ХОЛОДИЛЬНА ТЕХНІКА ТА ЕНЕРГОТЕХНОЛОГІЇ

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The combined effect of heating zone length and inclination angle on start-up, transient and operational characteristics of pulsating heat pipe

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Pulsating heat pipes (PHP) are novel heat transfer devices which have wide prospects of application in energy, refrigeration, cryogenic systems and electronics cooling because of simple design and high efficiency of heat transfer. However, heat transfer characteristics of PHP depend on many parameters. This paper is dedicated to experimental investigation of the impact of heating zone length and angle of inclination on the start-up and operational characteristics of PHP. The investigation involved a systematic variation of the heating zone length and inclination angle with measuring of key performance indicators, including start-up heat flux density and temperature, transient heat flux density, and thermal resistance, for water, methanol and pentane as a heat carrier. 5-turn PHP made of copper capillary tube with inner diameter 1,1 mm was used as experimental sample. Main operational modes of PHP were defined and described in the paper based on obtained experimental data. Results indicate that increasing the heating zone length from 10 to 50 mm at all tested inclination angles significantly enhances the thermal performance of PHP by reducing start-up, transient heat flux densities and thermal resistance. Specifically, thermal resistance decreased by up to 51,8% and start-up, transient heat flux densities up to 68-71% with longer heating zone lengths. Also, it was shown that maximum transferred heat flux increased up to 59% with increasing in heating zone length. These findings suggest that optimizing heat zone length can improve start-up efficiency and overall heat transfer performance. The impact of inclination angle varies with the coolant used; generally, water outperforms methanol and pentane across all orientations. Methanol ranks next, with pentane showing the least performance. However, methanol and pentane are viable choices for low heat flux applications in vertical bottom heating mode. The study provides valuable insights for the design of PHP in energy, refrigeration and electronics cooling systems, highlighting the importance of heating zone (HZ) length configuration in achieving optimal performance.
Keywords: *Pulsating heat pipe; Heating zone length; Heat flux density; Temperature; Start-up characteristics; Transient characteristics; Inclination angle; Thermal resistance*

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1. Introduction

Effective heat transfer in modern energy systems, refrigeration equipment and electronics cooling has become increasingly challenging due to trends on rising of heat power with simultaneous equipment downsizing. Ensuring reliability and high-performance parameters under these conditions demands specialized thermal techniques. The Akachi-invented Pulsating Heat Pipe (PHP) [1] is a state-of-the-art thermal technology valued for its simple construction and ability to transfer heat over significant distances. PHPs utilize the phase change phenomenon and oscillatory motion to transfer heat [2]. These comprise a long capillary tube bent into a serpentine shape and partially filled with working fluid. Their simple design makes them suited for use in energy, refrigeration, cryogenic and electronics systems that demand small sizes, light weight and efficient heat transfer [3]. However, their performance depends on a complex interplay of parameters. It is heavily influenced by various design and operational parameters, including the channels geometry [4-7], working fluids physical properties [8], and the specific conditions under which they operate [9-11]. Optimizing these factors is crucial for enhancing the thermal efficiency and reliability of pulsating heat pipes (PHPs), and thus these primary design parameters have been extensively explored in the past. Among the key design factors, the combined impact of heating zone (HZ) length and inclination angle on PHP performance is under-explored, yet it is a critical parameter significantly influencing PHP efficacy.

2. Analysis of the Latest Research

Some recent studies have demonstrated that modifying the heating and condenser regions affects thermal resistance and heat transfer rates, concluding that a longer heating zone relative to the condensing zone length reduces thermal resistance [12, 13]. Whereas, lately in paper [14] varying the evaporator-to-condenser length ratios from 0,4 to 1,2 in 0,2 increments found that a 0,8 ratio yielded the best PHP performance, with thermal resistance dropping of approximately 6 times at the same heat flux. Research has also been done on the impact of heating zone length alone, maintaining a constant condenser zone length [15]. This study investigated ethane PHP on pulse tube refrigerators with heating zone length ranging from 40 to 240 mm, and similar results were obtained, although stable operation was only achieved with a heating zone length of 120 mm. Most studies have been conducted by varying both the condenser length and heating zone length together, or using larger lengths, often overlooking the dimensions of modern electronic equipment such as CPU coolers, which typically have an overall height of 150-155 mm. To the best of the author's knowledge, no study has specifically investigated the influence of heating zone length on PHP performance at various orientations relevant to electronics cooling. Therefore, investigating the sole effect of heating zone length on PHP performance at various orientations relevant to electronics cooling remains an unsolved and urgent task.

3. Purpose and Objectives of the Study

The purpose of the present study is to investigate the combined impact of heating zone length and inclination angle on the start-up, transient and operating parameters of PHP. To achieve this purpose following objectives are set:

– to present the proposed design of PHP and investigate the combined influence of HZ length and inclination angle on its starting, transient and operating characteristics;

– to evaluate the thermal performance of PHP using different working fluid under varying HZ length and inclination angle;

– to identify optimal configurations of HZ length and inclination angle that enhance starting, transient and operating characteristics for different fluids.

4. Experimental sample and setup

The PHP consisted of five turns made of copper capillary tube with inner/outer diameter 1,1/2,1 mm, and were designed with different heating zone lengths of 10 mm, 30 mm, and 50 mm. The condensing zone length was kept constant at 100 mm, while the overall length of the PHP remained the same for all heating zone lengths. Overall height (length) of PHP was chosen to be equal to 154 mm. With a 50 mm heating zone and a fixed 100 mm condensation zone, the adiabatic zone is almost absent. For 10 mm and 30 mm heating zones, the adiabatic zone lengths will be 44 mm and 24 mm, respectively. To conduct the experiments, PHP was mounted on a metal plate along with an ohmic heater placed on the heating zone and a cooler positioned on the condensing zone. Insulating material was kept between cooler and plate to avoid heat leakages from cooler to the plate. To lower the thermal resistance between the PHP and cooler, a thermal grease with a thermal conductivity of 4,5 W/(m·K) was employed between their surface contacts. The metal plate was equipped with levelling screws to allow for the adjustment of the inclination angle. The investigation included five inclination angles: +90° (vertical position with bottom heating), +45°, 0° (horizontal position), -45°, and -90° (vertical position with top heating). Data from all thermocouples was collected by multichannel data acquisition module. Temperature of cooling water was set to 22°C and maintained at constant level by means of a thermostat. Mass flow rate of cooling liquid was also maintained at constant level, and it was measured with rotameter (fig. 1).

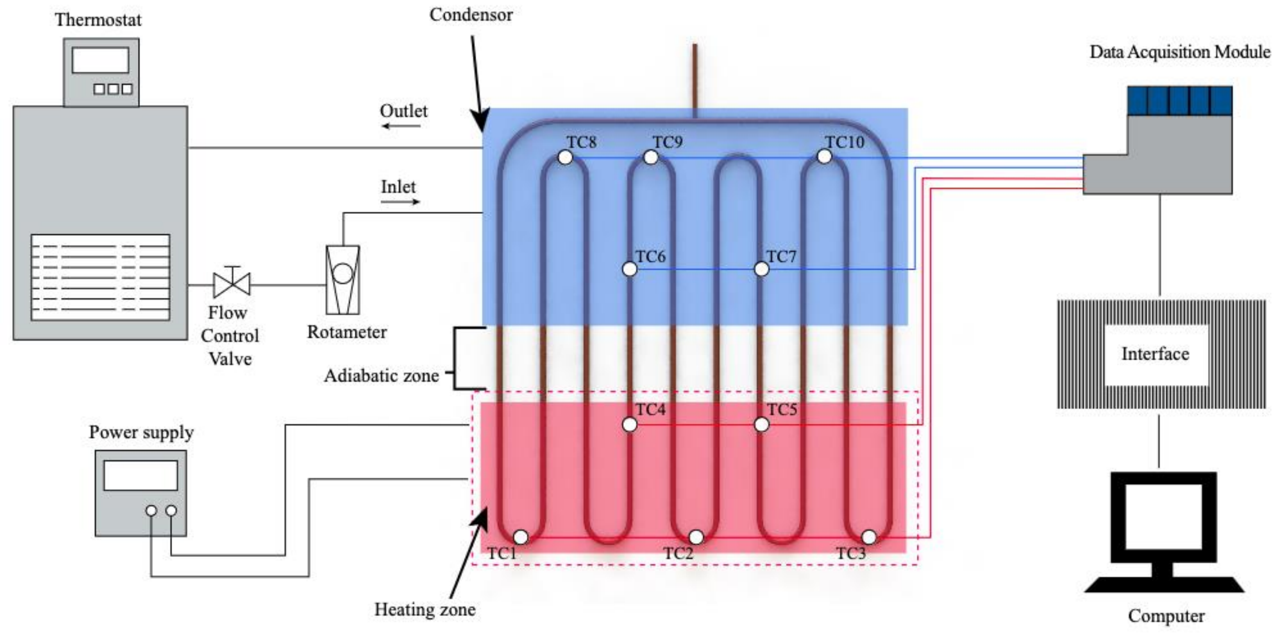
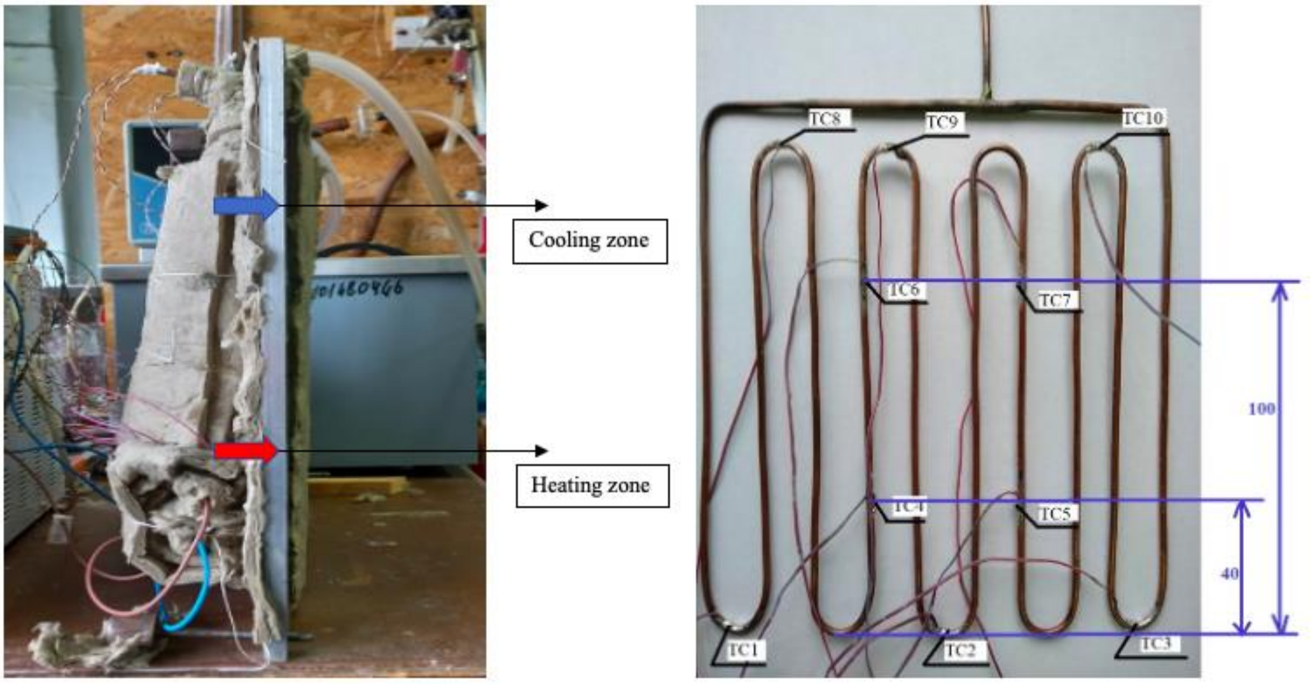


***Figure 1** – Scheme of the experimental set up*

PHP along with heater and condenser were covered with thermal insulation made of basalt fibre to reduce heat leakages to environment. Fig. 2 shows the experimental sample and thermocouple placement. All the geometrical details and investigated factors are listed in the Table 1.



a) b)

***Figure 2** – Experimental sample photograph at vertical bottom heating mode (a) and thermocouple placement (b)*

***Table 1**– Main design parameters for the PHP and factors investigated*

Design parameters		Factors investigated	
Parameter	**Value**	**Factor**	**Value**
Inner/outer diameter	1,1/2,1 mm	Heat carrier	Pure liquids: water, methanol, pentane
Number of turns	5	Filling ratio	50±0,5%.
Overall width	142 mm	Heating zone length	10, 30, 50 mm
Overall height	154 mm	Inclination angle	+90°, +45°, 0°, -45°, -90°
Heating zone length	10, 30, 50 mm	Heat input	0-80 W
Condensing zone length	100 mm		

5. Experimental data processing

Thermal resistance(R), a significant performance parameter of PHP, is evaluated to understand their heat transfer characteristics and determined using equation (1)

$$R = \frac{\overline{t}_h - \overline{t}_c}{Q_{transf}} \quad (1)$$

The average temperatures of the heating zone (t_h) and the cooling zone (t_c) , are calculated as:

$$\overline{t}_h = \frac{\sum_{i=1}^{k} t_i}{k} \quad (2)$$

$$\overline{t}_c = \frac{\sum_{i=1}^{k} t_i}{k} \quad (3)$$

where (t_i) – average measurement of each thermocouple placed in the heating zone during steady state mode, °C.

The transferred heat flux (Q_{transf}) is calculated by the equation of thermal balance as below:

$$Q_{transf} = G \cdot C_p \Delta t_{cool} \quad (4)$$

where G – mass flow rate of the cooling water, kg/s; C_p – isobaric heat capacity of the cooling water, J/(kg·K); Δt_{cool} – temperature difference of cooling water, °C.

The transferred heat flux density (q) is calculated using the transferred heat flux and the area corresponding to different heating zone lengths:

$$q = \frac{Q_{transf}}{F_h} \quad (5)$$

where F_h – heat transfer area in the heating zone, m^2.

Additional specific heat flux densities are similarly formulated, each associated with distinct operational phases of the PHP. For instance, the start-up heat flux density (q_{start}) is determined using the transferred heat flux at the PHP's start-up moment. Similarly, the heat flux density corresponding to pulsation mode operation (q_{puls}) utilizes the transferred heat flux at the transition from thermosyphon to pulsation mode. The maximum heat flux density (q_{max}) is calculated with the highest transferred heat flux before any crisis or local instability within the PHP occurs. Additionally, the start-up temperature (t_{start}) is defined as the average of the heating zone temperatures at start-up. Experimental error estimation was performed using the method outlined in [16] and the Engineering Equation Solver (EES) [17], which applies statistical and mathematical techniques for uncertainty analysis. The relative errors in determining key parameters, such as total transferred heat flux (Q_{transf}) and thermal resistance (R), were observed to be in range from a minimum of 3,2% to a maximum of 3,6%.

6. Operational modes of pulsating heat pipe

The various operating modes of the PHP, when tested with water at a 30 mm HZ length in vertical bottom heating mode, are illustrated in Figure 3. Upon the initial heat input of 5 W, temperatures begin to steadily increase, and heat transfer occurs primarily through heat conductivity mode once a steady state is achieved. In this mode, occasional unstable single pulsations were also observed, but they did not last long. As the heat input rises to 10 W, boiling begins in the heating zone, leading to a significant decrease in temperatures in this region, while the condensation zone temperatures slightly increase. This is the start-up point of PHP, the average start-up temperature in this case is observed to be 62,2 °C and start up heat flux density was observed to be 833,2 W/m^2. Upon increasing the heat input to 10 W, the heating zone temperature continues to rise until the saturation temperature is achieved, causing temperature jumps as shown in Figure 3. This stage is referred to as the thermosyphon mode of operation.

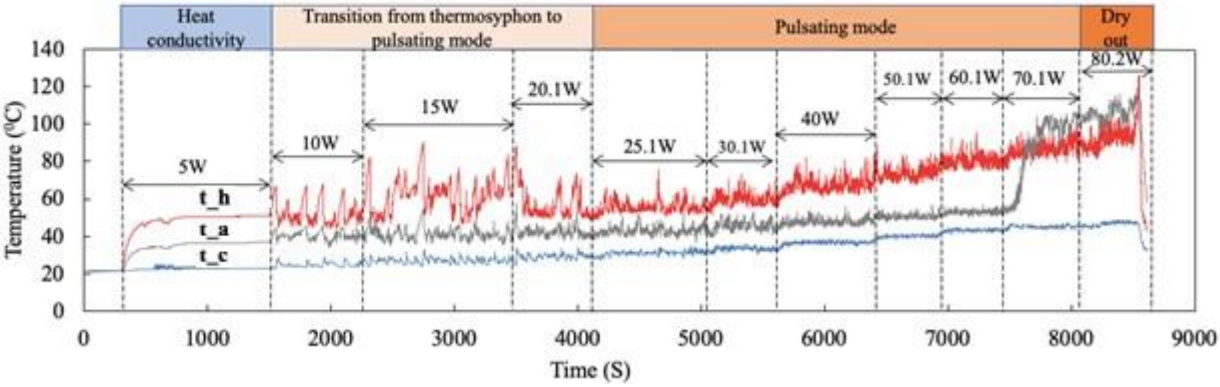


Figure 3 *– Variation of temperature with time at various heat input (t_h, t_a, t_c – average temperatures of heating, adiabatic and condensing zone respectively)*

Further increases in heat input up to 20,1 W lead to both stable and unstable pulsations, indicating a transient phase between thermosyphon and pulsating modes. In this mode of operation heat carrier oscillates with large amplitude and low frequency. Hydrodynamically, the heat carrier moves primarily in the slug regime. When the heat input reaches 25,1W, the system transitions to the pulsating mode of operation at heat flux density of 2014,1 W/m^2. Stable pulsations occur, signalling stable boiling and high heat transfer, resulting in optimal thermal performance. However, as the heat input reaches 80,2 W, local drying out begins inside the PHP, marked by drastically increasing of average temperatures in the heating and adiabatic zones, prompting the cessation of heat input. It has to be noted here, that for such working fluids as methanol and pentane transition mode from thermosyphon to pulsating was not observed due to their less heat carrying capacity than that of water.

7. Results of investigation

7.1. Start-up and transient characteristics

The following table 2 provides the comparative analysis of the t_{start}, q_{start}, q_{pulse}, q_{max}, and maximum transferred heat flux (Q_{max}) in vertical bottom heating mode for various working fluids.

Table 2 reveals important characteristics of pulsating heat pipe (PHP) at various heating zone (HZ) lengths, using water, methanol, and pentane as working fluids. Water consistently demonstrates the highest start-up temperatures across all lengths suggesting a slower initial thermal response. In terms of maximum transferred heat flux, water exhibits the highest values for all HZ lengths which are almost independent from these lengths. Methanol, although generally higher than pentane, but both heat carriers show a decreasing trend with increasing of HZ length for all stated in table 2 performance parameters, except maximum transferred heat flux Q_{max}. As for the maximum transferred heat flux Q_{max}, it increases with increasing of HZ length. Thus, it can be recommended to use methanol or pentane as heat carrier for PHP with long HZ when low start-up and transient characteristics are more important than high transferred heat flux Q_{max}, but if high value of Q_{max} is more important, then water is the better choice.

Table 2 *– Comparative analysis of performance parameters of various working fluids at various HZ lengths (90° inclination angle)*

HZ length (mm)	Working fluid	t_{start}, (°C)	q_{start} (W/m^2)	q_{pulse}, (W/m^2)	q_{max}, (W/m^2)	Q_{max}, (W)
10	Water	61,2	1539,0	2611,1	14202,6	63,7
	Methanol	55,8	1747,0	2270,7	5622,2	25,2
	Pentane	41,5	810,7	810,7	8086,4	36,3
30	Water	64,4	849,6	1049,9	5586,0	63,7
	Methanol	48,2	716,4	1108,4	3045,5	34,7

Table 2 continuation

HZ length (mm)	Working fluid	t_{start} , (°C)	q_{start} (W/m^2)	q_{pulse} , (W/m^2)	q_{max} , (W/m^2)	Q_{max} , (W)
50	Water	61,9	494,6	748,3	3701,0	67,8
	Methanol	43,7	518,9	780,0	2598,9	40,1
	Pentane	37,7	169,4	169,4	2468,5	45,2

Combined influence of inclination angle and HZ length on start-up heat flux density q_{start} is shown on fig. 4. At horizontal orientation (inclination angle 0°), all heat carriers show the highest values of start-up heat flux density indicating more energy needed to initiate PHP operation because of absence of gravity influence on fluid movement inside PHP. Although PHP with pentane did not start working at all in the horizontal orientation, however, it consistently required lower starting heat flux at all other orientation potentially making pentane more efficient for PHP operation at non-horizontal orientations. Increasing of both inclination angle and HZ length leads to decreasing of start-up heat flux density for all heat carriers. The only exception is water at horizontal position for which the lowest value of q_{start} was obtained for 30 mm HZ length. According to obtained experimental data, the performance of PHP is improving with increase in HZ length, but smaller input power is necessary for PHP to start at lower HZ length. This information is crucial for designing PHP systems with optimal performance by selecting appropriate working fluids and operating angles based on specific application needs.

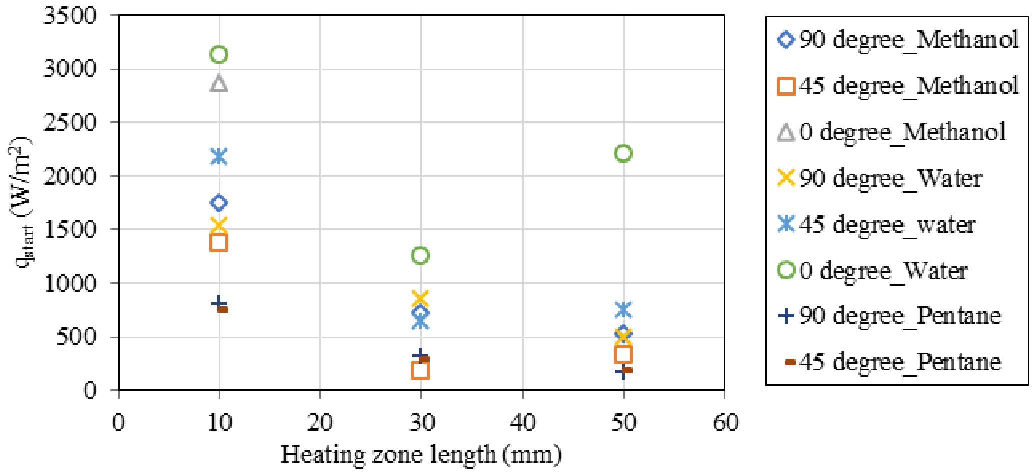


***Figure 4** – Effect of heating zone length and inclination angle on start-up heat flux density*

The temperature at which beginning of movement of the working fluid inside PHP starts, which is indicated by beginning of temperature pulsations in all PHP zones, is defined as start-up temperature (t_{start}). Influence of inclination angle and HZ length on start-up temperature depends on heat carrier (fig. 5). Start-up temperature decreases with increase in HZ length for methanol and pentane at all inclination angles. The lowest value of (t_{start}) for water was observed at HZ length of 30 mm and the highest one – at length 10 mm for inclination angles of 0° and +45°. At inclination angle +90° start-up temperature for water is almost independent from HZ length. Methanol and water demonstrate the lowest value of (t_{start}) at inclination angle +45°C and the highest one – at 0° for all tested HZ lengths. Influence of inclination angle on start-up temperature of PHP with pentane is almost absent.

The lowest t_{start} value of 37,7°C in this investigation was achieved with pentane at a 50 mm HZ length and an inclination angle of +90°. In general, the lowest start-up temperatures were observed for pentane at all combinations of HZ lengths and inclination angles, the highest ones – for water, and methanol was in between of them.

It was observed, that increasing of both HZ length and inclination angle leads to decreasing of the heat flux density corresponding to beginning of pulsation mode, which is defined as transient heat flux density q_{pulse}, for all tested heat carriers (fig. 6).

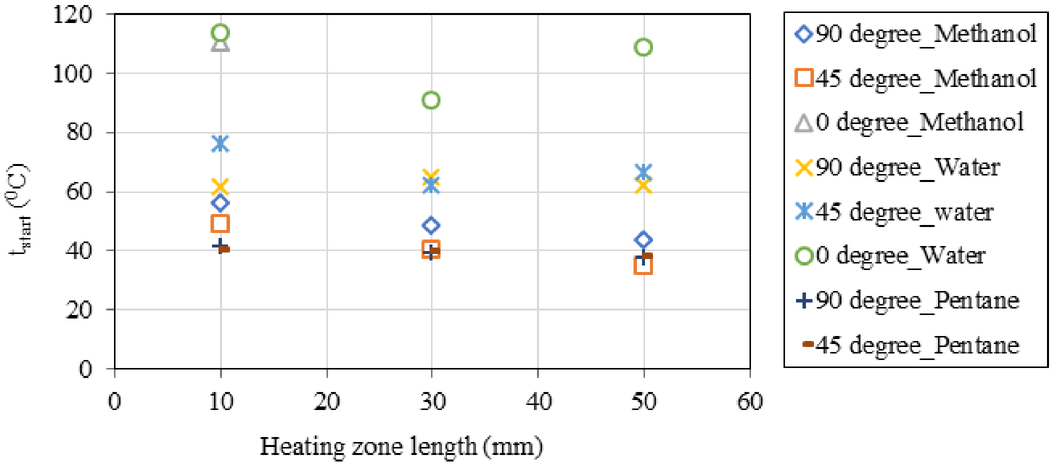


Figure 5 *– Effect of heating zone length and inclination angle on start-up temperature*

The only exception was water at HZ length of 10 mm where value of q_{pulse} for inclination angle +90° was higher than that one for angle +45°. Among all working fluids, pentane exhibited the lowest of q_{pulse} value, reaching 169,4 W/m^2 at an HZ length of 50 mm. This suggests that pentane is well-suited for applications where PHP operation requires a transition to pulsation mode at low heat flux densities.

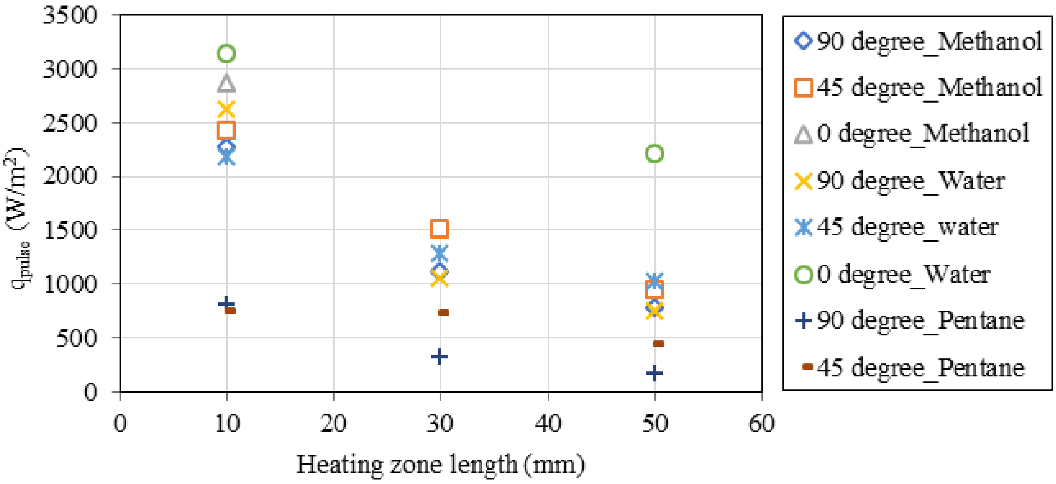
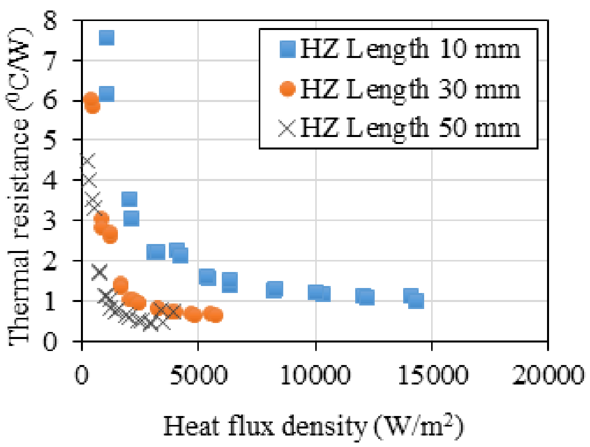


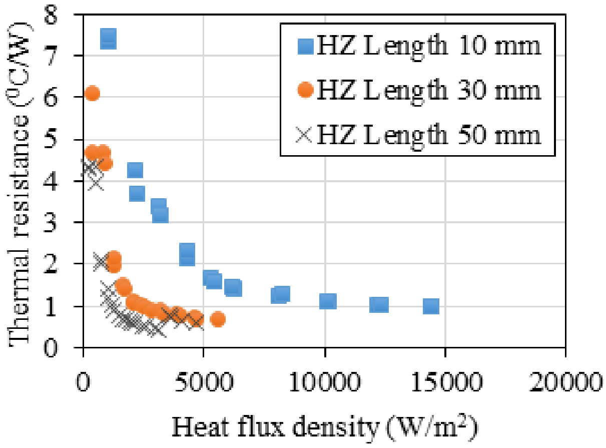
Figure 6 *– Effect of heating zone length and inclination angle on transient heat flux density*

7.2. Operational characteristics

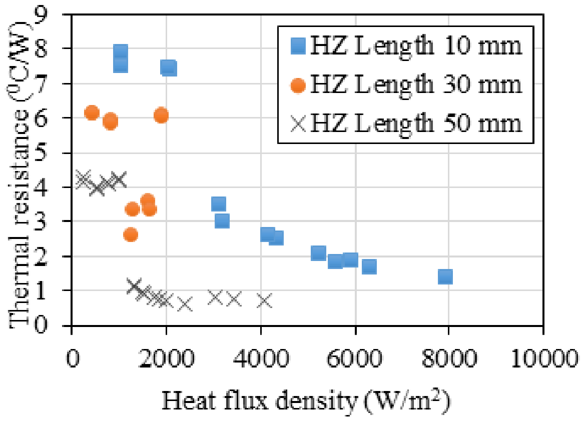
The overall thermal resistance serves as a key indicator for evaluating PHP thermal performance. Fig. 7 illustrates how PHP thermal resistance varies with heat flux density across different heating zone (HZ) lengths and orientations. As heat flux density and HZ length increase, thermal resistance decreases, with reductions of 50,6% for water, 51,8% for methanol, and 18,9% for pentane. At high heat flux densities (Fig. 7, e-g), thermal resistance shows a slight increase for methanol and pentane, suggesting the occurrence of dry-out phenomena in the HZ. The influence of HZ length on thermal resistance can be attributed to the combined effects of heating and adiabatic zone (AZ) lengths. When the HZ length reaches 50 mm (the maximum in this study), the AZ is nearly absent, allowing the heat carrier to transfer almost all absorbed energy from the HZ (aside from environmental heat losses) directly to the condensation zone. Conversely, as HZ length decreases, AZ length increases, requiring additional energy to overcome AZ hydraulic resistance. This provokes increasing of temperature difference along PHP and increasing of PHP thermal resistance as a consequence. The lowest thermal resistance was obtained for water (0,45 °C/W) and methanol (0,47 °C/W) at vertical bottom heating mode (+90°) for HZ length of 50 mm.



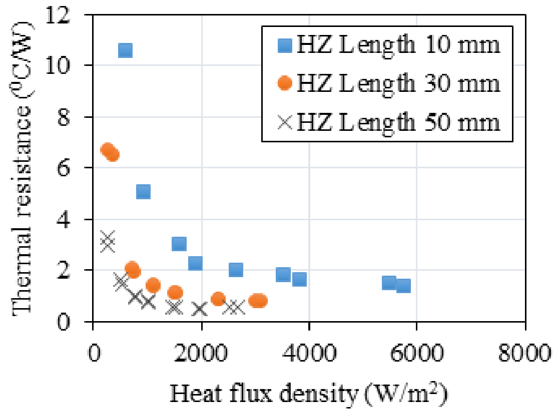
(a) Water – orientation 90°



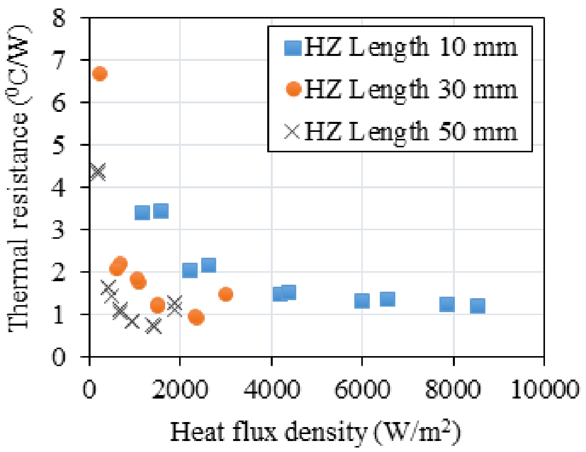
(b) Water – orientation 45°



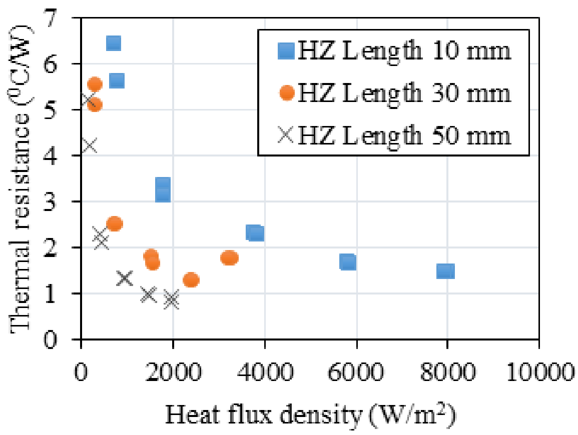
(c) Water – orientation 0°



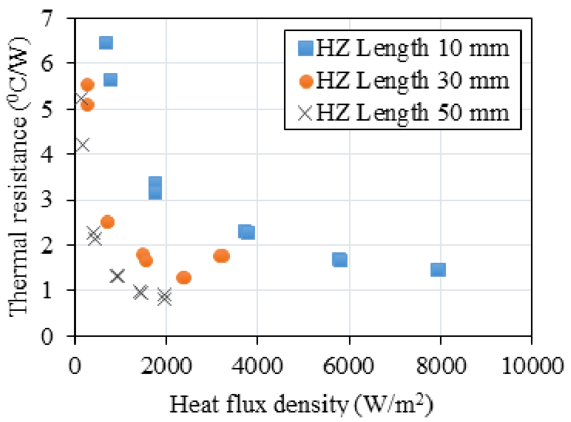
(d) Methanol – orientation 90°



(e) Methanol – orientation 45°



(f) Pentane – orientation 90°



(g) Pentane – orientation 45°.

Figure 7 *– Effect of heat flux density on thermal resistance at various heating zone lengths and inclination angles*

Fig. 8 demonstrates the effect of HZ length on maximum transferred heat flux Q_{max} across different inclination angles. At an inclination angle of +90°, all heat carriers exhibited a similar trend, with the maximum transferred heat flux increasing as the heating zone length increased. A different trend was observed at an inclination angle of +45° for methanol and water: as the heating zone length increased from 10 to 30 mm, the value of Q_{max} decreased, followed by an increase when the heating zone length reached 50 mm. Thus, minimal value of Q_{max} for these heat carriers at angle +45° corresponds to HZ length of 30 mm. Maximum transferred heat flux of PHP with pentane was almost independent of HZ length at inclination angle +45°. At horizontal position (0°) water demonstrated similar trend to that at +45° while PHP with methanol started to work only at 10 mm HZ length and PHP with pentane didn't start working at all. The lowest value of Q_{max} was obtained at inclination angle 0° for all tested heat carriers and the highest one – at +45° or +90° depending on heat carrier and HZ length. Water exhibited the highest maximum transferred heat flux, which was in the range from 60 to 75 W, due to its high heat of evaporation while for all other fluids this value was below 50 W. This indicating a less possibility of using methanol and pentane for high heat flux application and making water a best choice for such applications.

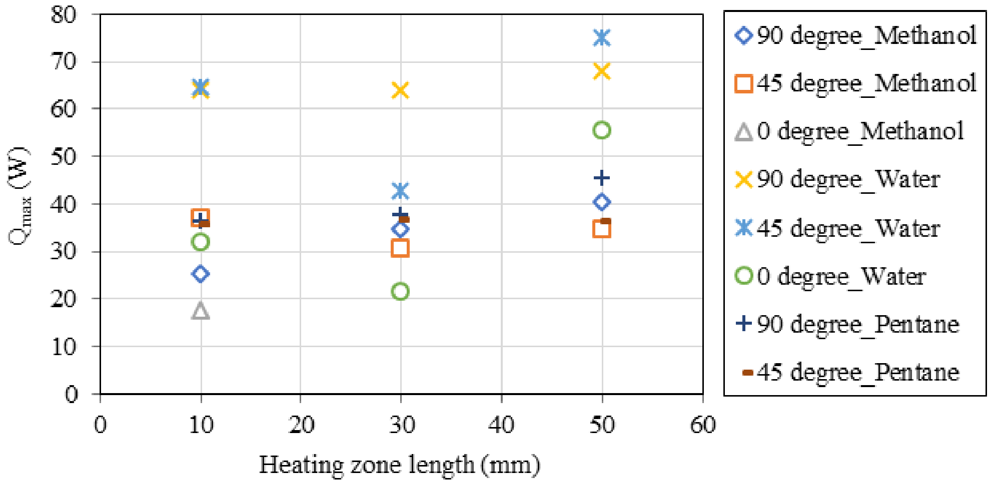


***Figure 8** – Effect of heating zone length and inclination angle on maximum transferred heat flux*

8. Conclusions

On the basis of conducted experimental study, following conclusions can be drawn:

– increasing of the heating zone length from 10 to 50 mm leads to: decreasing of start-up temperature, start-up heat flux density, transient heat flux density, PHP thermal resistance and increasing of maximum transferred heat flux. In other words, increasing of the heating zone length improves PHP performance;

– influence of inclination angle on PHP performance depends on heat carrier and HZ length, but, in general, PHP has better characteristics at bottom heating mode of operation (+45°, +90°) than in horizontal position (0°) where only PHP with water works at all tested HZ lengths. PHP with any of tested heat carriers doesn't start working in top heating mode (-45°, -90°);

– PHP with pentane has the lowest values of start-up temperature (37,7°C), start-up heat flux density (169,4 W/m^2), transient heat flux density (169,4 W/m^2), and PHP with water – the highest ones. Using of water and methanol as PHP heat carrier provides the lowest thermal resistance (0,45-0,46 °C/W). The highest maximum transferred heat flux (up to 75 W) corresponds to PHP with water;

- pentane can be recommended for applying as heat carrier for PHP working in bottom heating mode when low start-up and transient characteristics are necessary, but if high maximum transferred heat flux is more important than water will be the better choice.

CRediT author statement

Mane K.: data processing, data analysis, writing – the original draft; **Alekseik Ye.**: performing of experimental investigation; conceptualization; writing – reviewing and editing.

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Комбінований вплив довжини зони нагріву та кута нахилу на стартові, перехідні та робочі характеристики пульсаційної теплової труби

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Пульсаційні теплові труби – це нові теплопередавальні пристрої, що мають широкі перспективи використання в енергетичних, холодильних, кріогенних системах та для охолодження електрон-

ного обладнання завдяки простоті свої конструкції та високій ефективності теплопередачі. Однак, теплопередавальні характеристики ПТТ залежать від багатьох параметрів. Стаття присвячена експериментальному дослідженню впливу довжини зони нагріву та кута нахилу на пускову температуру і густину теплового потоку, перехідну густину теплового потоку та термічний опір ПТТ. Дослідження було проведено на 5-витковій ПТТ, виготовленій із мідного капіляра із внутрішнім діаметром 1,1 мм. В якості теплоносія використовувались: вода, метанол і пентан. На основі отриманих експериментальних даних було виділено та описано основні робочі режими ПТТ. Результати показують, що збільшення довжини зони нагріву від 10 до 50 мм при всіх досліджених кутах нахилу призводить до зниження термічного опору до 51,8%, а також до зниження пускової та перехідної густин теплового потоку до 68-71%. Крім того досліджувався вплив довжини зони нагріву на максимальну теплову потужність, яку передає ПТТ. Було показано, що збільшення довжини зони призводить до збільшення потужності, що передається, до 59%. Ці дані свідчать про те, що оптимізація довжини зони нагріву може покращити ефективність запуску та загальну ефективність теплопередачі. Вплив кута нахилу залежить від використаного теплоносія; але при всіх досліджених кутах нахилу ПТТ з водою мала найнижчий термічний опір, а ПТТ з пентаном – найнижчі стартові та перехідні характеристики. Стаття надає цінну інформацію для проектування ПТТ для енергетичних, холодильних систем та охолодження електроніки, підкреслюючи важливість довжини зони нагріву (ЗН) для досягнення оптимальних характеристик

Ключові слова: *Пульсаційна теплова труба; Довжина зони нагріву; Густина теплового потоку; Температура; Пускові характеристики; Перехідні характеристики; Кут нахилу; Термічний опір*

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