Experimental Thermal and Fluid Science 35 (2011) 645–652

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Artificial boiling heat transfer in the free convection to carbonic acid solution

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ARTICLE INFO

Article history:
Received 5 July 2010
Received in revised form 27 December 2010
Accepted 27 December 2010
Available online 30 December 2010

Keywords:
Heat transfer
Convection
Negative solubility
Gas bubbles

ABSTRACT

Free convection phenomenon has been experimentally investigated around a horizontal rod heater in carbonic acid solution. Because of the tendency of the solution to desorb carbon dioxide gas when temperature is increased, bubbles appear when cylinder surface is heated. The bubbles consists mainly carbon dioxide and also a negligible amount of water vapor. The results present that dissolved carbon dioxide in water significantly enhances the heat transfer coefficient in compare to pure free convection regime. This is mainly due to the microscale mixing on the heat transfer surface, which is induced by bubble formation. In this investigation, experiments are performed at different bulk temperatures between 288 and 333 K and heat fluxes up to 400 kW m^{-2} at atmospheric pressure. Bubble departure diameter, nucleation site density and heat transfer coefficient have been experimentally measured. A model has been proposed to predict the heat transfer coefficient.

1. Introduction

Free convection mechanism plays an important role in many industrial heat transfer processes. There are many developed correlations in the past few decades to predict the free convection heat transfer coefficients for different conditions, however, the effects of the dissolved gases, with negative solubility in liquids have never been considered. Generally, the homogeneous gas/liquid solutions can be classified in two different groups: (1) positive soluble and (2) negative soluble systems, i.e. the slope of solubility saturation curve relative to temperature are positive for the positive soluble and negative for the negative soluble solutions. Carbon dioxide/water solution is a negative soluble system; accordingly, any heating surface which is exposed to this solution would locally release a fraction of dissolved gas, which is exceeding the saturation level of the gas in liquid. The released gas forms bubbles, analogous to boiling phenomenon, however with different mechanisms. In the boiling phenomenon, the bubbles absorb the latent heat of vaporization, in contrast, in the mentioned system, bubbles absorb the heat of solution. In both cases, the heat transfer coefficient is highly enhanced in compare to pure convection heat transfer. This enhancement is mainly related to the intense micro-convection; the result of bubble formation and local movements of liquid around the heating surface. Fig. 1 presents the solubility function of carbon dioxide in water versus temperature [1]. Carbonic acid has many industrial applications such as soda pop, as a gas in the medical field, pharmaceutical, cosmetics, oil shale, food processing aid, medical, anesthetic, fuel, industrial, lasers, bottling, contact lens cleaner, engines, hydrolysis of starch, drugs, and welding. The phase-change heat transfer coefficients and pressure loss factors required for the design of boilers and evaporators involve some of the most complex thermo-fluid phenomena.

In this investigation, saturated carbon dioxide/water solution has been selected as a negative soluble gas/liquid system and a horizontal rod heater is used as the heating surface. This phenomenon has close interaction to bubble dynamics and convection heat transfer. A brief literature review is accordingly presented.

2. Literature review

2.1. Bubble departure diameter

Bubble departure diameter is known as a key parameter in many phenomena including boiling, bubble column systems, etc. The detailed impact of physical properties such as interfacial tension, heat of evaporation, viscosity and thermal conductivity on the bubble departure diameter are still not well understood. There are many proposed correlations for predicting the bubble departure diameter in boiling phenomenon. The Fritz [2] model is one

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0894-1777/$ - see front matter
doi:10.1016/j.expthermflusci.2010.12.014

Nomenclature

A	area, m^2
C_p	heat capacity, J kg^{-1} °C^{-1}
d_b	bubble departure diameter, m
f	bubble departure frequency, Hz
g	gravity acceleration, m s^{-2}
k	thermal conductivity, W m^{-1} °C^{-1}
N	number of nucleate site
Nu	Nusselt number, []
P_r	reduced pressure, []
Ra	Rayleigh number, []
Pr	Prandtl number, []
q	heat flux, W m^{-2}
Q	heat, W
Re	Reynolds number, []
s	distance, m
T	temperature, K or °C
T_b	bulk temperature, °C

Greek letters

α	heat transfer coefficient, W m^{-2} °C^{-1}
θ	contact angle, degree
σ	surface tension, N m^{-1}
ρ	density, kg m^{-3}

Subscripts

b	bubble or bulk
c	convection
l	liquid
s	surface
th	thermocouples
v	vapor

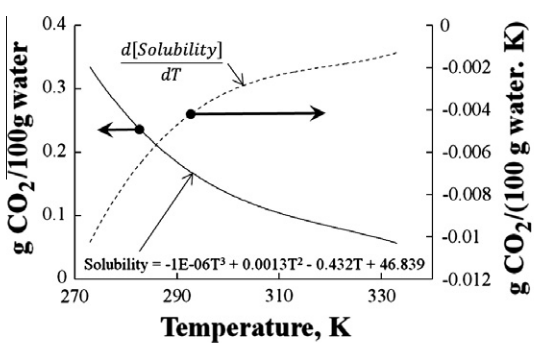

Fig. 1. Solubility of carbon dioxide in water [1].

of the most longstanding models for prediction of the bubble departure diameter in boiling of either pure liquids or liquid mixtures. This correlation is based on force balances on a single bubble departing the solid surface and includes an empirical tuning parameter. Stephan [3] has modified the Fritz [2] model by involving three dimensionless number including the Jacob, Prandtl and Archimedes numbers, which shows some improvements in compare to Fritz [2] model for some systems. Van Stralen and Zijl [4] proposed an empirical model for boiling systems by considering bubble growth mechanisms. This model includes Jacob number and thermal diffusivity of the solution. Cole [5] modified the bubble contact angle and included the effect of pressure through a modified Jacob number. Zeng et al. [6] assumed that the dominate forces leading to bubble detachment would be the unsteady growth and the bouncy forces. They developed their model based on an empirical expression for bubble growth mechanisms. This model can be used only if specific information on the vapor bubble growth parameters is available. In this empirical correlation, it is assumed that the departure time is just one-half the time period, which is same as suggested by McFadden and Grassman [7]. Yang et al. [8] developed a correlation by considering the analogy between nucleate boiling and forced convection heat transfer. The key parameter of this model is given graphically as a function of Jacob number. Recently, Alavi Fazel and Shafaee [9] proposed a new correlation for bubble departure diameter for electrolyte solutions. In this model, the dimensionless Bond number is related to Capillary number. In some of the existing models, the dimensionless Jacob number is involved including Ruckenstein [10], Cole and Rohsenow [11], Cole [5], Van Stralen and Zijl [4] and Stephan [3] correlations. This dimensionless number is a function of surface temperature, which is fundamentally unknown in any given system. However, the surface temperature could be predicted through an iterative procedure by the existing correlations developed for predicting the boiling heat transfer coefficient conjugated with the Newtonian cooling law. A significant error should be expected through this iterative procedure; especially where the surface characteristics in the predictive correlations for boiling heat transfer coefficient is not implicated. These calculations could be more complicated in the sub-cooled pool boiling phenomenon.

No specific correlation for prediction of bubble departure diameter for the bubbles which are released by heating a negative soluble gas/liquid system has been found in the past literature. However because of the similarity between the mechanisms of bubble formation in the mentioned systems and the boiling phenomenon, in this article, the correlations for prediction of the bubble departure diameter in boiling phenomenon has been used to predict the bubble diameter. In general, because of the very complex nature of bubble formation phenomenon, development of a theoretical basis model for prediction of the bubble departure diameter it still not possible and requires more extensive researches. In this investigation, the Fritz [2] correlation has been applied to predict the bubble departure diameter by the following mathematical form:

$$d_b = 0.0146\theta\sqrt{\frac{2\sigma}{g(\rho_l - \rho_v)}} \tag{1}$$

which θ the contact angle, proposed equal to 45° for water and 35° for mixtures by Fritz [2].

2.2. Convection heat transfer

Convection is the transfer of heat from one point to another within a fluid, gas, or liquid by the mixing of one portion of the fluid with another. In free convection, the motion of the fluid is entirely the result of differences in density resulting from temperature differences; in forced convection, the motion is produced by mechanical means.

2.2.1. Forced convection

The Nusselt number, as a key parameter for forced convection heat transfer is known to be a function of the Reynolds number and Prandtl number. There are many proposed correlations in the literature to predict the forced convection heat transfer coefficient