Applied Energy 108 (2013) 477–485

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

Bubble dissolution in horizontal turbulent bubbly flow in domestic central heating system

Y.T. Ge [a],*, A.M. Fsadni [a], H.S. Wang [b]

[a] *Mechanical Engineering, School of Engineering and Design, Brunel University, Uxbridge, Middlesex UB8 3PH, UK*
[b] *School of Engineering and Materials Science, Queen Mary University of London, Mile End Road, London E1 4NS, UK*

HIGHLIGHTS

- Experimental study on the bubble dissolution inside horizontal pipes.
- The dissolution rates measured for bubble size ratios are within 12% per second.
- The effect parameters on dissolution rates are investigated.
- The bubble dissolution model has been developed.

ARTICLE INFO

Article history:
Received 13 August 2012
Received in revised form 14 February 2013
Accepted 23 March 2013
Available online 18 April 2013

Keywords:
Bubble dissolution
Horizontal bubbly flow
Central heating systems
Experiment
Modelling

ABSTRACT

In a domestic central heating system, the phenomenon of microbubble nucleation and detachment on the surface of a boiler heat exchanger finds its origins in the high surface temperature of the wall and consequential localised super saturation conditions. If the surrounding bulk fluid is at under-saturated conditions, then after exiting the boiler, the occurrence is followed by bubbly flow and bubble dissolution. A comprehensive understanding of the fundamentals of bubble dissolution in such a domestic wet central heating system is essential for an enhanced deaeration technique that would consequently improve system performance. In this paper, the bubble dissolution rate along a horizontal pipe was investigated experimentally at different operating conditions in a purpose built test rig of a standard domestic central heating system. A high speed camera was used to measure the bubble size at different depths of focal plane using two square sectioned sight glasses at two stations, spaced 2.2 m apart. A dynamic model for bubble dissolution in horizontal bubbly flow has been developed and compared with experimental data. The effects of several important operating and structural parameters such as saturation ratio, velocity, temperature, pressure of the bulk liquid flow, initial bubble size and pipe inside diameter on the bubble dissolution were thus examined using the model. This model provides a useful tool for understanding bubble behaviours in central heating systems and optimising the system efficiency.

1. Introduction

The generation of microbubbles under super saturated conditions in a closed system is a common phenomenon subsisting in major industrial and energy processes including those of chemical, pharmaceutical, food, heating (Joelsson and Gustavsson [1]), renewable energy (Chen and Yang [2]) or power generation (Wang et al. [3]). The appearance of a secondary bubble phase is mostly undesirable due to its negative effects on system performance. For example, in a domestic wet central heating system, the occurrence of microbubbles could result in cavitations' corrosion, unwanted noise, blockages and inefficient performance due to radiator cold spots. Hence, the lifetime of dissolving bubbles, droplets, and solid particles in an isothermal bulk phase is a major consideration in the design of equipment in a variety of industrial applications.

Microbubbles in a domestic wet central heating system nucleate on the surface of the primary heat exchanger due to elevated wall temperatures, thereby resulting in super saturation or near super saturated conditions in the vicinity of the wall. It is known from experimental results that the bubble nucleation rates range between 0.3 and 4 bubbles per cm^2 per second and the mean bubble diameters at the boiler exit vary from 0.13 to 0.39 mm (Fsadni et al. [4]). In addition, under most operating conditions the water in the system pipe work is at under-saturated conditions. Hence, the highest bubble density is found at the immediate exit of the boiler, and consequently, the average bubble diameter and density are expected to decrease with the distance from the boiler unit as mass transfer through dissolution takes place. Passive deaerators

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* Corresponding author. Tel.: +44 1895 266722; fax: +44 1895 256392.
E-mail address: yunting.ge@brunel.ac.uk (Y.T. Ge).

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http://dx.doi.org/10.1016/j.apenergy.2013.03.055

Nomenclature

C	gas concentration (kg/m^3)
D_b	bubble diameter (mm)
d_h	hydraulic diameter (mm)
D_g	gas diffusivity (m^2/s)
d_i	inside diameter of pipe (mm)
m_b	specific mass flux on the bubble boundary (kg/m^2 s)
P	pressure (bar)
R	radius of the bubble (m)
R_i	radius of the bubble at station HSG1 (mm)
R_1	radius of the bubble at station HSG1 (mm)
R_2	radius of the bubble at station HSG2 (mm)
Re	Reynolds number, $U_f d/\nu$
s	depth of sight glass focal plane measured vertically downwards from the top plane of the sight glass (mm)
Sc	Schmidt number, ν/D_g
Sh	Sherwood number, $\beta D_b/D_g$
T	time (s)
Δt	time interval (s)
T_f	bulk fluid temperature (°C)
U_f	bulk fluid velocity (m/s)
X^T	gas solubility factor (m^3/kg bar)

Greek symbols

α	saturation ratio
ε	bubble size ration R_2/R_1
β	mass transfer coefficient (m/s)
ν	kinematic viscosity of liquid (m^2/s)
ρ	density of liquid (kg/m^3)

Subscripts

1	at horizontal sight glass (HSG1), see Fig. 1
2	at horizontal sight glass (HSG2), see Fig. 1
ave	average
b	bubble, bulk
f	fluid
Exp	experimental
g	gas in bubble
gas	gas in the central heating system
i	inner, initial
Pre	predicted
R	bubble boundary with radius R
sat	saturation, maximum

are installed at the flow line of the boiler so as to capture bubbles, thus ensuring that the dissolved air content in the system water is reduced, consequently reducing the saturation ratio and the nucleation rate at the heat exchanger wall. Therefore, a comprehensive analysis of the expected rate of dissolution for the bubbles present in such a system is considered as essential for the optimal positioning of such a device.

From public literature, the bubble dissolutions due to gas diffusion at under-saturated conditions have been extensively studied but are mostly based on theoretical analysis. Kress and Keyes [5] investigated and quantified the liquid phase controlled mass transfer to bubbles in co-current turbulent pipe flow using an empirical correlation to calculate mass transfer coefficients. They reported that data obtained for the mass transfer in agitated vessels could not be directly used to predict mass transfer in pipeline flow, as lower mass transfer rates were expected in agitated vessels due to the relative ineffectiveness of the turbulence. Lezhnin et al. [6] examined the dissolution of air bubbles in water flowing in a horizontal pipeline, where in contrast to the nearly constant pressure used in the present study, the pressure dropped from several bars to atmospheric. They therefore classified the mass transfer mechanism in under-saturated bubbly flow as turbulent diffusion. Other studies by Hesketh et al. [7] and MartÍnez-Bazán et al. [8] investigated the bubble breakup in turbulent pipe flow. However, the effect of such a phenomenon is considered minimal for the conditions of the present study, due to the small bubble diameters and quasi-spherical bubble shape characterising such systems (Fsadni et al. [4]). Most studies on bubble dissolution in under-saturated solutions have been done for isolated gas bubbles and were based on the Epstein and Plesset [9] gas diffusion model such as Duda and Vrentas [10] and Cable and Frade [11]. These studies found their origin as a result of a direct interest in the dynamics of bubble dissolution or in the need to obtain a value for the diffusivity of the gas in a liquid with a known solubility. The theoretical interpretation of these experiments has been based on the consideration of an isolated sphere in spherically symmetrical conditions. Hence, at under-saturated conditions, the bubble dissolves at a rate controlled by the diffusion of gas through the liquid. Similarly, the bubble growth rate at supersaturated conditions is also dependent on the diffusion of gas through the liquid. These bubble growth and condensation rates have been investigated in boiling and subcooled flow boiling conditions, whereby models have been developed to predict the ratio of the actual to maximum bubble diameters at pre-determined time intervals by Prodanovic et al. [12] and Akiyama and Tachibana [13]. On the other hand, a number of adaptations have been developed for the symmetrically isolated bubble model. However, such adaptations require correlations in order to compensate for the imperfect bubble spherical shape and diffusion field. Similar adaptations have been done for the dissolution of microbubbles attached to a wall under flow conditions by Cable [14] and Kentish et al. [15]. Such models have also been adapted in medical science involving the analysis of gas bubble dissolution in whole blood and plasma by Yang et al. [16].

So far few experimental data directly related to bubble dissolution in central heating or associated systems are available. Moreover, limited attention in literature, to date, has been paid to the expected dissolution of free bubbles in turbulent flow with minimal slip.

In this paper, the bubble dissolution in horizontal turbulent bubbly flow has been examined experimentally in a test rig of domestic central heating system. A high speed camera is used to measure and record the bubble sizes across two separate pipe sections at different operating states. A dynamic bubble dissolution model is developed and compared with the measurements. The model is therefore utilised as an efficient design and analysis tool to predict the effects of fluid saturation ratio, velocity, temperature, pressure and initial bubble size on the bubble dissolution rate, which are significant factors in the understanding of bubbly behaviours in domestic central heating systems.

2. Experimental set-up and procedure

A schematic layout of the experimental test rig is shown in Fig. 1. A Commercial condensing boiler is connected to a 22 mm diameter (outer) copper pipe work consisting of a radiator and a buffer vessel. The condensing boiler is used since it is mandatory equipment for new buildings in most European Union member states (Semmens and Ahmed [17]) due to its high efficiency and consequently energy saving properties (Chen et al. [18]). The boiler