Effect of Fouling on Heat Transfer Surfaces in Boilers

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Abstract
Accumulation of unwanted materials inside pipes, machines or heat exchangers leads to various problems in liquid bearing systems, thereby interfering with its function. In this study, thermal circuit was developed, mathematical model formulated and subsequently used in the simulation of the effect of fouling on heat transfer surfaces in boilers. The investigation involved five different fouling materials, basic mechanism of deposit, techniques to control deposit in boiler and the results reveal that fouling progresses with time, and that fouling layers decreases and increases the inside and the outside diameter of the boiler tubes respectively, thus causing an increase in the pressure drop. It was also observed that one of the fouling materials, gypsum, investigated, exhibited higher deposition rate than all others considered in the study. This predicted information can be helpful in the reduction of fouling problems in boilers, noting that fouling of heat transfer surfaces is unavoidable but can be reduced to barest minimum, hence significant savings in power plant.

Keywords: fouling resistance, thermal circuit, heat transfer, coefficient, pressure, boiler

INTRODUCTION
Fouling in technical terms is the accumulation of unwanted material on heat transfer surfaces, where the material consists of either living organisms (bio-fouling) or a non-living substances (inorganic or organic). Fouling is usually distinguished from other surface-growth phenomena in that it occurs on a surface of a component, system or plant performing a defined and useful function, and that the fouling process impedes or interferes with this function. Fouling in boilers is dependent on the type of boiler design and the fuel being fired. Fouling in a chemical recovery boiler, a coal fired boiler, and a biomass fired boiler are different in many ways. In a chemical recovery boiler, fuel being used has a large quantity of alkaline inorganic material. This makes it necessary to operate the boiler in a narrow band and to 'soot blow' the heat transfer surface more frequently when compared to a coal fired boiler. In the case of a biomass fired boiler, even though the inorganic material percentage is very low, a large amount of fouling due to its very low melting temperatures can occur. The presence of alkaline materials like sodium and potassium salts make the coal ash have a very high tendency toward fouling in the convection heat transfer surfaces in boilers. Primarily the sulphates like calcium sulphate and sodium sulphate in vapor form in flue gases make the first layer of deposit on the heat transfer tubes which gives the binding strength for the deposit.

Whatever the cause of exact nature of the deposit, an additional resistance to heat transfer is introduced and the operational capability of the heat exchanger is correspondingly reduced. In many cases, the deposit is heavy enough to significantly interfere with fluid flow and increase the pressure drop required to maintain the flow rate through the exchanger. The rate of fouling depends on fouling factor, which varies from liquid to liquid, where always the temperature plays a key role. More so, the accumulation leads to various problems in fluid (liquid) bearing systems which can have a negative effect on total plant performance, causing lower production capacity and higher maintenance cost (Huque, Ali, and Kommalapati, 2009).

Some of the investigations in recent times on fouling were on types of deposition (Couch, 1994, Benson, Jones and Harb, 1993, Gupta, Rushdi, Browning and Wall, 2001), the possible causes (Su, Pohl, Holcombe and Hart, 2001, Skea, Bott and Beltagui, 2002)and the resulting problems (Babajide, 2007). The mechanisms and technologies available for the prevention of deposition problems in boilers were investigated under soot blowers (Bergemann, 2008), ash behavior prediction tools (Ma, Iman, Sears, Kong, Rokanuzzaman, McCollor and Benson, 2007), wet pretreatment of brown coal-fired power utility boiler using mineral additive (Vuthaluru, 1999), monitoring of fouling tendencies and rate (Valero and Cortes, 1999, Masia, n.d., Korbe, Losurdo, Lensselink, Ceiplik and Verhoeff, 2005, Kalisz and Pronobis, 2005), use of internal micro-cameras (Hansen and Blankinship, 2006), slagging indices to determine the composition of the ash present (Gupta,
Zheng, Wall, Tsumita, Kajigaya and Suzuki, 1994),
local blending to produce different effect in boiler
(Rushdi, Sharma and Gupta, 2003, Lawrence, Kumar,
Nandakumer and Narayana, 2006), antifouling
coatings using ceramics (Geoff, 2008), antifouling
technology (Young and Liu, 1999) and
intelligent sooth blowing (Korbe, Losurdo,
Lensselink, Ceiplik and Verhoeff, 2005 ;Teruel,
Cortes, Diez and Arauzo, 2005).

The major concern to researchers and boiler
engineers, therefore, has been to improve the
efficiency and performance of boilers, either by
experimental studies, computational techniques, or
technical experience gained over a period of time.
From the above, it is obvious that investigation on the
fouling on boilers is non-conclusive, hence the
present study.

**METHODOLOGY**
The study was holistically handled by developing the
thermal circuit and formulating the necessary models.

**Thermal Analysis**
The thermal circuit and the developed expressions for
the cross section to the direction of flow is represented below:

\[
\begin{align*}
&dR_0 = \frac{1}{UA} = dR_h + dR_{h,f} + dR_c + dR_{c,f} + dR_t \\
&or \quad \frac{1}{UA} = \left(\frac{1}{(hA)_h} + \frac{1}{(h_{f}A)_h} + \frac{1}{(h_{c}A)_c} + \frac{1}{(h_{c,f}A)_c} + \frac{1}{(h_{t}A)_t}\right) .
\end{align*}
\]

For uniformly distributed heat transfer surface areas,
\[
\frac{dA}{A} = \frac{dA_h}{A_h} = \frac{dA_c}{A_c} = \frac{dA_w}{A_w} .
\]

Thus,
\[
\frac{1}{UA} = -(\frac{1}{(hA)_h} + \frac{1}{(h_{f}A)_h} + \frac{1}{(h_{c}A)_c} + \frac{1}{(h_{c,f}A)_c} + \frac{1}{(h_{t}A)_t})
\]

where,
\[
R_w = \left[\frac{\delta x}{k_w A_w} \right] + \sum_{i} \left(\frac{\delta x}{k_i A_i} \right).
\]

\[
A_w = LBN_p = 2\pi LN
\]

Equations 8a and 8b are for flat wall and circular tube
respectively.

For a negligible tube wall thermal resistance,
\[
1 = \frac{1}{U_0} = \frac{1}{h_h} + \frac{1}{h_{f,h}} + \frac{1}{h_{c,h}} + \frac{1}{h_c}
\]
fouling resistance is determined by subtracting the
fouling resistance when the test section is clean (at
time zero) from that when fouled or dirty (Allmon,
Watson and Carpenter, 1991, Sadik and Hongtan,
2002), so that,
\[
R_f = R_d - R_c \text{ or } R_f = \frac{1}{U_f} - \frac{1}{U_c}
\]
The convective
heat transfer coefficient \( h_t \) is calculated using Dittus –
Boelter equations given by (Khurmi and Gupta,
2005, Cengel and Turner, 2001),

\[
\frac{\delta}{k} = \frac{1}{2\pi LN} \sum \left(\frac{d_{i+1}/d_i}{\delta_{x,i}}\right)
\]

For the heat transfer across boundaries,
\[
\frac{T_h - T_c}{dR_0} = U dA (T_h - T_c)
\]

and

**Figure 1: Thermal Circuit Model**
\[ \Delta T_m = \frac{T_1 - T_2}{\ln \left( \frac{T_1 - T_s}{T_2 - T_s} \right)} \]

Experimentally, the

\[ Q = UA \Delta T_m \]

\[ U_{sc} = \frac{Q}{A \Delta T_{m,c}} = \left( \frac{\dot{m}C_p}{(A \Delta T_{m,c})} \right) \]

\[ U_{sf} = \frac{Q}{A \Delta T_{m,f}} = \left( \frac{\dot{m}C_p}{(A \Delta T_{m,f})} \right) \]

\[ \Delta T_m = \frac{(T_s - T_i) - (T_s - T_o)}{\ln \left( \frac{T_s - T_i}{T_s - T_o} \right)} \]

\[ R_f = \frac{A}{\dot{m}C_p} \left[ \frac{(T_s - T_i) - (T_s - T_o)}{(T_o - T_i) \ln \left( \frac{T_s - T_i}{T_s - T_o} \right)} \right]. \]

Common existing fouling type is the “asymptotic” mode (Sadik and Hungtan, 2002), represented by the expression:

\[ R = R^* \left( 1 - e^{-\beta t} \right) \]

Where \( R^* \) is the asymptotic, fouling resistance \((m^2°C/kW)\) and \( \beta = 1/t_c \).

Percentage reduction in \( U_{sc} \) due to fouling:

\[ \Delta U = \frac{U_c - U_{sc}}{U_c} \times 100\% \]

or

\[ \Delta U = \frac{U_c R_f}{1 + U_c R_f} \times 100\% \]

Since \( R_f = \frac{1}{U_{sc}} - \frac{1}{U_{sf}} \).

Percentage reduction in heat transfer rate:

\[ \Delta Q = \frac{Q_c - Q_{sf}}{Q_c} \times 100\% \]

\[ = \frac{(UA\Delta T_m)_c - (UA\Delta T_m)_f}{(UA\Delta T_m)_c} \times 100\% \]

**Modeling**

With constant flow rate of fluid and controlled deposition rate of reaction, the mass balance over a controlled volume is given as:

Input = Output + Accumulation

Rate of deposition = Rate of removal + Rate of foul accumulation

which implies that, as given by (Sadik and Hungtan, 2002),

rate of foul accumulation = rate of deposition – rate of removal

\[ \frac{dR_f}{dt} = \phi_d - \phi_r. \]

If the deposit rate is constant and the removal rate is ignored, then

\[ R_f = \phi_f t \]

(Taborek, Aoki, Ritter, Palen and Knudsen, 1972) proposed that rate of deposition could be given as,

\[ \phi_d = \gamma_i R_e \left( \gamma_i \right)^e \]

where,

\[ R_e = \gamma_2 e^{-\frac{E}{R T_i}} \]

So that,

\[ \phi_d = \gamma_i \gamma_2 e^{-\frac{E}{R T_i}} \left( \gamma_i \right)^e. \]

The removal rate is given by,

\[ \phi_r = \gamma_3 \frac{\tau_s}{R_b} \]

where,

\[ \gamma_4 \frac{1}{\rho_f} \left( \frac{W}{A_o} \right)^2 \]

\[ \tau_s = \frac{\rho_f \left( \frac{W}{A_o} \right)^2}{R_b} \]

so that,

\[ \phi_r = \gamma_3 \gamma_4 \frac{W}{\rho_f R_b \left( \frac{W}{A_o} \right)^2} \]

therefore,

\[ \frac{dR_f}{dt} = \gamma_1 \gamma_2 e^{-\frac{E}{R T_i}} \left( \gamma_i \right)^e - \gamma_3 \gamma_4 \frac{W}{\rho_f R_b \left( \frac{W}{A_o} \right)^2} \]

hence,
Effect of Fouling on Pressure drop

The frictional pressure drops in the tube for a single-phase flow as given by (Sadik and Hungtan, 2002), is:

\[ \Delta P = 4f \left( \frac{L}{d_i} \right) \left( \frac{U_i^2}{2} \right). \]  

Pressure drop under clean condition:

\[ (\Delta P)_c = 4f_i \left( \frac{L}{d_i} \right) \left( \frac{U_i^2}{2} \right). \]  

Pressure drop under fouled condition:

\[ (\Delta P)_f = 4f_i \left( \frac{L}{d_i} \right) \left( \frac{U_i^2}{2} \right). \]  

so that that of the pressures is given as,

\[ \frac{\Delta P_f}{\Delta P_c} = \left( \frac{d_i}{d_j} \right)^5. \]  

Assuming fouling does not affect the friction factor (i.e. \( f_i = f_j \)) then,

\[ \frac{\Delta P_f}{\Delta P_c} = \left( \frac{d_i}{d_j} \right)^5. \]

RESULTS

The findings of this investigation are presented in figures 2 to 5. Figure 2 shows variation of fouling resistance with thickness. For all the materials investigated, the fouling resistance is found to be directly dependent on the fouling thickness and for any particular thickness, the resistance from Gypsum to heat transfer is least which increases for the other materials in the following order: Serpentine, Calcite, Biofilm and highest for Hermitaite. Though not indicated in the figure, it is to be noted that fouling does not immediately commence with the commisioning of a new boiler to heat transfer processes. For any particular tube in contact with liquid and gas on each side of the tube as show in figure 3, a polytrophic dependence of fouling resistance on time is observed. In any particular day after fouling has commenced, the resistance is greater on the water side of the tube than on the gas side, indicating possible solidification of the deposition on the surface of the tube in contact with water due to the lower temperature of the boiler tube side, and for the deposit to fuse to the tube wall and not rebound from the inertia force, it is necessary that the particles be sticky, which is often referred to as sintered or cemented deposits that form on convection surfaces due to an improper feed water treatment. As indicated in figure 4, the resistance in small diameter tubes of the boiler builds up sharp resistance to heat transfer, which decays asymptotically with Gypsum having
higher deposition buildup for all the materials investigated, as the tube diameter increases. As the internal diameter of the tube increases, the fouling pressure drops, due possibly to the reduced effluence of the strength of the first layer of deposition as illustrated in figure 5.

CONCLUSION

Fouling is an extremely complex phenomenon due primarily to a number of variables affecting it. This predicted information can be helpful in the reduction of fouling problems in boilers, noting that fouling of heat transfer surfaces is unavoidable but can be reduced to barest minimum, hence significant savings in power plant.

REFERENCES


APPENDIX

Figure 1: Graph of fouling resistance against fouling thickness

Figure 2: Fouling resistance against time

Figure 3: Fouling thickness against internal diameter of boiler tube

Figure 4: Fouling pressure drop against internal diameter of boiler tube