between different types of fuel available at the facility, which can influence these buildup issues. Therefore, continuous monitoring and use of advanced forecasting methods are vital to ensure heaters operate as long as possible.

A typical crude oil refinery fired heater comprises two primary sections: the radiant section, where heat is mainly absorbed by radiant tubes through direct radiation from the heating flame and flue gasses (CO_2 and H_2O) and the convection section, where convection tubes absorb heat primarily through convection from combustion gases [1]. Some designs incorporate shock tubes between these sections as these tubes are subject to higher heat flux due to the impact of both radiation and convection heat transfer. Heat is generated by burning fuel and is transferred to the process fluid within these tubes through direct contact, radiation, and convection. The flue gases are then expelled through a stack, as illustrated in Fig. 1.

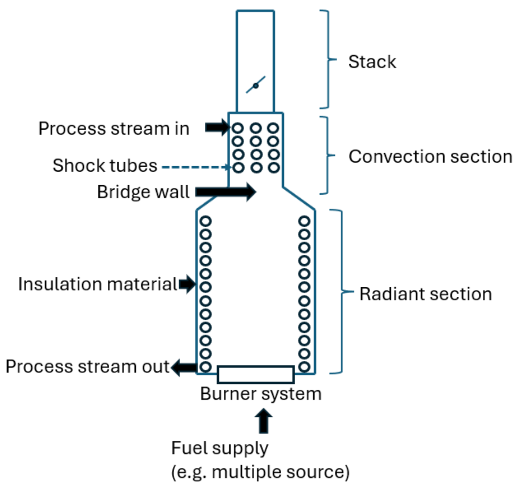

Fig. 1: Schematic of fired heater components. A natural draft fired heater is assumed in the illustration, hence, air preheaters and associated components are not shown.

The heater’s construction includes refractory lining inside the firebox casing which facilitates the heat transfer in the radiant section for the tubes

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exposed to the burners, and the convection section facilitating hot gas flow through tube bundles. Enhancements like finned tubes increase heat absorption, and corbels direct gases for improved heat transfer. A crossover connects coil sections, and a shield section protects the convection tubes from direct heat. Conditions in combustion equipment vary widely from relatively low temperatures at the stack to over 1500 °C in the radiant sections of the furnace and over 1800 °C in the flame [2]. The American Petroleum Institute sets the design rules, including choosing materials, arranging burners, and ensuring efficiency [3]. Air supply and gas removal methods—natural, forced, induced, or balanced—each uniquely impact the system's function.

Critical performance indicators for fired heaters encompass their heat utilization efficiency, radiant heat output, bridge wall temperature, and pressure drop. These factors are vital for maintaining the heater's efficiency and safety. Performance degradation occurs due to unwanted deposits on heat transfer surfaces. This manuscript introduces a methodology to monitor deposition, enabling an assessment of fouling tendencies in relation to the types of fuel used.

FOULING AND SLAGGING

Fouling, the accumulation of unwanted materials on processing equipment surfaces, is a multifaceted issue posing significant challenges in heat transfer. Evaluation of fouling in fired heaters via heat transfer modeling is a technology which the industry does not yet fully utilize. The complexity of fouling is intensified by the growing use of heavy, unconventional oil sources, deeper residue conversion, stricter environmental regulations and fuel standards, and enhanced production complexity.

Fired heater fouling problem can be seen in areas such as tube interiors [4–13], tube exteriors (radiant and convection sections) [2, 14], burners [15, 16], air preheaters [17], and selective catalytic reduction (SCR) systems [18] (Fig. 2). Fouling types typically prevalent in fired heaters include:

- Particulate fouling involves the accumulation of suspended particles from liquid or gas streams onto heat transfer surfaces, influenced by particle concentration and fluid flow velocity.
- Reaction fouling including coking occurs due to chemical reactions on heat transfer surfaces and the process fluid.
- Corrosion fouling involves the accumulation of corrosion products from the reaction of the heat transfer surface material.

Ensuring that the process-side fluid moves properly is important to avoid problems like direct flame contact or slow flow, which can hinder heat transfer and damage the heater. Coking or fouling, where carbon builds up inside tubes, can block flow and reduce heat transfer, creating safety hazards. Inside fired heater tubes, particulate, reaction, and corrosion fouling are common, with reaction fouling, particularly coking, being the most prevalent. Coking is driven by factors like temperature, residence time, velocity, and feed composition. Coking has been extensively discussed in literature, e.g., [4–13]. Heaters processing crude feeds, especially those utilizing alternative heavy feedstocks like bitumen from tar sands, are highly susceptible to such fouling.

Fouling on the exterior of tubes, known as gas-side fouling, occurs due to particles in flue gases, which range in size from sub-micron to several millimeters and vary in shape from nearly spherical to highly irregular, and in consistency from solid to molten. This variation is influenced by the type of fuel used and the design of the equipment.

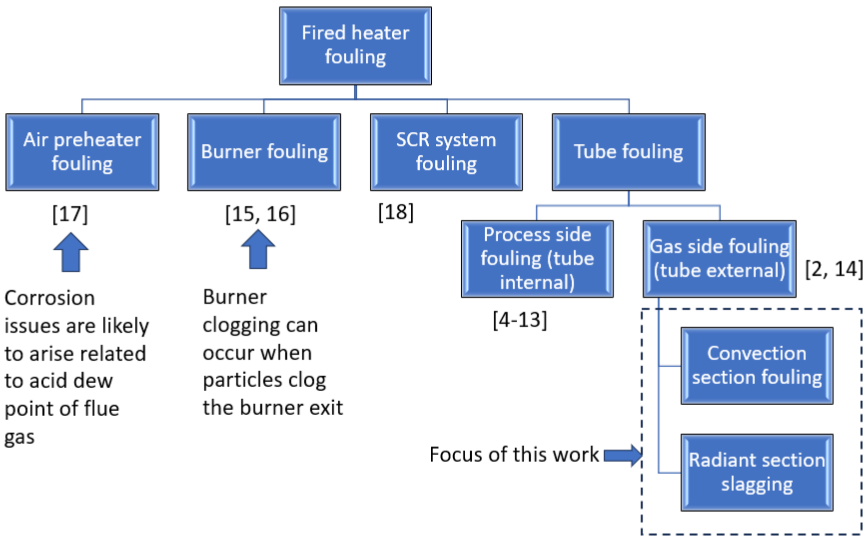

Fig. 2: Classification of fired heater fouling

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Gas-side fouling frequently affects heat exchanger surfaces across various industries, resulting from heat recovery in particle-laden gas streams that can corrode or cause reactions. Such deposit can accumulate on diverse surfaces, extending beyond heat exchangers to include transfer lines, valves, dryers, reactors, combustion areas, and stacks. The severity of these deposits is influenced by factors such as operating temperature, fluid velocity, particle size and quantity, and their chemical properties.

The cause of fuel-related fouling might be consistent or sporadic, but it typically results in reduced efficiency and increased fuel consumption. In combustion systems, persistent fouling is often linked to the fuel's quality and chemical properties, while intermittent build-up is usually due to suboptimal combustion control or incomplete fuel burning.

FUEL CLASSIFICATION

The source of fuel/energy supply to the fired heater plays a major role in gas-side fouling dynamics. An earlier fuel classification by Marner and Suitor [14] was revisited and extended in Table 1. Usage of hydrogen generated at a centralized location is an option investigated [19] and implemented by the refineries, e.g. [20], as this method allows installation of carbon capture and storage (CCS) device on one centralized location and not at each fired heater.

MODEL FORMULATION

The crude preheating system and the fired heater associated with an atmospheric distillation system was constructed because the performances of the crude preheat train and the fired heaters are interrelated.

The heat exchangers of the crude preheat train were modeled using HTRI ***Xist***® to ensure compliance with industry standards. This step was crucial for creating reliable and precise exchanger geometry files.

Having a detailed fired heater model is vital in fouling estimation analysis [21, 22]. The fired heater was modeled using ***Xfh***® *Ultra*. This software aids in simulating the complex thermal and fluid dynamics within fired heaters. The program employs two distinct but complementary approaches: the single-zone method for the firebox and a 3D incremental approach for the convection section. For the firebox, the single-zone method is utilized. This approach simplifies the complex environment of the firebox into a single, well-defined zone. It accounts for key factors such as fuel combustion, heat absorption by the walls, and the radiant heat transfer to the tubes within the firebox. In contrast, the convection section of the heater is modeled using a more intricate 3D incremental approach. This method divides the convection section into smaller, manageable segments or 'increments', allowing for a detailed analysis of the flue gas temperatures and heat transfer characteristics throughout this section. Each segment is analyzed individually, considering the specific conditions and characteristics, such as temperature gradients and heat transfer rates. By assembling these segments into a comprehensive 3D model, the program provides a detailed and accurate representation of the temperature distribution and heat transfer processes within the convection section.

Table 1: Energy sources for process fired heaters

Category	Energy source	Description
1	Fossil fuels	Subcategory 1: Gaseous fuels (hydrocarbon based)
		Subcategory 2: Light petroleum fuels
		Subcategory 3: Heavy petroleum fuels
		Subcategory 4: Coal
		Subcategory 5: Coal-derived fuels
		Subcategory 6: Tar, sand, and shale-derived fuels
		Subcategory 7: Hydrogen via selective catalyst reduction or derived from fossil fuels by other methods
2	Hydrogen	Derived from non-fossil-based source
3	Electricity	Electric heaters
4	Agricultural wastes	Saw dust, wood chips, paper pulp, bagasse, rice hulls, nut shells, fruit pits, hog fuel
5	Miscellaneous wastes	Solid wastes including plastics, refuse, waste lube oil, etc.
6	Process fuels	Gases produced by process fuels such as phosphorous, sulphur, etc.
7	Simulated fuels	Gases produced from laboratory studies
8	Aerosols	Non-reacting gases containing suspended particulate matter
9	Miscellaneous	Special cases which do not fall under any of the above

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Finally, the overall heat exchanger network was designed using HTRI SmartPM™, which integrates the ***Xist*** heat exchanger models and fired heater models onto a single digital platform. This integration connects directly to the plant data historian, effectively creating a digital twin of the system. This digital twin model, enhanced in fidelity and utility, accurately reflects real-world operations. It incorporates design sheets, mechanical drawings of the heat exchangers and fired heaters, process flow diagrams, P&IDs (Piping and Instrumentation Diagrams), and connections to the plant data historian.

The thermal resistance of the fired heater was calculated for each time step as follows:

Step 1 – Connect to the data historian: Data for fuel flow rates, fuel compositions, process stream inlet and outlet flow rates, temperatures and pressures, and bridge wall temperature are obtained from the data historian.

Step 2 – Evaluate fuel energy supply: Determine the total energy provided by all fuel sources, denoted as Q_f.

Step 3 – Assess energy received by all process streams: Calculate the energy absorbed by all process streams and other relevant entities referred to as ΣQ_s.

Step 4 – Determine heat loss: Ascertain the amount of heat lost in the system, represented as Q_{loss}.

Step 5 – Calculate furnace efficiency: Use the collected data to compute the efficiency of the furnace, η.

Step 6 – Process stream duty calculation for clean furnace: For a furnace in a clean state, calculate the duty (heat transfer) to the streams, $\Sigma Q_{s,i}$.

Step 7 – Assume average thermal resistance: Estimate an effective overall thermal resistance for both the convection ($R_{f,conv}$) and radiant ($R_{f,rad}$) sections of the furnace. The work in this manuscript utilized the commercial software tool Xfh Ultra to evaluate heat distribution within the convection and radiant sections. Several public literature sources detail the steps involved in fired heater rating calculations [30].

Step 8 - Optimize thermal resistance values: Identify the optimal values of $R_{f,conv}$ and $R_{f,rad}$ that achieves the targeted furnace efficiency while minimizing the discrepancy between the measured and calculated temperatures at the bridge wall.

CASE STUDY

Fouling and slagging in the Aspropyrgos refinery atmospheric distillation unit fired heater was analyzed using the constructed digital twin model described in the previous section. A section of the crude preheat train and the fired heater is shown in Fig. 3. The preheat train consisted of 28 individual shells and a fired heater. The fired heater consists of a shared convection section between the crude distillation unit (CDU) furnace (atmospheric furnace) and the vacuum distillation unit (VDU) furnace (vacuum furnace). The flue gas from the vacuum furnace passes through the convection section of the atmospheric furnace. Fig. 4 shows the (a) convection and (b) radiant sections of the firebox constructed in ***Xfh** Ultra*. The convection section consists of shock tubes, finned tubes, and a tube bank for convection steam. The radiant section consists of four parallel paths.

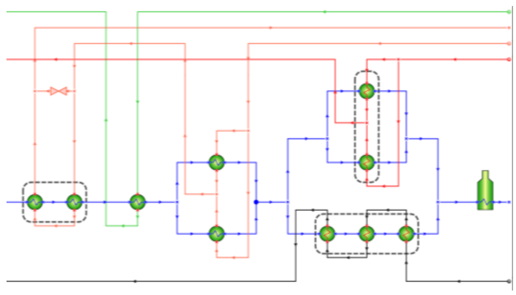

Fig. 3: Section of crude preheat train and the fired heater constructed in HTRI SmartPM platform.

(a)

(b)

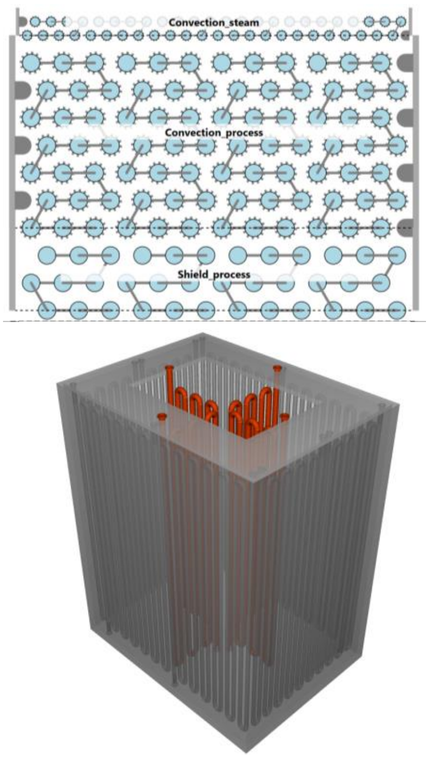

Fig. 4: Schematic of the ***Xfh** Ultra* fired heater model: (a) convection and (b) radiant section.

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The fired heater uses a combination of three different fuel sources: fuel gas, off gas, and fuel oil. Off gas stream is the overhead gas stream which contains light gaseous hydrocarbons produced in the CDU during the distillation process. This stream is by-design internally consumed in the CDU furnace along with the other fuel streams (fuel gas and fuel oil). Typically, off gas provides less than 10% of the furnace duty. This mixture is depicted in the fuel supply plot (Fig.5). In this scenario, the selection of fuel types was primarily influenced by their availability at the site. Typically, liquid fuel is considered a less favorable option due to its complex integration with combustion air. This process involves multiple stages such as atomizing, vaporizing, and mixing. Each of these steps adds potential points of failure to the operation. The chart illustrates fuel gas and off gas consumption in terms of volumetric flow rate, alongside fuel oil consumption measured in mass flow rate. The point marked as Time A indicates a notable shift where the consumption of fuel oil substantially increased, while the usage of fuel gas simultaneously decreased. The introduction and increased use of fuel oil in 350 days in operation has been identified as a significant factor affecting gas-side fouling behavior. The composition of the fuel gases, which varies depending on the source and process, has been accounted for by importing composition data from the data historian (Fig. 6).

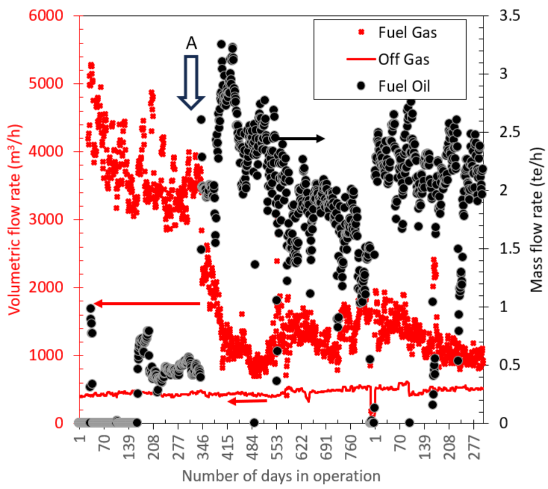

Fig. 5: Fuel usage dynamics.

By comparing the calculated and measured bridge wall temperatures (shown in Fig. 7), the effective thermal resistances of the convection and radiant sections were back-calculated. Only the radiant section thermal resistance is shown in Fig. 8. At the point of putting together this manuscript, the firebox of the VDU section was not yet connected to the data historian, meaning the convection section's analysis does not include the dynamics of the VDU section's flue gas. This study focuses on one of several fired heater digital twin models implemented, with the findings below indicative of general trends observed:

1. The introduction of fuel oil leads to a noticeable rise in the thermal resistance of the fired heater.
2. The convection section typically exhibits considerably higher thermal resistance compared to the radiant section.
3. In this particular case, cleaning the external surfaces of the tubes, followed by monitoring, revealed that deposits predominantly formed on the outside of the tubes, rather than inside. This was then tracked to the quantity of fuel oil usage. This is evident in Fig. 8 where the thermal resistance has dropped to zero following the tube external clean.
4. Post-cleaning, a marked increase in deposit accumulation is observed in the thermal resistances of the radiant section, corresponding with the ongoing usage of fuel oil.

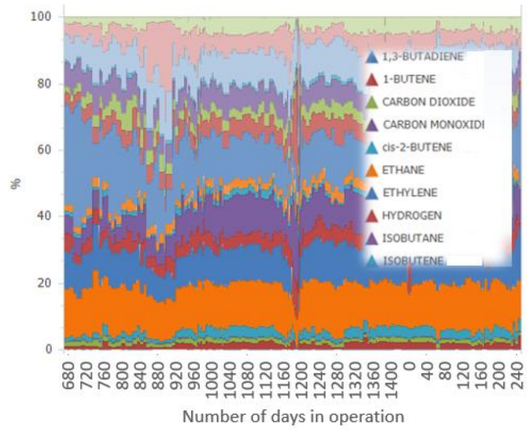

Fig. 6: Illustration of gas composition imported to SmartPM.

The mechanism of gas-side fouling formation involves multiple steps, as illustrated in Fig. 9. Various studies in the literature have explored different aspects of gas-side fouling, ranging from experimental and theoretical analyses [23–26] to computational fluid dynamics [27]. The non-linear fouling behavior observed in the dashed line (b) marked in Fig. 8 might be explained by the thermophoretic behavior discussed in Owen's work [28]. Despite a decrease in adiabatic flame temperature with the introduction of fuel oil (shown in Fig. 10), there is an increasing trend over time in the calculated temperature difference between the wall and the gas (Fig. 11). In the analysis, the maximum wall temperature is defined as the maximum peak wall temperature facing the flames. The tendency towards non-linear deposition, especially at temperature differences around 500 °C, is attributed to the changing thermal properties of the solid and gas [2].

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Additionally, monitoring the acid dew point of the flue gas exiting the convection section is crucial to prevent low-temperature corrosion in air preheaters [29]. This monitoring becomes particularly important as the introduction of fuel oil has caused an approximate 30 °C rise in the acid dew point calculated by the fired heater software. The high acid dew point value (approx. 135 °C) limits the heat recovery opportunity from the flue gas.

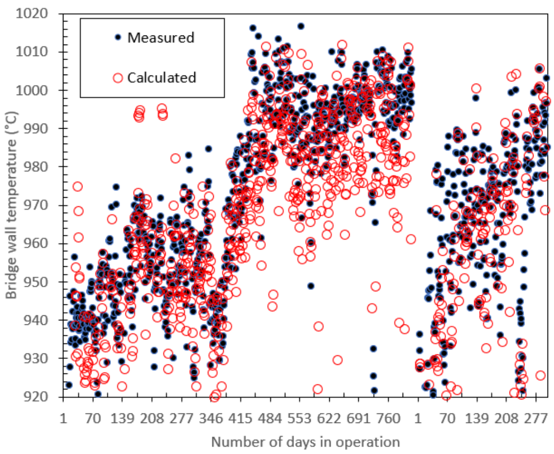

Fig. 7: Calculated and measured bridge wall temperature.

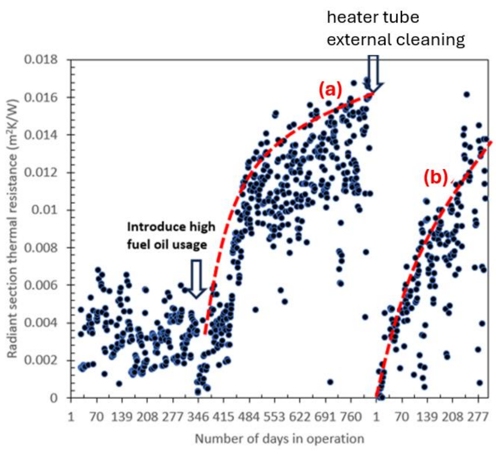

Fig. 8: Equivalent average thermal resistance of the radiant section. Dashed lines (a) and (b) indicate visual trend on the resistance increase.

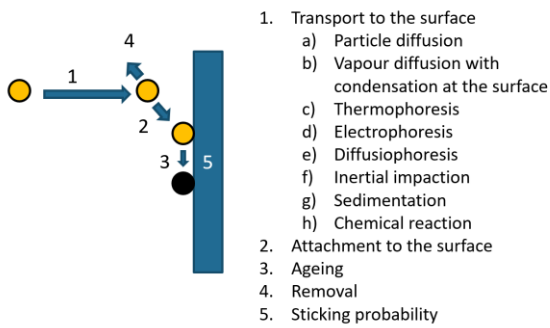

Fig. 9: Example of possible gas-side fouling mechanisms.

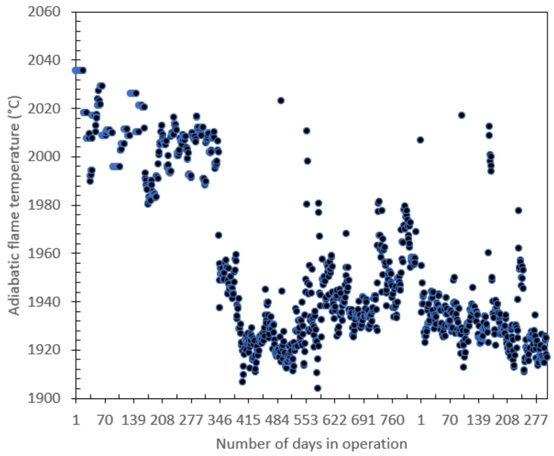

Fig. 10: Calculated adiabatic flame temperature.

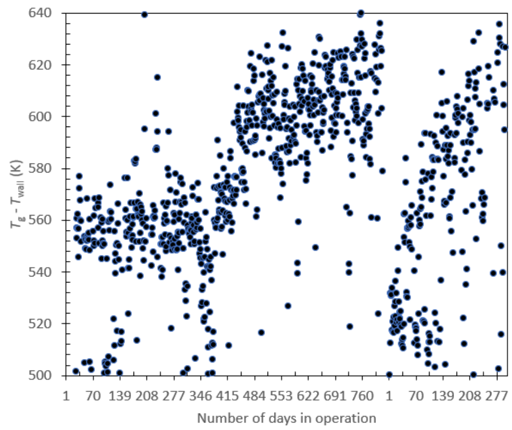

Fig. 11: Calculated difference between the firebox gas temperature, T_g, and the maximum radiant section wall temperature, T_{wall}.

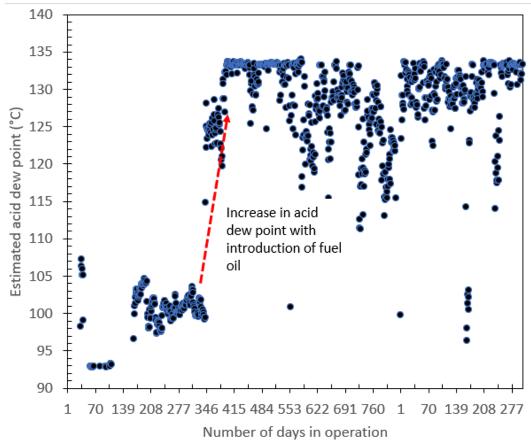

Fig. 12: Estimated acid dew point of flue gas leaving the convection section.

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FOULING MITIGATION VIA DIGITAL EXPERIMENT

Currently, at the refinery taken for this case study, on-line cleaning via soot blowing is performed in these furnaces but has effect only on the convection section. The monitoring of furnace fouling through the Xfh Ultra tool is enabling the refinery to identify where the fouling is located (radiant/convection section) and consider possible offline cleaning when furnace is bottlenecking the unit. For future endeavors, with the development of the digital twin model, we can now conduct various 'what if' analyses, including examining the impact of switching to a 100% hydrogen fuel source. After the plant's shutdown and cleaning, we compared the current fuel usage (corresponding to day 70 following the last shutdown in Figure 5) with a hypothetical switch to hydrogen fuel. While switching to hydrogen, known for its clean-burning properties, could eliminate fouling/slagging issues on the gas side, the implications of such a switch are detailed in Table 2. Key findings include the following:

1. An increase in fuel volumetric flow rate suggests a need for investment in capital infrastructure, particularly in the piping system, to support the fuel supply.

2. A change in the Wobbe index of over 5% necessitates investing in new burners to maintain consistent heat supply.

3. The higher adiabatic flame temperature associated with hydrogen fuel could lead to increased thermal NO_x emissions unless offset by effective emission control technologies.

4. Elimination of gas-side fouling and reductions in CO_2 and SO_2 emissions (shifted to the centralized hydrogen generation source) are expected. However, the increased flame temperature from hydrogen fuel might result in higher heat flux and tubeside wall temperatures in the radiant section (see Fig. 13), warranting an investigation into the potential for tubeside fouling under these conditions.

Figure 13 presents data comparing clean states on (a) the maximum heat flux across tubes 1 to 60, (b) the peak internal wall temperatures for tubes 1 to 53, and (c) the peak internal wall temperatures for tubes 54 to 60, which are centrally located in the radiant section of the heater. The centrally located tubes experience the biggest impact in this example with the change in fuel mix due to significantly higher flame temperature. There is an approximately 5 C increase in the peak wall temperature in this section and the possible impact on coking with this increase now needs to be evaluated. As a visual guide for the operational profile, the convection section tubes are numbered from 1-30, and the radiant section tube numbering starts from 31 onwards (in Fig. 13).

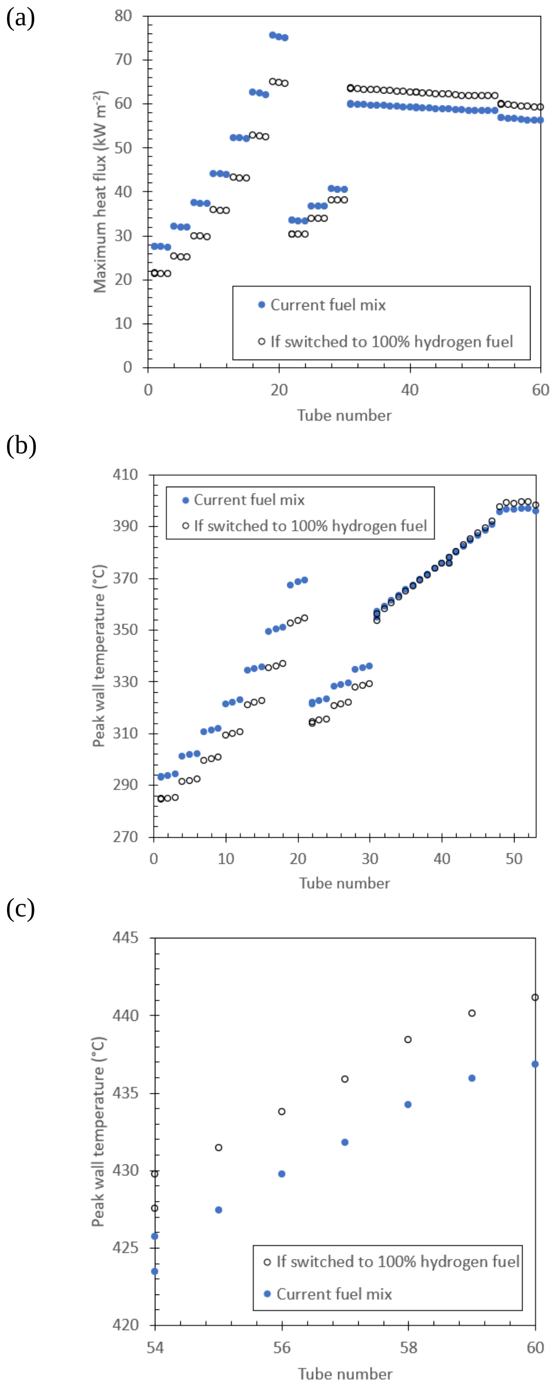

Fig. 13: Comparative analysis of operational performance on the tubeside of a fired heater utilizing two fuel scenarios: the existing fuel mix (denoted by filled circles) and a hypothetical switch to 100% hydrogen (denoted by hollow circles). The convection section includes tubes 1-30, while the radiant section includes tubes 31 and higher.

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Table 2: Comparison of current fired heater operation and if switched to 100% hydrogen usage

Parameter	Current fuel mix	If switching to 100% hydrogen is assumed
Average volumetric flow rate (Nm^3/s)	0.53	4.2
Wobbe index (MJ/Nm^3)	53.34	48.42
Adiabatic flame temperature (°C)	1931.1	2129.5
Average heat flux		
Radiant section (kW/m^2)	58.5	61.9
Convection section (kW/m^2)	43.3	36.8
LHV (kJ/kg)	42,640	120,000
CO_2 emission, te/day	296.8	0
SO_2 emission, te/day	1.131	0
NO_x emission estimate (no control)	N/A	38 ppmv
NO_x emission estimate (with control)	10 ppmv	13 ppmv
Gas-side fouling	Observed	Not expected (unless contaminants enter through excess air)
Process-side fouling	Not observed	Possible in radiant section due to increased heat flux and wall temperature

CONCLUSION

A methodology using a digital twin model was developed to track fouling in fired heaters. This approach utilized existing monitoring data, including fuel flow rates, composition, process stream data, and bridge wall temperature, and employed a combination of commercial software tools: HTRI SmartPM, ***Xist***, and ***Xfh** Ultra*. The model effectively detected fouling and slagging in the radiant section, a problem that arose with the switch to fuel oil. While the thermal resistance data from the convection section was not included for this manuscript, it displayed thermal resistance significantly higher (order of magnitude) than that of the radiant section.

Additionally, a 'what-if' scenario analysis using this digital model was performed to evaluate the impact of transitioning to hydrogen as a fuel source. The analysis suggested a potential reduction in emissions but also underscored the necessity for NO_x emission control technologies in the combustion system. It also raised concerns about possible internal tube fouling (coking) in the radiant section's central tubes due to higher heat flux and increased tube-side wall temperatures.

NOMENCLATURE

Q_f Duty supplied by fuel, MW
Q_{loss} Energy lost to environment, MW
Q_s Energy absorbed by the streams, MW
$R_{f,conv}$ Convection section resistance, $m^2K\ W^{-1}$
$R_{f,rad}$ Radiant section thermal resistance, $m^2K\ W^{-1}$
T_g Gas temperature, °C
T_{wall} Wall temperature, °C
η furnace efficiency

Subscript
i i^{th} process stream

Acronyms
CDU Crude Distillation Unit
VDU Vacuum Distillation Unit

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