

## EFFECT OF DROPLET DIAMETER ON OXYGEN STRIPPING IN DEAERATORS

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**ABSTRACT** Oxygen is the main cause of corrosion in hot well tanks, feed lines, feed pumps and boilers in process industries and thermal power plants. The corrosion is of the pitting type where the metal loss may not be great but deep penetration and perforations can occur in a short period and hamper the operation of the plant. A deaerator is a thermal equipment to remove non-condensable gases from the boiler feed water. In a deaerator, water is forced through a nozzle from the top and steam generally bled from the LP turbine enters at the bottom of the deaerator. The oxygen in water is stripped during the flow of water from the nozzle, which is referred to as the first stage. Most of the oxygen is stripped in this zone. The second zone constitutes the region where the water drips down from a tray. The overall performance of the deaerator depends on the percentage of oxygen removed in these two zones. In the first zone the water is in the form of droplet, the effect of residence time, droplet size on the stripping of dissolved oxygen, which is in direct contact with steam is studied based on the principle of mass diffusion. Lumped system analysis is applied by considering water dispersion as a mist of spherical droplets. It is observed that as the droplet size decreases from 0.03 to 0.002 mm, the concentration of oxygen decreases or the stripping of oxygen increases.

**Keywords:** Concentration of oxygen in water, droplet diameter, residence time, stripping of oxygen, deaerator

### 1. INTRODUCTION

Stripping of dissolved oxygen from droplets of water forced through a nozzle, which is in direct contact with steam, is the principle of operation of a deaerator. As the water is atomized into fine droplets, the upward flowing steam initially rises the temperature of water and later condenses on the droplet itself. Most of the studies are limited to the estimation of condensation heat transfer coefficients and not on the amount of oxygen stripping.

Brown [1] conducted experimental investigation of condensation of steam on a spray of water drops of diameters ranging from 0.125 – 0.520 mm and obtained heat transfer coefficient as high a value of 27,000 W/m<sup>2</sup> K. Ford and Lekic [2] developed a correlation equation for the estimation of the growth of liquid droplet during condensation of steam in direct contact for three different diameters using high-speed photography. The experiment was conducted for different initial sub cooling of droplets below the saturation temperature of steam considering unsteady state heat transfer by modeling the liquid droplet as a sphere with negligible heat transfer at the interface. Sundararajan and Ayyaswamy [3] have carried out studies on the effect of residence time on

condensation parameter for three droplet sizes 0.25, 0.3, 0.35 mm. Later Huang & Ayyaswamy [4] presented new correlation based on theory and showed close agreement with the available experimental data. Correlations are developed for average condensation velocity and heat flux associated with condensation on a moving droplet of diameters 0.50 and 0.60 mm in the presence of non-condensable gas. Celata et. al. [5] conducted experiments on direct contact condensation of steam on water sprays characterized by uniform size droplets ranging from 0.30 to 2.8 mm with droplets velocity varying from 0.85 to 9.0 m/s with pressures upto 0.6 MPa. All these authors did not consider the influence of nozzle on formation of droplet size. Minoru Takahashi et. al. [6] have studied the mechanism of condensation from spray nozzle both theoretically and experimentally. They concluded from their analysis that turbulence model predicted heat transfer in the first zone better than the pure conduction model. All the above researchers have studied condensation on liquid droplet of sizes ranging from 0.125 to 2.8 mm. In a deaerator, the dissolved oxygen is stripped off from a moving droplet generally of size varying from 0.002 to

0.010 mm. The literature relating the droplet size with oxygen removal rate having application in the design of deaerator is limited. Information linking

the average droplet size with the type of nozzle is not available in literature.

## 2. FORMULATION OF THE PROBLEM

The objective of the present analysis is to estimate the quantity of oxygen, which diffuses from the solvent water. It is formulated as the one related to diffusion of oxygen from the interface of the spherical droplet in the ambience of steam. To remove the dissolved oxygen from the droplet, the following assumptions are made in the analysis.

1. Droplet is spherical in configuration
2. Diffusion process occurs under isothermal conditions

The partial pressure of oxygen from the interface of spherical droplet into the surrounding steam determines the rate of mass transport of oxygen from the droplet. Assuming lumped system analysis to be valid, the mass balance for the gas diffusion can be written as

$$\frac{\pi}{6} d^3 \rho_L \frac{dX(t)}{dt} = -h_m C_A \pi d^2 \quad (1)$$

where

- $d$  - Diameter of the droplet,  $m$
- $X(t)$  - Concentration at any time  $t$ , expressed in  $kg$  of solute /  $10^9 kg$  of solvent
- $h_m$  - Mass transfer coefficient,  $m/sec$
- $\rho_L$  - Density of the solvent,  $kg/m^3$
- $C_A$  - Concentration of oxygen at  $y = 0$ ,  $kg/m^3$

The universal gas equation is assumed to hold good in evaluating the initial concentration of oxygen  $C_A$  at the beginning of the first stage

$$C_A = \frac{P_A M_A}{R T_a} \quad (2)$$

where

- $P_A$  - Partial pressure of  $O_2$  at the vapor-liquid interface,  $N/m^2$
- $R$  - Gas law constant [8314],  $J/kg-mole K$
- $T_a$  - Average temperature of the droplet i.e.  $[273 + (T_s + T_i)/2]$ ,  $K$

## 3. RESULTS AND DISCUSSION

The variation of heat and mass transfer coefficients with droplet diameter is shown in Figs. 1 and 2 respectively. The influence of droplet diameter on concentration of oxygen at the end of first stage is shown in Fig. 3. Evidently as the diameter of the droplet increases, the concentration

Further in the evaluation  $X(t)$  from Eq. (1) the mass transfer coefficient  $h_m$  should be known apriory. For spherical geometry the heat transfer coefficient under forced convective condition is given by the established dimensionless equation of Whitaker [6]

$$Nu_d = 2 + \left[ 0.4 Re_d^{0.5} + 0.02 Re_d^{2/3} \right] Pr^{0.4} \left[ \frac{\mu_\infty}{\mu_w} \right] \quad (3)$$

Based on the principle of analogy between heat and mass transfer the following equation holds good for evaluation of mass transfer coefficient

$$Sh_d = 2 + \left[ 0.4 Re_d^{0.5} + 0.02 Re_d^{2/3} \right] Sc^{0.4} \left[ \frac{\mu_\infty}{\mu_w} \right] \quad (4)$$

Further Henry's Law gives the relationship between the partial pressure of oxygen at the interface with the concentration of oxygen in the droplet. Thus,

$$P = \phi H_C X \quad (5)$$

where

- $P$  - Partial pressure in  $N/m^2$
- $X$  - Concentration of oxygen in parts per billion (ppb) in the solvent water
- $H_C$  - Henry's constant
- $\Phi$  - Conversion factor for a given solute oxygen in solvent water =  $(18 \times 10^{-9})/32$

Combining Eqs (2) and (5) the concentration of oxygen  $C_A$  in p.p.b can be obtained

$$C_A = \Phi H_C M_A X(t) / R T_a \quad (6)$$

Using Eq. (6), Eq. (1) can be rewritten as

$$\frac{dX(t)}{dt} = -[6 \times \Phi] [Sh] \left[ \frac{H_C M_A D X(t)}{d^2 \rho_L R T_a} \right] \quad (7)$$

with the initial condition at  $t = 0$ ,  $X = X_i$ . The solution of Eq. (7) can be obtained as

$$\frac{X(t)}{X_i} = \exp \left\{ -[6 \times \Phi \times Sh] \left[ \frac{H_C M_A D t}{d^2 \rho_L R T_a} \right] \right\} \quad (8)$$

at the end of first stage increases. In Fig. 4 the effect of droplet diameter on percentage of oxygen stripping is shown. This can be attributed to the fact that diffusion decreases as condensation of steam on the surface of the droplet decreases. The effect of droplet diameter on oxygen stripping in

percentage for different deaeration pressures is shown in Fig. 5. As the deaeration pressure increases there is decrease in oxygen stripping for a value of droplet diameter.

The stripping of dissolved oxygen from droplet plays an important role in diminishing the oxygen content from the droplet. The stripping of oxygen in percentage increases as the droplet diameter decreases from 0.03 mm to 0.002 mm and is almost negligible for the droplets having diameter greater than 0.01 mm. The effect of residence time on oxygen stripping for different droplet diameters is shown in Fig. 6. As the residence time increases, the percentage of oxygen stripping increases. The effect of inlet water temperature on oxygen stripping for the first zone is shown in Fig. 7. There is no significant effect of droplet temperature on oxygen stripping compared to droplet diameter and residence time.

As the droplet diameter decreases, the resistance for transferring the heat decreases and hence the temperature of droplet increases rapidly. Consequently as the temperature increases, the solubility of oxygen in water decreases.

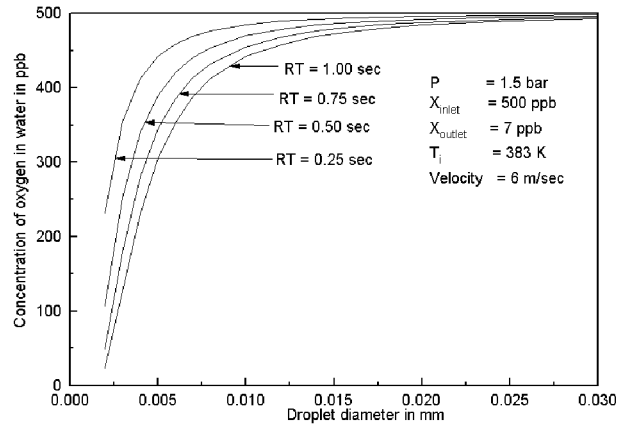


Fig 3 Effect of droplet diameter on oxygen concentration at the end of first stage for different residence time

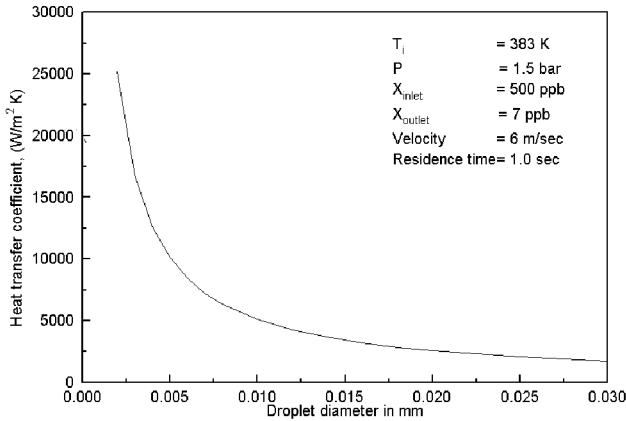


Fig 1 Effect of droplet diameter on heat transfer coefficient

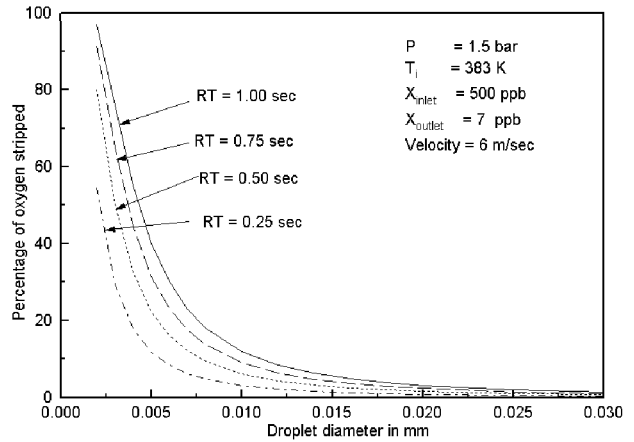


Fig 4 Effect of droplet diameter on oxygen stripping

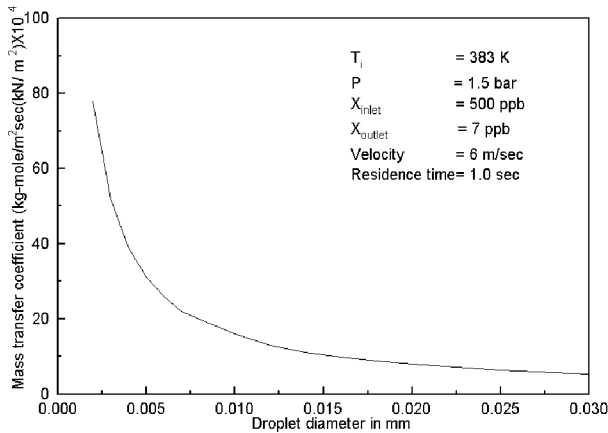


Fig 2 Effect of droplet diameter on mass transfer coefficient

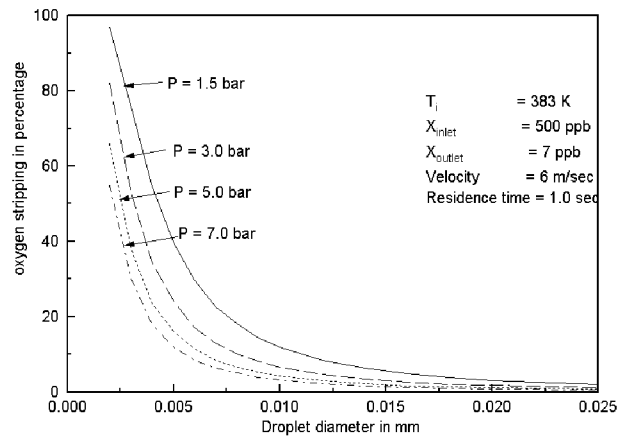


Fig 5 Effect of diameter on oxygen stripping at different pressures

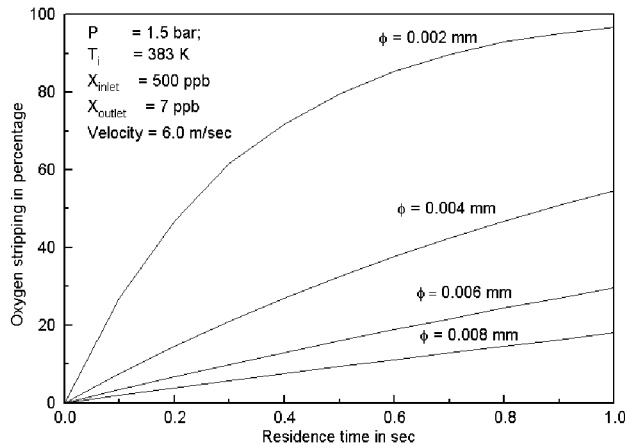


Fig 6 Effect of residence time on oxygen stripping

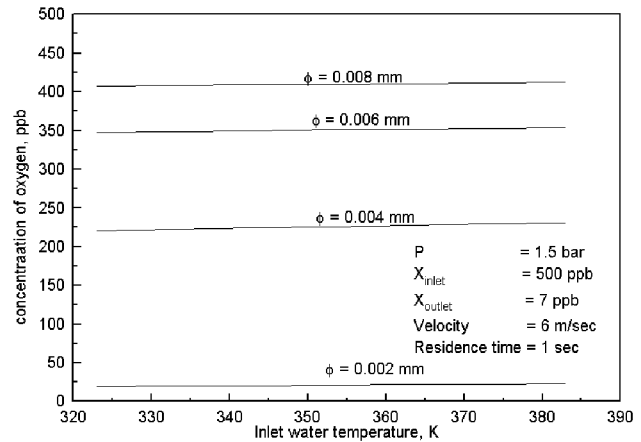


Fig 7 Effect of inlet water temperature on concentration at the end of the first stage

#### 4. NOMENCLATURE

$C$	concentration, $\text{kg}/\text{m}^3$
$d$	diameter, $\text{m}$
$D$	diffusion coefficient, $\text{m}^2/\text{sec}$
$h$	heat transfer coefficient, $\text{W}/\text{m}^2 \text{K}$
$h_m$	mass transfer coefficient, $\text{m}/\text{sec}$
$H_c$	Henry's law constant, $\text{N}/\text{m}^2 / \text{ppb}$
$k$	thermal conductivity of vapor, $\text{W}/\text{mK}$
$M$	molecular weight, $\text{kg}/\text{kg-mole}$
$Nu_d$	Nusselt number, $h d/k$
$P$	pressure, $\text{N}/\text{m}^2$
$Pr$	Prandtl number, $\nu/\alpha$
$R$	gas law constant, $\text{J}/\text{kg mole K}$
$Re_d$	Reynolds number, $V d / \nu$
$Sc$	Schmidt number, $\nu/D$
$Sh_d$	Sherwood number, $h_m d/D$
$t$	time, $\text{sec}$
$T$	temperature, $\text{K}$

$V$	relative velocity of the droplet, $\text{m}/\text{sec}$
$X$	mass fraction of $O_2$ in water, $\text{ppb}$

#### Greek symbols

$\alpha$	thermal diffusivity of vapor, $\text{m}^2/\text{sec}$
$\nu$	kinematic viscosity of vapor, $\text{m}^2/\text{sec}$
$\mu$	viscosity of the fluid, $\text{kg}/\text{m-sec}$
$\rho$	density, $\text{kg}/\text{m}^3$
$\infty$	surrounding

#### Subscripts

a	average
A	oxygen
d	droplet
i	inlet
L	liquid
S	saturation
w	water

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