Düzce University
Journal of Science & Technology

Research Article

Thermo-Fluidic Analysis of Pulsating Heat Pipes Charged with Water-Based Immiscible Fluid Pairs

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DOI: 10.29130/dubited.1115581

ABSTRACT

Immiscible fluids may provide operational flexibility for pulsating heat pipes (PHPs) due to thermo-hydrodynamic diversity lead by each pure component. In this regard, present paper focuses on the thermo-fluidic analysis of non-uniform pulsating heat pipes charged with water-based immiscible fluid pairs. Research parameters cover gravity effect via the inclination angles (IA) of 0º and 90º, and fluid pair effect via two different water-based immiscible binary fluids as Water (W) – Hexane (H), and Water (W) – Pentane (P). The volumetric mixing ratios are W:H=1:1, 1:4, 4:1, 1:0, 0:1, and W:P=1:1, 1:4, 4:1, 1:0, 0:1; and the non-uniform flat plate type pulsating heat pipe (FP-CLPHP) has alternating-sequence parallel channels. The experiments are performed at the filling ratio of 40% (FR=40%), and flow phenomena is visualized. As some conclusions; at vertical orientation, the FP-CLPHPs having binary fluids of water-pentane show better thermal performance compared to the pure counterparts. Especially, the heat transfer characteristics of W:P=1:1 are the best ones among all the pure and binary fluids. On the other hand, as a conclusion of combination of non-uniform design and suitable thermophysical properties, the FP-CLPHPs charged with pure pentane, pure hexane or binary fluid of W:P=1:4 can work independent from gravitational force.

Keywords: *Immiscibility, Pulsating heat pipe, Fluid pairs, Thermo-fluidic analysis*

Su Bazlı Karışmayan Akışkan Çiftleriyle Yüklü Atımlı Isı Borularının Termo-Akış Analizi

ÖZ

Birbiriyle karışmayan akışkanlar, her bir saf bileşenin sebep olabileceği termo-hidrodinamik farklılık nedeniyle, atımlı ısı boruları (PHP'ler) için çalışma esnekliği sağlar. Bu kapsamda, bu çalışma su bazlı karışmayan akışkan çiftleri ile yüklenmiş üniform olmayan atımlı ısı borularının termo-akışkan analizine odaklanmaktadır. Araştırma parametreleri; 0º ve 90º eğim açıları (IA) aracılığıyla yer çekimi etkisini ve su (W) – hekzan (H) ve su (W) – pentan (P) olmak üzere iki farklı su bazlı karışmayan ikili akışkanlar aracılığıyla akışkan çifti etkisini kapsamaktadır. Hacimsel karışım oranları; W:H=1:1, 1:4, 4:1, 1:0, 0:1 ve W:P=1:1, 1:4, 4:1, 1:0, 0:1'dir ve üniform olmayan düz plaka tipi atımlı ısı borusu (FP-CLPHP) alternatif sıralı paralel kanallara sahiptir. Deneyler %40 dolum oranında (FR=40%) yapılmıştır ve akış olayları görüntülenmiştir. Bazı sonuçlar şu şekildedir: düşey konumda, su-pentan ikili akışkanlarına sahip FP-CLPHP'ler, saf akışkanlı olanlara kıyasla daha iyi ısıl performans göstermiştir. Özellikle, W:P=1:1'in ısı transfer karakteristikleri bütün saf ve ikili akışkanlar arasında en iyidir. Diğer taraftan, üniform olmayan tasarım ve uygun termo-fiziksel özelliklerin birleşiminin bir sonucu

Received: 11/05/2022, Revised: 17/01/2023, Accepted: 06/03/2023

olarak, saf pentan, saf hekzan veya W:P=1:4 ikili akışkanıyla yüklü FP-CLPHP'ler yer çekimi kuvvetinden bağımsız çalışabilir.

Anahtar Kelimeler: *Karışmama, Atımlı ısı borusu, Akışkan çiftleri, Termo-akış analizi*

I. INTRODUCTION

After introduction to the scientific community by Akachi [1] at the ends of 20th century, the pulsating heat pipes have drawn much attention; and thus, especially for the last two decades, the PHPs with their different forms are widely studied. One of the basic reasons of this attention is the available potential of these unique devices regarding cooling of future micro electronic systems for space applications in addition to earth counterparts. In this context, some efforts are performed in the literature [2, 3]. Also, cooling of LED chips or CPUs [4, 5], and practices in solar and cryogenic fields [6, 7] are among the other examples for utilization of PHPs. Other reason can be linked to working principle of the PHPs. PHSs are the passive devises and do not need any external force for operation. In this way, they provide advantages against micro-flow boiling [8, 9]. Also, the PHPs noiselessly operate, and thus they gain an advantage over other promising techniques such as vortex tubes [10] and impinging jets [11, 12]. In addition to operational advantageous, the complexity and unsolved physical facts in thermo-fluid-geometric framework keep the interest alive for future scientific research.

In recent years, especially researchers dealt with non-uniform pulsating heat pipes, and various working fluid types such as mixtures. First known study focusing on non-uniform flat-plate closed loop pulsating heat pipes was conducted by Chien et al. [13]. In that study, the success of the alternating sequence of parallel channels on solving of the failure of PHPs having less turns with the lack of gravity support was introduced to the literature. They used pure water as the fluid; and they reported that at horizontal position the heat pipe only worked for the filling ratio of greater than 50%. Tseng et al. [14] focused on non-uniform PHPs; however, they obtained the nonuniformity by pressing one the consecutive circular passages. In this way, different cross-sectional areas were obtained in alternating sequence. The PHP was charged with only pure fluids of HFE-7100, water and methanol. They concluded that at horizontal orientation non-uniform design was better; however, with increasing heat input thermal resistance began to significantly increase after a minimum for both of the PHP types. For high heating powers, greater than namely 60W, water presented the lowest thermal resistance, while, for low heat inputs, HFE-7100 showed lower thermal resistance. Kwon and Kim [15] studied on five-turn FP-CLPHP charged with pure fluids of Ethanol and FC-72. Via dual diameter channel characteristics, the heat pipe could operate at horizontal orientation; and they attributed this to dominance of capillary pressure difference over the viscous pressure drop. The conditions corresponding to the greater values than 2×10^5 of this ratio were addressed as the gravity-independent operation case. Jang et al. [16] fully dealt with influence of geometrical characteristics on PHP performance. In this regard, they investigated ratio of the cross-sectional area of neighboring channels (asymmetric ratio; 1 – 4), and aspect ratio (2 .5 – 5) of channel pair. Based on their results, it can be concluded that effect of asymmetric ratio strongly depended on heat input level. Also, for a given asymmetric ratio, the lowest value of aspect ratio provided lowest thermal resistance, especially from medium to high heat inputs. Aref et al. [17] adapted a dual-diameter CLPHP to a solar collector. Difference in diameter was provided between the condensation region and other regions. In other words, the parallel channels in all regions had same diameter; however, the ones in the condenser section were different from the ones in evaporator and adiabatic sections. For medium (50% - 60%) and high filling ratio (60% - 70%), the dual diameter one showed better thermal characteristics than the single diameter one; however, for lower filling ratio both of them showed similar performance. Thermal performance of the solar collector could be increased up to 72.4% via dual diameter heat pipe.

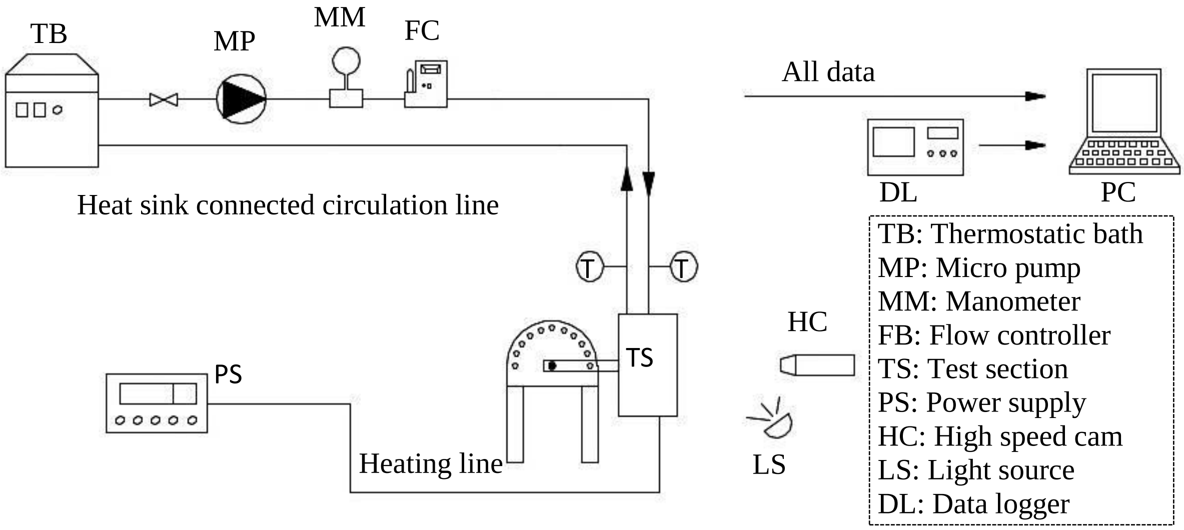
As summarized above, geometric structure has significant influence on operational characteristics of FP-CLPHPs. The main reason is the generation of different forces causing disequilibrium among the neighboring channels. In addition to the geometry, another key factor for the heat pipe performance is the working fluid. In this regard, in recent years, a special attention is shown to it, especially to different types of mixtures. Shi et al. [18] conducted an experimental study on circular type conventional PHPs charging with ethanol based binary mixtures (ethanol-water; ethanol-methanol; ethanol-acetone). At the filling ratios lower than 62%, mixtures were observed as superior compared to pure counterparts. A complex relation was experienced between mixing ratio and filling ratio (FR). At FR = 45%, ethanol and water mixture at the mixing ratio of 2:1 presented higher thermal performance, while at FR = 55%, ethanol and acetone mixture at the mixing ratio of 4:1 was reported as the best working fluid. Inhibition in the phase-change, level of the pressure-temperature variation at saturation conditions, and dynamic viscosity were addressed as dominant factors on mixture performance. Cui et al. [19] conducted experiments regarding circular type bended PHPs charged with methanol-based mixtures (methanol – water; methanol – acetone; methanol – ethanol). The mixing ratios were 2:1; 4:1; 7:1, and also pure states were studied. At FR = 45%, due to the water, dry-out problem was prevented at relatively high heating powers. Also, in this filling ratio, adding acetone to methanol lead to decrease in thermal resistance compared to pure components. For filling ratios greater than or equal 62%, the FP-CLPHPS charged by mixtures and pure fluids showed similar characteristics. An interesting study focusing on uniform-channel FP-CLPHPs having an immiscible fluid pair of water and HFE-7100 was conducted by Xu et al. [20]. The inclination angles investigated were 30^o, 45^o, 60^o, 75^o and 90^o. They concluded that fluid pair provided positive contributions to thermal performance of the heat pipe, gravity had significant influence on heat pipe operation, and first boiling components lead to oscillate the other one and increased heat transfer. Bao et al. [21] used sodium stearate as surfactant in water, and experimentally studied PHPs with that fluid. It was reported that using surfactant making the PHP possible to start at lower heating powers. The 20-ppm surfactant solution also provided decrease in thermal resistance by 27.8% at FR = 56.7%, compared to the pure deionized water. Zhou et al. [22] experimentally investigated a circular pipe type PHP charged with graphene oxide nanofluid in which water was the base fluid. It was concluded that there was a strong relation between graphene oxide (GO) concentration and filling ratio. At high filling ratios such as 80%, using GO nanofluid could not improve startup performance; while at lower filling ratio start up performance was able to be improved. At optimum filling ratio and concentration, an enhancement up to 54.34% was obtained in thermal performance.

In above paragraphs, the great attention to the non-uniform PHPs and mixture type fluids are summarized. It should be stated that the combination of non-uniform FP-CLPHPs and mixtures have been introduced to the literature by only the authors [23 – 25] of the present paper, recently. However, different combinations of the pure fluids have a great potential to present different results. Thus, the goal of the present paper is to experimentally investigate the thermal characteristics of non-uniform FP-CLPHPs charged with water based immiscible binary fluids. To the best of the authors' knowledge, this is the first study focusing on experimental investigation of non-uniform (alternating sequence of channels) FP-CLPHPs charged by Water – Hexane and Water – Pentane. Also, effect of gravity support and mixing ratio are examined, and flow physics is interpreted via flow visualization.

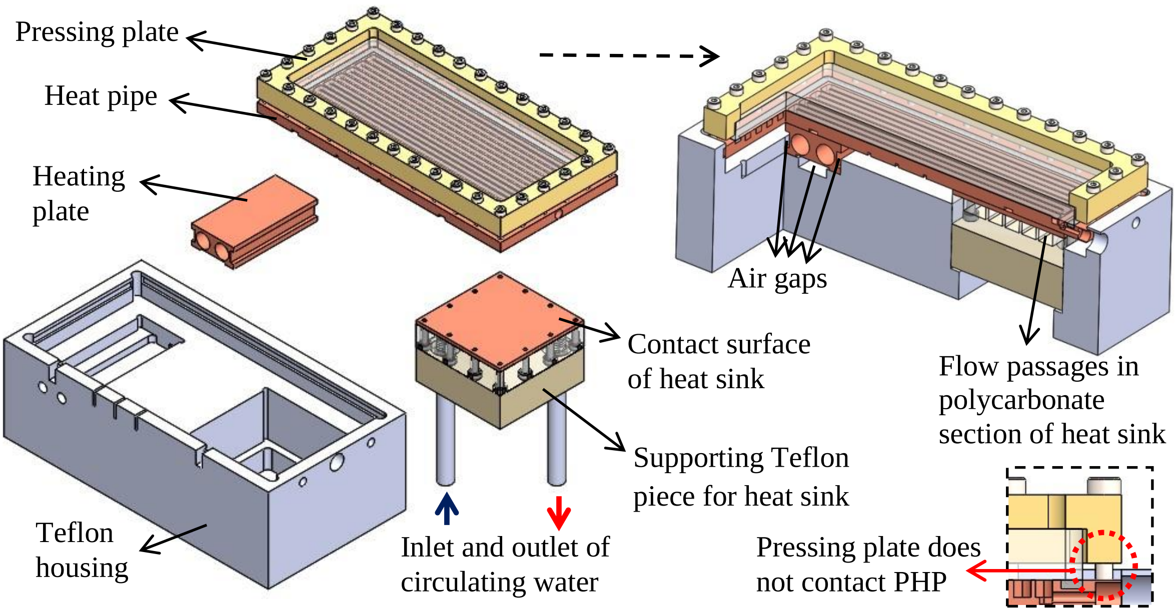
II. EXPERIMENTAL PART WITH RELEVANT EQUATIONS

A. INTRODUCTION OF EQUIPMENT USED IN EXPERIMENTS

Both the schematic of the experimental setup and exploded view with sectional details of test section are clearly presented in Fig. 1a and b. Description of the relevant parts and explanations are performed as below:



(a)



(b)

***Figure 1. (a)** Schematic of the experimental setup, and **(b)** exploded view with sectional details of test section*

The setup may be divided into five subsections as circulation line regarding heat sink (for condenser section of PHP), test section, heating line regarding heating plate, visualization unit, and data processing unit. The main part is the test section, and the others are auxiliary parts. Test section includes a flat plate type pulsating heat pipe, a heating plate, a heat sink, and Teflon housing. Test section is designed so as to minimize the heat loss. Thermal conductivity of Teflon housing is nearly 0.25 $Wm^{-1}K^{-1}$. Two groves are engraved into the Teflon to place the heating plate and heat sink. Heating plate includes two cartridge heaters connected to heating line, in other words, power supply. To affectively transfer heat to the evaporator section of the PHP, a copper block (high conductivity material) is preferred. To minimize the heat loss, air gaps are engraved at bottom and side surfaces of the heating plate, whose top surface directly contacts evaporator section of the PHP (see Fig. 1b). To effectively transfer heat from the condenser section, and to calculate the relevant heat value, a special-designed-heat sink is used. Heat sink has two sub-parts as 2 mm thick copper top surface, and (nearly) 10 mm thick bottom piece. Material of the top surface is copper, while the bottom piece is made of polycarbonate (nearly 0.2 $Wm^{-1}K^{-1}$). Flow passages are engraved into the polycarbonate piece. Top copper surface directly contacts condenser section of the PHP; thus heat can be effectively transferred from condenser to water supplied via circulation line. In the circulation line, there are a set of devices (clearly defined in Fig. 1a) to control the operational conditions (to provide constant temperature at the inlet of heat sink and constant flowrate throughout the heat sink). The heat pipe is placed over the heating plate and heat sink (evaporator section to heating plate, and condenser section to heat sink). Between evaporator and condenser sections, there is adiabatic section exposed to thin air gap (see Fig. 1b).

In pulsating heat pipes, there are dominant and effective phase-change phenomena. To clearly analyze physical phenomena, and to understand complex relations between geometry, flow, and heat transport, a visualization study should be conducted. Therefore, upper surface of the PHP should be covered by a transparent material. Also, the relevant material should be strongly resistant against working fluids (mostly alcohols). Thus, a tempered glass (thermal conductivity is nearly 1 $Wm^{-1}K^{-1}$) has been chosen as the cover plate in the present paper. To operate the heat pipe, a leak-proof and closed internal volume should be obtained; and for this, the glass plate is compressed to the PHP via a brass-frame by 32 miniature bolts. However, the brass frame does not directly contact with the PHP (clearly seen, in Fig. 1b). After placement of all the components, the test section is located on a platform, and then, side surfaces of Teflon housing are covered via insulation materials (extruded polystyrene (XPS) sheets, thermal conductivity of nearly 0.033 $Wm^{-1}\,K^{-1}$). Some other details such as real photographs of the experimental setup or thermocouple locations can be found in the recent articles of the authors [23 – 25].

A. 1. Steps Followed in Experiments

There are five different mixing ratios (including pure states), two different immiscible binary fluids, two different angles and heat load interval in the experimental range. The reason of using two different angles is actually to investigate the effect of gravity support on the heat pipe performance. Also, heat inputs are applied with 5 W intervals up to the evaporator section reaching nearly 110ºC mean temperature. The followed procedure can be briefly summarized as follows:

- The ambient air is conditioned to 24 ºC
- Heat pipe is vacuumed. The gauge pressure read from the manometer screen is -1.012 bar which corresponds to 125 Pa as absolute value (note that atmospheric pressure is 1.01325 bar).
- Circulation line starts up.
- The desired working fluid is charged into the heat pipe at the content of 40% of heat pipe internal volume. Volume of working fluid to internal volume of heat pipe is the filling ratio.
- The mechanism on which the FP-CLPHP placed is a movable one, and thus, it can be adjusted to the desired position, in the present paper, namely, horizontal or vertical orientation.
- Heat input is supplied via the cartridge heaters. The first value is 5W, and it increases at 5W steps. At each heat input, at the steady-state, temperature readings are logged. When temperature of the evaporator section reaches approximately 110 ºC, the system is ended; and for a new research parameter the defined procedure is repeated.

A. 2. Data Reduction

The formulas or equations used in determination of the thermal performance of a pulsating heat pipe are well-known in the open literature. One of the main performance indicators of the FP-CLPHP is the thermal resistance which is shown as below:

$$R_{th} = \frac{(T_e - T_c)}{Q_{ac}} \tag{1}$$

where, T_e is the average evaporator temperature, T_c is the average condenser temperature and Q_{ac} is the actual heating power. Here, it should be stated that Q_{ac} is commonly used in the literature [13, 26, 27], and this expression also includes heat loss as stated by Spinato et al. [27]. The explicit form of the Q_{ac} is presented below:

$$Q_{ac} = \frac{Q_i + Q_o}{2} \tag{2}$$

The heating power applied via the AC power supply is denoted with Q_i, while the heat removed via the cooling water passing through the heat sink is denoted with Q_o. One each T-type thermocouples are placed at the inlet and outlet of the heat sink component. The inlet temperature for heat sink is set to 20 ºC, while the outlet temperature is read depending on the experimental conditions. The flow rate of the cooling water is set to the desired value of 20 ml min^{-1}. Thus, the heat removed via heat sink (Q_o) can be simply determined as in the following:

$$Q_o = \dot{m} c_p \left(T_{he} - T_{hi}\right) \tag{3}$$

In Equation (3), mass flow rate and specific heat of cooling water are denoted with $\dot{m}$ and c_p, respectively. On the other hand, exit and inlet temperatures at the heat sink are represented as T_{he} and T_{hi}. It should be underlined that thermal resistance is not the unique performance indicator of a PHP. In addition to it, evaporator temperature and start-up characteristics are also important in the performance-evaluation. In this regard, all the mentioned tools are considered in the result and discussion part.

In a recent article of the authors [24], a comprehensive analysis regarding uncertainty was performed. In this context, explicit form for thermal resistance was presented. By following the same procedure, in the present paper (based on the present data), the maximum uncertainty of the thermal resistance is obtained as ±5.4%. It should be noted that the uncertainty in temperature readings as a measured parameter is ± 0.1°C (after calibration).

III. RESULTS AND DISCUSSION

In this section, experimental results obtained for the conditions of five different mixing ratio (1:1, 1:4, 4:1, 1:0; 0:1), two different immiscible binary fluids (Water-Hexane, Water-Pentane), two different angles (0º, 90º), and a wide range of heating power are presented. The filling ratio is constant as 40%, and flow is visualized via high-speed camera. For pulsating heat pipes, operational parameters have complex and combined effects on thermal performance. Therefore, the results are presented in an interrelated manner, as follows:

A. EVALUATION OF THE BEHAVIOR OF PURE FLUIDS REGARDING FP-CLPHPs

In the present study, it is focused on immiscible binary fluids, and in this regard, two different binary working fluids are investigated. To get useful information before discussion of the results belonging to the fluid-pairs, behavior of the FP-CLPHPs charged with pure fluids is presented in Figs. 2a-d. For the relevant experimental conditions, at vertical, namely bottom heat operation mode, the lowest thermal resistance and evaporator temperature values are obtained for the FP-CLPHP charged with water. In addition, at relatively high heat inputs (> 30W), thermal resistance of pentane charged heat pipe drops below the one of hexane charged. On the other hand, when the gravity effect is removed, other words, the heat pipe is placed horizontally, results completely change. Thermal resistance values for the pentane and hexane cases significantly drops with increasing heat input, which means successful operation of the heat pipe. On the other hand, trend of thermal resistance of water case is relatively horizontal, for more precisely, from 5 W to 25 W, there is a relatively small drop, and then nearly horizontal distribution is obtained. This kind of trend means that heat pipe does not properly operate at the relevant conditions; and relatively small drops in thermal resistance signify only some weak and discontinuous pulsations.

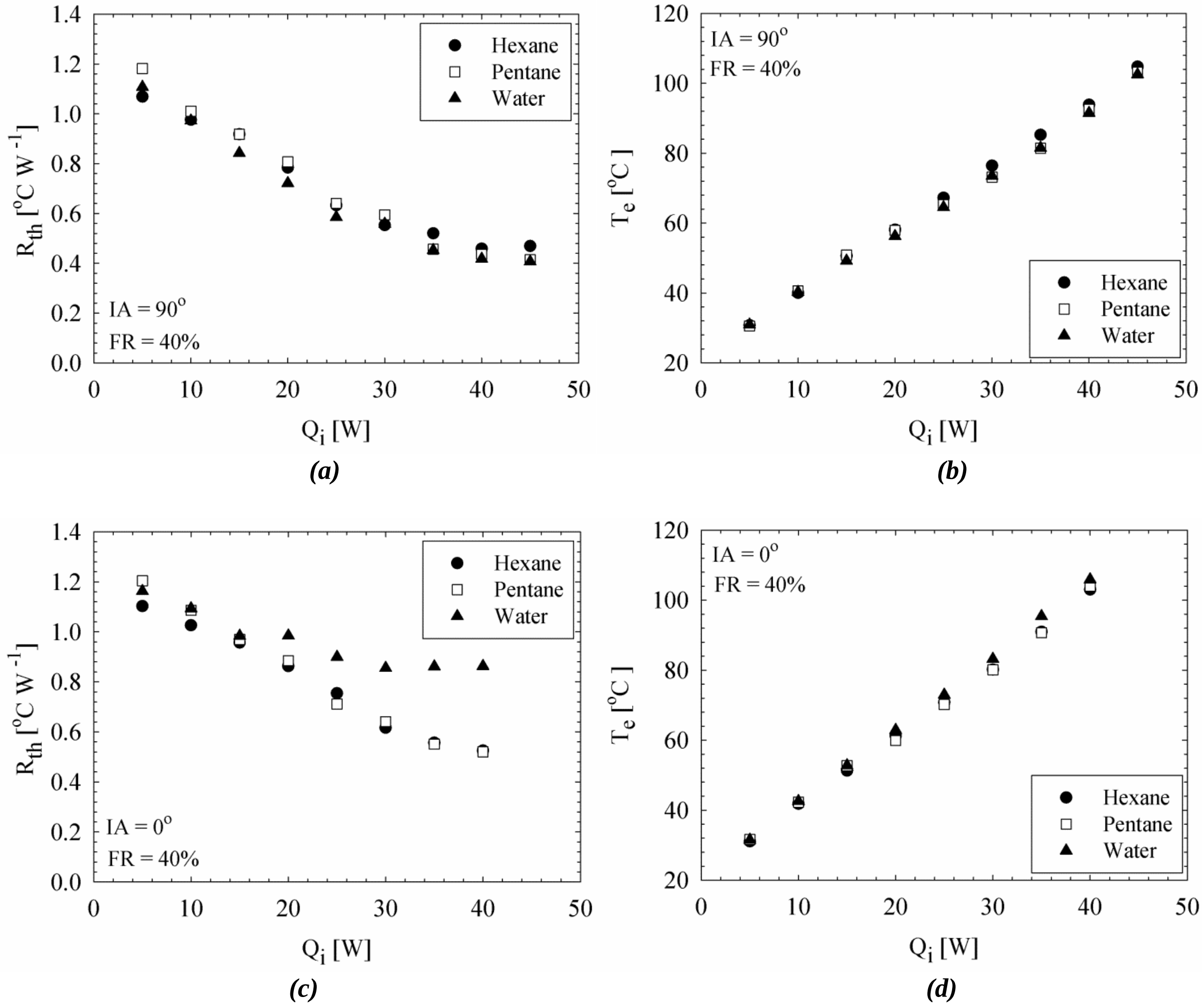


Figure 2. *Thermal resistance and evaporator temperature variation of pure fluids with heat load for both the vertical and horizontal orientations.*

B. SCRUTINIZING OF THE RESULTS OBTAINED FOR FP-CLPHPs CHARGED BY BINARY FLUIDS

In Figure 3, the results regarding the binary fluid of water-pentane are presented. As seen from Fig. 3a, at vertical orientation, in other words, at the condition of full gravity support, the FP-CLPHPs having binary fluids of water-pentane show better thermal performance compared to the pure counterparts. Especially, the heat transfer characteristics of W:P=1:1 are the best ones among all the pure and binary fluids. In this regard, thermal resistance and evaporator temperature of the heat pipe charged with W:P=1:1 are significantly lower than the other cases, and startup performance is the highest. At the heat input of 10 W (HI = 10W), a sharp drop is obtained in thermal resistance data for W:P=1:1, which means starting of the relevant heat pipe to operation in active manner. At vertical position, thermal resistance in the case of W:P=1:1 reaches the minimum value of 0.38 °C W^{-1}, and in the whole heat input range it is provided decrease in thermal resistance nearly by 40.4% compared to worst case (W:P=0:1, pure pentane, 15W). On the other hand, from Fig. 3b, as compatible with the thermal resistance, average evaporator temperature is generally lower for the FP-CLPHP charged with W:P=1:1; and in this case, for the whole heat input range approximately up to 6.3 ^{o}C temperature drop is obtained. As a conclusion, at vertical orientation, the FP-CLPHPs charged with W:P=1:1 provides significant advantages for safe and stable operating conditions, and prevents thermal stress based problems. When the support of the gravity is removed, results completely change as seen in Figs. 3c and d. In horizontal condition, only the FP-CLPHPs charged with pure pentane (W:P=0:1) or W:P=1:4 properly operate, and the FP-CLPHPs charged with other fluids collapse. The common characteristic of the unsuccessful working fluids is that they contain only water or relatively high volumetric content of water. These important results should be discussed or scrutinized with the help of fluid thermo-physical properties, non-uniform design of the heat pipes and flow images, as in the following:

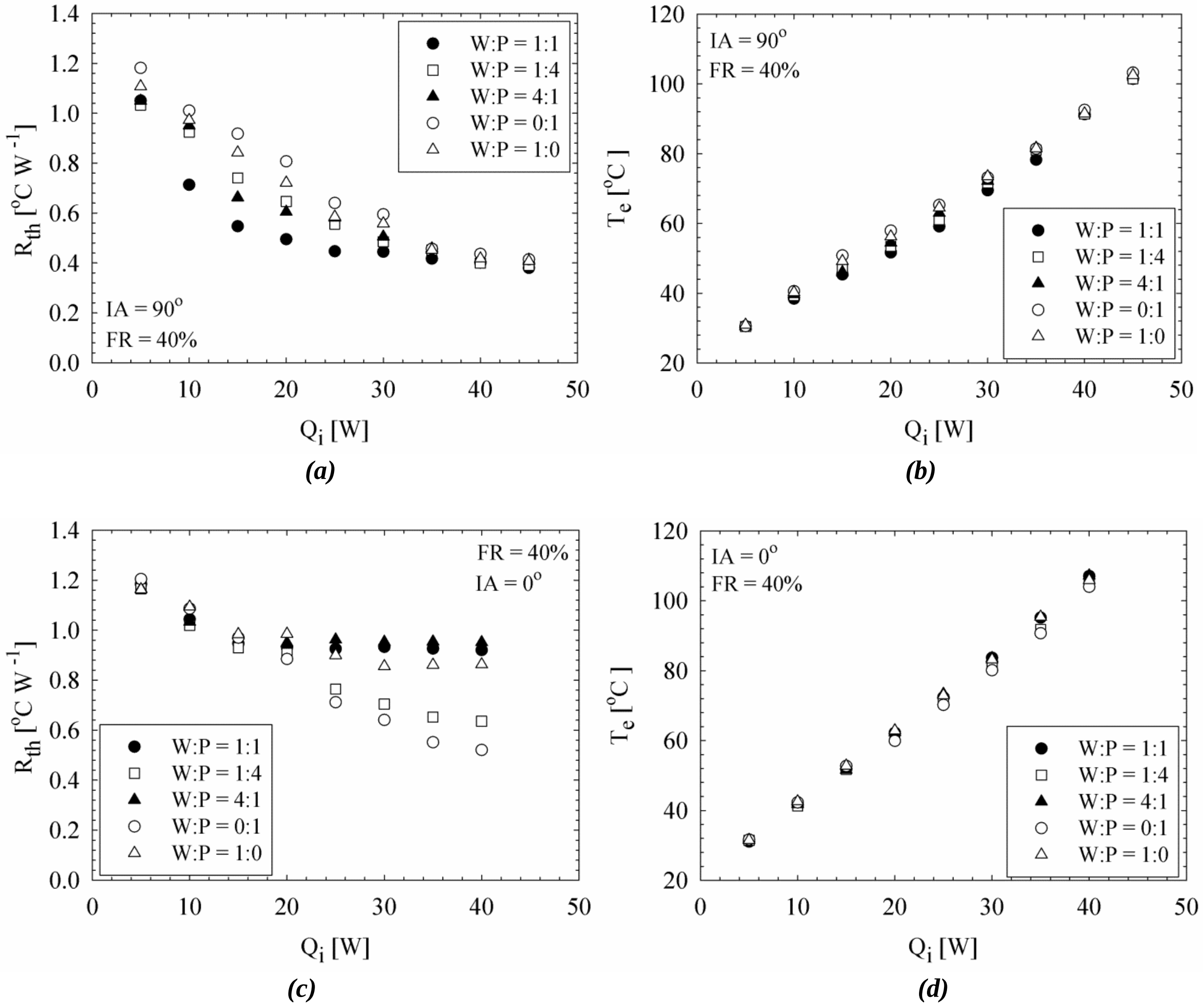


Figure 3. *Thermal resistance and evaporator temperature variation of water/pentane binary fluid with heat load for both the vertical and horizontal orientations.*

In Table 1, some important properties of the fluids are presented. In this regard, Table 1, Fig. 2 and Fig. 3 are evaluated together with the support of flow images. It should be stated that properties in Table 1 are presented at 20 °C (and 80 °C for $(dP / dT)_{sat}$) as compatible with the literature [32]. Except $(dP / dT)_{sat}$, other properties presented in Table 1 do not significantly change with temperature for the temperature range considered in this study. On the other hand, dependence of $(dP / dT)_{sat}$ on temperature is more significant. Therefore, considering the nearly average of the working temperature range, 80 °C was preferred for this property. However, it should be noted that temperature changes based on operational conditions; and the relevant values presented for 20 °C or 80 °C are used to perform a qualitative analysis as also underlined by Han et al. [32]. From Fig. 2a and Fig. 3a, it is seen that, at vertical orientation, the performance of pure water or water based immiscible fluids are generally better than the other ones. However, when the support of gravity is removed (see Fig. 2c and Fig. 3c) pure water and the cases including water content greater than 50% of total volume cannot actively operate. The probable main reasons are high density, high boiling point and high viscosity of water compared to the other fluids. Also, the inhibition in the phase change of the fluid having relatively higher boiling point is the other major reason. It should be stated that Han et al. [32] defined this process as phase-change-inhibition effect. In the present FP-CLPHP, the neighboring channels have different cross-sectional area; and at vertical orientation, with the support of non-uniform channel design, pressure perturbations increase, nucleating water bubbles rise in the flow passages, and due to higher density of water component, water droplets flow down towards the evaporator region, again. Also, boiling point of water is higher, and early boiling component, for example pentane, increases internal pressure and easily prevents nucleation of water. Therefore, water collects at the evaporator region, and it is mainly in the liquid phase. It should be noted that at vertical orientation, evaporator region corresponds to the bottom side of the heat pipe. Figures 4a and b represent the flow images of W:P=1:1 and W:P=4:1, respectively. As seen in Fig. 4a, at the side walls of the channels in the evaporator and adiabatic region, there are wavy liquid films; such that they are actually liquid drops flowing down to the U bends of the evaporator region. The reasons of this dropwise type back flow are relatively high density of water, relatively high pressure applied to water by pentane vapor (or vapor pressure of the component having low boiling point), different pressure forces existed in consecutive channels due to non-uniform channel design, and capillary effect due to sharp corners of the rectangular channels. As a result, for immiscible fluids, water as a component is prone to keep in liquid state and collect at bottom region and increasing water content begins to restrict flow flexibility in the flow passages, which may lead to decrease in thermal performance. However, at vertical orientation, due to gravity support and non-uniform structure of the heat pipe, collected water in the bottom moves as liquid columns in U bends or performs a reciprocating motion in the columns of the relevant channel.

Table 1. *Some properties of the pure fluids at atmospheric pressure: water [18], pentane [28, 29], and hexane [30].*

Thermo-physical properties	**Pentane**	**Deionized water**	**Hexane**	**Temperature [ºC]**
Boiling point [°C]	36.06	100	68.7	
Latent heat of vaporization [kJ kg^{-1}]	366.9	2257	335	
Surface tension (x 10^3) [N m^{-1}]	15.8	72.8	18.5	
Liquid density [kg m^{-3}]	625.5	998	659	20
Liquid dynamic viscosity (x 10^3) [Pa s]	0.242	1.01	0.3	
Liquid specific heat [kJ kg^{-1} $°C^{-1}$]	2.33	4.18	2.24	
Liquid thermal conductivity [W m^{-1} $°C^{-1}$]	0.138	0.599	0.128	
Saturation pressure variation with temperature $(dP / dT)_{sat}$ (x 10^3) [Pa $°C^{-1}$]	10.1	1.9	4.27	80

Notes:

Clapeyron Equation [31] is used to obtain the values of $(dP / dT)_{sat}$. The required values for $(dP / dT)_{sat}$ can be obtained from the Ref. [28].

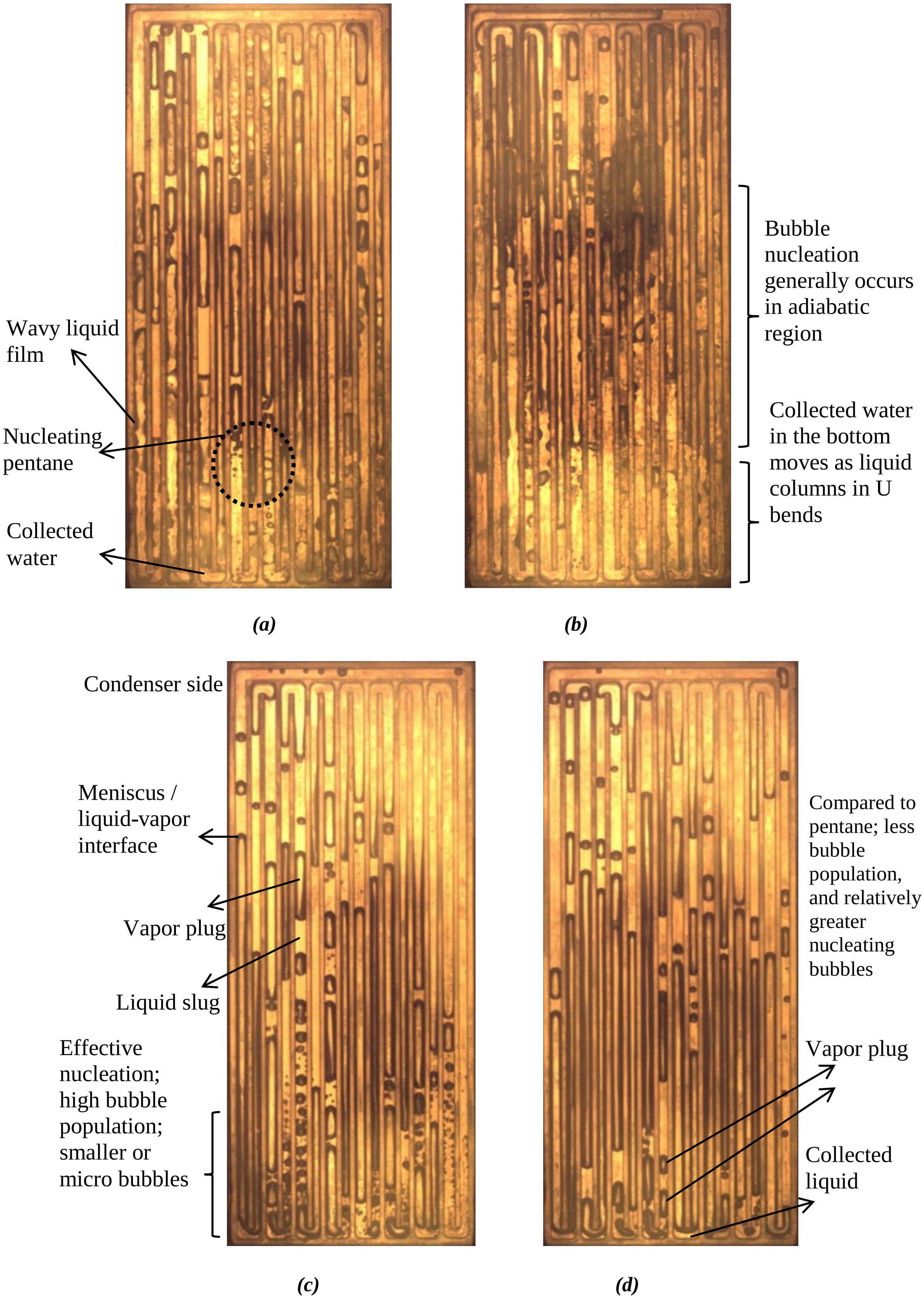


Figure 4. *Flow images at HI=30W, IA=90º, and FR=40%: W:P=1:1* ***(a)****, W:P= 4:1* ***(b)****, W:P=0:1* ***(c)****, and W:H=0:1* ***(d).***

Also, micro liquid droplets can be carried from evaporator to adiabatic or condenser region by pressure perturbations, advancing vapor plug of other component and friction between two components (as mist flow). Despite limitations in the circulation of the flow, combination of this type of flow with the superior thermal characteristics of water presents successful results in terms of thermal performance. From Table 1, latent heat of evaporation of water is nearly seven times of the ones of pentane and hexane, liquid specific heat of water is nearly two times of the others, and thermal conductivity of water is nearly five times of the others. Also, it should be stated that liquid droplets flowing down throughout the channel side walls rewet the hot surface and decrease wall temperature.

Regarding pure fluids, Figs. 4c and d are presented. As seen in Fig. 4c, pentane provides many smaller, even, micro bubble nuclei in the evaporator region. The reason of high populated and smaller type bubbles is the relatively low surface tension of pentane. Nucleating bubbles transform to larger bubbles under heat load, also, the bubbles coalescing each other form larger ones, too. Also, viscosity of pentane is the lowest among the available ones in Table 1, and the value of $(dP/dT)_{sat}$ of pentane is the highest. Low viscosity makes the flow motion easier, and high $(dP/dT)_{sat}$ makes the pressure fluctuations stronger. Therefore, when the optimum volume or volumetric ratio of water and pentane is brought together, optimum thermal performance is obtained at vertical orientation.

In spite of the results presented regarding vertical orientation, when the heat pipe is placed horizontally, the results of water and pentane immiscible binary fluids (W:P) completely change, as seen in Figs. 3c and d. Based on the results, at horizontal condition, only the FP-CLPHPs charged by pure pentane (W:P=0:1) and binary fluids of W:P=1:4 successfully operate. Other ones collapse. In horizontal position, effect of gravity and the positive role of high density disappear. The additional unbalanced forces being generated depending on non-uniform channel design are insufficient to drive high viscosity and relatively weightier fluid. Of course, this may also be related to the filling ratio or mass content. Therefore, the FP-CLPHPs having greater than or equal 50% volumetric ratio of water cannot work at horizontal orientation. On the other hand, the heat pipes having pure pentane or the binary fluids of W:P=1:4 properly operate in the lack of gravity support. As reported in the literature [13, 27], the uniform heat pipes having few turns collapse in the lack of gravity support. However, non-uniform design of pulsating heat pipes provides additional unbalanced forces such as evaporation momentum force, capillary force and shear force [24]; and thus, as a conclusion of combination of suitable thermophysical properties and geometry, the FP-CLPHPs charged with pure pentane or binary fluids of W:P=1:4 can work independent from gravitational force.

As additional information obtained via flow visualization results regarding binary fluids is that: as seen in Figs. 4a and b, the fluid having low boiling point in the binary ones nucleates towards outlet of the evaporator region or at the adiabatic region; and thus, separate vapor plugs and liquid slugs distribute in the flow passages (adiabatic and condenser regions). Increasing water content (see Fig. 4b) means higher liquid volume collecting in the evaporator region, and thus nucleation sites are shifted towards condenser side.

After the binary fluids of water and pentane, the results of binary fluids of water and hexane are presented in Figs. 5a-d. Detailed underlying physical mechanisms and geometric characteristics are stated in the above paragraphs, and thus, here, differences are presented in comparative manner. As seen in Figs. 5a and b, at vertical orientation, water as a pure fluid is better in terms of heat transfer performance than both the pure hexane and any other water-hexane binary combinations. On the other hand, at horizontal orientation, only the FP-CLPHP charged by pure hexane (W:H=0:1) properly works (see Fig. 5c). As a result, the heat pipes having any of the water-hexane binary fluids cannot operate at the lack of gravity support, and at vertical condition, they perform lower thermal performance compared to pure water or pure hexane. These results are obviously different from the ones of water-pentane binary fluids. As remembered from Fig. 3a, water-pentane binary fluids work better than pure counterparts, and even at horizontal orientation (see Fig. 3c), the FP-CLPHP charged with W:P=1:4 successfully operates in addition to pure pentane. In spite of using same geometry, obtaining these results can be explained with differences in the thermo-physical properties of pentane and hexane. This information also provides important knowledge regarding key properties. From

Table 1, it is seen that the main difference between pentane and hexane is related to the value of $(dP / dT)_{sat}$. Zhu et al. [33] associated high values of this parameter with stronger pressure impulses, and also, present results support the importance of $(dP / dT)_{sat}$. High value of $(dP / dT)_{sat}$ of pentane improves pressure perturbations and triggering of water.

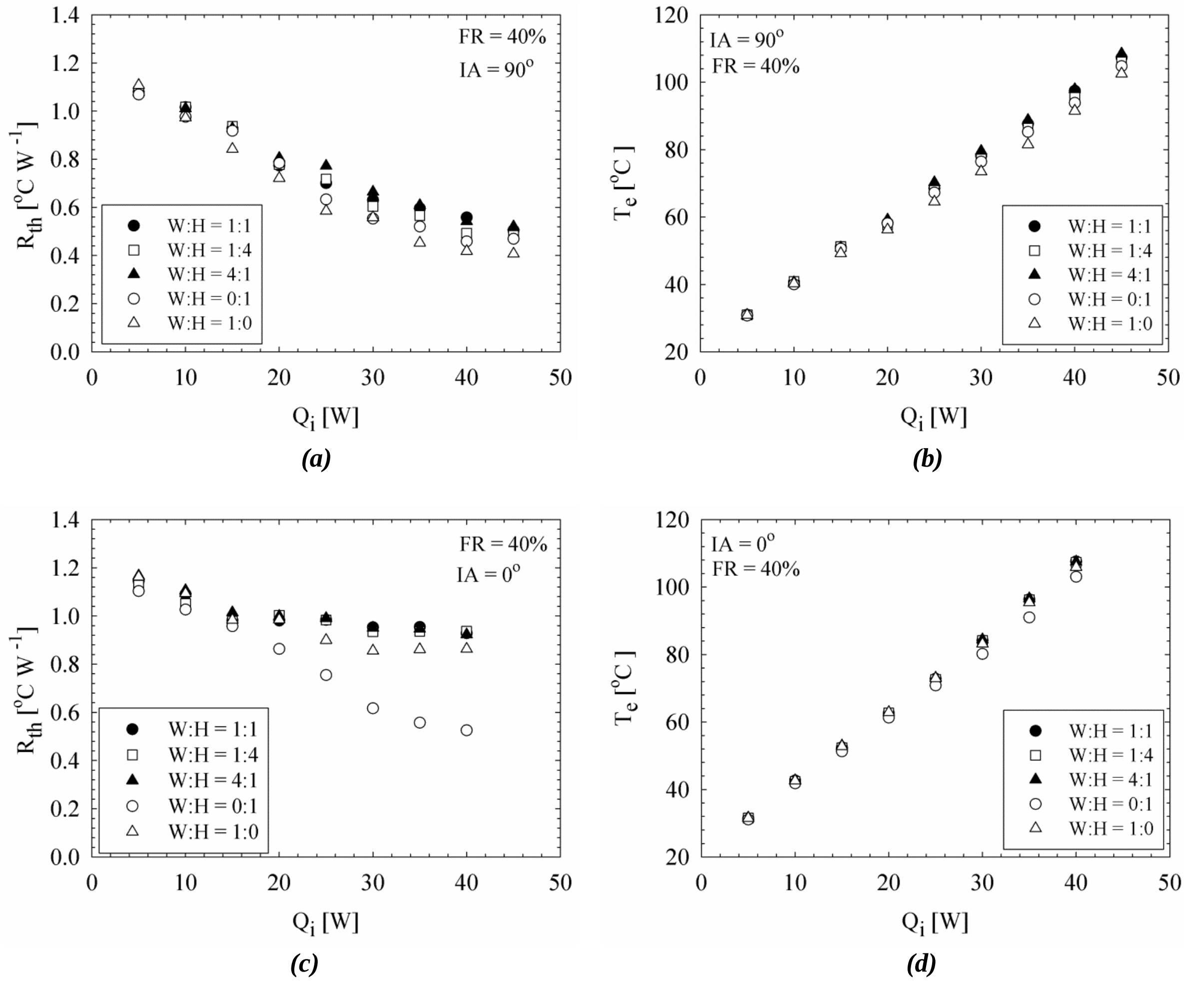


Figure 5. *Thermal resistance and evaporator temperature variation of water/hexane binary fluid with heat load for both the vertical and horizontal orientations.*

C. SCRUTINIZING OF THE RESULTS OBTAINED FOR FP-CLPHPs CHARGED BY BINARY FLUIDS

Influence of gravity on performance of the FP-CLPHPs charged with pure and binary fluids is presented in Fig. 6 and Fig. 7, respectively. Actually, physical mechanisms regarding vertical and horizontal orientations are well reported in the previous section. However, in this section, the graphs are presented directly over IA = 90º and IA = 0º. In Figure 6a, it is seen that trend of the thermal resistance data with increasing heat input is very different for vertical and horizontal conditions. At vertical location, thermal resistance data significantly decreases with increasing heat input, which means effective working of the relevant heat pipe. Increasing heat input improves nucleation characteristics, speed up the flow, increases pressure pulsations and pressure-based forces. However, one of the most influential sources of internal pressure perturbations is the turn number, and at horizontal position, collapsing of heat pipes having few turns is an important obstacle for miniaturization. To solve this problem, in the present paper a non-uniform FP-CLPHP is used. However, it is seen that thermo-physical properties, or in other words, fluid selection has key importance, and operational or geometrical characteristics of heat pipes cannot be considered separately from each other.

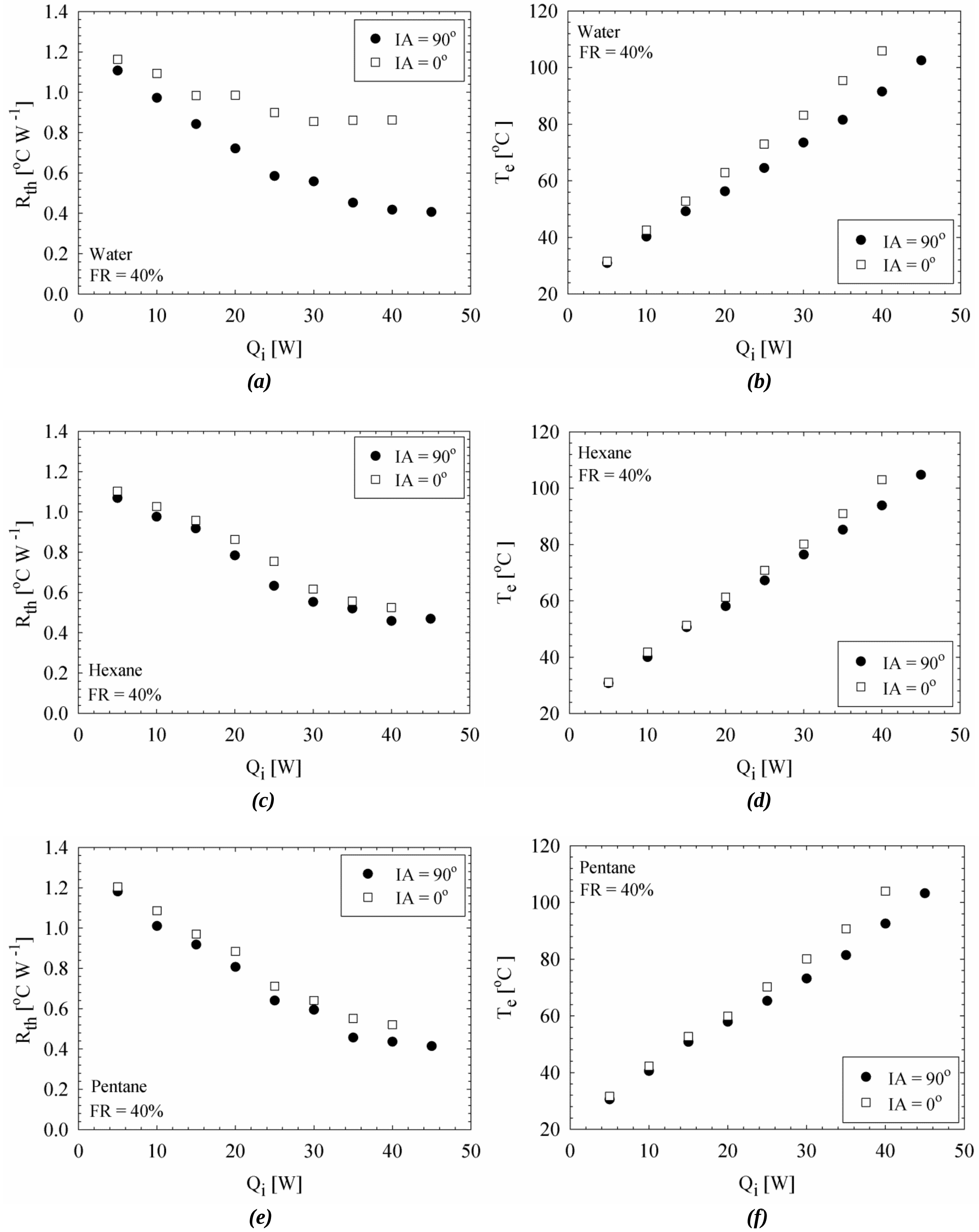


Figure 6. *Influence of gravity on performance of the FP-CLPHPs charged with pure fluids.*

In this regard, when one of the pure pentane, pure hexane or the binary fluid of W:P=1:4 is used as the working fluid, non-uniform heat pipe can successfully operate at horizontal position in spite of having only eight turn numbers (see Figs. 6c and e, and Fig. 7e). Additional unbalanced forces such as evaporation momentum force, capillary force and shear force [24] provided via the usage of non-uniform FP-CLPHP, high value of $(dP / dT)_{sat}$, low viscosity and low surface tension (in terms of easy nucleation, and thus better pressure perturbation) are all responsible for successful operation in the lack of gravity support. On the other hand, it should be stated that higher values of latent heat of evaporation, specific heat and thermal conductivity gain extra importance when the flow motion starts in the channels.

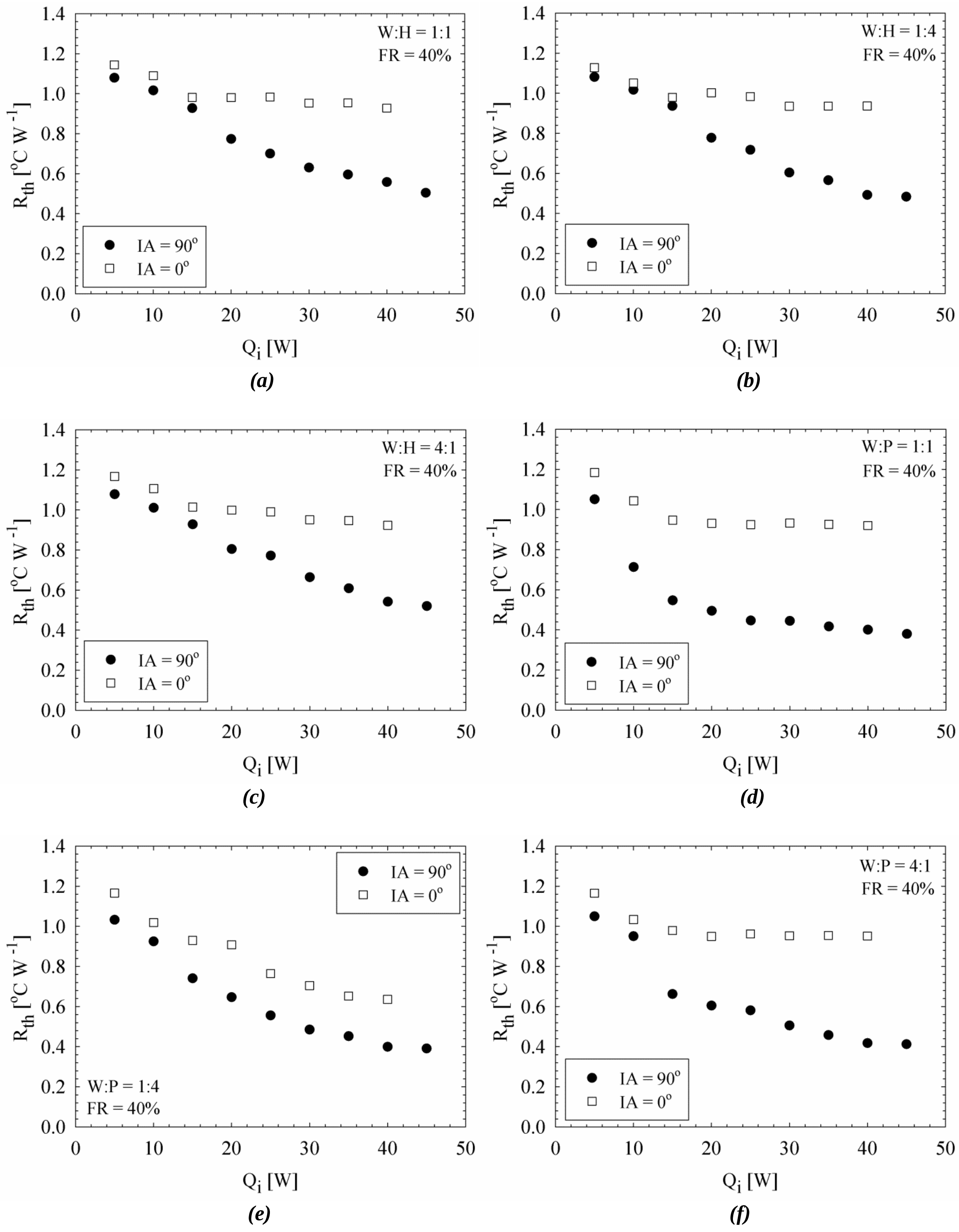


Figure 7. *Influence of gravity on performance of the FP-CLPHPs charged with binary fluids.*

IV. CONCLUSION

Present paper focuses on thermo-hydrodynamic evaluation of non-uniform FP-CLPHPs charged with immiscible binary fluids. An experimental effort is conducted in a wide range of parameter. Main conclusions and remarks are stated as below:

- Regarding the pure fluids, at vertical orientation, the lowest thermal resistance and evaporator temperature are obtained for the FP-CLPHP charged with water. On the other hand, at high heat inputs (> 30W), thermal resistance of pentane charged-heat-pipe drops below the one of hexane charged. At horizontal orientation, thermal resistance values for pentane and hexane cases significantly drop with increasing heat input, which means successful operation of the heat pipe. On the other hand, the water charged FP-CLPHP cannot operate with the lack of gravity support.
- At the condition of full gravity support, the FP-CLPHPs having binary fluids of water-pentane show better thermal performance compared to the pure counterparts. Especially, the heat transfer characteristics of W:P=1:1 are the best ones among all the pure and binary fluids. Thermal resistance in the case of W:P=1:1 reaches the minimum value of 0.38 $^{o}C\ W^{-1}$, and in the whole heat input range it is provided decrease in thermal resistance nearly by 40.4% compared to worst case (W:P=0:1, pure pentane, 15W).
- Regarding the pure states or the binary fluids of water and pentane, at horizontal condition, only the FP-CLPHPs charged with pure pentane (W:P=0:1) or the binary fluid of W:P=1:4 properly operate, and the FP-CLPHPs charged with other fluids collapse. The common characteristic of the unsuccessful working fluids is that they contain only water or relatively high volumetric content of water (equal or greater than 50% of total fluid volume). The probable main reasons are high density, high boiling point and high viscosity of water, and phase-change inhibition phenomenon.
- The heat pipes having any of the water-hexane binary fluids cannot operate at the lack of gravity support, and even, at vertical condition, they show lower thermal performance compared to pure water or pure hexane. These results are obviously different from the ones of water-pentane binary fluids.
- Non-uniform design of pulsating heat pipes provides additional unbalanced forces such as evaporation momentum force, capillary force and shear force; and thus, as a conclusion of combination of suitable thermophysical properties and geometry, the FP-CLPHPs charged with pure pentane, pure hexane or binary fluid of W:P=1:4 can work independent from gravitational force.
- Additional unbalanced forces such as evaporation momentum force, capillary force and shear force provided via the usage of non-uniform FP-CLPHP, high value of $(dP / dT)_{sat}$, low viscosity and low surface tension (in terms of easy nucleation, and thus better pressure perturbation) are all responsible for successful operation in the lack of gravity support. On the other hand, it should be stated that higher values of latent heat of evaporation, specific heat and thermal conductivity gain extra importance when the flow motion starts in the channels.

ACKNOWLEDGEMENTS: The Scientific and Technological Research Council of Turkey (TUBITAK) supported this study with the project number of 217M341.

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