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Study on mass transfer of turbulent air flow sweeping liquid surface

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ABSTRACT

Different forces in interface of gas–liquid in the process of turbulent air flow sweeping liquid surface were analyzed. Characteristics of flowing section were done and Prandtl mixing length theory was used, the principle of turbulent flow mass transfer in the process of turbulent air flow sweeping liquid surface was studied. Effect of Reynolds number, gas flow structure and Prandtl mixing length on the mass transfer were analyzed. It indicated that the turbulent flow mass diffusion coefficient and mass transfer coefficient were involved with the state of gas flow and was affected by gas flow structure. The results are in favor of lucubrate study and engineering application of mass transfer in gas–liquid interface.

1. Introduction

Mass transfer across gas–fluid interface represents a crucial phenomenon, and its proper account is very important in many engineering processes. Optimization of mass transfer units requires profound understanding of the mass transfer processes principle. Film theory (1904, Nernst and 1923, Whiteman), penetration theory (1935, Higbie) and surface renewal theory (1951, Danckwerts) are well known that provide relationship between mass transfer coefficient and mass diffusion coefficient. But these theories were studied on the assumption of mass transfer mode and mechanics characteristic of interface was not considered. Meanwhile, the effect of flow state on mass transfer was not given. Ohta and Suzuki [1] used VOF method to simulate interphase mass transfer. Steeman [2] studied the different definitions of the convective mass transfer coefficient for water evaporation into air. Jajuee [3] studied mass transfer basing the surface-renewal-stretch model. Jabrallah [4] analyzed mass transfer principle in the process of falling film evaporation in the balance of gas–liquid phase and did not solve the difficult the Navier–Stokes equations. There are two mechanisms which frequently arise in gas–liquid multiphase system [5]: Diffusion through Stagnant Film (DTSF) and Equi-Molal Counter Diffusion (EMCD). Baten and Krishna [6,7] studied the DTSF interphase mass transfer from Taylor bubble. Banerjee [8] used the VOF method to study of heat and mass transfer in stratified flow through the automotive filler pipe [8,9]. In these studies, they implemented the source terms in the transport equations based on EMCD. The effect of freestream turbulence intensity on droplet mass transfer is investigated [10–12].

Pauken [13] performed experiments by evaporating heated water from a circular pan in low speed wind tunnel. The forced convection was dominated by the air velocity and the free convection was the density difference between the air at the surface of water and the ambient air. This study and others [14,15] all demonstrate that natural convection is important factor when the air speed is low. Lyczkowski [16] performed a numerical analysis for fully developed laminar forced convection heat transfer in rectangular ducts. Martemyanov [17] investigated the turbulent mass transfer in tubes at large Schmidt numbers. Wei-Mon [18] and Ekambavanan [19] analyzed the heat and mass transfer characteristics along an inclined heated plate over which the water flows downward as a film.

The above literatures review suggests that convective mass transfer coefficients have been studied for laminar flow along vertical wall or in horizontal tube, but not for turbulent airflow sweeping through liquid surface. In addition, the effect of airflow state on gas–liquid interface has not been analyzed. And different forces at interface of gas–liquid, such as surface tension and pressure produced by airflow kinetic energy, were not considered. Since little information is available that effect of turbulent airflow state on mass diffusion is studied, the theoretical analysis in this paper is predominantly conducted.

In this paper, beginning from the point of mechanics at air–liquid interface, the mechanics characteristic of interface and turbulent airflow state are considered, mass transfer between air flow and liquid surface is analyzed based on boundary theory to give the mass-transfer principle of airflow sweeping liquid surface in some humidity difference. It would be in favor of further understanding

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Nomenclature

c	density (kg/m^3)
C_A	vapor density (kg/m^3)
C_W	concentration value at interface (kg/m^3)
D_{AB}	molecule mass diffusion coefficient (m^2/s)
$f(x)$	velocity distribution along x-direction (m/s)
J	mass transfer flux (kg/(m^2 s))
m_A	mass transfer quantity (kg)
u	velocity along x-direction in boundary (m/s)
U	turbulent velocity (m/s)
$U_{\max}$	maximum velocity (m/s)
V_0	vertical fluctuation velocity (m/s)
δ	thickness of velocity boundary (m)
λ	distance when V_y is rapid decline (m)
r	wave radius (m)
ρ	density (kg/m^3)
Sh	Sherwood number
C	proportion coefficient
$C_{A\infty}$	concentration value of mainstream (kg/m^3)
D	mass diffusion coefficient (m^2/s)
D_E	turbulent mass diffusion coefficient (m^2/s)
h_m	mass transfer coefficient (m/s)
l	Prandtl mixing length
Sc	Schmidt number
u_∞	velocity of mainstream (m/s)
U_0	transverse fluctuation velocity (m/s)
v	velocity along y-direction in boundary (m/s)
V_y	velocity along y-direction (m/s)
δ_c	thickness of concentration boundary (m)
v	kinematic viscosity (m^2/s)
g	acceleration of gravity (m/s^2)
σ	surface tension coefficient (N/m)
Re	Reynolds number

Subscripts

s	gas–liquid interface
x	local condition along x-direction
w	liquid surface
∞	free stream
y	local condition along y-direction
max	maximal value

the mass transfer mechanism between airflow and liquid surface from flow point of view.

2. Physical model and formulation

Physical model of turbulent air flow sweeping liquid surface is illustrated schematically in Fig. 1. The flow is two-dimensional.

In turbulent flow state, mass transfer equation is

$$j = (D_{AB} + D_E)dc/dy \tag{1}$$

where J is mass transfer flux (kg/(m^2 s)), D_{AB} is molecule mass diffusion coefficient (m^2/s), D_E is turbulent mass diffusion coefficient (m^2/s), c is density (kg/m^3).

By vortex attenuation model of Levich [20], gas–liquid interface stabilization is determinate by surface tension of gas–fluid interface. Tiny vortex dumpling in liquid face is determined by

$$\frac{\partial U_x}{\partial x} + \frac{\partial V_y}{\partial y} = 0 \tag{2}$$

From the Levich model, U_x is irrelevant with y-direction. So, it is got

$$V_y = -\int \frac{\partial f(x)}{\partial x} dy = -f'(x)y = Cy \tag{3}$$

For the Levich model, as $y = \lambda$, $V_y = V_0$ and as $y = 0$, $V_y = 0$. Where V_0 is fluctuation velocity of corresponding V. From this, it can be got

$$V_y = V_0 y/\lambda \tag{4}$$

where λ is distance when V_y is rapid decline.

As V_y is disappear in gas–fluid interface where the kinetic energy translates into pressure energy, pressure P is produced in interface which produces a wave that the radius is r and balances the interfacial tension. It is given

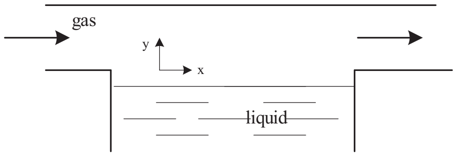

Fig. 1. Physical model.

$$\pi r^2 P = 2\pi r\sigma \tag{5}$$

where σ is surface tension coefficient.

As considering gravity, P is determined

$$P = 2\sigma/r + pgy \tag{6}$$

Experimental data [21] shows

$$y_s = y_{\max}\exp(-4x^2/l^2) \tag{7}$$

where $y_{\max}$ is the peak value of wave and l is Prandtl mixing length.

From the above results,

$$r = \left[\frac{l \cdot y''_s}{(1 + y'^2_s)^{3/2}}\right]_{x=0} = l^2/8y_{\max} \tag{8}$$

and

$$P = \frac{2\sigma}{r} + \frac{\rho g l^2}{8r} = \frac{2}{r}\left(\sigma + \frac{\rho g l^2}{16}\right) = \frac{2\sigma_s}{r} \tag{9}$$

where $\sigma_s = \sigma + 16 \cdot \rho g l^2$ as considering gravity. Based on experiment [14], $r = 2\sigma_s/\rho V_0^2$

According to exponential analysis, it can be got

$$\lambda = \sigma/\rho V_0^2 \tag{10}$$

There is viscosity laminar flow bottom in gas–fluid interface by the boundary theory. Considering the continuity in the process of mass transfer, the turbulent mass diffusion coefficient is

$$D_E = V_y \cdot l = \frac{y \cdot V_0}{\lambda} \cdot l \tag{11}$$

As $l = 0.4y$, D_E is given by the following equation

$$D_E = 0.4y^2 V_0/\lambda \tag{12}$$

From formula (10) and formula (12), D_E is

$$D_E = 0.4y^2 \rho V_0^3/\sigma \tag{13}$$

From literature [22], the velocity distributing of turbulent flow is given

$$\frac{U}{U_{\max}} = \left(\frac{y}{R_0}\right)^n \tag{14}$$

where as Re $\approx 10^5$, $n = 1/7$.