Chemical Engineering Science 131 (2015) 76–83

Contents lists available at ScienceDirect

Chemical Engineering Science

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

A new model for the drag coefficient of a swarm of condensing vapour–liquid bubbles in a third immiscible liquid phase

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HIGHLIGHTS

- A semi-analytical model for C_D of a two-phase bubble swarm was developed.
- Cell model configuration with potential (but not inviscid) flow was assumed.
- Effect of condensation progressing was included.
- Drag coefficient for Reynolds numbers ($0.1 \leq \mathrm{Re} \leq 1000$) was found.
- Drag coefficient increases with condensation ratio and void fraction.

ARTICLE INFO

Article history:
Received 2 December 2014
Received in revised form
12 February 2015
Accepted 29 March 2015
Available online 3 April 2015

Keywords:
Drag coefficient
Two-phase bubbles
Direct contact condensation
Cellular model configuration
Potential non inviscid flow

ABSTRACT

A semi-analytical model for the drag coefficient of a swarm of two-phase bubbles, condensing in direct contact with an immiscible sub-cooled liquid, has been developed. The analysis used a cellular model configuration, assuming potential (but not inviscid) flow around the reference two-phase bubble in the cell. The effect of the condensation ratio within the two-phase bubbles was included using an approximate relation. The drag coefficient for a wide range of Reynolds numbers ($0.1 \leq \mathrm{Re} \leq 1000$) has been found using the viscous dissipation integral method, and the effect of the liquid content within the two-phase bubble or the half opening angle (β), and the system void fraction (α) were examined. The drag coefficient has been found to increase with the condensation ratio and with the void fraction of the system. The present model agrees well with previously available experimental data and theoretical predictions for single bubbles or particles.

1. Introduction

Direct contact heat exchange with change of phase is an efficient heat transfer mechanism. Generally, it involves injection of drops or bubbles, as a dispersed phase, into a column of another immiscible liquid, as a continuous phase. The temperature of the continuous phase must be above the boiling point of the drops for evaporation, or less than the saturation temperature of the bubbles in the case of condensation. Using direct contact heat transfer between two immiscible fluids, utilizing a three-phase direct contact heat exchanger (Song et al., 1999), has many advantages over conventional configurations. For instance, it eliminates the metallic heat transfer surface between the fluids, which is prone to corrosion, fouling and also increases the heat transfer resistance. Direct contact heat exchangers can also be operated with a very low temperature driving force, and with smaller mass flow rates of the transferring fluids. Convenient separation of the fluids and a high heat transfer coefficient (about 20-100 times more than a single phase or surface type heat exchanger) (Peng et al., 2001) can also be achieved. Therefore, direct contact heat exchange can be used in several industrial applications, such as water desalination by freezing, geothermal power generation, crystallization, waste heat recovery, energy storage, and solar energy.

In order to obtain an optimal design of a direct contact boiler or condenser, a good understanding of the fluid mechanics and heat transfer characteristics in such systems is necessary. However, condensation of one or two-component bubbles in a cold liquid has proved difficult to study theoretically (Kalman and Mori, 2002; Kalman, 2003, 2006) and experimentally (Chen and Mayinger, 1992). There are several factors which must be accounted for

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http://dx.doi.org/10.1016/j.ces.2015.03.053
0009-2509/

when considering the driving force for condensation (i.e. the temperature difference), between the condensation bubbles and the surrounding fluid. These are the external and internal resistances, and finally the resistance associated with the condensate accumulated inside bubbles in the case of two components or two phase bubble condensation (Kalman, 2003).

There are a large number of experimental and theoretical investigations related to direct contact condensation of a single two-phase bubble in an immiscible liquid, (e.g. Sideman and Hirsch, 1965; Isenberg and Sideman, 1970; Moalem and Sideman, 1973; Jacobs and Major, 1982; Higeta et al., 1983; Raina et al., 1984; Lerner et al., 1987; Wanchoo, 1993; Kalman and Mori, 2002 and Kalman, 2003) and bubble trains (Sideman and Moalem, 1974; Lerner and Letan, 1990 and Kalman, 2006). More recently, Mahood et al. (2014a, 2014b, 2015a, 2015b) studied, experimentally and theoretically, the direct contact condensation of a swarm of two-phase bubbles in a three-phase condenser.

Only two investigations have addressed the drag coefficient of a single two-phase bubble condensing in an immiscible liquid; both of them were experimental studies. Higeta et al. (1979) have estimated the drag coefficient of a pentane bubble condensing in glycerol and a steam bubble condensing in silicon oil. They concluded that the two-phase bubble behaves as an inviscid fluid sphere at early stage of condensation (relatively high *Re* number), while it is approximated by a rigid sphere at the last stage of condensation (low *Re* number). The second study was carried out experimentally by Wanchoo et al. (1997). Three different dispersed phases, n – pentane, isopentane and furan were condensed in distilled water and in aqueous glycerol solutions of 75% wt and 98.3%. Their results for a very low Reynolds number ($Re < 0.1$) surprisingly fell under the drag coefficient results of an inviscid fluid sphere (bubble), which does not agree with other experimental results, for example (Higeta et al., 1979). Wanchoo et al. (1997) justified these results by citing the mobility of the condensate film surrounding the bubble surface and the strong internal circulation. This was rejected by Kalman and Mori (2002).

All previous theoretical investigations have been carried out with an aim of studying the hydrodynamics and heat transfer of condensing two-phase bubbles in an immiscible liquid. These studies have largely relied on the expressions derived for gas bubbles or solid spheres. These models however, did not include the change in the two-phase bubble's contents due to the condensation. The condensate, of course, accumulates within the two-phase bubble and the vapour content decreases. The two-phase bubble therefore undergoes a continual change of viscosity because of the increased liquid content and the reduced vapour content. That leads to a change in the drag force on the two-phase bubble, which normally affects the two-phase bubble's velocity, and consequently the heat and the mass transfer. The lack of investigations considering the condensation of a swarm of two-phase bubbles in immiscible liquid is a clear obstacle facing the development of a full-sale direct contact condenser. The present investigation tries to remove part of the obstacle by studying the drag coefficient experienced by a swarm of two-phase bubbles condensing in an immiscible liquid. The effects of the ongoing condensation and the overall void fraction on the drag force on the two-phase bubbles will be discussed.

2. Modelling

Let us assume a spherical two-phase (vapour/liquid) bubble condensing in a Newtonian liquid which is immiscible with the liquid condensate and is completely free of surface active material. The surface tensions of the continuous fluid and the condensate are assumed to be high enough to keep the two-phase bubble spherical in shape, and the liquid condensate is confined within the mother bubble throughout the condensation process. Whilst this configuration is a simplification, there is experimental evidence to support the existence of such two-phase bubbles (e.g. Sideman and Hirsch, 1965; Isenberg and Sideman, 1970). Of course, if the balance between body forces and surface tension changes significantly, different bubble shapes may emerge, or the vapour and condensed liquid could detach forming vapour bubbles and liquid droplets. Nevertheless, for the development of an initial model, such as proposed below, this is a reasonable assumption. This is particularly true for the fluids and injection rates that are typical of direct contact condensers. A viscous-potential flow is assumed around the reference two-phase bubble with a cell configuration model.

In addition, the following assumptions are made:

- There is a sufficient (constant) temperature difference between the two-phase bubble and the continuous phase (cooling phase) along the column to complete condensation of the two-phase bubble.
- The direct contact condensation process ends in a spherical liquid drop, which then rises to the top of the vessel to mix with the bulk accumulated liquid condensate.

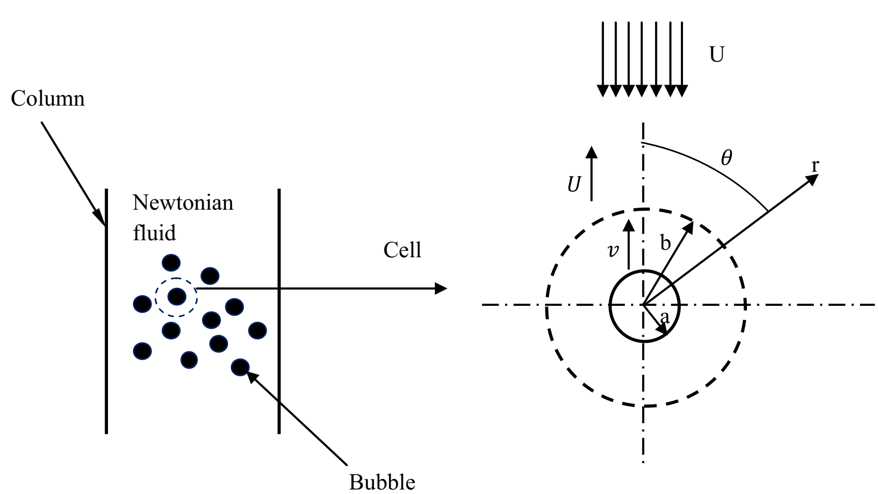

Fig. 1. Schematic representation of the cell model.