

SIMPLE AND CLEAR APPROACH TO INDUSTRIAL BOILER CIRCULATION ANALYSIS

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ABSTRACT

Circulation in 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. In natural circulation industrial boiler system the rate of flow in the circulation system is governed by flow resistances and differences in density between downcomer tube circuits and heated riser circuits. Control of these resistances allows adequate flow of water to parallel circuits. Adequate water flow through the boiler's heat absorbing circuits is necessary to cool the tubes. To insure proper boiler circulation, a simple, clear and comprehensive approach will be described in this paper covering all aspects in boiler circulation analysis. The analysis will detail all boiler circulation circuits explaining all forces imposed on them including thermosyphon as well as friction forces.

INTRODUCTION

Adequate circulation occurs when there is sufficient flow of water into tubes for adequate cooling. The supply of water is referred to as circulation in the boiler. Two types of circulations are known in the industry. Their knowledge comes from the source of the force which is required to move the water and steam-water mixture through the circulation system.

- Natural circulation where the driving force is an invisible thermal pump.
- Forced circulation where the driving force is divided between thermal and mechanical pumps.

In natural circulation system the rate of flow in the circulation system is governed by flow resistances and differences in density between downcomer tube circuits and heated riser circuits as indicated in Figure 1. Control of these resistances allows adequate flow of water to parallel circuits. Adequate water flow through the boiler's heat absorbing circuits is necessary to cool the tubes. Under normal circumstances, steam is generated by the process of "nucleate boiling." Steam bubbles are formed and rapidly released on the inner tube surface. The tube surface is maintained continuously wetted,

allowing high heat transfer rates between the tube and the circulating steam/water mixture.

Tube metal temperatures are typically maintained 10°F to 50°F (6°C to 28°C) above the saturation water temperature at the boiler drum pressure. At certain conditions, with a relatively large steam fraction and at a high heat transfer rate, a departure from nucleate boiling (referred to as DNB) may occur. DNB is characterized by "film boiling" during which a thin film of steam remains on the inner tube surface, insulating the tube metal from the cooling effect of the steam/water mixture. The tube metal temperature increases rapidly to near the local flue gas temperature, exposing the tube to potential failure. In addition, such conditions can accelerate the formation of heavy deposition of boiler water chemicals in these regions.

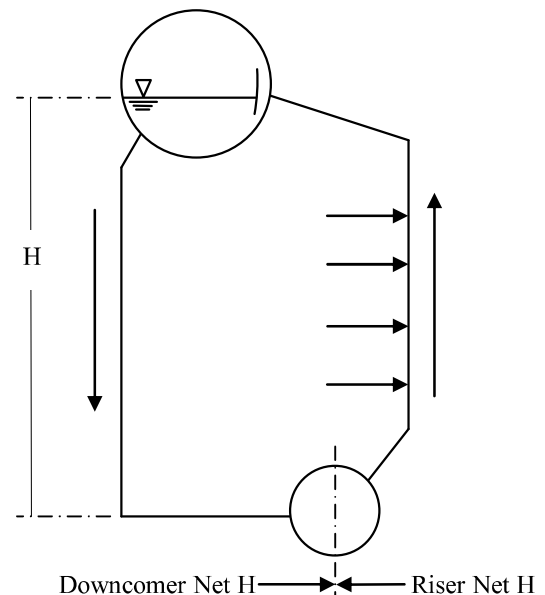


Figure 1

The flow of water through a circuit should be more than the steam generated to protect the tube from overheating be

continuous cooling. Boiler tubes, its feeding downcomer (when separately used outside the heated area), relief tubes are arranged in to obtain an optimum flow to safeguard the tubes. The ratio of the actual mass flow through the circuit to the steam generated is called circulation ratio. Depending on the boiler design parameters and configuration of the boiler this number would be anywhere between 5 & 60. In low pressure boilers, this number is on the higher side as the density difference between water & steam is high.

NOMENCLATURE

g	[ft/sec ²]	Acceleration of gravity (use 32.2 ft/sec ²)
f	[-]	Friction factor (use 0.006)
d_o	[in]	Outside diameter of a tube or a pipe
L	[ft]	Length of a circuit
n	[-]	Number of tubes in a circuit
V	[ft/sec]	Velocity of water or steam mixture
V_o	[ft/sec]	Velocity entering first heated circuit
q	[btu/hr-ft ²]	Heat absorption rate of outside service of a tube
v_g	[ft ³ /lb]	Specific volume of saturated vapour at drum pressure
v_f	[ft ³ /lb]	Specific volume of saturated water at drum pressure
v_{fg}	[ft ³ /lb]	Specific volume change due to evaporation at drum pressure
h_{fg}	[btu/lb]	Latent heat of vaporization at drum pressure
K	[-]	Flow area ratio, dimensionless
K_b	[-]	Bend loss coefficient, dimensionless
ΣK	[-]	Number of velocity heads lost due to entrance, exit, and bends, dimensionless
H	[ft]	Vertical height
ρ_c	[ft ³ /lb]	Density of steam-water mixture in downcomer tubes at drum pressure
ρ_o	[ft ³ /lb]	Density of saturated water at drum pressure
ρ_s	[ft ³ /lb]	Density of subcooled liquid at drum pressure
β	[-]	Percent steam by volume in steam-water mixture
λ	[-]	Percent steam by weight in steam-water mixture
CR	[-]	Circulation ration, dimensionless
N	[ft/sec.ft]	Change of velocity per foot of length of heated tube due to generation of steam within the tubes, $=d_o q v_{fg} / 75 d_i^2 h_{fg}$

DESIGN CRITERIA

Circulation calculations are normally made to check the suitability of a desired arrangement of the circulation system in industrial boilers. Analysis of the calculations will show where changes, if any, in number or size of downcomers, feeders or risers will improve either the distribution or total flow of water.

1. Design Conditions

The circulation calculations are based on conditions in the unit that will produce the worst effect on circulation. The following conditions shall be used.

- a. The maximum steam flow that the unit is guaranteed to supply.
- b. The maximum drum operating pressure of the unit.
- c. Several fuel specifications. The calculations should be based on the fuel that produces the greatest furnace absorption rates. A unit designed for present firing of gas with future conversion to coal, and which requires a future change in the furnace, shall have the circulation design checked for both present and future arrangements.
- d. Absorption rates as determined from performance calculations for conditions (a), (b), and (c) above. Absorption rates are based on flat projected heating surface for furnace surfaces and are based on full circumference surfaces for boiler surfaces, that is, surfaces located downstream of the furnace outlet.

- e. Steam entrainment values for evaluating the gravity head and pressure drop in the heated upflow circuits and in the downcomer pipes and feeders.

In a given unit, circulation systems will be under the most severe condition at full load or overload as these outputs represent the maximum values in heat absorption and pressure drum. Natural circulation systems are designed at maximum loads with provisions being made to keep within design limitations of velocity and proportion of steam by volume in the steam-water mixtures.

The water velocity at the entrance of heated tubes is important as a means of inducing sufficient mass flow of water and steam-water mixture within a tube to produce turbulent flow and gain benefit of high heat transfer coefficient and to keep tube entrances clear of any sludge or scale. The velocity should be greater when entering a furnace water wall tube than entering tubes exposed to less intense heat, such as side wall tubes in a convection pass, or boiler tubes in two-drum boilers. In the design of modern high pressure, high capacity steam generators the water velocity entering furnace wall tubes is usually more than 3 ft/sec. Table 1 is a guide for fixing maximum velocities at design conditions in various locations and under various conditions:

Table 1

Circuit	Velocity	Remarks
1) Furnace water walls; Bare tubes with or without fins sloped more than 30°	2 ft/sec	Above 1500 psi
	1 ft/sec	Under 1500 psi
2) Furnace water walls; Bare tubes without fins, slope less 30°. No heat on top of tubes.	3 ft/sec	All pressures
3) Furnace water walls; Bare tubes without fins, slope less than 30°. Receiving heat on top of tube.	5 ft/sec	All pressures. Generally unsatisfactory.
4) Vertical boiler tubes	0.5 ft/sec	All pressures
5) Horizontal boiler tubes	4 ft/sec	All pressures
6) Water cooled burner throats	1 ft/sec	All pressures

STEAM BY VOLUME

The importance of steam by volume criterion lies in the need to keep sufficient water unevaporated in the heated tubes to continually wet tube wall and maintain heat transfer coefficient that adequate velocity help produce. Unevaporated water will also wash concentrated solids from highly heated tubes, carrying water salts to more quiescent zones where the collection may be removed from the unit. In the below formula steam by volume and steam by weight is expressed as a fraction:

$$\beta = \lambda v_g / [\lambda v_g + (1 - \lambda)v_f] \dots\dots\dots(1)$$

$$\lambda = \left(\frac{\beta}{v_g}\right) / \left[\left(\frac{\beta}{v_g}\right) + \frac{1-\beta}{v_f}\right] \dots\dots\dots(2)$$

From equation 1 above steam by volume β is calculated by using the amount of steam generated in a circuit over the amount of water entering a circuit. The amount of steam is calculated by the amount of heat absorbed by the riser section

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area of the circuit. The amount of water is calculated when assuming a velocity of water entering a circuit when knowing its cross sectional area. The result of the steam by volume in a circuit is then corrected using equation 2.

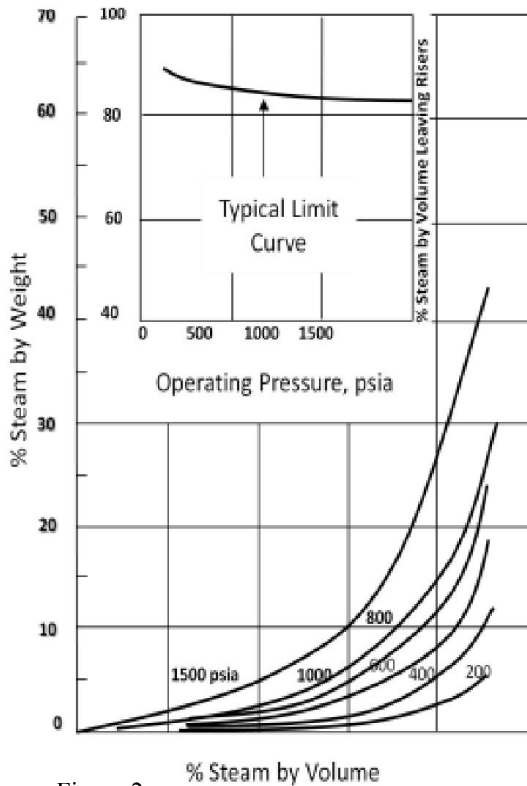


Figure 2

CALCULATION SUMMARY

The calculation procedures require that two fundamental relationships be satisfied:

1. The sum of the gravity head plus losses (head required) in upflow circuits such as furnace waterwalls and boiler bank risers must equal the gravity head minus losses (head available) in the downcomers.
2. The weight of fluid flowing in the downcomers must equal the sum of the weights of fluid entering the wall or tube bank fed by these downcomers, assuming no blowdown, except from the steam drum.

The calculation of circulating flow is done by a graphical method. The normal procedure is to determine the head required for all upflow circuits over a range of flows and then to calculate the head available in the downcomer circuits that feed the upflowing circuits. A plot of the heads versus flow produces an intersection between the curves for head available and head required. This intersection is referred to as the balance point and indicates the flow and head at which the upflow and downflow circuits will balance.

CALCULATION PREPARATION

Preparation for the circulation analysis will insure a simple start and insures more accurate results of the analysis. The first step in a circulation analysis is to perform boiler performance analysis to determine boiler temperature profile including temperatures at the furnace exit, downstream of the superheater, and downstream of the boiler bank tubes. In addition, the heat flux in the furnace area need to be established. Heat flux in the furnace is a function of the heat release within the furnace and it varies between 1.8 to 0.5 times the average heat flux across the furnace. The rate of flue gas in the boiler is determined in the boiler performance analysis as well as the moisture percentage in the flue gas. Temperature profile within the boiler, furnace heat flux, flue gas rate, and moisture percentage all determine the amount of heat absorbed in the absorption surfaces in the boiler.

Other important part of circulation analysis preparation is to keep track of all the heat transfer surfaces and to divide them within separate circuits with definite mapping of the start of the circuit, its route, the amount of heat absorbed by the circuit, and its end.

CIRCULATION CALCULATIONS DETAILS

Circulation analysis calculations start from the heat transfer analysis in the boiler by calculating absorbed heat by heat transfer surfaces within boiler components. Absorbed heat can be checked in accordance to the following list:

1. Net heat entering the boiler furnace which is contained with the combusted fuel.
2. Net heat leaving the boiler furnace.
3. Heat absorbed in furnace by radiation.
4. Heat absorbed by screen tubes.
5. Heat absorbed by riser tubes in the boiler bank tubes.
6. Heat absorbed by downcomer tubes.

Then gravity head and flow losses are made in accordance with the following formulation:

1. Upflow or riser circuits: Gravity heads and flow losses are calculated using the below equations.

$$\text{Friction Loss} \quad \Delta P = \frac{4fL}{di} \frac{Vo^2}{2g} \left(1 + \frac{NL}{2Vo}\right) \dots\dots(3)$$

$$\text{Acceleration Loss} \quad \Delta P = \frac{Vo^2}{2g} \frac{2NL}{Vo} \dots\dots\dots(4)$$

$$\text{Entrance and Exit Loss} \quad \Delta P = 1.5 \frac{Vo^2}{2g} \dots\dots\dots(5)$$

$$\text{Bend Loss} \quad \Delta P = K_b \frac{Vo^2}{2g} \left(1 + \frac{NL}{2Vo}\right) \dots\dots(6)$$

$$\text{Gravity Head} \quad GH = \frac{HVo}{NL} \ln\left(1 + \frac{NL}{Vo}\right) \dots\dots\dots(7)$$

Again, vapor fractions by weight and volume can be calculated according to the following equations and compared to results in equations 1 and 2.

Vapor fraction by weight $\lambda = \frac{NL}{V_o} \frac{v_f}{v_{fg}} \dots\dots\dots(8)$

Vapor fraction by volume $\beta = \frac{v_g}{v_{fg}} \frac{\frac{NL}{V_o}}{[1+\frac{NL}{V_o}]} \dots\dots\dots(9)$

Circulation ratio $CR = \frac{1}{\lambda} \dots\dots\dots(10)$

2. Downcomer circuit: Gravity heads and flow losses are calculated using the following equations:

Downcomers circuits with entrainment

1. Gravity head = $\frac{\rho_e}{\rho_o} H \dots\dots\dots(11)$

2. Friction, Bends, Entrance, and Exit Losses

$\Delta P = \frac{\rho_o}{\rho_e} (K)^2 \frac{v_o^2}{2g} [0.288 \frac{L}{d_i} + \Sigma K] \dots\dots\dots(12)$

Downcomers circuits with subcooling

1. Gravity head = $\frac{\rho_x}{\rho_o} H \dots\dots\dots(13)$

2. Friction, Bends, Entrance, and Exit Losses

$\Delta P = \frac{\rho_o}{\rho_x} (K)^2 \frac{v_o^2}{2g} [0.288 \frac{L}{d_i} + \Sigma K] \dots\dots\dots(14)$

Downcomers circuits with subcooling

1. Gravity head = $H \dots\dots\dots(15)$

2. Friction, Bends, Entrance, and Exit Losses

$\Delta P = (K)^2 \frac{v_o^2}{2g} [0.288 \frac{L}{d_i} + \Sigma K] \dots\dots\dots(16)$

separated from water. Pressure drop or losses can be calculated using equations 3 through 6 and can be subtracted from gravity head GH in equation 7 and that accounts for the head required in the riser tube area. Similarly, the head available in the downcomer tubes is calculated in equations 11 through 16 for all circuits in a boiler. There is an important note in the analysis of boiler circulation and that is the keeping track of the circuit configuration and knowing amounts of heat being absorbed by each section of the circuit insures accurate steam generation and boiler circulation values.

All above calculations are performed with velocity assumptions to obtain a range of flows in the riser tube circuits to determine the ahead available in the downcomer tube circuits. upflow and downflow circuits balance is decided by plotting heads versus flows where an intersection between curves for head available and head required is referred to as the balance point. Information from the balance point such as velocities and steam fraction by weight will be checked against limit curves as shown in Figure 2 to insure adequate boiler circulation design.

CONCLUSION

To insure proper boiler circulation, a simple, clear and comprehensive approach has been summarized in this paper covering all aspects in boiler circulation analysis. The analysis details all boiler circulation formula and explaining all forces imposed on them including thermosyphon as well as friction forces.

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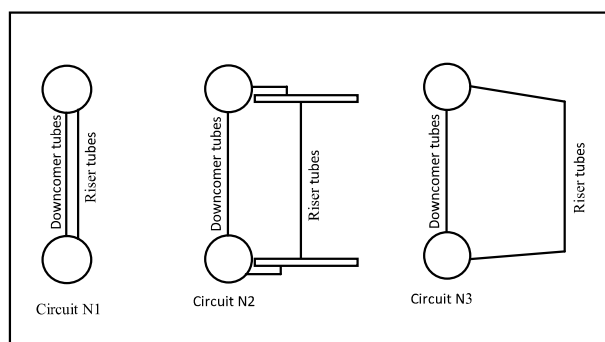


Figure 3

In an industrial boiler, there are several circuits producing steam with different heat absorption rates and different configurations, therefore, producing different amounts of steam. For example, As shown in Figure 3 above, there are three types of circuits in one boiler where in all circuit N1, N2, and N3 water flows from the steam drum through downcomer tubes to the water drum then water-steam mixture flows upward following different routes to the steam drum where steam is