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Experimental Investigations on the Thermal Performance of a Vertical Closed Loop Pulsating Heat Pipe Using Binary Mixture of Fluids

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ABSTRACT

This paper presents the experimental investigations conducted on a vertical closed loop pulsating heat pipe (VCLPHP) to evaluate the thermal performance. The values of thermal resistance and heat transfer coefficient obtained in the experimentation is used as evaluation parameters. The VCLPHP used has capillary tubes having an inner diameter of 2mm and outside diameter 3mm and bent into 5 turns. The lengths of the evaporator, adiabatic and condenser sections are 50, 90 and 70mm, respectively. The binary mixture of fluids used are acetone – ethanol and ethanol - methanol mixtures. The thermal performance of these binary mixtures were then compared with conventional working fluids such as acetone, ethanol and methanol. The fill ratios was changed from 50 to 80% in steps of 10% and the heat inputs were varied between 60 to 90W in steps of 10W. However, the mixing proportions for all mixtures was maintained as 1:1. All the experiments were conducted in the vertical position (90°). The experimental results showed that, the overall performance of acetone was the best with the lowest thermal resistance and highest heat transfer coefficient as compared to all pure fluids and among fluid mixtures the acetone-ethanol mixture showed the best thermal performance.

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1. INTRODUCTION[1]

The rapid technology advancements in the field of electronics has led to development of superior electronic devices/systems capable of working faster than ever before. This improved performance is a result of the large scale use of the IC chips through compaction and miniaturization in the modern day electronic devices. Although by such compaction and miniaturization the processing speed has nevertheless improved, but on the other hand, has resulted in an increase in heat evolution and temperature rise from such devices[1]. As a result, the chip power of the devices is gradually increasing. In the present time the minimum and maximum chip power is expected to reach to 175W and 360W, respectively; beyond the year 2020 it is expected to rise even further [2]. Hence, thermal management of electronic devices has not only become a necessity but poses a real challenge for scientists and engineers to develop new methods and technologies. In this direction, the thermal management solutions earlier proposed were: Air/liquid jet impingement, forced liquid convection, spray cooling, thermo electric cooling and refrigeration cooling. In 1971, the concept of pulsating heat pipe (PHP) was first proposed by Smyrnov and Savchenkov [3] to investigate heat transfer patterns. Later, in 1990, the pulsating heat pipe was introduced from an engineering perspective by a Japanese scholar named Hisateru Akachi [4]. The PHP is a passive heat transfer device with meandering capillary tubes arranged in a planar orientation [5]. The tubes are first evacuated and then filled with working fluid. The surface tension causes the working fluid to distribute itself naturally into liquid slugs and vapor bubbles [6]. The working fluid boils in the evaporator zone by heat absorption to form vapor bubbles. This results in sudden increase in pressure which pushes the fluid to the condenser zone. As the condenser zone is

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relatively cooler, the vapor bubbles condense to liquid by which the pressure reduces. This pressure imbalance in the system is the driving force for the pulsating movement of the working fluid [7]. Due to the existence of the pressure and temperature non-equilibrium conditions, the pulsating movement inside the PHP is self-sustained [8].

The advantages of the PHP can be realized in its simple structure, easy fabrication, low cost and high heat transfer capabilities [9]. Hence, PHP may be considered to be effective in electronics cooling for removing large heat fluxes. Although, different designs of the PHP are available, the closed loop pulsating heat pipe (CLPHP) is the most preferred due to its high thermal performance [10]. With a complex thermo-hydrodynamics involved in its operation, the PHP has deluded researchers in completely understanding its behavior and performance [11]. To this end, considerable research has taken place in the recent past to study the thermal performance both experimentally and through numerical investigations [12]. As the performance of PHP is dependent on various parameters, the experimental studies are focused on characterizing PHP based on diameter, orientation, working fluid used, fill ratio and heat input [13-15]. The numerical investigations mainly analyze the thermal performance by considering the movement of the liquid slugs and vapor bubbles inside the PHP [16].

The selection of the working fluids is a challenge as a number of fluids qualify in the working temperature range between 50°C and 150°C [17]. The working fluids have their own advantages in different applications. Zhang et al. [18] investigated PHP performance using different working fluids like FC-72, water and ethanol. Their studies indicated that a minimum heat input requirement for starting the oscillatory motion in a PHP is dependent on the working fluid. Rittidech and Nimkon [19] have found in their experimental studies that the heat transfer rate of the PHP increased when the working fluid was changed from ethanol to R123. Rao et al. [20] conducted experimental investigations on the single loop brass PHP using the working fluids such as acetone, ethanol, methanol and propanol. It was found that, acetone displayed better thermal performance as compared to other working fluids due to its lower latent heat and low boiling point. Similar results were obtained by Rama-Narasimha et al. [21] and Naik et al. [22] in their investigations on single loop PHP. Clement and Wang [23] conducted experimental investigations on a closed loop PHP using acetone, methanol and DI water as the working fluids. The PHP was made of copper. The fill ratios varied between 30 and 70% and the heat input varied between 80 and 180W. Methanol showed better performance as compared to acetone and DI water in terms of time required for attaining steady state and evaporator-condenser temperature differences.

The choice of a single working fluid becomes difficult in some situations due to influence of thermophyscial properties such as density, latent heat, viscosity and surface tension [24]. Mixture of two fluids as a binary mixture, improve the properties of the resultant fluid. For example, the sensible heat and latent heat can be combined to lower the effects of surface tension and latent heat which helps in faster movement of the working fluid and aids in quicker startup [25]. Pachghare and Mahalle [26] studied the effect of binary mixtures on the thermal performance of a CLPHP. The working fluids used were methanol, ethanol, acetone and water and different binary mixtures. It was found that, the performance of pure acetone was the best as compared to other fluids and fluid mixtures. Khandekar et al. [27] studied the thermal performance of azeotropic mixture of water and ethanol which was further compared with performance of ethanol. It was observed that no appreciable change in performance among the two fluids. Wang and Cui [28] conducted experimental investigations on vertical looped PHP using different fluids and fluid mixtures. The pure fluids used were Methanol, ethanol, acetone, water. The binary fluid mixtures considered were methanol-water, ethanol-water and ethanol-acetone. It was found that, the thermal resistance of methanol-water mixture is lower than methanol and water. For the acetone-water mixture, the thermal resistance of acetone-water was in between that of acetone and water. For ethanol-acetone mixture, the thermal resistance is more than that of ethanol and acetone.

The studies on different fluid mixtures reported so far are limited in number and their results are not conclusive. Also, the performance comparison between two fluid mixtures such as acetone – ethanol and ethanol – methanol is still not available. In view of this, in this study, experimental investigations on a vertically oriented multi loop PHP called VCLPHP is carried out using the binary mixtures of fluids such as acetone – ethanol and ethanol – methanol. The VCLPHP used has five turns with the inner and outer diameters of the tubes being 2 and 3mm, respectively. Further, the performance is compared with that of the pure fluids: acetone, ethanol and methanol. The performance comparison is made using thermal resistance and heat transfer coefficient values to decide the most suitable working fluid.

2. EXPERIMENTAL SET UP

The experimental setup in a schematic form is shown in Figure 1.

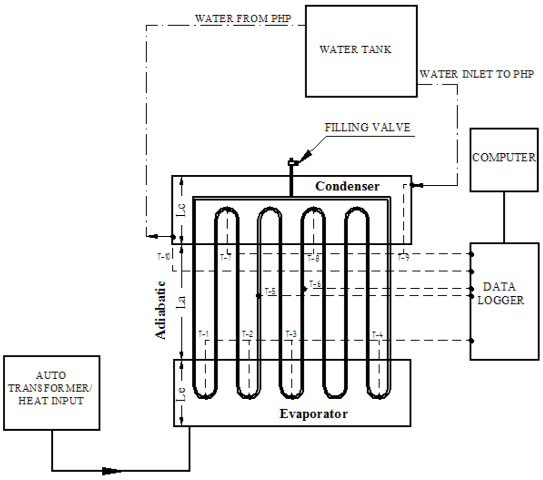

Figure 1. Schematic diagram of the experimental setup of VCLPHP

It has a vertically oriented closed loop pulsating heat pipe having five turns. It is operated in the bottom heating mode (evaporator at the bottom and condenser at the top). The capillary tubes are made of copper. The inner and outer diameter of the capillary tubes are 2 and 3mm, respectively. The evaporator, adiabatic and condenser sections measure 50, 90 and 75cm, respectively while the total length is 204mm. The evaporator section is heated by means of two mica strip heaters of capacity 200W each and are well insulated from all sides using glass wool. An auto transformer is used for providing regulated heat supply to the heaters. The adiabatic section is provided with glass tubes made of borosilicate glass. The glass tubes also help in better flow visualization. High temperature resistant silicon rubber tubes are used to fill the gaps between copper and glass tubes. A water bath is provided at the condenser end for the continuous supply of cold water at a rate of 7ml/s to provide maximum cooling at the condenser. Eight T-type thermocouples (4 at the evaporator, 2 at adiabatic section and 2 at the condenser section) record temperatures at evaporator, adiabatic and condenser sections. The thermocouples were calibrated using steam and ice and was found to be consistent with the standard calibration curve. Experiments were repeated to ensure the consistency of the thermocouples. The temperature data of the thermocouples are saved to a computer through a data logger. The temperatures were recorded at a frequency of 1 second. The experiments were conducted in the following manner:
Preparation of the fluid mixtures:

Pure fluids of acetone and ethanol, acetone and methanol (in the proportion of 1:1) were mixed in equal volumes of 100ml each into a container and stirred well. The air inside the PHP tubes was completely evacuated. A correct volume of the individual fluid and fluid mixture matching a fill ratio of 60%, was filled into the PHP. The required heat input of 60, 70, 80 and 90 Watts was set by varying the voltage and current of the autotransformer. The temperature readings were recorded using the data logger after the temperatures have reached the steady state condition. Cooling water as coolant is circulated through the condenser section from the supply tank at a slow rate for efficient cooling. All the experiments were conducted in vertical bottom heating mode (90°) using the working fluid mixtures. The performance parameters such as thermal resistance, heat transfer coefficient were obtained from the values of temperature differences between evaporator and condenser and necessary graphs were plotted. From the graphs obtained the best performing fluid mixture is identified. The important parameters used for evaluating the performance of the PHP are the thermal resistance (Rth) and heat transfer coefficient (h). The resistance encountered by the heat while flowing through a medium is called as thermal resistance (Equation (1)). It is the difference between the average evaporator and average condenser temperatures (Te -Tc) to the heat input (Q). This parameter helps in signifying the resistance encountered by the heat flow across the fluid medium from the evaporator end to the condenser end.

Convective heat transfer coefficient is a quantitative characteristic of convective heat transfer between a fluid medium (a fluid) and the surface (wall) over which the fluid flows (Equation (2)). Heat transfer coefficient signifies the flow of heat from evaporator to condenser. The PHP temperature data were obtained for both the pure and binary mixtures in the following manner: Different values of heat inputs were provided to the evaporator section and the temperatures at different points were recorded. As the heat dissipates at the condenser end the temperature differences were recorded and the average temperature was also recorded. The differences in average temperatures between evaporator and condenser were obtained.

$$Rth = \frac{T_e - T_c}{Qin} \tag{1}$$

where, Q_{in} = heat input in Watts, $(T_e - T_c)$ = Temperature difference between average evaporator temperature and average condenser temperature, °C. R_{th} = thermal resistance, °C/W

$$h = \frac{Qin}{As(T_e - T_c)} \tag{2}$$

h = heat transfer coefficient, W/m^2°C. A_s = surface area, m^2

2.1. Temperature Uncertainty/Error Analysis of Thermocouples

The temperatures recorded both in the evaporator and condenser fluctuate due to the pulsating flow observed in the evaporator and condenser sections of the PHP. Eight 'T' type thermocouples were used for measuring temperatures in the evaporator and condenser sections. Four thermocouples measuring temperatures (T1, T2, T3, and T4) were placed in the evaporator, two thermocouples (T5, T6) in the adiabatic region and two thermocouples (T7, T8) in the condenser region. Due to the fluctuations, the uncertainty analysis of the measured temperatures is evaluated as follows.

$$\%U_e = \sqrt{\left(\frac{\Delta T_1}{T_1}\right) + \left(\frac{\Delta T_2}{T_2}\right) + \left(\frac{\Delta T_3}{T_3}\right) + \left(\frac{\Delta T_4}{T_4}\right)} \quad (3)$$

$$\%U_a = \sqrt{\left(\frac{\Delta T_5}{T_5}\right) + \left(\frac{\Delta T_6}{T_6}\right)} \quad (4)$$

$$\%U_c = \sqrt{\left(\frac{\Delta T_7}{T_7}\right) + \left(\frac{\Delta T_8}{T_8}\right)} \quad (5)$$

It was found the uncertainty measured for the temperatures using Equations (3), (4) and (5) was about 5%.

where,

U_e = Uncertainty in the evaporator section

U_a = Uncertainty in the adiabatic section

U_c = Uncertainty in the condenser section

T1, T2, T3, T4 = Temperatures measured at points 1, 2, 3 and 4 in the evaporator section

T5, T6 = Temperatures measured at points 5, 6 in the adiabatic section

T7, T8 = Temperatures measured at points 7, 8 in the condenser section

ΔT1, ΔT2, ΔT3, ΔT4, ΔT5, ΔT6, ΔT7, ΔT8 = Differences in temperatures at the stated point.

3. RESULTS AND DISCUSSION

3.1. Effect of Heat Input on Thermal Resistance and Heat Transfer Coefficient for Different Fill Ratios

Figures 2 and 3 shows the variation of thermal resistance and heat transfer coefficient for varying heat inputs (Q) and fill ratios for the acetone-ethanol mixtures. It may be observed that with an increase in heat input from 60 to 90W, the thermal resistance decreases for all fill ratios. The thermal resistance was the least for a fill ratio of 60%. Also, from the literature it can be noted that maximum heat transfer occurs for a fill ratio in the range 50 to 60% [9]. For a 50% fill ratio, initially, only 50% of the liquid is present as compared to the total volume of the PHP. With the increase in heat input, the liquid starts to vaporize which increases the vapor volume as compared to liquid volume. Although, a faster movement is observed, the heat transferred will be less. This is because of the low thermal conductivity of vapor coupled with low sensible heat of the liquid available increases thermal resistance. The high thermal resistance is indicated by the increase in the temperature difference between evaporator and condenser. From Figure 3, it is also evident that, the heat transfer coefficient increases with a better heat transfer rate. In the case of 60% fill ratio, the liquid available is just enough to facilitate faster movement. Although, the liquid vaporizes with increase in heat input, the little extra volume of liquid present just compensates for the loss due to liquid vaporization. This together with the availability of both sensible and latent heat reduces the thermal resistance. Low thermal resistance is an indication of high heat transfer. This is also clear from the plot of heat transfer coefficient (Figure 3). As the fill ratio increases further i.e. for 70 and 80%, the presence of more liquid than vapor, may not facilitate fast movement of the fluid as the time required for vapor formation is more. This results in heat accumulation and increase of (T_e-T_c). Hence, the thermal resistance increases thereby lowering the heat transfer rate which can also be observed from Figure 3 in the plot of heat transfer coefficient.

3.2. Effect of Heat Input on Thermal Resistance for Different Fill Ratios for Ethanol-Methanol Mixture

Figures 4 and 5 show the variation of thermal resistance and heat transfer coefficient for different heat inputs and fill ratios for the ethanol-methanol mixture.

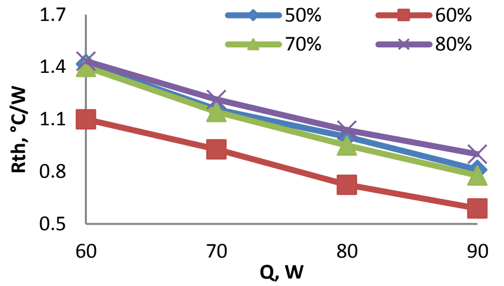

Figure 2. Effect of varying fill ratio on thermal resistance for acetone-ethanol mixture

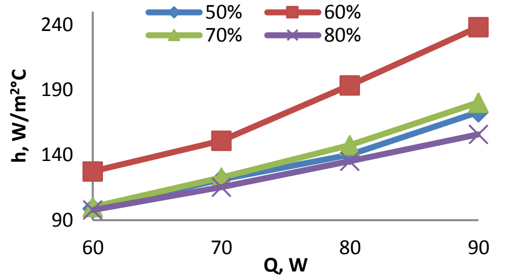

Figure 3. Effect of varying fill ratio on heat transfer coeffeceint for acetone-ethanol mixture

The heat input is varied from 60W to 90W insteps of 10W and the fill ratios are varied from 50 to 80% in steps of 10%. It may be observed that, with the increase in heat input from 60 to 90W, the thermal resistance decreases. The thermal resistance was the least for a fill ratio of 60% and maximum for 80%. The trends obtained are similar to that obtained in the acetone-ethanol mixture as in Figure 4. The rationale behind the lowering of the thermal resistance at 60% fill ratio is due to the sufficiently available liquid slugs and vapor plugs. Due to the sufficient pressure difference created between evaporator and condenser, brisk movement of the working fluid is possible which gives rise to better heat transfer. For higher fill ratios due to the more liquid mass inventory, the pulsating action is reduced and due to which the thermal resistance increases.

Hence, it can be concluded that 60% fill ratio will provide the optimum performance in terms of low thermal resistance and high heat transfer coefficient.

3.3. Effect of Heat Input on Thermal Resistance for Different Liquid and Liquid Mixtures at 60% Fill Ratio

Figures 6 and 7 shows the variation of thermal resistance and heat transfer coefficient for different heat inputs varying from 60 to 90W in steps of 10W. It may be observed that heat transfer coefficient increases with increase in heat input. Among all the fluids and fluid mixtures, acetone shows the lowest thermal resistance while it is the highest for ethanol.

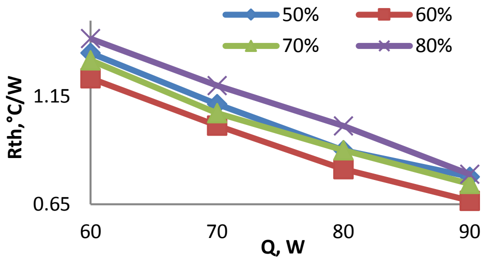

Figure 4. Effect of Thermal Resistance with varying heat input and fill ratio for ethanol-methanol mixtures

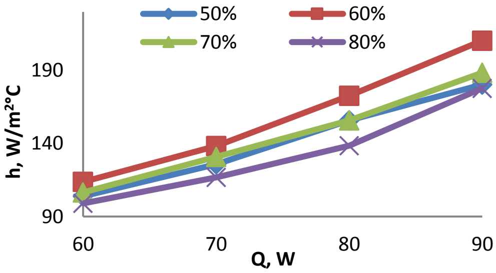

Figure 5. Effect of varying fill ratio on heat transfer coeffecient for ethanol-methanol mixture

Among the different fluid mixtures used, the lowest thermal resistance was observed for acetone-ethanol mixture The highest resistance was however observed for ethanol-methanol mixture.

The desired performance of acetone and acetone-ethanol mixture may be due to the favorable thermal properties. Acetone has the lowest saturation temperature of 56.25°C which is required for its quicker evaporation which is also facilitated by low value of latent heat facilitated by low value of latent heat of 495 kJ/kg as observed in Table 1. Whereas, ethanol and methanol with higher saturation temperatures of 64.7°C and 78.3°C, respectively delays the vaporization time. This coupled with high latent heat of 960 and 1084kJ/kg results in slow startup and circulation observed inside the PHP. The acetone-ethanol mixture also showed a better performance in comparison to ethanol-methanol mixture both in terms of thermal resistance and heat transfer coefficient.

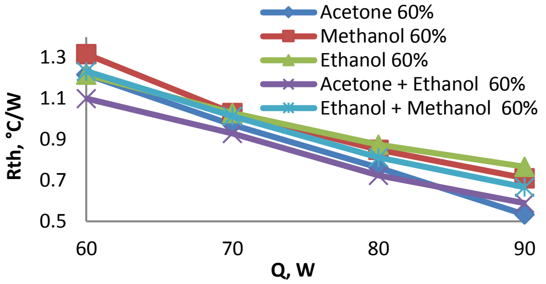

Figure 6. Effect of varying heat input on heat transfer coeffeceint for different fluids

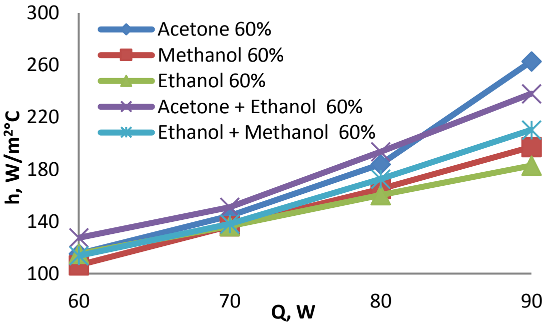

Figure 7. Effect of varying heat input on heat transfer coeffeceint for different fluids

TABLE 1. Thermal Properties of Working Fluids

Working Fluid	Evaporator Temp. (°C)	Latent heat (kJ/kg)	Saturation temperature (°C)
Acetone	80	495	56.25
Ethanol	80	960	78.3
Methanol	80	1084	64.7

The better performance can be attributed to the presence of acetone which aids in the quicker startup and circulation. The lower performance of ethanol-methanol mixture may be due to the presence of methanol which has the highest latent heat which does not facilitate quicker startup.

4. CONCLUDING REMARKS

An experimental investigation of thermal performance of a multi loop PHP using different working fluids was conducted. The effect of heat input, working fluid and fill ratio on the performance of PHP were studied through experimentation. The following are the conclusions drawn from the study.

(1) Among the fluid mixtures used, acetone-ethanol showed the best performance mixture with the lowest thermal resistance of 0.725°C/W and a heat transfer coefficient of 193.6W/m^2°C. For the ethanol-methanol mixture the average thermal resistance recorded was 0.82°C/W and the heat transfer coefficient was 172.59 W/m^2°C. As the thermal performance of acetone-ethanol mixture was better as compared to ethanol-methanol mixture, the former can be considered a suitable working fluid for PHP.

(2) Since, the thermal performance of the acetone-ethanol mixture is comparable to that of acetone, the mixture can be used as a working fluid. It also shows that acetone-ethanol and ethanol-methanol mixtures performs better as compared to methanol and ethanol.

(3) Whenever the application of pure acetone is not possible, due to lack of availability etc. acetone-ethanol mixture and ethanol-methanol mixtures can be used as working fluids in the operation of PHP. Since, the thermal performance of the acetone-ethanol mixture is comparable to that of acetone, the mixture can be used as a working fluid. It also shows that acetone-ethanol and ethanol-methanol mixtures performs better as compared to methanol and ethanol.

(4) Whenever the application of pure acetone is not possible, due to lack of availability etc. acetone-ethanol mixture and ethanol-methanol mixtures can be used as working fluids in the operation of PHP

5. SCOPE FOR FUTURE WORK

The present study can be further extended as follows.

Experiments can be conducted for different PHP diameters. More number of turns can be considered in the construction of PHP. The Validation of the experimental results can be done using a suitable mathematical model. The experiments can be repeated under different vacuum conditions. Experiments can be conducted for different inclination. The thermal performance of fluid mixed proportions for each component can be varied. Thermal performance of azeotropic mixtures can be studied experimentally.

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Thermal Resistance

چکیده

در این مقاله، مطالعات آزمایشگاهی انجام شده بر روی یک لوله گرمای پالستیک عمودی بسته با حلقه عمودی (VCLPHP) برای ارزیابی عملکرد حرارتی ارائه شده است. مقادیر مقاومت حرارتی و ضریب انتقال گرما به دست آمده در آزمایش به عنوان پارامترهای ارزیابی استفاده می شود. VCLPHP دارای لوله های مویرگی با قطر داخلی ۲ میلی‌متر و قطر خارجی ۳ میلی متر و به ۵ نوبت خم شده است. طول بخش های تبخرکننده، آدیاباتیک و کندانسور به ترتیب ۵۰، ۹۰ و ۷۰ میلی متر است. مخلوط دوتایی از مایعات مورد استفاده استون – اتانول و اتانول – متانول مخلوط می باشند. عملکرد حرارتی این مخلوط های دوتایی سپس با مایعات کار مرسوم مانند استون، اتانول و متانول مقایسه شد. نسبت پر شدن از ۵۰٪ تا ۸۰٪ در مراحل ۱۰٪ تغییر کرد و ورودی های گرما بین ٦۰ تا ۹۰ وات در ۱۰ وات متغیر بود. با این حال، نسبت مخلوط برای تمام مخلوط به عنوان ۱: ۱ حفظ شد. تمام آزمایش ها در موقعیت عمودی (۹۰ درجه) انجام گرفت. نتایج آزمایشی نشان داد که عملکرد کلی استون بهترین است با کمترین مقاومت حرارتی و بیشترین ضریب انتقال حرارت در مقایسه با تمام مایعات خالص و در میان مخلوط مایعات، مخلوط استن و اتانول بهترین عملکرد حرارتی را نشان می دهد.

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