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Presentation and evaluation of a new model for bubble growth in two-component solution pool boiling

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ABSTRACT

In this study, the heat transfer coefficient of the pool boiling is evaluated in the nuclear region for the fluid at different concentrations of water-ethanol solution on a horizontal cylinder at 1 atm. For this purpose is examined the diameter of the growing bubble of water-ethanol solution in a heat flux range of 1 to 60 $kW.m^{-2}$ in different concentrations on the horizontal cylinder of stainless steel. The results show that by an increase in heat flux, bubble diameter increases. The diameter of the bubbles created in heat flux is examined and compared with different dynamic models that according to the calculated average error of the model. Hamzehkhani model has better consistency with the experimental data. Recently, optimization methods have been widely used in fuzzy equilibrium calculations. Among these methods, genetic algorithms can be used to calculate the binary interaction components of activity coefficient patterns in equilibrium systems. The equations and relations of previous for the solution have a high error in predicting the heat transfer coefficient, so using the obtained data and applying the genetic algorithm. A newer experimental equation is presented which has a good fitting with the experimental data.

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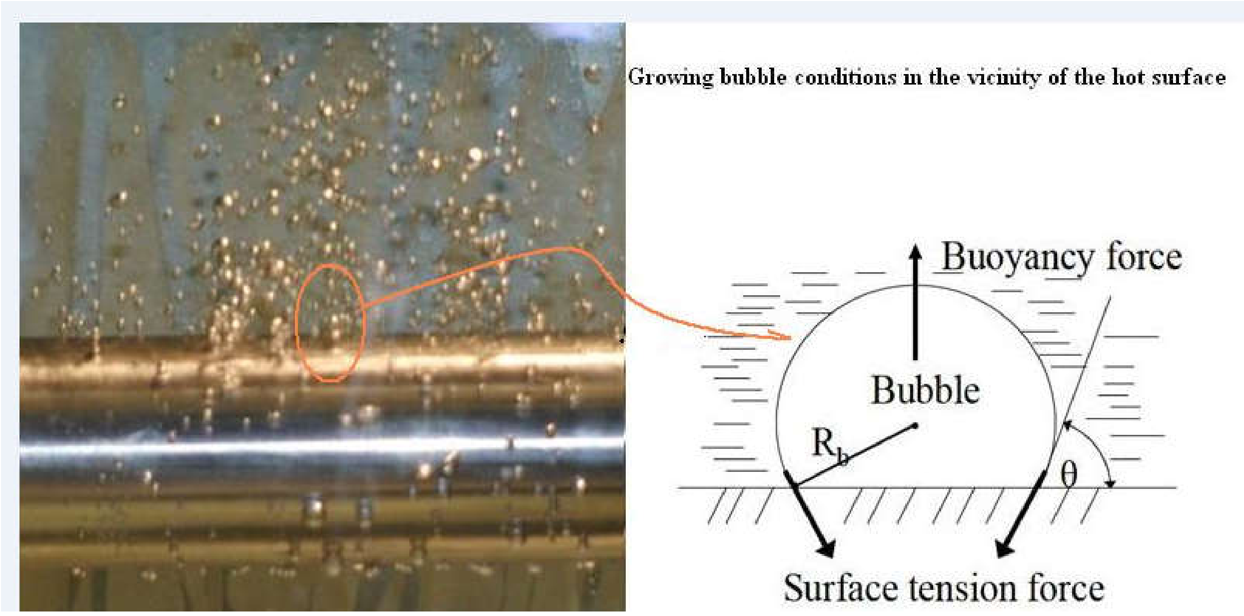
GRAPHICAL ABSTRACT



1- INTRODUCTION

Boiling is one of the applications of heat transfer and has several sub-processes that are the subject of many studies that have led to many experimental results. In most energy conversion systems and heat exchangers, boiling heat transfer is used for high efficiency. These sub-processes are in the form of bubble dynamics [1]. Boiling is considered as convective heat transfer method with fluid phase change. This phase change happens at constant temperature and is transferred a large amount of heat in this way [2]. In boiling, a heat transfer rate is very rapid, so in the design of a compact heat exchanger, this phenomenon is used for heating or cooling [3]. When a liquid is in contact with a surface that has a temperature (T_s) above the saturation temperature of the liquid (T_{sat}), liquid and solid level boiling will occur and with increasing temperature difference between the surface and liquid, will increase the heat transfer coefficient ($q_{\cdot}$) [4]. Appropriate form of Newton's law of cooling is as follows:

$$q_{\cdot} = h\,(T_s - T_{sat}) = h\Delta T_e \qquad (1)$$

Where ΔT_e is called excess temperature and *h* is the convective heat transfer coefficient. This process involves the formation of vapor bubbles on the surface that has grown and disconnected from it. Therefore, in pool boiling, the fluid is stagnant and its movement occurs near the solid surface by free convection and turbulence caused by the bubble growth and separation. Maximum heat intensity q_{max} is usually called critical temperature.

At this point, a high vapor is formed and sometimes prevents moistening of hot surface and the liquid [5]. In nuclear boiling with extra heat, we can obtain a little high-temperature coefficient and convection heat transfer rate, so is desirable the functioning of most engineering devices in these conditions [6]. The boiling process is used as an application process in many industrial processes such as chemicals, refrigeration, power generation, air conditioning, nuclear reactor coolers, and many other industrial processes to transfer heavy heat loads [7-9]. Construction, design, and optimization of these industrial units, especially industrial boilers, require scientific prediction of the boiling heat transfer coefficient between the heating surface and the boiling liquid. Researchers have tried to improve and advance this issue by presenting different models. This phenomenon covers different liquids and mixtures, so it is not possible to use only one experimental model.

When bubbles are produced on the surface of heat transfer at the boiling of two-component solutions, equilibrium thermodynamic of vapor and liquid phases allows the simultaneous presence of liquid and vapor phases in equilibrium form, despite the difference in concentration of volatile and nonvolatile components [10-12]. The growth of bubbles complexly depends on the additional temperature, surface material, thermodynamic properties of the fluid, and surface tension. On the other hand, the formation of steam and boiling on the surface is also effective on heat transfer, the formation of steam and boiling on the surface is also effective on heat transfer. For the first time, using a laboratory device, it detected different states of pool boiling. The intensity of the heat flow from a horizontal steel cylinder to a two-component mixture of water and ethanol is determined by measuring the (I) current intensity and the (V) potential drop. The temperature of the cylinder can also be obtained by knowing how the electrical resistance changes with temperature.

In this study, the growth of bubbles in the water-ethanol solution has been examined and evaluated in different heat flux concentrations and while examining them with different dynamic models using genetic algorithms, a new model is presented and compared with other models.

2. Laboratory method

All chemicals used in this study are from Merck Co., Germany.

- Preparing the testing machine

The pool boiling device is of the most common and the most suitable devices for measuring the boiling heat transfer coefficient, which is called Garanflow measuring device. The device has a rod heater section is a cylinder for and of stainless steel 316 (details in Table 1). The cylindrical heater has a length and diameter of 250 and 25 mm, respectively, and in cross-section of the cylinder, there are 4 holes for the placement of thermocouple sensors using silicon paste, the depth of these holes is 50 mm. There is an auto trans (power source section has a voltage between zero and 300 volts) to apply heat flux in the range of 30 to 240 V and a boiling vessel made of tempered glass (objective is to view and record boiling images) with high strength of 550 degrees with dimensions (151×244×230 mm^3). The experiment is done for distilled water and at a heat flux from 1000 to 60000 $W.m^{-2}$. During pool boiling, in each heat flux, videos and photos are taken by an imaging system camera with 1200 frames and after analyzing, the bubble growth has been recorded. The instrumentation system section includes a thermocouple (type K-type in the range of 0 to 700 ^{o}C), temperature display, and an ammeter (of multimeter type with an accuracy of 0.1 A). After each stage of the experiment, data related to that step are recorded and processed. Figure 1 shows the array of these devices.

Table 1. Profile of horizontal cylinder made of stainless steel

Metal Type	Specifications	Thermal conductivity	EC
Stainless steel	Low thermal conductivity, resistance to corrosion	15 $W·m^{-1}·K^{-1}$	$0.75 \frac{m}{\Omega.mm^2}$

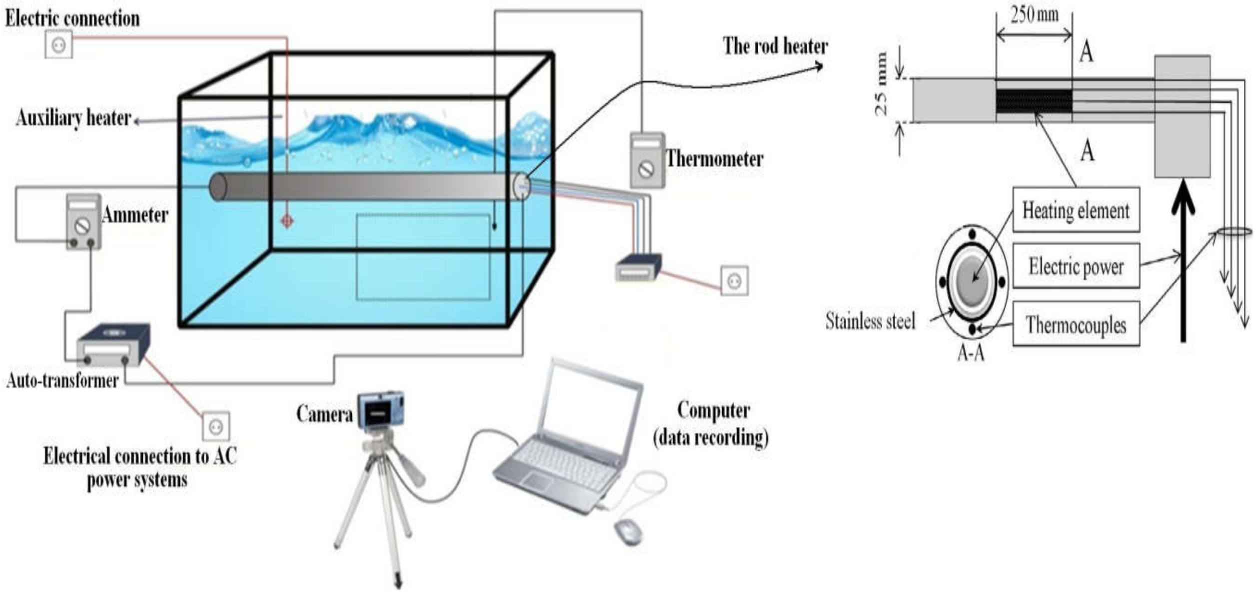


Fig 1: Overview of boiling pool device.

At first, we fill the experiment container with a known volume of solution with concentration and composition intended, and the volume used in this experiment is 7000 ml. Four thermocouple sensors are placed on the cylindrical body. Then we turn on preheat heater so that the solution reaches saturation temperature. To remove air bubbles in the liquid phase, the solution is kept for some time at saturation temperature. After the system reaches stabilized state, by voltage changes, test data is recorded.

3. Results and Discussion

During the natural convective heat transfer, wall temperature increases with heat flux increase until the first bubbles (core) are made in small holes at the warm surface where boiling is in the range of 5 to 30 °C and bubble separation starts at the temperature 87 °C, and boiling process starts in the central heater at 100 °C. For the stability of the system, it is kept in this condition for 10 min and then the central heater is in service. In this study, first, bubble formation stages were conducted for pure water, and after preparing water-ethanol solution in concentrations 3%, 7%, and 12% of volume percentage, the experiments carried out for pure water is repeated. Due to the increase in heat flux, it is a calculated physical and thermodynamic property of the water-ethanol solution. Table 2 shows the physical parameters of the solution at different temperatures for a concentration of 3% volume.

Control of saturation temperature and its concentration of water-ethanol solution compared to pure water are more important. After completion of images, tests and images taken in every heat flux, we select 20 bubbles, and the diameter of each bubble is measured by the EDIUS software package and then the average diameter of each heat flux is considered. Figure 2 shows images of bubbles in various concentrations and heat fluxes.

With the increasing heat flux of water-ethanol solution on stainless steel cylindrical rod, a diameter of bubbles increases that is seen in Figure 3, and according to Figure 2, by an increase in the flux in all three concentrations, coherence and mixing of solution increase.

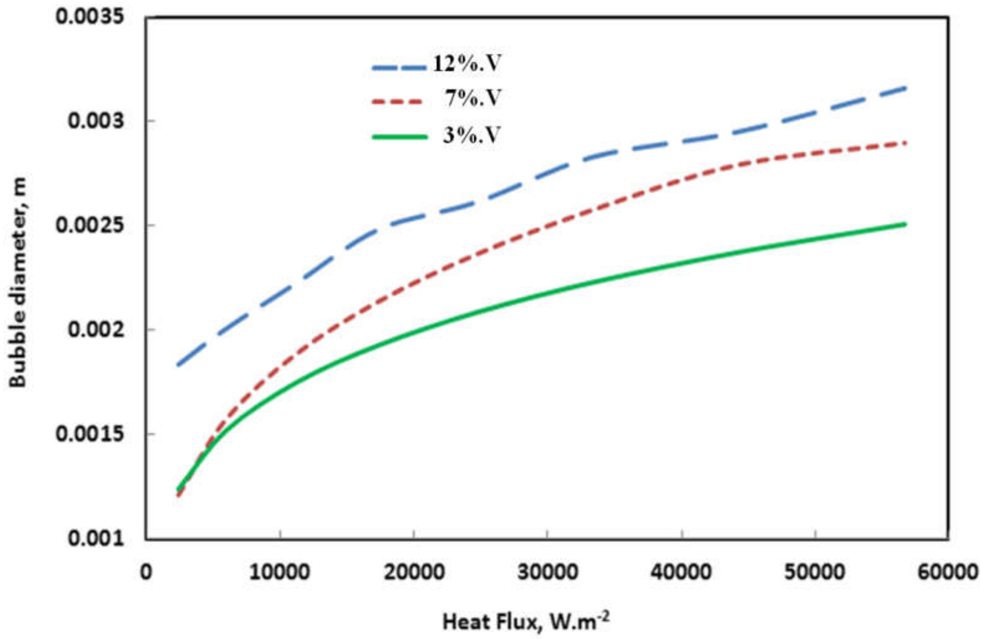


Figure 2. Investigation of Bubbles growth stages in different heat flux for water-ethanol concentration of 3%, 7% and 12% by *volume*.

Table 2: Physical and Thermodynamic properties of water-ethanol solution at different temperatures for the concentration of 3% volume

$(^oC)\theta$	$_l/kg.m^{-3}\rho$	$_g/kg.m^{-3}\rho$	$/N.m^{-1}\sigma$	$\mu_l/Pa.S$	$\mu_g/Pa.S$	$H_{fg}/J.kg^{-1}$	$K_l/W.m^{-1}.C^{-1}$
97.85	957.917	0.628	0.048	3.058×10^{-4}	1.993×10^{-5}	190.843×10^{4}	0.625
98.59	953.917	0.626	0.047	2.959×10^{-4}	2.081×10^{-5}	188.843×10^{4}	0.624
99.22	950.917	0.624	0.045	2.877×10^{-4}	2.193×10^{-5}	187.193×10^{4}	0.624
99.72	948.498	0.623	0.044	2.803×10^{-4}	2.286×10^{-5}	185.803×10^{4}	0.623
100.17	945.917	0.621	0.043	2.724×10^{-4}	2.363×10^{-5}	184.393×10^{4}	0.623
100.59	943.689	0.620	0.042	2.664×10^{-4}	2.453×10^{-5}	183.043×10^{4}	0.622
101.01	940.999	0.619	0.041	2.589×10^{-4}	2.544×10^{-5}	181.643×10^{4}	0.622
101.41	938.919	0.618	0.040	2.509×10^{-4}	2.656×10^{-5}	179.843×10^{4}	0.621

After testing and examining the diameter of the bubbles at different heat flux and concentrations, water-ethanol solution, the experimental results are compared with six models of Firitz, Cole, Stephen, Jamialahmadi, Alavi Fazel, and Hamzehkhani [13-18]. Table 3, is given relationships to calculate the diameter of the bubble in these models.

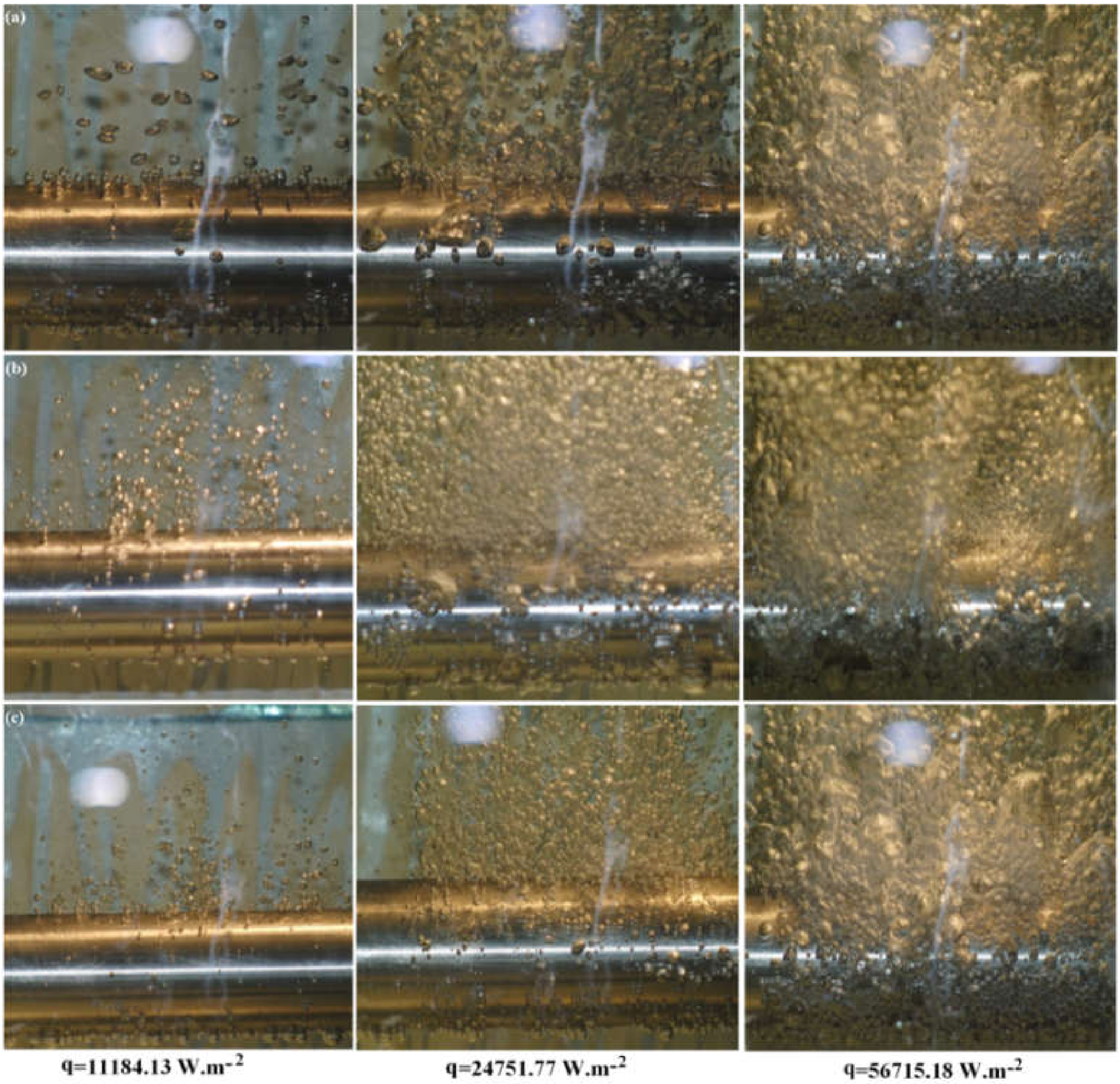


Fig 3. The bubble diameter is measured for water-ethanol solution in terms of different heat fluxes.

After testing at various concentrations and evaluating levels of bubble separation diameter by relations and according to experimental results, the absolute average error for a water-ethanol solution was estimated according to Eq. (2) [19].

$$A.A.E\% = \left| \frac{D_{cal}}{D_{\exp}} - 1 \right| \times 100 \quad (2)$$

In Tables 4 to 6, the absolute average error for a water-ethanol solution is recorded, and according to error table, it can be said that for the water-ethanol solution at a concentration of three, seven, and twelve percent of the volume of the model by Hamzehkhani has the best coordination with the experimental data. Moreover, Jamialahmadi's model has been introduced for electrolyte solutions. The reason for this is a high error of the equation with the experimental data.

Table 3. Dynamic models for calculating the separation diameter of the bubbles in the boiling process.

Presenter	Model
Firitz[13]	$D_b = 0.0146\,\beta\left(\frac{2\sigma}{g(\rho l - \rho \upsilon)}\right)^{0.5}$
Cole[14]	$D_b = 0.04\,Ja\left[\frac{\sigma}{g(\rho l - \rho \upsilon)}\right]^{0.5}$
Stephan[15]	$D_b = 0.25\left[1 + \left(\frac{Ja}{\Pr}\right)^2 \frac{100000}{Ar}\right]^{0.5} \sqrt{\frac{2\sigma}{g(\rho_l - \rho_g)}}$
Jamialahmadi[16]	$D_b = \frac{1}{96.75 + \frac{0.01425\,(\frac{q}{A})}{\ln(\frac{q}{A})}}$
Alavi Fazel[17]	$D_b = mN_{Ca}^{\,n}\left[\frac{\sigma}{g(\rho l - \rho \upsilon)}\right]^{0.5}$
Hamzekhani[18]	$Bond_{number}\ (Bo = \Delta\rho g d^2 / \sigma)$ $Bo = Ca^a Ar^b Ja^c$ $a = 0.18089$ $b = 0.2052$ $c = 0.55811$

Table 4. Percentage error of the relationships and laboratory test results of water-ethanol bubble diameter in 3% by volume of the different heat fluxes.

Hamzehkhani Model	Alavi Fazel model	Jamialahmadi Model	Stephen Model	Cole Model	Firitz Model	Flux (W.m^{-2})
20.7	65.1	439.2	28.5	56.1	14.9	2352.9
14.9	56.5	367.9	22.6	48.8	15.0	5928.2
14.5	51.7	294.6	20.2	45.1	15.2	11184.1
14.9	49.9	229.9	20.8	44.2	15.1	17356.8
14.6	46.4	190.5	18.8	42.1	19.3	24751.8
13.3	45.3	148.1	19.5	42.0	25.4	33369.1
13.1	42.4	117.6	17.5	40.0	28.5	44278.2
14.9	41.4	85.5	18.6	40.5	33.2	56715.2
15.1	49.8	234.2	20.8	39.5	22.7	**A.A.E%**

The results show, that all concentrations of the water-ethanol solution have increased with increasing heat flux heat transfer coefficient. As it is known, there is no special order between the studied concentrations on the graphs, which can be expressed by reducing the difference between the molar concentration of liquid phase and vapor of the volatile component, the heat transfer coefficient increases, which depends on the selective evaporation of the volatile component. The results show that at higher molar concentrations, the heat transfer coefficient increases. A similar case has been observed for boiling water-mono ethylene glycol and citric acid at 1atm on a cylindrical heater [20, 21].

As the data show, the values of the heat transfer coefficient obtained from the relations are different. Due to the fact that the boiling pad covers a wide range of liquids and mixtures, it is impossible to predict the heat transfer coefficient of all these mixtures and liquids by an experimental model so far, because the solutions are expressed based on the assumptions and physical properties. As seen in the tables, each of the existing relationships also has a different deviation of laboratory data whose error is different for different concentrations. In all relationships, such as laboratory data, the heat transfer coefficient increases by increasing the thermal flux.

Table 5. Percentage error of the relationships and laboratory test results of water-ethanol bubble diameter in 3% by volume of the different heat fluxes.

Hamzehkhani Model	**Alavi Fazel model**	**Jamialahmadi Model**	**Stephen Model**	**Cole Model**	**Firitz Model**	**Flux ($W.m^{-2}$)**
24.8	46.8	717.9	95.6	33.9	23.9	2352.9
19.1	44.4	496.6	58.4	19.1	14.7	5928.2
15.9	42.7	365.6	37.1	15.2	20.5	11184.1
14.0	41.5	283.1	24.1	14.1	29.9	17356.8
12.6	40.5	221.1	14.5	20.5	36.6	24751.8
11.6	39.6	172.5	17.1	25.6	41.8	33369.1
10.7	38.8	129.9	42. 5	30.2	46.3	44278.2
10.3	35.9	102.3	17.7	31.6	48.3	56715.2
14.9	41.2	311.1	38.4	23.8	32.7	**A.A.E%**

Table 6. Percentage error of the relationships and laboratory test results of water-ethanol bubble diameter in 12% by volume of the different heat fluxes.

Hamzehkhani Model	**Alavi Fazel model**	**Jamialahmadi Model**	**Stephen Model**	**Cole Model**	**Firitz Model**	**Flux ($W.m^{-2}$)**
24.2	48.0	699.5	172.6	79.9	9.1	2352.9
19.7	42.3	518.2	122.5	46.2	11.1	5928.2
17.1	38.1	402.2	93.6	27.2	22.8	11184.1
15.5	35.1	324.8	75.8	15.5	30.0	17356.8
14.3	32.4	264.2	62.7	16.9	35.3	24751.8
13.4	30.1	215.0	52.3	16.0	39.4	33369.1
12.6	27.9	170.5	43.2	15.8	43.1	44278.2
11.9	25.9	133.7	35.6	10.8	46.1	56715.2
16.1	34.9	341.0	82.3	28.5	34.9	**A.A.E%**

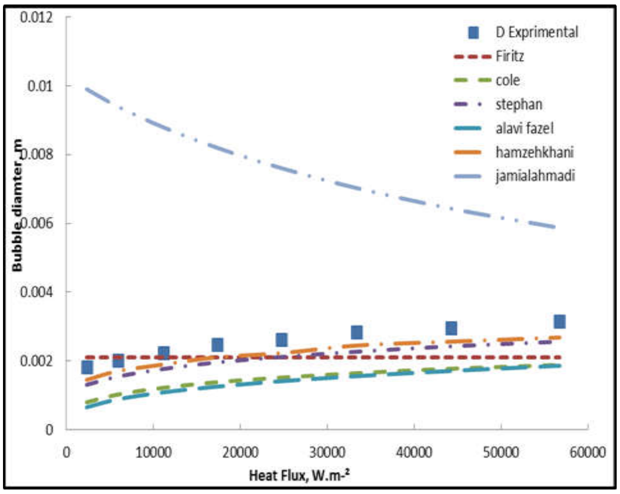


Fig 4. Comparison of experimental results of water-ethanol solution with predicted results of the relationships at a concentration of 3% by volume.

In all relationships, such as laboratory data, the heat transfer coefficient increases by increasing the thermal flux. Figures 4 to 6 show experimental values in terms of the heat flux at different concentrations of water-ethanol solution. As can be seen in Figures 4-6, increasing heat flux, increases the heat transfer coefficient for all concentrations and models under study. At all concentrations at temperatures below 20 °C, they show different behaviors.

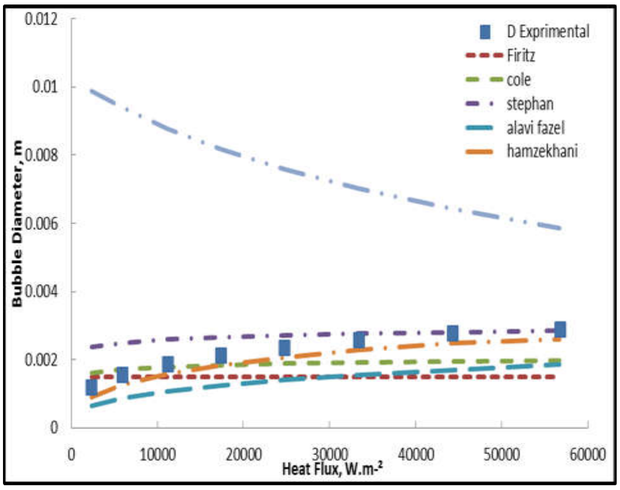


Fig 5. Comparison of experimental results of water-ethanol solution with predicted results of the relationships at a concentration of 7% by volume.

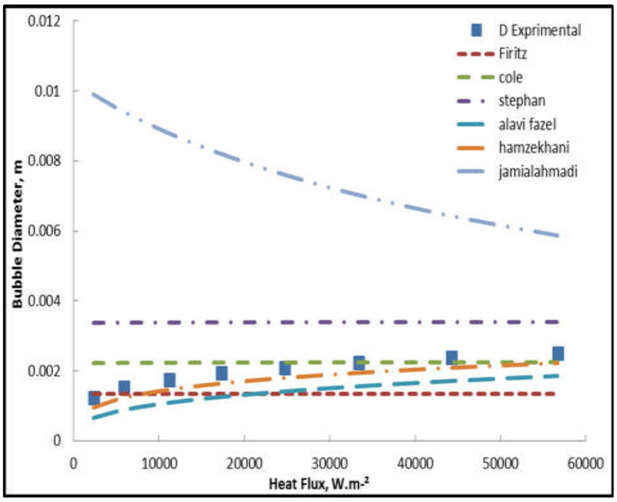


Fig 6. Comparison of experimental results of water-ethanol solution with predicted results of the relationships at a concentration of 12% by volume.

At the azeotropic point, all relations except Jamialahmadi, show the same error with respect to the experimental data, because at the azeotropic point the value of the heat transfer coefficient is the same as the value of the ideal heat transfer coefficient.

4. New proposed model

The basis for estimating and calculating the experimental model is experimental data. In this study, the database is above 150 laboratory data in the desired conditions. Using the technique of genetic algorithm based on the database, the effectiveness of each parameter is evaluated as power, which is an effective measure in dimensionlessness of effective parameters in estimating the heat transfer coefficient in two-stream solutions.

Given the bubble diameter obtained, the error rate calculated is very high. Thus, using a genetic algorithm, we present a new model that overlaps well with the experimental data. Using the genetic algorithm, the optimum model is as follows:

$$Bo = (ja^{g_o} + g_1) \times (Ca^{g_2} + g_3) \quad (3)$$

Parameters g_0 to g_3 are calculated in such a way that heat transfer coefficient by a genetic algorithm that error of boiling in the pure liquid is minimized, and its numerical value is as follows:

Table 7. The g_0 to g_3 parameters of the new model.

g_0	g_1	g_2	g_3
-0.75	18.69	0.26	-0.02

After substituting the values provided in the relation provided, the improvement of the correlation coefficient of the model with R^2=0.96 is obtained in Fig.7.

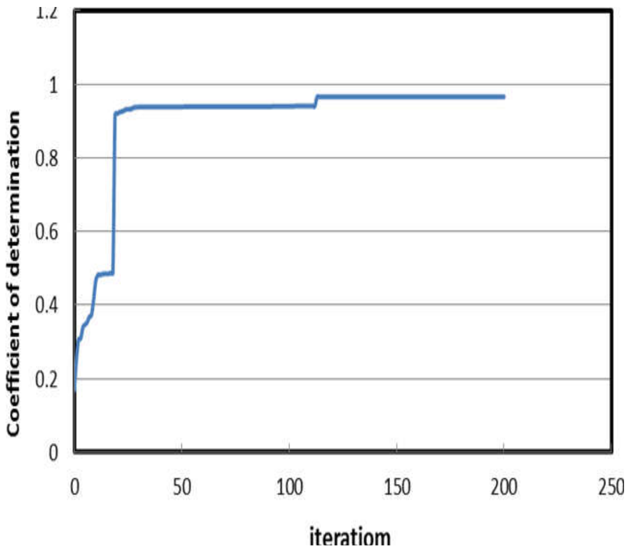


Figure 7. Correlation of the new model.

Bo comparison obtained from experimental data shows good agreement with the new model as shown in Figure 8.

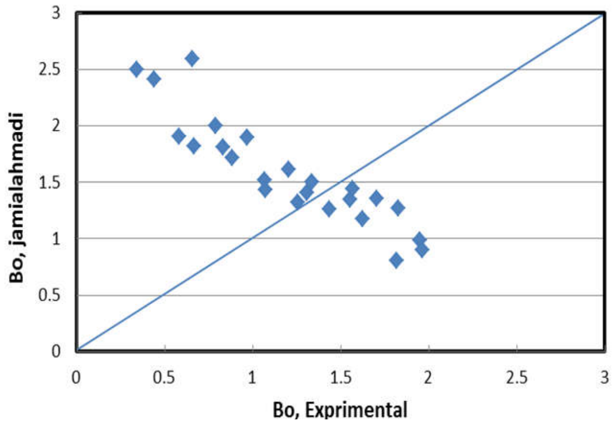


Fig 8. Comparison of laboratory Bo with new model Bo.

Figure 9 shows a comparison of Bo experimental two-component water-ethanol solution data with the new model and other models.

Moreover, in Figure 10 can be seen optimizing (converge to the optimum genes) of the equation by genetic algorithm.

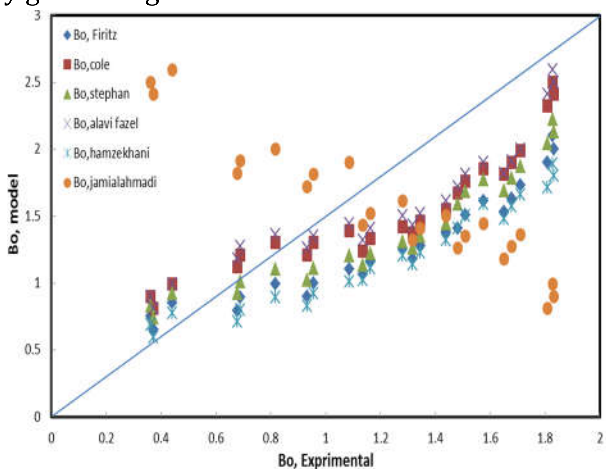


Fig 9. Comparison of Bo of the new model with other dynamic models.

Table 9. Comparing of the average error of existing models with the new model.

Model	New model	Hamzekhani	Alavi Fazel	Stephan	Firitz	Cole	Jamialahmadi
A.A.E%	11.76	14.23	41.50	15.83	17.42	37.62	88.50

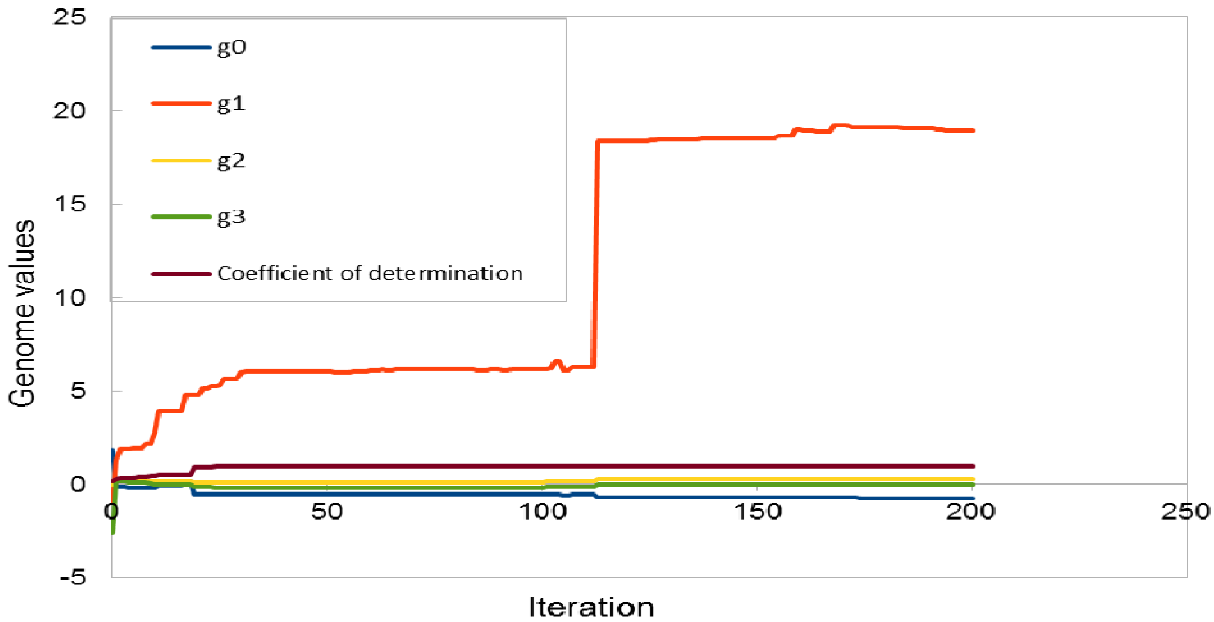


Fig 10. The quality of convergence of genes in genetic algorithms for the optimal solution.

Nomenclature

Pr	Prandtl number
Bo	Bond number
Ca	Capillary number
Ja	Jacob number
Ar	Archimedes number
A	Area (m^2)
k	Thermal conductivity ($Wm^{-1}K^{-1}$)
d	Diameter (m)
q	Heat flux (Wm^{-2})
h_{fg}	Latent heat of vaporization (Jkg^{-1})
F_p	Excess pressure force (N)
F_D	Liquid drag force (N)
F_σ	Surface tension force (N)
F_i	Inertia forces (N)
F_b	Buoyancy forces (N)
g	Gravity ($m\,s^{-2}$)
R	Bubble radius (m)
t	Time (s)
V	Velocity (ms^{-1}) or Voltage (V)
I	Electrical current (A)
c_p	Specific heat at constant pressure ($J\,kg^{-1}\,K^{-1}$)
T	Temperature (K)

Greek symbols

ρ	Density ($kg\,m^{-3}$)
α	Thermal diffusivity ($m^2\,s^{-1}$)
σ	Surface tension ($N\,m^{-1}$)
θ	Contact angle, degree
β	Contact angle, degree
Δ	Difference
μ	Dynamic viscosity (Pa s)

Subscripts

l	Liquid
b	Bubble
v	Vapor
s	Saturation

5. Conclusion

In this study, concentration and heat flux is evaluated on the process of bubble growth in a two-component water-ethanol solution. The bubble growth process is studied by different dynamic models. Due to the change in the concentration of the solution, the overlapping of relationships is different; whose reason is surface tension changes with concentration. With increasing heat flux in water-ethanol solution, heat transfer coefficient increases Changes in heat transfer coefficient as a function of concentration in boiling water and ethanol solution do not follow a specific trend.

Most models have diverged with increasing concentration. Among the models, the model by Hamzehkhani is close to experimental data obtained and has the less average error. All models show the least error at a concentration of

7% by volume. In this study, using genetic algorithms, a new model is developed where the dimensionless number of Bo of the new model is consistent with Bo parameter with the experimental data.

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