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Experimental Investigation of Gas Bubble Behaviours in a Domestic Heat Pump Water Heating System

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Abstract**—**The growing awareness of global warming potential has internationally aroused interest and demand in reducing greenhouse gas emissions produced by human activity. Much national energy in the UK had been consumed in the residential sector mainly for space heating and domestic hot water production. Currently, gas boilers are mostly applied in the domestic water heating which contribute significantly to excessive CO_2 emissions and consumption of primary energy resources. The issues can be solved by popularizing heat pump systems that are attributable to higher performance efficiency than those of traditional gas boilers. Even so, the heat pump system performance can be further enhanced if the dissolved gases in its hot water circuit can be efficiently discharged. To achieve this target, the bubble behaviors in the heat pump water heating system need to be extensively investigated. In this paper, by varying different experimental conditions, the effects of various heat pump hot water side parameters on gas microbubble diameters were measured and analyzed. Correspondingly, the effect of each parameter has been investigated. These include varied system pressures, water flow rates, saturation ratios and heat outputs. The results measurement showed that the water flow rate is the most significant parameter to influence on gas microbubble productions. The research outcomes can significantly contribute to the understanding of gas bubble behaviors at domestic heat pump water heating systems and thus the efficient way for the discharging of the associated dissolved gases.

Keywords**—**Dissolved gases in water, heat pump, domestic water heating system, microbubble formation.

I. INTRODUCTION

THE growing awareness of increasing temperature of the earth's atmosphere has internationally aroused interest in reducing greenhouse gas emissions produced by human activity [1]. The goal of maintaining the rise of global temperature lower than 2 °C as a part of the agreement of parties was the prime outcome of the 21st session of the U.N. Framework Convention on Climate Change Conference of the Parties [1]. At present, UK residents prefer to use gas boilers for domestic water heating and it contributes to excessive CO_2 emissions and consumption of primary energy resources. However, if these gas boilers could be replaced by heat pump productions, which have higher performance efficiency, a significant saving of CO_2 emissions can be achieved. The research of heat pump products has obtained many achievements but further system performance improvement is still required. One significant strategy is to discharge efficiently the dissolved gases in hot water flow associated with the heat pump indoor heat exchanger.

To discharge bubble production in hot water circuit of heat pump system, passive deaerators are widely installed in the heat pump water heating systems. There are many journal papers about subcooled boiling and two-phase flow through microchannel [2]-[8] but the data and theoretical scientific models to predict two-phase flow characteristics in heat pump water heating system in open literature are limited at present. The performance of the deaerators installed in the heat pump water heating systems is lower than expected. Also, the improvements of the design of passive deaerators are limited by the gap of the study in this field.

Bubble diameters detached from the surface of a heat exchanger has been studied and discussed by many researchers [2]-[8]. Dean [2] published the early study of the formation of bubbles in a supersaturated liquid. Winterton [3] reported the bubble detachment model in the aspect of mechanics analysis. Jones et al. [4] realized the insufficiency of classical nucleation models developed by Blander and Katz [5] and discussed bubble generation in low supersaturated liquid. Fsadni et al. [6] extend Winterton's theoretical model to other shapes of ducts and report the bubble detachment diameters in a boiler central heating system. This work contributes to the design of deaerators in a boiler water heating system. Yin et al. [7] achieved experimental investigation on sub-cooled boiling flow on a flat wall of a microchannel. They reported that the bubbles had not departed from the wall. There are two sliding stages of a bubble on a flat wall, one is the slow sliding stage and the other is the accelerated sliding stage. They also reported the characteristics of the bubble in two stages are significantly different. The diameter of bubble in slow sliding stage was constant while in the accelerated stage it decreased along with the increase of fluid velocity. Hoang et al. [8] obtained a mechanistic model for predicting the maximum diameter of attached bubble nucleating in a sub-cooled flow boiling.

There are many other researchers studied bubble diameters detached from the heat transfer wall. This knowledge can be used in much industry area such as designing of a heat exchanger but it is not enough for designing a system to discharge these bubbles. This is because of the involving of turbulent flow in a plate heat exchanger. Experimental investigations of gas-liquid turbulent flow characteristics inside a plate heat exchanger have been conducted by many researchers such as [9]-[11]. Strong turbulent flow affects bubble diameter delivered off the plate heat exchanger. Abdelmessih et al. [12] considered the bubble collapse and the

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effect of fluid velocity but the heat exchange wall is still flat which is different from the plate heat exchanger.

Grabenstein et al. [13] experimentally investigated two-phase flow in a corrugated gap created by two adjacent plates of a PHE. They used polyurethane casted plates instead of standard stainless-steel plates to achieve the visualized two-phase flows. They observed three different flow regimes which are bubbly flow, film flow and slug flow respectively. They also studied the pressure drop in a PHE and had a comparison between the predicted pressure drop and the experimental data. Bonjour et al. [14] discussed the coalescence phenomenon during boiling on a vertical heated wall. The coalescence phenomenon is shown in Fig. 1. The heat fluxes were varied and the wall was superheated at different temperatures. Moreover, they reported that the coalescence phenomenon caused a decrease in the bubble frequency. Hsieh et al. [15] experimentally investigated the sub-cooled flow boiling of the refrigerant and water in a vertical PHE with a chevron angle of 60 degree. It is reported that particularly at low mass flux and high saturation temperature, boiling curves change significantly during onset of nucleate boiling (ONB). Moreover, the boiling hysteresis phenomenon is significant when a refrigerant mass flux is low and sub-cooled boiling is affected significantly by the mass flux of the refrigerant. In addition, the heat transfer coefficient had been improved slightly by increasing the inlet sub-cooling and saturation temperature.

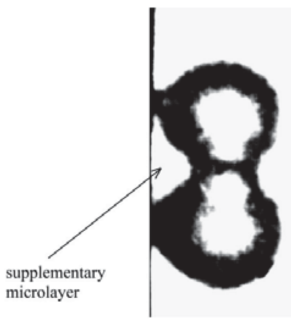

Fig. 1 Coalescence of two bubbles on a vertical heated wall [14]

The effect of buoyancy on bubble nucleation and flow is concerned with bubble behaviours in sub-cooled flow boiling in a domestic water heating system and it has been investigated by many researchers such as [16], [17]. Zhang et al. [16] extensively studied the effect of buoyancy in dynamics. They claim that the effects of buoyancy are not particular concerned with microscopic cavitation bubbles, while the effects of buoyancy on the large bubbles are essential, but the effects are still important to understand the bubble flow distribution in the pipe. Pamperin and Rath [17] studied the effect of buoyancy on bubble nucleation and reported that the effect of buoyancy on the size of nucleated bubbles weakens with the increase of Weber number *W*.

In the domestic field, air bubbles always appear in the closed heat pump water heating system causing the reduction of the heating efficiency. Some gas bubbles dissolve into the water again in the returning cold piping. And the cold water can absorb much quantity of gas while the system cools down.

The bubbles could easily cause the gas to block water pipes of a heat pump system and poor water flow circulation. This might lead to the temperatures of parts of the heating area, where is planned to be heated, are lower than the expected value. [18]. The gas bubbles seriously affect the practical heating effect of the heat pump system. The bubbles remaining in the system will flow with water cyclically through the pipe of the heat pump system. The bubbles remaining in the system will flow with water cyclically through the pipe of the heat pump system and make a lot of noise [19]. The noise is especially loud when the bubbles flow through the uncovering fin system. As a result of this phenomenon, the sleep quality of the home users is affected seriously by the noise of the heat pump system. The bubbles mainly contain the nitrogen, but still have some oxygen and other corrosive gases [20]. These corrosive gases in the piping of a heat pump system can lead the system equipment to be corroded including the terminal heat sink and the heat equipment. This problem causes substantial economic losses in the condition of the lack of protective measures. And consequently, as environment-friendly equipment, an optimised heat pump water heating system should have significant environmental benefits.

From the public literature, Ge and Fsadni have done many researches on the field of the domestic wet central heating system [21], [22]. The main difference between the heat pump heating system and the boiler central heating system is the maximum temperature of supply water and the temperature of the wall of heat exchanger. The range of the maximum supply water temperature of the domestic heat pump water heating system is 55-60 ^{o}C, which is much lower than the boiler. Therefore, the phenomenon of bubble production in the heat pump water heating system is lower than the boiler central heating system is predicted.

In this paper, the experimental investigation of bubble behaviours in horizontal turbulent two-phase sub-cooled flow boiling has been examined experimentally in a test rig of heat pump water heating system.

II. Experimental Setup and Uncertainties

A. Experimental Setup

The experimental setup has been designed to investigate gas bubble behaviours in a domestic heat pump water heating system. It is redesigned from the previous study to adapt to present heat pump subcooled boiling study [6]. The schematic diagram of experimental setup is shown in Fig. 2. The air source heat pump, an outdoor water heating unit as shown in Fig. 2, is provided by KINGSPAN Limited and it is connected to 22 mm BSP copper tubing which supplies buffer vessel. The subcooled water heated in the plate heat exchanger of heat pump is held in the buffer vessel. The buffer vessel is connected to the cooling system, which contains three heat exchangers supplied with mains water, showed in Fig. 2 and the water in the system is powered by a water pump into the cooling system. The total gas pressure monitoring system (TGM) is used to measure the total gas pressure in the system as shown in Fig. 2. The working temperature of the TGM is 20 ~45°C. The TGM consists of a pressure transducer, semi-permeable silicone membrane and a two-hole tube sheet which allows water goes through the holes and have a contact with the silicone membrane. The partial gas pressure is calculated through the subtraction of the relevant water vapour pressure from the total gas pressure. Seven stainless steel sheathed K-type thermocouples and three pressure transducers are installed along the piping working in heat pump unit and domestic water heating system. Electromagnetic flow meter is used to measure system fluid flow rates. In addition, the expansion vessel is installed at a position on the supply pipes to reduce the system pressure vibration as shown in Fig. 2.

The heat pump system is installed outside and connected to piping system through the drilled hole across the wall. The drilled hole across the wall is horizontal and makes sure the tubing can directly connect to the plate heat exchanger outlet. The sight-glass is installed on this horizontal part inside as shown in Fig. 2. One light source is used to provide the enough bright for the high-speed camera capturing bubbles.

All the signals from the transducers, thermocouples and electromagnetic flow meter are collected by the National Instrument cDAQ-9172 chassis and NI9211, NI9203, NI9481 data modules. A programme of LabVIEW software is used to collect and save the signals. All the signals were calibrated and the calibrating equations are programmed in the LabVIEW software. The system fluid flow rate, the system pressure, the system heating load and the system saturation ratio might affect the gas bubble behaviours such as gas bubble diameters and void fractions as these four parameters were varied in the experiment. The experimental parameters are shown in Table I.

TABLE I
EXPERIMENTAL TESTING PARAMETERS

Test	Bulk fluid flow rate in tubes (liter/hour)	System pressure (bars)	Heating load (kW)	Saturation ratio at wall conditions	System exit temp. (ºC)	System return temp. (ºC)
1	600-1150	2.2	6	1.1	55	47-50
2	750	1.8-2.5	6	1.08	55	50
3	750	2.2	4.8-7.9	1.08	55	50
4	750	2.2	6	1.01-1.20	55	50

Equation (1) is used to calculate the saturation ratio, which is defined by Jones et al. [4]. The Cgas is the actual dissolved gas concentration present in the bulk fluid; The C_{sat} is the maximum concentration at saturation conditions and other conditions are same with C_{gas}.

$$Sr = \frac{C_{gas}}{C_{sat}} \tag{1}$$

The air consists of 78% nitrogen, 21% oxygen and 1% others. The oxidation process in the system leads to iron oxide and hydrogen gas. Hence, nitrogen is the dominant gas in the closed loop heat pump water heating system. And the property of nitrogen is used to represent the properties of the dissolved gas in this stage study.

Equation (2) is used to calculate the actual dissolved gas content, C_{gas}.

$$C_{gas} = p_g X^T \tag{2}$$

The p_g (pa) is the partial gas pressure, defined by Lubetkin and Blackwell [23], which can be calculated by:

$$Gas\ Pressure\ P_T = Vapour\ P_v + Partial\ pressure\ of\ gas\ p_g \tag{3}$$

B. Image Process

Images captured by the Phantom V5.1 camera are saved in the computer. The self-coded Matlab program is used to conduct the image processing. The Sobel Filter, a blurring filter, is used in the program to determine bubble in or out of focal plane. The dirt particles and stains on the sight glass are motionless. Hence, they are treated as the background during the image processing and thus removed. The first one is the original picture. The second one is the picture after background removed. Bubbles are blurry when they are not in the focal plane. Fig. 5 shows the recognised sharp bubbles. To calibrate size of the picture to determine size of the bubble, a D_{ball} = 2 mm metal ball is put on the surface of the sight glass. The metal ball's pixel size P_{ball} was measured. The resolution of the picture $P_{picture}$ is 1024 * 1024 pixels.

$$D_{Picture} = P_{Picture} \times \frac{D_{ball}}{P_{ball}} \tag{4}$$

C. Uncertainty Analysis

To increase the accuracy of average bubble diameter, 5 different positions from the top to the bottom of a cross section of the supply pipe are measured. Manual measurement errors during these repeat tests are considered as potential errors. The electromagnetic flow meter has an accuracy of 0.5%. The pressure transducers have and accuracy of 0.3%. The stainless steel sheathed K-type thermocouples have an accuracy of 0.1 K. The effect of these errors is considered minimal for current research.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The sight-glass is installed horizontally near the plate heat exchanger exit as shown in Fig. 2 to investigate the bubble behaviours due to the sub-cooled boiling. For each test, 5000 images were captured by the camera in 3 minutes. The big number of images ensures the accuracy of the experiment. This experiment investigated four parameters which may affect bubble diameter in a domestic heat pump water heating system. The experimental conditions achieved are illustrated in Table I. The relationship between average bubble diameter and the system pressure p, water volume flow rate Vw, the saturation α and the system heating load Q are illustrated in Figs. 8-11.

To maintain the supply water temperature at 55 °C, a control formula is applied in the cooling system as shown in Eq. 5. It is much better than the on-off control for decreasing temperature fluctuation.

$$55+0.5\times\left|\sin\left(\frac{\pi T_x}{6}\right)\right|=T_c \qquad (5)$$

When Tc is smaller than T2, the cooling system is open. The control method is illustrated in Fig. 6.

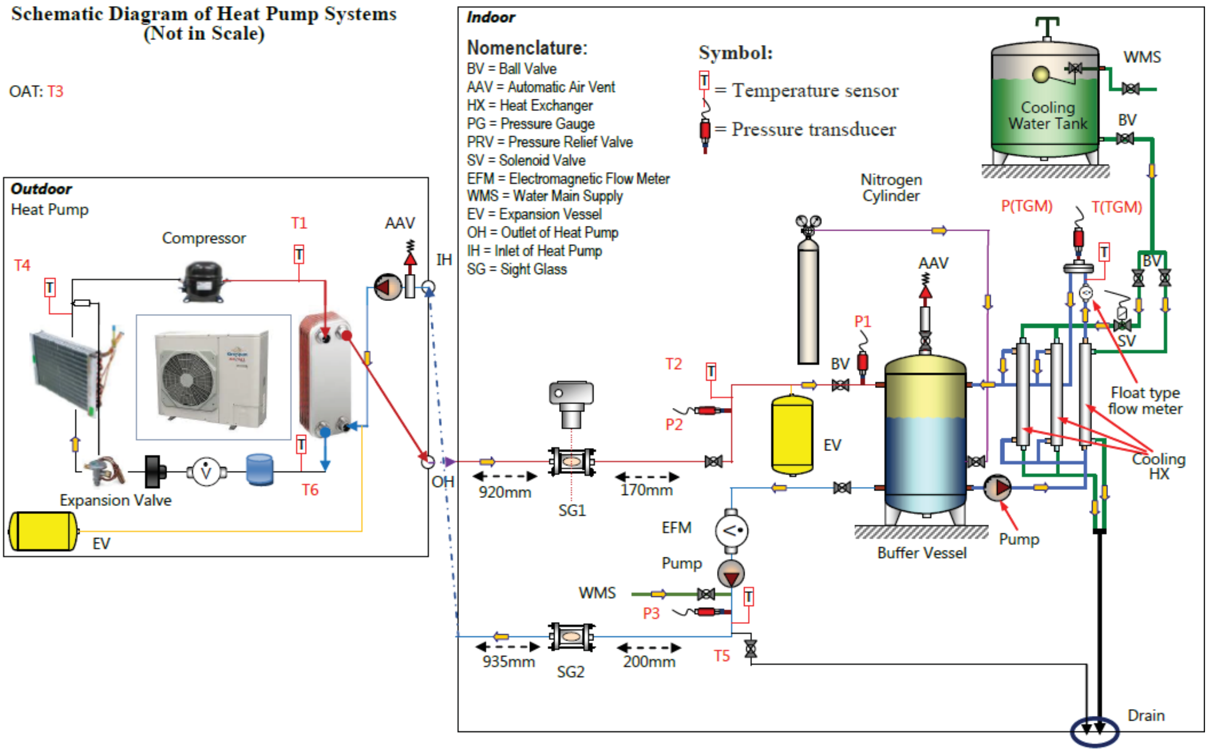

Fig. 2 Schematic diagram of heat pump system

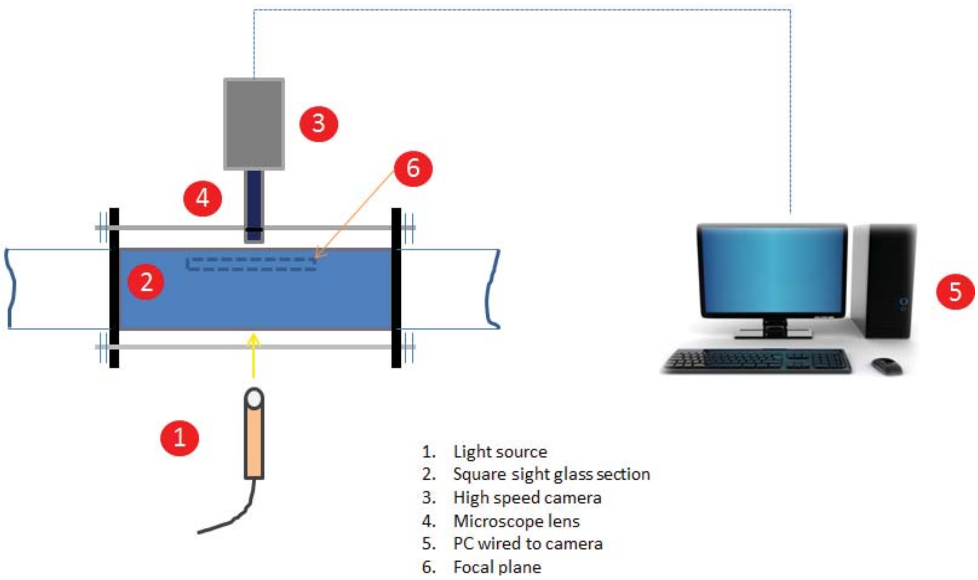

Fig. 3 Horizontal sight-glass for bubble capturing

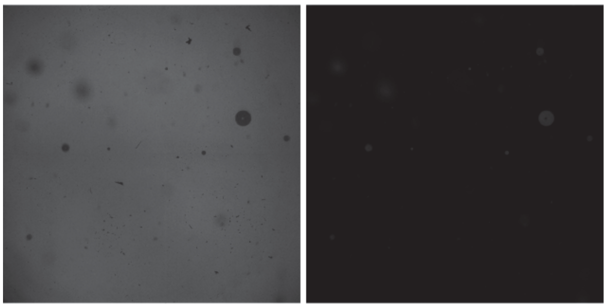

Fig. 4 Removing image background

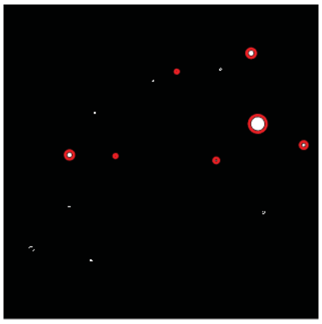

Fig. 5 Recognized bubbles

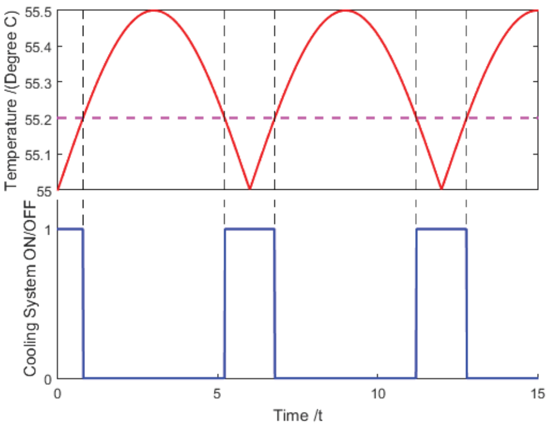

Fig. 6 Cooling system control method

The average bubble diameter increases along with the increase of water flow rate at the exit of plate heat exchanger in a heat pump water heating system as shown in Fig. 8. This is a different phenomenon as many previous researches on flow boiling shows average bubble diameter decrease along with the increase of water flow rate [3], [4], [7]. The reason of this phenomenon is bubbles collide and coalesce in the plate heat exchanger. These bubbles involve in strong turbulent flow. The Tsai et el. [11] studied the flow distribution in a chevron-type plate heat exchanger which illustrates the velocity vectors around the contact points. The Fig. 11 illustrates the number of bubbles decreases along with the increase of water flow rate. This trend has a good agreement with Bonjour et al. [14]. This proves the phenomenon of bubbles collide and coalesce in the plate heat exchanger. The dispersion of bubble average diameter increases along with the increase of water flow rate.

The system pressures were varied from 1.8 to 2.5 bars in experiments. The average bubble diameter slightly increases along with the increase of the system pressure as shown in Fig. 9. Also, the dispersion of bubble average diameters increases along with the increase of system pressure. As the fluid is in turbulent flow in plate heat exchanger, the increase of Reynolds number, *Re*, is considered the reason.

The heat pump heating loads were varied as 4.8, 6.6 and 7.9 kW. The average bubble diameters roughly keep same along with the increase of system heating load as shown in Fig. 10. As the experimental equipment is limited, the refrigerant side's thermocouples are installed at the surface of the copper pipe. The temperature of refrigerant came out of the compressor varies from 93-98 °C. Then the refrigerant went into the plate heat exchanger. Therefore, the bubble nucleated due to sub-cooled boiling. According to the results, heating load has limited effect on bubble average diameter and the effect of turbulent flow is dominant. The system saturation ratio has limited effect on bubble average diameter in plate heat exchanger. Fsadni et al. [6] studied the effect of system saturation ratio on bubble average diameter. He discussed the system saturation ratio has limited effect on bubble average diameter as well.

To investigate the bubble distribution behaviours vertically in the pipe, 5 layers in different depths were measured. The relationship between bubble average diameters and layers are illustrated in Fig. 13. As shown in the figure, average bubble diameters decrease as the layer position is deeper. This is because big bubbles are lift up by the effect of buoyancy of water. The tests are repeated at three different water flow rates, 750 l/h, 900l/h and 1000 l/h.

As illustrated in the Fig. 8, the higher average bubble diameter generally presents at the higher water flow rate. For flow in a pipe, the Reynolds number can be calculated by the equation as follows:

$$Re=(QD_H)/vA \tag{6}$$

The hydraulic diameter of the pipe in this experiment is 20 mm. And the kinematic viscosity ν at 55oC and 2.2 Bars is 5.11E-7 m2/s. Hence, the Reynolds number of the flow rate 1200 l/h, 1000 l/h and 800 l/h are 4.15E+4, 3.46E+4 and 2.77E+4 respectively at measuring position.

This experiment presents the higher volume flow rate results in the bigger bubble average diameter at exit position of plate heat exchanger. And lower volume flow rate results in the smaller bubble average diameter at exit position. These results are affected by the turbulent flow.

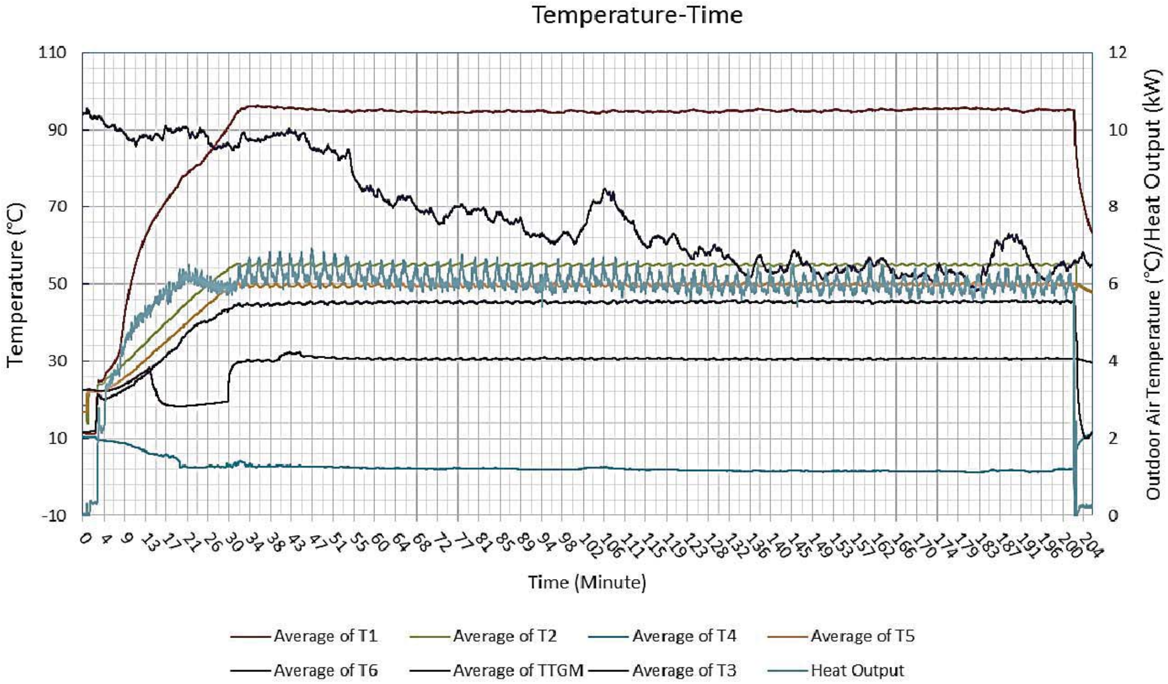

Fig. 7 Experimental conditions

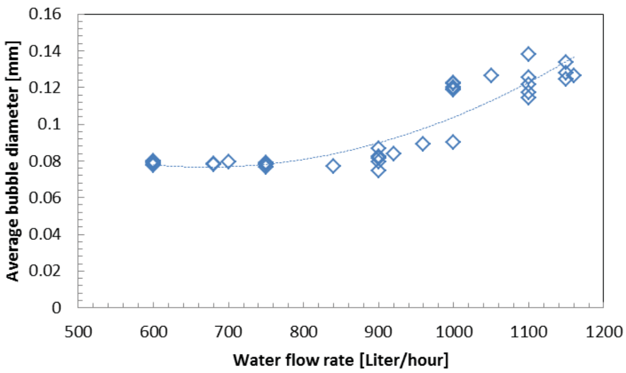

Fig. 8 Experimental bubble diameters with the water flow rate

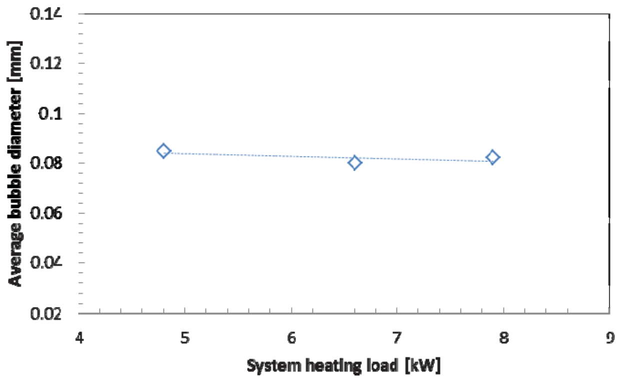

Fig. 10 Experimental average bubble diameters with system heating load

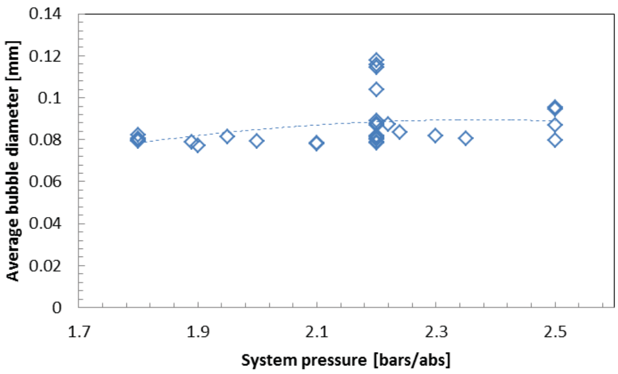

Fig. 9 Experimental bubble diameters with the system pressure

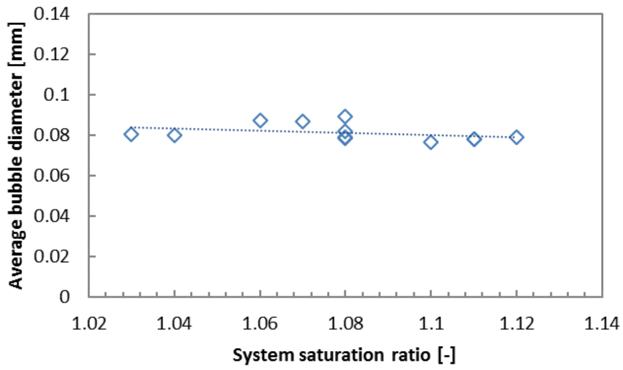

Fig. 11 Experimental average bubble diameters with SR

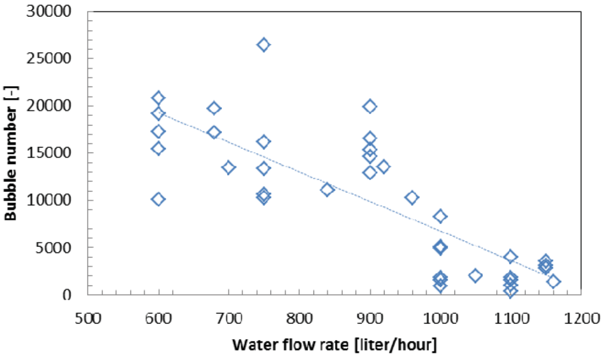

Fig. 12 Bubble number with water flow rate during 3 minutes

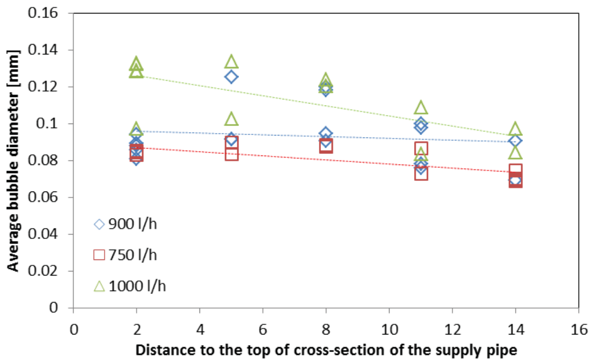

Fig. 13 Average bubble diameters with layers

IV. Conclusions

Air source heat pump systems are advantageous over conventional gas boilers for domestic water heating in term of operational efficiency. However, the unavoidable dissolved gases in the heat pump water loop need to be discharged efficiently so as to further improve the heat pump performance. This paper has illustrated an experimental study of bubble behaviours in the heat pump water heating system. The measurements have been conducted to find common trend of bubble distribution in turbulent bubbly flow in super-saturated water.

The increases of water flow rate can result in the bigger average bubble diameters at exit of PHE at water side and the less bubble number. The system heating load and saturation ratio have limited effect on the average bubble diameter. The increases of the system pressure can result in the slightly bigger average bubble diameter in the domestic heat pump water heating system. The average bubble diameter decreases with the deeper measurement position in a horizontal pipe.

The fully study of the bubble distribution in the heat pump water heating system can improve the design of deaerating system and improve the domestic heat pump water heating system performance. Further studies should theoretically analyse the effect of the turbulent flow on a sub-cooled flow boiling.

Acknowledgments

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Nomenclature

C_{gas} Actual dissolved gas concentration present in the bulk fluid, (standard cm^3 / Litre Water)
C_{sat} Maximum gas concentration at system temperature, (standard cm^3 / Litre Water)
D_{ball} Dimensions of the ball, (mm)
$D_{picture}$ Dimensions of the picture, (mm)
P The system pressure, (bar)
P_g Partial gas pressure, (bar)
P_{ball} Pixels of the ball, (mm)
$P_{picture}$ Pixels of the picture, (mm)
Q The system heating load, (kW)
Re Reynolds number, (-)
Sr Saturation ratio, (-)
T_1 Condenser inlet temperature, (°C)
T_2 Supply water temperature, (°C)
T_3 Outdoor air temperature, (°C)
T_4 Evaporator temperature, (°C)
T_5 Return water temperature, (°C)
T_6 Condenser outlet temperature, (°C)
T_{tgm} Total gas measurement temperature, (°C)
V_w Volumetric flow rate, (Litre/Hour)
W Weber number, (-)
X^T Gas solubility factor, (standard cm^3 / kg bar)
α System saturation ratio, (-)
ν Kinematic viscosity, (m^2/s)
ρ Density of liquid, (kg/m^3)

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