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A CORRELATION FOR ADIABATIC THERMAL RESISTANCE OF HORIZONTAL PULSATING HEAT PIPES

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Abstract. *In this paper a new correlation for thermal resistance of the adiabatic section in pulsating heat pipes in the horizontal position is presented. The correlation is based on the Kutateladze number and was adjusted with new experimental data for polymeric tube pulsating heat pipes. The experimental tests were obtained for pulsating heat pipes of 20 to 80 number of turns, 1.6mm and 2.0 mm internal diameter and for R134a refrigerant. The mean absolute error between the values obtained experimentally and the values obtained via the proposed correlation varied in the range of 11% to 54%.*
Keywords: *Correlation, Adiabatic Thermal Resistance, Pulsating Heat Pipe, Horizontal, Kutateladze number*

1. INTRODUCTION

Pulsating heat pipes are a relatively new class of heat tubes, considered a promising device in thermal management, especially with regard to the cooling of miniaturized components, according to Ferreira (2020). Pulsating heat pipes was propesed by Akachi (1990), its heat transfer mechanism is based on the oscillating or pulsating motions of the vapor bubbles and the liquid plugs along the tube, presents three basic regions: the evaporator, the condenser and the adiabatic section. The Fig. 1 shows the typical structure of a pulsating heat pipe.
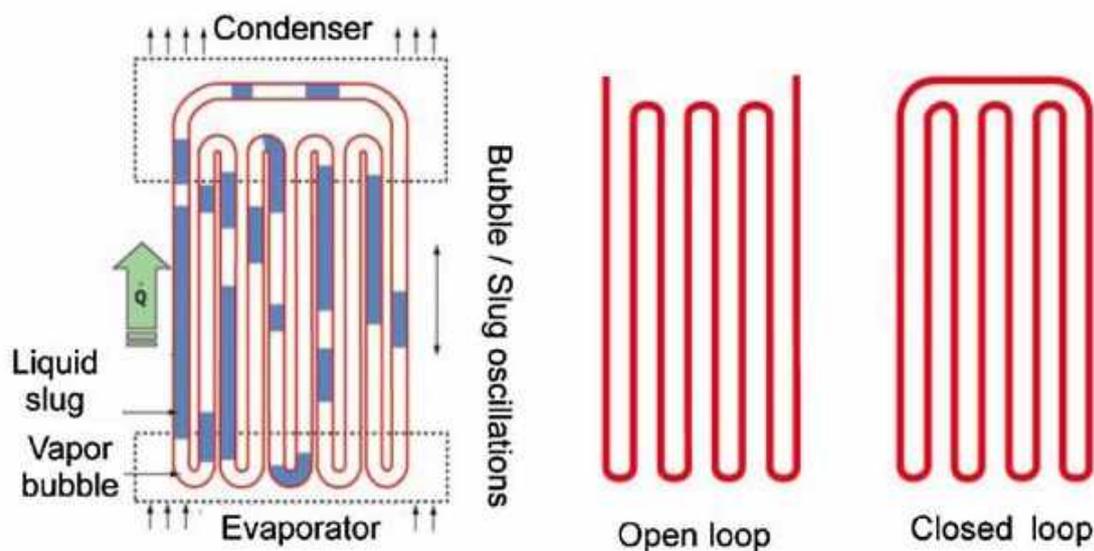

Figure 1. Schematic of a pulsating heat pipe and its design variations, Charoensawan et al. (p. 2011, 2003)

According to Khandekar et al. (2003) the proposition of correlations with a wide range of applicability is convenient to use dimensionless numbers. These numbers should consider the slope of the pulsating heat pipe α, the properties of the working fluid, the inner diameter of the pipe D_i, the number of turns, N, of the pulsating heat pipe, the length of the evaporator, L_e, the length of the condenser, L_c, the total length of the tube L_t and the filling ratio, FR.

This work presents a new correlation for thermal resistance of the adiabatic section in pulsating heat pipes in the

horizontal position, based on the Kutateladze number, Ku.

2. LITERATURE REVIEW

The Kutateladze number, Ku, is dimensionless number used to represent the thermal performance of a pulsating heat pipe. According to Rittidech et al. (2003) it can be defined to the Eq. (1),

$$Ku = \frac{\dot{q}}{h_{lv} \cdot \rho_v^{0.5} \left[\sigma \cdot \vec{g} \cdot (\rho_l - \rho_v) \right]^{0.25}} \tag{1}$$

where, $\dot{q}$, is the heat flux.

In their work, Rittidech et al. (2003) used copper tube with internal diameters equal to 0.66 mm, 1.06 mm and 2.03 mm, with ethanol, water and R123, and filling ratio equal to 50 % , in the horizontal position, to propose a correlation for predicting the heat flux, $\dot{q}$, based on the Kutateladze number, Ku, Eq. (1). The correlation is shown in Eq. (2),

$$Ku_{0°} = 0.0052 \left[\left(\frac{D_i^{4.3} L_t^{0.1}}{L_e^{4.4}} \right) N^{0.5} \left(\frac{\rho_v}{\rho_l} \right)^{-0.2} Pr_v^{-25} \right]^{0.116} \tag{2}$$

where, N, equal to the number of turns in the adiabatic section and Pr_v, is the Prandtl number of the vapor, defined according to Eq. (3),

$$Pr_v = \left(\frac{c_p \cdot \mu}{k} \right)_v \tag{3}$$

The Fig. 2 shows the comparison of the results obtained by Rittidech et al. (2003), Lin et al. (2000) and Maezawa et al. (1996).
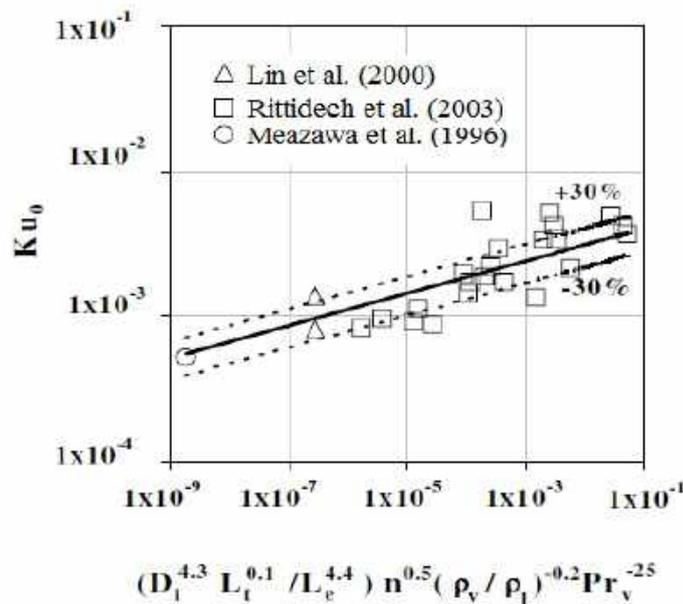

Figure 2. The comparison between Ku_{model} and Ku_{exp}, Rittidech et al. (2003, p. 506)

Rittidech et al. (2003) concluded that the correlation can be used to predict the heat flux in the horizontal position, even without including the oscillation parameters and the circulation phenomena that occur in the pulsating heat pipe.

Katpradit et al. (2005) used pulsating heat pipe of the copper with internal diameters equal to 0.66 mm, 1.06 mm and 2.03 mm, with ethanol, water and R123 and filling fraction equal to 50%, the proposed correlation for the horizontal position, $Ku_{0°}$, is given by Eq. (4), the error obtained was equal to $\pm$ 18 %. Fig. 3 shows the comparison between Ku_{exp} and Ku_{model}.

$$Ku_{0°} = 53.680 \left[\frac{D_i}{L_e}\right]^{1.127} \left[\frac{C_p T}{h_{lv}}\right]^{1.417} \left\{ D_i \left[\frac{\vec{g}(\rho_l - \rho_v)}{\sigma}\right]^{0.5} \right\}^{-1.32} \tag{4}$$
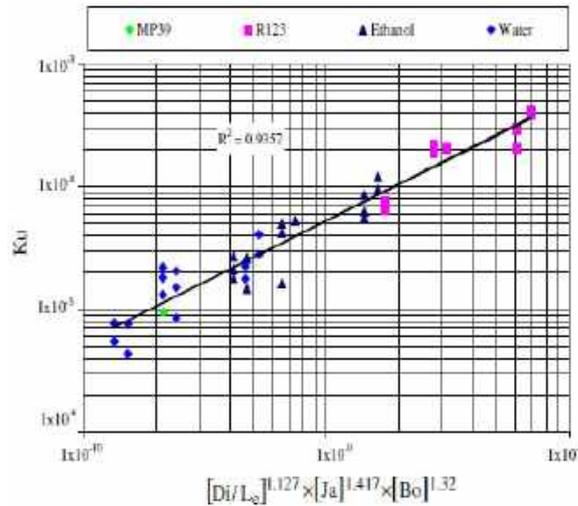

Figure 3. Correlation of Ku with $[D_i/L_e]^{1.127} \times [\text{Ja}]^{1.417} \times [\text{Bo}]^{1.32}$ for horizontal, Katpradit et al. (2005, p. 2148).

Sakulchangsatjatai et al. (2016) used pulsating heat pipe of the copper tubes with internal diameters of 1.5 mm, 1, 78 mm and 2.16 mm, with R123, R141b, acetone and ethanol and a filling fraction equal to 50 %. The correlation for the horizontal, $Ku_{0°}$, is given by Eq. (5). The deviation presented by the correlation was equal to $\pm$ 37 %. The Fig. 4 presente the comparison between Ku_{model} and Ku_{exp}.

$$Ku_{0°} = 9.62.10^{-3} Ka^{0.152} Pr_l^{0.905} Ja^{-0.110} \left(\frac{L_e}{D_i}\right)^{-1.212} \tag{5}$$

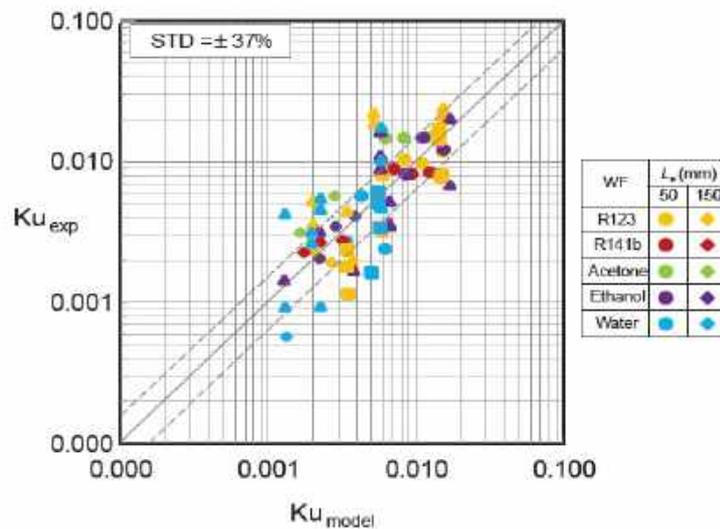where, Ka, is Karman number and, Ja, is Jakob number.

Figure 4. The comparison between Ku_{model} and Ku_{exp}, Sakulchangsatjatai et al. (2016, p. 1563).

3. EXPERIMENT DESCRIPTION

The experimental bench was designed to allow relatively simple modification of the experimental parameters over a wide range of conditions, such as number of turns, tube diameter, angle of inclination, working fluid and filling ratio. For the horizontal tests, the test facility was configured such as the evaporator and condenser are located on the same level in respect to the gravitational field. The transient method was used to determine the thermal resistance of the adiabatic section where the temperature of the evaporator is imposed instead of heat flux, as shown in Moreira, Colmanetti and Tibiriçá (2019), to determine the heat rate.

In experiments presented in the Fig. 5 the pulsating heat pipes were inserted between two reservoirs, the evaporator reservoir and the condenser reservoir. The evaporator reservoir was filled with water that was heated with an electrical resistance up to the desired temperature around $60°$C. In order to avoid stratification of the temperature field of the water inside the evaporator reservoir , an pump with flow rate 180 l/h and power equal to 4 W was inserted in the same to mix the water. The condenser reservoir was kept always at $0°$C using a mixture of ice and liquid water. For data acquisition type K thermocouples were used for water temperature measurements inside the evaporator reservoir, $T_{water,e}$, for the temperatures at the input and output of the pulsating heat pipe evaporator, T_e, and for the temperatures of the input and output of the condenser section, T_c, indicated by the symbols T_1, T_2, T_3 and T_4, where L is the distance between evaporator and condenser. The pulsating heat pipes were made of polyamide flexible tube, two diameters were tested, one with internal diameter of 1.6 mm and a second with 2.0 mm. The number of turns of the tested pulsating heat pipes were 20, 40, and 80. The pulsating heat pipes were filled with R134a with a filling ratio equal at 60%.
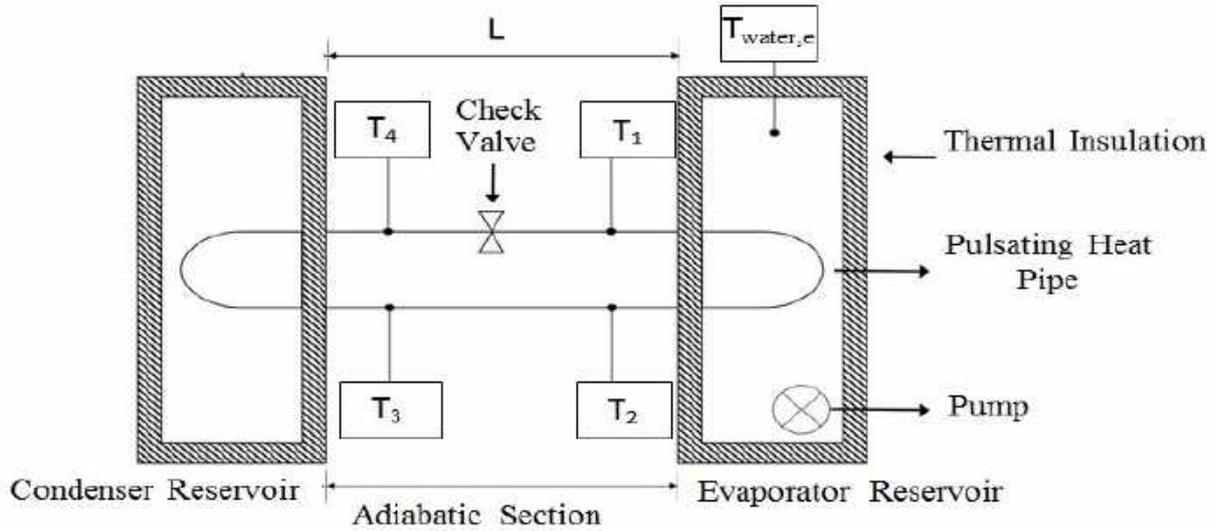

Figure 5. The experimental set-up in horizontal.

4. DATA REDUCTION PROCEDURE

The heat transfer in the pulsating heat tubes were is determined using the transient method, based on the variation of the water temperature in the evaporator reservoir along time. The rate of change of internal energy, dE/dt, that occurs in the water in the evaporator, is given by Eq. (6),

$$\frac{dE}{dt} = \frac{m_{water,e} \cdot c_{p,water} \cdot \Delta T_{water,e}}{\Delta t_{\Delta T_{water,e}=2°C}} \qquad (6)$$

The mass of water in the evaporator reservoir, $m_{water,e}$, was equal at 3 kg in all cases studied. The specific heat, $c_{p,water}$, of water is equal at 4180 J/kg.K. The temperature variation, $\Delta T_{water,e} = 2°$C, was constant in all cases and, $\Delta t_{\Delta T_{water,e}=2°C}$, is the time interval in seconds for the variation, of $\Delta T_{water,e} = 2°$C the water temperature in the evaporator reservoir.

The heat lossess in the evaporator due to the temperature difference between the water in the evaporator reservoir, $T_{water,e}$, and the ambient temperature, T_∞, is given by Eq. (7),

$$Q_{amb} = (T_{water,e} - T_\infty)/R_\infty \qquad (7)$$

where, R_∞, is the average thermal resistance between the water in the evaporator reservoir and the external environment.

This ambient thermal resistance, R_∞, was measured without using pulsating heat tubes to cool the water in the evaporator and determined in accordance with the Eq. (8),

$$R_\infty = \frac{(T_{water,e} - T_\infty)}{Q_{losses,environment,withoutTubes}} \tag{8}$$

The average value measured for R_∞ was equal to 2.245°C/W for ambient temperatures, T_∞, close to 25°C. Heat lossess to the environment without the use of pulsating heat tubes, $Q_{losses,environment,withoutTubes}$, are calculated according to the Eq. (9),

$$Q_{losses,environment,withoutTubes} = \frac{m_{water,e} \cdot c_{p,water} \cdot \Delta T_{water,e}}{\Delta t_{\Delta T_{water,e}=2°C}} - W_{mean,pump} \tag{9}$$

the $\Delta t_{\Delta T_{water,e}=2°C}$ is the time interval required to vary $\Delta T_{water,e} = 2°C$ the water temperature in the evaporator reservoir, $T_{water,e}$ without the use of pulsating heat tubes and $W_{mean,pump}$, is the mean pump power.

To calculate the mean pump power, $W_{mean,pump}$, the value of the pump power $W_{pump} = 3$ W was used, according to the manufacturer's specification. The time the pump was on, $\Delta t_{pump,on}$, was equal to 45 s, and time, $\Delta t_{\Delta T_{water,e}=2°C}$ to was the time needed for the water in the evaporator reservoir to change 2°C.

$$W_{mean,pump} = \frac{W_{pump} \cdot \Delta t_{pump,on}}{\Delta t_{\Delta T_{water,e}=2°C}} \tag{10}$$

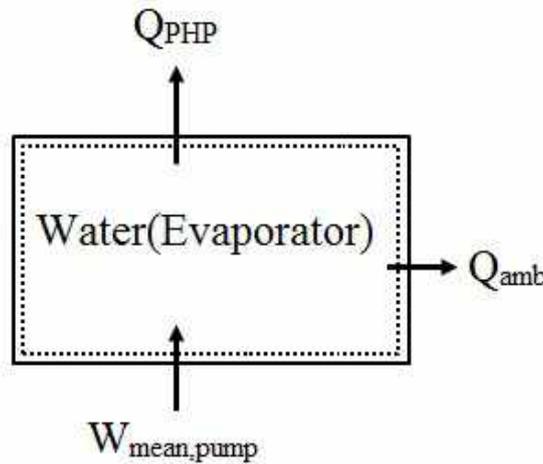The energy balance in the water within the evaporator reservoir of the pulsating heat pipe is shown in Fig. 6

Figure 6. Energy balance in the water within the evaporator reservoir of the pulsating heat pipe.

From the 1ª law of thermodynamics, the energy balance can be developed as follows, and the heat rate transfered by the pulsating heat pipe determined.

$$Q - W = \left(\frac{dE}{dt}\right)_{water,e} = m_{water,e} \cdot c_{p,water} \cdot \left(\frac{dT_{water,e}}{dt}\right)$$

$$\cancel{Q_{input}}^{\,0} - Q_{output} - W = m_{water,e} \cdot c_{p,water} \cdot \left(\frac{dT_{water,e}}{dt}\right)$$

$$-Q_{PHP} - Q_{amb} - W = m_{water,e} \cdot c_{p,water} \cdot \left(\frac{dT_{water,e}}{dt}\right)$$

$$Q_{PHP} = -\left[m_{water,e} \cdot c_{p,water} \cdot \left(\frac{dT_{water,e}}{dt}\right)\right] - Q_{amb} - W$$

$$Q_{PHP} = -\left[m_{water,e} \cdot c_{p,water} \cdot \left(\frac{-\Delta T_{water,e}}{\Delta t}\right)\right] - Q_{amb} - (-W_{mean,pump})$$

$$Q_{PHP} = m_{water,e} \cdot c_{p,water} \left(\frac{\Delta T_{water,e}}{\Delta t}\right) + W_{mean,pump} - Q_{amb} \tag{11}$$

5. DEFINITION OF ADIABATIC THERMAL RESISTANCE

The thermal resistance of the adiabatic region of the pulsating heat pipe, R_{lvPHP}, is defined according to the Eq. (12),

$$R_{lvPHP} = \frac{T_e - T_c}{Q_{PHP}} \tag{12}$$

where T_e is the evaporator outlet temperature and T_c is the condenser outlet temperature and the input power, Q_{PHP}, defined according to Eq. (11).

6. CORRELATION FOR THE THERMAL RESISTANCE OF THE ADIABATIC SECTION IN THE HORIZONTAL POSITION.

The database used to obtain the correlation in the horizontal position of the adiabatic section, was obtained from the experimental results with a total of 32 experimental data. With this database, a new correlation was proposed, $Ku_{hor,new}$, based on the Kutateladze number, Ku, defined according to Eq. (1). The new correlation, $Ku_{hor,new}$ is a function of the inner diameter, D_i, the length of the evaporator, L_e, the total length of the pipe, L_t, the number of turns in the adiabatic section, N, the filling ratio, FR, the vapor phase densities, ρ_v, and the liquid phase, ρ_l of the working fluid, according to the Eq. (13),

$$Ku_{hor,new} = f(D_i, L_e, L_t, N, FR, \rho_v, \rho_l) \tag{13}$$

The values of the vapor phase densities, ρ_v, and the liquid phase, ρ_l, were obtained from the operating temperature, $T_{op} = (T_e + T_c)/2$, where T_e and T_c, are the evaporator and condenser outlet temperatures from the experiments, these values were calculated in the EES (*Engineering Equation Solver*) and stored in a .txt file, the values of the geometric parameters were also stored in .txt files, afterwards all data was imported with the load command by Matlab.

Based on the analysis of dimensionless numbers, the new correlation, $Ku_{hor,new}$, has the following form, Eq. (14),

$$Ku_{hor,new} = a\left(\frac{D_i}{L_e}\right)^b \left(\frac{L_t}{L_e}\right)^c N^d \left(\frac{\rho_v}{\rho_l}\right)^e FR^f \tag{14}$$

The coefficients and exponents of Eq. (14) were obtained using the Matlab. The correlation for the horizontal position is shown in Eq. (15),

$$Ku_{hor,new} = 8.9133\left(\frac{D_i}{L_e}\right)^{-1.0621} \left(\frac{L_t}{L_e}\right)^{0.0995} N^{-0.7187} \left(\frac{\rho_v}{\rho_l}\right)^{6.0936} FR^{-15.9608} \tag{15}$$

The Tab. 1 shows the range of values of the dimensionless used to generate the correlation in horizontal position is shown in Eq. (15).

Table 1. Range of values of the dimensionless used to generate the correlation in horizontal position.

Dimensionless	Range of values
D_i/L_e	0.0008 - 0.004
L_t/L_e	4
N	20 - 80
ρ_v/ρ_l	0.035-0.05
FR	0.6

The mean absolute error, ϵ, is defined according to the Eq. (16), and $\lambda_{30\%}$ is the percentage of values that have a relative error less than 30%.

$$\epsilon = \frac{1}{N}\sum_{i=1}^{N} \frac{|Ku_{exp} - Ku_{hor,new}|}{|Ku_{hor,new}|} \tag{16}$$

7. RESULTS

Fig. 7 shows the comparison between the Kutateladze number with the experimental data, Ku_{exp}, and the Kutateladze number based on the correlation, $Ku_{hor,new}$. Absolute mean error was obtained ϵ = 35.0 % and $\lambda_{30\%} = 46.9\%$ considering the complete database.
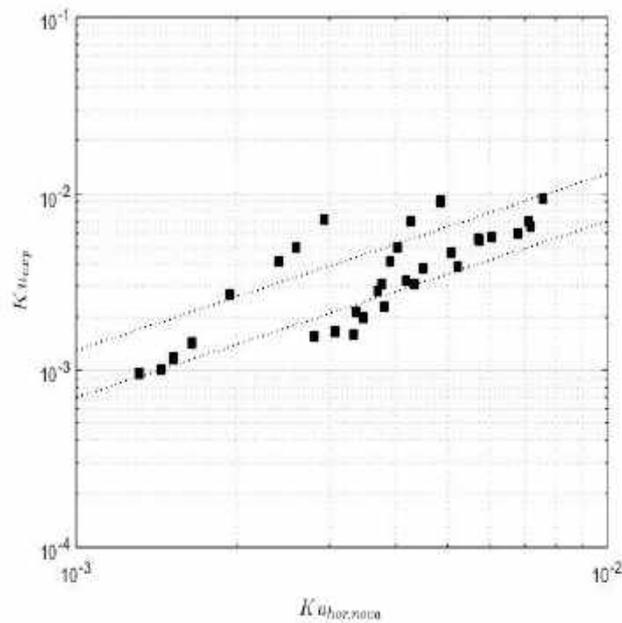
Figure 7. Comparison between the experimental Kutateladze, Ku_{exp}, and the Kutateladze number, Ku_{prev}, based on the correlation, Eq. (15), in the horizontal position.

The experimental values obtained for the thermal resistance in the adiabatic region, R_{lvPHP}, of the pulsating heat pipe were compared with the correlations proposed by Rittidech et al. (2003) and Katpradit et al. (2005), and also with the correlations obtained in this work for the horizontal position presented in Eq. (15). The Fig. 8 shows the comparison between thermal resistances, for the internal diameter equal to 1.6 mm, 40 turns in the adiabatic section, using R134a and $FR = 60\%$.
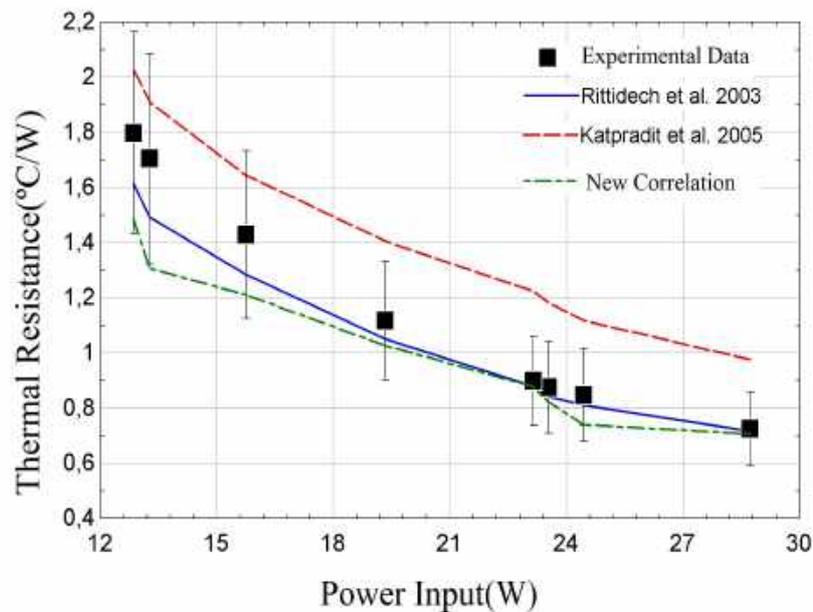

Figure 8. Comparison between thermal resistances for $D_i = 1.6$ mm and number of turns, $N = 40$ turns.

The Fig. 9 shows the comparison between thermal resistances, for the internal diameter equal to 1.6 mm, 80 turns in the adiabatic section, using R134a and $FR = 60\%$
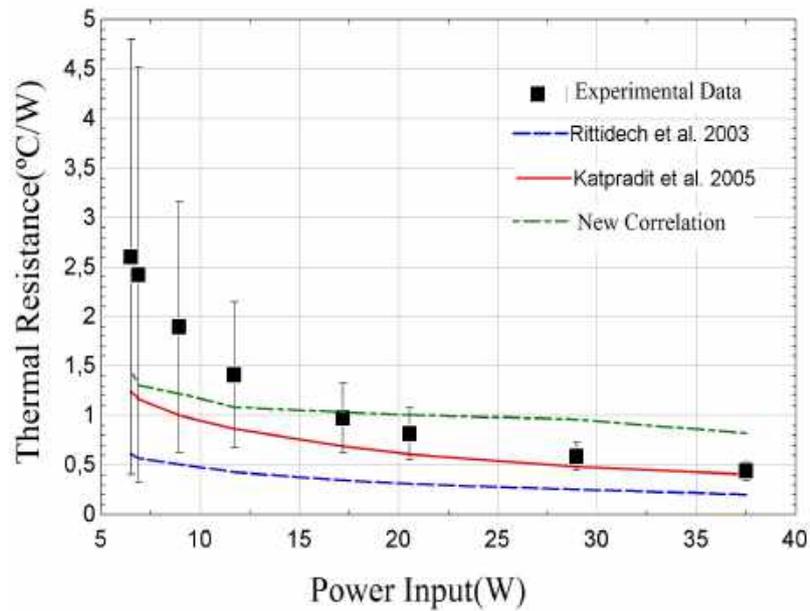
Figure 9. Comparison between thermal resistances for D_i = 1.6 mm and number of turns, N = 80 turns.

The Fig. 10 shows the comparison between thermal resistances, for 2.0 mm internal diameter, 20 turns in the adiabatic section, using R134a and FR = 60 %
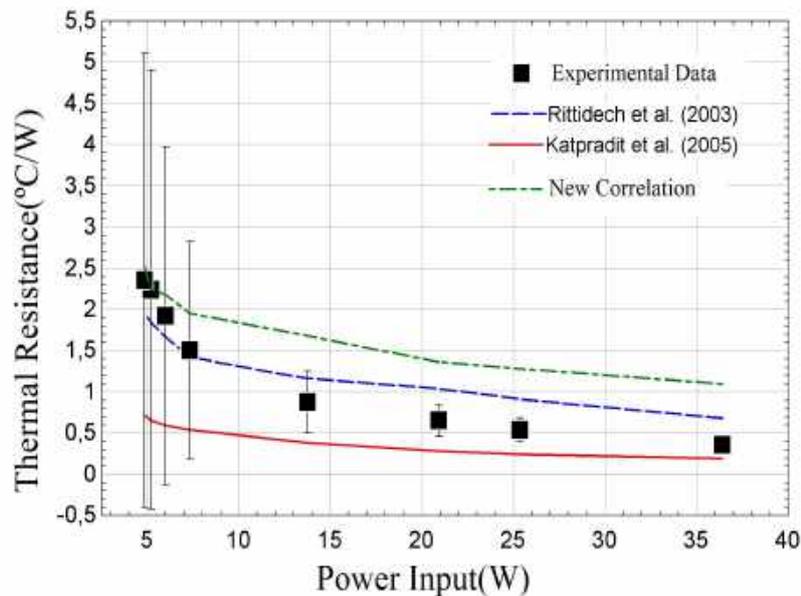

Figure 10. Comparison between thermal resistances for D_i = 2.0 mm and number of turns, N = 20 turns.

The Fig. 11 shows the comparison between thermal resistances, for internal diameter equal to 2.0 mm, 40 turns in the adiabatic section, using R134a and FR = 60 %
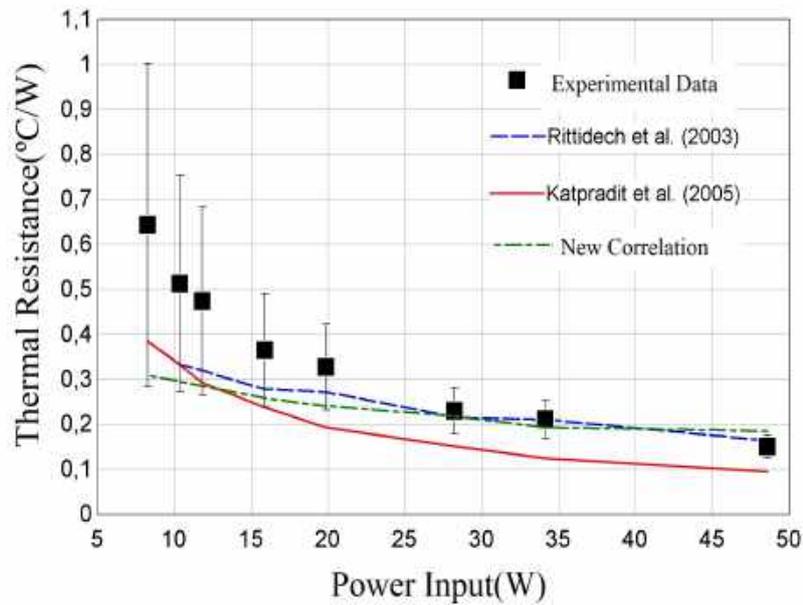
Figure 11. Comparison between thermal resistances for D_i = 2.0 mm and number of turns, N = 40 turns.

The Tab. 2 presents the values of the absolute mean error ϵ using the correlations proposed by Rittidech et al. (2003) and Katpradit et al. (2005), and also the correlation obtained in this work presented in Eq.(15).

Table 2. Values of the absolute mean error ϵ and $\lambda_{30\%}$ for the case studies.

Diameter(mm)	Nº of Turns(N)	Correlation	Absolute Mean Error (ϵ)	$\lambda_{30\%}$
1.6	40	Rittidech et al.(2003)	6.3%	100%
		Katipradit et al.(2005)	25.5%	62.5%
		New correlation horizontal, Eq.(15)	11%	100%
	80	Rittidech et al.(2003)	67%	25%
		Katipradit et al.(2005)	16%	50%
		New correlation horizontal, Eq.(15)	41%	10%
2.0	20	Rittidech et al.(2003)	38%	50%
		Katipradit et al.(2005)	61%	0%
		New correlation horizontal, Eq.(15)	54%	37.5%
	40	Rittidech et al.(2003)	20.5%	62.5%
		Katipradit et al.(2005)	38%	0%
		New correlation horizontal, Eq.(15)	28%	62.5%

As we can see in Tab. 2 that the correlations of Rittidech et al. (2003) and Katipradit et al. (2005), predicted the experimental data with absolute mean error in the range of 6.3% to 67% in horizontal position. The proposed correlation, Eq. (15) presented an absolute mean error, in the range of 11% to 54%. Regarding the values of $\lambda_{30\%}$, correlations of Rittidech et al. (2003) presents values in the range of 25% to 100%, Katipradit et al. (2005) presents values in the range of 0% to 62.5% and tha new proposed correlation, presents values in the fax of 10% to 100%. Based on the values of $\lambda_{30\%}$ it can be concluded that the proposed correlation has a performance very close to the correlations of Rittidech et al. (2003), but superior performance when compared with the correlation of Katipradit et al. (2005).

8. CONCLUSIONS

The application of pulsating heat pipe made of metallic materials, such as copper and aluminum, are not suitable for the new technologies of video monitors and solar panels, according to Ferreira (2020). The main use of pulsating heat pipe polymeric is due to the low cost, high flexibility and low thermal conductivity. Thus, the study of this type of pulsating heat pipes deserves special attention.

The development of a new correlation for the horizontal position is a major contribution to the literature, as this position requires more experimental studies to better understand the operation of the pulsating heat pipe.

9. ACKNOWLEDGEMENTS

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