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Heat transfer to a horizontal cylinder in a shallow bubble column

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ABSTRACT

Heat transfer coefficient correlations for tall bubble columns are unable to predict heat transfer in shallow bubble columns, which have unique geometry and fluid dynamics. In this work, the heat transfer coefficient is measured on the surface of a horizontal cylinder immersed in a shallow air–water bubble column. Superficial velocity, liquid depth, and cylinder height and horizontal position with respect to the sparger orifices are varied. The heat transfer coefficient is found to increase with height until reaching a critical height, and a dimensionless, semi-theoretical correlation is developed that incorporates superficial velocity, liquid properties, and height. Additionally, the more minor effects of flow regime, column region, and bubble impact are discussed. Notably, the heat transfer coefficient can be as high in the region of bubble coalescence as in the bulk of the column, but only if bubbles impact the cylinder. The correlation and discussion provide a framework for modeling and designing shallow, coil-cooled bubble columns.

1. Introduction

Shallow bubble columns have more intricate fluid dynamics than tall columns as a result of the short distance between the gas sparger and the free surface. Heat transfer to tubing within shallow bubble columns merits further study because of the usefulness of coil-cooled shallow bubble columns in humidification–dehumidification (HDH) desalination [1]. Most bubble column reactors are orders of magnitude taller than those used for dehumidification [2,3], and therefore the reactor modeling and design literature has generally focused on the developed (i.e., height-independent) flow region in the middle of the column and neglected to address the entry region near the sparger and the region of bubble coalescence at the free surface. In contrast, a shallow bubble column may have no region of developed flow. Heat transfer coefficients on internal heat exchange elements in sieve tray columns, which are similar in depth to shallow bubble columns, have not been studied because sieve trays have historically been used without such elements. In this work, we investigate heat transfer to cylindrical heat exchange elements in shallow bubble columns.

The results presented herein have applications in the design of shallow bubble column heat and mass exchangers such as bubble column dehumidifiers. The use of sieve tray columns (without coils) for humidification or dehumidification was proposed by Barrett and Dunn in 1974 [4], but more recently, shallow, coil-cooled bubble columns in a multi-tray configuration have proven useful in dehumidification for HDH desalination [1,5]. In a bubble column dehumidifier, warm, moist air is bubbled though a volume of cool water. The concentration gradient from the warm bubble center to the cool bubble surface drives condensation on the surface of the bubble. The heat leaving the bubbles is then transferred to a cooling coil with a small surface area. Condensation in the presence of high concentrations of noncondensable gases leads to low heat transfer coefficients. However, the key advantage of the bubble column dehumidifier lies in moving the resistive condensation process off an expensive solid surface and onto the surfaces of bubbles.

Bubble columns for dehumidification must be shallow in order to minimize the hydrostatic pressure drop and thus the blowing power necessary for dehumidification. In modeling bubble column dehumidification, Tow and Lienhard [3,6,7] find the literature lacking in studies of heat transfer in shallow bubble columns.

Many geometric parameters affect heat transfer in tall bubble columns with internal heat exchange elements (internals) [8]. Several studies measure the heat transfer coefficient on internals such as cylinders [9–13] and tube bundles [14] in tall columns. Little is known, however, about the effect of geometry on the heat transfer coefficient in shallow bubble columns with internals. Tow and Lienhard [15] found that cylinder diameter does not significantly affect the heat transfer coefficient outside cylinders in a shallow columns. The influence of additional geometric parameters relevant to shallow columns has not been studied extensively. The heat transfer coefficient has been shown to vary with radial [13] and vertical [16,13] position in a tall column, and with vertical

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Nomenclature

A	probe copper area [m^2]
A_c	probe cross-sectional area [m^2]
C_H	cylinder height coefficient (Eq. 9) [−]
D	diameter [m]
H	vertical position of probe center [m]
L	length [m]
P	perimeter [m]
R	electrical resistance [Ω]
T	temperature [°C]
V	column volume [m^3]
ΔP	pressure drop [Pa]
ΔV	voltage [V]
$\dot{E}$	power, input or dissipated [W]
$\dot{Q}$	heat transfer rate [W]
$\dot{V}$	volume flow rate [m^3/s]
c_p	specific heat at constant pressure [J/kg-K]
d	column liquid depth [m]
g	gravitational acceleration [m/s^2]
h	average heat transfer coefficient [W/m^2-K]
k	thermal conductivity [W/m-K]
m	fin parameter [m^{-1}]
u_g	superficial gas velocity [m/s]
v_b	bubble rise velocity [m/s]

Named ratios

$\mathrm{Fr_D}$	Froude number = $u_g^2/(gD)$ [−]
$\mathrm{Nu_L}$	Nusselt number (of arb. length L) = hL/k [−]
Pr	Prandtl number = $\mu c_p/k$ [−]
$\mathrm{Re_D}$	Reynolds number = $u_g D/\nu$ [−]
St	Stanton number = $h/\rho c_p u_g$ [−]

Greek

ϵ	specific power dissipation [W/kg]
η	Kolmogorov length scale [m]
μ	liquid dynamic viscosity [Pa-s]
ν	liquid kinematic viscosity [m^2/s]
ϕ	liquid volume fraction [−]
ρ	liquid density [kg/m^3]
τ	Kolmogorov time scale [s]

Subscripts

∞	column liquid
ave	average
C	column
cr	critical
end	probe end caps
p	probe

position in a short column [15]. Narayan et al. [1] proposed that horizontal position of internals with respect to the gas sparger orifices could affect heat transfer coefficients. The heat transfer coefficient in the coalescing region at the top of the column has been shown by Prakash et al. [17] to be significantly lower than in the bulk in an air–water–yeast system, but this has not been studied in an air–water system. Finally, to our knowledge, the effect of liquid depth on heat transfer coefficient or flow regime has not been studied.

In this paper, the heat transfer coefficient for a horizontal cylinder in a shallow (<10 cm deep) air–water bubble column is measured over a range of gas superficial velocities. Liquid depth, cylinder height, and cylinder horizontal position relative to the sparger orifices are varied in order to determine the effect of height, column region, flow regime and bubble impact (bubbles directly hitting the coil) on the heat transfer coefficient. Of the variables considered, cylinder height proves to have the most pronounced effect on heat transfer coefficient. Therefore, a semi-theoretical correlation for the heat transfer coefficient in shallow bubble columns is developed in the form of a height correction factor applied to Deckwer's [18] theory for tall bubble columns. Finally, the minor effects of column region, flow regime and bubble impact that are excluded from the correlation are discussed qualitatively to inform shallow bubble column design.

1.1. Theoretical background

Many correlations predict the heat transfer coefficient in bubble columns, but there is significant disagreement between them in terms of heat transfer coefficient magnitude, superficial velocity dependence, and included geometric variables. Several reviews of bubble column heat transfer coefficient correlations are available [2,8,12,19–21], and the spread in the predictions is demonstrated by a comparison of ten correlations by Hikita et al. [22]. Most correlations are semi-theoretical with forms that depend on the assumed mode of heat transfer. Many correlations assume heat is transported by microscale eddies produced by the dissipation of bubbles' flow work. Others consider fluid elements with a different length scale, such as the bubble diameter or distance between bubbles. Other disparities may be due to differences in measurement methods and, particularly in the case of correlations for internals, geometry.

We have found no correlation developed for tall columns that satisfactorily predicts the heat transfer coefficient in a shallow column, but we have demonstrated agreement with several correlations with respect to the dependence on superficial velocity [15]. One of these correlations is Deckwer's [18], which is straightforward and widely-used. This semi-theoretical correlation is based on the dissipation of bubbles' flow work by small (Kolmogorov scale) eddies which interact periodically with the heat transfer surface. Turbulence is assumed to be isotropic and uniform throughout the column. The thermal interactions between eddies and the solid surface are modeled as conduction through a semi-infinite slab with a characteristic time equal to the Kolmogorov time scale, $\tau = \sqrt{\nu/u_g g}$. The application of an empirical constant leads to the correlation, Eq. (1) [18]:

$$\mathrm{St} = 0.1(\mathrm{Re}_D \mathrm{Fr}_D \mathrm{Pr}^2)^{-1/4}. \tag{1}$$

To rewrite Eq. (1) in a simpler form, we consider a bubble column with volume V, liquid density ρ, and liquid fraction ϕ. Assuming high density ratio between liquid and gas, the total energy dissipation rate $\dot{E}$ is the product of specific dissipation rate ϵ and liquid mass:

$$\dot{E} = \epsilon V \rho \phi. \tag{2}$$

The power input is determined by the volume flow rate of bubbles and the hydrostatic pressure drop through the column. Bubbles flow in at volume flow rate $\dot{V}$ against the pressure drop $\Delta P = \rho\phi g d$, where d is the liquid depth. The column cross-sectional area is V/d. The power input is then:

$$\dot{E} = \dot{V}\Delta P = u_g(V/d)\rho\phi g d = u_g V \rho \phi g, \tag{3}$$

where u_g is the superficial gas velocity.