DEVELOPMENT OF MODEL FOR THE SIMULATION OF AN INDUSTRIAL DEAERATOR FOR BOILER FEED WATER PRODUCTION

Dr. Jackson Akpa
Rivers State University
NIGERIA
akpa.jackson@ust.edu.ng

Dr. Dagde K.K
Rivers State University
NIGERIA
dagde.kenneth@ust.edu.ng

Believe Moses
Rivers State University
NIGERIA
believedan.md@gmail.com

ABSTRACT

This research considers a mathematical model development for deaerator performance simulation considering current operating parameters and monitoring trend of performance based on the flow-regimes and operating conditions. This research is aimed at generally minimizing the cost of boiler feed water (BFW) production by reducing energy losses and achieving ≤1ppm oxygen concentration in boiler feed water with minimum chemical deaeration requirement. To achieve this, Mass & Energy balance was done on the deaerator under study, models were also developed to predict the actual steam and venting rate required for appropriate mechanical deaeration, and the oxygen continuity equation was adopted and solved to estimate oxygen concentration in feed water from deaerator. The outcome of this research showed that current deaerator performance was <40% and deaerator excess steam /venting rate losses could be minimized to mitigate artificial rain around deaerator and still achieve minimum oxygen concentration in deaerator outlet by maintaining balanced heat load to the deaerator during operation. Owing to deaerator design specification and result of simulation, case study deaerator should be operated at a temperature ≥108°C as this after simulation corresponds to an oxygen concentration of ≤1.33ppm at the deaerator outlet, a control valve should be utilized at deaerator vent to regulate venting based on operating conditions. Further studies should consider studying how conductivity/other properties of water affect deaeration.

Keywords: Deaeration, Eliminox, Low pressure steam, Return Condensate, Corrosion.

INTRODUCTION

Deaeration simply involves removal of entrained or dissolved gases from water which will serve as feed to boilers or for use in other process units. The gases of concern in boiler operation are mainly oxygen and carbon dioxide which as a result of natural causes are present in water. The presence of Oxygen and carbon dioxide in untreated water act as corrosion causatives in boilers as well as steam plant materials. The rate of the corrosion is directly proportional to the quantity of the gas present in the feed water, this corrosion action is further accelerated in high temperature conditions which in practice would be experienced in boilers during steam generation. Primarily, the function of deaeration is mainly to reduce the concentration of both dissolved oxygen and carbon dioxide in water to minimum levels such that its potential to cause corrosion to boiler materials such as alloy steel and carbon steel is totally eliminated at prevailing boiler operating conditions (temperature and pressure) as well as other transport equipments (pump parts, and pipes) (Deaerator White Paper for use in boilers;2011, pg 1-7).

Deaerators are mechanical devices which remove dissolved gases from boiler feed water. Deaeration process helps protect steam system from the effects of corrosive gases. It achieves this by reducing the concentration of dissolved oxygen and carbon dioxide to levels where corrosion effect is minimized. Generally, dissolved oxygen level of 5ppm or even lower is required to prevent corrosion in most high-pressure boilers. Although oxygen concentrations of up to 43 ppb can be tolerated in low-pressure boilers, but equipment life is extended at very little or no extra cost by simply limiting the oxygen concentration to 5 ppm or even trace as required by some industries. It is worthy of note that dissolved carbon dioxide is completely removed by the deaerator (mechanical deaeration).Deaerators can be used in any chemical industry or in power plants where boilers are employed for steam production from boiler feed water (B.F.W). Deaerator serves the purpose of removal of unwanted dissolved gases and dissolved oxygen from the boiler feed water before entering into boilers. Most deaerators are designed such that dissolved oxygen content in the outlet water (discharge) is about 7 ppm by wt% (http://www.chemicalengineeringsite.com/deaerators-purpose-principle).

At elevated temperature, boiler parts such as feed water piping, pumps, and economizers are subject to severe oxygen (O2) corrosion attacks even though a minute level of oxygen is present in the water, There is a constant financial challenge of not only changing corroded boiler parts, but there is also the physical risk of boiler blow-out which could occur when boiler vessel has under gone scaling and corrosion.

Generally Iron or steel are the major materials used in designing boilers, boiler feed water piping, as well as other downstream equipments. Corrosion of these materials is often caused by three key factors namely: Temperature, dissolved oxygen concentration and pH value which in turn influence the aggressiveness of boiler corrosion. The greater the temperature, and the lower the pH value the higher the aggressiveness of the feed water in causing corrosion. The amount of dissolved oxygen in feed water is a huge factor in determining the amount of corrosion that will occur.

Furthermore, carbon dioxide can combine with condensate to form carbonic acid which can massively corrode boiler feed water & steam handling equipments.*(Connor S, (2015).)*

$$CO_2 + H_2O \longrightarrow H_2CO_3 \text{ (Carbonic Acid)}$$

Corrosion rate as a result of dissolved O_2 and CO_2 doubles steadily as temperature Increases.
Iron begins to dissolve when in contact with water

$$\underset{\text{Iron}}{Fe} + \underset{\text{Water}}{2H_2O} \longrightarrow \underset{\text{Ferrous Hydroxide}}{Fe(OH)_2} + \underset{\text{Hydrogen}}{2H^+}$$

Increased presence of O_2 will cause the ferrous hydroxide to form ferric hydroxide (Rust)

$$4Fe(OH)_2 + O_2 + H_2O \longrightarrow 4Fe(OH)_3 \text{ (Ferric Hydroxide [RUST])}$$

These amongst many further emphasize the importance and relevance of a deaerator in any efficient boiler system. In to maintain an effective boiler system the deaerator performance must be at optimum at all times both for existing and newly installed deaerator units.

This research aims to develop a mathematical model for the simulation of an existing industrial deaerator performance to achieve desired oxygen concentration in feed water with minimal chemical injection and reduce energy expended to achieve desired mechanical deaeration.
To achieve these, the following was carried out;

- Mass/Energy balance on the deaerator.
- Use model developed to estimate the actual venting rate and low pressure steam requirement to deaerator corresponding to return condensate flow conditions.

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- Outline current deaerator operating parameters and estimate efficiency of deaeration.
- To reduce energy losses by developing a balance between the steam required to achieve optimum deaeration and return condensate to deaerator.

DEAERATOR TECHNOLOGY

During deaeration, feed water is steadily heated to saturation temperature while maintaining a minimum vent and pressure drop. This action ensures optimum thermal operational efficiency. Deaeration is carried out by sprinkling the feed water over multiple tray layers designed to enable large contact surface between the liquid droplets and steam used for deaeration. The steam used for scrubbing is fed from the bottom of the deaerator. When the steam contacts the boiler feed water, it gradually brings it to saturation temperature and the dissolved gases in the feed water are released through the vent valve. Treated water drops to the storage vessel beneath the deaerator *(Babcock et. al, 2005).*

Since the solubility of oxygen in water is reduced through heating, steam causes the feed water to give up the dissolved oxygen more readily. Steam is and still remains a highly efficient medium for heating and breaking up the water droplets via scrubbing, Often a very small quantity of steam is vented to the atmosphere during deaeration. Most of the steams used in heating and scrubbing are condensed and they become part of the deaerated water and return to the storage of the deaerator. The design of a proper deaerator system largely depends on the quantity of gases to be removed and the desired oxygen concentration after deaeration. This depends on the ratio of boiler feed water to return condensate and the deaerator operating pressure. Deaerators require low pressure (LP) steam to heat the water to its full saturation temperature which corresponds to the steam pressure in the deaerator to drive away dissolved gases. Steam flow may either be parallel, counter or cross to the flow of water. Deaerators consist of the deaeration section, a storage tank, and a vent opening. Inside the deaeration section, steam bubbles through the water, heating and agitating it. Non-condensable gases associated with the feed water and a portion of steam are released through the deaerator vent. Steam to the deaerator enables the stripping action and heats up the mixture of boiler feed water and return condensate to its saturation temperature. Often, a portion of steam will condense, but a fraction (5% - 14%) must be continuously vented to accommodate the stripping requirement of the deaerator. Design practice usually is to obtain the steam required for heating and ensure the flow is enough for stripping. Where rate of return condensate is high (>80%) with the pressure of condensate high when compared to the deaerator pressure, then a little portion of steam would be required for heating. When properly installed and operated, deaerators are designed to provide continuous boiler operation, even with significant load changes without any form of involvement from the operator. Variation in temperature, level of water and pressure in a deaerator can cause not only "Water Hammer", but malfunction of auxiliary-equipment and boiler also operational anomalies. As a result deaerators are usually well instrumented (Evaluating deaerator operation -www.hpac.com/building-controls).

Principle of Deaerators

Deaerators normally operate based on the principles stated below;

Henrys Law

Solubility of a gas in a liquid is directly proportional to the partial pressure. Hence if the partial pressure of the entrained gas is decreased by adding steam to the deaerator, its solubility will decrease and the gas is driven away from the water.

Inverse Solubility of Water

When temperature of water is increased, dissolved oxygen in the feed water decreases. Hence when the temperature of water is increased by adding low pressure steam into the deaerator, solubility of dissolved gas is decreased and the gases are driven from water. (http://www.chemicalengineeringsite.com/deaerators-purpose-principle).

Deaeration Efficiency and Principles:

(1) Feed water should be atomized into droplets to increase the area available for both steam and water to contact, as this aids the removal of dissolved gases.
(2) The water should be heated to its saturation temperature in other to achieve a 'zero' gas solubility environment.
(3) Major contact must be established between water and steam in other to enable gases be scrubbed out within a lesser duration.
(4) Gases removed by deaeration should be sufficiently diluted with steam in other to establish minimum partial pressure above the surface of water.
(5) Gases removed from feed water should be vented. I other to maintain operational efficiency, vent steam losses should be maintained at a minimum rate.(American boiler manufacturers association.(2011)).

Deaeration Methods

Water deaeration is achieved by either chemical or mechanical methods.
For chemical deaeration stage, different chemicals can be adopted to react with the oxygen in water. The products of this reaction are not harmful to the boiler systems. There exist various chemicals which can be introduced into water to also react with the carbon dioxide and change it into a neutral form.

Basically, mechanical deaeration removes non-condensables, instead of transforming the carbon dioxide and oxygen in the water supply. Mechanical deaeration reverses the mechanism by which the gases initially go into solution with water.

Theory of Mechanical Oxygen Removal

The solubility of oxygen is proportional to the partial pressure acting when it comes in contacts with the water (Henry's Law). The atmosphere (21% oxygen) is the source of oxygen in water, At a temperature 15ºC, water in will absorb up to 10 ppm of oxygen when exposed to the atmosphere.

As earlier stated, solubility of oxygen in water will decrease as the temperature of water rises. When this occurs, the amount of water vapor in the atmosphere above the water will also increase. This means that lesser Oxygen can be held by water when its temperature increases, the amount of oxygen approaches 'zero' as the water reaches its saturation temperature.
Based these physical attributes, oxygen can be dislodged from water by raising the temperature and reducing the concentration of O_2 in the atmosphere above the water.(American boiler manufacturers association.(2011)).

Mechanical deaeration of feed water is mainly achieved by scrubbing the feed water using low pressure steam of 3.5 kg/cm^2.g to remove dissolved oxygen/carbon dioxide. Typically, mechanical deaeration occurs in the deaerating section of deaerators. By heating action of steam the dissolved gases in the water is released into the steam and forced out through the vent. Venting is allowed to take place to ensure complete deaeration. The efficiency of deaeration (mechanical) depends on the temperature and pressure of the steam used for

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deaeration and the type of deaerator. A steam plume is advised to be maintained at all times to ensure complete venting. Although complete removal of CO_2 can be achieved by mechanical deaeration, Oxygen can still exist to about 10-7ppm, depending on deaerator efficiency. Hence chemical deaeration is carried out to achieve complete removal of oxygen.

Chemical Deaeration:

This method of deaeration is basically carried out in the storage section of the deaerator which holds the deaerated water. In this process, an oxygen scavenger is used to achieve complete removal of oxygen. Eliminox or hydrazine (N_2H_4) is injected into the storage section of the deaerator to allow the Oxygen scavenger maximum time to react with the oxygen before it causes any damage. Eliminox reacts with the remaining trace of oxygen in water to form Ammonia(NH_3),Water (H_2O) and Nitrogen (N_2) (at elevated temperatures) with nitrogen been vented out.

There exist different chemical species which react rapidly with available oxygen. They are often referred to as oxygen scavengers. These scavengers have 2-categories namely;
(i) Weak bases (hydrazine and its alternatives) (2) Sulfites (IC Controls Limited (2015))

Deaerator Steam Consumption

Deaerator steam consumption is equivalent to the sum of steam needed to raise the temperature of deaerator feed water to its saturation temperature, and the amount vented with the non-condensables, subtracting any form of steam lost via failed steam traps or steam flashed from hot condensate. The heat balance calculation is carried out with the deaerator feed water at its lowest temperature. The vent rate of steam and non-condensables is a function of a deaerators size (feed-water capacity), type, and the rate of makeup water supply. Operating vent rate is at its maximum rate with the introduction of a cold stream of oxygen-rich makeup water.
The steam requirement for deaeration is approximately 1% of feed-water flow for every 10°C rise in temperature within the deaerator.

Mathematically, Steam required (Ib/hr) = $(T_{out} - T_{in}) \times \frac{0.01}{10°F}$ (2.7)

This value is however only an approximation, since the heat content of the steam and water will vary considering operating temperature. (James, M. 2004).

METHODOLOGY

The processes taken to develop the models for a pressure type deaerator are based on first principle and are presented below:

Deaerator Model

The model developed is based on both the law of conservation of mass and energy. The change of any parameter generates a transient process by which the system is evolving towards a new steady-state regime. The balance to be carried out below.

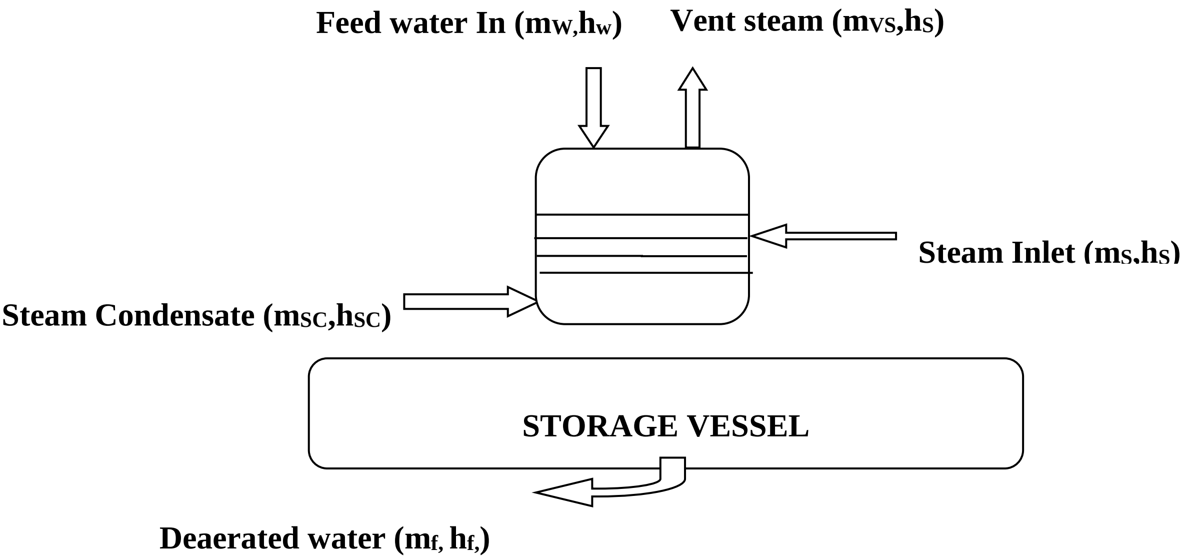


Figure.1 Simple Deaerator Schemati

Model Assumptions

1. Negligible pressure drop as the steam enters the deaerator such that the deaerator pressure is equal to the steam pressure.
2. Deaerator unit is operating under steady state conditions, such that accumulation within the deaerator is negligible.
3. Deaerator dome and feed water tank are under similar thermodynamic conditions and can be treated as one vessel.
4. Heat loss through the walls of the deaerator is negligible due to insulation of the wall dQ = 0.
5. The Deaerator has no additional heat or mass losses.
6. The vent steam enthalpy is same as the enthalpy of saturated vapor at the deaerator pressure. The energy contribution of the vented non condensable is also assumed to be negligible.
7. The deaerator water enthalpy is same as the enthalpy of saturated liquid at the deaerator pressure.
8. The heating and deaeration process are both completed in the preheater stage of the deaerating dome.

Mass Balance on a Typical Deaerator Unit

$$\frac{\textbf{Accumulation in Deaerator}}{\textbf{Time}} = \frac{\textbf{Input to deaerator}}{\textbf{Time}} - \frac{\textbf{Output of deaerator}}{\textbf{Time}} \quad (1)$$

Inlet Feed Stream = $m_W + m_S + m_C \equiv m_i$ (2)

Outlet Feed Stream = $m_v + m_f \equiv m_o$ (3)

Hence mass balance on the entire deaerator is given as follows,

$$\frac{d[\rho V]}{dt} = \sum_{in} m_i - \sum_{out} m_o \quad (4)$$

$$\frac{d[\rho V]}{dt} = (m_w + m_s + m_c) - (m_{vs} + m_f) \quad (5)$$

Equation (3.5) becomes

$$\rho\frac{dV}{dt}+V\frac{d\rho}{dt}\equiv\frac{dm_s}{dt}=(m_w+m_s+m_c)\ -\left(m_{vs}+m_f\right) \quad (6)$$

Since the deaerator volume is constant, hence

$$\frac{dV}{dt}=0$$

$$\boldsymbol{V\frac{d\rho}{dt}=(m_w+m_s+m_c)-\left(m_{vs}+m_f\right)=0} \quad (7)$$

Hence since the unit is operating under steady state condition, equation (7) can be written as:

$$\left(m_{vs}\left(\frac{kg}{hr}\right)=(m_w+m_s+m_c)-\left(m_f\right)\right) \quad (8)$$

Equation (3.7) is the mass balance equation for a typical deaerator system.
Where,

m_{vs} Mass flow rate of vented steam (kg/s).

but Vented steam mass flow rate $m_{vs}\equiv(\text{Vent rate x } M_w)$ (9)

recall Vent Rate $\left(\frac{Ib}{hr}\right)=(24.24\ \times P_a\times D^2)$

m_f Mass flow rate of deaerated water (kg/s).

Total deaerator mass flow $(m_f)=(m_c+\ m_w\ )$ (10)

m_w Mass flow rate of feed water to deaerator (kg/s).

m_s Mass flow rate of low pressure steam into deaerator (kg/s).

m_c Mass flow rate of return condensate to deaerator (kg/s).

m_{cs} Mass of Condensed steam

Energy Balance on Deaerator:

$$\left(\frac{\text{Accumulation of total energy}}{\text{time}}\right)=\left(\frac{\text{Input of total energy}}{\text{time}}\right)-\left(\frac{\text{Output of energy}}{\text{time}}\right)\pm\left(\frac{\text{Heat added by steam or vented}}{\text{time}}\right) \quad (11)$$

$$\frac{dE}{dt}=\frac{d(U+K+P)}{dt}=\textstyle\sum_{IN}m_ih_i+\sum_{OUT}m_oh_o+Q\pm W_s \quad (12)$$

But the deaerator unit is stationary, V= 0, hence

$\frac{dk}{dt}=\frac{dp}{dt}=0\ \therefore\frac{dE}{dt}\equiv\frac{du}{dt},$ but $\frac{du}{dh}=\frac{dH}{dt}$ for liquid systems.

Where $H=mc_pdT, W\equiv 0,$

$$\frac{d\left(\rho Vc_pdT\right)}{dt}(m_wh_w+m_sh_s+m_ch_c)-(m_{dw}h_{dw}+m_{vs}h_{vs}) \quad (13)$$

$$\frac{\rho Vdh}{dt}=\frac{du}{dt}=(m_wh_w+m_sh_s+m_ch_c)-(m_{dw}h_{dw}+m_{vs}h_{vs}) \quad (14)$$

$$\left(\frac{du}{dt}=\frac{(m_wh_w+m_sh_s+m_ch_c)-(m_{dw}h_{dw}+m_{vs}h_{vs})}{\rho V}\right) \quad (15)$$

Considering steady state condition, rearranging equation (15) becomes,

$$\left(m_s\left(\frac{kg}{hr}\right)=\frac{(m_fh_f+m_{vs}h_{vs})-(m_wh_w+m_ch_c)}{h_s}\right) \quad (16)$$

Equations (7) and (15) are the model equations for a typical deaerator system.
The following relations are established to predict the energy requirement of the system at various flow conditions.

Total Outlet Energy Flow to Deaerator $=h_fm_f+h_{vs}m_{vs}$ (18)

Minimum Inlet Energy Flow = h_wm_w

Additional Energy flow needed$= (h_f m_f + h_{vs} m_{vs}) - (h_w m_w)$ (19)

Oxygen Continuity Equation:

In order to determine the outlet oxygen concentration, the model solves the equation for oxygen diffusion from a falling droplet. According to (Sharma et. al, 2010) assuming that there is no oxygen in the inlet stream, the component continuity equation for oxygen diffusion from a spherical droplet can be written as,

$$\frac{dw_{O2}(t)}{dt} = -6\,\frac{Sh \cdot Do_{2mc} \cdot w_{O2}(t)}{D^2} \quad (20)$$

Integrating the equation above, we have that,

$$\left(Wo_2(t) = W_{O_{2in}} e^{-6\left(\frac{Sh.D_{O_{2mc}}}{D^2}\right)t_{mt}}\right) \quad (21)$$

Where

DO_2	Diffusivity of oxygen in water
D	Droplet Diameter
T_{mt}	Time available for mass transfer
WO_2	Inlet Concentration of Oxygen in Deaerator feed Stream. (This value in this research is estimated theoretically using Solubility of Dissolved Oxygen chart at Various Pressure/Temperature Conditions)

Sherwood number (Sh)

This is the ratio of convective mass transfer to the mass Diffusivity.

$$(Sh = K.L/D_{AB}) \quad (22)$$

Where

K	Overall Mass Transfer coefficient
L	Length of Sheet.
D_{AB}	Diffusivity of A in B.

Typically Sh-number for pipes $\equiv$ 3.66 and for falling films $\equiv$ 3.41

Steam Venting Rate

The rule of thumb in the deaerator industry is that the vent valve passes a maximum of 1/10 of 1% of the deaerator capacity. The exact vent rate can be calculated as follows;

$$\text{Vent Rate}\left(\frac{Ib}{hr}\right) = (24.24 \times P_a \times D^2) \quad (23)$$

Where

Pa – Deaerator Operating Pressure (PSI) (Absolute)
(Design Deaerator Pressure 0.7Kg/cm2)
(Deaerator Operating Pressure 0.6 kg/cm2 – 0.47 Kg/cm2)

D – Diameter (Inches) of opening in the manual valve or orifice
(4 Inch $\equiv$ 10.16 cm)

The maximum loss of steam is a requirement in all plant operations and one area to ensure no unnecessary loss is occurring in the deaerator operation.

Operating/ Model of Deaerator

Process operating data of a deaerator at the case study was used in this study. This data are as shown in Tables 1, 2 and 3.

Deaerator Specifications

Table 1.Deaerator design specifications

Deaerator Type	Spray-Tray
Design Temperature	245 °C
Design Operating Pressure	0.72 Kg/cm^2
Deaerating Heater Length	4790mm
Storage Section Length	12328mm
Material Of Construction	Stainless Steel (S.S 304)

Table 2: Deaerator process parameters

PARAMETER	UNIT	Makeup (MW)	Return Condensate (MC)	Deaerator Output (MF)	Steam to Deaerator (M_S)
Feed Water Flow	(Kg/hr)	233,390	15,190	254,300	5,900
Operating Pressure	(Kg/cm^2)	2.0	2.4	0.3	3.2
Design Pressure	(Kg/cm2)	1.87	3.6	0.7	3.52
Design Temperature	(°C)	101	148	115.5	228
Operating Temperature		95	130	110	160
Design Vent loss (M_{VS})	Kg/hr	-	-	-	180
Operating Vent loss (M_{VS})					320

Table 3: Deaerator Operating Conditions

Operating Pressure($Kg/cm^2.g$)	*Design Pressure($Kg/cm^2.g$)*	*Efficiency of Deaerator (100%)*	*Operating Temperature (°c)*
0.7	*0.7*	*100*	*115*
0.43	*0.7*	*61.43*	*110*
0.38	*0.7*	*54.29*	*109*
0.33	*0.7*	*47.14*	*108*
0.28	*0.7*	*40*	*107*
0.24	*0.7*	*34.29*	*106*
0.19963	*0.7*	*28.52*	*105*
0.157561	*0.7*	*22.51*	*104*

0.116684	*0.7*	*16.67*	*103*
0.0384029	*0.7*	*5.49*	*101*

RESULTS & DISCUSSION

The models for deaerator were developed and simulated using MATLAB compiler. The results are presented in tabular form and the graphs plotted from the result would be discussed below:

Steam Requirement and Return Condensate Load Balance

Deaerators use steam to heat the water to the full saturation temperature corresponding to the steam pressure in the deaerator and to scrub out and carry away dissolved gases. However, in industries, due to the need for energy saving and optimum utilization, to reduce the steam required to achieve deaeration steam condensate (return condensate) is utilized as feed to deaerator to help raise the temperature of incoming feed water to the deaerator. steam condensate in this case of study is gotten from a Benfield reboiler exchanger. Medium pressure Steam of 38.3kg/cm^2.g and 248°C is introduced to the shell side of the exchanger to heat up Benfield solution in the tube side. The steam after heat exchange with the tube side solution (Benfield Solution) condenses. This condensate from the exchanger is still at a temperature of approximately 130°C hence still has an enthalpy enough to raise the temperature of the main feed water (demineralised water) to the deaerator to its saturation temperature.

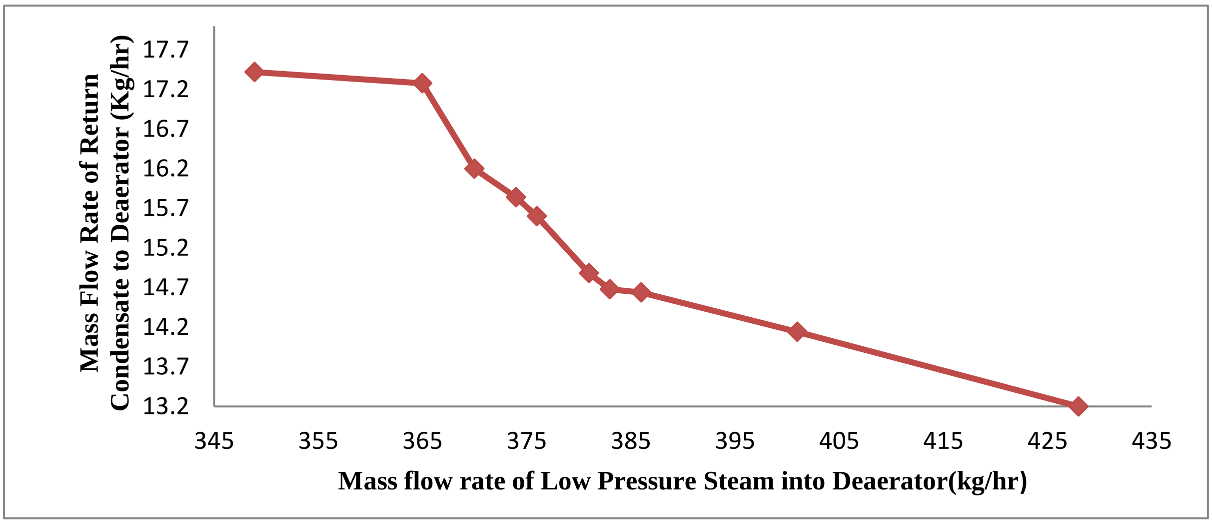
Also, the relationship between mass of steam to the deaerator required in other to achieve desired mechanical deaeration and Return Condensate is inverse. Hence as return condensate load (M_c) increases, the mass of steam (M_s) reduces and vice-versa.

The limitation of this case study deaerator is the absence of data sheet outlining proportionate amount of steam required based on the flow of return condensate to the deaerator. As a result the flow of steam to the deaerator during deaerator operation is either in excess resulting in energy loss or less resulting in inadequate deaeration and subsequently more chemical deaeration demand. In practice, Based on the mass balance above the appropriate mass of steam required based on flow of return condensate can be estimated at all times. This in turn would

- Improve and maintain deaerator efficiency
- Reduce energy loss via excess steam
- Reduce chemical deaeration required.

The result of the simulation as plotted below shows that as return condensate load to deaerator increases, the steam requirement for deaeration decreases. This trend satisfies the inverse steam and return condensate relationship.

Graph 1.Low pressure steam relationship with Return condensate



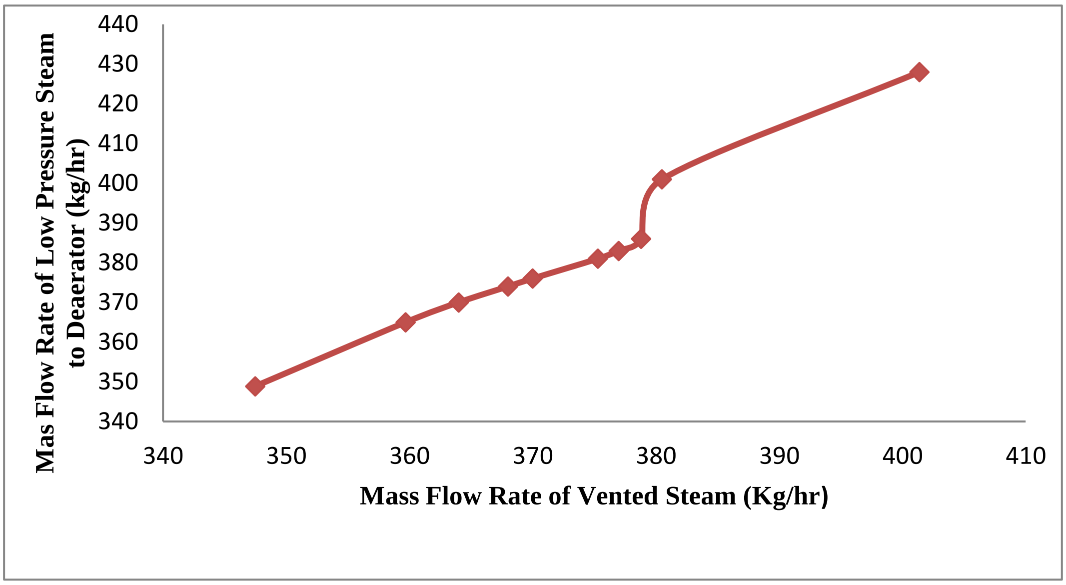
Steam Requirement and Vent Rate

The deaerator steam consumption is theoretically equal to the steam required to heat incoming water to its saturation temperature, plus the amount vented with the non-condensable gases, less any flashed steam from hot condensate or steam losses through failed traps. The vent rate is a function of deaerator type, size (rated feed water capacity), and the amount of makeup water.

Since a deaerator must vent the non-condensable gases into atmosphere to avoid re-oxygenation of the deaerated water, to accomplish the goal of venting non-condensable gases the deaerator will vent a small percentage of steam. With the high cost of steam production, and industries energy & cost saving drive, the deaerator vent must be investigated maintained within corresponding operating conditions to ensure less or excessive venting of steam is not occurring.

Hence from the result of the simulation, the corresponding venting rate for a deaerator based on flow and operating conditions can be observed from the graph presented below. From the energy balance result, it can be seen that as the mass flow of steam (M_s) to the deaerator increases, the flow rate of vented steam (M_{vs}) also proportionately increases. This ensures, appropriate venting of the non-condensables at corresponding operating pressure/temperature and avoids re-oxygenation of the deaerated water. This outcome ensures excessive loss of energy/steam is minimized and deaerator efficiency is maintained at desired.

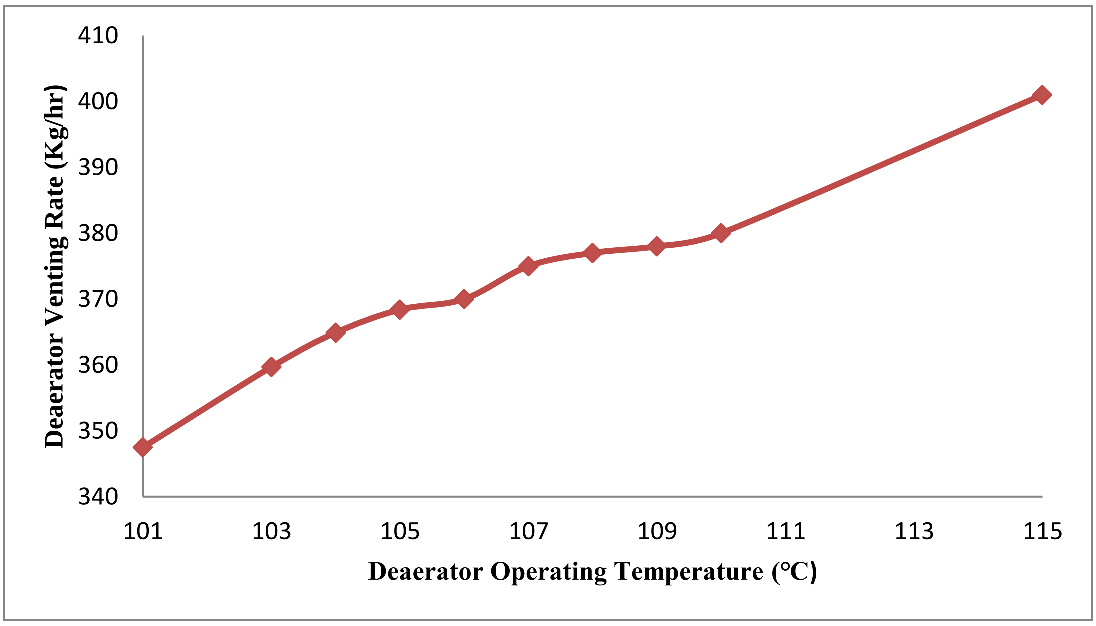
Graph 2. Deaerator Steam Requirement and Vent Rate



Deaerator Vent Rate and Operating Conditions

The basic operating conditions which drive mechanical deaeration are temperature and pressure. These two parameters are the basis of mechanical deaeration and have a direct relationship to the vent rate of any deaerator. As shown in the graphs below, as the Temperature or pressure of the deaerator increases during operation, the rate of venting of steam/non condensable increases.

Graph 3. Deaerator Venting Rate and Operating Conditions

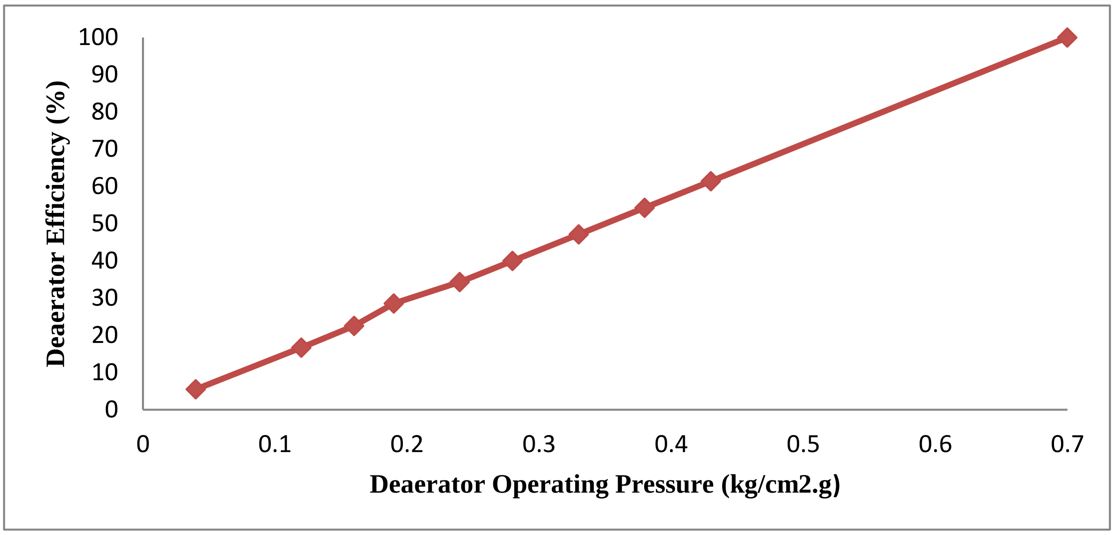


As the operating conditions of the deaerator increases, there is a need to vent appropriate amount of steam corresponding to the operating condition of the deaerator in other to ensure complete venting of the non-condensables and maintain efficiency.

EFFICIENCY OF DEAERATION

The efficiency of the deaerator is a function of mainly the operating conditions (temperature and pressure) within the deaerator. Using operational data, from the graph below, the operating efficiency of the deaerator can be estimated.

Graph 4. Deaerator Operational Pressure and Efficiency



At current plant conditions, the case study deaerator using a remote pressure indicator controller (PIC) is operating between 0.28- 0.0.33kg/cm^2 this corresponds to an operating efficiency of about 0.40% – 0.47%. Hence to improve performance, deaerator should be operated at a temperature ≥ 108°C as this corresponds to an outlet oxygen concentration of ≤1ppm.

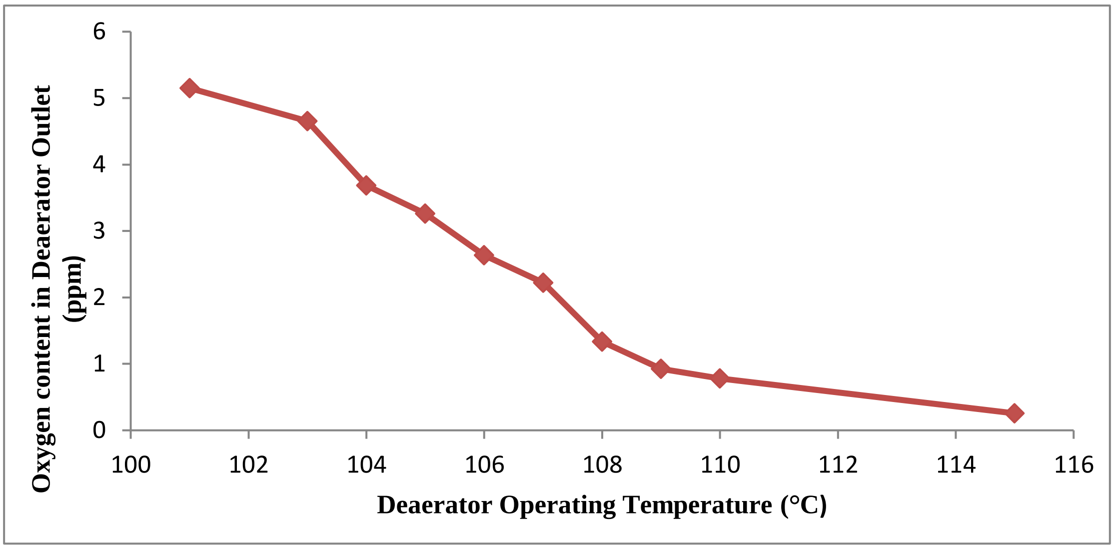
Oxygen Concentration and Mechanical Deaeration

As the partial pressure within the deaerator decreases, the concentration of oxygen left in the water decreases. By estimating the quantity of oxygen in the deaerator outlet, the corresponding dosage of oxygen scavenger (Eliminox) to be used can be estimated. This is necessary to ensure the following;

- Protection of boilers and boiler parts against corrosion effect of Oxygen.
- Increased boiler feed water quality.
- Ensure appropriate chemical deaeration.
- Reduce cost

From the graph below, it can be seen that the minimum oxygen content achievable is 0.256ppm at an efficiency of 100%. To achieve minimal chemical deaeration it is recommended that deaerators operating within this range should not be operated less than 0.38kg/cm^2≈109°C and not greater than 0.7kg/cm^2≈ 115°C to avoid steam (energy) loss and re-oxygenation of the deaerated water as a result of steam flashing (Often as a result of over pressure).

Graph 5. Oxygen Concentration in Deaerated water and Operating Temperatures



The table below outlines the results of the Oxygen continuity equation adopted to estimate the concentration of oxygen in boiler feed water to deaerator in the absence of an online analyzer as the case in the case study deaerator.

Table 4. Deaerator Outlet Oxygen Content at various operating conditions

Operating Pressure (Kg/cm^2)	Operating Temperature (°C)	Solubility of oxygen in Water (DO_2)(cm^2/sec)	Outlet Oxygen concentration ($WO_2(t)$)(ppm)
0.7	115	120×10^{-6}	0.256
0.43	110	110.4×10^{-6}	0.78
0.38	109	108.9×10^{-6}	0.926
0.33	108	105.7×10^{-6}	1.332
0.28	107	101.2×10^{-6}	2.22
0.24	106	99.7×10^{-6}	2.635
0.19963	105	97.83×10^{-6}	3.259
0.1575561	104	96.75×10^{-6}	3.684
0.116684	103	94.7×10^{-6}	4.651
0.0384029	101	93.8×10^{-6}	5.15

Cost Implication of Chemical Deaeration

To achieve required chemical deaeration, a batch of Eliminox (N_2H_4) solution is prepared in an injection tank using 6-Litres of Eliminox per batch, and making up tank level using demineralised water or steam condensate. Based on the requirement to ensure that there is a trace of Eliminox in the boiler feed water been fed to the steam drum at all times (This signifies the complete removal of carbon dioxide and oxygen) about 18-litres of Eliminox is dosed per day to achieve this with a constant injection pump rate of about 0.2litre/min. This volume of Eliminox required can be reduced to about half.

Calculations for Chemical Deaeration Cost Implication

Theoretically, Volume of Eliminox required per 1ppm of Oxygen = 1ppm per 1ppm of Oxygen.
Injection Tank Capacity = 190 Litres
Injection rate = 0.2 litres/Min.

Eliminox Injection rate per hour = $\frac{0.2\text{ lit}}{\text{Min}} \times \frac{60\text{Min}}{\text{hr}} = 12\text{Litres/hr}$

Duration of One Batch in Injection tank $\frac{190\text{lit}}{12 lit./\text{hr}} \equiv 16\text{hrs}$

With 6liters of Eliminox dosed per batch, =12 liters Of Eliminox is consumed per operational day of 24hours.
Hence; Volume of Eliminox required/day =12 Litres.
Volume of Eliminox/drum = 220 Liters
Cost of 1 drum of Eliminox = #200,000

Eliminox usage per month = $\frac{12\text{litrs}}{\text{day}} \times \frac{31\text{days}}{\text{Month}} = 372\text{litres}$

Volume of Eliminox per month =372litres $\times \frac{1\text{drum}}{220\text{litres}} \equiv 1\frac{1}{4}$ drums of Eliminox

Hence,
Cost of chemical Deaeration per month ≡ #200,000.00 ×2= # 400, 000.00
Cost of chemical Deaeration per year ≡ #400,000.00 ×12= # 4,800,000.00
From oxygen concentration chart, at optimum temperature of 108°C oxygen concentration is ≈ 2.2ppm.
Hence amount of Eliminox required = $2.2 \times 14 + 4 = 34.8$
Amount of Eliminox required in
the solution (95% Concentration) $= 34.8\text{ppm} \times \frac{100}{95} = 36.6\text{ppm}$
Amount of Eliminox required per year

$$\frac{12\text{litres}}{\text{hour}} \times \frac{8760\text{hours}}{year} \times \frac{36.6\text{ppm of dissolved oxygen}}{1000\text{ppm}} = 3847.392\text{ Litres/Year}$$

But 1-drum of Eliminox = 200Litres, hence

Eliminox Used per year $= \frac{3847.392\text{Litres}}{\text{year}} \times \frac{1\text{Drum}}{200 Litres} = \frac{19.2\text{ drums}}{year}$

Annual Cost of Eliminox =19.2 drums/year × (#200,000.00)/drum
Annual Cost of Eliminox = **#3,847,392/year**

Cost Saving on Chemical Deaeration

Table 4 below shows the present cost of chemical deaeration, the cost of chemical deaeration at optimum operating conditions and the cost saved on chemical deaeration if deaerator is operated at optimum conditions.

Table 5. Shows Possible Cost Saving on Chemical Deaeration

Present Operational Cost (#)	Optimum Operational Cost (#)	Amount Saved (#)
# 4,8000,000.00	# 3,847,392.00	# 952,608,00

CONCLUSIONS

Corrosion poses a threat to plant operations as well as plant equipments, as a result it is imperative to consider methods and operations which mitigate or eliminate the occurrence of corrosion in process vessels. Hence for boiler systems in process plants, deaerators are adopted to remove corrosion causing elements from boiler feed water to ensure boiler systems are protected from corrosion. Furthermore, a deaerator is not only an essential auxiliary component of plants reliable feed-water system, but the heart of a boiler mass-flow and thermal-energy that can be used to identify energy-savings opportunities. With correct venting rate, improved steam water contact within the deaerator, significant economic and energy saving can be achieved with improved deaerator efficiency requiring less chemical deaeration. This research can be adopted to simulate deaerator performance/behaviour and also predict outlet concentration of oxygen in deaerated water.

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