Claus waste heat boiler economics Part 1: process considerations

The design of the waste heat boiler has a critical role to play in determining process operations, reliability and economic performance in the sulphur recovery unit

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Higher sulphur feedstocks offer margin advantages to refiners and gas producers but with challenges to uptime metrics and environmental constraints as downsides. To meet economic objectives, such competing requirements must all be met reliably without equipment failure. One key piece of equipment that can impact uptime is the Claus waste heat boiler (WHB). The WHB operates under harsh conditions with serious reliability challenges. It is one of the most fragile equipment items in the sulphur recovery unit (SRU). Not only does it provide heat recovery from the thermal section of the SRU, but it also affects the unit's hydrogen balance and COS levels because of recombination reactions. Peak heat flux at the front end of the boiler tubes can lead to over-heating and reliability problems. The design of the WHB plays a critical role in determining the extent of the recombination reactions as well as the peak heat flux, all while balancing capital cost and operational reliability. Part 1 of this two-part series discusses general process considerations including the effects of tube length, pressure drop, and COS/H_2 reactions on sulphur recovery. Part 2 examines details of how operating conditions and WHB design affect tube wall temperature and the important reliability implications of that relationship.

The SulphurPro simulator provides a modern heat transfer rate and chemical reaction rate based model of the WHB. The quantitative behaviour of the WHB itself and how it subtly affects SRU performance hinges critically on the recombination reactions that occur at the front of the WHB:

$H_2 + \frac{1}{2} S_2 \rightleftharpoons H_2S$
$CO + \frac{1}{2} S_2 \rightleftharpoons COS$

These reactions are so important because not only do they influence sulphur recovery, air demand, and hydrogen production in the SRU, they also affect the heat flux and therefore performance and mechanical longevity of the WHB. These reactions occur towards the front (inlet) side of the WHB and are exothermic. As will be seen in Part 2, the heat associated with them tends to increase heat flux especially in the vicinity of the critical tube-to-tubesheet joint.

Radiative heat transfer, coupled with the exothermic recombination reactions, collectively increase the peak heat flux at the front of the boiler well above predictions from models that ignore or discount these factors. Ceramic ferrules are often used to protect the front end of the tubes from excessive heat, but detailed modelling shows that, at high mass velocity, the tubes can experience greatly elevated tube wall temperatures well downstream of the ceramic ferrules. Details of this modelling effort are presented in Part 2 of this article, lending theoretical support to documented failures in the industry. Also in Part 2, tube wall temperatures, pressure drop, and heat flux predictions from the model are examined down the length of the tubes for oxygen enriched vs air only operations, and the implications of sulphidic corrosion with its resulting effect on boiler tube life and SRU reliability economics are examined with this new information.

Flow rate and composition of AAG and SWAG feed streams

	Amine AG + TGU recycle	SWS AG
Flow rate, std. m^3/h	4000	26
H_2S, mol%	88.2	33.1
CO_2, mol%	6.4	-
NH_3, mol%	-	40.9

Table 1

Case study: important parameters in WHB design

There are many parameters in Claus WHBs that need to be very carefully considered in the design phase. Many of the parameters are mutually interdependent – changing one affects several others. In a typical WHB design, the tube size and process-side mass velocity will be chosen to meet a fixed outlet temperature specification. The following case study looks at a typical 125 lt/d sulphur plant with two converter stages processing both amine acid gas (AAG) and sour water acid gas (SWAG) under low level oxygen enrichment (see **Figure 1**). **Table 1** shows the conditions of these two acid gas feed streams. The WHB was sized by fixing the process-side mass flux, the tube size and the process outlet temperature. The tube count and tube length were adjusted to meet the target specifications. A matrix of three tube sizes and four mass fluxes was evaluated. The tube sizes were set at 1.5in, 2in and 3in outside diameter and process-side mass fluxes were set at 2, 3, 4, and 5 lb/ft^2·s. The results were obtained using the kinetic heat

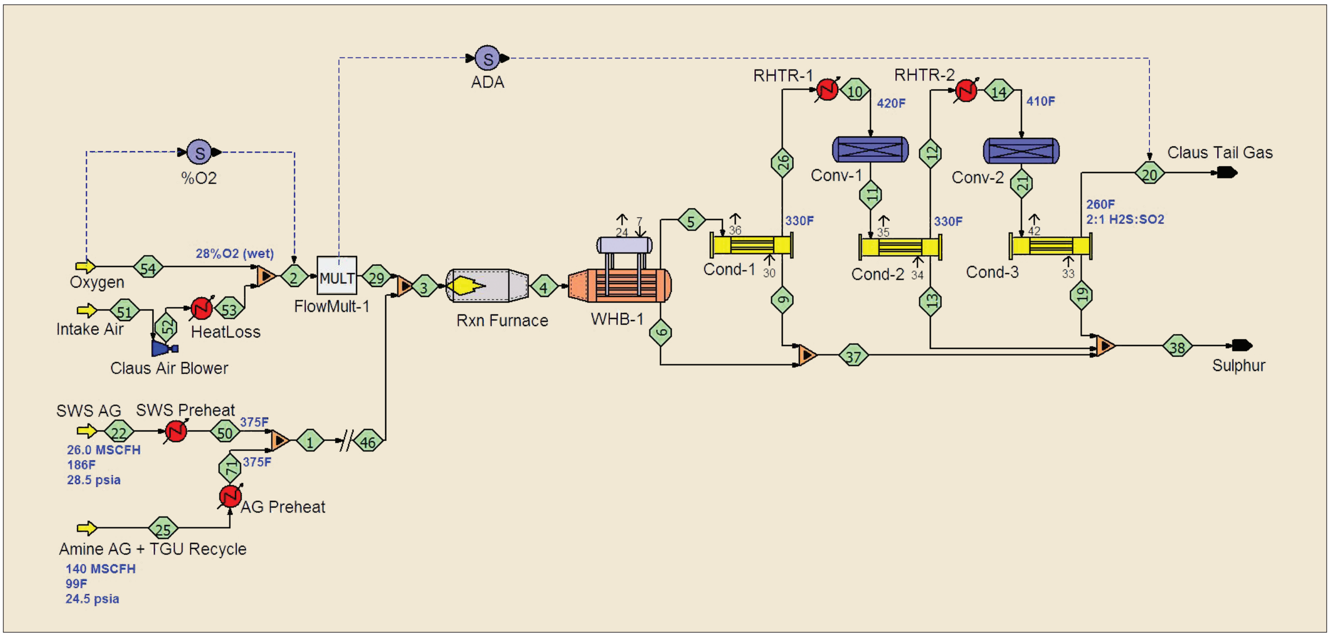

Figure 1 Case study sulphur recovery unit flowsheet

transfer and chemical reaction rate based SulphurPro SRU Simulator (available standalone or integrated within ProTreat Version 6.4).

Table 2 shows values of other design parameters assumed for this application of the model. The boiler produces 350 psig saturated steam from preheated boiler feed water.

Table 3 illustrates how, in meeting an outlet temperature specification of 550°F (288°C), the overall tube length increases with mass velocity at three tube diameters. Because the hot gas is moving faster at the higher mass velocities, less heat is transferred from the gas in a given tube length, thus the overall length of the tube bundle must be increased to meet the outlet temperature target. Besides the amount of cooling provided by the WHB, another parameter of importance is pressure drop through the exchanger. In a sulphur plant, pressure drop is at a premium and must be considered in all aspects of the design. Tube size and length have a large effect on pressure drop. Using smaller tubes decreases the overall length of the tube bundle, but it also increases pressure drop per unit length, so a balance must be struck. Neglecting any single factor of the design can lead to design busts and catastrophic operations failures. The driving factors for any project design are meeting the requirements safely and reliably whilst minimising cost. Sometimes these factors are at odds with each other – the interaction between design parameters can be complex. The base cost of a WHB depends directly on the amount of material needed for construction. Boiler tube length, tube diameter, and tube count all influence the amount of material needed.

As expected, at each tube size, as the mass flux (lb/ft²·s) through the tubes increases, the overall tube length needed to achieve a fixed outlet temperature increases. At the smallest tube size (1.5in) and

Design parameters

Parameter	
Outside convective heat transfer coefficient, Btu/h·ft²·°F	150
Tube wall emissivity for radiative heat transfer, unitless	0.9
Inside fouling resistance, h·ft²·°F/Btu	0.008
Outside fouling resistance, h·ft²·°F/Btu	0.002
Tube material	Carbon steel
Tube wall thickness, inches	0.1085

Table 2

Effect of mass flux and tube diameter on tube length (ft) needed to reach 550°F

Tube OD, inches	2 lb/ft²·s	3 lb/ft²·s	4 lb/ft²·s	5 lb/ft²·s
1.5	19.2	22.5	25.3	27.9
2.0	27.7	32.6	36.9	40.7
3.0	44.8	53.3	60.5	66.9

Table 3

Pressure drop (psi) calculated across the tube bundle vs mass flux and tube OD

Tube OD, inches	2 lb/ft²·s	3 lb/ft²·s	4 lb/ft²·s	5 lb/ft²·s
1.5	0.112	0.282	0.548	0.925
2.0	0.105	0.265	0.517	0.875
3.0	0.095	0.243	0.476	0.807

Table 4

the lowest mass flux (2 lb/ft²·s), the boiler tube length is least (19.2 ft). But, with smaller boiler tubes, the overall tube count must be increased to process the specified mass flux. A direct consequence of the higher tube count and smaller tube diameter is a greater total surface area per length of tube bundle available for heat transfer so that the shorter tubes will achieve the same specified outlet temperature.

Pressure drop is another factor. It increases with increasing mass flux and decreasing tube diameter. **Table 4** shows the calculated pressure drop through the tube bundle. This does not account for the exchanger effluent nozzle exit loss, and it assumes clean tubes (no dirt factor).

The data of **Table 3** suggest that the smallest possible tubes and lowest possible mass flux requires the shortest tubes, but the data of **Table 4** suggest the largest possible tube size with the lowest mass flux is best. The answer as to which is preferred (at least from a process engineering perspective) involves not just minimising the pressure drop, but also maximising hydrogen production in the SRU and concurrently maximising sulphur recovery efficiency. Also of paramount importance is the consideration of protecting the critical tube-to-tubesheet joint with ceramic ferrules. Allowing for the insulation thickness of the ferrules, the smallest practicable tube is about 1.5in OD. Tubes smaller than this would result in overly severe pressure drop and flow constrictions.

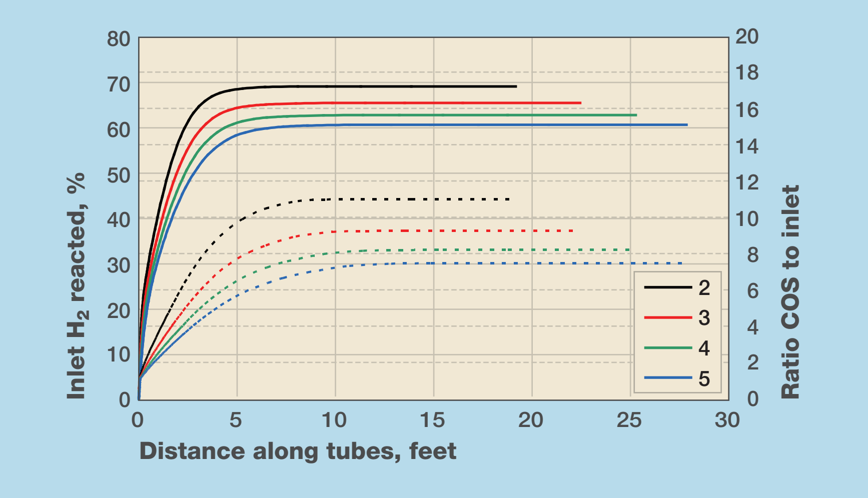

Figure 2 The extent of the recombination reactions depends on distance from WHB tube inlet; parameter is mass flux (lb/ft²·h) through 1.5in diameter tubes

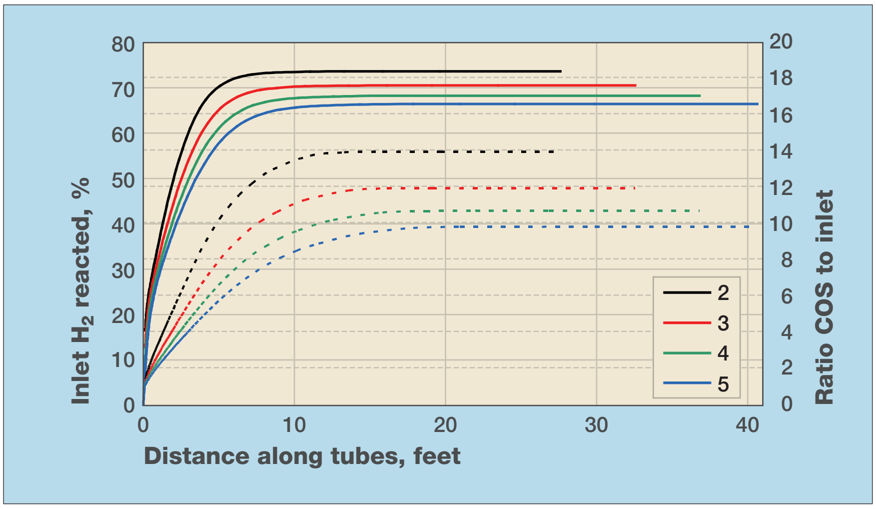

Figure 3 The extent of the recombination reactions depends on distance from WHB tube inlet; parameter is mass flux (lb/ft²·h) through 2in diameter tubes

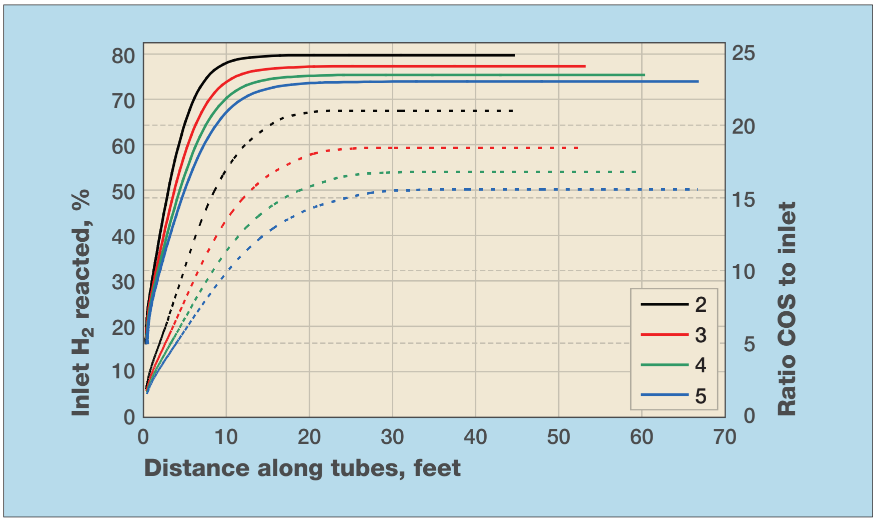

Figure 4 The extent of the recombination reactions depends on distance from WHB tube inlet; parameter is mass flux (lb/ft²·h) through 3in diameter tubes

Recombination reactions and sulphur recovery

Although the main purpose of the WHB is to remove the heat generated in the reaction furnace and recover it as steam, an unavoidable outcome involves the gas shift (recombination) reactions that occur near the front end of the boiler tubes. These reactions are very fast at high temperatures, but the reaction rates slow to a stop as the process gas is cooled.[1] Accurately predicting the extent of these reactions is an important reason to use a quality simulator to design the WHB. The approach to modelling the WHB varies from simulator to simulator. Most simulators account only for the heat transfer in the WHB and completely neglect the important recombination reactions to be discussed here. These reactions play a large role in determining how the WHB performs;

thus, they affect the reliability of the design. Sulphur redistribution (spontaneous shifts among the allotropes S_2, S_6, and S_8) also has a fairly significant effect on the heat flux across the exchanger tubes. Simulators that do not calculate the redistribution and do not account for the recombination reactions will inaccurately calculate the heat flux and thermal performance of the exchanger, especially in the tube inlet region near the critical tube-to-tube sheet joint.

There are two main reactions that occur in the inlet of the WHB tubes:

$$H_2 + \frac{1}{2} S_2 \rightleftharpoons H_2S$$
$$CO + \frac{1}{2} S_2 \rightleftharpoons COS$$

These are kinetically (reaction rate) limited, exothermic reactions that can have a significant effect on the peak heat flux at the front end of the exchanger. Since the rates of these reactions are determined by reaction kinetics, they depend on two factors – namely, residence time and temperature – with residence time determined by the mass flux through the tubes. Temperature directly affects reaction rates but it also plays a role in the residence time because it affects gas density and, therefore, gas velocity. As the velocity in the tubes increases, the gas flows faster, providing less residence time in the boiler tubes. Less residence time works to offset the faster reaction kinetics at higher temperature. **Figures 2** to **4** illustrate the effect of mass flux on the two recombination reactions under the conditions already outlined in **Table 1** at tube diameters of 1.5in, 2in, and 3in, respectively. The solid lines show how the percentage of hydrogen in the inlet gas that is converted back to H_2S changes with distance along the WHB tubes. In the figures, the 'Ratio COS to Inlet' shows COS (dashed lines) at each point along the boiler tubes ratioed to the COS present in the inlet gas to the WHB.

Figures 2 to **4** show that the recombination reactions occur fairly rapidly, typically completing in the first quarter of the boiler tube length, and they continue well beyond the region protected by the ferrules. As the velocity through the tubes increases, the reactions tend to be quenched more rapidly, which leaves more hydrogen and sulphur in the WHB effluent. Additionally, less COS is made, increasing the sulphur conversion. As **Table 5** shows, these factors collectively translate into higher thermal sulphur conversion and hydrogen make. In the case of hydrogen, having more available is beneficial to the TGU from both a reliability perspective (added protection from SO_2 breakthroughs) and by reducing opex generated by external hydrogen consumption. Smaller boiler tube diameters lead to better WHB protection from SO_2 breakthroughs. Smaller tubes also significantly improved sulphur recovery, especially important in today's world of strict sulphur emissions regulations.

From a hydrogen and sulphur recovery standpoint, this evidence that smaller diameter boiler tubes and higher mass velocities are more desirable is important when considering operational flexibility. At turndown conditions, an operating unit will tend to make less hydrogen because of the lower mass velocity in the tubes. This is a characteristic that can be seen only with a truly rate based simulator.

Beyond process chemistry considerations, there are other important aspects of WHB design. To minimise capital cost, overall tube length and tube count must optimise, and to ensure that the unit has sufficient hydraulic capacity, pressure drop must be considered. Beyond these, the heat flux is a critical parameter of at least equal, if not greater, importance in the design and operation of WHBs. These factors will all be considered in Part 2 of this article.

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Reference

1 Karan K, Mehrotra A K, Behie L A, Including radiative heat transfer and reaction quenching in modeling a Claus plant waste heat boiler, *Ind. Eng. Chem. Res.*, 33, 2651–2655, 1994.

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Effect of WHB tube size and mass flux on hydrogen in tail gas and sulphur recovery

	1.5in boiler tubes				2in boiler tubes				3in boiler tubes			
Mass flux, lb/ft^2·s	2	3	4	5	2	3	4	5	2	3	4	5
Tail gas H_2, mol%, dry	4.24	4.73	5.09	5.37	3.55	4.00	4.31	4.55	2.82	3.16	3.41	3.61
Net excess H_2 in tail gas, mol%, dry	3.50	4.11	4.54	4.88	2.63	3.18	3.58	3.88	1.59	2.06	2.41	2.67
% Sulphur recovery	96.16	96.26	96.32	96.38	95.98	96.09	96.15	96.21	95.76	95.84	95.93	95.99

Table 5