# Study of circulation ratio for natural circulation in water-tube boiler at different operating conditions.

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**Abstract**. The basic objective of the paper is to identify the desired circulation ratio for the natural circulation of water tube boilers in different operating conditions. This requires the basic study of heat flux and the mode of the boiling heat transfer, and the phenomenon like departure from nucleate boiling and tube overheating. The parameters, which need to be studied are heat flux, pressure, dryness fraction, void fraction, liquid velocity and their impact on the required circulation ratio. For a natural circulation boiler, the circulation ratio is one of the most important design parameters as the other design parameter like critical heat flux and skin temperature are mainly derived from the circulation ratio. The required circulation ratio can vary with the boiler pressure, liquid velocity and maximum heat flux. This study is intended to provide input for the safe and optimum design of a natural circulation boiler.

## 1. Introduction

The continuous motion of water and steam mixture ensures continuous and efficient removal of heat from the heating surface of the boiler. This motion is usually referred to as circulation. Boilers with natural circulation have a wide range of applications such as power cycles and industrial heating processes. The motive force driving the steam/water mixture through the tubes (water tube boilers) or over tubes (fire tube boilers) in natural-circulation systems is the difference in density between cooler water in the downcomer circuits and the steam/water mixture in the riser tubes. This flow must be adequate to cool the tubes and prevent overheating. As this flow involves two-phase flow, the flow pattern is a very important parameter in designing of the steam generator. The flow pattern strongly affects the flow stability and heat transfer characteristics in a steam generating equipment. This study explains the role of the circulation ratio on the efficient and reliable operation of a boiler.

## 2. Boiler Circulation

Boilers are designed with economizer, evaporator and superheater depending on the design parameters. Economizers add sensible heat to water. The economizer water outlet temperature will be closer to saturation temperature. The water is forced through the economizer by the boiler feed pumps. Evaporators may be multi-tubular shells, water wall tubes, boiler bank tubes or bed coils as in fluidized bed combustion (FBC) boiler. In evaporators, the latent heat is added. The addition of heat is done at boiling temperature. Superheaters add heat to steam. That is the heat added to steam leaving the Boiler

steam drum / Boiler shell. The steam passes through the Superheater tubes under the boiler operating pressure.

Boiler Circulation is the movement of water, mixture of steam & water, or steam through the boiler. Saturated water is, the densest in a boiler circuit, and may contain some steam bubbles. Figure 1. shows the typical arrangement for the water-tube, natural-circulation boiler with an external steam drum and external downcomers and riser pipes. Feedwater enters the drum from an economizer. This mixes with the steam/ water mixture inside the drum. Downcomers carry the resultant cool water to the bottom of the evaporator tubes while external risers carry the water/steam mixture to the steam drum. The heat transfer tubes also act as risers for generating steam.
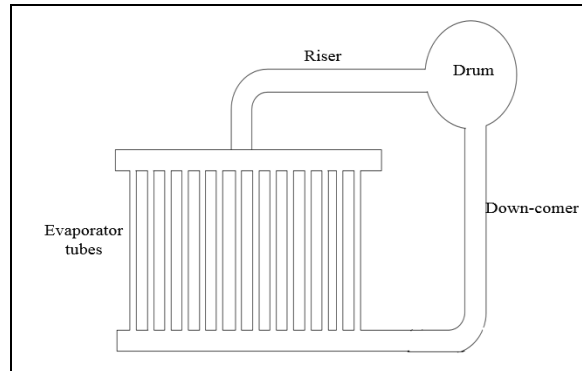


**Figure 1.**Circulation circuit of boiler

Tube failures occur due to conditions known as departure from nucleate boiling (DNB) when the actual heat flux in the boiling circuit exceeds a critical value known as critical heat flux-a function of the variables. When this occurs, the rate of bubble formation is so high compared to the rate at which they are carried away by the mixture that the tube is not cooled properly, resulting in overheating and failure. If there is not enough flow through a riser tube the tube metal will get overheated and maybe burst.



**Figure 2.**Riser fluid flow

**3. Circulation Ratio**
The ratio of the actual mass flow through the circuit to the steam generated is called circulation ratio.

$$Circulation\ ratio = \frac{ms+mw}{ms} \tag{1}$$

This is primarily the reciprocal of the outlet dryness fraction. The circulation ratio is the function of tube diameter, no. of tubes, tube orientation, rate of heat transfer & the available height.

The flow of water through a circuit should be more than the steam generated to protect the tube from overheating. The Boiler tubes, its feeding downcomer pipes, relief tubes/pipes are arranged in such a way that the desired flow be obtained to safeguard the tubes.

Circulation ratio (CR) by itself does not give a complete picture of the circulation system. CR must be used in conjunction with heat flux, steam pressure, tube size, orientation, the roughness of tubes, water quality, etc., to understand the boiling process and its reliability.

*The following can be the impact of the lower circulation ratio.*
Tube deformation/tube leakage failures/tube to fin weld failures take place. The failure mode varies depending upon the flow, heat input, tube size, boiler configuration, and water quality.

## 4. Reliability criteria
The reliability of the circulation circuit should be checked for the various flow abnormality like flow stagnation, flow reversal, flow stratification, departure from nucleate boiling, heat transfer in the dry out region.

*4. 1 Flow stratification*
This phenomenon mostly occurs in the tube with lower upward inclination and lower mass velocity. In this case, steam flows in the upper part of the tube and water in the lower part of the tube. This is also referred to as a separated flow. Consequently, the upper part of the tube can be overheated or burn out due to the poor steam side heat transfer coefficient. The difference in temperature of the upper and lower side of the can also cause tube bending.

Flow stratification is primarily function of flow rate, tube inclination and the heat flux. The flow rate in a horizontal tube or a tube with lower upward inclination angle should be large enough to avoid the phase stratification. If the heat flux is sufficiently low, small bubble generated can flow along the upper wall without coalescence and does not cause phase stratification.

On the other hand, at high heat flux, high velocity of two-phase mixture & disturbances induced by high generation rate of the vapor prevent phase stratification but induce intermittent flow.

The phase stratification mainly occurs at the moderate heat flux and the lower velocity. This phenomenon is more pronounced in the horizontal tube and decreases with an increase in upward angle. The problem is aggravated with the tube with downward inclination.

The criterion for the flow stratification is mainly based on the Froude number, which is the ratio of the horizontal component of momentum and the gravity force.

One of the most common correlations for the calculation of critical velocity can be expressed as follows.

$$\frac{j_l}{\sqrt{gd}} = 0.538 \tag{2}$$

Where,
$j_l$- Volumetric flux of the liquid,
$g$ - Gravitational acceleration,
$d$ - Tube diameter (equivalent diameter of channel cross-section)

Other correlation for the calculation of critical mass flux, $G_{cr}$ (kg/m$^2$s) (Styrikovich's formula) can be expressed as follows

$$G_{cr} = 0.38k \frac{\left(\frac{\rho_l}{\rho_v}\right)^{1/2}}{\left\{\frac{\sigma}{(\rho_l - \rho_v)g}\right\}^{1/4}\left\{1 + x\left(\frac{\rho_l}{\rho_v} - 1\right)\right\}} \left(\frac{x}{1-x}\right)^{3/4} d^{1/2} \tag{3}$$

where,

$\rho_l$- Density of liquid,

$\rho_v$- Density of vapour,

$\sigma$ – Surface tension,

$x$ – Quality of mixture,

$j_l$- Volumetric flux of the liquid,

$j_v$- Volumetric flux of the vapour,

$k$ – Flow parameter

$$k = \frac{\alpha}{\left(\frac{j_v}{j_v + j_l}\right)} \qquad\qquad (4)$$

where, $\alpha$ - Void fraction

As the objective of this work is to deduce the circulation ratio, which is the reciprocal of outlet dryness fraction, one need to study the impact of velocity and pressure on the critical dryness fraction.
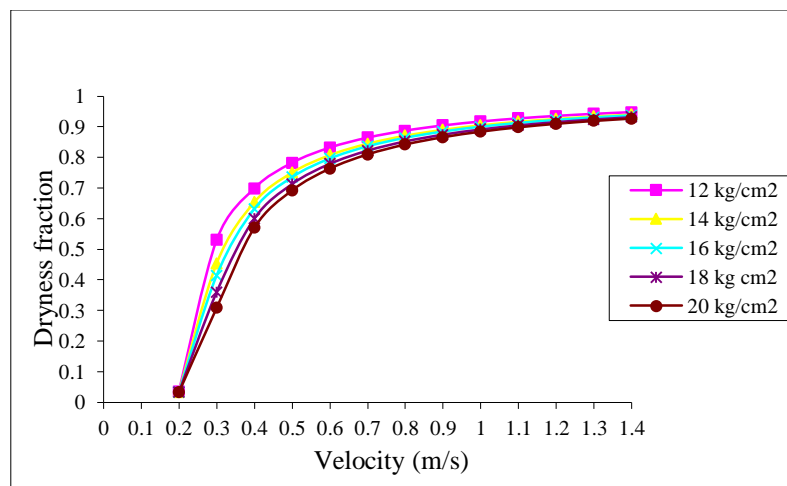


**Figure 3.**Stratification Criteria.

The result of this study has been plotted in figure 3. The observations can be summarized as follows. Acceptable dryness fraction decreases with an increase in velocity and the rate of increase in dryness fraction with respect to velocity decreases at higher velocity. Acceptable dryness fraction decreases with an increase in pressure.

*4. 2 Departure from nucleate boiling*

The nucleate boiling regime is characterized by high heat transfer coefficient, which is a very important boiler design parameter as it determines the ability of flow regime to remove the heat from the heat transfer surface. As the heat flux reaches the critical limit, the sharp reduction in the heat transfer coefficient is observed causing higher metal temperature and possible tube "burnout". This phenomenon is called departure from the nucleate boiling and the critical limit of the heat flux is called "Critical heat flux". The flow pattern and the mechanism of the heat transfer are closely associated with the boiling process.

The following are the various flow patterns and the associated mode of heat transfer.

*Subcooling boiling*- The core liquid is not saturated but bubbles are generated on the wallowing to high wall temperature & the bubble collapse in the core liquid.

*Saturated nucleate boiling* – The fluid is in the saturated state & the bubble generated on the wall is distributed in whole tube cross-section.

*Saturated forced convective boiling*- There is a thin liquid layer with an annular flow pattern.

*Post dry out heat transfer* – the flow pattern is mist flow & most of the liquid is transferred from all surface to the steam, the droplets are heated by the superheated steam & evaporation occurs on the droplet surface.

### 4.2.1 Heat transfer in nucleate boiling

Heat transfer performance is very high in the saturated nucleate boiling region and the saturated forced connective region because a liquid layer exists on the tube wall.

The following correlation (Schrock and Grossman) is used to calculate the heat transfer coefficient for both nucleates and forced convection boiling.

$$h = 170 \frac{\lambda_l}{d} Re^{0.8} Pr^{1/3} \left\{ \frac{q}{GL} + 0.00015 \left( \frac{1}{X_{tt}} \right)^{0.66} \right\} \tag{5}$$

Where,

$h$- Heat transfer coefficient,

$\lambda_l$ - Characteristics dimension,

$Re$- Reynolds number

$Pr$- Prandtl number,

$q$- Heat flux,

$G$- Mass flux (kg/m$^2$s),

$L$- Latent heat of evaporation,

$X_{tt}$ is the Martinelli parameter, which is a two-phase friction multiplier, can be expressed as follows.

$$X_{tt} = \left( \frac{1-x}{x} \right)^{0.9} \left( \frac{\rho_l}{\rho_v} \right)^{0.5} \left( \frac{\mu_l}{\mu_v} \right)^{0.1} \tag{6}$$

In equation 5 for the heat transfer coefficient, the first term shows the effect of nucleate boiling and the second term shows that of connective heat transfer. As per equation, in saturated nucleate boiling characterized by low steam quality region, the first term dominates and the heat transfer increases with heat flux.

At higher steam quality, the flow pattern shifts to forced convection boiling and the heat transfer increases with an increase in liquid velocity.

### 4. 2. 2 Heat Transfer in post dry out region.

The popular correlations available for the calculation of exit dryness fraction are empirical in nature. As per these correlations, exit dryness fraction is the strong function of heat flux. In ordinary steam-generating tubes in the boiler in which the maximum heat flux is usually lower than $4 \times 10^5$ W/m$^2$, the value of dryness fraction is not practically affected by the heat flux. For such equipment, exit dryness fraction decreases with an increase in mass flux. This phenomenon can be mainly attributed to the increases shear force at the annular interface of liquid and steam causing an increased rate of droplet generation and disappearance of the liquid layer at higher mass flux.

The following correlation (Doroshchul and Nigmatulin) can be used for the calculation of exit dryness fraction.

$$x_d = \left[ 0.0031 \frac{\sigma}{\vartheta_l (\rho_l - \rho_v)} \frac{(\rho_l)}{G} \right]^{1/2} \tag{7}$$

Where,

$\sigma$- Surface tension

$\vartheta_l$ - Kinematic viscosity

$\rho_l$ - Liquid density

$\rho_v$ - Vapour density

This correlation can be used to analyze the effect of mass flux and pressure on the exit dryness fraction.
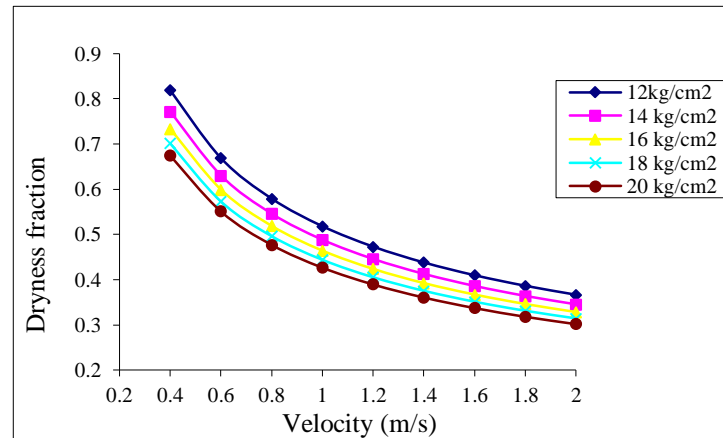


**Figure 4.** Dryout quality.

This demonstrates that the exit dryness fraction decreases with an increase in mass velocity and pressure. The effect of mass velocity on the exit dryness fraction has been explained earlier. As the pressure increases, the Kinematic viscosity and the difference between liquid and gas density decrease causing the disappearance of the liquid layer from the interface area. Due to this effect, exit dryness fraction decreases with an increase in pressure.

As the dry out is a phenomenon related to the flow configuration the value of $x_d$ is little affected by the heat flux, through the heat flux affected the distance to the dry-out point from the tube inlet. The wall temperature rise owing to the high-quality region called "burnout". But even if to dry out occurs at low heat flux conditions, physical burnout of the tube does not necessarily occur because of the small rise in the wall temperature.

*4. 3 Void fraction*

In two-phase flow, void fraction is defined as the ratio of the gas flow area to the total flow area. It is the function of the volume flow rates volumetric flux of the gas, volumetric flux of the liquid, liquid density, Vapour density & surface tension geometrical dimensional of channel & mass fluxes of the steam & water. In steam water two-phase flow, the properties of steam & water are the function pressure consequently the void fraction reduces to the function of mass fluxes, the steam quality & the channel dimension.

According to smith's (1969) empirical formula for void fraction, Void fraction is the function of steam quality and the density ratio, which in turn is the function of pressure but independent of mass flow rate and channel dimension.

$$\alpha = \left[1 + 0.4\frac{\rho_v}{\rho_l}\left(\frac{1-x}{x}\right) + 0.6\frac{\rho_v}{\rho_l}\left(\frac{1-x}{x}\right)\left\{\frac{\frac{\rho_l}{\rho_v}+0.4\left(\frac{1-x}{x}\right)}{1+0.4\left(\frac{1-x}{x}\right)}\right\}^{1/2}\right]^{-1} \qquad (8)$$

This correlation can be used to analyze the effect of dryness fraction on void fraction, which is an important parameter for the reliability consideration of steam generating equipment.
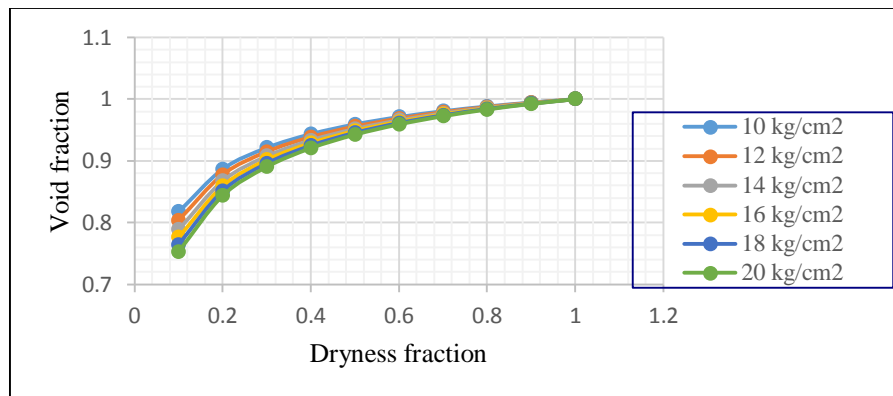
**Figure 5**.Void fraction Vs Dryness fraction

In the natural circulation boiler, void fraction is used as a design criterion. As per design norms, the void fraction at the exit of the tube should be less than 0.7. As the void fraction can be expressed as an exit dryness fraction, critical exit dryness fraction can be plotted as a function of pressure.
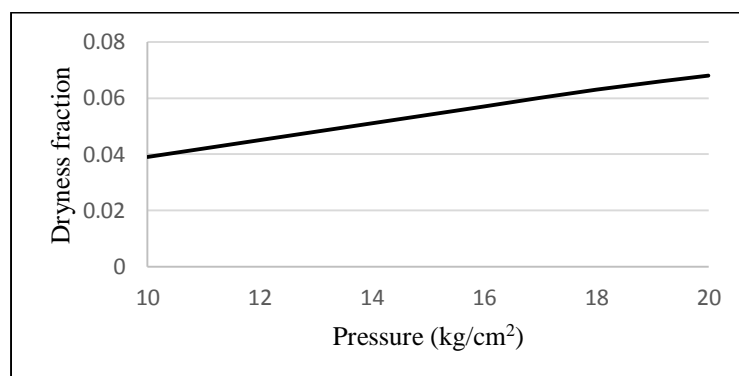


**Figure 6.** Effect of pressure on acceptable dryness fraction

This analysis demonstrates the effect of pressure on the acceptable dryness fraction as per void fraction criteria.

## 5. Conclusion

The study can be used to deduce the design criteria for the design of natural circulation circuit of the boiler. The most important design aspect of the natural circulation circuit is to ensure a sufficient mass flux of circulating water to avoid burnout of evaporator tubes.

The following are the practical design considerations for a natural circulation boiler.

*Circulation velocity:*

Circulation velocity is a very important design criterion for a horizontal tube or a tube with an upward inclination less than $10^0$ to avoid phase stratification.  This becomes more critical in the circuit having less circulation ratio or higher dryness fraction. The critical dryness fraction as a function of velocity and pressure has been plotted in the earlier section.

*Void fraction:*

Void fraction is another important design criteria for natural circulation circuit design.  As the void fraction is primarily function of the dryness fraction and pressure, acceptable dryness fraction can be deduced from the void fraction criteria. The acceptable value of dryness fraction has been plotted in the previous section. Acceptable dryness fraction has been also deduced from the departure from nucleate boiling criteria. As this dryness fraction is higher than the acceptable dryness fraction from the void fraction criteria.

The acceptable dryness fraction from void fraction criteria is considered as design norms.

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## Nomenclature

$g$ Acceleration due to gravity, m/s$^2$

| | |
|---|---|
| $X_{tt}$ | Martinelli parameter |
| $j$ | Volumetric flux |
| $d$ | Tube diameter, (equivalent diameter of channel cross-section), m |
| $x$ | Quality of mixture |
| $k$ | Flow parameter |
| $h$ | Heat transfer coefficient |
| $\lambda_l$ | Characteristics dimension |
| $Re$ | Reynolds number |
| $Pr$ | Prandtl number |
| $q$ | Heat flux |
| $G$ | Mass flux, kg/m$^2$s |
| $L$ | Latent heat of evaporation, J/kg |

## Greek

| | |
|---|---|
| $\alpha$ | Void fraction |
| $\sigma$ | Surface tension, N/m |
| $\rho$ | Density, kg/m$^3$ |
| $\mu$ | Viscosity, kg/s-m |
| $\xi$ | Roughness |

## Subscripts

| | |
|---|---|
| $l$ | Liquid |
| $v$ | Vapour |