Pool boiling heat transfer coefficient of pure liquids using dimensional analysis

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H I G H L I G H T S

- Dimensionless groups were created linking new boiling heat transfer coefficient to physical properties of boiling liquids.

- Boiling heat transfer coefficient of liquids increased slowly through an increase in heat flux.

- A precise correlation was achieved to link dimensionless groups by optimizing the model using genetic algorithm.

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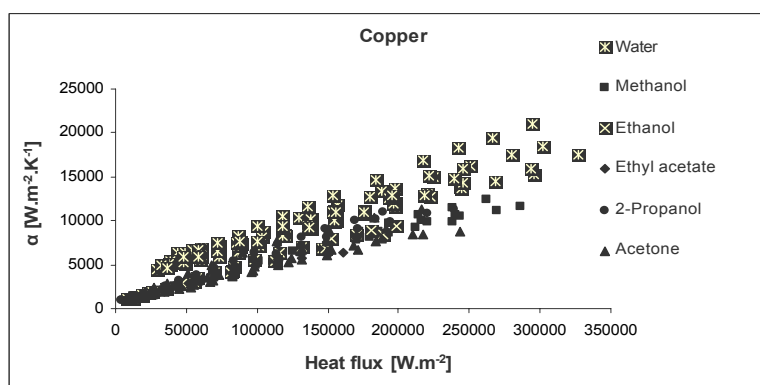
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The pool boiling heat transfer coefficient of pure liquids were experimentally measured on a horizontal bar heater at atmospheric pressure. These measurements were conducted for more than three hundred data in thermal currents up to 350 kW.m^{-2}. Original correlations and the unique effect of these correlations on experimental data were discussed briefly. According to the analysis, a new empirical relationship implying a performance superior to other available correlations is presented.

1. Introduction

Free movement mechanism plays an important role in industrial heat transfer processes. In recent decades, a lot of free convections have been presented for predicting heat transfer coefficient developed in different situations such as various geometrical situations. Boiling plays an important role in many chemical engineering issues such as cooling cycle, strength, and distillation processes. Proper design of the equipment requires understanding of the boiling process and predicting the boiling heat transfer coefficient. Due to the high boiling heat transfer coefficient in the nuclear area, this area is very important. In general, nuclear boiling is defined as the formation of vapor bubbles in active positions of the surface, when the surface temperature is higher than the liquid saturation temperature in contact with the surface.

Movement processes which are accompanied with a fluid phase change involve boiling, too. Boiling is one of the most popular and very complicated processes in engineering science because of its multiple sub-processes. These sub-processes are realized as dynamics of bubbles including the diameter of bubbles separation, compression of bubble generator sources per unit area, and bubble generation frequency. Understanding and more accurate modeling of the boiling process requires modeling of these sub-processes.

1.1. Literature review

Despite extensive research in the field of nuclear pool boiling, fundamental mechanisms of this process, including sub-processes such as bubble diameter, density of bubble generation points and bubble separation frequency, have not been fully understood. A lot of relationships have been presented to predict the boiling heat transfer coefficient of pure liquids that are generally empirical or semi-empirical.

Pool boiling proposed by Kutateladze in 1952 is one of the oldest equations for pure liquids [1]. This experimental model, with two dimensionless parameters, calculates the heat transfer coefficient without considering the heat transfer surface roughness. By the end of 1962 McNelly's model [2] was used as the most reliable predictor of pure liquids heat transfer coefficient. The model was only reliable for the prediction of pure and single-component materials and

includes physical properties of the liquid phase while boiling as well as vapor phase.

In early 1963 Mostinski [3] carried out numerous tests on the critical heat flux using corresponding states. In the same year, he presented results of his experiments using a mathematical model. Boyko-KruzhilinIn [4] introduced a more complete model in 1967 in which physical properties of heat transfer coefficient were used for calculation and prediction of heat transfer coefficient. This model, obtained by dimensional analysis, calculates more accurate values for pure liquid heat transfer coefficient. After numerous tests on various fluids, Labantsov [5] proposed his empirical relationship in 1972. Since his relationship is based on experimental data for more than 200 materials, it provides a good overlap for this data. One of the most accurate equations to predict the boiling heat transfer coefficient of pure liquids was offered by Stephan and Abdelsalam [6]. Introducing this exact relationship, Stephan has sharply declined the deviation of heat transfer coefficient from experimental data. He used groups of six fold thermo-physical properties which facilitated calculations of heat transfer coefficient prediction due to sorting values of these groups and creating linear relationship for the multiplication of these properties by each other. The diversion rate of the model, used for more than 500 materials, is about 5-16%.

Gorenflo [7] is the innovator of a new experimental system for estimating the heat transfer coefficient. By doing numerous tests he offered a new multi-parameter model in 1984 and again in 1993. The relationship presented by Alavi Fazel et al. [8] was based on measured data (of water, ethanol, methanol, acetone and 2-propanol) and dimensional analysis. Simplicity is one of the benefits of this relationship. In addition, via principle of corresponding states and dimensional analysis, Sarfaraz introduced his model for the pool boiling heat transfer coefficient of pure liquids in 2013 [9]. Table 1 shows equations to predict the heat transfer coefficient of pure liquids.

2. Experimental device

The instrument applied for data collection and measurement is known as Gorenflo's pool boiling device. The device is made of a smooth stainless steel surface cylinder located inside a glass enclosure with high thermal tolerance. There are four thermocouples

Table 1. Relationships for estimating the boiling Hhat transfer coefficient of pure liquids.

Researcher	Model
Kutateladze [1]	$\alpha = \left[3.37E - 9\dfrac{k_l}{l^*}\left(\dfrac{H_{fg}}{C_{pl}q}\right)^{-2} M_*^{-4} \right]^{\frac{1}{3}}$
McNelly [2]	$\alpha = 0.225\left(\dfrac{C_{pl}q}{H_{fg}}\right)^{0.69}\left(\dfrac{Pk_l}{\sigma}\right)^{0.31}\left(\dfrac{\rho_l}{\rho_v}-1\right)^{0.33}$
Mostinsk [3]	$\alpha = (3.596E - 5)P_c^{0.69}q^{0.7}\left[1.8(\dfrac{P}{P_c})^{0.17} + 4\left(\dfrac{P}{P_c}\right)^{1.2} + 10\left(\dfrac{P}{P_c}\right)^{10}\right]$
Boyko-Kruzhiline [4]	$\alpha = 0.082\dfrac{k_l}{l^*}\left[\dfrac{H_{fg}q}{g(T_s+273.15)k_l}\left(\dfrac{\rho_v}{\rho_l-\rho_v}\right)\right]^{0.7}\left[\dfrac{(T_s+273.15)C_{pl}\sigma P}{H_{fg}\rho_v l^*}\right]^{0.33}$
Labantsov [5]	$\alpha = 0.075\left[1 + 10\left(\dfrac{\rho_v}{\rho_l-\rho_v}\right)^{0.67}\right]\left[\dfrac{k_l^2}{v\sigma(T_s+273.15)}\right]^{0.33}q^{0.67}$
Stephan and Abdelsalam [6]	$\alpha = 0.23\dfrac{k_l}{d_b}\left(\dfrac{qd_b}{k_lT_s}\right)^{0.674}\left(\dfrac{\rho_v}{\rho_l}\right)^{0.297}\left(\dfrac{H_{fg}d_b^2}{\hat{\alpha}_l^2}\right)^{0.371}\left(\dfrac{\hat{\alpha}_l^2\rho_l}{\sigma d_b}\right)^{0.35}\left(\dfrac{\rho_l-\rho_v}{\rho_l}\right)^{-1.73}$
Gorenflo [7]	$F_p = 1.73Pr^{0.27} + 6.1Pr + 0.68Pr/(1-P_r)$ $\alpha = \alpha_0 F_q F_p F_{WR} F_{WM}$
Alavi Fazel [8]	$\alpha = \dfrac{3.253\sigma^{0.125}H_{fg}^{0.125}(q/A)^{0.876}}{T_{sat}\hat{\alpha}^{0.145}}$
Sarafraz [9]	$\alpha = \dfrac{3.0219\sigma^{0.12}\Delta H_{fg}^{0.1107}q^{0.8045}}{T_{sat}\hat{\alpha}^{0.1398}}$
Rohsenow [10]	$\dfrac{C_{pl}\Delta T_{sat}}{H_{fg}P_r^s} = C_{sf}\left[\dfrac{\left(\dfrac{q}{A}\right)}{\mu l H_{fg}}\sqrt{\dfrac{\sigma g_c}{g(\rho_l-\rho_v)}}\right]^{-0.33}$
Nishikawa [11]	$\alpha = \dfrac{31.4P_c^{0.2}}{M_w^{0.1}T_c^{0.9}}\left(8R_p\right)^{0.2(1-P_r)}\dfrac{\left(P_r^{0.23}\right)q^{0.8}}{(1-0.99P_r)^{0.9}}$
Fujita [12]	$\alpha = 1.21\,(q/A)^{0.83}$
Cooper [13]	$\alpha = 55P_r^{0.12-0.443Rp}\,(-\log P_r)^{-0.55}\,MW^{-0.5}\,(q/A)^{0.67}$

on the cylinder surface. The thermocouples arithmetic mean at any moment and after the final correction indicates cylinder surface temperature. The main heater of the experiment is placed at the center of the cylinder which operates near the boiling point. The pool boiling phenomenon occurs by contribution of this heater. Figures (1) and (2) display full details of the device [14].

A silicone paste is used to reduce the thermal contact resistance between the thermocouple and holes. The required voltage is provided by urban power supply and is regulated by an autotransformer. In order to remove roughness, cylinder surface is polished by smooth sandpaper with roughness of 400 micrometers and is
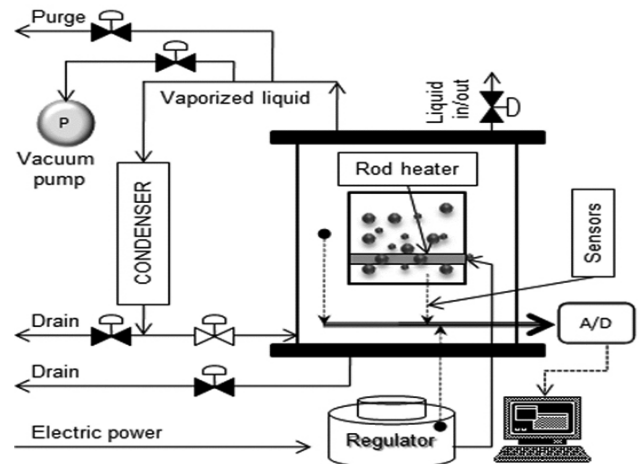

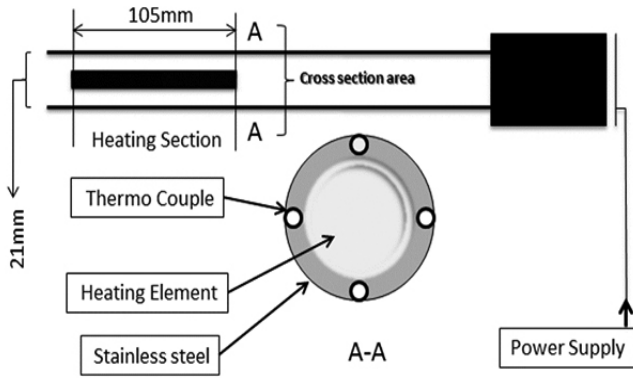**Fig. 1.** Laboratory device details [14].

Fig. 2. Laboratory main heater details [14].

Fig. 3. The effect of heat transfer level on the heat transfer coefficient rate of pure liquids.

refined by fine polishing oil. Moreover, in order that temperature sensors operate precisely, sensors diameter was 2 mm with a length of 100 mm. The container volume is about 4 liters. A condense is placed on top of the container in order to restore the steam produced from the boiling process. This experiment is based on Newton's cooling law as seen in equation (1).

$$q = h \, (T_w - T_{sat}) \qquad (1)$$

This article examines some of the most important physical properties of pure liquids including liquid phase density, surface tension, liquids' specific heat capacity and vaporization enthalpy.

2.1. Experimental results

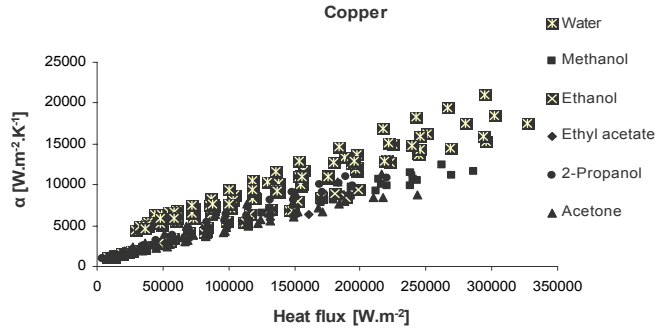Figure 3 shows row experimental values of boiling

heat transfer for the tested liquids. According to the graph, boiling heat transfer coefficient of any liquid increases slowly as the heat flux increases. However, there are small fluctuations that are primarily related to experimental error and residual effect. Note that A/D function (analog to digital convertor) is sensitive to environmental conditions.

3. Available correlation functions

A purely theoretical and predictive model has not been offered due to the complexity of the boiling phenomenon. There are a lot of parameters impacting pool boiling heat transfer which require extensive research in order to be correlated with boiling heat transfer coefficient without any empirical tuning parameter. Table 2 shows the ordinary physical constants of test pure liquids. Some important physical properties of test pure liquids during experiments are presented in Table 3. Table 4 compares

Table 2. Summarization of the boiling point and critical important constants of pure liquids.

Chemical component	T_b (°C)	V_c (m³/kg.mol)	P_c (kPa)	T_c (K)	Mw (g/mol)	ω
Water	100	0.056	22055	647.069	18.153	0.3449
Methanol	64.7	0.117	8084	512.5	32.043	0.5658
Ethanol	78.4	0.168	6120	514	46.069	0.6436
Ethyl acetate	77.1	0.286	3880	523.3	88.105	0.3664
2-Propanol	82.5	0.222	4765	508.3	60.095	0.6544
Acetone	56.5	0.209	4701	508.2	58.08	0.3065

Table 3. Important physical properties of pure liquids.

Physical properties	Water	Methanol	Ethanol	Ethyl acetate	2-Propanol	Acetone
liquid phase density (kg.m⁻³)	968.79	749.60	743.66	828.64	720.93	749.48
surface tension [N/m]	0.058	0.018	0.017	0.016	0.014	0.018
specific heat capacity [J/kg.K]	4219	2823	3003	2133	3414	2595
vaporization enthalpy (j.kg⁻¹)	2263717	1096692	845032	365769	664324	508699

Table 4. Percentage of average absolute error for pure liquids.

Model	Acetone	2-Propanol	Ethyl acetate	Ethanol	Methanol	Water
Kutateladz	91.3	80	94.93	62.8	95.4	42.11
McNelly	60.14	42.59	75.93	20.76	30.13	18
Mostinski	13.22	21.9	18.98	14.38	15.82	15.73
Labantsov	14.34	43.64	14.1	37.97	14.83	14
Boyko-Kruzhiline	19.71	21.79	71.44	15.97	13.84	18.61
Stephan-Abdelsalam	42.88	34.48	48.85	11.43	64.16	14.45
Nishikawa	35.42	14.17	36.46	18.67	38.1	79.6
Fujita	255.9	176	246	174.7	225.3	110.3
Cooper	66.37	60.68	47	52	93	22.15
Gorenflo	14.33	16.92	13.78	48	14.41	15.76
Alavi Fazel	50.18	24.44	41.41	26	58	35.19

functions of available predictive and major correlations with current experimental data. Absolute relative error referenced in the table is calculated by equation (2).

$$A.D.D.\% = \frac{\text{Estimated Value from correlation - Experimental data}}{\text{Experimental data}} \times 100 \quad (2)$$

4. New experimental model

In this study, all groups were created without considering probable dimension. All dimensionless groups were extracted using more than 300 experimental data and the database available in this article and employing Buckingham theory. The model is optimized via genetic algorithm. A precise correlation is achieved to link dimensionless groups by the following:

$$Nu = (Pr)^{g0} (Re)^{g1} (p/p_c)^{g2} (\rho_v/\rho_l)^{g2} \quad (3)$$

In this equation, *Nu*, *Pr*, *Re*, p/p_c, and ρ_v/ρ_l represent Nusselt dimensionless number, Prandtl dimensionless number, Reynolds dimensionless number, the ratio of atmospheric pressure to critical pressure in [Pa], and vapor density to liquid density in [kg/m³], respectively. Parameters of g0 to g3 are calculated by genetic algorithm such that the boiling heat transfer coefficient error of pure liquids reaches the minimum value (Table

Table 5. Parameters of the proposed model

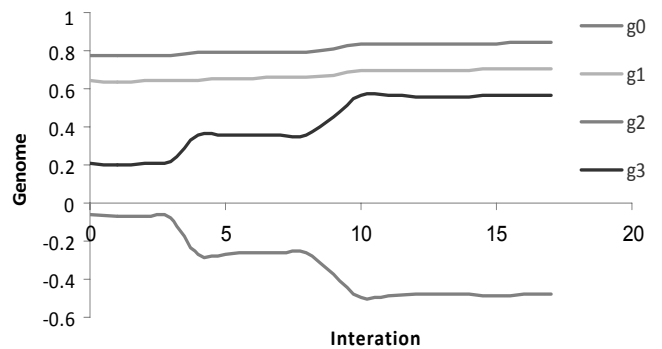| Genome	g0	g1	g2	g3
Optimum	0.907	0.755	-0.743	0.849

Fig. 4. Gene convergence of the genetic algorithm with optimal reply.

5). As seen in Figure 4, the output of the program encoded by the genetic algorithm technique indicates powers as the equation's unknowns.

Figure 5 illustrates the comparison between experimental values and values predicted by the proposed model that represents good overlap of the model with experimental data.
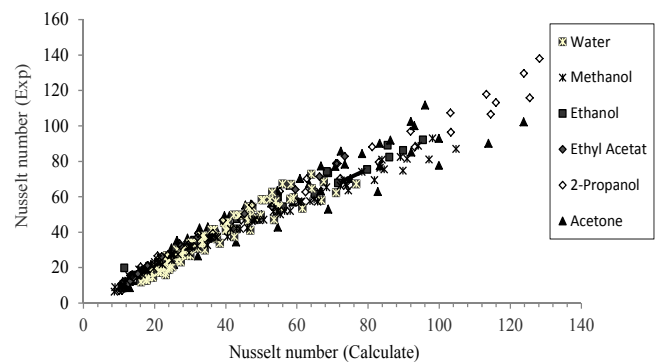

Fig. 5. A comparison of the calculated Nusselt's dimensionless number for the experimental results and predicted values.

5. Conclusion

Pool boiling heat transfer coefficient for pure liquids, such as water, acetone, isopropanol, methanol and ethanol, were measured experimentally at atmospheric pressure. Correlations of the main prediction for transferring the boiling heat of pure liquids were briefly investigated. The comparison between experimental data and available main correlations imply a significant error. So far, numerous relationships have been proposed to predict heat transfer coefficient in pure liquids. In each of the available models, some parameters are taken into account while others are neglected. Our objective was to find a highly accurate relationship for predicting the boiling heat transfer coefficient of pure liquids, through which this parameter can be related to dimensionless groups.

In this paper, based on dimensional analysis, dimensionless groups were created that can link the new boiling heat transfer coefficient to physical properties of boiling liquids. This new correlation provides more accuracy than other available correlations.

Nomenclature

A	Area, m^2
C	Heat capacity, $J.kg^{-1}.^oC^{-1}$
d_b	Bubble departing diameter, m
F_P	See Gorenflo [7] equation
F_q	See Gorenflo [7] equation
F_{WM}	See Gorenflo [7] equation
F_{WR}	See Gorenflo [7] equation
G	Gravitational acceleration, $m^2.s^{-1}$
ΔH_{fg}	Heat of vaporization, $J.kg^{-1}$
K	Thermal conductivity, $W.m^{-1}.^oC^{-1}$
l*	See Boyko-Kruzhilin [4] equation
n	See Gorenflo [7] equation
N	Number of components
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
P	Pressure, Pa
q	Heat, W
Ra	Roughness, m
s	Distance, m
T	Temperature, K
Δ	Difference
α	Heat transfer coefficient, $W.m^{-2}.^oC^{-1}$
$\hat{\alpha}$	Thermal diffusion, $m^2.s^{-1}$
ρ	Density, $kg.m^{-3}$
σ	Surface tension, Dy/cm or $N.m^{-1}$

Subscripts

b	Bulk
c	Critical
i	Component
id	Ideal
l	Liquid
o	Reference
r	Reduced
s	Saturated or Surface
th	Thermocouples
v	Vapor

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