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WATER CIRCULATION INVESTIGATION TO AVOID TUBE FAILURE IN WATER TUBE BOILERS

HUANG J

John Thompson, Sacks Circle, Belville South, 7530, Cape Town, South Africa
jianchangh@johnthompson.co.za

Abstract

Industrial water tube boilers work on the principle of natural circulation. It is very important at the design stage to ensure that there is enough water present at all parts of the flow passages, otherwise pipe overheating will possibly occur which often leads to tube failure. This paper introduces the water circulation analysis employed in John Thompson, using traditional homogeneous models as well as modern software. The study provides some insight into the circulation characteristic and guidance for new designs, to ensure safe boiler operation. The calculation theory and principles are presented along with characteristic figures. A case study is given which may assist operating engineers and technicians to understand the boiler in more depth from a sensible perspective.

Keywords: boiler, water circulation, tube failure

Introduction

In boiler systems, water circulation refers to the flow of water, steam and their mixtures in tubes around the water/steam circuits. Industrial water tube boilers work on the principle of natural circulation. There are other types of circulation of water/steam that can be employed in a boiler; for example, forced circulation which involves pumps. Natural circulation is particularly common in industrial water tube boilers because of its simplicity and reliability, and also for economic reasons. Natural circulation refers to a system where water is driven through the system by buoyance forces, in other terms, density differences due to heating inputs into the system. In general, sub-cooled water flows down through a large diameter pipe called a downcomer, passes though bottom headers and then enters the vertical pipes forming the furnace wall, rising up as a mixture of water and steam. A boiler system with natural circulation is shown schematically in Figure 1.

It is very important at the design stage to ensure that there is enough water present at all parts of flow passages, including the four panel wall tubes, the main bank tubes in the case of a bi-drum boiler, and the evaporator tubes in the case of a mono-drum boiler. Overheating can take place simply because there is not enough water flow to 'cool off' the metal tube from the inside. Any investigation into water circulation should provide answers to three questions:

1. How should the two-phase flow resistance be calculated?
2. What is the circulation ratio at any local point of a boiler tube system?
3. What are the criteria to ensure safe operation?

This paper will address these questions, giving a general introduction and also the calculation methods. A case study will be presented using these methods.

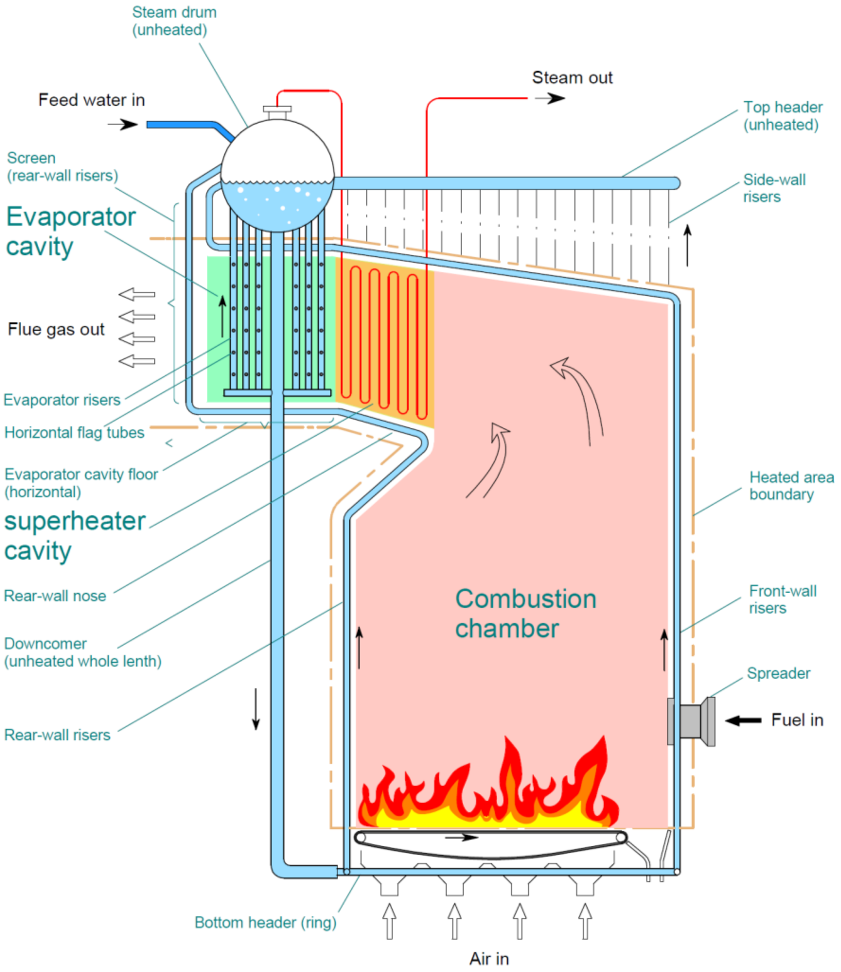

Figure 1. Industrial water tube boiler with natural circulation.

Two-phase flow pressure drop through a pipe

The two-phase flow of water/steam though a boiler system is determined by a balance between the driving force, which is the density difference, and flow resistance balance. The most commonly used method for two-phase pressure drop in boiler application is the homogeneous model, which assumes the two-phase as single-phase possessing mean fluid properties. These properties basically include the mean density and mean viscosity. Figure 2 shows the momentum conservation in a homogeneous model. The model has been in use in various forms in adiabatic two-phase flow and refrigeration systems for a considerable time (Collier and Thome, 1994). Two important assumptions in a homogeneous model are:

1. equal vapor and liquid velocities: $\bar{u} = u_{\mathrm{f}} = u_{\mathrm{g}}$,
2. thermodynamic equilibrium between the phases.

Components of pressure gradients can be derived from the momentum conservation equation:

$$-A \cdot dP - F_{\mathrm{fric}} - F_{\mathrm{elev}} = \dot{m} \cdot d\bar{u} \qquad (1)$$

The individual forces are:

$$\begin{cases} F_{\text{fric}} = \tau_{\text{w}} S_{\text{wet}} dz = \tau_{\text{w}} \dfrac{4A_{\text{c}}}{d_{\text{h}}} dz = \dfrac{4\tau_{\text{w}}}{d_{\text{h}}} \cdot A_{\text{c}} dz & (a) \\ F_{\text{elev}} = \bar{\rho} g \sin\theta \cdot A_{\text{c}} dz & (b) \\ F_{\text{acce}} = \dot{m} d\bar{u} = G \dfrac{d\bar{u}}{dz} \cdot A_{\text{c}} dz & (c) \end{cases} \tag{2}$$

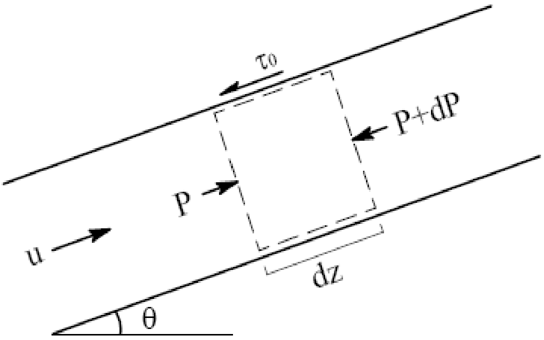

Figure 2. Conservation of momentum in a homogeneous model.

For the frictional pressure gradient, τ_{w} is expressed in terms of a two-phase friction factor:

$$\tau_{\text{w}} = \frac{1}{4} f_{\text{tp}} \left(\tfrac{1}{2} \bar{\rho} \bar{u}^2 \right) = \frac{1}{8} \cdot f_{\text{tp}} \frac{G^2}{\bar{\rho}} \tag{3}$$

The two-phase frictional pressure gradient can now be expressed as:

$$-\left(\frac{dP}{dz} \right)_{\text{fric}} = \frac{4\tau_{\text{w}}}{d} = f_{\text{tp}} \frac{G^2}{2\bar{\rho} d} \tag{4}$$

The two-phase friction factor f_{tp} can be calculated using any single-phase friction factor equation with the Reynolds number determined using mean fluid properties or, alternatively, f_{tp} can be determined directly from measured two-phase pressure drops. The latter usually has higher accuracy for the specified testing conditions.

The homogeneous model assumes the two-phase flow as single-phase, and there are three properties to be defined, namely the two-phase mean velocity, density and viscosity. The mean density $\bar{\rho}$ is defined by the basic conservation of mass:

$$\bar{\rho} = \frac{\dot{m}}{Q} = \frac{\dot{m}}{Q_{\text{g}} + Q_{\text{f}}} = \frac{1}{\dfrac{x}{\rho_{\text{g}}} + \dfrac{1-x}{\rho_{\text{f}}}} \tag{5}$$

The mean velocity $\bar{u}$ is determined accordingly:

$$\bar{u} = \frac{\dot{m}}{\bar{\rho} A_{\mathrm{c}}} \tag{6}$$

The two-phase mean viscosity can be evaluated in many ways, while the following conditions must be satisfied:

$$\begin{cases} x = 0, \bar{\mu} = \mu_{\mathrm{f}} \\ x = 1, \bar{\mu} = \mu_{\mathrm{g}} \end{cases} \tag{7}$$

Three definitions are summarised by Collier and Thome (1994), as given in Equation (8). Of these, the most commonly used definition of $\bar{\mu}$ is probably that proposed by McAdams *et al* (1942), which has the form similar to the definition of $\bar{\rho}$. Another definition of $\bar{\mu}$ often used in the design of water tube boilers is $\bar{\mu} = \mu_{\mathrm{f}}$ (Chisholm, 1983), but this definition does not meet the conditions specified in Equation (7). Other definitions of mean two-phase viscosity are also possible. Collier and Thome (1994) argued that the failure to establish an accepted definition is that the dependence of the friction factor on viscosity is small.

$$\begin{array}{lll} \text{McAdams et al., 1942:} & \bar{\mu} = \left(\dfrac{x}{\mu_{\mathrm{g}}} + \dfrac{1-x}{\mu_{\mathrm{f}}} \right)^{-1} & (a) \\ \text{Cichitti et al., 1960:} & \bar{\mu} = x\mu_{\mathrm{g}} + (1-x)\mu_{\mathrm{f}} & (b) \\ \text{Dukler et al., 1964:} & \bar{\mu} = \bar{\rho} \left[\mathrm{x} \dfrac{\mu_{\mathrm{g}}}{\rho_{\mathrm{g}}} + (1-x) \dfrac{\mu_{\mathrm{f}}}{\rho_{\mathrm{f}}} \right] & (c) \end{array} \tag{8}$$

When the mean fluid properties defined, pressure gradients of the three components can then be integrated stepwise to obtain the pressure drops, provided a number of simplifications are made. These include assuming f_{tp}, ρ_{f}, and ρ_{g} as constant and x changes linearly over the channel length. The final form of the integration of the three components can be given as:

$$\begin{cases} -\Delta P_{\mathrm{fric}} = \displaystyle\int_{\mathrm{z=0}}^{\mathrm{z=L}} f_{\mathrm{tp}} \cdot \frac{G^2}{2\bar{\rho} d} \cdot dz = f_{\mathrm{tp}} \cdot \frac{G^2}{2\rho_{\mathrm{f}} d} \cdot L \cdot \left[1 + \frac{x_{\mathrm{i}} + x_{\mathrm{o}}}{2} \left(\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{g}}} - 1 \right) \right] & (a) \\ -\Delta P_{\mathrm{acce}} = \displaystyle\int_{\mathrm{z=0}}^{\mathrm{z=L}} G d\bar{u} = G\left(\bar{u}_{\mathrm{o}} - \bar{u}_{\mathrm{i}}\right) = G^2 \left(x_{\mathrm{o}} - x_{\mathrm{i}}\right)\left(\frac{1}{\rho_{\mathrm{g}}} - \frac{1}{\rho_{\mathrm{f}}}\right) & (b) \\ -\Delta P_{\mathrm{elev}} = \displaystyle\int_{\mathrm{z=0}}^{\mathrm{z=L}} \bar{\rho} g \sin\theta \; dz = \frac{\rho_{\mathrm{f}} \rho_{\mathrm{g}}}{\rho_{\mathrm{f}} - \rho_{\mathrm{g}}} \cdot \frac{Lg \sin\theta}{x_{\mathrm{o}} - x_{\mathrm{i}}} \cdot \ln \frac{1 + x_{\mathrm{o}} \left(\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{g}}} - 1 \right)}{1 + x_{\mathrm{i}} \left(\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{g}}} - 1 \right)} & (c) \end{cases} \tag{9}$$

The homogeneous model provides a simple method for computing *acceleration* and *gravitational* components of pressure drop, and remains a common method of evaluating two-phase *frictional* pressure gradients. Up until the 1940s, this method, with mean viscosity taken as that of liquid, was used exclusively in designing water tube boilers with good agreements. Later research indicated that this was because of the high mass velocity in such devices (Chisholm, 1983).

Circulation ratio

In a two-phase flow boiling system, the circulation ratio is defined as the mass ratio of liquid entering to the amount of liquid vaporised in the pipe section:

$$R = \frac{\dot{m}}{\dot{m}_{\mathrm{g,out}}} = 1/x_{\mathrm{out}} \tag{10}$$

The circulation ratio is an important factor, as it indicates the amount of steam generated at the tube exit. Sufficient water presence at all parts of the boiler system is essential to ensure that the tubes are adequately cooled. For a given piece of pipe, local values of the circulation ratio can be calculated as for the whole tube, provided the local heat inputs are known. The calculation of circulation ratio requires heat and momentous balance of the fluid, in this case water. Heat input is the driving force for circulation as it generates steam and reduces the density of the mixture, which flows up and cooler water with higher density enters from the bottom. The two-phase flow resistance due to friction, acceleration and elevation is to be balanced by this buoyance force, and the balance of the two forces determines the flow rate. At a given mass flow rate and heat input, the exit vapour quality for a two-phase inlet can be calculated by:

$$x_{\mathrm{out}} = x_{\mathrm{in}} + \frac{q \cdot \Delta L - m \cdot c_{\mathrm{p}} \cdot [T_{\mathrm{sat}}(P_{\mathrm{in}}) - T_{\mathrm{in}}]}{m \cdot i_{\mathrm{fg}}} \tag{11}$$

The above equation has to be solved together with Equation (9), and an iteration procedure is required to determine the mass flow rate and exit vapour quantity. In the real case, water enters the riser in a sub-cooled condition and the tubes have to be divided into single and two-phase zones to allow for temperature changes in the single-phase zone. Also, to determine local values of circulation ratio, tubes have to be divided into multiple sections and calculated individually.

Criteria of boiling crisis

Boiling crisis refers to a situation which is characterised by a sharp reduction of the local heat transfer coefficient. In the case of a temperature controlled heating surface, the heat flux will be considerably reduced. For a heat flux controlled heating surface, as found in industrial boiler panel walls, the condition manifests itself as a sharp increase in surface temperature, which can potentially result in tube failure. This condition is also often referred to as ‘burn out’, and the heat flux at this point refers to the critical heat flux. Flow boiling is a very complex phenomenon, the physical mechanism of which is not fully known to date. What happens in boiling crisis is a change of boiling mode, a change from nucleate boiling to film boiling, manifesting as the replacement of liquid by vapour adjacent to the heat transfer surface. Proper design parameters such as heat flux input, pipe diameter and inclination angle play a considerable role in ensuring that there is always sufficient water in the pipe, thus avoiding the boiling crisis.

There is no simple and generally accepted method of determining the boiling crisis point from known parameters including flow rate, heat flux, steam by volume, pipe diameter and inclination angle. One of the methods proven by practise is to use the steam by volume at specific system pressure, as shown in Figure 3, wherein SBV refers to steam by volume (percentage), and L/D refers to the ratio of pipe length to internal diameter. The figure shows that, for instance, at operating pressure of 40 bar, the circulation ratio shall be greater than 10 for long tubes. It is worth mentioning that often more than one criterion are used to ensure that the boiler circulation is in a safe range.

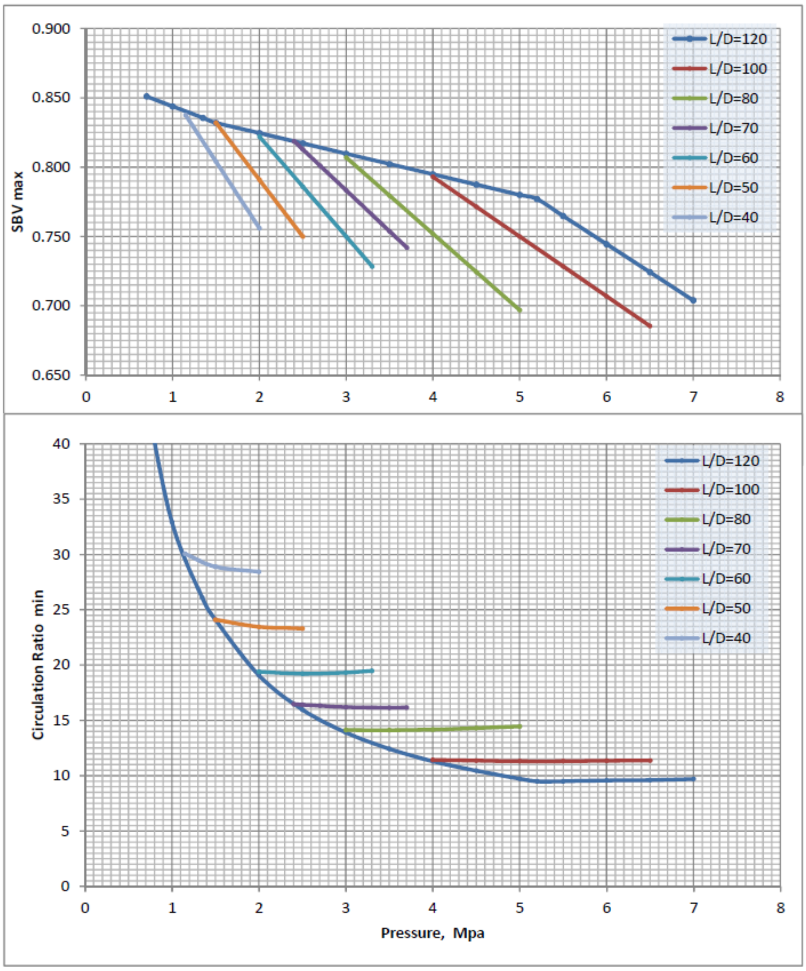

Figure 3. Circulation ratio and steam by volume vs pressure.

A case study

A case study was carried out on a John Thompson 80 bar mono-drum boiler design. The study covers the boiler as a whole unit as well as individual sections. Steinmuller GmbH, a German based design company, did the calculation separately and their result is included in this study. Additionally, an engineering design software package, Flownex (2012 version), was also employed to model the circulation system. The results from these three approaches are presented briefly in Table 1, and show satisfactory agreement.

Table 1. Circulation ratios of a John Thompson mono-drum boiler.

Rear wall	
John Thompson	30.7
Steinmuller	28.0
Flownex	27.8
Side walls	
John Thompson	20.2
Steinmuller	22.0
Flownex	22.7
Evaporator	
John Thompson	10.2
Steinmuller	11.0
Flownex	11.1

Circulation and tube failure

Tube failure manifests as physical damage to tube walls, and the reasons vary. Physical impacts, unsuitable tube material, chemical reactions which reduce the wall thickness, oxidisation of tube metal and solids deposits on internal surfaces due to unsatisfactory water treatment, material fatigue, and thermal fatigue due to sharp and large metal wall temperature changes, are some of the causes. Good circulation design cannot solve the abovementioned problems but bad design can cause or accelerate tube failure. In general, a tube with bad circulation will suffer from overheating. Good circulation design (safe ranges depending on tube geometry and operational parameters such as flow rate and heat input) will achieve optimal vertical tube heights, tube diameters and inclination angles at given heat input distribution.

Conclusion

The concepts and calculation method of water and steam circulation of industrial water tube boilers is presented. The homogeneous two-phase flow model can be handy and effective to determine the circulation characteristics in industrial water tube boilers. Precautions have to be taken, however, for the treatment of certain two-phase flow parameters. Multiple criteria are required to determine a safe design range to avoid boiling crisis in boiler tubes which can potentially result in tube failure.

NOMENCLATURE

A	area	m^2
d	diameter	m
F	force	N
f	fanning friction factor	–
G	mass velocity	$kg/(m^2\cdot s)$
g	gravitational constant	m/s^2
i_{fg}	latent heat of vaporization	J/kg
L	length	m
$\dot{m}$	mass flow rate	kg/s
P	pressure	Pa
ΔP	pressure difference	Pa
Q	volumetric flow rate	m^3/s
q	heat flux	W/m^2
R	circulation ratio	–
S_{wet}	wetted perimeter	m
T	temperature	°C
u	velocity	m/s
x	vapour quality, $x = \dot{m}_g / \dot{m}$	–
z	channel axial co-ordinate	m

Greek

μ	viscosity	Pa·s
$\bar{\mu}$	two-phase mean viscosity	Pa·s
θ	inclination angle	degrees
ρ	density	kg/m^3
τ_w	shear stress at the wall	N/m^2

Subscripts

c	cross-section
elev	elevation
f	liquid phase
fric	friction
g	gas/vapour phase
h	hydraulic
i	inlet
o	outlet
sat	saturation

REFERENCES

Chisholm D (1983). *Two-phase Flow in Pipelines and Heat Exchangers*. Longman Inc, New York, USA.

Collier JG and Thome JR (1994). *Convective Boiling and Condensation*. Third edition, Oxford University Press, New York, USA.

Dukler AE, Wicks M and Cleveland RG (1964). Frictional pressure drop in two-phase flow: B. An approach through similarity analysis. *AIChE Journal* 10(1), 44-51.