Heat Transfer Correlations for Small Closed End Heat Pipe with Special Vapor Chamber

Duangkamon Hemathurin[1], Narong Srihajong[1], Paisan Kumthong[1], Juthamat Silon[1]

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Abstract

In this paper, the empirical correlations for heat transfer characterizations of a small closed end heat pipe with special vapor chamber (SCEHP/SVC) are carried out. The heat transfer performance was introduced by a correlation function of dimensionless parameters namely Kutateladze number (Ku), Bond number (Bo), Weber number (We), Froude number (Fr), Prandtl number (Pr), Jacob number (Ja), Density ratio (DR) and Aspect ratio (AR). SCEHP/SVCs were consists of two main parts such as a small closed end and special vapor chamber (where located at the bottom). Small closed end was made of small copper tubes with 2, 3 and 4.5 mm ID. Number of turns was 10. Special vapor chamber was an ID of 14.5, 17.5 and 20.5 mm. The evaporator, adiabatic and condenser sections were of equal length 50, 100 and 150 mm, with an inclination angle 60° and 90°. Water, ethanol and R-134a were selected as working fluids with filling ratios 30, 40 and 50% of the volume of a special vapor chamber. The operating temperatures were 60, 70 and 80°C that heated by hot water at the evaporator section, while the condenser section was cooled by cold water to 20°C. Experiments were recorded when the system reached a steady state, so as to calculate the heat flux. All experimental results of the heat flux of SCEHP/SVCs at inclined 90° orientation could be correlated in terms of modified Kutateladze number (Ku^*) as follows;

$$\mathrm{Ku}^*_{90} = 2.25\left[\mathrm{Bo}^{-1.2}\mathrm{We}^{-2.309}\mathrm{Fr}^{1.249}\,\mathrm{Pr}^{1.503}\,\mathrm{Ja}^{-4.318}\mathrm{AR}^{0.877}\mathrm{DR}^{1.232}\right]$$

That correlation was used to predict the heat flux with standard deviations (STD) of ±22.12%.

Keywords: Correlation, heat flux, Small closed end heat pipe with special vapor chamber

Introduction

Heat pipes (HP) are efficient heat transfer devices, which utilize working fluid to transfer heat from a heat source to a heat sink within a closed pipe[1]. Nowadays, there are many types which depend on various mechanisms such as gravity assisted, capillary force, osmotic membrane or centrifugal force[2]. As is widely know the advantages of a thermosyphon and oscillating heat pipe are high heat transfer performance and a simple structure.

Saehang and Srihajong[3] invented a new type of heat pipe called a "Small closed end heat pipe with special vapor chamber" or SCEHP/SVC. Its design is based on an oscillating heat pipe mixed with thermosyphon in the hope to improve its performance. The. Proposed SCEHP/SVCs structure is illustrated in (Figure 1)

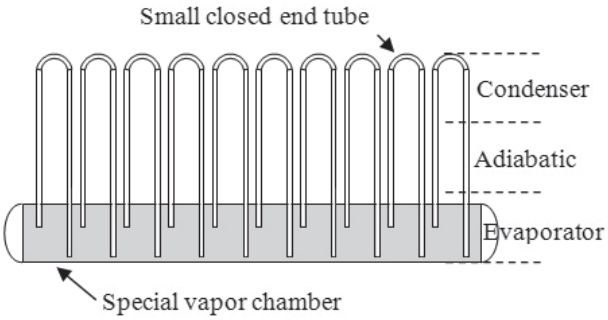

Figure 1 Small closed end heat pipe with special vapor chamber (SCEHP/SVC) using in experiments.

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[1] *Department of Mechanical Engineering, Faculty of Engineering, Rajamangala University of Technology Isan Khon Kaen Campus, Thailand, 40000*
E-mail: dkmhmtr9@hotmail.com

The aim of this paper is to study the effects of dimensionless parameters (i.e. Kutateladze number (Ku), Bond number (Bo), Weber number (We), Froude number (Fr), Prandtl number (Pr), Jacob number (Ja), Density ratio (DR) and Aspect ratio (AR)) on the SCEHP/SVCs heat flux and establish an empirical correlation in order to predict the heat transfer performance in the vertical position (90°).

Materials and Methods

The experimental setup was divided into two parts; a small closed end tube (SCE) and special vapor chamber tube (SVC) (see Figure 1). The SCEs set of 10 copper tubes with 2, 3 and 4.5 mm ID were bent in a U-shape, whereas SVCs were also made of copper tube with 14.5, 17.5 and 20.5 mm ID. The SCEHP/SVCs were conducted with 50, 100 and 150 mm of section lengths (equal length in three sections). The experiments employed water, ethanol and R-134a as working fluid, 30%, 40% and 50% of filing ratio.

The schematic diagram of the experiment is shown in (Figure 2). The evaporator section was heated with hot water at 60°C, 70°C and 80°C but the condenser section was cooled by cold water 20°C. It was conducted at an inclination angle of 90° from horizontal plane.

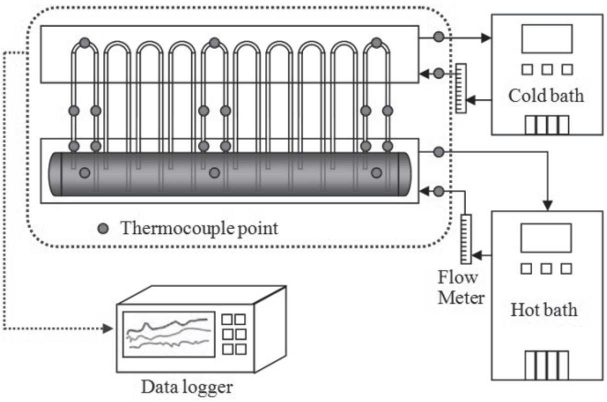

Figure 2 Schematic set up of experiments.

All components of test rig are shown in (Figure 2) They include a Yokogawa MV1000 data logger with ±0.7°C accuracy, Thermocouple type-K with accuracy ±0.5°C, EYELA CA-112CE cold bath (±2°C accuracy), Thermo Fisher Scientific EX-35 hot bath (±0.01°C accuracy) and two floating rotameters. the experiment procedure was conducted as follows, firstly, Set experiment on all parameters as shown in (Table 1). Then, set the desired temperature on the hot bath and cold bath. Next, supply the hot water and cold water to the water jacket of the evaporator and condenser respectively. When the system reaches a steady state, the temperature at thermocouple attach points are recording by the data logger in 10 minute interval. Then, loading the recorded data for calculating the heat flux and dimensionless parameters also. Finally, analyze the results.

Table 1 Tested parameters

Parameters	Value
SCEs ID	2, 3 and 4.5 mm
SVCs ID	14.5, 17.5 and 20 mm
Working fluid	Water, Ethanol, R-134a
Filling ratio	30%, 40% and 50%
Section length	50, 100 and 150 mm
Inclination angle	90 degree
Working temp.	60, 70 and 80°C

The heat flux was calculated by using calorific method is defined as;[4]

$$Q_c = \dot{m}_c Cp_c \left(T_{out} - T_{in}\right)_c \tag{1}$$

$$\dot{q}_c = \frac{Q_c}{2\pi D_o L_c N} \tag{2}$$

Where, Q_c: heat transfer at condenser section (W), $\dot{m}_c$: coolant water mass flow rate (kg/s), Cp_c: specific heat of coolant water (J/kg.°C), $T_{in,out}$: inlet and outlet temperature (°C), $\dot{q}_c$: the condenser heat flux (kW/m^2), D_o: the outer diameter of small closed end tube (mm), L_c: the condenser section length (mm) and N: number of turn.

Furthermore, in order to formulate an empirical correlation to predict the heat flux, which derived from dimensionless parameter group, It is necessary to consider all parameters (heat pipe geometric, heat input, volumetric filling ratio, tested orientation and working fluid etc.) that are associated with appropriate dimensionless numbers. Thus, the dimensionless numbers involved are: Ku, Bo, We, Fr, Pr, Ja, DR and AR.[5]

$$q_c = f\left\{\mathrm{Ku}, \mathrm{Bo}, \mathrm{We}, \mathrm{Fr}, \mathrm{Pr}, \mathrm{Ja}, \mathrm{DR}, \mathrm{AR}\right\} \tag{3}$$

The Kutateladze number (Ku) is introduced as an measure of the heat transfer performance[6], so the other numbers could function in terms of Ku defined by;

$$\mathrm{Ku} = f\left\{\mathrm{Bo}, \mathrm{We}, \mathrm{Fr}, \mathrm{Pr}, \mathrm{Ja}, \mathrm{DR}, \mathrm{AR}\right\} \tag{4}$$

Based on the analysis of the empirical correlation, multi linear regression was applied on Eq.(4) as power series.

$$\mathrm{Ku}^* = c_0\{(\mathrm{Bo})^{c_1}(\mathrm{We})^{c_2}(\mathrm{Fr})^{c_3}(\mathrm{Pr})^{c_4}(\mathrm{Ja})^{c_5}(\mathrm{DR})^{c_6}(\mathrm{AR})^{c_7}\} \tag{5}$$

Where Ku^*: modified Ku, $c_0 \ldots c_7$: regression constants that need to determined..

Then, taking the logarithm on both side of Eq.(5) and thus solved with least square method. Finally, correlation in modified Ku (Ku^*) form can be developed for the heat flux predicts (q^*_{pre}) become by Eq.(6).

$$q^*_{pre} = \mathrm{Ku}^* \times \left(h_{fg}\rho_v \left[\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2} \right]^{0.25} \right) \tag{6}$$

Results and Discussions

Experimental results have been reported as follows;

1. Effect of Kutateladze number (Ku)

The Ku is the ratio of obtained heat flux to critical heat flux of the working fluid at the evaporator section. When Ku has a value of more than one it mean s the pool boiling phenomena has occurred. Thus, Ku can be expressed as;

$$\mathrm{Ku} = \frac{q}{h_{fg}\rho_v \left[\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2} \right]^{0.25}} \tag{7}$$

Where, h_{fg}: latent heat of vaporization (J/kg), ρ_v: vapor density (kg/m^3), ρ_l: liquid density (kg/m^3), σ: surfacetension (N/m), g: gravitational acceleration (m/s^2).

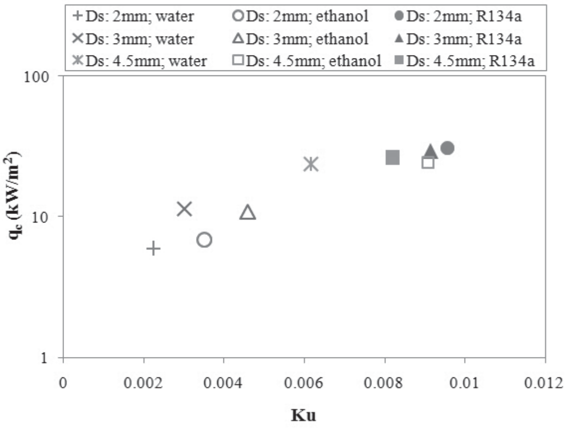

Figure 3 Relationship between heat flux and Kutateladze number. (Le: 50mm, De: 14.5 mm, Filling ratio: 40%, Working temp.: 80°C, Vertical position)

In (Figure 3), it can be seen that the Ku value increases following the working fluid type: R-134a, ethanol and water. The heat flux further increases with increasing Ku value.

2. Effect of Bond number (Bo)

The Bo is the ratio of buoyancy force to working fluid surface tension. It also represents the state of vapor bubbles that occur in nucleate boiling at the evaporator section. If Bo value is high, we can say that working fluid boils.

$$\mathrm{Bo} = D_i \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{0.5} \tag{8}$$

Where, D_i : tube inner diameter (mm)

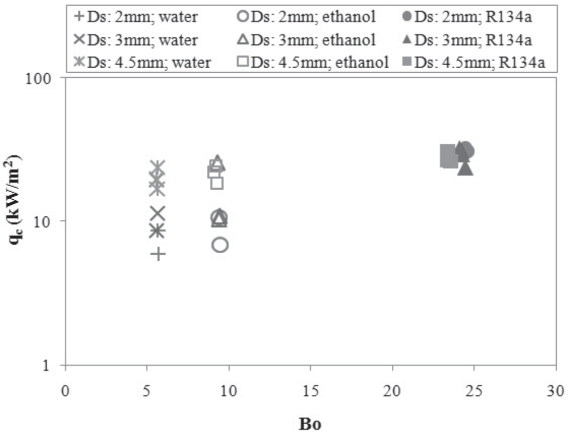

Figure 4 Relationship between heat flux and Bond number. (Le: 50mm, De: 14.5 mm, Filling ratio: 40%, Working temp.: 80°C, Vertical position)

The Ja value can be simply divided in three groups according to working as shown in (Figure 4). The result shows that maximum heat flux achieved when using R-134a.

3. Effect of Weber number (We)

The We is the ratio of dynamic force to surface tension force as expressed is Eq.(9). It represents the counter current interaction between the liquid film and vapor flow which occur inside evaporator and condenser section.

$$We=\frac{Q^2}{\rho_v D_i^3 h_{fg}^2 \sigma} \quad (9)$$

From experiments it was found that the We value increases with decreasing small closed end tube size. In the tested heat pipe, which is charged with water and ethanol, the obtained heat flux slightly decreases as the small closed end tube size decreases as shown in (Figure 5), This is the result of counter current phenomena inside the tube.

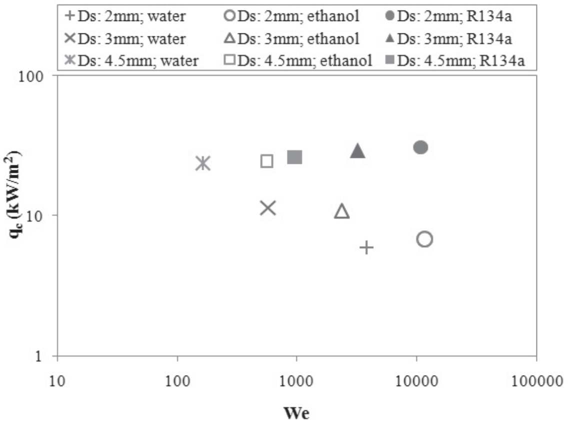

Figure 5 Relationship between heat flux and Weber number. (Le: 50mm, De: 14.5 mm, Filling ratio: 40%, Working temp.: 80°C, Vertical position)

4. Effect of Froude number (Fr)

The Fr is the ratio of the inertia force of vapor to the gravity force of the condensate liquid. It also represents the counter current be the same with We as earlier mentioned. and seen in (Figure 6)

$$Fr=\frac{Q^2}{\rho_v D_i^5 h_{fg}^2 g} \quad (10)$$

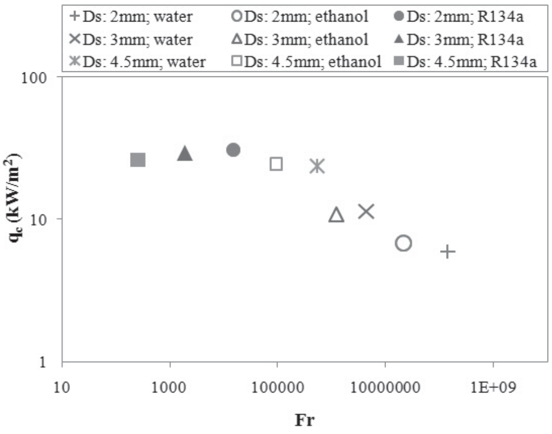

Figure 6 Relationship between heat flux and Froude number. (Le: 50mm, De: 14.5 mm, Filling ratio: 40%, Working temp.: 80°C, Vertical position)

5. Effect of Prandtl number (Pr)

The Pr is the ratio of the momentum diffusivity to thermal diffusivity of liquid as shown in Eq.(11). It represents convection of heat transfer phenomenon inside the heat pipe.

$$Pr=\frac{\mu_l Cp_l}{k_l} \quad (11)$$

Where μ_l: liquid viscosity (Pa.s), Cp_l: specific heat capacity of liquid (J/Kg.°C), k_l: liquid thermal conductivity (W/m.K)

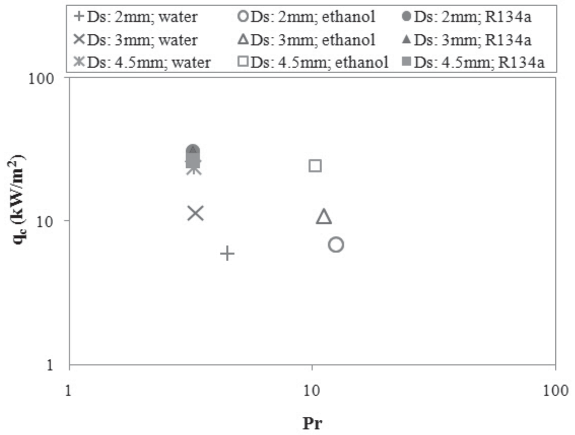

Figure 7 Relationship between heat flux and Prandtl number. (Le: 50mm, De: 14.5 mm, Filling ratio: 40%, Working temp.: 80°C, Vertical position)

In the results shown in (Figure 7), if the Pr value is low, it leads to high heat flux.

6. Effect of Jacob number (Ja)

The Ja is the ratio of latent heat to working fluid sensible heat. It represents the changing phase process of working fluid in the heat pipe.

$$Ja=\frac{h_{fg}}{Cp_l T_v} \quad (12)$$

Where T_v: vapor temperature (°C)

As we can see in (Figure 8), the Ja value is clearly classified by working fluid type. Moreover the heat flux gradually decreased when the small closed end tube size decreases.

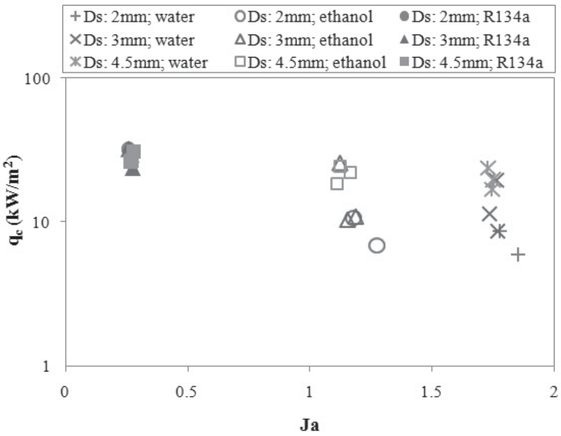

Figure 8 Relationship between heat flux and Jacob number. (Le: 50mm, De: 14.5 mm, Filling ratio: 40%, Working temp.: 80°C, Vertical position)

7. Effect of Density ratio (DR)

The DR is the ratio of vapor density to liquid density of the working fluid.

$$DR=\frac{\rho_v}{\rho_l} \quad (13)$$

Increased DR value is according to working fluid type, The tube size has a significant effect on the heat flux. (see Figure 9)

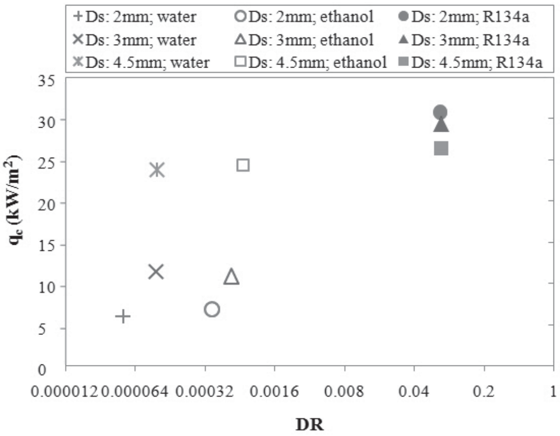

Figure 9 Relationship between heat flux and Density ratio. (Le: 50mm, De: 14.5 mm, Filling ratio: 40%, Working temp.: 80°C, Vertical position)

8. Effect of Aspect ratio (AR)

The AR is a dimensionless parameter which formulate based on the small closed end and special vapor chamber dimension as expressed in Eq.(13).

$$\mathrm{AR}=\left(\frac{\mathrm{De}}{\mathrm{Ds}}\right)\left(\frac{\mathrm{Lv}}{\mathrm{Le}}\right) \qquad (14)$$

Where De: diameter of the SVCs tube (mm), Ds: diameter of SCEs tube (mm), Lv: length of SVCs tube (mm) and Le: evaporator section length (mm). see in (Figure 10)

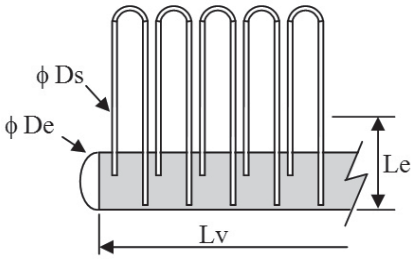

Figure 10 The dimension parameters of the tested heat pipe.

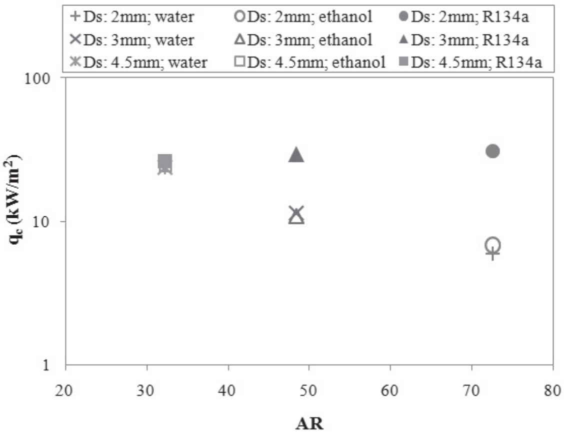

Figure 11: Relationship between heat flux and Aspect ratio. (Le: 50mm, De: 14.5 mm, Filling ratio: 40%, Working temp.: 80°C, Vertical position)

In (Figure 11) it shows that both water and ethanol have the same trend, AR increasing as a result of decreased heat flux but R-134a has no affect to heat flux at all.

9. Correlation equation

From the empirical correlation in terms of modified Ku form of Eq.(4) and Eq.(5) can be determined by the least squares technique as mentioned in section 2. Thus, the heat transfer correlation for SCEHP/SVCs in vertical position (90°) was;

$$\mathrm{Ku}_{90}^{*}=2.25\left[\frac{\mathrm{Bo}^{-1.2}\,\mathrm{We}^{-2.309}\,\mathrm{Fr}^{1.249}}{\mathrm{Pr}^{1.503}\,\mathrm{Ja}^{-4.318}\,\mathrm{AR}^{0.877}\,\mathrm{DR}^{1.232}}\right] \qquad (15)$$

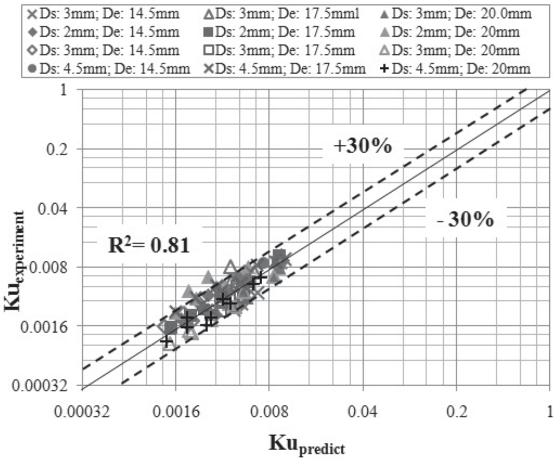

Figure 12 Comparison of experimental Ku vs. predicted Ku.

From (Figure 12), it shows the relationship between the Ku-experiment and Ku*-predict which obtained from Eq.(15) with the coefficient of determination (R^2) was 0.81. It could be observed that the data were scatted; approximately 85% of deviations are falling within ±30% band.

Conclusion

This paper's study on the empirical correlation for predicts the heat flux of the SCEHP/SVCs in vertical position was investigated. It could be concluded that, the non-dimension parameters namely Ku, Bo, We, Fr, Pr, Ja, DR and AR. established correlation (expressed as Eq. (16)) and can predict the heat flux, has the standard deviation (STD) of ±22.12% as illustrated in (Figure 13).

$$qc_{pre}^{*} = 2.25\left[\begin{matrix} Bo^{-1.2}We^{-2.309}Fr^{1.249} \\ Pr^{1.503}\,Ja^{-4.318}AR^{0.877}DR^{1.232} \end{matrix}\right] \times \left(h_{fg}\rho_v\left[\frac{\sigma g\left(\rho_l\text{-}\rho_v\right)}{\rho_v^2}\right]^{0.25}\right) \quad (16)$$

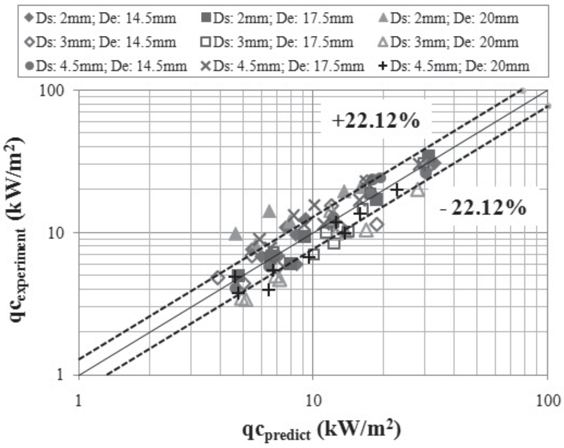

Figure 13 Comparison the heat flux experiment vs. prediction in vertical position.

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