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Factors Affecting Waste Heat Boiler Design and Operation: Part 2 †

In Part 1 of this series, we reviewed qualitatively factors beyond mass flux that can have vital consequence in the design and operation of a Waste Heat Boiler (WHB). Here in Part 2 we use a case study to give more quantitative substance to these factors. In particular, the case study shows that unless the boiler is treated as a heat transfer device with simultaneous chemical reactions and radiative heat transfer, these complicating factors may go unnoticed.

Case Study Basis

To illustrate how many design parameters are interconnected, a series of case studies was conducted using the kinetic and heat transfer rate-based simulator, SulphurPro®. In each scenario, the starting point was a sound, optimized design. Modifications then were made away from this "solid design point" to quantitate the effects to WHB heat transfer performance and reliability.

The starting point for the base-case design is 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 is kettle style producing 600 psig saturated steam with a design outlet temperature of 600°F, tube side pressure drop of 0.4 psi, and an allowable steam side pressure drop of 5 psi. The tubes are 2½ inch OD x 10 BWG carrying a mass flux of 3 lb/s·ft^2. The utility side fouling factor and process side fouling factor are assumed to be 0.003 hr·ft^2·°F/Btu and 0.0005 hr·ft^2·°F/Btu, respectively.

The results and concepts also apply to a thermosiphon type WHB. To gain an appreciation of how design variations affect economics, the relative WHB cost was taken as 100 for a properly designed boiler.

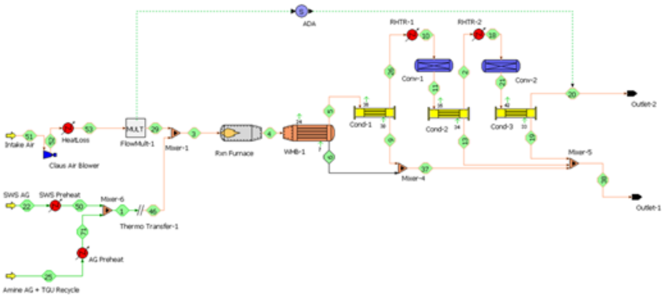

Figure 1 SRU Flowsheet for Case Study

To emphasize adequately the importance of the water side and its effect on reliability, cost, and physical size, we focus on varying 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

Table 1 shows case study results of varying tube ligaments† at tube lengths of 34 and 27 ft. For a tube ligament of 2.0 inches, Table 2 shows results of varying tube length to reach 600F outlet gas temperature (columns 1 and 2) and of using very short and very long tubes. Results correspond to mass fluxes of 3.0 (black) and 1.5 lb/s·ft^2 (**red**).

Table 1 Effect of Varying Tube Ligament on WHB Performance

	Flux = 3.0 lb/s·ft^2	**Flux = 1.5 lb/s·ft^2**				
Tube Ligament (inches)	**1.25**		**0.25**		**2.0**	
Tube Bundle ΔP (psi)	0.21	**0.045**	0.22	**0.046**	0.21	**0.045**
Gas Outlet (°F)	600	**600**	684	**650**	600	**600**
Peak Tube Wall (°F)	541	**523**	931	**802**	541	**523**
Sulfidic Corrosion (mpy)	2.2	**1.8**	99.5	**32.1**	2.2	**1.8**
O/A Heat Flux (MBtu/h·ft^2)	10.1	**6.4**	9.8	**6.3**	10.1	**6.4**
Peak Heat Flux (MBtu/h·ft^2)	33.6	**21.9**	23.3	**18.7**	33.6	**21.9**
Duty (MMBtu/h)	28.3	**28.7**	27.5	**28.3**	28.3	**28.7**
Shell ID (ft)	4.3	**6.2**	3.2	**4.5**	5.2	**7.4**
Relative Cost	100	**133**	69	**92**	124	**165**

Table 2 Effect of Varying Tube Length on WHB Performance

	Flux = 3.0 lb/s·ft^2	**Flux = 1.5 lb/s·ft^2**				
Tube Length (feet)	**34**	**27**	**6**		**60**	
Tube Bundle ΔP (psi)	0.21	**0.045**	0.09	**0.023**	0.29	**0.071**
Gas Outlet (°F)	600	**600**	1562	**1410**	507	**498**
Peak Tube Wall (°F)	541	**523**	541	**523**	541	**523**
Sulfidic Corrosion (mpy)	2.2	**1.8**	2.2	**1.8**	2.2	**1.8**
O/A Heat Flux (MBtu/h·ft^2)	10.1	**6.4**	24.6	**14.7**	5.98	**3.03**
Peak Heat Flux (MBtu/h·ft^2)	33.6	**21.9**	33.6	**21.9**	33.6	**21.9**
Duty (MMBtu/h)	28.3	**28.7**	12.2	**14.7**	29.5	**30.2**
Shell ID (ft)	4.3	**6.2**	4.3	**6.2**	4.3	**6.2**
Relative Cost	100	**133**	33	**54**	143	**214**

Tube Ligament Spacing

Below the recommended minimum spacing of 1.25 inches, peak tube wall temperature varies profoundly with the choice of ligament spacing. Table 1 shows excessive tube wall temperatures for the 0.25 inch ligament spacing 931°F and 802°F for mass fluxes of 3.0 and 1.5 lb/s·ft^2, respectively. Reduced service life to between one and a few years can be expected at these temperatures because of accelerated sulfidic corrosion. With tight ligament spacing, keeping the mass flux low reduces peak wall temperature, but not to acceptable levels.

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† Ligament spacing is the distance between adjacent tube walls

Figure 2 compares longitudinal tube wall temperature profiles for the two mass flux designs with tube ligament spacing of 0.25 inches. Both designs result in tube wall temperatures greatly elevated above the industry recognized limit of 650°F along a large portion of the exchanger's length. The lower mass flux design shows improvement but not to acceptable levels. *Clearly, problems with service life are driven more by the water-side heat transfer performance than by the design choice of mass flux*. The wobble in tube wall temperature part way along the tubes is attributed to the exothermic shifting of sulphur allotropes from mostly S_2 in the hot region at the front end to S_6 and S_8 as the process gas is cooled.

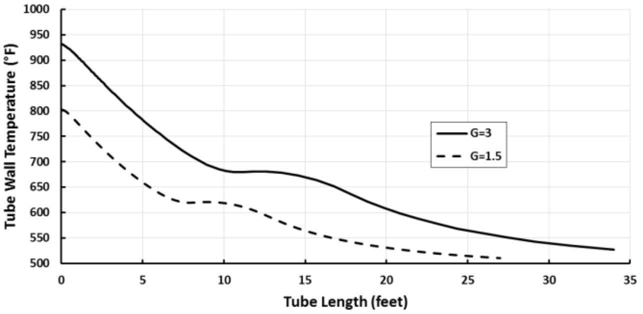

Figure 2 How Tube Wall Temperature Varies with Tube Length at Mass Fluxes of 3.0 and 1.5 lb/s·ft^2 with Tube Ligament of 0.25 inches

Capital cost considerations favor higher mass flux designs across the board. However, while capital cost for the improper tube ligament spacing looks quite attractive, the service life reduction makes the short life cycle cost prohibitive.

Tube Length

Tubes that are too short miss the heat transfer performance objective. With 6-ft tubes, the boiler outlet temperature is 1562°F when the mass flux is 3 lb/s·ft^2 and 1411°F when it is 1.5 lb/s·ft^2. The outlet gas is far above the desired outlet temperature of 600°F. The cost, however, looks superb for this flawed case (only 33-38% of the Base Case). However, tube length is critical to providing the necessary heat transfer surface area. This demonstrates in a fairly obvious way the risk of focusing exclusively on mass flux.

Providing the WHB with extra (and excessive) tube length (60 feet) not only leads to more costly designs across the board, but the pressure drop increases greatly. Compared to the optimal 34-ft tube length, 60-ft tubes have about 20% higher pressure drop. It is important to use tubes of the right length.

Water/Steam Side Hydraulics

Although not evaluated directly, the effect of under-sizing BFW nozzles is either to collapsed tubes from overheating by vapor blanketing, or to loose water level on the water side causing the tubes to melt into the bottom of the exchanger.

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

Table 3 Effect of Steam Outlet Pipe Size

Nominal Pipe Size (inches)	Pressure Drop (psi)	Outlet Gas Temperature (°F)	Peak Wall Temperature (°F)
6	0.1	600	541
4	7.5	602	543
3	29	604	546

Fouling

Poor BFW quality and blowdown practices are very subtle points to miss, but very costly to learn. We are aware of instances where boilers operating on air-only failed in 45 and 60 days in parallel SRU trains by 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.

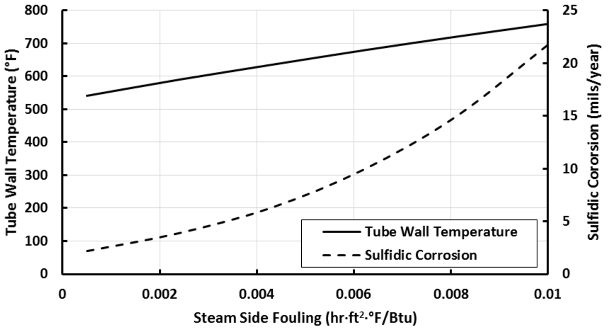

Figure 3 Effect of Fouling on Tube Wall Temperature

Conclusions

Mass flux is not the only parameter affecting 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.

Limiting the mass flux can result in less economical WHB designs that may not be warranted in many cases. This note 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

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†Taken from a paper coauthored with Elmo Nasato