Heat Mass Transfer (2017) 53:1983–1994
DOI 10.1007/s00231-016-1958-3

ORIGINAL

Heat transfer performance of a pulsating heat pipe charged with acetone-based mixtures

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Received: 19 June 2016 / Accepted: 8 December 2016 / Published online: 20 December 2016

Abstract Pulsating heat pipes (PHPs) are used as high efficiency heat exchangers, and the selection of working fluids in PHPs has a great impact on the heat transfer performance. This study investigates the thermal resistance characteristics of the PHP charged with acetone-based binary mixtures, where deionized water, methanol and ethanol were added to and mixed with acetone, respectively. The volume mixing ratios were 2:1, 4:1 and 7:1, and the heating power ranged from 10 to 100 W with filling ratios of 45, 55, 62 and 70%. At a low filling ratio (45%), the zeotropic characteristics of the binary mixtures have an influence on the heat transfer performance of the PHP. Adding water, which has a substantially different boiling point compared with that of acetone, can significantly improve the anti-dry-out ability inside the PHP. At a medium filling ratio (55%), the heat transfer performance of the PHP is affected by both phase transition characteristics and physical properties of working fluids. At high heating power, the thermal resistance of the PHP with acetone–water mixture is between that with pure acetone and pure water, whereas the thermal resistance of the PHP with acetone–methanol and acetone–ethanol mixtures at mixing ratios of 2:1 and 4:1 is less than that with the corresponding pure fluids. At high filling ratios (62 and 70%), the heat transfer performance of the PHP is mainly determined by the properties of working fluids that affects the flow resistance. Thus, the PHP with acetone–methanol and acetone–ethanol mixtures that have a lower flow resistance shows better heat transfer performance than that with acetone–water mixture.

1 Introduction

The pulsating heat pipe (PHP) proposed in the 1990s by Akachi [1, 2] is an increasingly popular heat transfer element. PHPs are widely used in aerospace applications, electronic components heat transfer and other fields because of its compact size, simple structure, low cost and other advantages. The pulsating heat pipe operates in a manner very different from the operation of an ordinary heat pipe [3–5]. Compared with ordinary heat pipes which transfers heat via phase change, the PHP not only transfers heat via phase change but also transfers the sensible heat via gas–liquid pulsating. In addition, a PHP does not have the capillary heat transfer limitation via wick in an ordinary heat pipe, and it can be bent arbitrarily [6].

The heat transfer performance of a PHP is mainly determined by several factors, such as the pipe diameter, cross-sectional shape, setting angle, filling ratio and the physical properties of working fluids. For example, Khandekar et al. [7] investigated the effect of the heat pipe diameter on the heat transfer performance of a closed loop pulsating heat pipe (CLPHP). The working fluid was pure R123 with filling ratios of 30, 50 and 70%. The heat transfer performance of the 2-mm diameter PHP was found to be better than that of the 1-mm diameter PHP. Ayel et al. [8] experimentally studied the CLPHP with rectangular cross section, using pure FC-72 as the working fluid. When the CLPHP was placed horizontally, the CLPHP with rectangular cross section was more sensitive to gravity variation than that with a circular cross section. Burban et al. [9] investigated the heat transfer performance of PHPs with acetone, water,

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methanol and pentane at three inclined angles (−45°, 0°, 45°). They concluded that the thermal resistance of PHPs was relatively small at the inclination angle of 45° when the heating power was between 0 and 25 W and the filling ratio was 50%. Barua et al. [10] experimentally studied the thermal resistance of the PHP with water and ethanol at five filling ratios (100, 82.5, 63, 41.3 and 28%). They found that the PHP with water at 70% filling ratio and ethanol at 80% filling ratio represented the best heat transfer performance than that at other ratios. Clement et al. [11] compared the heat transfer performance of PHPs with acetone, methanol and deionized water when the filling ratio ranged from 30 to 70% and heating power was between 80 and 180 W. It was reported that the heat transfer performance of the PHP with acetone was better than those with other pure working fluids. Han et al. [12] experimentally investigated the heat transfer performance of PHPs with deionized water, acetone, methanol and ethanol. Their results indicated that the PHP with acetone, which has low boiling point, was the easiest to dry out among others at low filling ratio. At high filling ratio, the thermal resistance of PHPs with pure working fluids mainly depended on the dynamic viscosity at low heating power (<50 W). For the fluids with lower dynamic viscosity, the flow rate would be higher, and therefore the heat transfer performance of the PHP was better. At high heating power (>65 W), the thermal resistance of PHPs with several pure working fluids became closer and approached the heat transfer limitation of PHPs with pure working fluids.

To improve the heat transfer limitation of PHPs, the PHP with nano-fluids has been widely studied. Karthikeyan et al. [13] experimentally studied nano-fluids of Cu-deionized water and Ag-deionized water, when the heating power was between 50 and 240 W. They reported that the heat transfer limitation of the PHP with nano-fluids was 33.3% higher than that with pure deionized water. Ji et al. [14] experimentally investigated the heat transfer performance of the PHP with Al_2O_3-water for four particle sizes (50, 80 nm, 2.2 and 22 μm) and found that the start-up power of the PHP became lower with the decrease of the particle size. Tanshen et al. [15] experimentally studied the thermal resistance of the PHP with multi-walled carbon nanotube (MWCNT) nano-fluids under four mass ratios (0.05, 0.1, 0.2 and 0.3 w%). They found that the inner evaporation pressure of the PHP reached the maximum and the thermal resistance of the PHP was minimized at the mass ratios of 0.2 w%.

Unlike pure working fluids and nano-fluids, binary mixtures are composed of two pure fluids with different boiling points, latent heat of vaporization and heat capacity. A PHP with different mixture under different volume ratio will behaviour different heat transfer performance. Long et al. [16] found that the working temperature for thermosiphon with N_2–Ar mixture could range from 64.0 to 150.0 K, which was wider than that with pure N_2 and pure Ar. Mameli et al. [17] studied the heat transfer characteristics of the PHP with ethanol–water mixture (mass ratio of 95.5% ethanol and 4.5% water). They found that the thermal resistance of the PHP was basically consistent with that with pure ethanol. Achghare et al. [18] experimentally studied the thermal resistance of the PHP with water–acetone, water–methanol and water–ethanol under 50% filling ratio, and compared the respective results with those of pure water, acetone, methanol and ethanol. They concluded the heat transfer performance of the PHP with water–methanol mixture was better than that with water–acetone mixture and water–ethanol mixture under the high heating power. However, the influence of the filling ratio on the heat transfer performance of the PHP had not been discussed. Zhu et al. [19] experimentally investigated the start-up characteristic and heat transfer performance of PHPs with a water–acetone binary mixture. They reported that the start-up characteristic of the PHP with water–acetone mixtures under 13:1, 4:1, 1:1, 1:4, and 1:13 mixing ratios performed better than those with pure water under 35, 45 and 62% filling ratios. At low filling ratios (35 and 45%), the water–acetone mixture under 1:13 mixing ratio improved the dry out to 65 W, meanwhile, the dry out of the PHP with pure acetone occurred at 50 W. At high filling ratios (62, 70%), the heat transfer performance of the PHP with water–acetone mixtures was not as good as that with pure water or pure acetone. In 2016, Xiaoyu Cui et al. [20–22] experimentally analyzed the heat transfer performance of the PHP with water-based, methanol-based and ethanol-based mixtures as working fluids. In summary, the phase change inhibition effect of zeotropic mixtures improved the anti-dry-out ability inside the PHP at low filling ratios and the flow resistance to the additional mass transfer between the liquid phase and the vapor phase due to the different concentrations retarded the flow and increased the thermal resistance of the PHP with mixtures at high filling ratios. Patel et al. [23] studied the influence of working fluids on start-up mechanism and the thermal performance of a CLPHP. For pure working fluids, acetone was the easiest to start up and represented the best heat transfer performance among acetone, methanol, ethanol and water. For water-based mixtures, the PHP charged with water–acetone showed better thermal performance than that charged with water–methanol or water–ethanol.

In our investigation the acetone-based mixtures were used as working fluids. Acetone is widely used in PHPs because of its low boiling point, liquid specific heat and latent heat of vaporization, which makes PHPs with pure acetone start up more easily. However, the PHP with pure acetone is also easy to dry out under large heating power. Thus, adding other working fluids with high specific heat, high latent heat of vaporization into acetone may improve

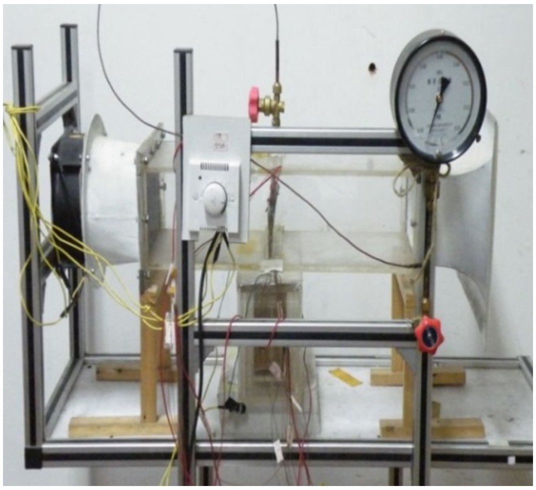


Fig. 1 PHP experimental setup

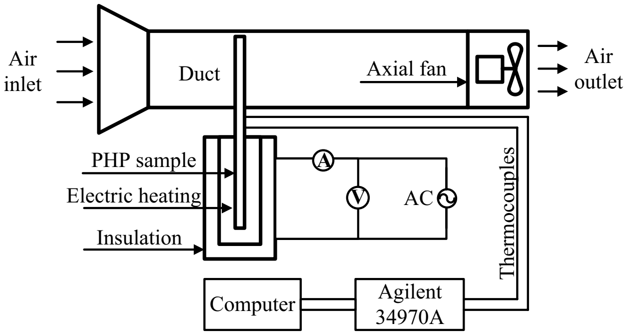


Fig. 2 PHP experimental setup diagram

the heat transfer performance of PHPs. We experimentally investigated the heat resistance of the PHP with acetone–methanol and acetone–ethanol under 2:1, 4:1, and 7:1 volume mixing ratios. The results were compared with the heat resistance of the PHP with acetone–water under the same mixing ratios. The filling ratios were 45, 55, 62 and 70%, respectively. Finally, the trends of heat transfer performance of the PHP with different binary acetone-based mixtures were discussed.

2 Experimental setup and uncertainty analysis

2.1 Experiment device

The test rig for measuring the heat transfer performance of the PHP consists of the electric heating and air cooling equipment, charging and evacuating system, data acquisition system and the PHP sample to be tested, as shown in Figs. 1 and 2. The condensation section (CS) of the PHP is cooled by air flow introduced by an axial flow fan (air speed = 1.5 m/s). The adiabatic section and evaporation section (ES) of the PHP sample are located in a transparent glass chamber to decrease the heat loss to the environment. The ES is heated via electrical wires twining outside the tubes of the ES (see Fig. 3).

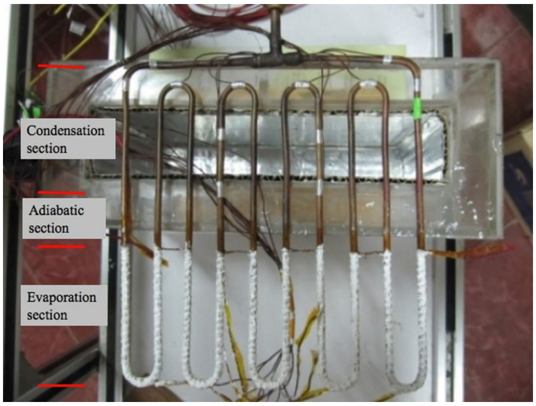


Fig. 3 The tested PHP

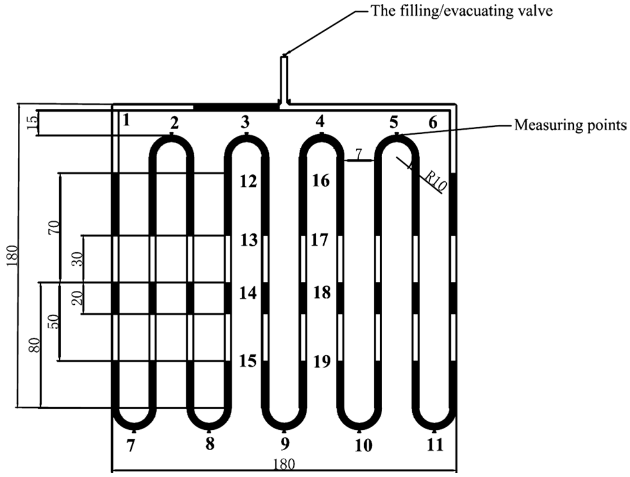


Fig. 4 Arrangement of thermocouples

Figure 3 is the photo of the tested PHP. The size of the PHP, the length of the ES and the positions of the thermocouples is shown in Fig. 4. The whole width and length of our PHP are both 180 mm, and the length of evaporation section, adiabatic section and condense section are 80, 20 and 80 mm, respectively. It has four turns in CS section and five turns in ES section. Radius of each turn is 10 mm. The inner and outer diameters of the PHP are 2 and 4 mm, respectively. At top position of the PHP there is a valve used for charging and evacuating. There are 20 thermocouples in the PHP sample. The CS temperature is recorded by thermocouples 1–6 on the top bends, and the ES temperature is recorded by thermocouples 7–11 at the bottom

Table 1 Thermo-physical properties of working fluids at standard atmospheric pressure [24]

Working fluids	Boiling point T_S (°C)	Liquid density ρ_l (kg/m^3) (20 °C)	LHV H_{fg} (kJ/kg)	Liquid specific heat C_{pl} (kJ/(kgK)) (20 °C)	Dynamic viscosity $\upsilon_l \times 10^3$ (Pa·s) (20 °C)	$(dp/dT)^*_{sat}$ $\times 10^3$ (Pa/K) (80 °C)	Thermal conductivity λ_l (W/(mK)) (20 °C)	Surface tension $\sigma \times 10^3$ (N/m) (20 °C)
Acetone	56.2	792	523	2.35	0.32	6.27	0.170	23.7
water	100	998	2257	4.18	1.01	1.92	0.599	72.8
Methanol	64.7	791	1101	2.48	0.6	6.45	0.212	22.6
Ethanol	78.3	789	846	2.36	1.15	4.23	0.172	22.8

* $(dp/dT)_{sat}$ was calculated from RefProp Nist (version 8.0) and based on its great variation with temperature, the value at 80 °C instead of 20 °C is listed as representative

bends. The thermocouples 12–19 are located at the centre of the two middle pipes to measure the temperature variation along the pipes. Thermocouple 20 is used to measure the environmental temperature.

2.2 Uncertainty analysis

The thermal resistance of the PHP can be calculated by Eq. (1):

$$R = \frac{T_e - T_c}{Q} \tag{1}$$

where R is the heat resistance of the PHP, Q the heat load supplied by heating wires, $Q = UI$, T_e the average temperature of the ES, $T_e = \frac{1}{5}\sum_{n=7}^{11} T_n$, and T_c the average temperature of the CS, $T_c = \frac{1}{6}\sum_{n=1}^{6} T_n$

The relative errors of the heating power and thermal resistance can be estimated by Eqs. (2) and (3)

$$\frac{\delta Q}{Q} = \sqrt{\left(\frac{\delta U}{U}\right)^2 + \left(\frac{\delta I}{I}\right)^2} \tag{2}$$

$$\frac{\delta R}{R} = \sqrt{\left(\frac{\delta T_e}{T_c - T_e}\right)^2 + \left(\frac{\delta T_c}{T_c - T_e}\right)^2 + \left(\frac{\delta Q}{Q}\right)^2} \tag{3}$$

The accuracy of the ammeter and voltmeter is 0.5%, of which the measurement range is 1 A and 75 V, respectively. Take the PHP with deionized water with 62% filling ratio as an example. The measured voltage and current of the heat power was 31.07 V and 0.324 A, respectively. Thus, the relative error of the heating power is calculated by Eq. (4):

$$\frac{\delta Q}{Q} = \sqrt{\left(\frac{0.5\% \times 75}{31.07}\right)^2 + \left(\frac{0.5\% \times 1}{0.324}\right)^2} = 1.96\% \tag{4}$$

The calibrated T-type thermocouples and an Angilent 34970A unit are used for data acquisition. The accuracy of the thermocouples is ±0.1 °C and accuracy of Angilent 34970A is ±0.0256 °C. The minimum temperature difference between hot and cold ends is 12.6 °C. Therefore the relative error of thermal resistance is calculated by Eq. (5)

$$\frac{\delta R}{R} = \sqrt{2 \times \left(\frac{0.1 + 0.0256}{12.6}\right)^2 + (1.96\%)^2} \approx 2.41\% \tag{5}$$

When the coverage factor $K = 2$ is taken, the maximum uncertainty is calculated by Eq. (6):

$$U\mathrm{max} = \frac{\delta R}{R} \times K = 2.41\% \times 2 \approx 4.82\% \tag{6}$$

By this uncertainty analysis, it is confirmed that the maximum uncertainty of the measured thermal resistance in our experiment is less than 5%.

3 Physical properties of working fluids

The major thermo-physical properties of acetone, water, methanol and ethanol at standard atmospheric pressure are shown in Table 1. The working fluids with lower boiling point, liquid specific heat and latent heat of vaporization can start pulsating more easily inside the PHP, but their energy carrying ability is relatively low. Low value of dynamic viscosity means a low flow resistance in PHPs, which leads to a high flow rate and strong pulsating effects. Working fluids with large $(dp/dT)_{sat}$ indicates that a miniscule increase in temperature can lead to a large rise in pressure. This behaviour can accelerate the flow rate and improve the heat transfer performance of PHPs.

The PHP with acetone is the easiest to start up because its boiling point, liquid specific heat and latent heat of vaporization are the lowest among that of water, methanol and ethanol. However, the PHP with low energy carrying ability of acetone is also easy to dry out under high heat power, especially at low filling ratio. Moreover, the low value of viscosity and high value of $(dp/dT)_{sat}$ make its flow rate higher than that with water, methanol and ethanol, but its heat transfer rate is still low because of its low energy carrying ability. In this paper, acetone was mixed with high specific heat and high latent heat of vaporization working fluids, i.e. water, methanol and ethanol, to improve its energy carrying ability and delay the dry out in PHPs, which might have beneficial effects on the heat transfer performance of PHPs.

4 Thermal behaviours of the PHP with acetone-based binary mixtures

In our experiment the acetone-based binary mixtures were mixed with water, methanol or ethanol in acetone (mixing ratios were 2:1, 4:1 and 7:1). The test was carried out at the filling ratio of 45, 65, 70 and 90%, and under the heat power from 10 to 100 W. When the heat power was lower than 35 W, the PHP could not fully start up and the measured thermal resistance was not steady. Therefore, only the test result above 35 W was discussed.

4.1 Thermal behaviours of the PHP with acetone–water

The physical properties of acetone and water are quite different from each other. As shown in Table 1, at the standard atmospheric pressure, the $(\mathrm{d}p/\mathrm{d}T)_{\mathrm{sat}}$ of acetone is nearly three times than that of water. However, the specific heat of water is nearly twice as that of acetone and the latent heat of vaporization of water is over four times as that of acetone. Moreover, the acetone–water mixture is generally a positive deviation solution [19], as shown in Fig. 5, which represents the phase diagram of acetone–water mixtures at 1.101 atm. The blue and green curves represent dew point curve and bubble point curve of acetone–water mixture. Three yellow dashed lines represent three tested volume mixing ratios with corresponding mole fraction ratios listed in Table 2. The phase transition inhibition exists in the gasification process of acetone–water mixture under three mixing ratios. Considering the phase transformation and the physical properties of the acetone–water mixture, water has a strong complementarity with acetone in PHPs.

The thermal resistances of the PHP with pure acetone, pure water and acetone–water mixture are shown in Fig. 6 and the red circle shows the dry-out points. At low and medium filling ratios (see Fig. 6a, b), adding water can improve the anti-dry-out abilities in PHP, but at high filling ratios (see Figs. 6c, d), the thermal resistances of the PHP with pure working fluids are lower than that with acetone–water mixtures. This phenomenon is the same with Zhu et al. [19].

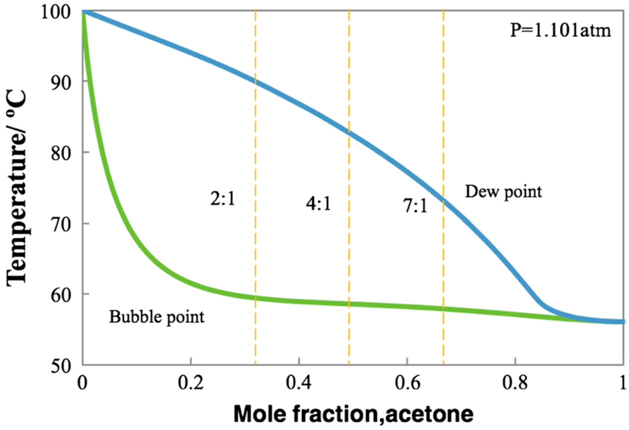


Fig. 5 Temperature/mole fraction (acetone–water)

4.2 Thermal behaviours of the PHP with acetone–methanol

The physical properties of acetone and methanol are closer to each other than that of acetone and water, as shown in Table 1. The specific heat as well as latent heat of vaporization of methanol lies between water and acetone, so the energy carrying ability of acetone–methanol mixture is lower than that of acetone–water mixture. However, the density and dynamic viscosity of methanol are also lower than those of water, which means that the flow resistance inside the PHP of acetone–methanol mixture is less than that of acetone–water mixture.

Figure 7 shows the phase diagram of acetone–methanol mixture at 1.101 atm. Because of the closeness of boiling points between acetone and methanol, the bubble point curve (green) and dew point curve (blue) of acetone–methanol mixture are relatively close and its gas–liquid coexistence region are much smaller than that of acetone–water mixture, as shown in Fig. 7. Unlike the gasification process of acetone–water mixture in the last section, the low boiling point component (acetone) of the acetone–methanol mixture inhibits little effect on its high boiling point component (methanol). In this section, acetone is mixed with methanol (which has similar physical properties and phase transitions to those of acetone) to investigate the difference

Table 2 Volume fraction of the working fluid for different mixing ratios and the corresponding mole fraction ratios

Volume ratio\ mixture	Acetone–water	Acetone–methanol	Acetone–ethanol
2:1	0.330	0.475	0.614
4:1	0.497	0.688	0.762
7:1	0.633	0.795	0.848

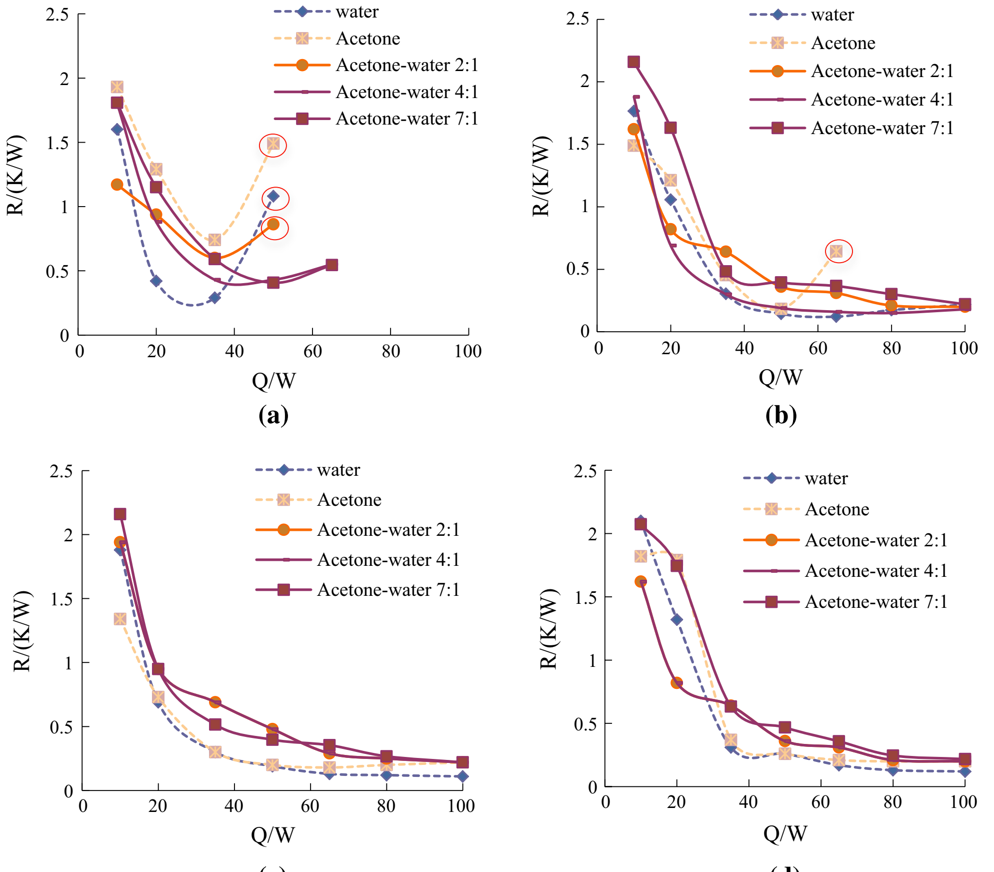
between the heat transfer performance of the PHP with acetone–methanol binary mixture and that with pure working fluids.

4.2.1 The heat transfer performance of the PHP with acetone–methanol at low and medium filling ratios

The thermal resistances of the PHP with acetone–methanol at a 45% filling ratio is shown in Fig. 8. When the heating power lies between 35 and 50 W, the thermal resistance of the PHP with pure acetone and pure methanol increases rapidly and the dry out appears at 50 W. Curves of thermal resistance of the PHP with acetone–methanol mixtures represent the same trend with that with pure working fluids. The thermal resistances of the PHP with acetone–methanol mixtures under 4:1 and 7:1 mixing ratios are located between those with pure acetone and pure methanol, and the thermal resistance of the PHP with acetone–methanol mixture under 2:1 mixing ratio is slightly lower than that with pure working fluids.

Since the specific heat and latent heat of vaporization of methanol are both larger than those of acetone, the energy-carrying ability of pure methanol is greater than that of pure acetone, and the thermal resistance of the PHP with pure methanol is lower than that with pure acetone. Consequently, energy carrying abilities of the PHP with acetone–methanol mixtures under 4:1 and 7:1 mixing ratios lie between that with pure acetone and pure methanol, so their thermal resistances are located between corresponding pure working fluids. Meanwhile, the thermal resistance of the PHP with acetone–methanol mixture under 2:1 mixing ratio is slightly lower than that with pure methanol. It is due to a small gas–liquid coexistence region in acetone–methanol mixture under 2:1 mixing ratio. The acetone component with low boiling point inhibits slightly the gasification process of methanol component with high boiling point and strengthens the anti-dry-out ability of the PHP.

Figure 9 shows the thermal resistances of the PHP with acetone–methanol at a 55% filling ratio. The thermal resistance of the PHP with pure working fluids decreases continually from 35 to 50 W and reaches the minimum at 50 W.



(a) **(b)**

(c) **(d)**

Fig. 6 Thermal resistances of PHP with acetone–water at different filling ratios **a** FR = 45%, **b** FR = 455%, **c** FR = 62%, **d** FR = 70%

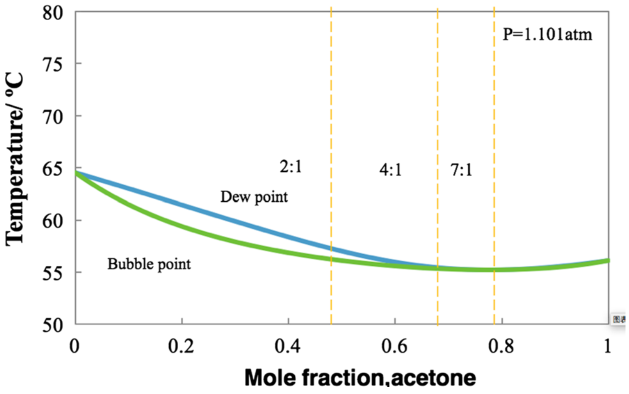


Fig. 7 Temperature/mole fraction (acetone–methanol)

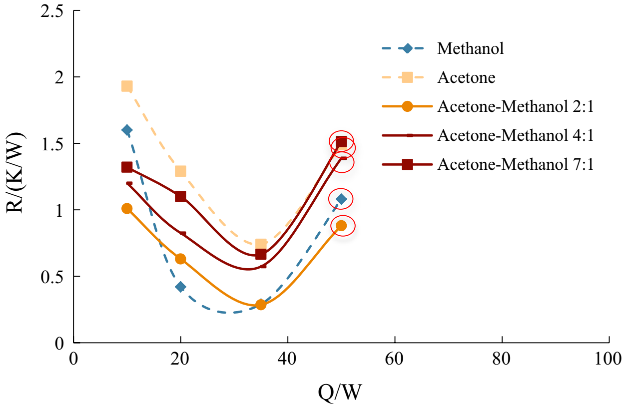


Fig. 8 Thermal resistances of PHP with acetone–methanol (FR = 45%)

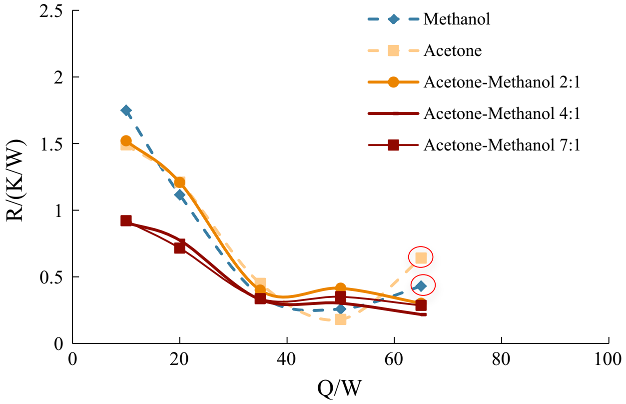


Fig. 9 Thermal resistances of PHP with acetone–methanol (FR = 55%)

The curves of thermal resistance of the PHP with acetone–methanol mixture at 55% filling ratio are closer than those at 45% filling ratio and maintain at a relative low thermal resistance in the heat power range between 50 and 65 W. The maximum heating power of both pure working fluids and acetone–methanol mixtures all increases due to the increasing of the quality of working fluids in the pipe. The thermal resistance of the PHP with acetone–methanol mixture is lower than that with pure working fluids at 65 W. Comparing with the test results for the filling ratio of 45%, the PHP with acetone–methanol mixture has a better heat transfer performance than that with pure working fluids at the medium filling ratio of 55%.

4.2.2 *The heat transfer performance of the PHP with acetone–methanol at high filling ratios*

Figure 10 shows the thermal resistances of the PHP with acetone–methanol at high filling ratios. At 62% filling ratio, as shown in Fig. 10a, Curves of the thermal resistance of the PHP with pure working fluids and acetone–methanol mixtures gradually approach to each other with increasing of heating power. Their thermal resistances lie at a similar level when the heating power is larger than 60 W. At 70% filling ratio, as shown in Fig. 10b, curves for the mixing ratio of 4:1 and 7:1 exhibit the similar behaviour with those at 62% filling ratio. When the heating power increases to 80 W, all the curves approach to the same level, e.g. at 100 W, difference between the thermal resistance of the PHP with the acetone–methanol mixture of 2:1 mixing ratio and those with the pure working fluids is less than 0.22 K/W for filling ratio of 62% and 0.21 K/W for filling ratio of 70%. It can be concluded that the PHP with pure acetone, methanol and acetone–methanol mixture have similar heat transfer performance at high heat power. This can be explained as follows. At high filling ratios, the heat transfer performance of the PHP is dominated by the energy carrying ability and flow rate inside the PHP. Since the specific heat and latent heat of evaporation of acetone and methanol are similar, the energy carrying ability of acetone–methanol mixture is similar to that of corresponding pure working fluids. We can also see, because of the similarity of acetone and methanol in density, viscosity and $(dp/dT)_{sat}$, the differences of flow resistance and expansion power inside the PHP between them and their mixture are relatively small. Therefore, the flow rate of pure working fluids inside the PHP is also similar to that of the acetone–methanol mixture, which yields the similar heat transfer performance of the PHP with pure acetone, pure methanol and acetone–methanol mixture at high filling ratios.

4.3 Thermal behaviours of the PHP with acetone–ethanol

Similar to the closeness between the physical properties of acetone and methanol, the physical properties of

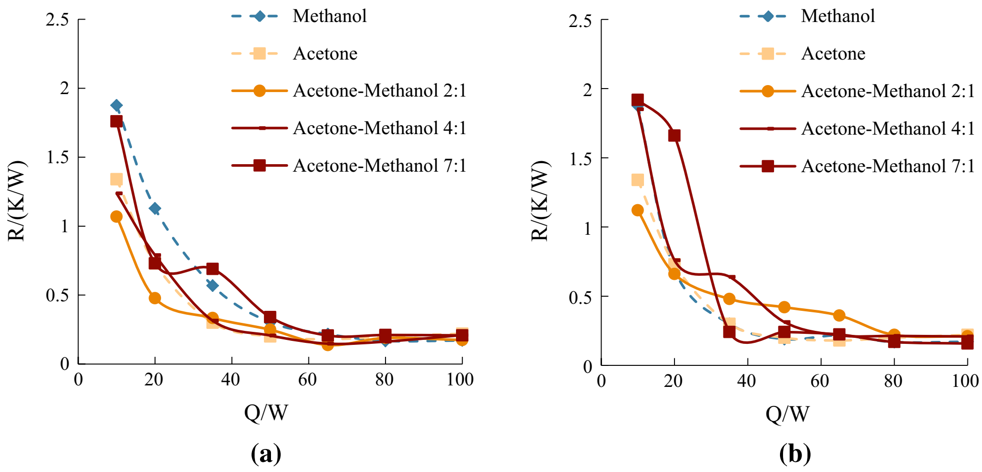


Fig. 10 Thermal resistances of PHP with acetone–methanol, **a** FR = 62%, **b** FR = 70%

acetone and ethanol are also close to each other, as shown in Table 1. The specific heat and latent heat of vaporization of ethanol lie between that of water and that of acetone, so the energy carrying ability of acetone–ethanol mixture is lower than that of acetone–water mixture. However, $(dp/dT)_{sat}$ of ethanol is approximately two times than that of water, so the acetone–ethanol mixture has more expansion power than acetone–water mixture in vapour phase.

In the aspect of phase transformation of the binary mixture, the acetone–ethanol mixture is also a positive deviation zeotropic solution [25]. The content of acetone component with low boiling point in the vapour phase is greater than that in the liquid phase. On the contrary, the content of ethanol component with high boiling point in the vapour phase is lower than that in the liquid phase [26, 27]. Comparing the phase diagram of acetone–ethanol in Fig. 11 with the phase diagram of acetone–water in Fig. 5, the difference of boiling points between ethanol and acetone (22.1 K) is only half of that between water and acetone (43.8 K). The bubble point curve (green) and the dew point curve (blue) of acetone–ethanol mixture are closer to each other than that of acetone–water mixture, so the phase transition inhibition between acetone and ethanol is weaker than that between acetone and water. In this section, acetone is mixed with ethanol (which has relatively similar physical properties and slightly different phase transitions to those of acetone) to investigate the difference between the heat transfer performance of the PHP with acetone–ethanol binary mixture and that with pure working fluids.

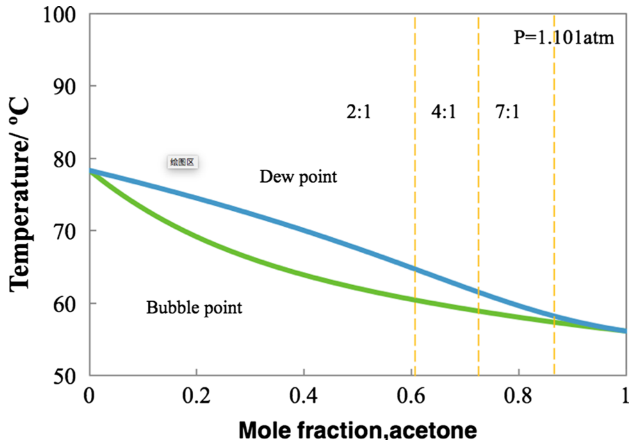


Fig. 11 Temperature/Mole fraction (acetone–ethanol)

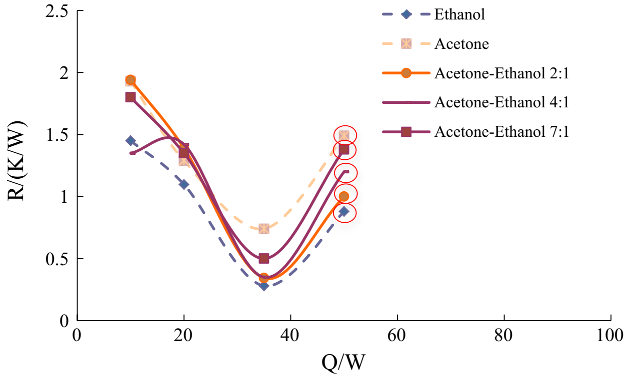


Fig. 12 Thermal resistances of the PHP with acetone–ethanol (FR = 45%)

4.3.1 *The heat transfer performance of the PHP with acetone–ethanol at low and medium filling ratios*

Figure 12 shows the thermal resistances of the PHP with acetone–ethanol at a 45% filling ratio. When the heating power is lower than 35 W, the thermal resistances of the PHP with pure acetone, pure ethanol and acetone–ethanol mixture increase as the heating power decreases. When the heating power is larger than 35 W, the thermal resistances of the PHP with pure working fluids (pure acetone and pure ethanol) rise up rapidly, and the dry out occurs at 50 W. The thermal resistances of the PHP with acetone–ethanol mixtures under three mixing ratios (2:1, 4:1, and 7:1) lie between those with pure acetone and pure ethanol. The curves of the thermal resistances of mixture exhibit a similar trend as those of the pure working fluids. Since the specific heat and latent heat of vaporization of ethanol is larger than those of acetone, the energy carrying ability of acetone–ethanol mixture lies between that of the pure acetone and pure ethanol. However, boiling points of acetone and ethanol are similar to each other, as shown in Fig. 11. The phase transition inhibition of acetone–ethanol mixtures is weaker than that of acetone–ethanol mixtures. Therefore, adding ethanol into acetone is not able to resist dry out at low filling ratio.

The measured thermal resistances of the PHP with acetone–ethanol at a 55% filling ratio are shown in Fig. 13. The thermal resistances of pure working fluids (pure acetone and pure ethanol) and their mixture (acetone–ethanol) represents similar trends to those at 45% filling ratio. When the heating power increases from 10 to 35 W, all thermal resistances of the PHP drop significantly. After the heating power has reached 35 W, the curves slow their declination. In addition to the thermal resistance of the PHP with acetone–ethanol mixture under 2:1 mixing ratio, all other curves reach the lowest point at 50 W and then turn up slightly, which means a decline in the heat transfer performance.

With the increasing of the filling ratio, the anti-dry-out ability of pure working fluids and their mixtures are enhanced. The maximum heating power is increased from 50 W for FR = 45% to 65 W for FR = 55%. For the heating power between 50 and 65 W, the thermal resistances of the PHP with acetone–ethanol mixtures under 2:1 and 4:1 mixing ratios are slightly lower than those with pure acetone and pure ethanol. With the increasing of the quality of working fluids inside the PHP at medium filling ratio, the phase transition inhibition of acetone–ethanol mixtures is observed. The acetone component with low boiling point suppresses the vaporization of the ethanol component with a high boiling point, which can slightly strengthen the PHP anti-dry-out ability.

By analyzing the heat transfer performance of the PHP with pure acetone, pure ethanol and acetone–ethanol mixtures at low and medium filling ratios (45 and 55%), it can be concluded that adding ethanol into acetone do not significantly improve the dry out inside PHPs.

4.3.2 *The heat transfer performance of the PHP with acetone–ethanol at high filling ratios*

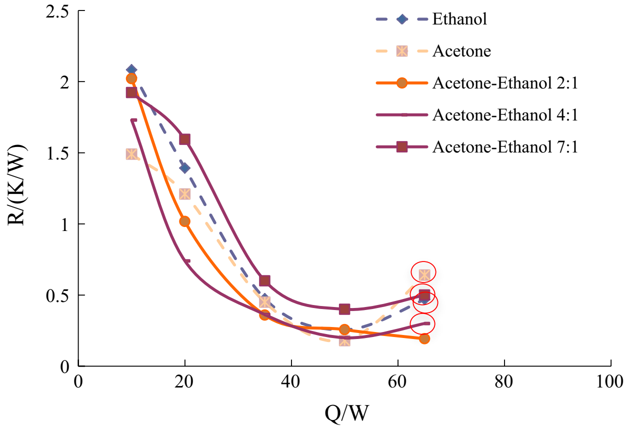


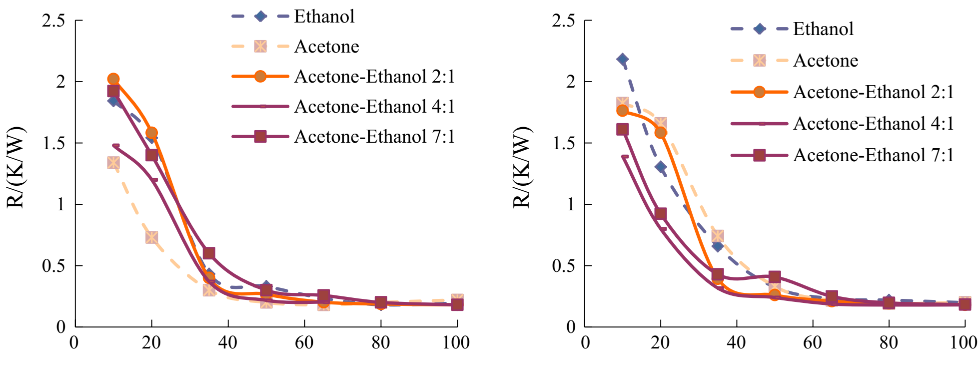
Fig. 13 Thermal resistances of PHP with acetone–ethanol (FR = 55%)

Figure 14 shows the thermal resistances of the PHP with acetone–ethanol at high filling ratios of 62 and 70%. For both cases, when the heating power reaches 35 W, the driving force provided by the vapour plug of the mixture is strong enough to push the working fluid to circulate. Subsequently, PHP with the pure acetone, pure ethanol and their mixtures under 2:1, 4:1 and 7:1 mixing ratios can be started up and maintain the circulation. The thermal resistances of the PHP with pure working fluids (pure acetone and pure ethanol) and their mixtures (acetone–ethanol) converge gradually after 35 W and reach to the same level after 65 W. When the heating power is larger than 80 W, all the curves approach together, as has been discussed in the last section.

4.4 Thermal behaviours of the PHP with an acetone-based binary

4.4.1 *The heat transfer performance of the PHP with acetone-based binary mixtures at low and medium filling ratios*

At low and medium filling ratios (45 and 55%), the heat transfer performance of the PHP is primary evaluated by the anti-dry-out ability. Figure 15 shows the thermal resistances of the PHP with pure acetone and the acetone-based binary mixtures of 4:1 mixing ratios, at 45% filling ratio. Before 35 W, thermal resistances of pure acetone and acetone-based mixtures are decreasing sharply. After 35 W, thermal resistances of the PHP with pure acetone, acetone–methanol and acetone–ethanol mixtures increase to a relative high value, as shown in Fig. 15. Due to the similarity in boiling points between acetone and methanol as well as acetone and ethanol, the phase transition process of acetone–methanol and acetone–ethanol mixtures is similar to that of pure acetone. Therefore, anti-dry-out abilities of acetone–methanol and acetone–ethanol mixtures are



(a) FR = 62% **(b)** FR = 70%

Fig. 14 Thermal resistances of PHP with acetone–ethanol, **a** FR = 62%, **b** FR = 70%

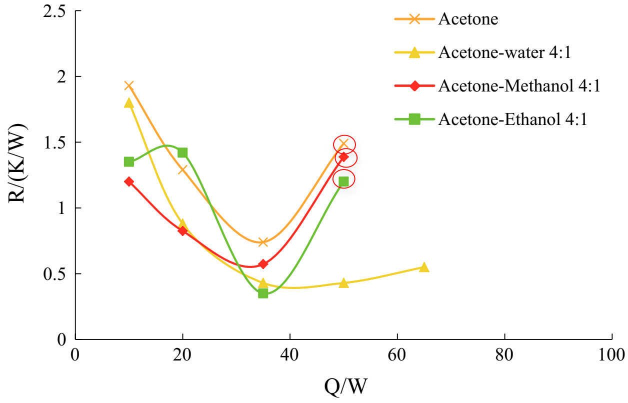


Fig. 15 Thermal resistance of PHP with acetone and acetone based mixture (MR = 4:1, FR = 45%)

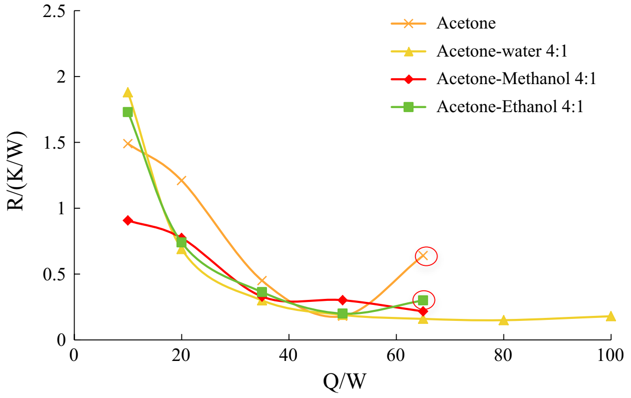


Fig. 16 Thermal resistance of PHP with acetone and acetone based mixture (MR = 4:1 FR = 55%)

similar to that of pure acetone. On the contrary, the PHP with acetone–water mixture maintains a low thermal resistance between 50 and 65 W. It can be found out that the difference of boiling points between acetone and water is relatively high, so a strong phase transition sequence exists in phase transition of acetone–water mixture, which represents a strong anti-dry-out ability inside PHP. Thus, adding methanol and ethanol into acetone can not improve the heat transfer performance of the PHP at a low filling ratio.

The thermal resistances of the PHP with pure acetone and acetone-based binary mixtures of 4:1 mixing ratio at 55% filling ratio represents similar trend to that at 45% filling ratio before 35 W, as shown in Fig. 16. Each curve of the PHP with acetone-based mixtures is closer to other curves than that at a 45% filling ratio between 35 and 65 W. With the increasing of the quantity of working fluids, the maximum heating power have all been improved for each working fluid, as shown in Table 3. The acetone–water mixture exhibits much stronger anti-dry-out ability than other working fluids (pure acetone, acetone–methanol and acetone–ethanol mixtures). In summary, at low and medium filling ratios (45 and 55%), the acetone–water mixture has a strong phase transition inhibition and better anti-dry-out ability inside the PHP, and the heat transfer performance of the PHP with acetone–water is, accordingly, better than that with pure acetone, acetone–methanol and acetone–ethanol mixtures.

Table 3 Maximum heating power at different filling ratios

	FR = 45% (W)	FR = 55% (W)
Acetone	50	65
Acetone–methanol	50	65
Acetone–ethanol	50	65
Acetone–water	65	100

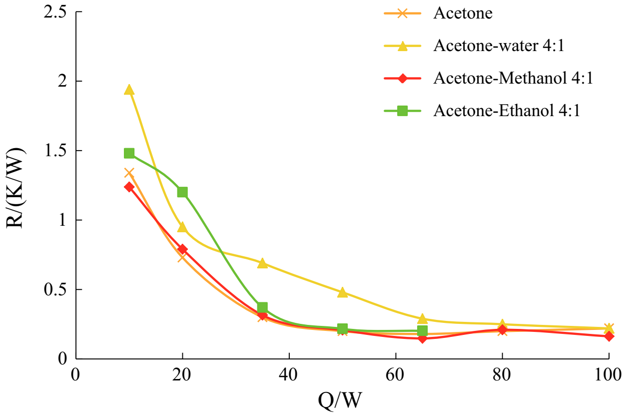


Fig. 17 Thermal resistance of PHP with acetone and acetone based mixture (MR = 4:1, FR = 62%)

4.4.2 The heat transfer performance of the PHP with acetone-based binary at a high filling ratio

At high filling ratios (62 and 70%), there are enough liquid to wet the ES even at high heating power (65–100 W), and the PHP is hard to dry out under this circumstance. Therefore, at high filling ratios, the heat transfer performance of the PHP mainly depends on its value of the thermal resistance under high heating power (65–100 W). Figure 17 shows the thermal resistances of the PHP with pure acetone and acetone-based binary mixtures under 4:1 mixing ratio at a 62% filling ratio; the thermal resistances of the PHP with acetone-based binary mixtures at 70% filling ratio exhibited similar trend as that at 62% filling ratio. As shown in Fig. 17, the thermal resistances of the PHP with pure acetone, acetone–methanol and acetone–ethanol mixtures decrease to a low value at 50 W. When the heat power lies between 65 and 100 W, the thermal resistances change slightly with the increase of the heating power. However, the thermal resistance of the PHP with acetone–water mixture is higher than that with pure acetone. When the heating power reaches 80 W, the thermal resistances of PHPs with acetone–water decreased to a level near that of pure acetone and acetone–ethanol, and then the thermal resistance maintains at a similar level between 80 and 100 W.

Because of the mass resistance, which is caused by the concentration difference in acetone–water mixture, the flow rate of acetone–water mixture reduces inside the PHP. But the physical properties of acetone are relatively close to that of methanol and ethanol, so the energy carrying abilities and flow rate inside the PHP with acetone–methanol and acetone–ethanol mixtures are similar to that with pure acetone. Overall, at high filling ratios (62 and 70%), the PHP with closeness of the physical properties of working fluids, i.e. acetone–methanol and acetone–ethanol mixtures, exhibit better hear transfer performance than that with acetone–water mixture and are similar to that with pure acetone.

5 Conclusions

This study compared and analysed the heat transfer performance and the flow characteristic of the PHP charged with acetone–water, acetone–methanol and acetone–ethanol mixtures at different volume mixing ratios (2:1, 4:1, and 7:1) and with pure working fluids. The following conclusions are drawn from the study:

1. At low filling ratio (45%), the phase transition inhibition in mixtures can significantly delay the dry-out inside the PHP. The thermal resistance of the PHP with acetone–water mixture that has large positive deviation is lower than that with pure working fluids (pure acetone and water) at 50 W. The phase transition inhibition of acetone–methanol and acetone–ethanol mixtures with small positive deviation is relatively weak, and the thermal resistances of the PHP with acetone–methanol and acetone–ethanol mixtures exhibit a similar characteristic with that of corresponding pure working fluids (pure acetone, methanol and ethanol), which do not strengthen the anti-dry-out ability inside the PHP.
2. At a medium filling ratio (55%), the heat transfer performance of the PHP is correlated to comprehensive influences by the phase transition characteristics and the physical properties of working fluids. The PHP with acetone–water mixture is not dried out throughout the whole range of heating power and the thermal resistance maintains at a low level. With the increasing of the quantity of working fluids, the dry-out is delayed inside the PHP with acetone–methanol and acetone–ethanol mixtures. The phase transition inhibition of acetone–ethanol mixture slightly improves anti-dry-out ability inside the PHP, which makes the heat transfer performance of the PHP with acetone–ethanol mixtures at 2:1 and 4:1 slightly better than that with pure acetone and ethanol.
3. At high filling ratios (62 and 70%), the heat transfer performances of the PHP with acetone-based mixtures are not as good as that with pure acetone. The closeness of the physical properties of acetone, methanol and ethanol results in similar heat transfer performance to that with pure acetone. The flow resistance inside the PHP with the acetone–water mixtures is greater than that with pure acetone, the flow rate inside the PHP is relatively slow and the heat transfer performance of the PHP with acetone–water mixture is worse than that with pure acetone.

Acknowledgements This study was funded by the National Natural Science Foundation of China under Grant No. 51076104.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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