Fouling-the silent heat transfer thief

Better boiler water chemistry can improve overall heat duty and efficiency by minimizing scale and sludge buildup

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A boiler's primary function is to achieve and to maintain maximum heat duty with the least operating costs and downtime. Scale and sludge are silent heat transfer thieves who slowly steal heat duty by reducing the overall heat transfer coefficient. The effects of scale and sludge are more pronounced in finned tube boilers. Tube side fouling on finned tubes generates higher tube wall temperatures. Ultimately, high heat fluxes result in tube failures.

Implementing a quality feedwater program for boilers pays off in improved exchanger efficiency, reduced operating costs and reduced

Clean is better. Boilers or heat recovery steam generators perform efficiently under clean conditions. Their performance is significantly affected by fouling either on the tube or gas side whether it is a fire tube or water tube exchanger. In addition to reduced duty, steam side cleanliness impacts the tube wall temperature leading to its overheating and failure in the long run.

Good water chemistry is an easy, efficient way to reduce the effects of steam-side fouling on boiler performance and tube wall temperature. Water tube waste heat recovery boilers shown in Figs. 1 and 2 will be used as examples. The concept applies to fired water tube or fire tube boilers and heat recovery steam generators also.

Water tube boilers. Typical water tube waste heat boilers (Fig. 1) are used in applications such as heat recovery from municipal waste incinerator exhaust or effluents from fluidized bed cat crackers. Bare tubes minimize fouling from particulates or ash in flue gases. Finned tube heat recovery boilers (Fig. 2) need clean gas streams such as exhaust from gas turbines or fume incinerators to perform well. The bare tube boiler usually operates at low heat flux inside the tubes, in the range of 10 to 30,000 Btu/ft^2/hr, while the finned tube waste heat boiler could operate under heat flux of 50 to 150,000 Btu/ft^{2}hr. It is extremely important that the proper water chemistry be maintained in finned tube exchangers. A small increase in steam side fouling factor on finned tubing can increase the tube wall temperature significantly compared to the bare tube boiler. A few calculations will demonstrate the different fouling effects between the tube types.

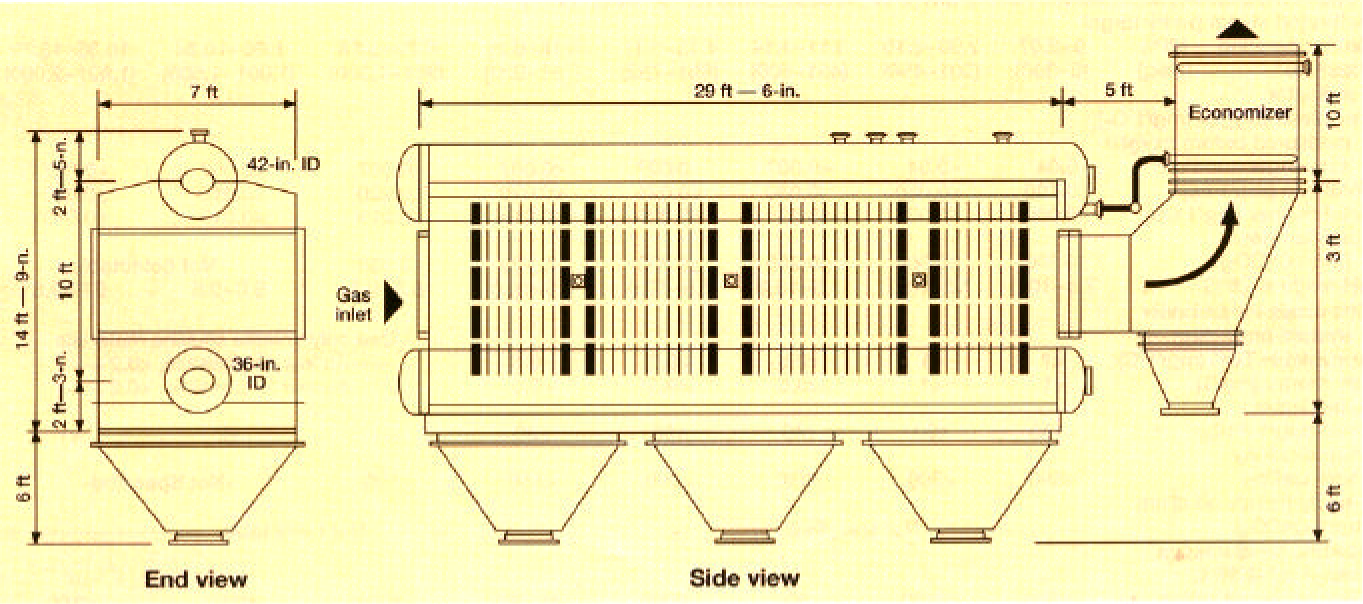

Fig. 1. Bare tube HRSG for incineration heat recovery.

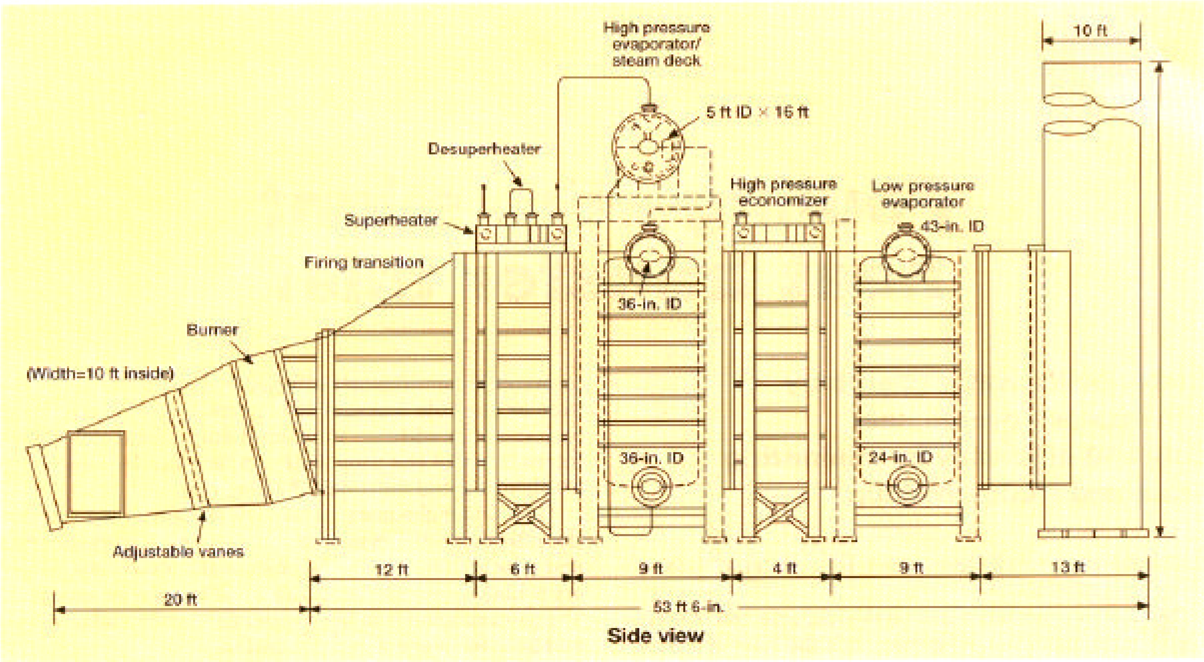

Fig. 2. Dual pressure HRSG with finned tubes for gas turbine recovery.

Design calculations. The surface area for the boiler is determined from Eq. 1

$$S = Q/U\Delta T$$

(1) where the duty is found by Eq. 2:

$$Q = WC_p (T_1 - T_2) h1 = W_S \Delta H$$

(2) If U is computed based on tube inner diameter, then the tube inner surface area should be used for S. Similarly, if U is based on tube outer diameter, S should be computed using the tube outer diameter. Remember that

Table 1. Suggested water quality limits*

Boiler type: industrial watertube, high duty, primary fuel fired, drum type Makeup water percentage: up to 100% of feedwater
Conditions: includes superheater, turbine drives or process restriction on steam purity Saturated steam purity target

Drum operating	MPa	**0-2.07**	**2.08-3.10**	**3.11-4.14**	**4.15-5.17**	**5.18-6.21**	**6.22-6.89**	**6.90-10.34**	**10.35-13.79**
Pressure	**(psig)**	**(0-300)**	**(301-450)**	**(451-600)**	**(601-750)**	**(751-900)**	**(901-1,000)**	**(1,001-1,500)**	**(1,501-2,000)**
Feedwater									
Dissolved oxygen (mg/1 0_2) measured before oxygen scavenger addition		**<0.04**	<0.04	**<!0.007**	**<0.007**	**< 0.007**	**<0.007 !**	**<0.007**	**<0.0.007**
Total iron (mg/1 Fe)		**<0.100**	**<0.05**	**<0.03**	**<0.025**	**<0.020**	**<0.02**	**<0.01**	**<0.01**
Total copper (mg/1 Cu)		**<0.05**	**<0.025**	**<0.02**	**<0.02**	**<0.015**	**<0.015**	**<0.01**	**<0.01**
total hardness (mg/1 $CaCO_3$)		**<0.300**	**<0.300**	**<0.200**	**<0.200**	**<0.100**	**<0.05**	**<0.05**	**-Not detectable**
pH range @ 25°C		**7.5-10.0**	**7.5-10.0**	**7.5-10.0**	**7.5-10.0**	**7.5-10.0**	**8.5-9.5**	**9.0-9.6**	**9.0-9.6**
Chemicals for preboiler system protection							**Use only volatile alkaline materials**		
Nonvolatile TOC (mg/1 °C)		<1	<1	<0.5	<0.5	<0.5	**As low as possible, <0.2**		
Oily matter (mg/1)		<1	<1	<0.5	<0.5	<0.5	**As low as possible, <0.2**		
Boiler water									
Silica (mg/1 $S10_2$)		**<**150	<90	<40	<30	<20	<8	<2	**<1**
Total alkalinity (mg/1 $CaCo_3$)		**<350**	**<**300	<250	<200	<150	<100	**-Not Specified-**	
Free hydroxide alkalinity (mg/1 $CaC0_3$)			**Not specified**				**Not detectable**		
Specific conductance (pmh$_o$/cm) @ 25°C without neutralization		**<3500**	**<3000**	**<2500**	**<2000**	**<1500**	**<1000**	<150	<100

'Adapted from ASME 1979 consensus. See ASME 1979 for a complete discussion.

the product U x S is the same whether U and S are based on tube ID or OD. U based on tube outer diameter is given by the following equation for bare tube boilers:

$$1/U_o = 1/h_o + (1/hi)(d./di) + ffi\ (d./d_i) + ffo + (d/24Km)\ln(do/di)$$

(3) and by the following equation for the finned tube boilers:

$$1/U= (AT/hiAi) + ffi\ (AT/Ai) + ffo + (ATd/Aw24Km)\ \ln(d/d_i) + 1/\eta\ ho$$

(4) The boiling heat transfer coefficient h_i inside the tubes will be very high on the order of 2,000 to 3,000 Btu/ft^2/hr °F. An error of 10% to 20% in its value will not affect U_o.

Correlations for computing h_o. The gas-side coefficient for bare and finned tube boilers consists of two components, namely *hc*- the convective heat transfer coefficient and *h*, - the nonluminous heat transfer coefficient. The *hc* is obtained from the Grimsons equation for bare tubes and from ESCOA correlations for finned tube boilers. [1-3] Tube-side fouling factor ff_i affects duty and tube wall temperatures and the impact is more significant in a finned tube boiler compared to a bare tube design.

Scale formation and fouling factor ff_o. Typically, with treated feedwater and boiler water that is maintained according to ASME or ABMA guidelines, a fouling factor of 0.0005 to 0.001 ft^2/hrF/Btu could be used. If the water chemistry is not properly maintained, then sludge and scale can accumulate on the inside of tubes hindering heat transfer. ASME and ABMA guidelines for water chemistry are listed in Tables 1 and 2.

Scale is a relatively hard and adherent deposit, while sludge is softer and can be easily dislodged. The buildup of scale is most severe in high heat flux areas. Scale buildup is associated with compounds whose solubilities decrease with increasing temperatures. Conversely, sludges are precipitated directly from the boiler water when their solubilities are exceeded. Scale and sludge increase the resistance to heat transfer and decrease U. Most importantly, sludge and scale raise the tube wall temperature. Fouling factor could be approximated by dividing the scale layer thickness by its conductivity:

ff_i = thickness of scale/conductivity

Heat flux. Using the electrical analogy as an example, one can show that the heat transfer across tubes is analogous to flow of current in an electrical circuit. Current is analogous to heat **flux,** while voltage drop is analogous to temperature difference and resistance and fouling factor are analogous. To compute the temperature drop across the fouling layer, multiply the heat flux by the fouling factor:

$$DT_f = q \times ffi \qquad (6)$$

Heat **flux** *q* computed on inner tube diameter basis is calculated by Eq. 7:

Table 2. Watertube boilers recommended water limits and associated steam purity

At steady state full load operation — drum type boilers ABMA-1982

Drum pressure, psig	Range total dissolved solids[1] boiler water, ppm (max)	Range total alkalinity[2] boiler water, Ppm	Suspended solids boiler water ppm (max)
0-300	700-3,500	140-700	15
301-450	600-3,000	120-600	10
451-600	500-2,500	100-500	8
601-750	200-1,000	40-200	3
751-900	150-750	30-150	2
901-1,000	125-625	25-125	1
1,001-1,800	100	[3]	
1,801-2,350	50		N/A
2,351-2,600	25		N/A
2,601-2,900	15		N/A
Once through boilers			
1,400 and above	0.05	N/A	N/A

[1] Actual values within the range reflect the TDS in the feed water. Higher val solids, lower values are for low solids in the feed water.

[2] Actual values within the range are directly proportional to the actual value water. Higher values are for the high solids, lower values are for low water.

[3] Dictated by boiler treatment.

[4] These values are exclusive of silica.

Table 3. Thermal conductivities of scale materials

Material	Thermal c
Analcite	
Calcium phosphate	
Calcium sulfate	
Magnesium phosphate	
Magnetic iron oxide	
Silicate scale (porous)	
Boiler steel	
Firebrick	
Insulating brick	

Table 4. Results of calculations

Case	1	2
1. Gas temp in	1,000	1,000
2. Exit temp	520	545
3. Duty	19.65	18.65
4. Steam flow	19,390	18,400
5. ff_i	.001	.01
6. Heat flux	9,314	8,162
7. Wall temp	437	516
8. Fin temp		
9. A_t/A_i	1.13	1.13
10. Fins	bare	bare
11. Tubes/row	20	20
12. No. deep	60	60
13. Length	8	8
14. Surf. area	5,024	5,024
15. Gas Δp	3.0	3.1

Units:
Temp., °F
Flow, lb/hr
Duty, MMBtu/hr
ff, ft^2/hr°F/Btu
heat flux, Btu/ft^2/hr
Surf. area, ft^2
Gas Δp, in., water column
Length, ft

$$q = U_o \times (A_t/Ai) \times (T - t) \qquad (7)$$

A_t, A_i refer to external and internal surface areas. T, t refer to gas and boiling water temperatures. Note that A_t/A_i will be very large for finned tubes compared to bare tubes. Hence, the temperature drop due to the same fouling factor can be large for boilers with finned tubes.

Example. A water tube boiler for a fume incineration system is required to cool 150,000 lb/hr of clean flue gases from 1,000°F to 520°F. Gas analysis is:

	vol%
$C0_2$	7
H_2O	12
N_2	75
0_2	6

Gas pressure is atmospheric. Steam pressure is 285 psig and feedwater is at 230°F. Carbon steel tubes of size 2 in. x 1.77 in. are used. Assume that the gas side fouling factor = 0.001 ft^2/hr°FBtu; metal thermal conductivity = 25 Btu/ft/hr°F; steam side coefficient = 2,000 Btu/ft^2/hr°F; and heat loss = 2%.

Design the boiler using a steam side fouling factor ff_i of 0.001 ft^2/hr°FBtu (0.025 in. thick calcium phosphate scale) and check the performance with a ff_i = 0.0 1(0.006 in. thick silicate scale).

Study three options: bare tubes, finned tubes with 2 x 0.75 x 0.05 x 0.157 (2 fins/in., 0.75 in. high, 0.05 in. thick with 0.157 in. serration) and finned tubes with the geometry 5 x 0.75 x 0.05 x 0.157 and transverse and longitudinal pitch = 4 in.

Boilers or heat recovery steam generators perform efficiently under clean conditions.

Solution. Calculations were performed using the methodology discussed in references 1-3. The results are listed in Table 4. Several important aspects may be noted:

1. Tube wall and fin tip temperatures increase significantly when ff_i increases, though U_o and heat flux are lower with increased fouling factor. The product of heat flux and ff_i determines the temperature drop across the fouling layer which increases the tube wall and fin tip temperature.
2. Duty decreases with increase in ffi. The decrement is large as a percentage with finned tubes compared to bare tubes. With 5 fins/in. design, the duty is much lower compared to 2 fins/in. design and significantly lower compared to bare tubes. We generate only 14,4001b/hr steam with 5 fin/in. compared to 18,4001b/hr with bare tube boiler for the same fouling factor, though the basic design is for the same steam generation with the same fouling factor of 0.001.
3. More surface area does not mean more duty. Increased fin density requires a larger surface area to transfer the same duty with a lower U_a. Also, the tube wall and fin tip temperatures are higher with increases in fin surface area for the same fouling factor.
4. Compared to bare tube design, a finned tube boiler is more compact, weighs less and has lower gas pressure drop for the same duty. However, one has to be careful about the falloff in performance and possible overheating of tubes with increase in tube-side fouling or scale formation.

Water chemistry is very important in boilers. Increases in the steam-side fouling factor due to formation of thick layer of scale or sludge can result in reduced duty and higher tube wall temperatures. The problem is exacerbated when the heat flux across the tubes increases due to use of extended surfaces. The larger the fin surface area (obtained by using high fin density), the higher the temperature at the tube wall and fin tip. Even in fired bare tube boilers, the furnace tubes should have proper cooling. Otherwise, high heat flux and scale formation can produce overheating at the tube wall and result in tube failure. Hence, one must be very watchful and monitor tube side fouling which is affected by the feedwater quality and proper boiler water maintenance. Even if tube failures may not be the immediate concern, the decrement in energy transferred may be substantial and prompt a review of current water treatment practices.

NOMENCLATURE

A_i	inner tube area, ft^2/ft
A_t	total external area, ft^2/ft
A_w	area of average wall, ft^2/ft
C_p	gas specific heat, Btu/lboF
d_o	tube outer diameter, in.
di	tube inner diameter, in.
ff	fouling factors inside tubes, ft^2/hr°F/Btu
ffo	fouling factors outside tubes, ft^2/hroF/Btu
hi	heat transfer coefficients inside tubes, Btu/ft^2/hr°F
h_o	heat transfer coefficients outside tubes, Btu/ft^2/hroF
DH_S	enthalpy absorbed by steam, Btu/lb
K_n,	thermal conductivity of tube, Btu/ft/hr°F
q	heat flux, Btu/ft^2/hr
Q	duty, MMBtu/hr
S	surface area, ft^2
ΔT	log mean temperature difference, °F
T,t	gas and steam temperatures, °F
U	overall heat transfer coefficient, Btu/ft^2/hr°F
W	gas flow, lb/hr
W_s	steam flow, lb/hr
h	effectiveness of fin, fraction

Subscripts

f	temperature drop across fouling layer
1	entering
2	leaving

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The author

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