Investigation Bubble Growth and Nucleation Rates during the Pool Boiling Heat Transfer of Distilled Water Using Population Balance Model

V. Nikkhah Rashidabad, M. Manteghian, M. Masoumi, S. Mousavian

***Abstract*—**In this research, the changes in bubbles diameter and number that may occur due to the change in heat flux of pure water during pool boiling process. For this purpose, test equipment was designed and developed to collect test data. The bubbles were graded using Caliper Screen software. To calculate the growth and nucleation rates of bubbles under different fluxes, population balance model was employed. The results show that the increase in heat flux from q=20 kw/m2 to q= 102 kw/m2 raised the growth and nucleation rates of bubbles.

***Keywords*—**Heat flux, bubble growth, bubble nucleation, population balance model.

I. Introduction

In recent years, many studies have been conducted on boiling heat transfer from pure substances and binary solutions. As pool boiling has many applications, and is a good beginning point for understanding flux changes, it has attracted special attentions, and several empirical and theoretical methods have been provided for its study [1].

In this research, the test equipment was developed to take pictures of bubbles from bubble initiation up to the steady state of boiling, as well as calculate and record all changes in the size of bubbles, number of bubbles, bubble settle time, and other changes in heat flux. Thereafter, the bubbles were graded. Finally, the growth and nucleation rates were calculated using population balance model.

II. Test

A. Test Equipment

The test equipment developed for this research has in general three main parts: instrumentation (temperature measuring systems), power supply system (autotransformer and heating system), and imaging system. The test container made of tempered glass had a thickness of 10 millimeter and the capacity of 35 liters. It was insulated by kaolite. The main element with the thermal power of 1000 watt, diameter of 0.8 cm, and length of 58cm was mounted at distance of 10cm from the bottom of the test container. The autotransformer was connected to the element, which triggers pool boiling.

Moreover, an auxiliary element was used as a pre-heater to bring the solution to the boil. When the solution reaches the boiling point, the element turns off. From that point, the main element heats the solution up to the steady state (supersaturated boiling), and calculations are performed based on this element, and the bubbles formed on it. Volume of the region of test equipment that imaging from it and used in calculation process is 6 liters.

An autotransformer was used to supply the voltage of 0 to 300 volts. In addition, a vacuum pump was employed for deaeration. A schema of the test equipment has been provided in the following:

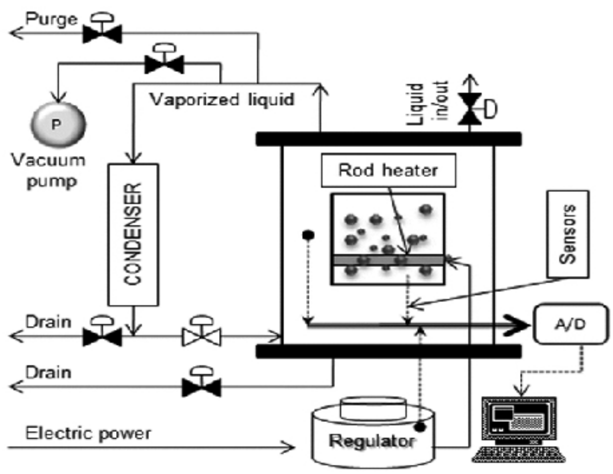

Fig. 1 The schema of test equipment

B. Test Method

The test was carried out under five different fluxes from q= 20kw/m^2 to q=102 kw/m^2. Under each flux, when the boiling solution (pure water) was supersaturated, the pictures of bubbles over the heater were taken, and the size and number of bubbles were studied by Calipers Screen software for modeling purpose.

III. Laboratory Data Analysis of Mathematic Modeling

A. Pool Boiling Of Pure Water

The results of the researches conducted by researchers like Kutateladze and Gogonin [2]. On pure water and organic solutions showed that the increase in superheating of heater's

Vahid Nikkhah Rashidabad and Mir Esmaeel are with Chemical Engineering Department, Terhan North Branch, Islamic Azad University, Iran.

Mehrdad Manteghian is with the Chemical Engineering Department, Tarbiat Modares University, Iran (e-mail: manteghi@modares.ac.ir).

S.Mousavian is with the Sama Technical and Vocational Training College, Islamic Azad University, Gachsaran branch, Gachsaran, Iran.

wall increases the size of the bubbles that are in the process of departure. As in the tests that are related to this project, pool boiling is of supersaturated type, all results of this state were recorded.

Figs. 2 and 3 show the increase in the diameter of bubbles because of superheating of the boiling pure water.

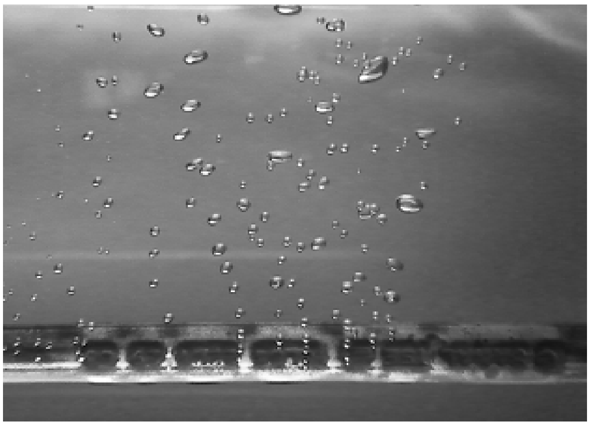

Fig. 2 Pool boiling of pure water under heat flux of 20 kw/m2

Fig. 3 Pool boiling of pure water under heat flux of 60 Kw/M^2

As shown in the image of pool boiling of pure water under higher heat flux, the bubbles of boiling water are significantly bigger than the bubbles under lower flux [3]-[7]. This is due to the higher cohesion of bubbles under higher heat fluxes.

The main factor involved in nucleation point, as well as formation and departure of bubbles is the decrease in local pressure in different contact points of heater and water. This is one of the most important reasons causing the number of bubbles arising out of pool boiling of pure water to be less than that of the bubbles in other solutions in the same conditions [8]-[12].

B. Population Balance Model

The general case of population balance equation:

$$\frac{\partial n}{\partial t}+\frac{\partial (Gn)}{\partial L}=\sum^{m}\frac{n_k Q_k}{V}+\bar{B}(L)-D(L) \tag{1}$$

$\frac{\partial n}{\partial t}$: Reserve bubble intensity with size L.

$\frac{\partial (Gn)}{\partial L}$: Increase or decrease in bubble caused by growth with size L.

$\sum_{K}\frac{n_k Q_k}{V}$: Intensify of intering or logging out bubbles with size L.

$\bar{B}(L)$: Production of bubbles with size L due to bursting of larger babbles.

$D(L)$: Removing of bubbles with size L due to bursting of larger babbles.

By applying the following assumptions In order to simplify the population balance equation In general, we arrive to the population balance model:

1- It is required the system to be in steady state. That is, no major change in properties of the system is carried out, and the nucleation growth (population of bubbles) is not subject to considerable changes.
2- Complete mixing of the solution is established. All properties are the same at all points.
3- Bursting of the bubbles and their coalescence is ignored.
4- Do not have enter and exit in the system.
5- All bubbles are considered Spherical.

General Population Balance of Bubbles is given by the following equation.

$$G\frac{dn}{dL}=-\frac{nQ}{V} \quad as\ \frac{Q}{V}=\frac{1}{\tau}:G\frac{dn}{dL}=-\frac{n}{\tau} \tag{2}$$

This differential equation can be solved simply as follows:

$$\frac{dn}{n}=\frac{dl}{G\tau}:\rightarrow Ln(n)=Ln(n.)-\frac{L}{G\tau} \tag{3}$$

where, n0 is the population density of the bubbles, whose size is close to zero. In other words, the closer the size of bubbles to zero is, the more the density of bubble population tends to n0.

Therefore, by constructing Ln(n) against L, a straight line with the slope of -1/Gτ and y-intercept of Ln(no) is achieved. Note: n_0 is the ration of growth and nucleation rates.

$$n_0 = B/G \tag{4}$$

B: nucleation intensity $\left(\frac{no}{m^3.s}\right)$

G: growth intensity (m/s)

τ : settle time of bubble in the solution (s)

Q: Heat flux (kw/m^2)

ΔL : Size Interval (m)

L : Channel mean size (m)

n: Population density $\left(\frac{no}{m^3.m}\right)$

IV. Growth and Nucleation Rates of Bubbles

To determine the growth and nucleation rates, it is required to determine the bubble size distribution under each heat flux, and then calculate the growth and nucleation rates of bubbles based on population balance model.

A. Bubble Gradation

The bubbles were graded under 5 different fluxes, and the growth rate and nucleation rate were also calculated.

The complete calculations have been provided for two different fluxes (low flux of q=20 kw/m2 and high flux of q=102 kw/m2).

TABLE I
BUBBLE SIZE DISTRIBUTION UNDER THE FLUX Q= 20 KW/M^2

ΔL	L	Number of Bubbles	$n = \frac{\text{Number of bubbles}}{\Delta L \times V}$	Ln(n)
4×0.0001	11×0.0001	6	2500	7.82
3.5×0.0001	15×0.0001	5	2381	7.77
5.5×0.0001	18×0.0001	12	3636	8.19
11×0.0001	26×0.0001	22	3333	8.1
18×0.0001	40×0.0001	18	1667	7.41
23.5×0.0001	62×0.0001	23	1631	7.4
11.5×0.0001	93×0.0001	6	869	6.767
13.5×0.0001	110×0.0001	4	493	6.2
20×0.0001	120×0.0001	5	416	6.03
20×0.0001	170×0.0001	3	250	5.521

By fitting Ln(n) against L, a 1st degree equation, whose slope is -1/Gτ and y-intercept Ln(n0) is achieved.

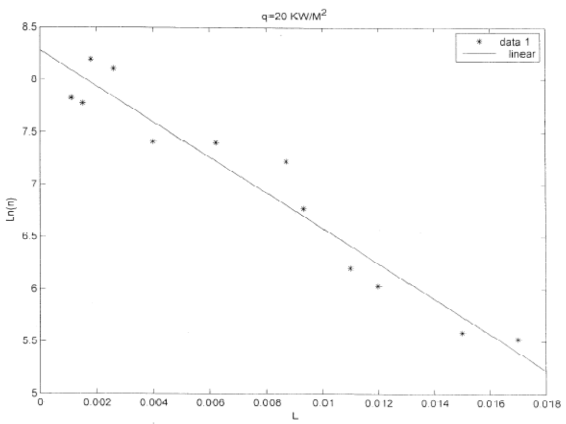

Fig. 4 Comparison of model results with experimental data in determination of nucleation and growth of bubbles in Q= 20 Kw/M^2

q = 20 kw/m^2

Linear model poly1: f(x) = $p_1 x + p_2$

Coefficients (with 95% confidence bounds): p_1 = -169.1 (-199.7, -138.5), p_2 = 8.271 (7.99, 8.552)

Goodness of fit: R-square: 0.9381

Calculation of growth rate and nucleation rate

$$-\frac{1}{G\tau} = -169.1 \text{ ، } \tau = 3 \text{ sec}$$

$$\rightarrow G = 0.00184\ m/s\ (growth\ \ rate)$$

$$Ln\,(n_\circ) = 8.271 \rightarrow n_\circ = 3909\ \frac{no}{m^3.m}$$

B = G * $n_\circ \rightarrow G = 0.00184 m/s\ (growth\,rate)$ = 0.00184 × 3909

= 7.2 $\frac{no}{m^3.s}$ (nucleation rate)

TABLE II
BUBBLE SIZE DISTRIBUTION UNDER THE FLUX Q= 102 KW/M^2

ΔL	L	Number of Bubbles	$n = \frac{\text{Number of bubbles}}{\Delta L \times V}$	Ln(n)
20×0.0001	20×0.0001	16	1333	7.2
20×0.0001	40×0.0001	14	1167	7.06
20×0.0001	60×0.0001	14	1167	7.06
20×0.0001	80×0.0001	10	833	6.725
20×0.0001	100×0.0001	7	6.36	6.36
20×0.0001	120×0.0001	8	666	6.501
20×0.0001	140×0.0001	5	416	6.03
20×0.0001	160×0.0001	5	416	6.03
20×0.0001	180×0.0001	4	333	5.8
20*0.0001	200*0.0001	6	500	6.214
20×0.0001	220×0.0001	5	416	6.03
20×0.0001	240×0.0001	8	666	6.501
20×0.0001	260×0.0001	6	500	6.214
20×0.0001	280×0.0001	4	333	5.8
20×0.0001	300×0.0001	3	250	5.521
20×0.0001	320×0.0001	2	166	5.115
20×0.0001	340×0.0001	2	166	5.115
20×0.0001	360×0.0001	2	166	5.115
20×0.0001	380×0.0001	2	166	5.115
20×0.0001	400×0.0001	3	250	5.521
20×0.0001	420×0.0001	3	250	5.521
20×0.0001	440×0.0001	2	166	5.115
40×0.0001	470×0.0001	1	41.65	3.73
40×0.0001	510×0.0001	2	83.3	4.42

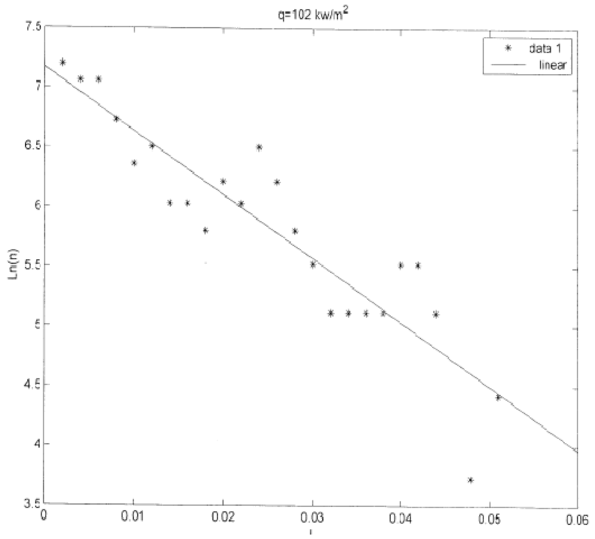

Fig. 5 Comparison of model results with experimental data in determination of nucleation and growth of bubbles in q= 102 kw/m^2

$$q = 102\frac{kw}{m^2}$$

Linear model poly1: f(x) = $p_1 x + p_2$

Coefficients (with 95% confidence bounds):

p_1 = -53.35 (-63.99, -42.7) ،p_2 = 7.17 (6.862, 7.478)

Goodness of fit: R-square: 0.8308

Calculation of growth rate and nucleation rate:

$$-\frac{1}{G\tau} = -53.35, \quad \tau = 1.2\ sec \ \rightarrow G = 0.0156 \, {}^{m}\!/_{s} \quad \text{(growth rate)}$$

$$Ln(n_{\circ}) = 7.17 \rightarrow n_{\circ} = 1212\frac{no}{m^3.m}$$

$$B = n_{\circ}.G \rightarrow B = 18.93\frac{no}{m^3.s} \quad \text{(nucleation rate)}$$

TABLE III
THE CHANGES IN GROWTH RATE AND NUCLEATION RATE OF BUBBLES DURING THE POOL BOILING OF PURE WATER UNDER DIFFERENT HEAT FLUXES

Heat flux q(kw/m^2)	Growth rate (m/sec)	Nucleation rate (no/m^3.sec)
20	0.00184	7.2
40	0.0038	8.02
60	0.0091	10.2
80	0.0093	18
102	0.0156	18.93

V. CONCLUSION

The results show that the increase in heat flux arising out of the increase in the number of bubbles can raise bubble growth and nucleation rates. There are several factors, such as solution type or the substance in the solution, which affect the number of bubbles and consequently the nucleation rate. Surface interaction is another factor effective in growth process and decrease in nucleation points. That is, the increase in surface interaction reduces the number of bubbles departed from the surface.

REFERENCES

[1] Nukiyama, S., 1934, "The maximum and minimum values of heat transmitted from metal to boiling water under atmospheric pressure", J. Japan Soc. Mech. Eng., 37, 367.

[2] Kutateladze, S. S., Gogonin, I. I., 1979, "Growth velocity and detachment diameter of vapor bubbles of various fluids under free convection conditions", Teplofizika Visokikh (in Russian), 4, PP.792-797.

[3] Zeng, L. Z., Mei, R., Klausner, J. F., 1993, "A unified model for the prediction of bubble detachment diameters in boiling systems", Int. J. Heat and Mass Transfer, 36, PP.2261-2279.

[4] Han, C. Y., Griffith, P., 1965, "The mechanism of heat transfer in nucleate pool boiling", Int. J. Heat and Mass Transfer, 8, PP.880-920.

[5] Christopher, D.M., Wang, H., Peng, X., 2006. "Numerical analysis of the dynamics of moving vapor bubbles", Int. J. Heat and Mass Transfer, 49, PP.3626-3633.

[6] Frost, W., Kippenhan, C.J., 1967. Bubble growth and heat transfer mechanisms in the forced convection boiling of water containing a surface active agent, Int. J. Heat Mass Transfer 10: 931-949.

[7] Kotchaphakdee, P., Williams, M.C., 1970. "Enhancement of nucleate pool boiling with polymeric additives", Int. J. Heat and Mass Transfer, 13, PP.835-848.

[8] Jamialahmadi, M., Blochl,R., Muller-Steinhagen,H., 1991 "Pool boiling heat transfer to saturated water and refrigerant 113", The Can. J. of Chemical Eng., 69, PP.746-754.

[9] Lee, H.C., Oh, B.D., Bae, S.W., Kim, M.H., 2003. "Single bubble growth in saturated pool boiling on a constant wall temperature surface", Int. J. Multiphase Flow, 30, PP.1849-1858.

[10] Mei. R., Chen, W., James., F., 1998. "An experimental investigation of bubble growth and detachment in vertical upflow and downflow boiling", Int. J. Heat and Mass Transfer, 41, PP.3857-3871.

[11] Mukherejee, A., Kandlikar, S.G., 2006. "Numerical study of single bubbles with dynamic contact angle during nucleate pool boiling", Int. J. Heat and Mass Transfer, 5.

[12] Ozbek, H., Philips, P., 2003. "Thermal conductivity of aquaes solutions from 20 to 330 degree centigrade", European Journal of Surgical Oncology (EJSO), 36, PP.5-9.