Tube Fouling and the Effects on Waste Heat Boiler Tube Wall Temperature[1]

Matthew D. Bailey, MBA
Optimized Gas Treating, Inc.
12337 Jones Rd. Suite 432
Houston, TX 77070
+1 281-970-2700
matt.bailey@ogtrt.com

Steven M. Fulk, PhD, Clayton E. Jones, MS, P.E., G. Simon A. Weiland
Optimized Gas Treating, Inc.
Technical Development Center
119 Cimarron Park Loop, Suite A
Buda, TX 78610
+1 512-312-9424
steven.fulk@ogtrt.com,
clay.jones@ogtrt.com, simon.weiland@ogtrt.com

ABSTRACT

Tube to tube-sheet failures in waste heat boilers (WHB's) have been well documented as a significant cost factor and reliability weak point in Sulphur Recovery Units (SRU's). Recombination reactions in the front section of the WHB greatly increase the heat flux near the critical tube to tube-sheet welds. Tube wall temperatures above 600°F allow high temperature sulfidic corrosion and cause failure in a short period of time.

An important factor influencing tube wall temperature is fouling. When boiler feed water is poorly treated, external fouling on the steam generation side of the tubes causes increased tube wall temperature from scale that insulates the cooler steam side from the hot tube wall. On the other hand, internal tube fouling in a WHB keeps the tube wall cooler by insulating it from the hot process gas. This paper uses a state-of-the-art SRU simulator to show how the tube wall temperature can exceed 600°F under some fouling scenarios and the resulting sulfidic corrosion impact on tube life and life cycle cost.

I. Introduction

The Waste Heat Boiler (WHB) is the most fragile piece of equipment in the SRU due to the heat produced in the reaction furnace and the corrosive environment it is exposed to. Several complicated processes are happening very quickly at the tube entrance including heat transfer by radiation and exothermic vapor phase chemical reactions. Under some circumstances, these mechanisms can

[1] Laurence Reid Gas Conditioning Conference, Norman, OK, February, 2018

increase heat flux to the point that peak tube wall temperatures can exceed 600°F which causes accelerated sulfidic corrosion on the tubes of the WHB. This corrosion can be critical because down time from corrosion failures can cause the plant to limit capacity or even shut down, costing the operator money. To protect this equipment from the harsh process conditions, ceramic ferules are installed at the tube to tube-sheet joints. This work will take a look at how process side and utility side fouling affect the tube wall temperature past these ferules using the state of the art rate-based simulator, ProTreat®.

Figure 1. Waste Heat Boiler (courtesy Schmidtsche Schack , Dusseldorf)

II. Important Parameters in WHB

Ceramic ferules are designed to protect the tube to tube-sheet welds in the front of the WHB. The designs of these inserts can be seen in Figure 2 and Figure 3.

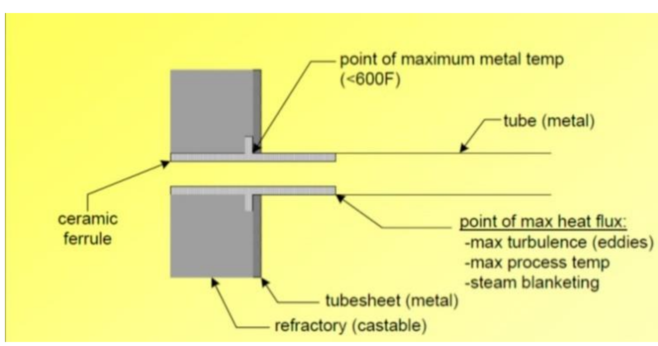

Figure 2. Thermal Protection by Ceramic Ferules

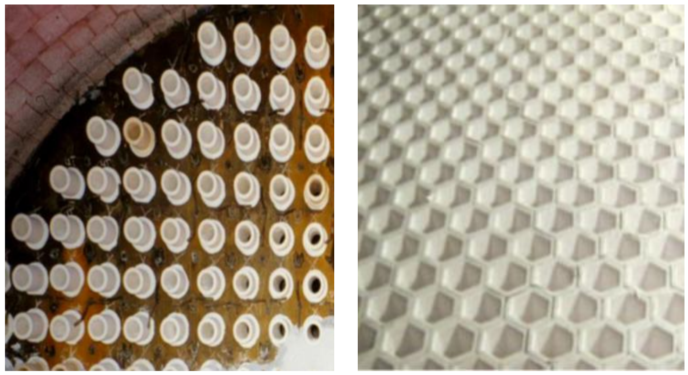

Figure 3. Types of installed Ceramic Ferules

Ferules and refractory are used to protect the tube-sheet and tubes from excessive temperature. Sulfidic corrosion can become significant when the carbon steel material is exposed to temperatures higher than 600°F in a corrosive environment. Figure 4 is a picture of sulfidic corrosion damage in a WHB.

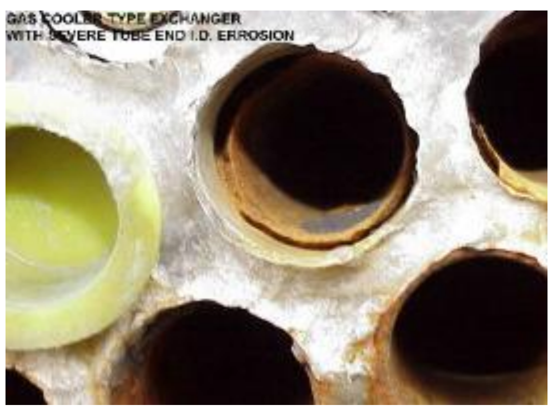

Figure 4. Sulfidic Corrosion at the Tube to Tube-Sheet Weld of a WHB

The main goal of the WHB is to reduce the high temperatures from the reaction furnace and generate steam. The WHB tubes are exposed to high temperature due to the hot process gas, but other effects exacerbate the high temperatures. The tube temperatures are amplified by the heat produced by the recombination reactions that occur in the front part of the boiler tubes as seen in equations (1) and (2). Heat is also generated by the Sulphur speciation shift as shown in equations (3) and (4).

$$H_2 + \frac{1}{2} S_2 \rightleftharpoons H_2S + \text{Heat} \quad (1)$$

$$CO + \frac{1}{2} S_2 \rightleftharpoons COS + \text{Heat} \quad (2)$$
$$3\ S_2 \rightleftharpoons S_6 + \text{Heat} \quad (3)$$
$$4\ S_2 \rightleftharpoons S_8 + \text{Heat} \quad (4)$$

These reactions are exothermic and typically occur at temperatures between 1500°F – 800°F. The recombination reactions (1) and (2) are usually kinetically limited due to the rapid cooling of the process gas. In other words, reactions (1) and (2) do not typically have time to reach equilibrium before the reaction rate stops due to decreasing gas temperature.

In the past, general simulators have taken three basic approaches in modeling these reactions:

1. Ignore local recombination kinetics and assume the reaction furnace is at equilibrium.
2. Empirically lump these reactions into the *reaction furnace* effluent. This approach gives a WHB inlet temperature that is too hot and exaggerates the true driving force available for heat transfer in the WHB.
3. Freeze the reactions by assuming they reach equilibrium at an empirically chosen quench temperature.

These techniques are conservative at best. With the use of a fully rate-based model, ProTreat®, we can take a more detailed look at how these reactions affect the tube wall temperature throughout the WHB and how fouling alters these results.

Predicting WHB tube wall temperature is a critical part of the design because corrosion rate – and therefore service life – is directly impacted by higher temperature.

III. Effects of Internal Fouling in WHB tubes

Fouling is defined as the accumulation and formation of unwanted materials on the surfaces of process equipment. In this case study, we will look at the fouling within the tubes of a WHB. Process side fouling can come from various sources including corrosion products and particulates such as soot formed in the reaction furnace. We will look at three cases of internal fouling with no external fouling present. Typical design values of the internal fouling resistance vary from 0.002 hr-ft^2-°F/BTU to 0.004 hr-ft^2-°F/BTU depending on who performs the design. We will also look at an extreme case of 0.005 hr-ft^2-°F/BTU.

Case Study: 3-Bed Claus System with O_2 Enrichment and a Tail Gas Unit (TGU)

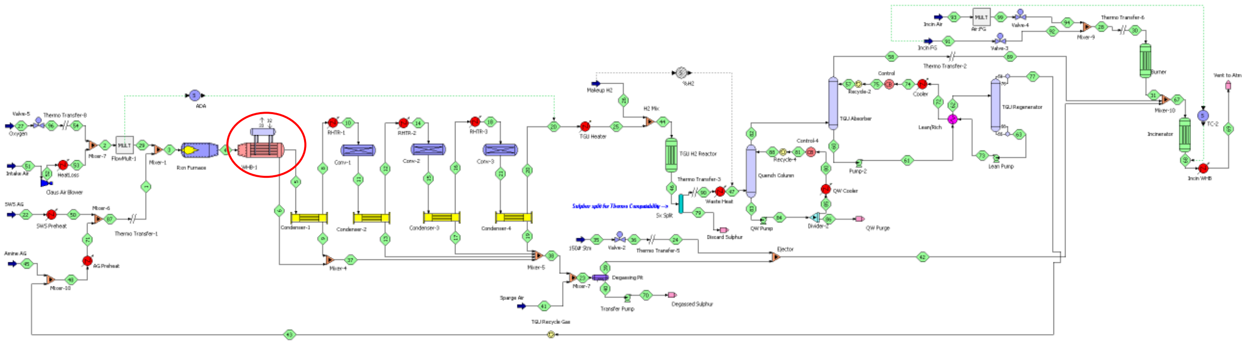

Figure 5. Flowsheet for WHB fouling study

Number of Tubes	211
Tube OD/ID, inches	2.25 / 2
Tube length, feet	44
Steam generation pressure, psig	630
BFW temperature, °F	489
Inside tube wall emissivity	0.9
Steam side HTC, Btu/hr-ft^2-°F	1000

Table 1. WHB Configuration & Parameters

	Case 1 (Base Case)	Case 2	Case 3	Case 4
Internal Fouling Resistance (hr-ft^2-°F/BTU)	**0**	**0.002**	**0.004**	**0.005**
WHB Process Gas Temp. Out (°F)	518	521	523	524
Max Tube Wall Temp (°F)	538	536	534	533
Max Heat Flux (BTU/h- ft^2)	43,100	41,500	39,900	39,300
COS in Tail Gas (ppmv, wet)	641	650	657	661

Table 2. Results from Internal Tube Fouling of a WHB

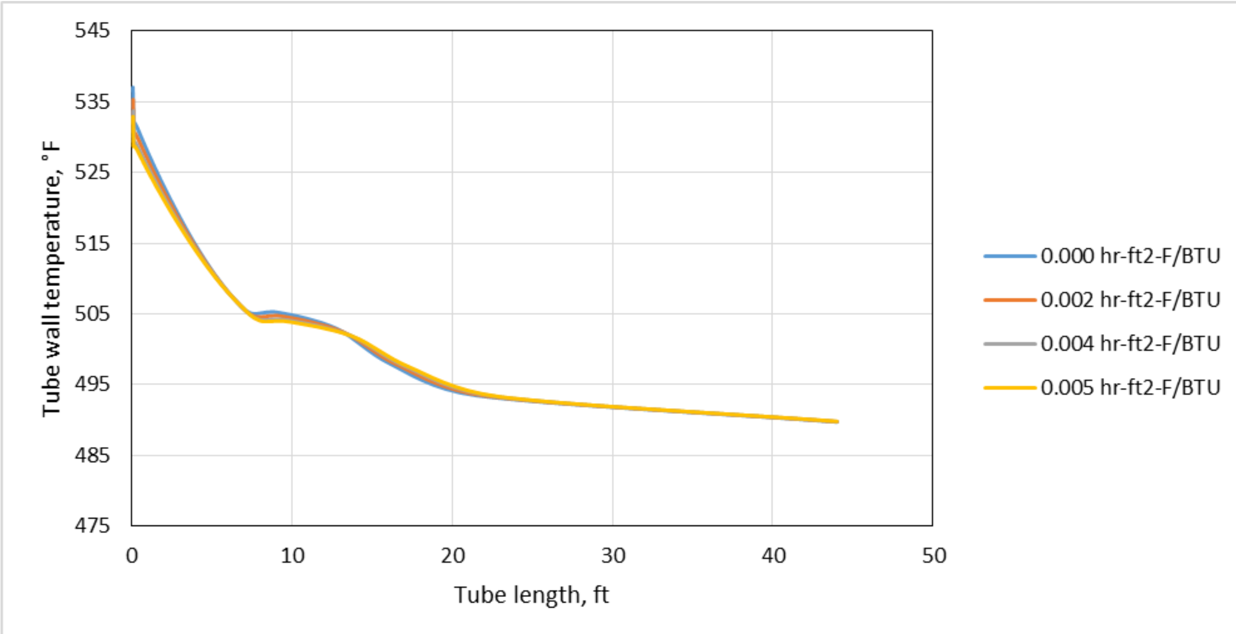

Figure 6. Tube Wall Temperature as a Function of Length for Different Internal Tube Fouling

Figure 6 shows a small "hump" around 505°F. This is from the Sulphur species shifting from all S_2 to more S_6 and S_8 as seen in equations (3) and (4) above.

As seen from the tables and plots from the rate-based simulation in ProTreat®, an increase of the internal fouling resistance on the inside of the tubes *decreases* the maximum tube wall temperature. The internal fouling acts as thermal insulation, protecting the tubes from the higher temperature of the process side. This may reduce the corrosion rate from the sulfidic corrosion mechanism; however, a large amount of internal fouling will cause plugging in the tubes, increasing hydraulic resistance and ultimately making the tubes useless.

IV. Effects of External Fouling on WHB tubes

The main source of fouling on the WHB steam side is scaling from untreated boiler feed water and improper blowdown practices. Dissolved solids from the water form layers on the outside of the tubes. Operators try to mitigate this problem using three main techniques:

1. Have a small continuous bleed on the bottom shell of the WHB
2. Perform a high-flow intermittent blowdown from the mud drum
3. Chemically rinse the tubes during turnarounds and shutdowns

If these techniques are not performed adequately, excessive scaling will occur on the steam side. We will now look at the same Case Study, this time using three common design values of external fouling resistances: 0 hr-ft^2-°F/BTU, 0.001 hr-ft^2-°F/BTU, and 0.0005 hr-ft^2-°F/BTU. To investigate further, we will also look at the extreme case of an external fouling resistance of 0.005 hr-ft^2-°F/BTU. We ignored any internal fouling while analyzing the three cases of external fouling.

	Case 1 (Base Case)	Case 2	Case 3	Case 4
External Fouling Factor (hr-ft^2-°F/BTU)	**0**	**0.0005**	**0.001**	**0.005**
WHB Process Gas Temp. Out (°F)	518	519	519	524
Max Tube Wall Temp (°F)	538	554	570	692
Max Heat Flux (BTU/h-ft^2)	43,100	42,800	42,500	39,600
COS in Tail Gas (ppmv, wet)	641	643	645	658

Table 3. Results from External Tube Fouling of a WHB

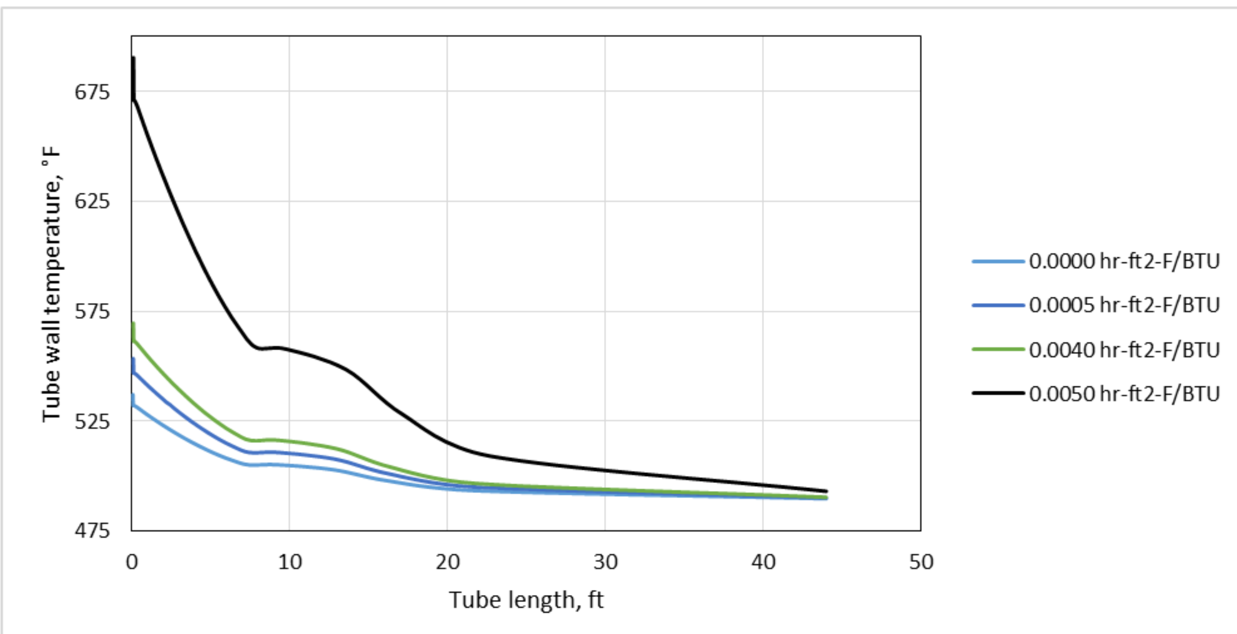

Figure 7. Tube Wall Temperature as a Function of Length for Different External Tube Fouling

From Table 3 and Figure 7, an increase of external fouling on the tubes creates a greater wall temperature throughout the WHB. Scaling acts as an insulation barrier between the tube and cooling medium, increasing the temperature of the wall. The tube wall has a reduced amount of direct contact with the boiler feed water to cool down the tubes.

It is clear from Figures 6 and 7 that fouling on the outside of WHB tubes has a much more dramatic impact on the tube wall temperature, and therefore on the sulphidic corrosion rate.

V. Higher Mass Velocity

WHB tubes are typically designed to operate with process-side mass velocity in the range of 2 to 5 lb/ft^2-s. The fouling cases studied so far were operating at mass velocity of 2.5 lb/ft^2-hr. We will now study the effect of mass velocity on tube wall temperature by using the base case simulation (no fouling on inside or outside of tubes) and varying the tube count to achieve mass velocities of 2 (low velocity) and 5 (high velocity) on the worst case of external fouling, 0.005 hr-ft^2-°F/BTU. The wall temperature profiles for these three scenarios can be seen below:

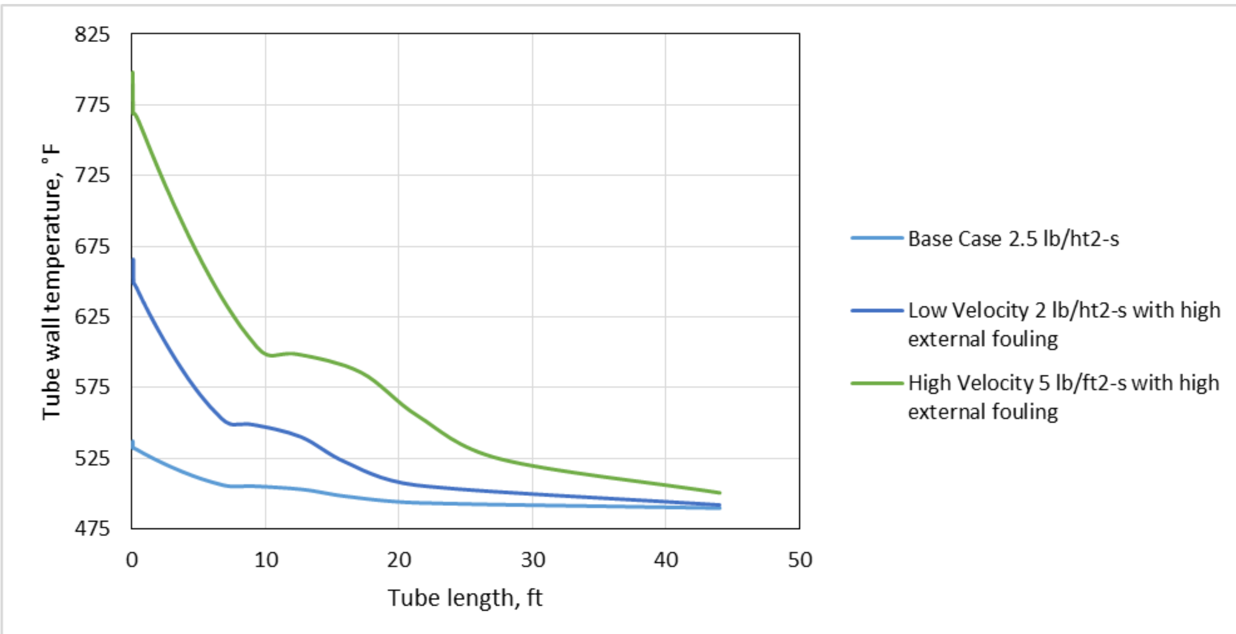

Figure 8. Tube Wall Temperature as a Function of Tube Length for Different Mass Velocities

From the plot above, a higher mass velocity, 5 lb/ft^2-s, and higher external fouling, 0.005 hr-ft^2-°F/BTU, produce higher wall temperatures; and, therefore, increase corrosion rates through the front end of the WHB.

VI. Economics

WHB design is a balancing act between competing economic factors. A more robust design will cost more capital up front, but it will carry a lower risk of unexpected downtimes during the planned operating life of the equipment. Unplanned Sulphur plant outages are very expensive since they typically require a reduction in throughput of the plant. Striking the best balance for a design requires quantitative knowledge of what impacts will follow from design decisions such as WHB Tube ID and Tube Count.

VII. Conclusions

Once a Sulphur plant is built and started up, the operator is “flying blind” with respect to WHB tube wall temperature. There’s no way to directly monitor this important parameter on line. Nonetheless, WHB tube wall temperature – and the associated sulfidic corrosion rate – have the potential to cause major operational upsets which can lead to lost capacity and lost operating income. Special care must be given to the design of the WHB to ensure that the equipment can reasonably be expected to perform to its intended capacity and life span, even in the face of variations in feed rate and reasonable allowances for fouling.

Fouling on either side of the WHB tubes is problematic for both operators and designers. WHB tube wall temperature is especially sensitive to external fouling on the boiler feed water side which inhibits the tube from seeing the full cooling effect of the boiling water. Using a rate based simulator, ProTreat®, provides real results by taking into account complex factors including radiation heat transfer and the kinetically-limited recombination reactions at the front end of the WHB. As an engineer, you should settle for nothing less.

REFERENCES

1. Awad, Mostafa M., “Fouling of Heat Transfer Surfaces”, Heat Transfer – Theoretical Analysis, Experimental Investigations and Industrial Systems. pp 505 – 542.

2. Hatcher, Nathan A., Jones, Clayton E., Weiland, Simon A., Fulk, Steven M., Bailey, Matthew D., “New Insights with Rate-Based Claus Waste Heat Boiler Modeling,” Brimstone Vail Conference 2017.

3. Hatcher, Nathan A., Jones, Clayton E., Weiland, Simon A., Fulk, Steven M., Bailey, Matthew D., “Claus Waste Heat Boiler Economics – Pay Me Now or Pay Me Later?,” Sulphur 2017 Conference.