34th
Oil | Gas | Fertilizers | Metallurgy | Industrial
CRU Sulphur 2018
+ Sulphuric Acid
International Conference & Exhibition

Factors Affecting Claus Waste Heat Boiler Design and Operation

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The Claus Waste Heat Boiler (WHB) is a critical piece of equipment in a Sulphur Recovery Unit (SRU); its fundamental purpose is as a heat transfer device used in energy recovery. Sulphur plant operators have recently been experiencing higher than normal WHB failure rates, perhaps from oxygen enrichment and pushing rates. The WHB has become the weak link in the SRU; consequently, increased attention is now being given to its design and operation. New performance standards are being considered to limit the mass flux of future designs; however, this may be an unwarranted oversimplification.

In this work, we demonstrate that although mass flux is certainly a parameter for design consideration, there are a host of additional factors particularly on the water side also having vital consequence. In some cases, limiting mass flux may lead to other unintended complications. Unless the boiler is treated as a heat transfer device with simultaneous chemical reactions and radiation, these complications may go unnoticed. Several important parameters beyond mass flux are evaluated and shown to have notable effects on WHB economics, reliability, safety, and on overall Claus unit performance.

SULPHUR PLANT WHB BACKGROUND

Sulphur recovery units essentially generate two products, sulphur and steam. In many cases the steam is more valuable than the sulphur. Steam is generated by recovering the significant amount of energy generated by the Claus process in both the thermal and catalytic stages. WHB High Pressure (HP) steam is typically generated at a pressure of 31 to 45 barg (450 to 650 psig) in the WHB downstream of the Claus Reaction Furnace. Low Pressure (LP) steam is usually produced around 3.5 barg (50 psig) in the condensers downstream of the catalytic converters. The HP steam is a valuable utility that is generated in the WHB that can be utilized for SRU catalytic indirect reheat, feed stream preheat and to drive a turbine on the combustion air blower. In most applications, the SRU is a net exporter of steam and the HP and LP steam generated in an SRU are utilized outside the SRU, e.g. LP heat source for amine reboiler, sour water stripper reboiler, steam tracing etc. or HP to spin a turbine.

In the past, the WHB more often generated low pressure steam. Many modern designs generate much higher pressure steam, thus presenting mechanical design and operating challenges. It is recommended that the design of SRUs, and in particular the WHB, be done by experienced sulfur technology licensors and EPC contractors with proper design expertise.

Modern WHB designs of the last 20 years are typically designed as follows:

- Pressure range: 31 to 45 barg (450 to 650 psig)
- Steam temperature: 236 to 258°C (457 to 496°F).

Excessive temperature, rapid process temperature changes and thermal cycling associated with start-ups and shutdowns affect the reliability of the WHB by degrading the tube sheet system (refractory/ferrules/tube sheet/tube-to-tube sheet joint/tubes). Thermal cycling is detrimental to the WHB tube sheet system longevity and reliability. Industry experience indicates that the Reaction Furnace/WHB could have a thermal-cycle life expectancy (a limited number of cycles) of as long as 20 years, in well-designed, operated and maintained systems, and as short as two to three years for inadequately designed, poorly operated and maintained systems. Damage to the tube sheet protection system due to poor operation results in unscheduled outages and impacts SRU reliability.

HEAT EXCHANGER FUNDAMENTALS

The heat exchanger design principles are based on the following requirements:

1. Heat transfer requirements (surface area),
2. Cost,
3. Physical size,
4. Pressure drop allowance.

In the process industry many heat exchangers are purchased as off-the shelf items and the selection is made on the basis of cost and specifications furnished by the various manufacturers. The Sulphur Recovery Unit WHB using water as the cooling medium is a more specialized application.

For the WHB, there are several factors particularly on the water side that are of vital importance. It has been well documented (reference 1, 2, 3) that the following design and operations considerations need to be addressed during the design development and operation of the WHB to provide the most robust design that can handle the desired longer operating runs:

- WHB tube diameter.
- WHB tube pitch.
- WHB tube wall thickness.

- Tubesheet thickness.
- Materials of Construction.
- Welding techniques for the tube-to-tubesheet welds.
- Kettle versus Thermosiphon design considerations.
- Ferrule design/installation considerations.
- Blowdown design/operating practices.
- Proper operator and maintenance personnel training.

WHB FAILURE MECHANISMS

There are a multitude of design options (tube ID and tube length) to satisfy the design principles listed above, but experienced designers understand that two primary considerations must be met for a reliable design; a maximum metal temperature and a maximum heat flux through the tube wall.

A recent industry survey of Waste Heat Boiler design and operation in existing SRUs was performed to explore the determining factors in good WHB design and operation practices (reference 4). This survey has indicated that neither **mass flux nor tube diameter** is an indicator of risk of failure. The survey confirms that the failure mechanisms can be attributed to a combination of factors which may be design or operation related.

Maximum Metal Temperature – High temperature sulfidation corrosion becomes increasingly significant at temperatures above 343 °C (650 °F). Therefore, a successful WHB design will have design conditions predicted to be well below this temperature. This takes into account such design features as tube sheet thickness and water side considerations for adequate distribution of boiler feed water and adequate removal for generated steam.

Image 1. Failure in the Waste Heat Boiler due to overheated tubes

Maximum Heat Flux – Heat flux is determined by the radiant contribution plus tube side (process gas) convective heat transfer coefficient, tube wall conductance and water side heat transfer coefficient. The primary variable driving heat flux is the process-to-water temperature difference, which varies by a factor of ten over the length of the tube. The radiation component can add approximately 20% to heat flux but is of no real significance below approximately 538°C (1,000°F). In the areas where failures are more prevalent (front-end), radiative heat transfer cannot be ignored or the heat flux will be under-predicted.

Image 2. Loss of WHB water level; tubes melted into a pile in the bottom of exchanger.

Avoiding conditions of steam blanketing on the boiler tubes is important. The heat flux rates over the entire tube length of the WHB should be evaluated, especially the turbulent entrance area near the end of the ferrule. The heat flux should not exceed 50% of maximum nucleate flux at design, and 65% for maximum service conditions. These limits will keep the tube wall within 10˚C (18°F) of the water boiling temperature at design, well below the 40˚C (72°F) break-over to Leidenfrost film boiling, which occurs when the critical maximum nucleate flux is exceeded. The in-service, fouled condition will be a substantially lower heat flux than maximum clean condition although tube wall metal temperatures are substantial higher.

A further complication results from a recirculation region that exists downstream from the ferrule. The turbulence introduced into the flow in this region enhances heat transfer at this location, in the form of eddy effects. In extreme cases this enhanced heat transfer leads to heat fluxes that cannot be successfully transferred to the WHB's water, leading to the phenomenon known as departure from nucleate boiling.

Emphasis should be placed on the importance of proper design of the boiler feed water, steam and intermittent blowdown connections. It is imperative that the correct amount of boiler feed water is directed to the critical inlet tube sheet location, and a boiler feed water distributor may be beneficial in ensuring that the colder water is properly distributed throughout the boiler.

Image 3. Failure to implement intermittent blowdown, tubes fouled.

WHB failure cause and effect analysis is a method leading to the listing of all possible reasons and outcomes associated with the failure looking at the entire WHB system and not just the process parameters through just one WHB tube. It is a process directed at uncovering possible or probable causal factors and their manifestation. The process identifies how they are linked, but does not necessarily lead to the root cause, or the removal of the reason to stop the recurrence of the problem. Focusing exclusively on mass flux will most likely lead to false conclusions. Data and advanced analytics produce unexpected correlations, and separating the real opportunity from the spurious tease is essential.

STUDY BASIS

To illustrate how many design parameters are inter-twined and connected, a series of case studies were conducted using the kinetic and heat transfer rate-based simulator, SulphurPro™. In each scenario, the starting point for design was considered to be a sound, optimized design. Modifications were made away from this "solid design point" to quantitate the impacts to the boiler heat transfer performance and reliability.

The basis for the initial base case design was a two stage Claus unit processing both Amine Acid Gas (AAG) and Sour Water Acid Gas (SWAG) at a rate of 125 LTPD Sulphur Feed as shown in Figure 1. The WHB was assumed to be a Kettle Style producing 41 barg (600 psig) saturated steam with a design outlet temperature of 600°F (316°C) tube side pressure drop of 0.028 bar (0.4 psi) and an allowable steam side pressure drop of 0.34 bar (5 psi) The tubes were set at 63.5 millimeter (2 ½ inch) 10 BWG and a mass flux of 14.6 $kg/(s \cdot m^2)$ [3 $lb/(s \cdot ft^2)$]. The utility side fouling factor and process side fouling factor were assumed to be 0.0005 $m^2 \cdot K/W$ (0.003 $(hr \cdot ft^2 \cdot °F)/Btu$) and 0.00009 $m^2 \cdot K/W$ (0.0005 $(hr \cdot ft^2 \cdot °F)/Btu$) respectively. The results and concepts also apply to a Thermosiphon Type WHB. To gain an understanding into how the design variation affect economics, the nominal WHB cost was assumed to be 100 for a properly designed boiler, per typical industry Best Design Practice.

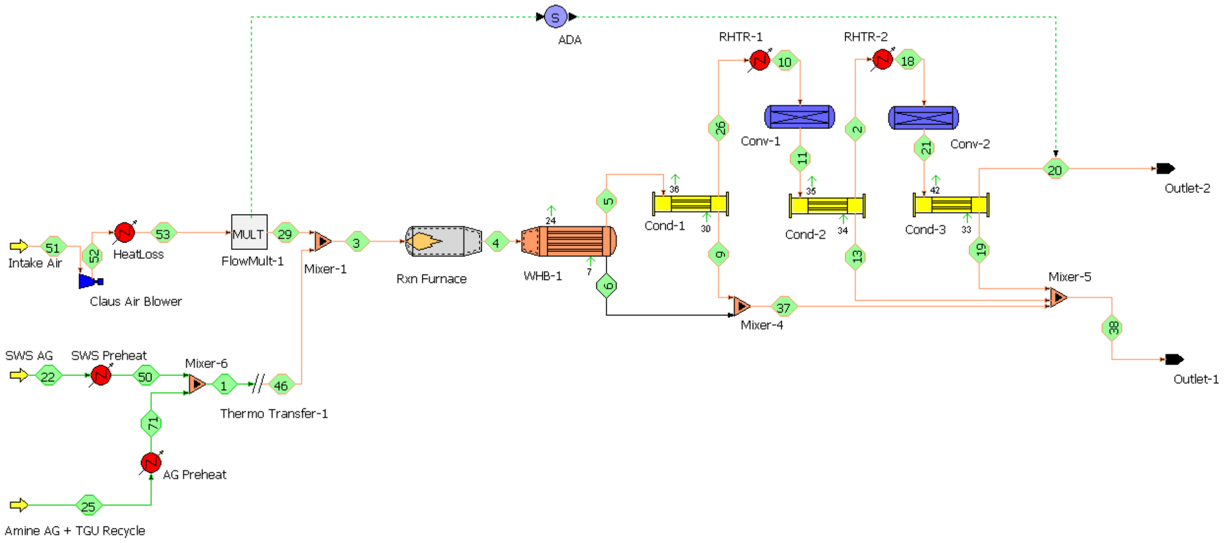

Figure 1. PFD of Claus Unit used for Study.

To emphasize the importance of the water side and the impact on reliability, cost, and physical size, this paper will focus on manipulating the tube ligament (space between tubes), tube length, and water side heat transfer performance parameters while measuring the calculated duty, process gas outlet temperature, peak tube wall temperature, overall heat flux, peak heat flux, shell diameter, tube length, and relative cost for each variation.

STUDY RESULTS

The results from the case study of tube ligament spacing and tube length are tabulated in Tables 1 and 2. Table 1 shows the Base Case variation results for mass flux of 14.6 kg/(s·m^2) [3.0 lb/(s·ft^2)]. Table 2 shows the impact of lowering the mass flux 7.3 kg/(s·m^2) [1.5 lb/(s·ft^2)] while holding all other variables constant.

Table 1a. Study Results with Mass Flux set to 14.6 kg/(s·m^2) [3 lb/(s·ft^2)] in Metric Units

	ΔP through Tube Bundle (bar)	WHB Gas Outlet T (°C)	Peak Tube Wall T (°C)	Sulfidic Corrosion (mils/y)	Overall Heat Flux (W/m^2)	Peak Heat Flux (W/m^2)	Calc. Duty (MW)	Shell ID (m)	Tube Length (m)	Relative Cost
Tube Ligament										
31.75mm	0.014	316	283	2.2	-31,868	-105,994	-8.3	1.3	10.4	100
6.35mm	0.015	362	500	99.5	-30,877	-73,502	-8.06	0.97	10.4	69.2
50.8mm	0.014	316	283	2.2	-31,868	-105,994	-8.3	1.6	10.4	124.5
Tube Length										
10.4m	0.014	316	283	2.2	-30,880	-105,994	-8.3	1.3	10.4	100
1.8m	0.006	850	283	2.2	-77,716	-105,994	-3.6	1.3	1.8	33.4
18.3m	0.02	264	283	2.2	-18,868	-105,994	-8.6	1.3	18.3	143.1

Table 1b. Study Results with Mass Flux set to 14.6 kg/(s·m^2) [3 lb/(s·ft^2)] in U.S. General Units

	ΔP through Tube Bundle (psi))	WHB Gas Outlet T (°F)	Peak Tube Wall T (°F)	Sulfidic Corrosion (mils/y)	Overall Heat Flux (Btu/(hr·ft^2))	Peak Heat Flux (Btu/(hr·ft^2))	Calc. Duty (MMBtu/hr)	Shell ID (feet)	Tube Length (feet)	Relative Cost
Tube Ligament										
1.25”	**0.21**	**600**	**541**	**2.2**	**-10,106**	**-33,600**	**-28.3**	**4.3**	**34**	**100**
0.25”	**0.22**	**684**	**931**	**99.5**	**-9,788**	**-23,300**	**-27.5**	**3.2**	**34**	**69.2**
2”	**0.21**	**600**	**541**	**2.2**	**-10,106**	**-33,600**	**-28.3**	**5.2**	**34**	**124.5**
Tube Length										
34’0”	**0.21**	**600**	**541**	**2.2**	**-10,106**	**-33,600**	**-28.3**	**4.3**	**34**	**100**
6’0”	**0.09**	**1562**	**541**	**2.2**	**-24,636**	**-33,600**	**-12.2**	**4.3**	**6**	**33.4**
60’0”	**0.29**	**507**	**541**	**2.2**	**-5,981**	**-33,600**	**-29.5**	**4.3**	**60**	**143.1**

Table 2a. Study Results with Mass Flux set to 7.3 kg/(s·m2) [1.5 lb/(s·ft2)] in Metric Units

	ΔP through Tube Bundle (bar)	WHB Gas Outlet T (°C)	Peak Tube Wall T (°C)	Sulfidic Corrosion (mils/y)	Overall Heat Flux (W/m2)	Peak Heat Flux (W/m2)	Calc. Duty (MW)	Shell ID (m)	Tube Length (m)	Relative Cost
Tube Ligament										
31.75mm	**0.003**	**316**	**273**	**1.8**	**-20,205**	**-69,086**	**-8.4**	**1.9**	**8.2**	**132.8**
6.35mm	**0.003**	**343**	**428**		**-19,846**	**-58,991**	**-8.3**	**1.4**	**8.2**	**91.6**
50.8mm	**0.003**	**316**	**273**	**1.8**	**-20,205**	**-69,086**	**-8.4**	**2.3**	**8.2**	**165.3**
Tube Length										
10.4m	**0.003**	**316**	**273**	**1.8**	**-20,205**	**-69,086**	**-8.4**	**1.9**	**8.2**	**132.8**
1.8m	**0.0016**	**766**	**273**	**1.8**	**-46,451**	**-69,086**	**-4.3**	**1.9**	**1.8**	**53.9**
18.3m	**0.005**	**259**	**273**	**1.8**	**-9,552**	**-69,086**	**-8.9**	**1.9**	**18.3**	**214.5**

Table 2b. Study Results with Mass Flux set to 7.3 kg/(s·m^2) [1.5 lb/(s·ft^2)] in U.S. General Units

	ΔP through Tube Bundle (psi))	WHB Gas Outlet T (°F)	Peak Tube Wall T (°F)	Sulfidic Corrosion (mils/y)	Overall Heat Flux (Btu/(hr·ft^2))	Peak Heat Flux (Btu/(hr·ft^2))	Calc. Duty (MMBtu/hr)	Shell ID (feet)	Tube Length (feet)	Relative Cost
Tube Ligament										
1.25”	0.045	600	523	1.8	-6,405	-21,900	-28.7	6.2	27	132.8
0.25”	0.046	650	802	32.1	-6,291	-18,700	-28.3	4.5	27	91.6
2”	0.045	600	523	1.8	-6,405	-21,900	-28.7	7.4	27	165.3
Tube Length										
34’0”	0.045	600	523	1.8	-6,405	-21,900	-28.7	6.2	27	132.8
6’0”	0.023	1410	523	1.8	-14,725	-21,900	-14.7	6.2	6	53.9
60’0”	0.071	498	523	1.8	-3,028	-21,900	-30.2	6.2	60	214.5

Tube Ligament Spacing

Peak tube wall temperature varies profoundly with the choice of tube ligament spacing below the recommended minimum spacing of 31.75 mm (1.25”). Both Tables 1 and 2 show excessive tube wall temperatures for the 6.35 mm (0.25”) ligament spacing (500°C [931°F] for 14.6kg/(s·m^2) [3.0 lb/(s·ft^2)] mass flux and 428°C [802°F] for 7.3kg/(s·m^2) [1.5 lb/(s·ft^2)] mass flux). Service life reduction to the order of one to a few years can be expected at these temperatures due to excessive high temperature sulfidic corrosion. Holding the mass flux lower reduces the peak wall temperature, but not to acceptable levels with the tight ligament spacing.

Figure 2 contrasts the tube wall temperature vs. length for the 14.6 vs. 7.3kg/(s·m^2) [3.0 vs. 1.5 lb/(s·ft^2)] mass flux designs with improper tube ligament spacing (6.35 mm [0.25”]). Both designs carry elevated tube wall temperature above the industry recognized limit of 343°C (650°F) through a large portion of the exchanger length. While the lower mass flux design shows improvement, the improvement is not to acceptable levels. **It is clear then that the problems with service life are driven more by the water side heat transfer performance vs. the process side design choice of mass flux**. The wobble in tube wall temperature from 1.8 to 3.4 meters (6 to 11 feet) in the G=7.3 kg/(s·m^2) [1.5 lb/(s·ft^2)] case and from 3 to 4.6 meters (10 to 15 feet) in the G=14.6kg/(s·m^2)[3.0 lb/(s·ft^2)] case can be attributed to the exothermic shifting of sulphur allotropes from mostly S_2 in the hot region at the front to more S_6 and S_8 as the process gas is cooled.

Cost considerations favor the higher mass flux design across the board. While the capital cost for the improper tube ligament spacing looks quite attractive, the service life reduction would make the life cycle cost prohibitive.

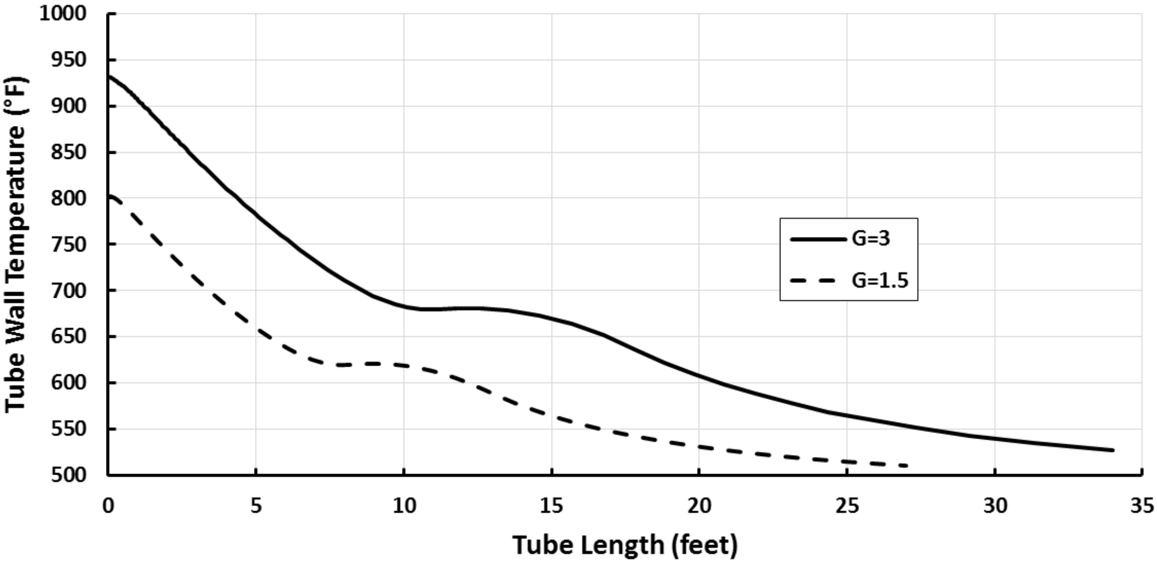

Figure 2 – Tube Wall T vs. Length for G=14.6 and 7.3 kg/(s·m^2)[3 and 1.5 lb/(s·ft^2)]for Improper6.35 mm (0.25”) Tube Ligament

Tube Length Considerations

It almost goes without saying that coming up short on tube length misses the heat transfer performance objective. At 1.8 m (6’) tube length, the boiler outlet temperature is 850°C (1562°F) for the mass flux of 14.6 kg/(s·m^2)[3 lb/(s·ft^2)] and 766°C (1411°F) for 7.3 kg/(s·m^2)[1.5 lb/(s·ft^2)] mass flux. The outlet temperature is way too high to meet the outlet temperature objective of 316°C (600°F). Cost, however, looks superb for this flawed case (33-38% of the Base Case). Tube length, however, as expected is a critical parameter to meet the heat exchange requirements by meeting the heat transfer surface area while demonstrating, albeit obvious, the risk of focusing exclusively on only mass flux.

Providing the WHB with extra (and excessive) tube length (18.3 m [60’] cases) not only leads to more costly designs across the board, the pressure drop increases unnecessarily. Compared to the optimal

10.4 m (34’) tube length cases, the 18.3 m (60’) tube length cases have approximately 20% higher pressure drop. Both of these scenarios represent design busts.

Water/Steam Side Hydraulics

Although not evaluated directly, the impacts of under-sizing BFW nozzles can be best summarized by the outcomes pictured in Images 1 and 2. Given enough process-side throughput, the exchanger cannot transfer enough heat and is starved to the point where vapor blanketing will occur.

Undersized steam outlet piping mandates that a higher steam chest operating pressure be used to overcome the piping pressure drop and push the steam into the header. The undersized steam outlet pipe size will cause back pressure on the bundle which will result in vapor blanketing of the tubes causing overheating and failure of the affected tubes. For the Base Case WHB Exchanger operating at 14.6 kg/(s·m^2)[3.0 lb/(s·ft^2)], under the assumption of 30.5 m (100’) equivalent piping length, a 152 mm (6”) line is necessary to keep the pressure drop below 0.34 bar (5 psi). The effect of under-sizing the steam outlet line is summarized in Table 3.

Table 3a. Steam Outlet Pipe Size Effects in Metric Units

Nominal Steam Pipe Size (mm)	In Line Pressure Drop (bar)	WHB Gas Outlet Temperature (°C)	Peak Tube Wall Temperature (°C)
152	0.007	316	382.7
102	0.52	317	383.3
76	2	318	385.5

Table 3b. Steam Outlet Pipe Size Effects in U.S. General Units

Nominal Steam Pipe Size (in.)	In Line Pressure Drop (psi)	WHB Gas Outlet Temperature (°F)	Peak Tube Wall Temperature (°F)
6”	0.1	600	541
4”	7.5	602	543
3”	29	604	546

Fouling Considerations

Poor BFW quality and blowdown practices are very subtle points to miss, but very costly to learn. The authors are aware of instances where boilers operating on air-only failed in 45 and 60 days in parallel SRU trains due to not using intermittent blowdown. To illustrate the impact of fouling, the steam side fouling resistance was varied in a case study from the Base Case in Figure 3. Peak tube wall temperature increases quite significantly, leading to a logical explanation for the short operating run lengths that can be expected by neglecting the water side heat transfer considerations.

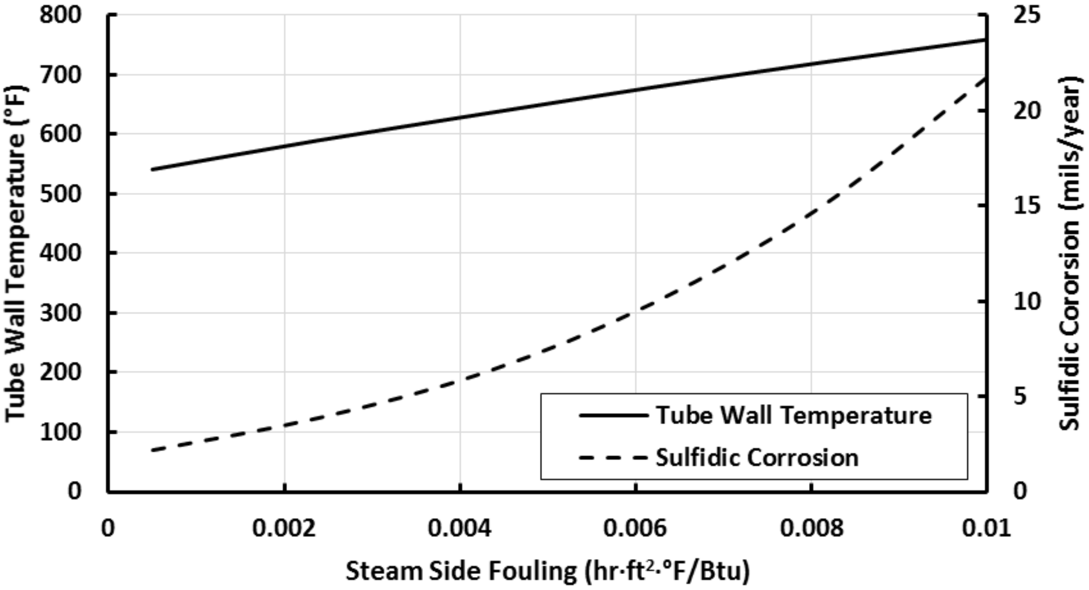

Figure3. Effects of Utility Side Fouling on Tube Wall Temperature and Sulfidic Corrosion

CONCLUSIONS

The case studies generated in this work affirm that there are many important design parameters besides mass flux that influence the heat transfer performance and reliability of the WHB. In particular, tube ligament spacing and cleanliness of the water side is paramount to the reliability of the Claus WHB.

While mass flux is an important parameter, it should be recognized that limiting the mass flux will result in less economical WHB designs that may not be warranted in many cases. This work demonstrates that the problems with service life in WHB's are driven more by the water side heat transfer performance vs. the process side design choice of mass flux

WHB failure cause and effect analysis is a method leading to the listing of **all** possible reasons and outcomes associated with the failure looking at the entire WHB system and not just the process parameters through just one WHB tube. Focusing exclusively on mass flux will most likely lead to false conclusions, as demonstrated here.

This paper was written in hopes that the industry will consider holistic guidelines in the design of Claus WHB's versus solely focusing on mass flux.

References

1. "Design and Operating Guidelines for a Robust and Reliable SRU Waste Heat Boiler" Marco van Son, Frank Scheel, Cliff Lawrence, Sarah Radovcich, Thomas Chow, Steve Pollitt, Domenica Misale-Lyttle and Elmo Nasato.Sulphur 2017 Abu Dhabi, February 2017.
2. "Evaluate waste heat steam generators", W.P. Knight, Hydrocarbon Processing. 1978.
3. "Examining the Impact of Waste Heat Boiler Design and Operation on WHB Reliability", Elmo Nasato, Domenica Misale-Lyttle, David Barrow and Michael Huffmaster, Sulphur 2015.
4. "Reliability of boiler tube protection systems – a case history: Operation in air-based and oxygen enriched conditions", N. Engelhardt, Domenica Misale-Lyttle and Elmo Nasato.Sulphur 2017 Atlanta, November 2017.