Effect of sodium hydroxide solution concentration on liquid entrainment in a steam boiler

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Abstract

Liquid entrainment or carryover is a phenomenon that liquid droplets are carried out from a boiler or steam drum during steam generation. The droplets may convey some dissolved solids and cause damage to steam equipment such as scaling deposits in valves and steam piping and erosion of turbine blades. The appearance of dissolved solids in boiler water mainly comes from the internal water treatment process by dosing some chemical substances into the boiler in order to prevent corrosion and scale formation. Trisodium phosphate (Na₃PO₄) is one of chemical substances commonly added during boiler operation to control the pH of boiler water. However, it can cause the occurrence of sodium hydroxide (NaOH) solution which results in the increase of total dissolved solid (TDS) concentration in boiler water. Therefore, this study is aimed to develop a test section in order to investigate the parameters affected by liquid entrainment in the boiler. The experiment is performed in ambient conditions under an air-water system. Three variable factors are taken into consideration, including the concentration of NaOH solution, the height of the water level in the test tank, and the gas superficial velocity which represents the flow velocity of steam during steam generation. The results show that the increase of the gas superficial velocity and the water level height resulted in the enhancement of the entrainment rate. The increase of the water level height played an important role on the liquid entrainment. The increase of NaOH concentration directly impacted the existing film bubbles and the longer stability of foam bubbles at the water surface which resulted in a higher entrainment rate. Therefore, TDS control was one of the most important factors which could be incorporated with the appropriate height of the water level and the consistency rate of steam generation in order to minimize the liquid entrainment.

Keywords: Carryover, Gas superficial velocity, Height of water level, Liquid entrainment, NaOH solution

1. Introduction

In the process of steam production in a boiler, saturated steam is preferred for heating processes due to advantages in heat transfer, while superheated steam is mostly used in power generation to prevent wetted steam which can erode turbine blades and decrease thermal efficiency. If the boiler is operated
under inappropriate or abnormal conditions, it may introduce some water droplets, solid and vaporous escaped from the water surface and carried out with the steam. This phenomenon is called carryover or liquid entrainment which is defined as the amount of liquid compared to the steam quantity that leaves the boiler. Carryover or liquid entrainment is an undesirable phenomenon because it can cause the damage to the equipment, especially turbine blades, and by depositing solids in the piping system and valves [1], as shown in Figure 1.

Priming and foaming are two main causes of carryover. When the contamination in water droplets leaves the steam drum during the heating process, it is called ‘priming’. Priming can be caused by improper boiler design, rapid changes in steam demand, and high levels of boiler water during the operation. It can say that priming is caused by mechanical factors. Another cause of carryover is called foaming. Foaming occurs when bubble film is built up on the surface of the boiler water and then released as the bubbles burst and went out with the steam [1]. Foaming can be caused by high solid contamination such as oil, fat, grease, organic matter and suspended solids in the boiler water and excess alkalinity which are effects of chemical factors.

Davis R F [2] studied the mechanisms of water droplets detachment. The first mechanism was called “Film drop” which was the bursting of steam bubble and then some small droplets were carried out of the free surface. Another one was called “Jet drop” when the bubble cavity collapsed, the liquid rim had enough momentum to rise up the center of depression, then the ejection of a tiny liquid jet occurred. The formation of a film drop and a jet drop are shown in Figure 2.

To prevent the liquid entrainment phenomenon, the quality of boiler water is needed to be controlled following Thailand’s laws and regulations. The total dissolved solid (TDS) content in boiler water is required to be controlled within the permissible limit of lower than 3,500 ppm and the pH value is required in the range of 8.5-11.8 [3]. To maintain the pH of boiler water within the regulations, trisodium phosphate (Na₃PO₄) is generally added into the boiler for caustic treatment purposes. It can interact with the water and produces disodium phosphate (Na₂HPO₄) and sodium hydroxide (NaOH) as the by-products [4]. Equation (1) illustrates the chemical reaction of those substances. However, if a solid alkali is not applied appropriately, it can cause the scale deposition on the steam turbine and risks caustic gouging.

\[
Na_3PO_4 + H_2O \rightarrow Na_2HPO_4 + NaOH \quad (1)
\]

Therefore, this study is aimed to investigate the effect of NaOH concentrations on the liquid entrainment in conjunction with the variation of the water level height and the flow velocity of fluids in a horizontal drum used in the experiment.

2. Entrainment rate
The movement of steam inside the boiler is one of the characteristics of two-phase flow. The term of “gas superficial velocity” \( (j_g) \) is commonly used to present the velocity of multiphase fluids. Gas superficial velocity is a hypothetical flow velocity which is referred to as the volumetric flow rate of gas.
flow through the pipe divided by the cross-sectional area of that pipe. It can be calculated as given in Equation (2):

\[ j_g = \frac{r_m \bar{P}_{in} A_{in} \bar{V}_{in}}{\rho_{atm} A_{sw}} \]  

(2)

where \( r_m \) is the discharge coefficient of mass flow rate. \( A_{in} \) and \( A_{sw} \) are the cross-section area of an inlet air pipe at flow meter and the average cross-section area at swell water level. \( \bar{P}_{in} \) is the inlet air density at the flow meter, \( \rho_{atm} \) is air density at atmosphere.

Variation of the gas superficial velocity was performed during the experiment to investigate its effect on the liquid entrainment. Therefore, a dimensionless number of entrainment rate \( E_{fg} \) was employed as a qualitative analysis of entrained liquid which is defined as a ratio of entrained liquid mass flux to the gas mass flux. The entrainment rate is given in Equation (3).

\[ E_{fg} = \frac{M}{\rho_g j_g A_{sw} t} \]  

(3)

where \( j_g \) is the gas superficial velocity referred at swell water level. \( M \) is the mass of entrained liquid, \( \rho_g \) is the density of gas phase in the tank and \( t \) is time.

3. Design of experiment

To achieve the objective of this study, a horizontal cylindrical drum with transparent flat heads was designed and fabricated to visualize the turbulence of water surface and the detachment of water droplets. The test tank was designed to be similar to a steam drum in a water tube boiler or fire tube boiler. An air-water system was adopted in this experiment by controlling conditions under ambient pressure and a temperature of 25°C. A method of geometric similarity was applied to determine the dimension of the test tank; the pipe size and the connections were based on the actual scale of the steam drum in the real power plant. Figure 3 shows the model of the drum and the scaling factor of dimension and Figure 4 presents the set of the experiment.

![Figure 3. The drum model and the scaling factor of dimension](image-url)
The pipe connected with the tank included four risers and one balancing pipe at the tank bottom and one outlet pipe at the top. A 1¼ inch diameter pipe was designed as a riser, however, a larger cross-section area of pipe can affect the entrainment phenomenon. Therefore, a grill with 3 mm diameter holes was installed on each riser to enhance uniform air flow distribution [5]. Four generations of low-cost capacity level sensors were developed to continuously measure the swell water level in the test tank. To select a high-quality sensor, it can be evaluated from the linearization between the frequency and the water level [6]. The pattern of square waves succeeded to provide a linear graph rather than other sensors as shown in Figure 5. This method was adopted in this study to overcome the human error from the image visualization for measuring the swell water level.

The initial water level height (H) of 0.24 and 0.28 m, the gas superficial velocity \( j_g \) of 0.3, 0.4 and 0.5 m/s and the NaOH concentration of 0, 1200, 2400 and 3500 ppm, which was presented in term of TDS were varied as parametric studies to evaluate the amount of liquid entrainment \( M \).

4. Results
To distinguish the liquid entrainment phenomenon, the amount of entrained water \( M \) into the gas phase as the droplets were collected and measured the weight at the end of 10-min experiment. The preliminary result reported the effects of the initial water level height and the gas superficial velocity on the amount of entrained liquid under the condition of pure water. The amount of entrained waters were plotted with respect to the gas superficial velocity in the different of initial water level height. Figure 6 shows that the increase of gas superficial velocity resulted in larger amounts of entrained liquid. The enlargement
of gas superficial velocity which means higher entrance on the mass flow rate of air can contribute turbulence on the liquid surface and the generation of numerous foam bubbles. If the flow velocity was high enough to overcome the surface tension, the breakup of air bubbles into small droplets can occur as expressed in Figure 7. It also can clearly notice that the initial water level height played as a key parameter affected on the rapid increase of liquid entrainment rather than the enlargement of gas superficial velocity.

The impurity of water may affect the amount of entrained liquid. In this study, NaOH which is commonly added to maintain boiler water at proper pH and alkalinity levels was emphasized its effect on the liquid entrainment. Excessive NaOH compound can cause the increase of water concentration or TDS which affects the increase of mechanical properties of liquid i.e., density, surface tension and dynamic viscosity [7]. The increase of NaOH concentration tended to enhance the swell water level. Foaming existed on the liquid surface with longer time stability and larger bubble coalescence which contributed to the liquid entrainment. Figure 8 presents the effect of NaOH concentration on the liquid entrainment which observes two distinctive results.

Firstly, the increase of TDS can cause a gradual decrease of entrained water which occurs at a low initial water level height of 0.24 m for all velocity cases. A second observation is at the condition of high velocity and high water level, an increase of NaOH solution displays enlargement of liquid entrainment, but the phenomenon declined significantly when the TDS excess was 2,400 ppm even if
the gas superficial velocity become very high. This was because the flow velocity of air cannot succeed in dealing with the increment of surface tension when the NaOH solution increased. It resulted in a lower amount of entrained liquid carried out with the air even the initial water level height and gas superficial velocity become higher.

Using the mass of entrained water as an indicator of the liquid entrainment phenomenon cannot represent the phenomenon under the different conditions. Therefore, a dimensionless number of entrainment rate \( (E_{fg}) \) was introduced for comparative analysis. The entrainment rates of all cases were plotted with respect to the ratio of dimensionless number between the gas superficial velocity and the height above water interface \( (j_g^* / h^*) \). The experimental results were compared with the calculation results from Ishii-Kataoka’s correlation as demonstrated in Figure 9. The results show that the experimental data have a tendency to agree with the calculation results. There were small deviations occurring between the calculation and the experiment since this correlation had been developed from the experimental results of a vertical cylindrical drum which was different from this study.

Figure 8. Influence of NaOH solution in various water level heights and gas superficial velocities on the liquid entrainment

Figure 9. Comparison of the experimental data with Ishii-Kataoka’s correlation when solid line and dash line are the trendline of calculation results from Ishii-Kataoka’s model at \( H = 0.24 \) m and \( 0.28 \) m, respectively.
5. Conclusions
The visualization of liquid entrainment phenomenon can successfully be observed via a horizontal drum with air-water system. The increase of three parameters, including with the initial water level height, the gas superficial velocity and the NaOH concentration or TDS, can impact on the enhancement of liquid entrainment but in a different magnitude. In the case of pure water without any effect on the water impurity, the increase of the initial water level height had a significant impact on the liquid entrainment rather than the rise of gas superficial velocity. When the effect of total dissolved solids was included, it seemed that the increase of NaOH concentration resulted in a larger number of bubbles and longer foam stability which impacted on the increase of liquid entrainment. For the case of high initial water level and high gas superficial velocity, it can be noticed that excessive increase of NaOH concentrations above some certain concentrations cannot increase the liquid entrainment because the NaOH solution can cause an increase of fluid properties, particularly the surface tension and the density. The increase of mechanical properties of fluids tend to obstruct the liquid entrainment.

From this study, it can be concluded that improper conditions such as a high water level operation, a rapid change of steam demand, and the accumulation of total dissolved solids in boiler water, should be avoided during the boiler operation because they may cause water droplets carrying out some solids and liquids with the steam. That can cause damage to the steam equipment.

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