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SCIENTIFIC PAPER

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SUBCOOLED FLOW BOILING HEAT TRANSFER OF ETHANOL AQUEOUS SOLUTIONS IN VERTICAL ANNULUS SPACE

The subcooled flow boiling heat-transfer characteristics of water and ethanol solutions in a vertical annulus have been investigated up to a heat flux of 132 kW/m^2. The variations in the effects of heat flux and fluid velocity, and concentration of ethanol on the observed heat-transfer coefficients over a range of ethanol concentrations implied an enhanced contribution of nucleate boiling heat transfer in flow boiling, where both forced convection and nucleate boiling heat transfer occurred. Increasing the ethanol concentration led to a significant deterioration in the observed heat-transfer coefficient because of a mixture effect that resulted in a local rise in the saturation temperature of ethanol/water solution at the vapor-liquid interface. The reduction in the heat-transfer coefficient with increasing ethanol concentration is also attributed to changes in the fluid properties (for example, viscosity and heat capacity) of tested solutions with different ethanol content. The experimental data were compared with some well-established existing correlations. Results of comparisons indicate existing correlations are unable to obtain the acceptable values. Therefore, a modified correlation based on Gnielinski correlation has been proposed that predicts the heat transfer coefficient for ethanol/water solution with uncertainty about 8% that is lower in comparison to other well-known existing correlations.

Keywords: flow boiling, heat transfer, ethanol, water, Gnielinski correlation, bubble generation.

Nowadays, flow boiling heat transfer has received more attention due to high, superior heat transfer rates and high potential applications in many industrial and non-industrial fields. For instance, the most common application of flow boiling is known in automobile car radiators and cooling systems and also in chemical processes, where many reactions occur in the gas phase. As an example of conducted studies, Zeitoun [1] performed a subcooled boiling test in a high heat flux condition; however, the test section for the boiling heat transfer was short in length and local bubble parameters were not provided. Early visualization experiments carried out by Hewitt *et al.* [2] showed that the bubbles affect the nucleation activity. The presence of moving bubbles leads to the wave-induced nucleation phenomenon observed by Barbosa *et al.* [3] who conducted experiments in a vertical annulus in which heat was applied to the inner surface of the tube. A dominance of nucleate boiling was observed at low qualities. At high qualities, nucleate boiling was partly or totally suppressed and forced convection became the dominant mechanism. Thus, one may conclude that in internal flow boiling, the heat transfer coefficient is a combination of two mechanisms, nucleate boiling and forced convection. The heat transfer coefficient might remain constant, decrease or increase depending on the contribution of these two mechanisms during forced saturation boiling. Lee *et al.* [4] and Kim *et al.* [5] performed subcooled boiling experiments and analysed the obtained results with CFD software. They truly distinguished the forced convection heat transfer mechanism from the nucleate boiling phenomenon. Subcooled flow boil-

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ing of heptane on both internally heated rod and resistance-heated coiled wire in an annular duct was examined by Müller-Steinhagen *et al.* [6]. Their results indicated that the boiling heat transfer coefficient increased with increasing heat flux but decreased with increasing system pressure and liquid subcooling, while independent of the mass velocity in the nucleate boiling regime. Hasan *et al.* [7] measured the subcooled nucleate boiling of R-113 flow in a vertical annular channel and showed that the boiling heat transfer coefficient was lower for higher pressure and subcooling. Moreover, the heat transfer coefficient increased with the mass velocity of the refrigerant flow. In all modern textbooks on heat transfer, the Gnielinski equation [8] for heat transfer in pipes is presented as the appropriate means for calculating Nusselt numbers for Reynolds numbers in the laminar to turbulent, transition and fully turbulent regimes. In the foregoing, a careful examination of the Gnielinski model has shown that it is inadequate in the test Reynolds number range particularly for ethanol and water mixtures. The number of investigations has increased rapidly in recent years, but some aspects of boiling still remain unclear. Also, due to the superior heat transfer coefficient in flow boiling regimes, most of researchers pay more attention to this particular mechanism of heat transfer. On the other hand, design of modern heat transfer equipment needs a better knowledge of the heat transfer. The topic of flow boiling predictions has been scrutinized for more than fifty years, as the interest in that kind of heat transfer started in the early 1960s. In the present, it is an intention to express the major approaches to modeling of flow boiling heat transfer in conventional and annular spaces and there is no intention to express deeply literature on flow boiling history. For an extensive literature survey of flow boiling in conventional-size channels the reader is referred to Kew *et al.* [9,10] or for small-diameter channels to Kandlikar [11,12], Chen [13] and Bergles *et al.* [14]. In general, all existing approaches are either the empirical fits to the experimental data, or form an attempt to combine two major influences to heat transfer, namely, the convective flow boiling without bubble generation and nucleate boiling. In general, that can be done in a linear or nonlinear manner. Alternatively, there is a group of modern approaches based on models that start from modeling a specific flow structure and in such a way postulate more accurate flow boiling models, usually pertinent to slug and annular flows. One of the first major works in this area was that of Dengler and Addoms [15] who in 1952 obtained local boiling coefficients for water in upward vertical flow through a 1-inch tube. In 1959, Celata *et al.* [16] reported data for binary mixtures in forced convection zone. They compared their data with other correlations such as Dengler, Addoms, Guerrieri and Talty [17], but in each case, found considerable scatter. They then proposed their own correlation. Chang *et al.* [18] presented a survey of performance and heat transfer characteristics of hydrocarbon refrigerants (R290, R600, R600a, R290/R600a and R290/R600) in a heat pump system. Sivagnanam *et al.* [19] studied subcooled flow boiling of binary mixtures on a long platinum wire and proposed correlations for the partial boiling and fully developed boiling. Sub-cooled flow boiling of water at high heat flux was experimentally investigated by Del Valle and Kenning [20]. They found that the heat transfer coefficient increased with the sub-cooling and heated wall thickness.

In this study, regarding the importance of flow boiling particularly in industry fields, flow boiling heat transfer of water/ethanol has been experimentally studied. Also, interactions of bubbles as an important subphenomenon of boiling are visually investigated. Finally, regarding the unacceptable results of Gnielinski for ethanol/water solution, a new modified correlation is proposed with lower deviation relative to experimental data.

EXPERIMENTAL

Experimental setup

Figure 1 schematically depicts a summary of the experimental apparatus and instruments that have been employed in the study. This device is composed of a vertical cylindrical thermal glass vessel with a diameter of 55 mm and height of 400 mm, and, in the middle of vessel, a stainless steel cylinder with diameter of 20 mm and height of 300 mm. Furthermore, for the vessel, an annulus space has been made which allows the fluids to go around the cylinder. At the center of stainless steel cylinder, a 1300 W bolt heater has been installed which provides the needed heat for the boiling phenomenon. To measure the surface temperature, four K-type thermocouples have been installed around the circumference of the cylinder as close as possible to the surface. The arithmetic average of measured values of four thermocouples was considered to determine the heating surface temperature at each heat flux. To measure the inlet and outlet temperature of fluid into the annulus, two thermocouples have been installed among the inlet and outlet lines that arithmetic average of inlet and outlet temperature of annulus was considered as a bulk temperature of fluid flow inside the annulus. To calculate the real surface temperature by correcting the minor temperature drop due to the small

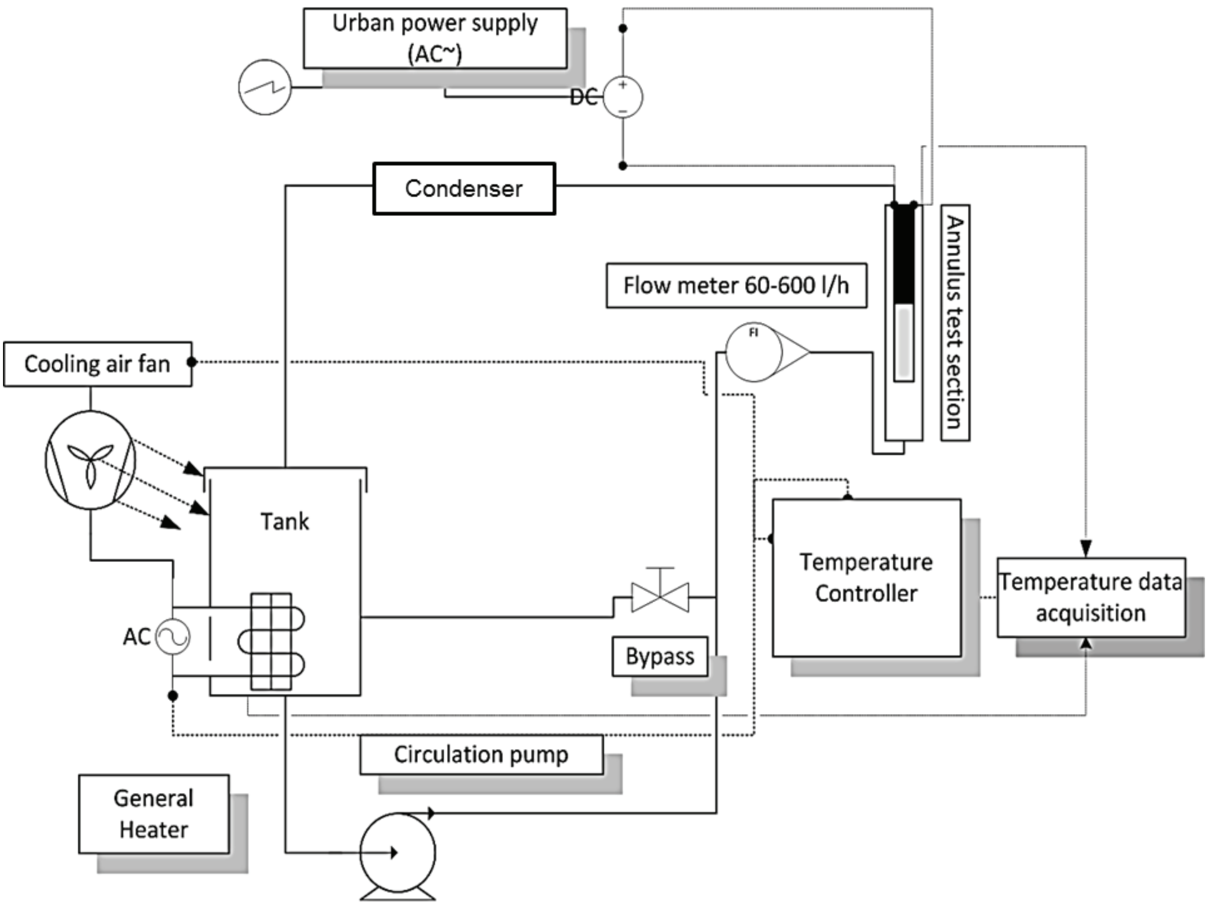

Figure 1. A scheme of the experimental apparatus.

distance between surface and thermocouple location, the Fourier's conduction equation [21] is used as follows:

$$T_s - T_b = (T_{th} - T_b) - (s / k)(q / A) \tag{1}$$

In this equation, s is the distance between the thermocouple location and heat transfer surface and k is the thermal conductivity of the heater material. The value of s/k is determined for each thermocouple by calibration of the test heater. The average temperature difference was the arithmetic average of the four thermocouple locations. The boiling heat transfer coefficient, α, is calculated by the following equation:

$$\alpha = \frac{\dot{m}c\left(T_{\text{outlet}} - T_{\text{inlet}}\right)}{\left(T_s - T_b\right)_{\text{ave}}} \tag{2}$$

For each experiment, a picture of boiling phenomena was taken using an ultra-high speed camera. Additionally, to remove the thermal contact resistant silicone paste was injected into the thermocouple wells. The temperature of the liquid inside the tank was constantly monitored and controlled to any predetermined set point by a thermal regulator and PID controller. To prevent temperature overshooting occurrence owing to the influence of heat of bolt heater given to the fluid, a cooling air fan was installed at the proper position near the reservoir tank. When the temperature of the tank fluid turns higher than controller set point value, the fan would start working to reduce the temperature of tank, turning the temperature back to the set point value. This way, the temperature of the fluid flow is kept approximately constant. To ensure that the outlet line flow had no vapor fraction, a mini helical condenser was installed in the line of outlet which normally reduces the temperature of the outlet below 303 K. Noticeably, cold water is used in this mini condenser (273 to 278 K). More details about characteristic of the heating section have been depicted in Figure 2. To eliminate the effect of surface roughness on nucleate boiling and bubble formation, the cylinder was polished several times using an emery paper with roughness of 400 μm. Also, a digital profile meter was employed to record the surface roughness of the heating section (Figure 3).

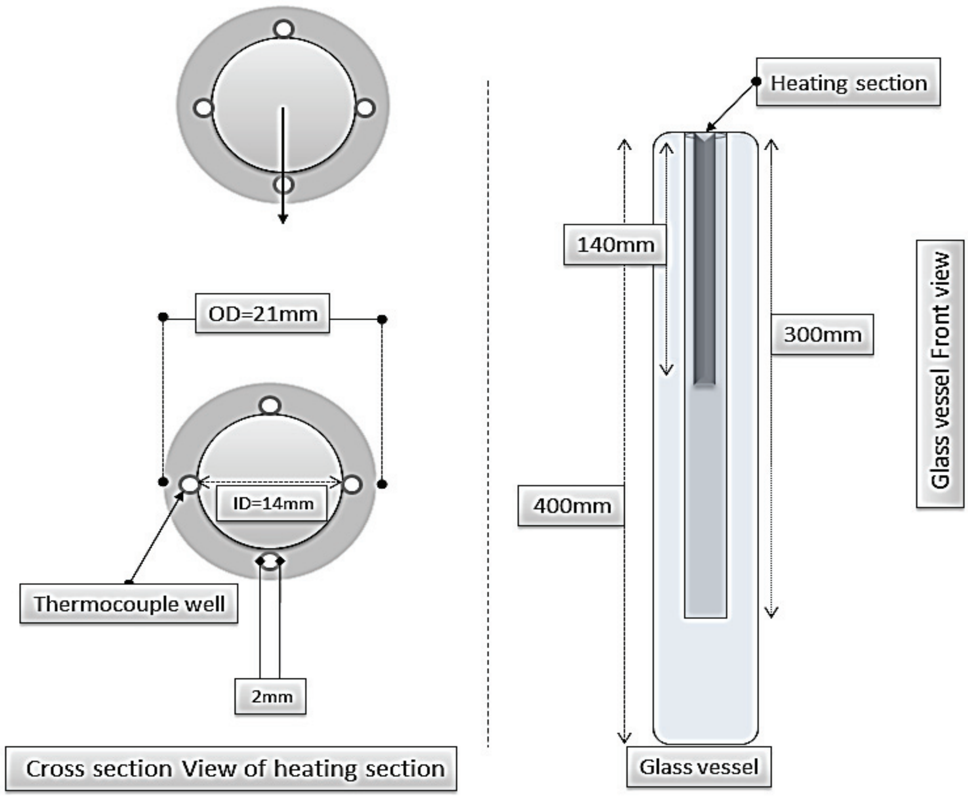

Figure 2. Details of heating section and vertical glass vessel.

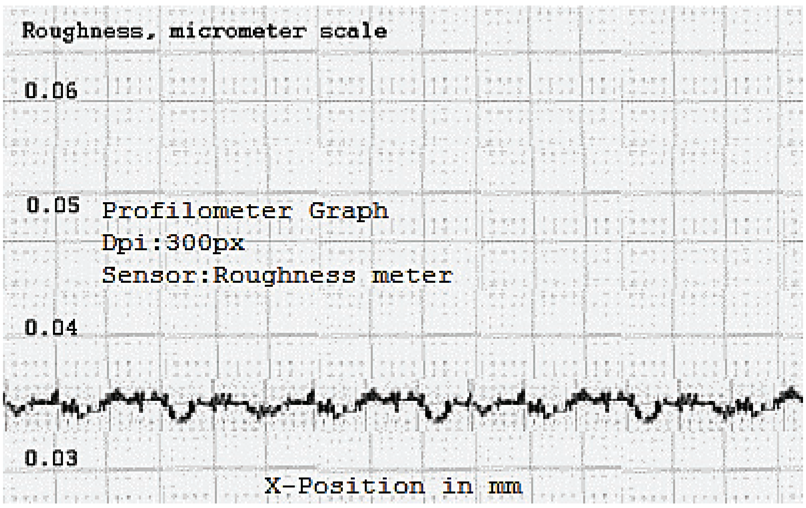

Figure 3. Surface roughness of vertical stainless steel cylinder.

As seen, the surface roughness was closely 0.03-0.04 µm, which could be considered as a standard smooth surface roughness.

Tested fluid properties

Aqueous solutions of ethanol have been selected as the test fluid. In brief, in terms of applicability of this research, it could be said that alcoholic beverages vary considerably in ethanol content and in foodstuffs they are produced from. Most alcoholic beverages can be broadly classified as fermented beverages, beverages made by the action of yeast on sugary foodstuffs, or distilled beverages (whose preparation involves concentrating the ethanol in fermented beverages by distillation). The ethanol content of a beverage is usually measured in terms of the volume fraction of ethanol in the beverage, expressed either as a percentage or in alcoholic proof units. Due to the special flow processes of alcoholic beverages, particularly closely to the saturation temperature for being ready for commercial uses, it is necessary to have enough knowledge about the circumstances of heat transfer and heat transfer coefficients of ethanol watery solutions to design the proper economic heating tools. Also, because of drastic changes of physical properties of fluids during the flow boiling process specially physical properties of water/ethanol solutions, which could have a significant influence on its heat transfer coefficient, thorough investigations were performed at weight fractions of 10-50% of ethanol in pure water. Additionally, the status of generated bubbles during the flow boiling phenomenon was visually investigated, as it was necessary for understanding the heat transfer mechanism of the fluid. Regarding some earlier literatures [5-18], it was found that a small portion of the heat transfer degradation was due to the effect of the nonlinear thermal physical properties, and the non-ideal mixing rule for estimating some fluid properties was more favorable than linear and ideal mixing rules. Therefore, all mixing rules for thermo physical properties of mixtures in present research are estimated using the following equations:

$$C_{PM} = x_1 C_{P1} + (1 - x_2) C_{P2} \tag{3}$$

$$K_{lm} = x_1 K_{l1} + (1 - x_1) K_{l2} - 0.72 x_1 (1 - x_1) \left| K_{l2} - K_{l1} \right| \tag{4}$$

$$\rho_{lm/vm} = x_1 \rho_{l1/v1} + (1 - x_1) \rho_{l2/v2} \tag{5}$$

$$\ln(\mu_{lm}) = x1 \ln(\mu_{l1}) + (1 - x_1) \ln(\mu_{l2}) \tag{6}$$

$$\mu_{vm} = \frac{y_1 \mu_{v1}}{y_1 + y_2 P_{12}} + \frac{y_2 \mu_{v2}}{y_2 + y_1 P_{21}} \tag{7}$$

where P_{ij} is defined as:

$$P_{ij} = \frac{\left[1 + \left(\frac{\mu_{vi}}{\mu_{vj}} \right)^{0.5} \left(m_i m_j \right)^{0.25} \right]^2}{\left(8 \left[1 + \frac{m_i}{m_j} \right] \right)^{0.5}} \tag{8}$$

It is notable that to find the physical properties of pure substances, famous well-known handbooks [31,32] were used. Similarly to previous papers and works, film temperature (arithmetic average temperatures of inlet and outlet of annulus) was considered as the temperature used to calculate the physical properties, particularly for heat capacity. Afterwards, thermo-physical properties were estimated for mixtures through Eqs. (3)-(8).

Experimental uncertainty

The combined standard uncertainty of a measurement result is used to represent the estimated standard deviation of the result. It is obtained by combining the individual standard uncertainties. The expanded uncertainty is obtained from the combined standard uncertainties multiplied by a coverage factor. The coverage factor of the standard uncertainties for this research is 2 for 95% confidence interval. The combined standard uncertainty depends on the uncertainties of the wall superheat and the heat flux. The heat flux was obtained by measuring the values of the voltage and the consequent current. Consequently, the experimental uncertainties of the heat flux are evaluated at about 2%. Additionally, the liquid phase composition of the flowing mixture is determined by continuously taking very small liquid samples at the inlet of the test section. The compositions of liquid phase were analyzed by an LC-10 AD liquid chromatography device with an uncertainty of 0.02% in weight fraction. Also, to ensure the weight fraction, Hyprotech^{TM} Hysys simulation was employed and results of stream compositions were compared to experimental results. As expected, deviations of simulated data in comparison with experimental data were less than 2%. Finally, the uncertainty of the heat transfer coefficients with the 95% confidence is around 11%. Table 1 represents the standard uncertainty values of the measurements and instruments.

RESULTS AND DISCUSSIONS

Initially, to check the validity of obtained results, pure water testing was performed and its heat transfer coefficient was experimentally measured. Obtained results at different heat fluxes were compared the Dittus-Boelter correlation, one of the most commonly used and well-established correlations. Estimated results indicate that experimental data for pure water at 353 K are reasonable in comparison with results of the Dittus-Boelter correlation. As shown in Figure 4, with increasing the heat flux, heat transfer coefficient increases. Subsequently, the experimental Nusselt number increases too. Therefore, increasing the Reynolds number leads to increasing the experimental Nusselt number. The primary calibration of the apparatus was done with pure water, because the flow boiling heat transfer coefficient of pure water is known and a rough comparison between pure water and computed results of Dittus-Boelter demonstrated that deviation of computed results from experimental data was less than 4%. Furthermore, experimental results related to the binary mixture of ethanol/water can be

Table 1. Measurement instruments and related uncertainties

Parameter	Instrument	Range	Uncertainty
Voltage regulator	Emerson, 300KVA	0-240 V	±0.5% of reading
Multi meter	Fluke instrument Co.	0.1μA to 10 A	±0.001% of reading
Temp. measuring system	K-type Thermometers	0-1300 °C	±0.1 K
Flow meter	Sarir-Teb Co.	10 L/h - 600L/h	±0.2% of reading

considered as valid data with more than 95% confidence.

It was found that experimental values of the heat transfer coefficient for the flow rate of 3.5 l/min are higher in comparison to other flow rates (Figure 4). Revolving the Reynolds number from 1900 (laminar territory) to more than 2300 (transient and turbulent zone) can be considered as one of the reasons of the sudden increase in heat transfer coefficient. For better understanding, Figure 5 typically represents the flow boiling heat transfer coefficient of pure water at different fluid speed.

Increase in heat transfer coefficient as a result of increasing fluid velocity is seen clearly. In turn, after ensuring that experimental results for pure water are valid, ethanol/water solutions were tested at various weight concentrations of ethanol into pure water. In this regard, there are many factors which influence on flow boiling heat transfer coefficient. In this research, respecting to the situation of experimental apparatus, effect of heat flux, flow rate of tested mixtures, mixture effect and concentration of constituent substances of mixtures as well as circumstance of generated bubbles on flow boiling heat transfer were investigated.

Effect of heat flux on flow boiling heat transfer coefficient

At any concentration or flow rate, experimental results indicate that heat transfer coefficient is a strong function of heat flux. Briefly speaking, increasing the heat flux leads to an increase of the flow boiling heat transfer coefficient at any circumstances of nucleate boiling before the point of critical heat flux, although increasing the heat flux could influence the rate of bubble generation and enhances the bubble generation, which is visually observed during all the experiments. For better understanding, Figure 6 presents the status of bubble formation at different heat fluxes. As can be seen, with increasing the heat flux, bubble formation strictly increases.

As expected, generated bubbles are almost uniform at any heat flux, which also implies that the heating section surface roughness is uniform. Figure 7 depicts the experimental flow boiling heat transfer coefficient and the effect of increasing the heat flux at different concentrations. As seen, there is less dependence on the concentration of fluid, and heat flux increases the flow boiling heat transfer coefficient directly.

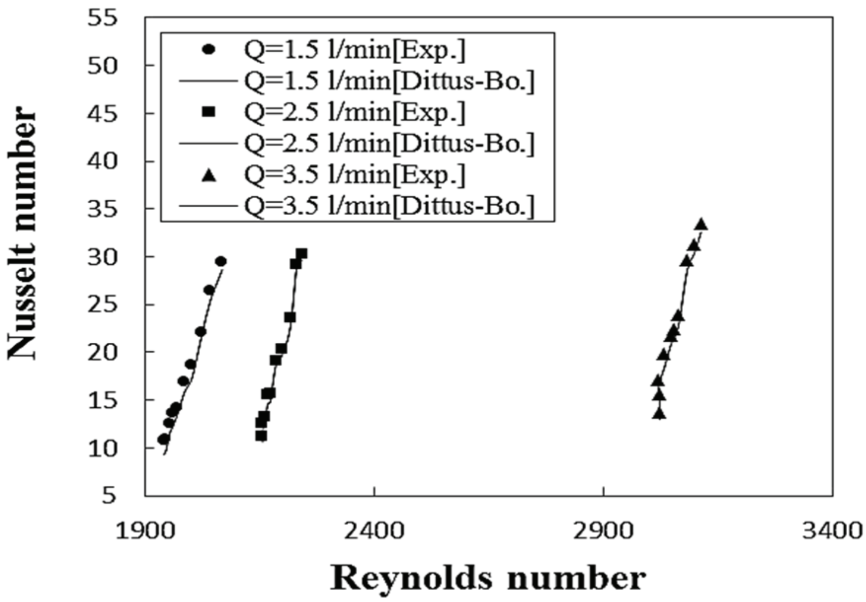

Figure 4. Results of experimental Nusselt number for pure water at 353 K.

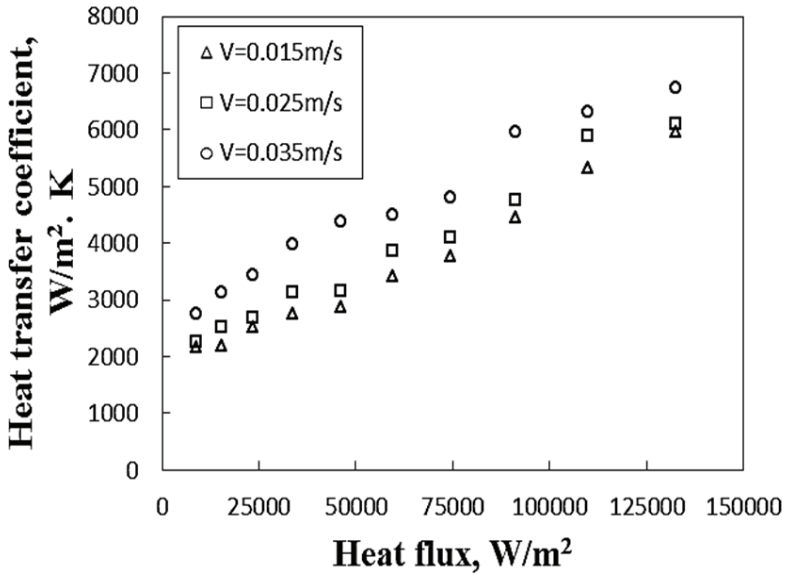

Figure 5. Experimental flow boiling heat transfer coefficient of pure water at 353 K.

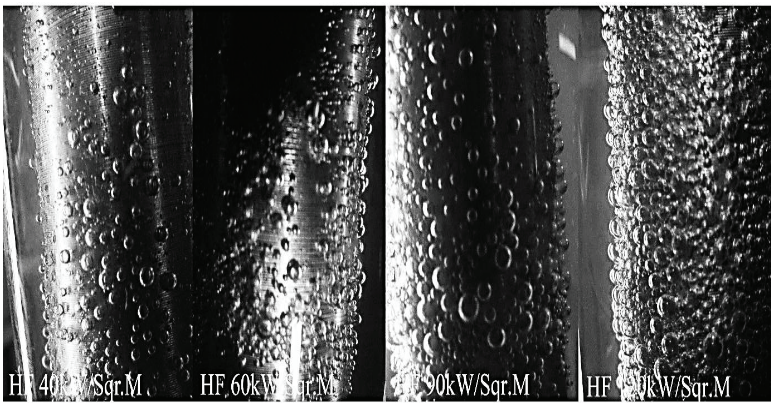

Figure 6. Bubble generation at various heat fluxes for ethanol/water solution.

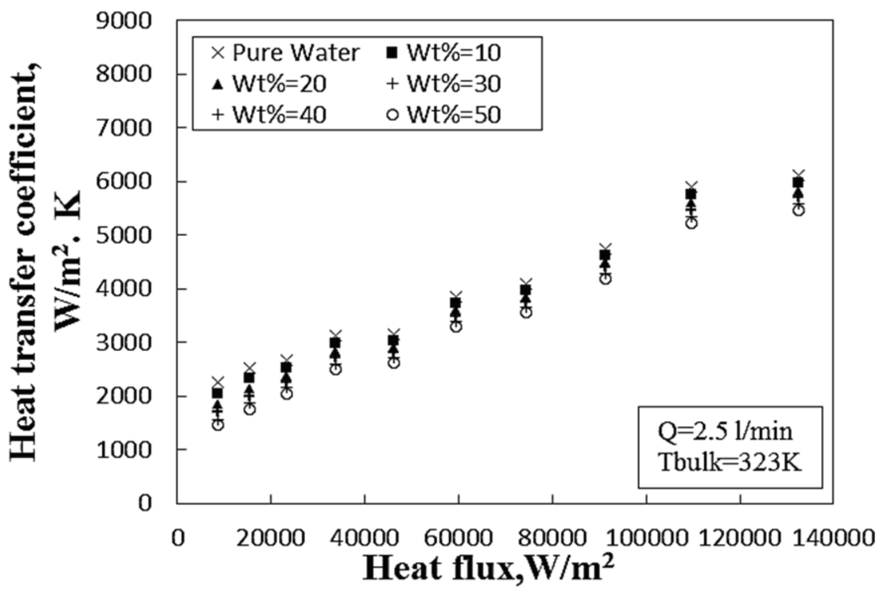

Figure 7. Effect of heat flux on flow boiling heat transfer coefficient.

Effect of mixture concentration on flow boiling heat transfer coefficient

Different concentrations of ethanol/water solution have been investigated to survey the effects of concentration on flow boiling heat transfer coefficient. Therefore, weight fractions of ethanol from 0.1 to 0.5 have been changed and values of experimental flow boiling heat transfer coefficient were recorded. The results demonstrated that the heat transfer coefficients of the tested mixtures at any concentration of ethanol are less than pure water. To justify this phenomenon, it is necessary to point out that the difference of concentration of the heavier component and the lighter component at the interface is one of the major reasons of deterioration of heat transfer coefficients. In the boiling process, particularly in binary and multi mixtures, the interface of vapor and liquid phase is depleted with lighter components and is enriched by heavier components due to the difference between their pressure vapors. Furthermore, heavier components need more heat to evaporate and leave the interface and in this circumstance, much more heat is needed. Therefore, with increasing the temperature of the surface, heat transfer coefficient is reduced compared to pure liquids. In boiling processes of pure liquids, the vapor and liquid phase and the interface are the same and there is no mass transfer besides the heat transfer process. However, in mixtures, other than heat transfer, mass transfer between captured vapor inside the generated bubbles and bulk of solution and interface of liquid/vapor and vapor phase also exists. Hence, heat transfer coefficients of mixtures are lower than pure states, whicg can truly be found through experimental results. Figure 8 represents the experimental Nusselt number and Reynolds number at different weight fractions of ethanol in mixtures. As shown, the influence of mixture effect is clearly shown, particularly, deterioration of heat transfer coefficient is seen at higher weight fractions of ethanol. Also, increasing the Reynolds number leads to increasing the Nusselt number that subsequently results in increasing the flow boiling heat transfer coefficient.

Effect of flow rate on flow boiling heat transfer coefficient

Figure 9 clearly shows the influence of different flow rates on flow boiling heat transfer coefficient. Heat transfer coefficients of mixtures have been measured at constant concentration of ethanol and at different heat fluxes. As shown in Figure 9, increase of flow rate results in increasing the heat transfer coefficient. Although, as expected, increasing the heat flux leads to increase in the heat transfer coefficient, too.

Characteristic properties of generated bubbles

Bubble generation is one of the most interesting phenomena in boiling processes. In flow boiling, due to the velocity of the fluid, generated bubbles departure the surface faster and rove into the bulk of flow. Recording still images of bubble generation through the flow boiling is very complicated. In this research, an ultra-high speed camera (Casio FX-1, Frame rate up to 2000 frame per second) was employed to record the high quality images. Afterwards, recorded images were used to estimate the bubble diameter and analyzed for determination of the bubble generation mechanism. Figure 10 depicts the bubble generation of water/ethanol solution at saturation temperature of 323 K.

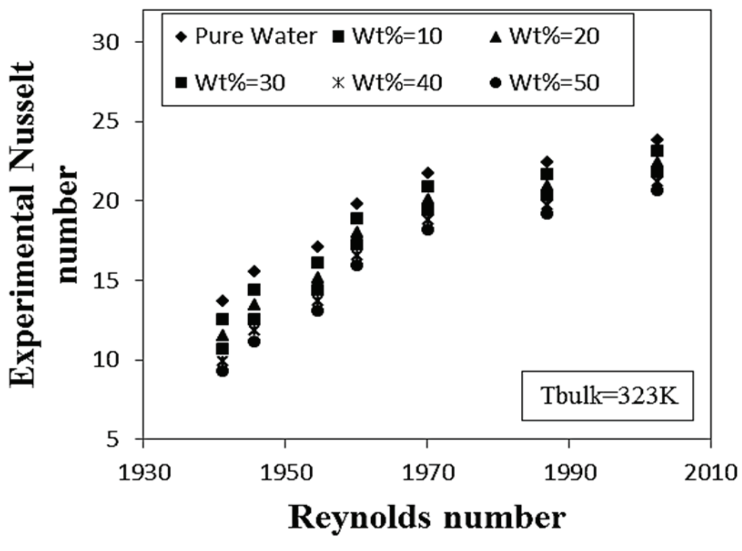

Figure 8. Experimental Nusselt values at different Reynolds numbers for various concentrations of ethanol/water solution.

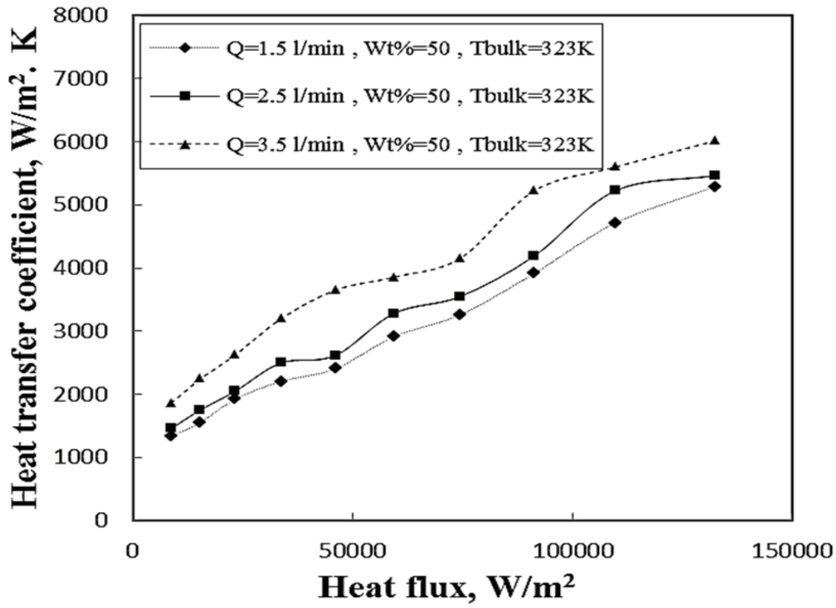

Figure 9. Effect of flow rate on flow boiling heat transfer coefficient of ethanol/water.

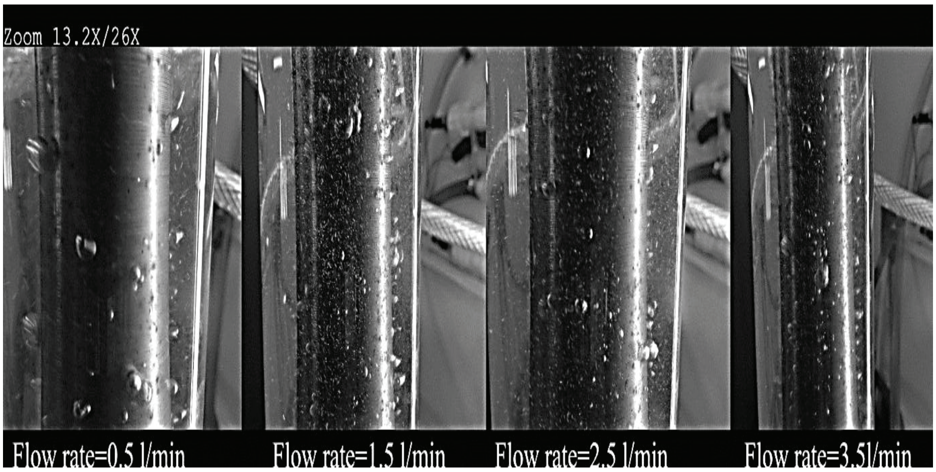

Figure 10. Status of bubble generation at different flow rate of ethanol/water solution.

As seen in Figure 10, at lower flow rates, apparent (visual) bubble diameters are higher in comparison with other flow rates. The main reason refers to the fact that at lower flow rates, due to enough time for the diffusion of light component vapors into the bubbles, the bubbles are enriched with vapors. In contrast, at higher velocities of fluid flow, there is not enough time for diffusion and vapors are not captured into the bubble due to the early departure time. Therefore, with increasing flow rate, the bubble diameter visually decreases which is truly given in Figure 10. In conclusion, visualization of the boiling processes indicated that the bubbles are suppressed by increasing the flow rate and inlet subcooling. Likewise, the boiling heat flux and inlet subcooling show large effects on the bubble population, coalesce and generation frequency. It is also noticeable that at a higher flow rate, the fluid can quickly sweep the bubbles away from the surface and hence causes significant increase in boiling heat transfer. The presence of bubbles in the fluid through the annulus makes a local agitation near the surface that increases the heat transfer significantly.

Comparison with well-established existing correlations

Experimentally obtained data have been compared to results of two well-known flow boiling correlations. The results indicate that these correlations obtain the reasonable value for heat transfer coefficient in comparison to experimental data, but a modification is needed to reduce the deviation of obtained results from experimental data. Figure 11 shows the computed results of Gnielinski and Dittus-Boelter correlations estimating the heat transfer coefficient of ethanol/water solution. Although the results are reasonable, the deviation of values from experimental data is not acceptable.

A 3D comparison between existing correlations and experimental data for flow rate 1.5 l/min at concentration of 10% of ethanol in water is given in Figure 12.

As shown, Dittus-Boelter computed results are more reasonable in comparison with Gnielinski. Hence, a modification is proposed to reduce the deviation value of Gnielinski for ethanol/water solutions. Gnielinski [8] proposed a semi-empirical correlation for flow boiling heat transfer coefficient at transient-turbulent flow regimes that is given as follows:

$$Nu = 0.0214(\mathrm{Re}^{0.8} - 100)\mathrm{Pr}^{0.4} \quad (10)$$

Although the proposed correlation may obtain the heat transfer for volatile mixture coefficient with uncertainty about 25%, with some statistical calculations and a simple modification it leads to:

$$Nu = 0.02326(\mathrm{Re}^{0.83} - 100)\mathrm{Pr}^{0.4201} \quad (11)$$

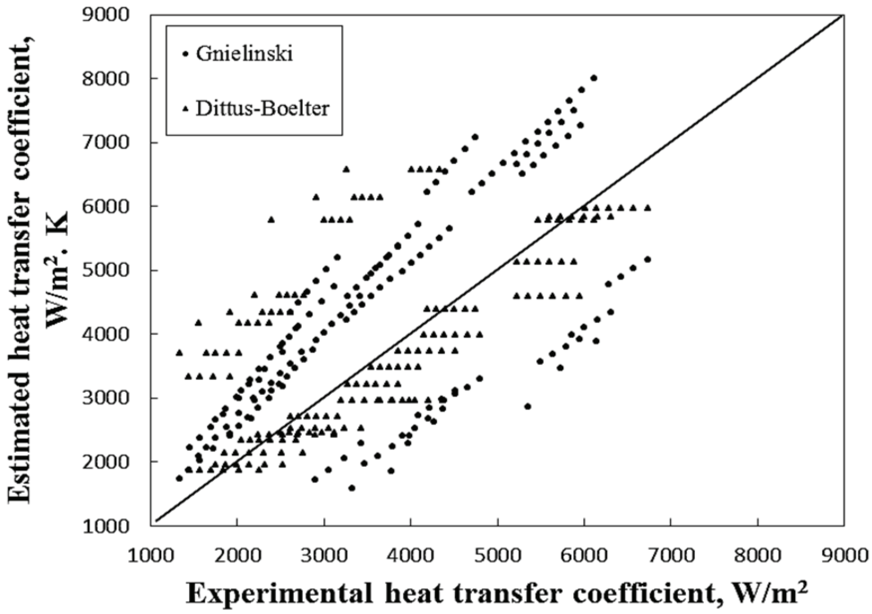

Figure 11. Computed results of Gnielinski and Dittus-Boelter correlations in comparison to experimental data.

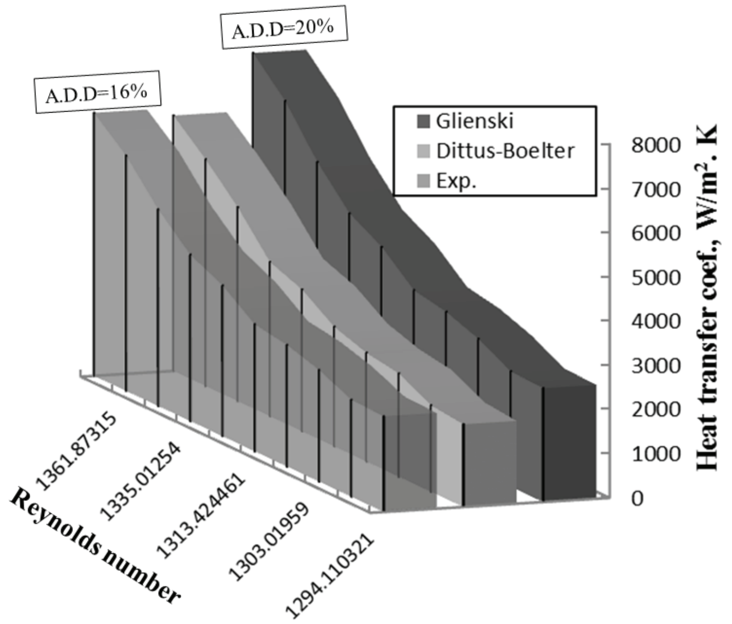

Figure 12. 3D exhibition comparison of existing correlations and experimental data.

However, it should be noted that this modification is applicable for ethanol/water volatile mixtures, and for any other mixture more experiments are needed. Figure 13 expresses the accuracy of the modified model in comparison to experimental data. As shown, the modified model represents the heat transfer coefficient for ethanol/water with uncertainty about 8% which was 16.03 and 19.95% for Dittus-Boelter and Gnielinski, respectively. The major reason for this deviation is that, owing to the low pressure vapor of ethanol compared to water, the saturation temperature of water/ethanol is significantly lower than pure water and subcooled flow boiling occurs at lower temperatures, and the presence of bubbles including the ethanol/water vapor locally lead to increase the turbulences of flow. In this particular case, the influence of the Reynolds number on flow boiling heat transfer coefficient must be considered more than in other mixtures, which is clearly seen in modified correlation.

transfer coefficient at any concentration of ethanol/ /water and at any flow rate.

- Increase of ethanol concentration in ethanol/ /water mixture deteriorates the heat transfer coefficient as a result of mixture effects and mass transfer resistance.
- Increase of flow rate of liquid leads to increase of the flow boiling heat transfer coefficient because of the increasing Reynolds number and, subsequently, Nusselt number. It should be noted that the influence of increasing the heat flux is much higher than the influence of flow rate.
- Recorded images express that bubble generation phenomenon, as expected, increases when heat flux is increasing and in contrast, with increase of liquid flow rate, the generated bubble diameter decreases.

Results of some existing well known, well established correlations were compared to experimental

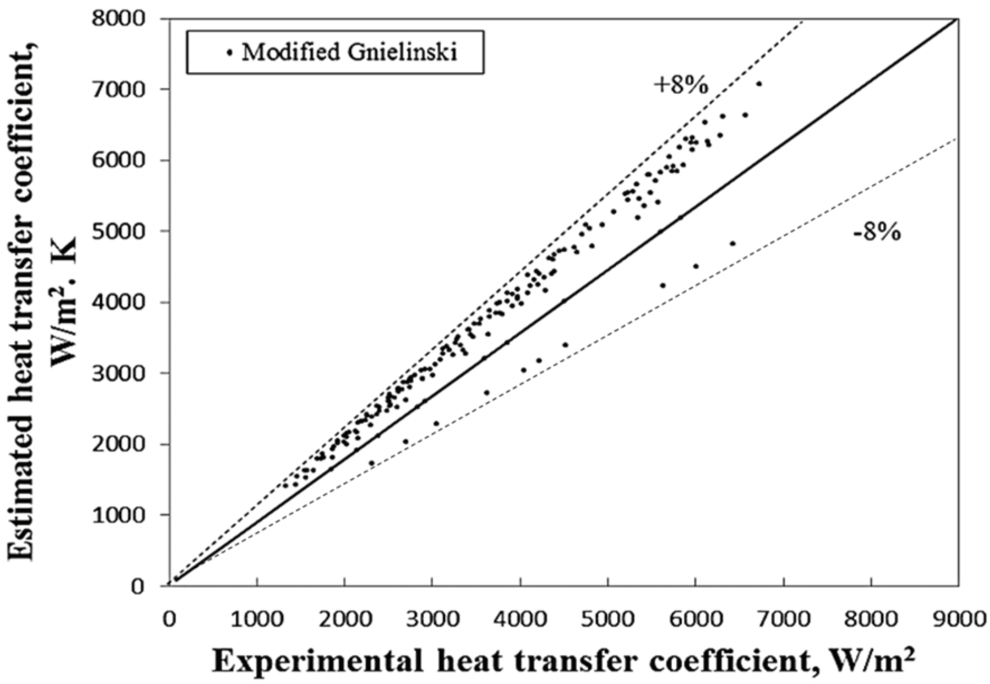

Figure 13. Results of modified correlation in comparison to experimental data.

CONCLUSIONS

Experimental studies on flow boiling heat transfer coefficient of ethanol/water solutions inside the annulus vertical space were carried out at different concentrations of ethanol up to heat fluxes of 132 kW/m^2. The obtained results indicated that:

- As expected, heat flux has a direct influence on flow boiling heat transfer coefficient. In fact, increasing the heat flux leads to increasing the heat

data. The results of the comparison implied that these correlations predict reasonable values for flow boiling heat transfer coefficient, but deviation values relative to experimental data were not acceptable. Furthermore, a new modified correlation based on Gnielinski correlation was modified that obtains reasonable values with uncertainty about 8% which is more accurate for ethanol/water solutions in comparison to the original form.

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Nomenclature

A Area, m^2
b Distance, m
C_p Heat capacity, J kg^{-1} K^{-1}
d_b Bubble departing diameter, m
H_{fg} Heat of vaporization, J kg^{-1}
k Thermal conductivity, W m^{-1} K^{-1}
$\dot{m}$ Mass flow rate of fluid
m Mixture
n Number of components
P Pressure, Pa
q Heat, W
R_a Roughness, m
T Temperature, k
x Liquid mass or mole fraction
y Vapor mass or mole fraction

Subscripts

b Bulk
c Critical
in Inlet
out Outlet
l Liquid
r Reduced
s Saturated or surface
th Thermocouples
v Vapor

Greek symbols

α Heat transfer coefficient, W m^{-2} K^{-1}
ρ Density, kg m^{-3}
μ Viscosity, kg m s^{-1}

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NAUČNI RAD

PRENOS TOPLOTE PRI POTHLAĐENOM KLJUČANJU PRI PROTICANJU VODENIH RASTVORA ETANOLA U VERTIKALNOM ANULARNOM PROSTORU

Ispitivane su karakteristike prenosa toplote pri pothlađenom ključanju vode i vodenih rastvora etanola u vertikalnom anularnom prostorusve do toplotnog fluksa od 132 kW/m^2. Promene efekata toplotnog fluksa, brzine strujanja i koncentracije etanola na koeficijent prenosa toplote u opsegu koncentracije etanola ukazuje na povećani doprinos nukleatskog ključanja ključanju pri proticanju, gde se odigravaju prenos i toplote prinudnom konvekcijom i nukleatskim ključanjem. Povećanje koncentracije etanola je vodilo značajnom pogoršanju koeficijenta prenosa toplote zbog efekta mešanja, koji je rezultovao lokalnim povećanjem temperature zasićenja vodenog rastvora etanola na granici faze para-tečnost. Smanjenje koeficijenta prenosa toplote sa povećanjemkoncentracije etanola se, takođe, pripisuje promenama fizičkih osobina (na primer, viskoziteta i toplotne provodljivosti) ispitivanih rastvora različite koncentracije. Eksperimentalni podaci su upoređeni sa postojećim korelacijama, a rezulati poređenja ukazuju da postojeće korelacije nisu upotrebljive. Zbog toga je pretpostavljena modifikovana korelacija zasnovana na korelaciji Gnielinskog, koja predviđa koeficijent prenosa mase za vodene rastvore etanola sa nepouzdanošću od 8%, što je najmanje u poređenju sa drugim poznatim korelacijama.

Ključne reči: ključanje sa proticanjem, prenos toplote, etanol, voda, korelacija Gnielinskog, formiranje mehura.