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Enhancement the Performance of Steam Generation Power Plants

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Abstract

This paper deals with study of the mechanism of heat transfer between the combustion of hot gases and water inside steam generator. The operating conditions in these applications are designed to maintain heat flux lower than critical heat flux (CHF) of tubes to prevent potential failure by overheating or burnout. Critical heat flux is a condition in which small increase in heat flux leads to abrupt wall overheating caused by transition from nucleate to film boiling.

A mathematical models are arranged, covered the parameters affected the mechanism of heat transfer such as fouling on both sides of tube surfaces. The results show good agreement with published work.

الخلاصـــــــة

أن هذه الدراسة تعنى بتحديد مميزات أداء وحدات توليد البخار في محطات الطاقة الكهربائية تحت تأثير الشوائب المترسبة ودراسة تأثير تلك الشوائب على فشل أنابيب المراجل البخارية .

تم عمل نموذج رياضي لتحديد مميزات أداء وحدات البخار بالاعتماد على التحليلات الحرارية والهيدروليكية الاساسية التي تصف سلوك جريان المائع تحت تأثير الشوائب المترسبة على جدران أنابيب المرجل البخاري والتي تؤثر على عناصر الدورة الحرارية وبشكل خاص معدل انتقال الحرارة والفيض الحراري الحرج.

لقد وجد هنالك تطابق بين النتائج التي تم الحصول عليها من التحليل الرياضي وبين ما نشر في الادبيات .

1. INTRODUCTION

Steam generator is the major component in the power plant. It is frequently called boiler. It is used to convert the liquid inside boiler tubes to the steam due to the hot gases of combustion on the outside of tubes. The combustion is accomplished in furnace. The mechanisms of heat transfer take place between combustion of hot gases and the liquid inside the tubes. It is well established that fouling on boiler tubes surface have a profound effect on heat transfer mechanism between hot gases and boiler tubes which is causing the overheating of the boiler tubes. Internal deposit developed during the water boiling process in the riser tubes of boiler fall in two categories. Some are found in situ based on the boiler itself such as the thin film of magnetite particles (Fe_3O_4) (1), which develops on the surface during operation. Other results from contaminating materials, which transported into the boiler from external sources such as corrosion products released from the feed water and condensate system leakage of corrosive materials. Deposit formation inside boiler tubes is still the most serious obstacle which causes considerable reduction in mass flow velocity, increasing heat losses, degradation in thermal efficiency and effect on the tube metal temperature. Several comprehensive reviews of worldwide research on fouling have been published.

Macbeth et. al. (2), Observed a small reduction in burnout heat flux of order (5-10) percent which results from a 0.1 mm thick deposit of porous magnetite compared to that of clean tube.

Macbeth et. al. (3), studied the effect of crud deposits on the frictional pressure drop in annular test section. They found the effect of crud deposit with single-phase water flow is large.

Glebov et. al. (4), give the results of test rig investigations of effective heat conduction of iron oxide.

Deposit of water wall Konakovo central power station. Results showed that with increasing in the multiplier parameter of heat flux and thickness deposition rate from (20 to 80) W/m, thermal conductivity of the deposits decreases from (0.7 to 0.55) W/mK.

Mizuno et. al. (5), investigated the effect of concentration, heat flux and pressure on the deposition of hematite particles on stainless steel.

Kitto (6), found that for large diameter boiler tube, the thin uniform deposits at sub critical pressure have only a moderate effect on frictional pressure drop. However, in super critical pressure boilers, the rippled deposits have been shown to dramatically increase the frictional pressure drop.

V. Ganaqpathy (7), studied the effect of fouling on both sides of boiler tubes. He found that exit gas temperature would increase, thus resulting in loss of energy and reduced steam production .Wall temperature can increase significantly leading to tube failures. Fouling on fireside leads to loss of steam output and can increase the gas side pressure drop.

2. MATHEMATICAL MODEL

The mathematical models which will be analyzed consist of a U-tube shape that compromised the down comer tube, where the fluids come to it from the bottom headers at liquid state. The other leg of U-tube represent the riser at which vapor nucleation occurs, starting with few individual sites at low heat fluxes to saturation steam at a quality which does not exceed 30% (8) before it return to the drum as shown in Fig.(1). After a long period of operation of boiler the fouling layer will be deposited on the waterside of the riser. The thickness of fouling layer decrease with the riser height, so that this thickness will be decreased to become a thin layer when part of the feed water changed to saturation steam upstream of the riser tube. The inside diameter (ID) deposit is generally concern in high temperature section. The thickest deposit may be expected on tubes that are in the hottest sections of boiler (9). As a result the use of hydrocarbons fuel in combustion process, solid product will be accumulated uniformly on the outer surface of the riser tube. Solid product facing the flue gas having a constant thickness and causing the riser tube to be fouled. Heat will be transported from the flue gases of combustion to the fluid flowing in the riser tubes (one dimension radial flow). The fouling layer causes a thermal resistance to the heat flow.

2-1 Water Tube Boiler Heat Transfer

In a boiler, the heat transfer takes place by conduction, radiation and convection between hot gases and liquid inside boiler tube as shown in Fig.(2). Since the overall performance of the furnace flow circuits is controlled to a large extent by the furnace radiation, the objective of the two-phase flow heat transfer evaluation is to prevent tube metal from overheating and failure. Boiling heat transfer coefficient is sufficiently high so that tube metal temperature is kept at acceptable levels as along as boiling conditions are maintained in the furnace tubes.

2-1-1 Radiation of Heat Transfer from Flue Gases

The main factors effecting radiant heat transfer in the boiler are: flame temperature, flame shape and fouling of heat transfer surfaces (10).

The heat produced by the furnace is expressed as:

$$q = HHV * \dot{m}_{fuel} * Losses \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The heat absorption by the tube (q) is expressed as:

$$q = st * sf * em * aso * \left(T_g^{\,4} - T_o^{\,4}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where

$$aso = \pi * d_o * L_r \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Shape factor will be taken unity (11), since the boiler furnace is like a large room. The flame emissivity value depends upon luminosity, furnace volume, and temperature. The emissivity factor it may range from a low approximately 0.65 to a high of nearly 0.95 (12).

Heat resulted from combustion process will be changed from the radiation form to the conductive form. Hence, heat rate passes through the heating surface of the tube will be given in the form:

$$q = \frac{1}{\sum R_T} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

$$R_T = R_{fo} + R_m + R_{fi} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

The thermal resistance, which resists the heat flow through the tube, can be defined in the following:

$$R_m = \frac{1}{2 * \pi * k_m * L_r} \ln(\frac{d_o}{d_i}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

$$R_{fo} = \frac{1}{2 * \pi * K_{fo} * L_r} \ln(\frac{d_{fo}}{d_o}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

$$R_{fi} = \frac{1}{2 * \pi * K_{fi} * L_r} \ln(\frac{d_i}{d_{fi}}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

The tube inside diameter which changes due to formation of fouling inside it is given as:

$$d_{fi} = d_i - 2t_{fi} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

For the fouling tube the surface area will be based on the outer diameter of the fouling tube (d_{fo}):

$$d_{fo} = d_o - 2t_{fo} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

2-1-2 Two-Phase Flow Heat Transfer

Chen (13) has proposed a correlation that has been generally accepted as one of the best available. The correlation covered both the saturated and the two phase forced convective region. It is assumed that both nucleate and convective mechanism occur to some degree over the entire range of the correlation mechanism are additive.

The suppression assumptions are used as in the following:

$$h_{Tp} = h_c + h_{nb} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

1. Convective contribution Based on the Deittus-Boelter relation ship for a liquid flowing alone in a heated conduit (13) proposed for two-phase flow fluid:

$$h_c = 0.023 * (\mathrm{Re}_f)^{0.8} * (\mathrm{pr}_f)^{0.4} * (\frac{K_f}{d_i}) * F \quad \ldots\ldots\ldots\ldots\ldots\ldots (12)$$

where:

$$\mathrm{Re}_f = \frac{G_i * d_i * (1 - x_i)}{\mu_f} \quad \ldots\ldots (13)$$

$$\mathrm{pr}_f = \left(\frac{\mu\,Cp}{K}\right)_f \quad \ldots\ldots (14)$$

The parameter F is calculated by (13)

$$F=1 \qquad \text{for} \quad 1/x_{tt} \le 0.1 \quad \ldots\ldots (15)$$

$$F = 2.35\left(\frac{1}{x_{tt}} + 0.213\right)^{0.736} \qquad \text{for} \quad 1/x_{tt} > 0.1 \quad \ldots\ldots (16)$$

where xtt is:

$$x_{tt} = \left(\frac{1 - x_i}{x_i}\right)^{0.9}\left(\frac{\rho_g}{\rho_f}\right)^{0.5}\left(\frac{\mu_g}{\mu_f}\right)^{0.1} \quad \ldots\ldots (17)$$

2. Nucleate boiling contribution (h_{nb})

Chen (13) equation was taken as the basis for the evaluation of the nucleate boiling component. Their pool boiling analysis was modified to account for the thinner boundary layer in forced convective boiling and the lower effective superheat that the growing vapor bubbles.

The modified Chen equation becomes:

$$h_{nb} = 0.00122 * C * \Delta T_{sat}^{\ 0.24} * \Delta P_{sat}^{\ 0.75} * S \quad \ldots\ldots (18)$$

where:

$$C = \frac{K_f^{\ 0.79} * CP_f^{\ 0.45} * \rho_f^{\ 0.49}}{\sigma^{0.5} * \mu_f^{\ 0.29} * h_{fg}^{\ 0.24} * \rho_g^{\ 0.24}} \quad \ldots\ldots (19)$$

$$\Delta T_{sat} = T_i - T_o \quad \text{(20)}$$

$$\Delta P_{sat} = P_i - P_{sat} \quad \text{(21)}$$

$$Re_{Tp} = Re_f * F^{1.25} * 10^{-4} \quad \text{(22)}$$

$$S = \begin{bmatrix} \left(1+0.12(Re_{Tp})^{1.14}\right)^{-1} & \text{For } Re_{Tp} < 32.5 \\ \left(1+0.42(Re_{Tp})^{0.76}\right)^{-1} & \text{For } Re_{Tp} > 32.5 \end{bmatrix} \quad \text{(23)}$$

When we use the Chen convective contribution for riser tube the formation of fouling must replace the inside diameter for clean tube with that of fouling tube.

2-2 Burnout Correlations

Several correlation are available (2,14,15). Ganaqpathy (15) was used to find the critical heat flux inside a vertical tube. The correlation has the following form:

$$q_{cr} = 0.016212*10^6 * (h_{fg} * d_{ir})(G_{ir}/10^6)^{0.51} * (1 - x_o) \quad \text{(24)}$$

where actual allowable burnout heat flux lower on the order (10 to 30) %.

$$q_{cr} = {}^{q_{cr}}\!/_{1.3} \quad \text{(25)}$$

The root mean square error (R.M.S) on available data was 15% and 8% at 140 bar and 80 bar respectively.

2-3 Boiler Tube Waterside Fouling

After along period of operation crude layer will be deposited on the waterside of the riser wall and the thickness is increased according to the increasing operation time. The deposit weight (w) was proportional to the heat flux according to the following equation (16):

$$W = \frac{q * ci * t}{h_{fg} + Cp(T_{sat} - T_b)} \quad \text{(26)}$$

The weight of crude deposits can be expressed as:

$$W = \rho_{fi} * t_{fi} \quad \text{(27)}$$

The thickness of crude deposit is given by:

$$t_{fi} = K_{fi} * R_{fi} \quad \text{(28)}$$

Sub. eq. (28) into eq. (27) yield:

$$W = \rho_{fi} * K_{fi} * R_{fi} \quad \text{(29)}$$

2-4 Water Tube Boiler Circulation

Rational design of boiler circuits to ensure the necessary circulation of the contained fluid requires the evaluation number of variables. In establishing these variables use is made of accumulated data on limiting values and design criteria derived from laboratory test and measurements from operating boilers.

The principle of circulation in any natural-circulation boiler is shown in Fig.(1). The saturated water flows from the steam drum high in the boiler, through the supply or "down comer" tubes, located in the cooler part of the boiler to the bottom or "mud drum". From mud drum, the water flows back to steam drum through the evaporator or "riser" are separated and the steam is washed and dried before it sent to the super heater. Basically the flow of water should:

➊ Prevent burnout

➋ Prevent on-load corrosion.

2-4-1 Pressure Losses in Riser Tube

Losses in riser tube include all the losses that take place in down comer tube in addition to acceleration losses. The individual pressure drops vary considerably along the riser the riser tube. In comparison with down comer tube, the case of two-phase requires additional information on the phase velocities and phase distribution.

The homogenous flow model remains the best for calculation. The losses in the riser tube consist of:

2-4-1-1 Acceleration Pressure Drop $(\Delta p_{acc})_{Tp}$

The change in static pressure drop of flow as a result of acceleration can be calculated from the change in flow momentum as follows (15):

$$\left(\frac{\partial P}{\partial l}\right)_{Tp} = G_i^{\,2} \geq \frac{\partial}{\partial l}\left[\frac{X^2 \upsilon_g}{\alpha} + \frac{(1-X)^2}{(1-\alpha)}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (30)$$

$$(\Delta\ P_{acl})_{Tp} = G_i^{\,2}\left[\left\{\frac{X^2}{\rho_g} + \frac{(1-X)^2}{\rho_f}\right\}_o - \left\{\frac{X}{\rho_g} + \frac{(1-X)^2}{\rho_f}\right\}_i\right] \ldots (31)$$

2-4-1-2 Hydrostatic Pressure Drop $(\Delta\ p_{grav})_{Tp}$

The change in the potential energy of the fluid. Homogeneous model gives this loss as:

$$(\Delta\, Pgrav)_{Tp} = \rho_{Tp} * g * L_r \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (32)$$

$$\rho_{Tp} = \frac{x}{\rho_g} + \frac{1-x}{\rho_f} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (33)$$

2-4-1-3 Friction Pressure Drop $(\Delta p_f)_{Tp}$

Kohler (17) defined the homogeneous flow model describes a two-phase flow in a similar way to single-phase.

$$(\Delta\, P_{frict.})_{SP} = f * \frac{L_d * G_i^{\,2}}{2 * d_{id} * \rho_f} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (34)$$

and:

$$(\Delta P_{frict})_{Tp} = \varphi L_0^{\,2} * (\Delta P_{frict})_{sp} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (35)$$

where:

$$\varphi L_o{}^2 = \frac{(\Delta P_{frict})_{Sp}}{(\Delta P_{frict})_{Tp}} \quad \text{……………………………………………} (36)$$

The Friedel equation (17) comprises an empirically determined products approach to calculate the two-phase multiplier. For vertical upward and horizontal flow this results:

$$\varphi L_0{}^2 = E1 + \left[\frac{3.42 * E2 * E3}{F_{rf}{}^{0.045} * W_{ef}{}^{0.035}}\right] * B \quad \text{……………………………………} (37)$$

where:

$$\mathbf{E1 = (1 - x)^2 + X^2\left[\frac{\rho_f f_g}{\rho_g f_f}\right]} \quad \text{………………} (38)$$

$$E2 = x^{0.78}\,(1-x)^{0.24} \quad \text{……………………………………………} (39)$$

$$E3 = \left(\frac{\rho_f}{\rho_g}\right)^{0.91}\left(\frac{\mu_g}{\mu_f}\right)^{0.91}\left(1-\frac{\mu_g}{\mu_f}\right)^{0.7} \quad \text{…………………………………..} (40)$$

where:

$$\mathbf{F_r = \frac{G_i{}^2}{g * d_{ir} * \rho_{Tp}}} \quad \text{……………………………………..} (41)$$

$$We = \frac{G_i{}^2}{\rho_{Tp}} \quad \text{………………………………………………………..} (42)$$

where (B) is term for rough tubes given as:

$$B = 0.5\left[1 + 10^{-200\,(\varepsilon/d_{ir})}\right] \quad \text{………………………………………………..} (43)$$

3. RESULTS AND DISCUSSION

The waterside and fireside distribution along the riser tube is depicted in Figures (3) and (4) respectively. It can seen that the temperature on both sides of tube is deceased when the fluid moves upwards as a result of decreasing the rate of heat transmitted from the flue gas to the flowing liquid inside the tube.

When the fouling deposits on the tube sides, both waterside and fireside temperature at each section will be increased, because the fouling have a low thermal conductivity which impend the heat produced from the flue gases to transmit across the tube wall to the fluid inside tube.

The increase in the temperature values directly proportional to the thickness of the fouling layer. So, it can be seen that the highest temperature is existing at the lower section of the tube.

The increase in the temperature will drastically reduce the life of the tube. Excessive stresses associated with thermal expansion and different loading, leading to the tube cracks and failure. It can be seen also that a small layer of fouling layer increases the exit gas temperature as shown in Fig.(5).

Figure (6) shows the behavior of heat flux. It can be seen that the heat flux is decreased along the riser height according to decrease in degree of superheat along the tube.

The degree of superheat is inversely proportional with increasing fouling thickness. The fouling acts as a thermal barrier to lower the heat flow through the wall and on the other hand increase the heat losses in comparison with the case of a clean tube.

The pressure drop due to acceleration is decreased along the riser tube as a result of the change in the momentum which its value upstream of the tube is reduced due to increase in the steam quality along with the decrease in thickness of the liquid film adjacent to the surface as shown in Fig.(7).

The increment in fouling layer at different segments of the tube caused a rapid increase in the acceleration pressure drop, which is associated with the increase in the steam quality as shown in Fig.(8).

The pressure drop due to friction is shown in Fig.(9). It can be seen that frictional pressure drop is increased with the increment in fouling layer. The effect of two-phase multiplier is very low on the variation of pressure drop due to friction since, its value slightly changed with increment of fouling layer because the seam quality remain unchanged as shown in Fig.(10). A possible explanation for this large frictional pressure drop in the case of fouling compared with that of clean is that deposits produced a bigger drag on the flow than clean tube (high mass velocity).

4. CONCLUSION

Fouling, like vapor blanketing, has other adverse effects than loss of heat transfer capabilities, especially when it occurs on the waterside of the boiler tubes. In this case tube overheats and failure may be hazard. Beyond these deposits fouling acts as concentration cell for corrosive agents, which in combination with higher corrosion rate at elevated temperature lead to tube failure.

The increase of wall temperature will drastically reduce the life of the tube. Excessive stresses associated with thermal expansion and different loading, lead to tube cracks and failure.

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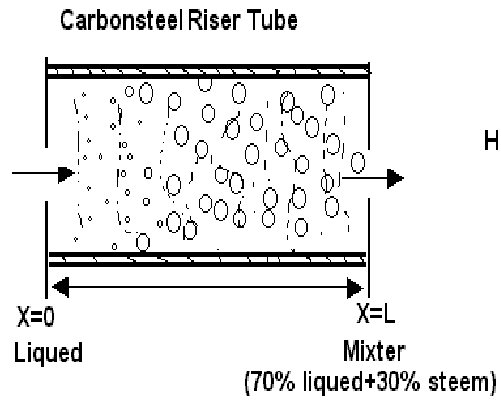
NOMECLATURE

Symbols		
Ci	Concentration of corrosion product	PPm
d_I	Inside diameter of clean riser tube	m
d_{id}	Inside diameter of down comer tube	m
d_{fi}	Inside diameter of fouled riser tube	m
d_o	Outside diameter of clean riser tube	m
d_{fo}	Outside diameter of fouled riser tube	m
Em	Flame emissive	
F	Convective boiling factor	
f	Friction factor	
Gi	Mass flow velocity	K g/m^{2}sec
H	Heat transfer coefficient	W/m^{2}K
H_{fg}	Latent heat of vaporization	J/kg K
Hi	Enthalpy of the fluid	J/kg K
K_{fi}	Thermal conductivity of Inside Fouling Layer	W/m K
K_{fo}	Thermal conductivity of Outside Fouling Layer	W/m K
K_m	Thermal Conductivity of Tube Metal	W/m K
L	Tube length	m
LHV	Lower heating value	KJ/kg
$\dot{m}$	Fluid mass flow rate	Kg/ sec
$\dot{m}_f$	Fuel mass flow rate	Kg/ sec
P	Boiler operating pressure	N/m^2
Pi	Saturation pressure at Inside Wall Temperature	N/m^2
P_{sat}	Saturation pressure at Fluid Saturation Temperature	N/m^2
ΔP_{acl}	Acceleration pressure drop	N/m^2
ΔP_{frict}	Acceleration pressure drop	N/m^2
ΔP_{grav}	Acceleration pressure drop	N/m^2
ΔT_{sat}	Degree of superheat	K
Q	Heat transfer rate	W
Q	Heat flux	W/m^2
q_{cr}	Critical heat flux	W/m^2
q_{crs}	Safety critical heat flux	W/m^2
R_t	Total thermal resistance	m^2 K/W
S	Supperation factor	
Sf	Shape factor	
St	Stefan Boltzman constant	

T_b	Bulk Temperature of fluid	
Tg	Flue gas temperature	K
Ti	Inside wall temperature	K
To	Outside wall temperature	K
t_{fo}	Thickness of outer fouling layer	m
t_{fi}	Thickness of inner fouling layer	m
T_{sat}	Saturation Temperature of Fluid	K
W	Weight of fouling layer	Kg/m^2
X	Local steam quality	
We	Weber number	
X_{cr}	Burnout steam quality	
X_{tt}	Martinelli parameter	
Z	Length of riser tube segment	m
Greek		
A	Void fraction	
E	Tube roughness	
H	Boiler efficiency	
M	Dynamic viscosity	Kg/m sec
P	Density	Kg/m^3
Σ	Surface tension	N/m
N	Specific Volume	m^3/kg
$\Phi^2 L_o$	Two-phase multiplier friction factor	
Subscripts		
C	Convection	C
D	Down comer	D
f	Fluid	f
f_I	Waterside	f_I
f_o	Fireside	f_o
G	Gas	G
I	Inlet	I
Nb	Nucleate boiling	Nb
O	Outlet	O
R	Riser	R



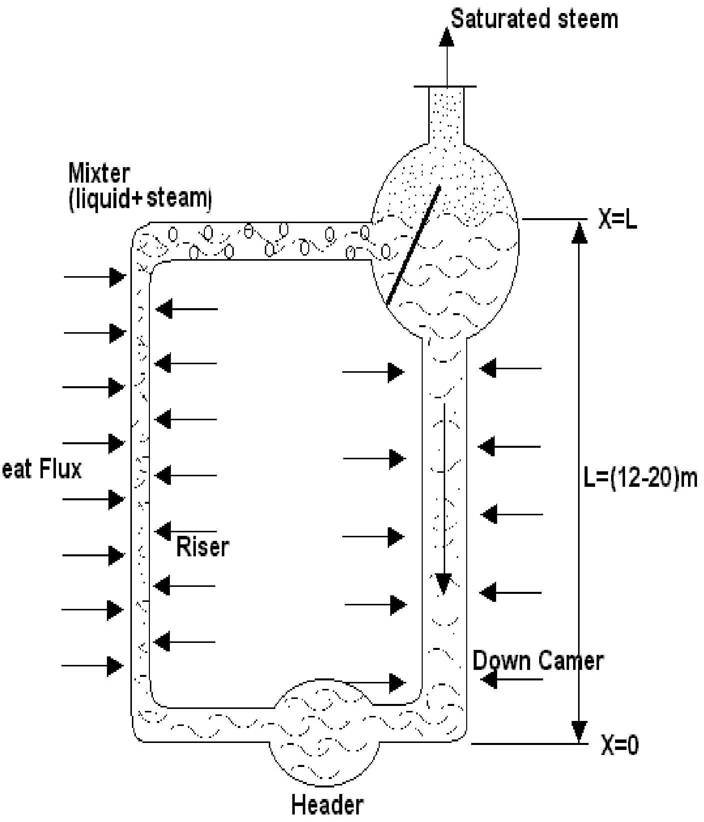


Fig.(2) Riser Tube (Case Study) ***Fig.(1) Elementary Water Boiler Tube***

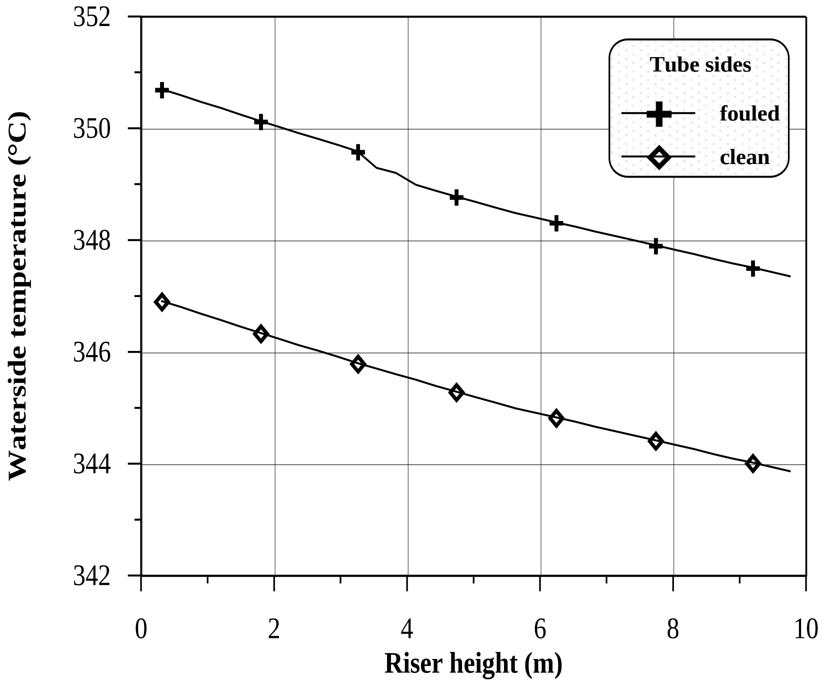


Fig.(3) Variation of Waterside Temperature along the Riser Height

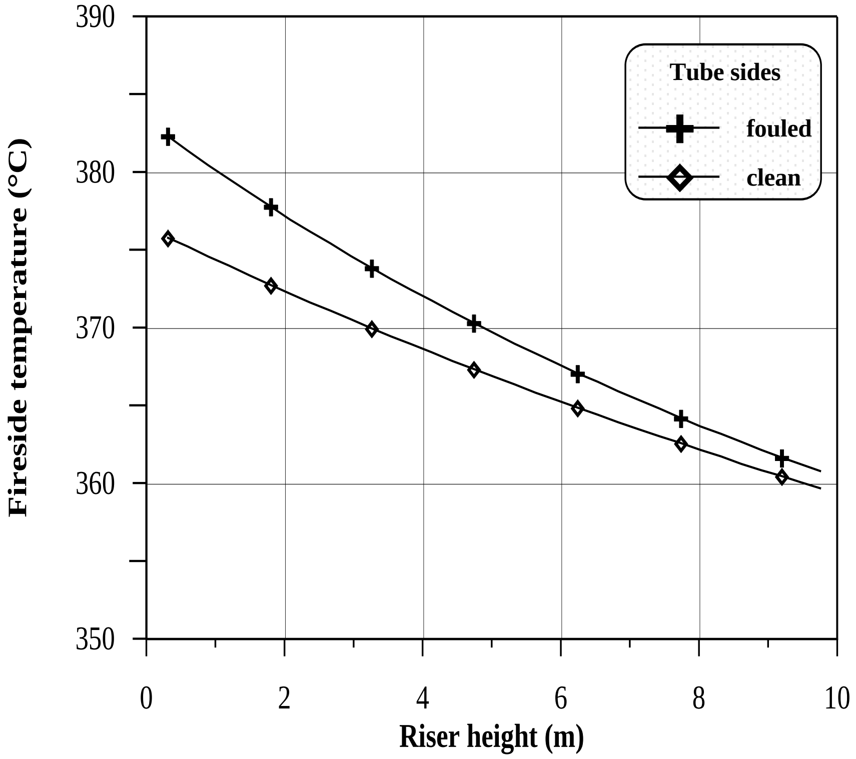


Fig.(4) Variation of Fireside Temperature along the Riser Tube

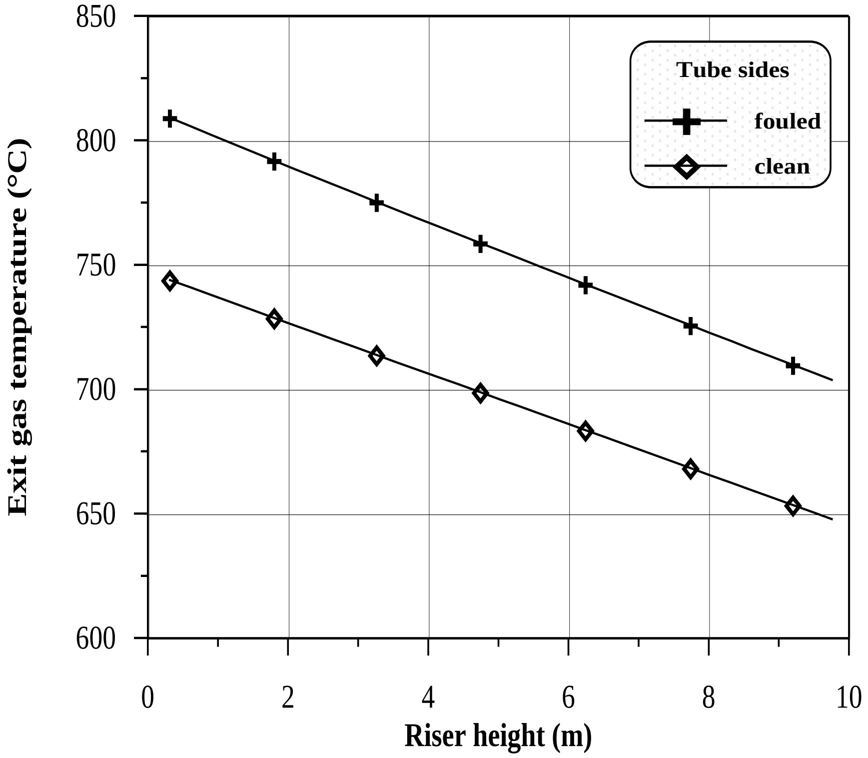


Fig.(5) Variation of Exit Gas Temperature along the Riser Height

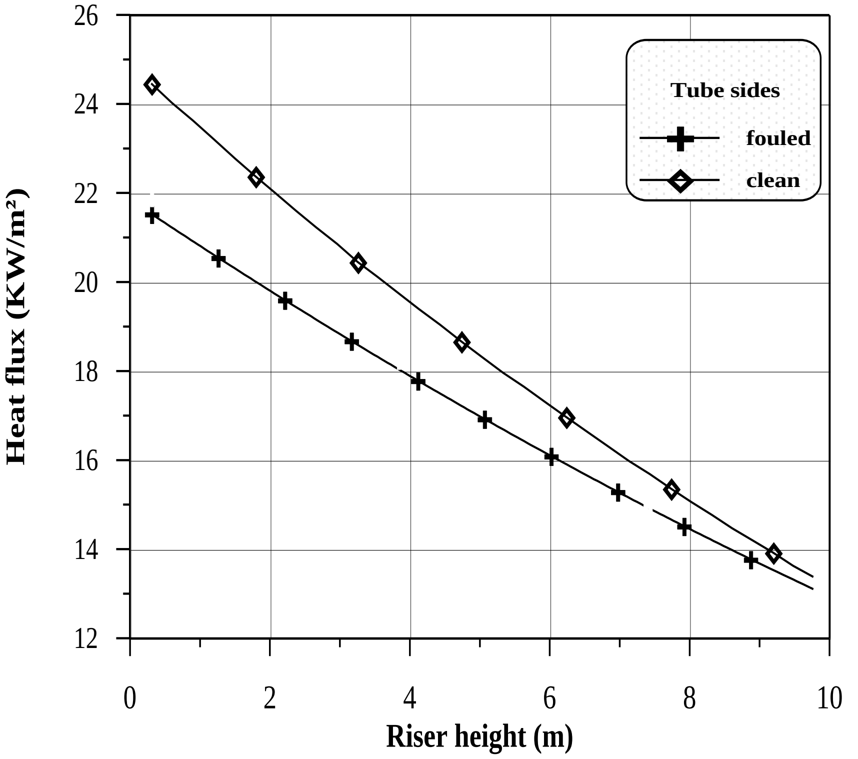


Fig.(6) Variation of Heat Flux along the Riser Height

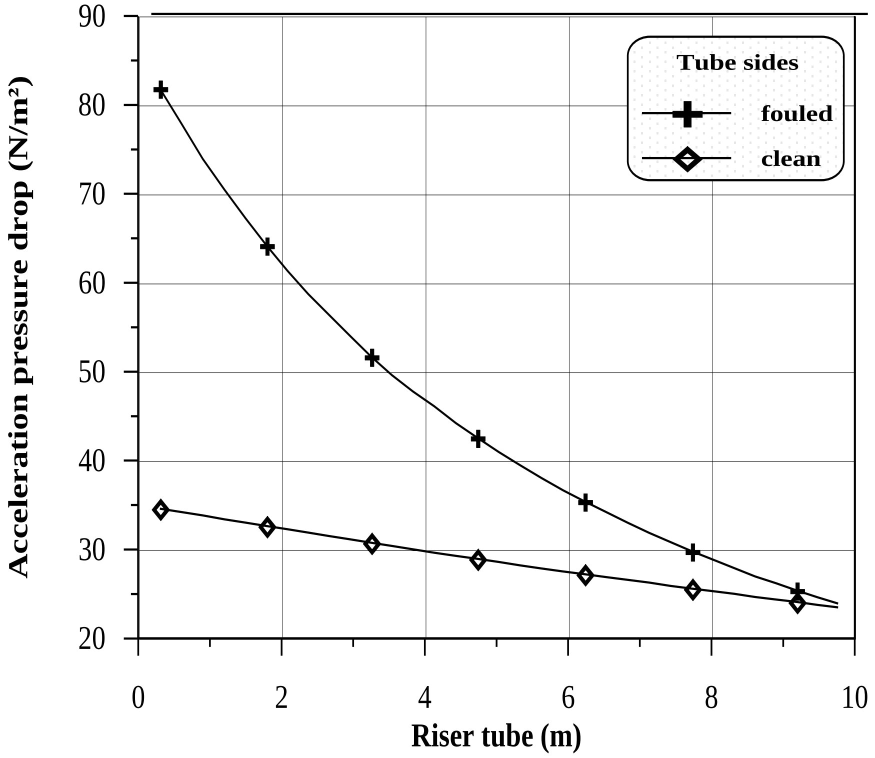


Fig.(7) Variation of Acceleration Pressure Drop along the Riser Height

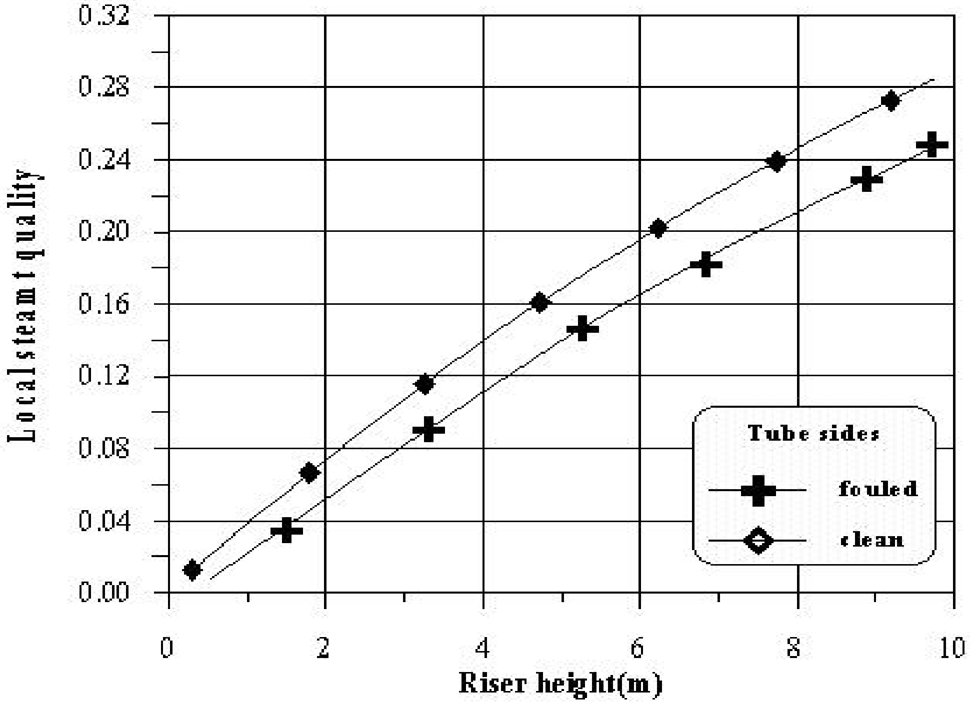


Fig.(8) Variation of Steam Quality along the Riser Height

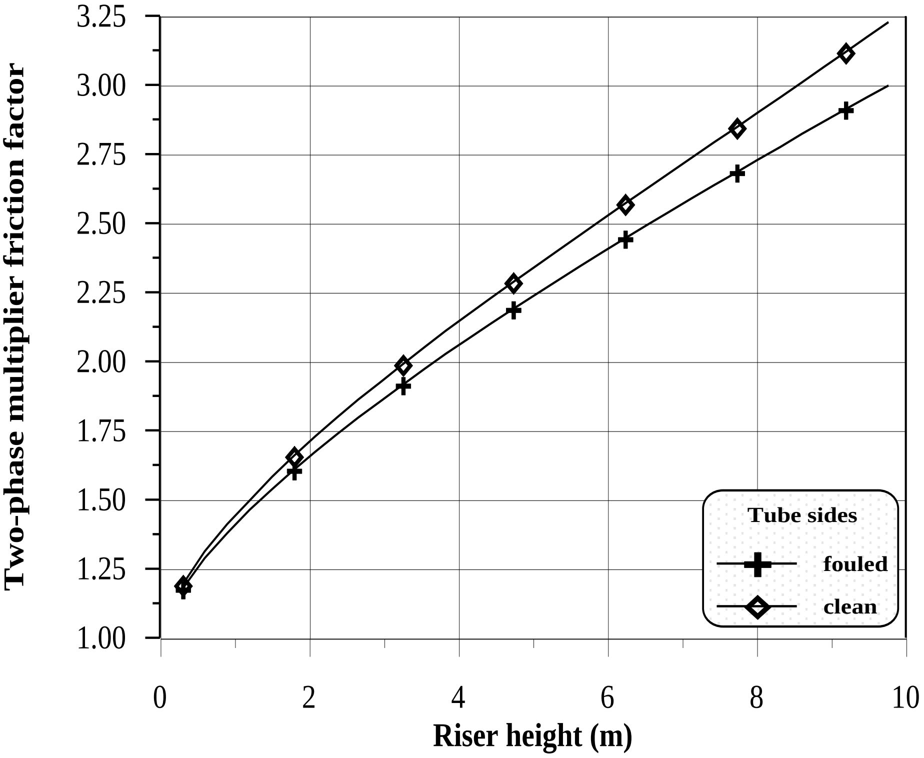


Fig.(9) Variation of Two-Phase Multiplier Friction Factor along Riser Height

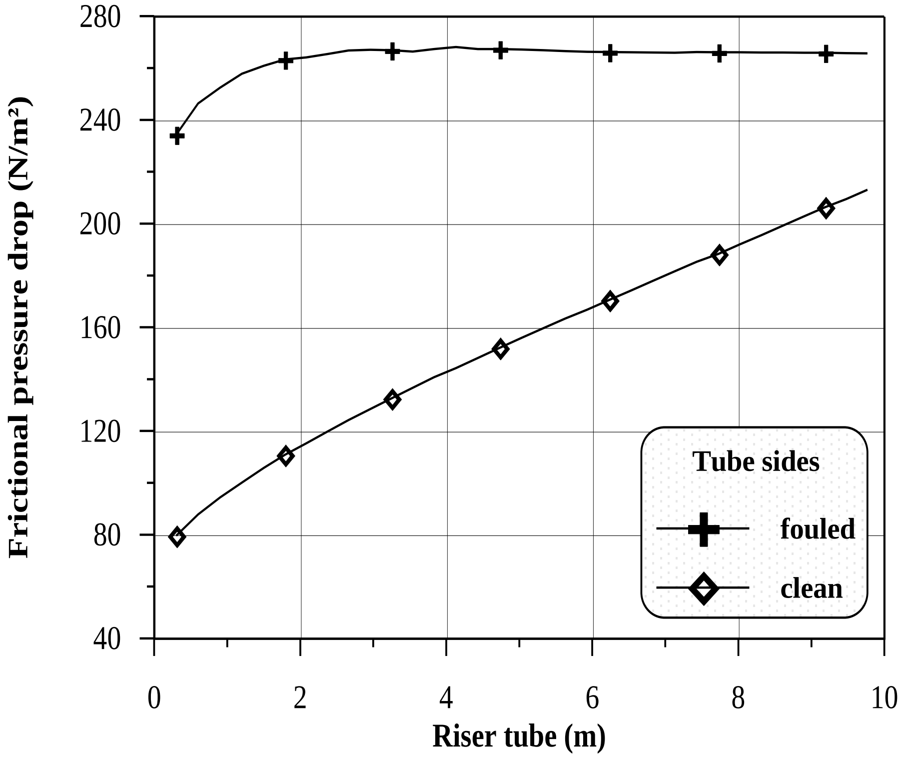


Fig.(10) Variation of Frictional Pressure Drop along the Riser Height