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Modeling and simulation of bubbling hot well deaerator in condensers of ships

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ABSTRACT

Application of deaerators in ship has been restricted due to space limitation. Thus far, the function of deaerator has been integrated into the hot well of the condenser. The condensate water would be heated to saturation by extracting steam from turbine, which would make the solubility of Oxygen in condensate water fall to zero according to Henry's law and Dalton's law. The purpose of this paper was to build a mathematical model of bubbling hot well deaerator in the condensers of ships. In this paper, the heat exchange rate was calculated by empirical formulas which took the specific structure and process of heat exchange into account. When the operating conditions were in the application ranges of the empirical formulas, the simulation model would be performed by utilizing them; otherwise, calculations would be done by the conservation of energy, which assured the simulation model could be used at any operating condition. Different from previous works, the solubility of Oxygen in heated condensate water could be calculated by an empirical formula. The simulation results showed that the structure and heat exchange process considered could be highly accurate at the steady-state operations, and the main parameters trend curves during dynamic-state operations were consistent with theoretical analysis. The solubility of Oxygen could be calculated and the simulation results at the steady-state operations were verified against the practical situation, the trend curves during dynamic-state operations were consistent with theoretical analysis.

1. Introduction

For marine power plants using either steam power or nuclear power, one of the most serious safety threats is the corrosion of pipelines and equipments. A major reason of corrosion is the Oxygen dissolved in feed water. For onshore nuclear power plants, the Oxygen could be efficiently removed in specialized deaerators. However, in marine power plants, this function has to be integrated into the hot well of condensers due to space limitation. The bubbling hot well deaerator is adopted by one kind of marine power plant, and the structure of such kind of hot well deaerator is offered by some researchers (Parkinson, 1951; Chen and Yuan, 1988; Takano et al., 1997).

Fig. 1 shows that the hot well deaerator is essentially a direct-contact heat exchanger. The condensate water would flow into the hot well deaerator from (1), then reach the bubbling area (2), where the water can meet the steam jetted by nozzles (3). When the condensate water reach saturation, the non-condensable gas could be isolated from the water by separator (4,5) and therefore be extracted by ejector (9).

According to Henry's law and Dalton's law, the solubility of Oxygen in water was mainly decided by the partial pressure of Oxygen and the temperature of water. When the water reached saturation, the partial pressure of Oxygen fall to zero, the Oxygen dissolved in condensate water would be removed completely.

Simulation of deaerator has been studied by many groups of people, the conservation of energy models (Yoo et al., 1996; Zhu et al., 1999) and the segmented models (Zhao et al., 2012) were representative. Most of their researching objects focus on specialized deaerator used in onshore nuclear power plant. However, since the working pressure of these specialized deaerators were much higher than hot well deaerators, some empirical formulas for specialized deaerator become unsuitable for hot well deaerator. Furthermore, some models were based on the conservation of energy so that neither deaerators specific structure nor heat transfer process would affect their simulation results. Therefore, these complex segmented models would be inappropriate for hot well deaerator because it is a single-segment deaerator.

Some researches of heat transfer during the vapor jetting into the water have been carried out. A way to calculate the heat

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Nomenclature

ρ_s	density of vapor in steam side (kg m^{-3})
V_s	volume of steam side (m^3)
τ	time (s)
G_s	mass flow of steam flown in (kg/s)
G_{sout}	mass flow of steam flown out (kg/s)
G_{sn}	condensate rate (kg/s)
c	length of hot well (m)
d	width of hot well (m)
H	height of hot well (m)
h	water level (m)
ρ_w	density of water in water side (kg m^{-3})
V_w	volume of the water side (m^3)
G_w	mass flow of water flown in (kg/s)
G_{wout}	mass flow of water flown out (kg/s)
X	the ratio of length to diameter of steam column
B	an empirical value decided by temperature, latent heat of vaporization and specific heat at constant pressure
G_0	mass flow rate of steam (kg m^{-2} s^{-1})
G_m	Empirical value given by Kerney et al. (1972), 275 kg m^{-2} s^{-1}
K	heat transfer coefficient (W m^{-2} K^{-1})
c_{pw}	specific heat at constant pressure (J kg^{-1} K^{-1})
Q	transferred heat (kJ)
A	heat transfer area (m^2)
Δt	difference temperature of steam and water (K)
h_{win}	enthalpy of water flow in (kJ/kg)
h_{end}	calculated enthalpy after heated (kJ/kg)
h_{sin}	enthalpy of the steam flow in (kJ/kg)
h_{wb}	saturation enthalpy of water (kJ/kg)
h_{sb}	saturation enthalpy of steam (kJ/kg)
P_{o2}	partial pressure of Oxygen (MPa)
t	temperature of water (°C)
S_{o2}	solubility of Oxygen (mol/kg)
$M_{o2,in}$	mass of Oxygen come into the hot well (g)
$M_{o2,out,s}$	mass of Oxygen being taken away by steam jet air ejector (g)
α	a coefficient which is used for characterizing the different pressure between upper and lower of hot well

exchanging was offered by Kerney et al. (1972) and Chun et al. (1996), their computational results were in good agreement with the experimental data (Jaster and Kosky, 1976; Rose, 1999). Tromans (2000) proposed an experiential formula to calculate the Oxygen solubility in water based on both experimental data and thermodynamic analysis, which could faithfully reproduce the experimental data (Braden and Simonson, 1978; Benson, 1979; Cramer, 1980).

The main purpose of this paper is to build a mathematical model of hot well deaerator based on the specific structure and direct-contact condensation heat exchanging process. The simulation results for both steady-state and dynamic-state operation are presented. Unlike previous works, the solubility of Oxygen in condensate water could also be calculated. The simulation result was verified against actual operating data.

2. Basic hypothesis

In order to build a mathematical model, this paper would ignore some influences; idealize some complex structures and processes. These assumptions include:

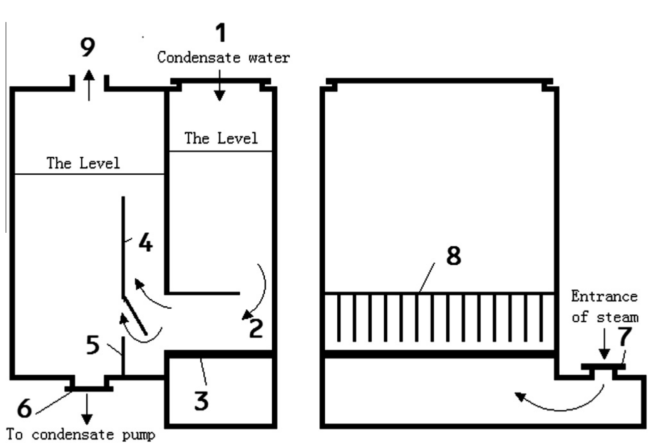

Fig. 1. The structure of bubbling hot well deaerator. 1-Entrance of condensate water; 2-bubbling area; 3-nozzles; 4, 5-separator; 6-exit of heated condensate water; 7-entrance of steam; 8-silencers; 9-ejector.

1. The heat transferred from the hot well to the environment is negligible.
2. The leakage of the hot well is negligible.
3. The non-condensable gases would have no effect on the condensate rate.
4. The pressure at any point in water side and the pressure at any point in steam side in hot well are all the same.
5. The temperature of steam will fall to saturation temperature after heating the condensate water.
6. The condensate rate would be calculated by direct contact condensation heat transfer model when the water could not reach saturation, and it would be calculated by conservation of energy under other conditions.

3. Mathematical model

This paper calculated the pressure of hot well deaerator by conservation of mass:

First consider the steam side:

$$\frac{d(\rho_s V_s)}{d\tau} = G_s - G_{sout} - G_{sn} \tag{1}$$

$$V_s = cdH - cdh \tag{2}$$

Then for the water side:

$$\frac{d(\rho_w V_w)}{d\tau} = G_w - G_{wout} + G_{sn} \tag{3}$$

$$V_w = cdh \tag{4}$$

Because of the low pressure inside the hot well, when the extracting steam from turbine was jetting into it, critical flow would happen. Thus, the parameters of steam would be selected according to critical parameters. If the parameters of steam and water were in the application ranges of empirical formulas, Chun et al. (1996) showed that the shape of steam column was an approximate conical shape. Kerney et al. (1972) purposed the following experiential formula to calculate the shape, working from 28 to 79 °C:

$$X = \frac{1}{1.932B}\sqrt{\frac{G_0}{G_m}} \tag{5}$$