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Thermal Characteristics of a Rotating Closed-Loop Pulsating Heat Pipe Affected by Centrifugal Accelerations and Numbers of Turns

Niti Kammuang-lue, Kritsada On-ai, Phrut Sakulchangsatjatai,*
Pradit Terdtoon
Department of Mechanical Engineering,
Faculty of Engineering, Chiang Mai University
239 Huay Kaew Rd., Suthep, Muang,
Chiang Mai, THAILAND 50200

**niti@eng.cmu.ac.th*

ABSTRACT

Objective of this study is to experimentally investigate the effect of centrifugal accelerations and numbers of turns on thermal characteristics of the rotating closed-loop pulsating heat pipe (RCLPHP). The RCLPHPs were made of a copper tube with internal diameter of 1.50 mm and bent into flower's petal-shape and arranged into a circle with 11, 22 and 33 turns. The evaporator section located at the outer end of the bundle while the condenser section placed around the center of the RCLPHP with no adiabatic section. Both sections had an identical length of 50 mm. R123, and ethanol was filled as working fluid respectively. The RCLPHP was installed on the test rig and it was rotated by the DC motor at the centrifugal acceleration of 0.5, 1, 3, 5, 10, and 20 times of the gravitational acceleration considering at the connection between the evaporator and condenser sections. Heat input was generated by electrical annular-plate heaters and varied from 24 to 42, 86, 132, and 174 W. Ceramic papers, wooden plate, and insulation sheet were consecutively attached on the outer side of the heaters in order to prevent the heat loss from the heater. It can be concluded that when the centrifugal acceleration increases, the thermal resistance per a unit area continuously decreases since the condensate flows back to the evaporator section more rapidly. Moreover, it can be found that when the number of turns increases, the absolute thermal resistance obviously decreases. On the other hand, the thermal resistance per

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unit area continuously increases as the increasing in the number of turns, since the friction loss due to the increase in the total length of the tube and in the number of the U-tube section retards the working fluid's circulation to be less active.

Keywords: *Rotating closed-loop pulsating heat pipe, Centrifugal acceleration, Number of turns, Thermal resistance, Thermal performance.*

Introduction

Heat pipe is one of heat transfer devices, which is popular at the present. Because it is easily applied on various devices; such as, laptop, smart phone, tablet, etc. Heat pipes generally consist of three sections, i.e., (i) an *evaporator section,* which receives heat input from heat source, (ii) a *condenser section*, where the heat pipe releases the heat to the heat sink, and (iii) an *adiabatic section,* located between an evaporator and a condenser section, which is generally covered by insulation to prevent heat loss. Since the heat pipe is evacuated and filled in with working fluid, when an evaporator section is heated, liquid working fluid inside an evaporator section consequently evaporates to vapor. Then, vapor flows through an adiabatic section toward a condenser section, respectively. At a condenser section, vapor condenses to be condensate and simultaneously releases the heat. Finally, condensate flows back to an evaporator section to receive heat. This operation takes place in perpetual cycle. The movement of the condensate from a condenser to an evaporator section can be done in several ways; such as, gravitational acceleration (thermosyphons), capillary force (wicked heat pipes) and pressure difference (pulsating heat pipes). Each way has different limitation, e.g., thermal performance of thermosyphons is unacceptable when it is installed in the horizontal plane according to lacking of the gravity [1]. Wicked heat pipes have the lowest thermal performance when capillary pressure is lower than vapor pressure since wick structure draws the condensate back to an evaporator section inefficiently [2]. Pulsating heat pipes cannot operate when pressure difference between an evaporator and a condenser section is very low due to lacking of driving force [3]. In this study, *pulsating heat pipe* (PHP) is focused since it has higher thermal performance than that of thermosyphons, and it can be easily fabricated compared with wicked heat pipes. The PHP is made of a copper capillary tube which is bent into an undulating bundle. The PHP was firstly introduced by Akachi *et al.* in 1995 [4]. Inner diameter of the PHP has to be smaller than the critical inner diameter to allow the working fluid to be able to arrange in the slug-train, which is a form that vapor plugs locate alternatively with liquid slugs along entire length of the tube [5]. Generally, the PHP can be classified into three types, i.e., a *closed-end pulsating heat pipe*

(CEPHP), a *closed-loop pulsating heat pipe* (CLPHP), and a *closed-loop pulsating heat pipe with check valve* (CLPHP/CV). This research focuses on the CLPHP because its thermal performance is higher than that of the CEPHP while it is easier to be fabricated than a case of the CLPHP/CV. A structure of the ordinary CLPHP is shown in Figure 1.

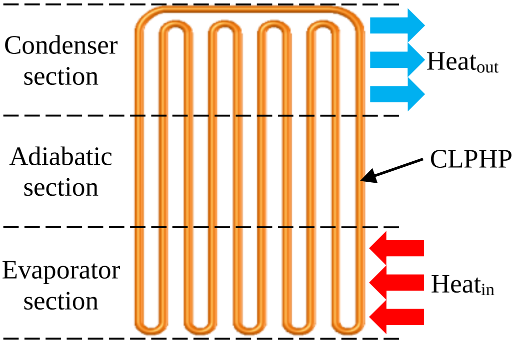


Figure 1: Structure of the ordinary closed-loop pulsating heat pipes.

In general, the CLPHP was frequently applied on stationary devices; such as, an ice storage system [6], a condenser in a vapor compression refrigeration system [7], and a race car's engine radiator [8]. However, the ordinary CLPHP cannot be directly applied on rotating machines with very high rotational speed, such as, disk brakes, superconductor bearings, and steam turbine's blades. Hence, Aboutalebi *et al.* [9] firstly developed a new shape of CLPHP by bending a tube into flower's petal-shape and arranged around a circumference of a radial part, which had accumulative heat, of a rotating machine and named as a *rotating closed-loop pulsating heat pipe* or *RCLPHP* in short. The basic structure of the RCLPHP is depicted in Figure 2. When the RCLPHP was rotated, liquid working fluid inside the heat pipe was pushed toward to the outer end of the tube bundle due to the centrifugal force. Therefore, the evaporator section must be located at the outer end and vice versa for the condenser section.

From the past study, the four-meandering turn RCLPHP of which the inner diameter was 2.03 mm, the evaporator, the adiabatic and the condenser section length was 100, 240 and 125 mm, respectively, and water was used as the working fluid, was experimentally investigated. It was found that when rotational speed increased from 50 to 175, 300, 425, 550, 625, and 800 rpm, the thermal resistance continuously decreased. When the heat input increased from 25 to 40, 55, 70, 85, and 100 W, the thermal resistance continuously decreased. In addition, it was concluded that the suitable filling ratio of the working fluid was 50% by total volume [9]. Moreover, another investigation on the horizontal CLPHP found that when the gravity decreased from 1.8g to 0.01g, the vapor plug clearly formed in the center core of the tube according to the effect of the surface tension. This evidence support that the gravity strongly affects flow pattern inside of the CLPHP [10]. Although effects of some parameters involving in the RCLPHP have been investigated, the tested RCLPHP was in the identical configuration, e.g., geometrical shape and working fluid. Therefore, the RCLPHP with different configurations must be carefully investigated quantitatively and qualitatively in order to obtain basic knowledge used to correctly design the RCLPHP for applying on the rotating machines. In addition, there is no past study that reported on effect of turns on the thermal performance of the RCLPHP; however, for the ordinary CLPHP, it was found as follows. In a case of the CLPHP with the internal diameter of 2 mm, the evaporator section length of 150 mm, and filled with water as the working fluid, when the number of turns increased from 11 to 16 and 26, the thermal resistance gradually decreased. Since the pressure difference between the evaporator and condenser sections is not in equilibrium, the circulation of the working fluid is more active [11]. Moreover, another past study found that when the number of turns increased from 5 to 7, 10, 16, and 30, the heat transfer rate of the CLPHP obviously increased [12]. These results correspond with the one obtained from aforementioned study.

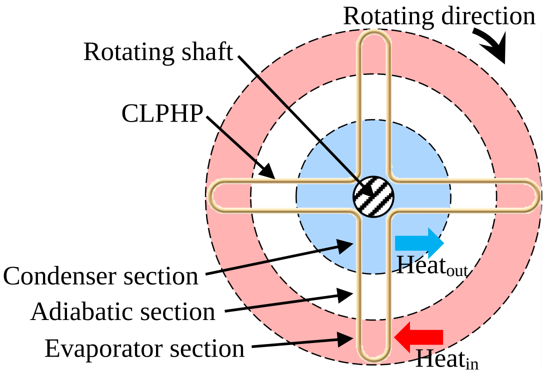


Figure 2: Structure of the rotating closed-loop pulsating heat pipes.

According to the above mention, these became the significance of this study with the objective to experimentally investigate the effects of centrifugal accelerations and numbers of turns on the thermal characteristics of the RCLPHP. The obtained knowledge will be very useful especially to any heat pipe designers and people involving in heat pipe manufacturing industries, since they can extensively utilize all obtained information in order to design, produce, and apply the RCLPHP onto any future actual applications.

Experimental Setup and Procedure

The RCLPHP was made from the copper capillary tube with an internal diameter of 1.50 mm. It was bent into flower's petal-shape and arranged into a layer of circle with 11 meandering turns. There were three sets of the RCLPHP with number of turns of 11 (1 layer), 22 (2 layers), and 33 (3 layers) as shown in Figure 3. The evaporator section located at the outer end of the bundle while the condenser section placed around the center of the tested RCLPHP. Both sections had an identical length of 50 mm. The RCLPHP had no adiabatic section in order to shorten a distance between the evaporator and the condenser section as shown in Figure 4 (a). The RCLPHP was evacuated, then the fundamental refrigerant which was R123 and ethanol was individually filled in as the working fluid with the filling ratio of 50% of total internal volume. An electrical annular-plate heater (220 VAC, maximum power 800 W) was attached on each side of the RCLPHP in order to generate the heat input to the evaporator section. Then, ceramic papers (Alfiso, Isotek 1260 paper, 3-mm thickness), wooden plate, and insulation sheet (Aeroflex, 3/8 in. thickness) were consecutively attached on the outer side of the heater in order to prevent the heat loss from the heater. Another insulation sheet was installed along a circumference of the RCLPHP set. The RCLPHP set was tightly secured by two steel crossbars as shown in Figure 4 (b). Finally, the RCLPHP set was installed on the test rig by securing both crossbars onto a shaft on the test rig. The test rig and experimental setup are schemetically shown in Figure 4 (c). Electrical current (220 VAC, 50 Hz) was supplied to the heaters through slip rings. The power supply into each heater was controlled by the power controller (Shimax, MAC3D, accuracy ±0.25% full scale) and simultaneously monitored for a validation of the heat input quantity by using watt meters (Axe, MMP, accuracy ±0.25% full scale). Quantities of the heat input of 24, 42, 86, 132, and 174 W were chosen in this study. The shaft was rotated by the DC motor (MY, model 1030, 24 VDC) with the maximum power of 750 W. Rotational speed of the RCLPHP set could be adjusted by the speed controller (MXA, model 066) powered by the DC power supply (ST, maximum power 720 W). In the meantime, the rotational speed of the RCLPHP set was monitored by the digital speed sensor. The rotational speed of 70, 100, 173, 223, 316, and 446 rpm were selected since they could converted into the centrifugal acceleration of 0.5, 1, 3, 5, 10, and 20 times of the gravitational acceleration with the consideration on a position at the connection between the evaporator and the condenser sections. Detail of the acceleration will be described in the next section. Temperature variation of each point was measured by twelve thermocouples (Omega, Type K, accuracy ±0.5 ^{o}C), which were connected to a handheld data logger (Lutron, BTM-4208SD, accuracy

±1.0 °C) secured on the shaft for temperature monitoring and recording. Location of the thermocouples was as follow. Two points each at the middle of the evaporator and the condenser section, two points for the air around the condenser section, one point for each heater, and one point each at inner and outer surface of lateral and radial insulation sheets as shown in Figure 4 (a) and (b).

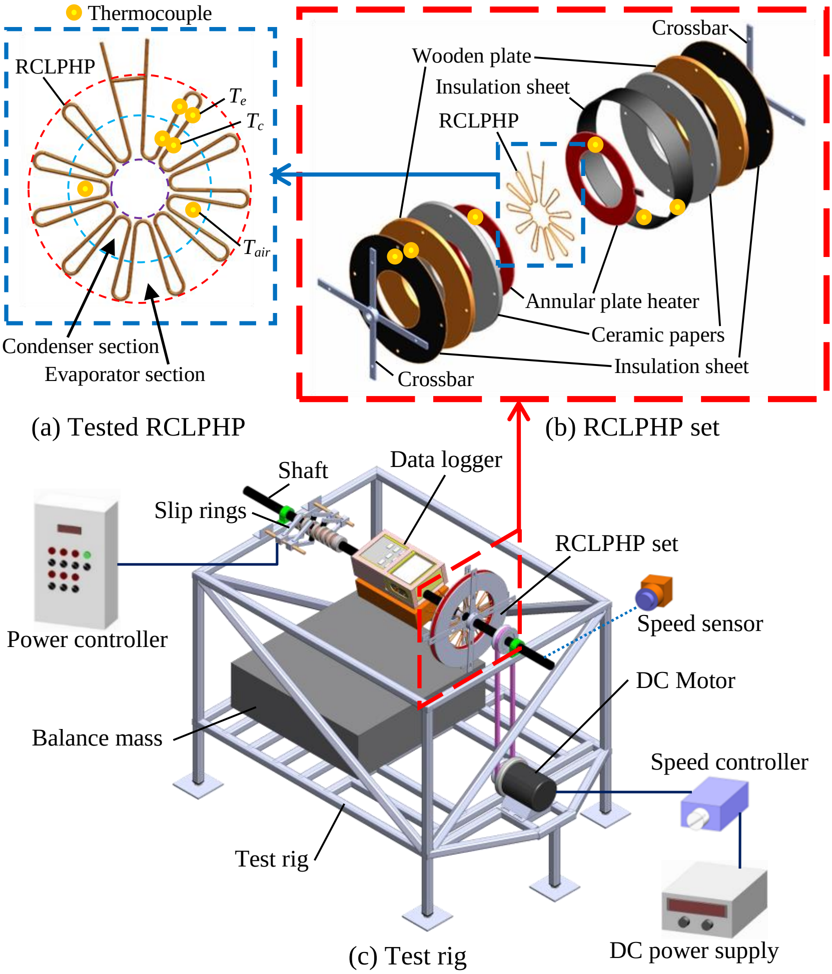
(a) 11 turns (b) 22 turns (c) 33 turns

Figure 3: The RCLPHP sets.

The experimental procedure was as follow. The RCLPHP set was rotated at constant speed corresponding to the slowest one. The power of the heaters was then adjusted to the lowest one. After the RCLPHP had reached the steady state, temperature at all points was recorded for a certain duration. The procedure was repeatedly conducted for higher reliability. The experiments were consequently conducted until all variable parameters were completely investigated. *Thermal resistance per unit area between the evaporator and condenser sections* ($z_{e\text{-}c}$), or *thermal resistance* in short beyond this point, represented the thermal characteristic of the RCLPHP in this study since it can be directly compared to other RCLPHPs with different geometrical size and heat input. The thermal resistance could be found from Equation (1), when $\dot{q}$ was the input heat flux entering the evaporator section and it could be found from dividing the power of the heaters ($\dot{Q}$) by the internal surface area of the tube in the evaporator section as derived in Equation (2). After that, the relationships between the thermal resistance and each variable parameter were plotted and discussed.

$$z_{e\text{-}c} = \left(\frac{T_e - T_c}{\dot{q}} \right) \tag{1}$$

$$\dot{q} = \frac{\dot{Q}}{\pi D_i \times L_e \times 2N} \tag{2}$$



(a) Tested RCLPHP

(b) RCLPHP set

(c) Test rig

Figure 4: The RCLPHP and experimental setup.

Results and Discussions

Definition of centrifugal acceleration

There are numbers of quantitative parameters involving in a rotation of the RCLPHP, such as, angular velocity, rotational speed, centrifugal acceleration, etc. Defining exact parameter to represent the rotational speed must suitably correspond to an analysis scheme. For instance, if the RCLPHPs with identical length are investigated, the annular velocity or rotational speed can be chosen as the quantitative parameter as in [9]. However, if extended comparison to other RCLPHPs with different lengths is needed, the most suitable parameter is the centrifugal acceleration (a_c), which is a function of the angular velocity (ω) or rotational speed (n) and the radius of an interesting location on the RCLPHP (r_c). In this study, the radius was defined to be considerred at the middle of the RCLPHP length, in turn, at a connection between the evaporation and the condenser sections, which equaled to 90 mm from the center. The centrifugal acceleration is expressed in Equation (3). It should be noted that the centrifugal acceleration was converted to a proportion of the gravitational acceleration (g = 9.81 m/s^2) since this proportion gives more understanding sense on the magnitude of the acceleration than the absolute value. The direction of centrifugal acceleration vector and the radius distance are depicted in Figure 5.

$$a_c = \frac{\omega^2 r_c}{9.81} = \left(\frac{2\pi n}{60}\right)^2 \frac{r_c}{9.81} \tag{3}$$

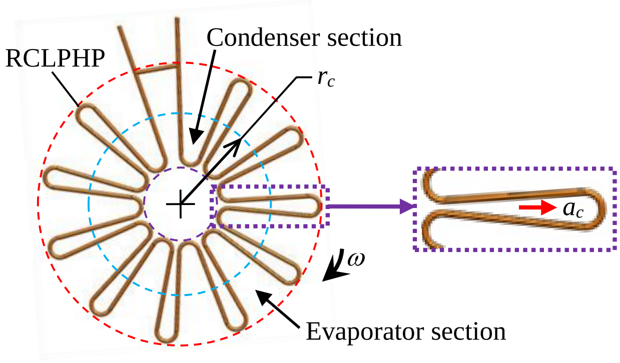
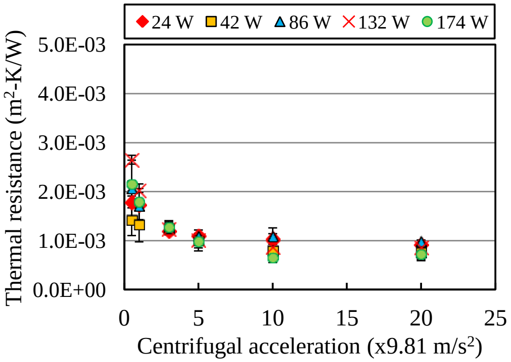


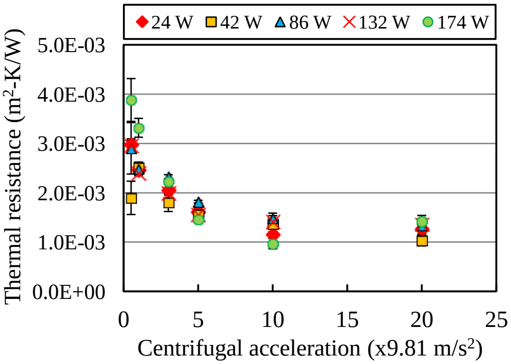
Figure 5: Centrifugal acceleration direction and radius distance.

Effect of centrifugal accelerations on thermal resistance

From the experiment on the RCLPHP, when the centrifugal acceleration increased, the thermal resistance obviously decreased. The relationship has the same characteristic in every magnitude of the heat input and the working fluids as shown in Figure 6 (a) and (b) for R123 and ethanol, respectively. For instance, it could be seen in a case of the R123 that when the centrifugal acceleration increased from 0.5g to 1g, 3g, 5g, 10g, and 20g, the thermal resistance decreased from 2.06×10^{-3} to 1.71×10^{-3}, 1.27×10^{-3}, 1.10×10^{-3}, 1.08×10^{-3}, and 9.88×10^{-4} m^2-K/W, respectively for the heat input of 86 W. The results appeared with a similar trend with another RCLPHP with ethanol that when the centrifugal acceleration increased from 0.5g to 1g, 3g, 5g, 10g, and 20g, the thermal resistance tended to decrease from 2.90×10^{-3} to 2.49×10^{-3}, 2.33×10^{-3}, 1.82×10^{-4}, 1.48×10^{-4}, and 1.33×10^{-4} m^2-K/W, respectively for the heat input of 86 W.



(a) R123 as working fluid



(b) Ethanol as working fluid

Figure 6: Effect of centrifugal accelerations on thermal resistance.

The physical reason that an increase in the centrifugal acceleration causes a decrease in the thermal resistance can be explained as follow. When the rotational speed of the RCLPHP increases, in turn, the centrifugal acceleration increases, the centrifugal force exerting on the working fluid also increases. Since this force has a radially outward direction, the working fluid, especially the liquid which has higher density than the vapor, is strongly pushed back to the evaporator section. This causes the condensate from the condenser section to return to receive the heat input in the evaporator section more quickly and continuously; therefore, the RCLPHP transfers the supplied heat out from the evaporator section more efficiently. This causes the temperature in the evaporator section to decrease and the thermal resistance following Equation (1) will consequently decrease.

An experimental evidence to confirm that the working fluid's circulating velocity increases as an increase in the centrifugal acceleration can be explained by emphasizing the temperature variation of the working fluid inside adjacent tubes within the same meandering turn in the middle part of the condenser section. In general, when working fluid's circulating velocity increases, the amplitude of working fluid's temperature always decreases since the heat dissipating velocity from the working fluid to the thermocouple tip is slower than the working fluid's flow velocity. The sensed temperature fluctuation between the lower temperature of liquid slugs and the higher one of vapor plugs in the two-phase flow slug-train will be minimized. On the other hand, it is found that when the flow velocity increases, the frequency of working fluid's temperature will increase. This is because number of the liquid slugs and vapor plugs passing the thermocouple tip in a specified time obviously increases as an increase in the flow velocity. Thus, the sensed temperature fluctuates more frequently [13]. It can be seen from the obtained results as shown in Figure 7 that when the centrifugal acceleration equals to 1g, the temperature amplitude is the maximum while the temperature frequency is the lowest. This shows that the working fluid's circulating velocity is relatively slow at low centrifugal acceleration. After that, when the centrifugal acceleration increases from 1g to 5g and 10g, the temperature amplitude obviously decreases and the temperature frequency tends to increase. Moreover, it is found that when the centrifugal acceleration equals or more than 1g, the temperature of the working fluid in the certain tube is always higher than that of in the adjacent tube in the same meandering turn. This can be implied that the working fluid circulates in one directional flow as an increase in the centrifugal acceleration. As it has been found from the past study that when the working flows in the one directional flow, the heat transfer rate of the ordinary CLPHP is apparently higher than a case of the CLPHP with the pulsating flow [14]-[17].

In addition, consideration on the condenser section shows that when the rotational speed of the RCLPHP increases, the convective heat transfer coefficient at the outer surface of the condenser section also increases since the relative velocity of the air moving through the surface is higher. The RCLPHP can simultaneously release the transferred heat out to the surrounding instantly. From a conjugation of phenomena in both the evaporator and the condenser sections, the RCLPHP is promoted to have lower thermal resistance as an increase in the centrifugal acceleration.

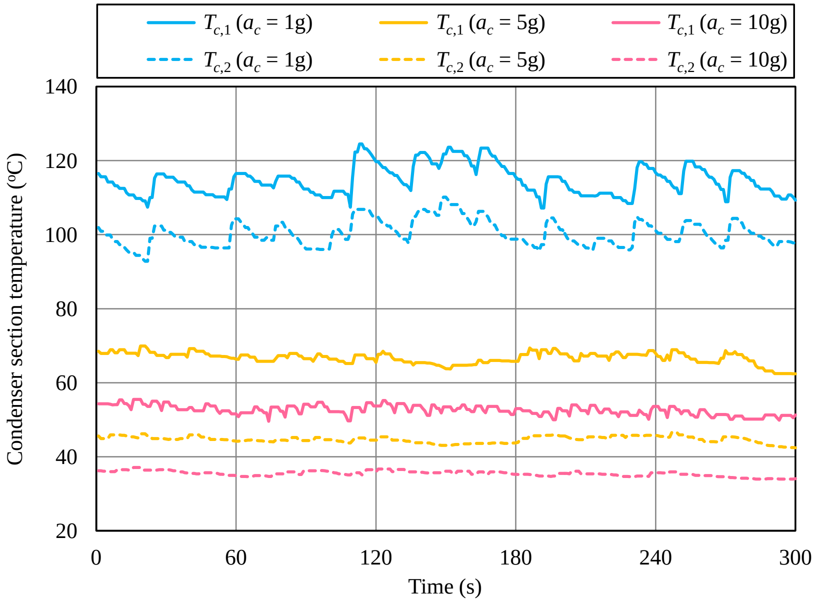


Figure 7: Temperature varitations of working fluid inside the condenser.

These results were compared to the results obtained in the past study [9] as shown in Figure 8. Since the tested RCLPHPs between this study and the past study were not identical, levels of the thermal resistance were relatively different. Direct comparison will lead misunderstanding. Thus, the thermal resistances from each study were normalized with the thermal resistance obtained from a case of the centrifugal acceleration of 1g (z/z_{1g}). The comparison found that the similar trends were obtained. However, it should be noted that since the working fluid of the RCLPHP in the past study was water, which differed from R123 and ethanol used in this study, slopes of an decrease in the z/z_{1g} are not the same. Moreover, they also found that when the centrifugal acceleration increases, the possibility of the dry-out to occur will consequently decrease.

It can be concluded that when the rotational speed increases, in turn, the centrifugal acceleration increases, the working fluid's circulating velocity increases and then the condensate rapidly and continuously flows back to the evaporator section. Simultaneously, the condenser section has higher convective heat transfer coefficient. Therefore, the thermal performance of the RCLPHP increases due to these conjugating effects.

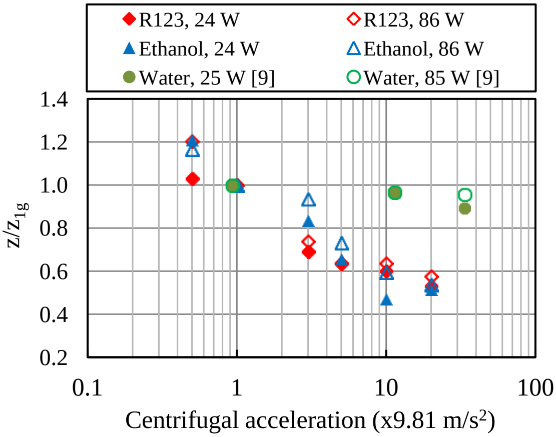
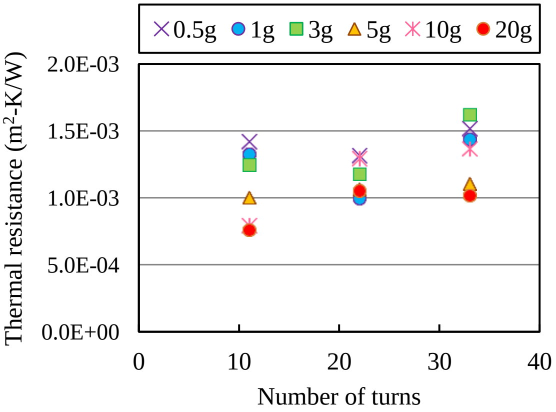


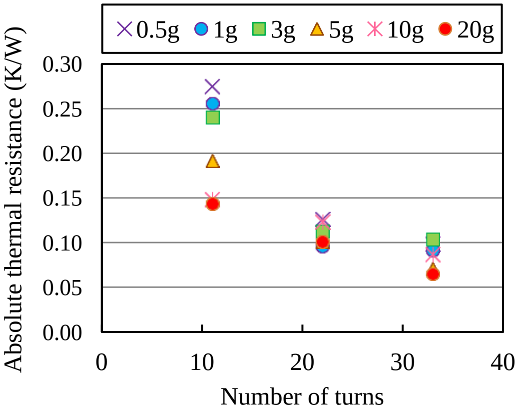
Figure 8: Comparison on effect of centrifugal accelerations on z/z_{1g}

Effect of numbers of turns on thermal resistance

From the experiment on the RCLPHP, when the number of turns increased, the thermal resistance tended to increased. For instance, it could be seen in a case of the R123 and the heat input of 42 W that when the number of turns increased from 11 to 22 and 33 turns, the thermal resistance increased from 1.00×10^{-3} to 1.07×10^{-3} and 1.11×10^{-3} m^2-K/W, respectively for the centrifugal acceleration of 5g, and from 7.95×10^{-4} to 1.30×10^{-3} and 1.37×10^{-3} m^2-K/W, respectively for the centrifugal acceleration of 10g as shown in Figure 9 (a). These results implied that when the number of turns increased, the *thermal performance per unit of heat transferring area* slightly decreased since the ratio of an increase in heat transfer rate was significantly lower than the ratio of an increase in the heat transferring area. However, when the results were compared by a term of the *absolute thermal resistance between evaporator and condenser sections*, it could be found in a case of the RCLPHP with identical configuration as aforementioned that when the number of turns increased from 11 to 22 and 33 turns, the absolute thermal resistance decreased from 0.19 to 0.10 and 0.07 K/W, respectively for the centrifugal acceleration of 5g, and from 0.15 to 0.12 and 0.09 K/W, respectively for the centrifugal acceleration of 10g as shown in Figure 9 (b). From both trends of the thermal characteristic of the RCLPHP, it can be initially concluded that when the number of turns increases, the overall thermal performance obviously increases. On contrary, the thermal performance per unit area decreases as the increase in the number of turns.



(a) Thermal resistance per unit area



(b) Absolute thermal resistance

Figure 9: Effect of numbers of turns on thermal resistance.

Physical reason describing how the number of turns affects on the thermal resistance of the RCLPHP can be explained as follow. In general, the number of turns of the RCLPHP and ordinary CLPHP is equivalent to the number of boiling sites in the heat pipe. The more boiling sites, the more driving force exerts on the working fluid's circulation. The heat transfer rate consequently increases with the increase in the number of turns. From this point, the absolute thermal resistance finally decreases as aforementioned results and this trend is well agreed with the results obtained from the previous studies [11]-[12]. On the other hand, when the number of turns increases, two factors subsequently increase, that are total length of a tube and number of a U-tube section. The increase in the total length of the tube causes an increase in the major loss of the working fluid flow inside of the RCLPHP. In the meantime, the increase in the number of the U-tube section leads the minor loss of the working fluid flow to increase. Sum of the major and minor losses promotes the friction loss on the working fluid circulation. These effects subsequently retard the increase in the thermal performance according to the increase in the number of turns. This is the reason why the heat transfer rate increases with lower proportion compared to the proportion of the increase in the heat transferring area. Finally, the thermal performance of the RCLPHP considering on the thermal resistance per unit area decreases as the increase in the number of turns.

It can be concluded that when the number of turns increases; although the higher number of turns, in turn, the number of boiling sites can drive the working fluid's circulation to be more active, the friction loss due to the increase in the total length of the tube and in the number of the U-tube section retards the circulation to be less active than it should be. Therefore, the thermal performance of the RCLPHP decreases.

Conclusions

Effects of centrifugal accelerations and numbers of turns on the thermal characteristics of the RCLPHP have been thoroughly investigated in this study. The RCLPHPs were made of a copper tube with internal diameter of 1.50 mm and bent into flower's petal-shape and arranged into a circle with 11 turns. R123, and ethanol was filled as working fluid. The RCLPHP was rotated at the centrifugal acceleration of 0.5, 1, 3, 5, 10, and 20 times of the gravitational acceleration considering at the connection between the evaporator and the condenser sections. Heat input was varied from 24 to 42, 86, 132, and 174 W. It can be concluded that when the centrifugal acceleration increases, the thermal resistance continuously decreases, in turn, the thermal performance increases in every heat input quantity. Because the condensate flows back to the evaporator section more rapidly when it is exerted with higher centrifugal acceleration. In addition, it can be concluded that when the number of turns increases, the friction loss due to the increase in the total length of the tube and in the number of the U-tube section retards the working fluid's circulation to be less active. Therefore, the thermal resistance increases, in turn, the thermal performance decreases. This can be implied that the RCLPHP can be acceptably applied on the rotating machines as an effective heat exchanger. However, other effects, such as, working fluid, internal diameter, evaporator section length, heat input, etc., are suggested to be investigated in the future in order to fulfill the basic knowledge of the RCLPHP.

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Nomenclature

a_c	centrifugal acceleration (×9.81 m/s^2)
D	diameter (m)
L	length (m)
N	number of turns (turns)
n	rotational speed (rpm)
$\dot{Q}$	heat transfer rate (W)
$\dot{q}$	heat flux (W/m^2)
r_c	radius (m)
T	temperature (K)
Z	absolute thermal resistance (K/W)
z	thermal resistance per unit area (m^2-K/W)
c	condenser section
e	evaporator section
i	inner
l	liquid
$1g$	at centrifugal acceleration of 1g or 9.81 m/s^2
ω	angular velocity (rad/s)

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