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Desired Circulation Ratio for Natural Circulation in Water-Tube Boiler

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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 a 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. The present work is to develop a circulation analysis model for the natural circulation of the water tube boiler and to check the boiler design for different failure modes. 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.*

***Keywords:** circulation ratio, departure from nucleate boiling, stratification, void fraction, dryness fraction*

I. INTRODUCTION

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. Salamah al-Anizi [1] investigated circulation in the industrial boiler is the continuous supply of water to the boiler heated tubes in order to sustain steady steam output without overheating tubes. Adequate circulation occurs when there is sufficient flow of water into tubes for adequate cooling. Kim and Choi [2] developed a model for providing an investigation of response of water level dynamics to change in steam demand and /or heating rate.

Circulation analysis is very critical in the design of natural circulation boiler. Depending on the type of circulation, a boiler can be classified into forced circulation boiler and natural circulation boiler. In a forced circulation boiler, a circulation pump is used to ensure water and steam flow in the heat transfer tubes of the boiler. In a natural circulation boiler, the difference in density of circulating fluid in riser and downcomer tubes act like a motive force for the water and steam circulation in the boiler.

As the density of saturated water is higher than the density of water and steam mixture, the pressure in downcomer column provides the necessary driving force for pushing water and steam mixture of riser tubes in the boiler drum. As the flow of water and the water/steam mixture through the boiler circuits is produced naturally by the force of gravity unlike the forced circulation boiler, this type of boiler is called a natural circulation boiler.

Syed-Ahmad M. Said [3] has developed models for water circulation in boiler to calculate the circulation ratio and the flow properties like velocity, steam quality, rate of steam generation, void fraction, and surface temperature.

Circulation ratio is defined as the ratio of the mass flow rate of steam/water mixture in the circulation loop to the steam generation rate in evaporator tubes. V Ganapathy [4] presented to study natural-circulation boiling circuits are in successful operation with CRs ranging from 4 to 8 at high steam pressures and 15 to 50 at low steam pressures. The circulation does not provide sufficient information about the flow circulation in individual tubes, which is very important for the thermal and hydraulic performance of the boiler. The parameters which affect the distribution of the flow in the parallel channel are header area, tube diameter, size and location of inlet port to the header, the direction of flow. Poor distribution and lower circulation ratio in a tube can lead to various problems like departure from nucleate boiling, phase stratification, higher void fraction and two-phase flow instability. V.Ganapathy [5-6] presented the investigation to study allowable and actual steam qualities should be apart in order to avoid Departure from Nucleate Boiling (DNB) problems. Nayak et al. [7-8] observed instabilities during various stages of natural circulation systems such as single phase, boiling inception and fully developed two-phase flow.

Two phase flow distribution analysis in a natural circulation boiler has different challenges as it has different resistance and driving forces for each loop. Driving force for different loops can be different due to different height and dryness fraction and dryness fraction is the function of flow and heat transfer. This makes the whole system of equation quite complex and circulation study is extremely useful for the design and analysis in natural circulation of boiler.

II. NATURAL CIRCULATION IN BOILER

As the natural circulation circuit of the water tube boiler is quite complex, the flow distribution among evaporating tubes cannot be analyzed easily.

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In the conventional approach, an equivalent flow resistance for parallel evaporating tubes, risers, and downcomer are estimated to calculate the overall flow in the circulation circuit.

This does not provide sufficient information about the flow circulation in individual tubes, which is very important for the thermal and hydraulic performance of the boiler. Circulation analysis is very critical in a design of natural circulation boiler. Depending on the type of circulation, a boiler can be classified in to forced circulation boiler and natural circulation boiler. In a forced circulation boiler, a circulation pump is used to ensure water and steam flow in the heat transfer tubes of the boiler.

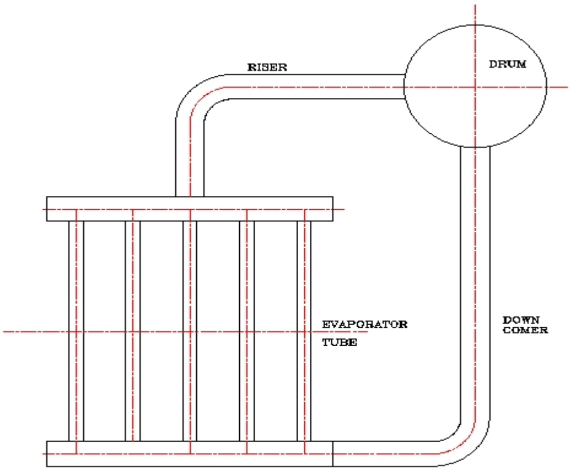

Fig. 1.Circulation circuit of boiler

Fig.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

A. Mathematical Modelling- Natural Circulation

A typical water tube boiler consists of drum, downcomer, evaporator tubes and riser. Fig.1 shows the typical circulation circuit of a boiler. Downcomer pipes are connected to the drum and saturated water of the drum flows through the downcomer. These downcomer pipes join the steam drum and the evaporator tubes. Saturated water of drum enters the evaporator tubes through the downcomer pipe and finally rises due to decrease in density as the evaporation starts in evaporator tubes. The evaporator tubes receive heat from flue gas and transfer it to the saturated water flowing through these tubes. This water and steam mixture re-enters the boiler drum through riser pipes. The difference of density in riser and downcomer column provides the driving head for the flow circulation in the evaporator tube. The driving head can be calculated as follows (Gullichsen J. [9]).

$$\Delta p = \rho_l gH - \rho_v gH \quad (1)$$

Where,

Δp – Driving force,

ρ_l –Density of saturated water in downcomer column.

ρ_v – Density of saturated water and steam mixture in riser column,

H- Height of riser and downcomer column.

And the pressure drop in the circuit can be calculated as follows,

$$\Delta P = KQ^2 \quad (2)$$

Where,

K - Flow resistance of the circulation loop,

Q - Flow in the circulation loop.

ΔP- Pressure drop in circulation circuit

Pressure drop can be calculated by Lockhart- Martinelli equation. In Lockhart Martinelli method of two-phase pressure drop calculation, pressure drop calculation is done assuming the single-phase flow and multiplying with two phase multipliers (Marian Trela, et al [10]).

The following equation shows the application of a two-phase multiplier for the calculation of pressure drop.

$$\Delta P_{friction} = \emptyset^2{}_{ltt} \times \Delta P_l \quad (3)$$

$$\Delta P_{friction} = \emptyset^2{}_{vtt} \times \Delta P_v \quad (4)$$

Where, ΔP_l and ΔP_v are the single-phase pressure drop for liquid and gas.

Their respective two-phase multipliers are calculated by using the following equation.

$$\emptyset^2{}_{ltt} = 1 + \frac{C}{X_{tt}} + \frac{1}{(X_{tt})^2}, for\ Re_l > 4000 \quad (5)$$

$$\emptyset^2{}_{vtt} = 1 + CX_{tt} + (X_{tt})^2, for\ Re_v < 4000 \quad (6)$$

Here, X_{tt} is Martinelli parameter and calculated by using following equation.

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9} \left(\frac{\rho_v}{\rho_l}\right)^{0.5} \left(\frac{\mu_l}{\mu_v}\right)^{0.1} \quad (7)$$

As the density in the riser column is the function of flow, eq. (1) can be also written as a function of flow. These two equations can be computationally solved to calculate the flow and the pressure drop in the circulation circuit. This can be graphically shown in fig.2, where driving force decreases with increase in flow and the pressure drop increases with increase in flow. The difference of density decreases at higher flow due to decrease in dryness fraction in riser column, which finally results in decrease in driving force The intersecting point, where these two lines join indicates the mass flow rate of the circuit.

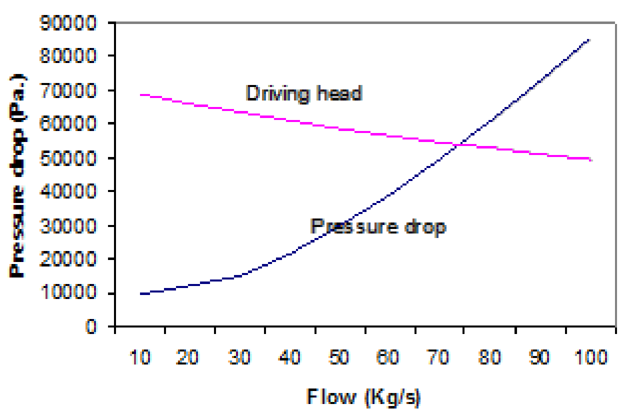

Fig. 2.The nature of circulation in a typical circulation circuit of a boiler.

III. DESIGN AND ANALYSIS

The design of the circulation circuit of a natural circulation of boiler is extremely critical as the heat transfer tubes require to have sufficient water flow to ensure cooling of these tubes.
It becomes more critical, if these heat transfer tubes are exposed to high flame temperature radiation leading to very high heat flux in a furnace section of a fired boiler. The performance of a circulation circuit is measured by circulation ratio. Circulation ratio is defined as the ratio of the mass flow rate of steam/water mixture in circulation loop to the steam generation rate in evaporator tubes.

$$Circulation\ ratio = \frac{ms + mw}{ms} \quad (8)$$

This is just an indicator of the hydraulic performance of the boiler but it does not provide the sufficient information about the failure mechanism of the boiler tubes. In some boiler design, a low circulation ratio like 5-10 can be sufficient, but in some other boiler design even a moderate circulation ratio like 20-30 is not enough.
The required circulation ratio is very important parameter in the water tube boiler design and is the function of boiler type, design and operating parameter. The design of a circulation loop requires the insight about the various failure modes due to poor circulation in the boiler.

Some of the prominent circulation problems can be listed as follows.

A. Departure from nucleate boiling.
B. Phase stratification.
C. Higher void fraction.
D. Flow instability.
E. Flow mal-distribution

A. Departure from nucleate boiling

In the normal circumstance, the mode of the boiling heat transfer in a boiler is the nucleate boiling. In this condition bubble generation takes place at the heat transfer surface and this bubble is carried away due to buoyancy effect, keeping the heat transfer surface wet. In this condition, the bubbles generated on the wall are well distributed in the whole tube cross section. If the heat flux is increased beyond a particular limit, the rate of bubble generation exceeds the rate at which it is carried away. This can cause steam blanketing over the heat transfer surface and can cause overheating of heat transfer tube due to reduction in cooling. This phenomenon is called departure from nucleate boiling. In this condition, a thin film of steam will be adhered at the heat transfer surface, which acts like insulation for the cooling of heat transfer tubes. This is the most prominent failure mode in a natural circulation boiler and is primarily function of heat flux, steam dryness & mass flow rate. In a normal steam generator, the average heat flux is much lower than the critical heat flux. But the peak heat flux can be higher due to higher flame temperature. Due to this reason the average heat flux should be limited to 25 % of the critical heat flux. The critical heat flux is the function of pressure, steam quality and the orientation of the heat transfer tube. A vertical tube can accept much higher heat flux than a horizontal tube. The critical heat flux decreases with the increase in boiler pressure and dryness-fraction.
As the circulation ratio is the inverse of steam dryness fraction, the boiler with higher circulation ratio can accept higher heat flux.

B. Phase stratification

In a horizontal tube, if the flow velocity is not sufficiently high, the bubble generated at the bottom surface rises to the upper wall and get accumulated. This creates the phase stratification, where the water and steam flow as separated phase. The phase stratification is primarily due to the dominance of gravitational force over the inertial force. It primarily occurs at lower velocity, where the inertial force is low. If the flow velocity is sufficiently high, the bubble generated at the bottom surface is carried by the flow. This does not allow phase stratification to take place. If the heat flux is high, it requires higher mass velocity to avoid phase stratification. The separated steam phase can lead the overheating of the tube and cause tube burnout, if it gets exposed to the high temperature flame. As the stratified flow can cause the tube burnout under high heat flux condition and the flow rate should be large enough to avoid phase stratification. The minimum mass flux required to avoid phase stratification is called the critical mass flux. At the moderate heat flux, it requires to have a critical mass flux to avoid flow stratification. This critical mass flux is the function of steam dryness and boiler pressure. The critical mass flux increases with increase in steam dryness fraction. The phase stratification phenomenon can be drastically decreased by increasing the tube inclination. It almost disappears if the inclination angle goes beyond 25^0 [11].

C. Higher void fraction

Void fraction is the ratio of volumetric flow rate of vapour phase to the total volumetric flow. Void fraction can be calculated by using Smith's correlation. (Smith, S. L. [12])

$$\alpha = \left[1 + 0.4\frac{\rho_v}{\rho_l}\left(\frac{1-x}{x}\right) + 0.6\frac{\rho_v}{\rho_l}\left(\frac{1-x}{x}\right)\left\{\frac{\frac{\rho_l}{\rho_v}+0.4\left(\frac{1-x}{x}\right)}{1+0.4\left(\frac{1-x}{x}\right)}\right\}^{1/2}\right]^{-1} \quad (9)$$

Higher void fraction means higher volume of the heat transfer tube is occupied by steam. This is a very important parameter for the prediction of the tube burnout problem. This is often used as an indicator to predict the reliability of a boiler, as the higher void fraction can lead to departure from nucleate boiling and multiphase flow instability. Due to the lower difference of vapour and liquid density in a high-pressure boiler, it has low void fraction even at higher dryness fraction. Due to this reason, a high-pressure boiler can tolerate lower circulation ratio in comparison with a low-pressure boiler.
In a boiler design the void fraction should be kept below a specified limit to eliminate tube overheating problem due to departure from nucleate boiling and two-phase flow instability.

D. Flow instability

If the boiler is made of many parallel tubes, some of these tubes can acts like riser and other can act like a downcomer. If a certain type of instability can cause upward flow in the downcomer and downward flow in riser tubes, it can cause an undesirable flow and pressure fluctuation in circulation circuit.

This phenomenon can be explained as follows. In normal condition, pressure drop increases with increase in flow but in certain circumstances pressure drop can actually decrease with increase in flow rate. This primarily happens due to decrease in steam dryness at higher flow, which finally results in decrease in circuit pressure drop. This behaviour of circulation circuit has been shown in fig.3.

In this case for a same pressure drop, there are three possible values of flow and flow can oscillate among these flow conditions, if a certain disturbance in circuit arises.

In some of the situation, flow can be significantly low causing tube burnout problem and this situation should be avoided by designing an appropriate circulation circuit.

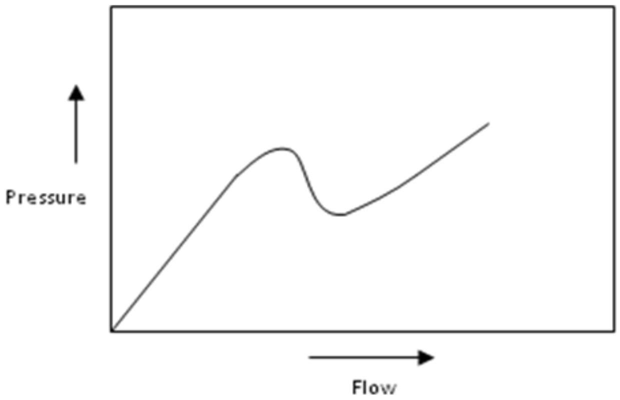

Fig.3. Flow pressure drop characteristics

E. Flow mal-distribution

As the circulation circuit in boiler is quite complex and normally flow distribution among riser is not analysed. In conventional approach, an equivalent flow resistance for parallel risers and downcomer is estimated to calculate the overall flow in circulation circuit. This does not provide the sufficient information about the flow circulation in individual tubes, which is very important for the thermal and hydraulic performance of the boiler.

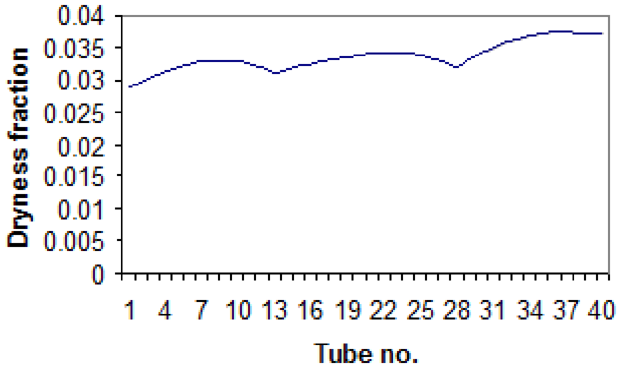

Fig.4. Flow mal-distribution in evaporator tubes (6 TPH CPF boiler manufactured by Thermax Ltd.)

Fig.4 presents the variation of dryness fraction in individual tubes. This shows approximately 30 % variation in dryness fraction among the parallel riser tubes. This type of variation can be seen in a well-designed circulation circuit. If proper care is not taken during the design, this variation can be extremely high and alarming. During the circulation circuit design, flow mal-distribution should be analysed and corrected by changing the size and position of the riser and downcomer. All the analysis mentioned in previous section should be done on the most critical tube identified by flow distribution analysis of a circulation circuit.

IV. RESULT & DISCUSSION

Case study

A. Geometrical description of a water tube boiler

A furnace of a water tube boiler of 35 TPH capacity designed and manufactured by Thermax Ltd is selected for the natural circulation analysis. Fig.5 shows the schematic of a water tube boiler with a reciprocating grate combustor. Boiler has two drums and are referred as steam and water drum. Steam and water drums are connected by set of convective tube bank. Heat is generated in the furnace due to the combustion of biomass over the reciprocating grate and is partially transferred to the water wall placed around the furnace. Hot flue gas enters the superheater tube bank and convective tube bank. Furnace is made of water tube design and the evaporation of water takes place after picking the heat from the flue gas. The water and steam mixtures move upward due to the buoyancy effect and finally enters the boiler drum through the risers. Evaporator tubes receive the water from downcomers connected to the water drum. This completes the natural circulation. A natural circulation network consists of downcomers to carry the drum water to evaporator tubes and risers to carry water-steam mixture to the steam drum.

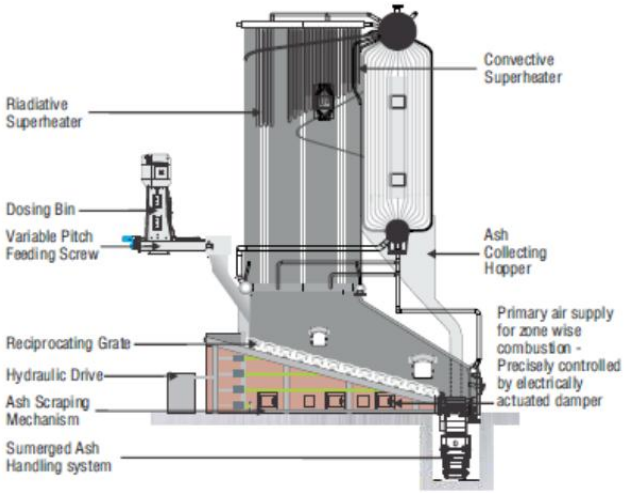

Fig.5. Schematic diagram of a water tube boiler

B. Basic construction of water tube boiler

Fig.6 shows the circulation flow diagram of the water tube furnace of the boiler. Due to symmetry, one half of the circuit has been taken for the analysis.

The length and diameter of all tubes, headers, risers and downcomers are given in Table 1 circulation network includes the drum with 7 risers, 4 downcomers and 94 evaporating tubes, which are placed in lower and upper manifolds.

The dimensional details of the circulation circuit are listed in Table1.

Table –I: Design parameters of the natural circulation in water tube boiler

Sr. No.	Description	Dimensions are in mm	Quantity
1	Bottom Header Dimension	OD 273 X 9.27 THK X 2300	1
2	Top Header Dimension-1	OD 323.9 X 10.91 THK X 2300	1
3	Top Header Dimension-2	OD 323.9 X 10.91 THK X 1200	1
4	Number of tubes	OD 50.8 X 3.25 THK X 8000	12
5	Number of tubes	OD 50.8 X 3.25 THK X 6500	23
6	Number of tubes	OD 50.8 X 3.25 THK X 6000	12
7	Downcomers	OD 168.3 X 7.11 THK X 2500	4
8	Risers	OD 219.1 X 8.18 THK X 4000	5
9	Risers	OD 219.3 X 8.18 THK X 3000	2

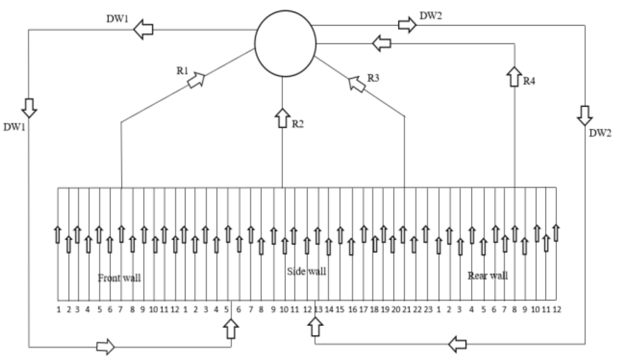

Fig.6. Flow diagram of a boiler

Furnace has been divided in ten zones length wise and the heat transfer in these zones have been analyzed by using plug flow model of furnace analysis. The result of plug flow furnace model is plotted in fig.7 showing heat transfer in each zone. These heat transfer data are used for the circulation analysis. Due to symmetry, only half of the furnace has been considered for the analysis. It consists of half of front wall (12 tubes), side wall (23 tubes) and rear wall (12 tubes). 56 equations have been generated to balance driving head and head loss for each loop. Lockhart Martinelli equations has been used for two phase pressure drop analysis.

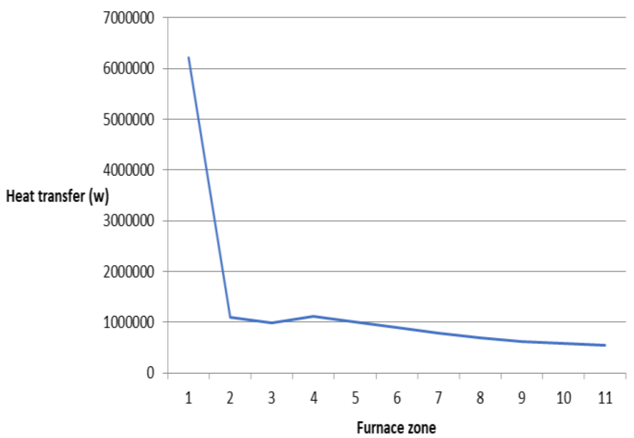

Fig.7. Heat transfer distribution in a water tube boiler

C. Heat flux – Departure from nucleate boiling

As departure from nucleate boiling is very important parameter and it is dependent on the peak heat flux. Peak heat flux has been calculated by using heat transfer data in the various zones. Peak heat flux is compared with critical heat flux to check the possibility of departure from nucleate boiling. Fig.8 shows the peak heat flux in the various zones of the furnace. Critical heat flux is $4\times10^6 W/m^2$ at 10 kg/cm^2 pressure. As the peak heat flux is approximately 25 % of the critical heat flux, design can be considered as safe.

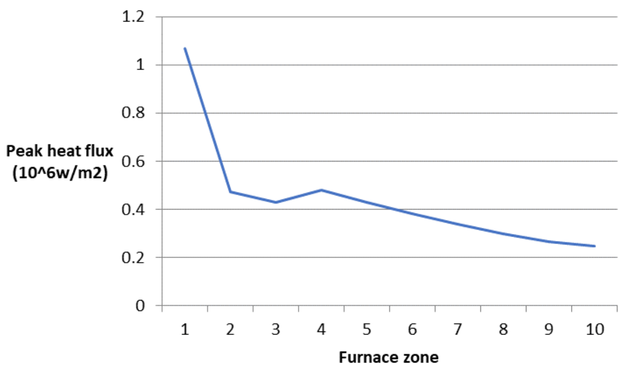

Fig. 8. Peak heat flux of water tube boiler

D. Circulation analysis- Dryness fraction

Natural circulation has been analyzed and the dryness fraction of the various tubes in the different walls have been plotted in fig 9. This graph presents the dryness fraction of each tube present in the different wall. Circulation ratio is the inverse of dryness fraction and the minimum value of circulation ratio is 42.

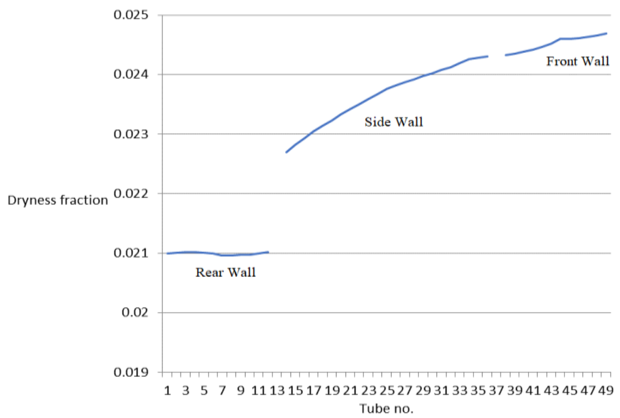

Fig. 9. Dryness fraction in the various wall of the boiler

E. Desired circulation ratio

Higher dryness fraction leads to higher void fraction and two-phase flow instability. It is recommended to have maximum void fraction of 0.7 at the outlet of evaporator tubes [13]. For a safe operation of a natural circulation boiler, the possibility of two-phase flow stability should be also checked. The stability criterion for the density wave oscillation is checked with phase change number and this number should be less than 11 [13].

Phase change number at the outlet of evaporator tube (X_e) is calculated by following equation.

$$X_e = \frac{\left(1 - \frac{\rho_v}{\rho_l}\right)}{\left\{\left(\frac{1}{\alpha_e} - 1\right) + \frac{\rho_v}{\rho_l}\right\}} \tag{10}$$

Using these two criteria, acceptable circulation ratio has been plotted. Fig.10 presents the required circulation ratio from the criteria of maximum void fraction and two-phase flow instability. Maximum of the dryness fraction can be checked for the void fraction & two-phase flow instability. As per this graph, actual circulation ratio is 42 against the required circulation ratio of 30 at design pressure of 10 kg/cm^2.

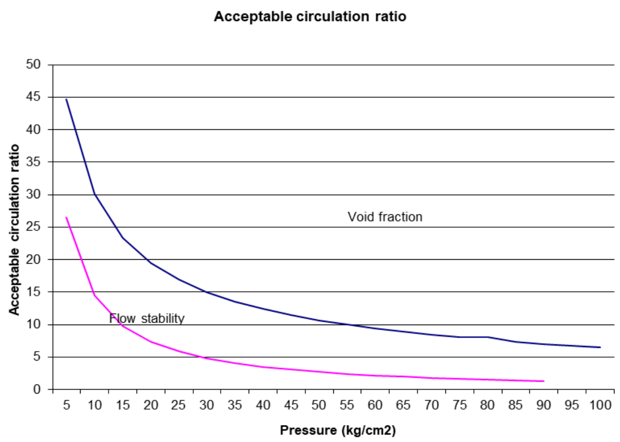

Fig.10. Acceptable circulation ratio as a function of Pressure.

F. Circulation analysis- velocity profile

Natural circulation boiler should be also checked for the possibility of phase stratification. Minimum velocity in tubes should be checked to avoid phase stratification. Recommended minimum velocity for a vertical tube should be 0.7 m/s and 1.2 m/s for horizontal tube [13]. Flow distribution analysis of natural circulation model can be used to plot the velocity distribution among the tubes. Fig.11 presents the velocity distribution among the tubes. This show the minimum velocity as 1.4m/s, which is quite higher than the required velocity.

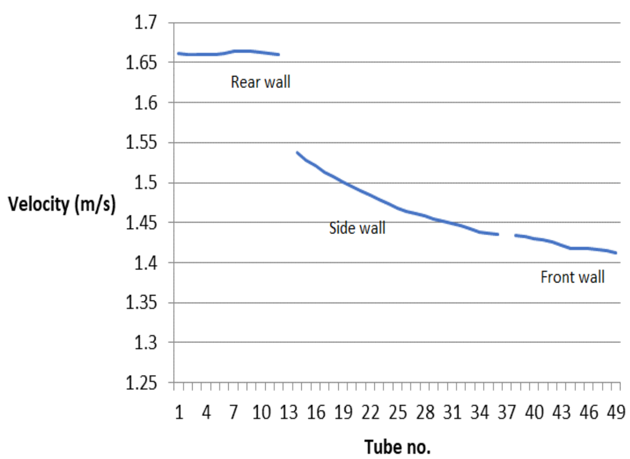

Fig. 11. Velocity profile in water tube boiler

Table-II: Summary report of failure analysis of a water tube boiler

Criteria	Parameter	Estimated Value	Acceptable design norms	
Departure from Nucleate boiling	Heat flux	4×10^6 W/m^2	Maximum 10^6W/m^2	
Void fraction	Circulation ratio	42	Minimum 30	
Two phase flow instability	Circulation ratio	42	Minimum 15	
Phase stratification	Velocity	1.4 m/s^2	Vertical tube	Horizontal tube
			0.7 m/s^2	1.2 m/s^2

V. CONCLUSION

The circulation study of the boiler is the most important aspect of the design of the natural circulation of water tube boiler. In most of the boiler industry, circulation study is limited to the estimation of an average circulation ratio of a boiler. As discussed in the various section of this article, that circulation ratio should be always studied for the various failure modes to evaluate the robustness of hydraulic design of a natural circulation of a water tube boiler. The circulation analysis has been conducted for the water tube boiler and checked against the different failure modes. Table-2 presents the summary of the circulation analysis and failure analysis for the different failure criteria. The water tube boiler design has been found safe in all condition. This study presents the systematic approach in circulation analysis and identification of desired circulation ratio.

The water tube boiler has been found safe in normal condition but heat flux may change in some abnormal operating condition. The critical heat flux should be checked in abnormal condition to eliminate failure.

NOMENCLATURE

Δp	Driving force, kg/cm^2
g	Acceleration due gravity, m/s^2
H	Height of riser and downcomer column
K	Flow resistance of the circulation loop
Q	Flow in the circulation loop
ΔP	Pressure drop in circulation circuit
X_{tt}	Martinelli parameter
$\emptyset$	Pressure drop multiplier
$\dot{m}$	Flow, kg/s
j	Volumetric flux
d	Tube diameter, (equivalent diameter of channel cross-section), m
x	Quality of mixture
X_e	Phase change number
k	Flow parameter
h	Heat transfer coefficient
q	Heat flux

GREEK

α Void fraction
ρ Density, kg/m^3
μ Viscosity, kg/s-m

SUBSCRIPTS

l Liquid
v Vapour

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Prof (Dr.) Mandar M. Lele has done Ph.D. from IIT Bombay and is having teaching experience of 23 years. He is currently working as Professor, Department of Mechanical Engineering in MAEER’s MIT COE, Pune. His areas of interest are HVAC, Heat pipes, Cryogenics and heat transfer applications. He has published more than 19 papers in International Journals. Three candidates have completed Ph. D. under his guidance. He has worked as a session chair for national and international conferences. He has been invited as a resource person and delivered the talks on Heat Transfer and Cryogenics. He has filed 02 patents in the area of heat and mass transfer.