Experimental Study on Heat Transfer Performance of Pulsating Heat Pipe with Refrigerants: Postprint

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Abstract

For 350MW and 600MW boilers under oxy-fuel combustion conditions, through reasonable control of primary and secondary air flow rates and correct selection and modification of mathematical models, the temperature distribution, heat flux distribution, and heat absorption distribution, etc. were obtained and compared with those under air-firing conditions. Through calculation, it was found that the primary and secondary air mixed well, forming good tangential firing combustion in the furnace, with the temperature under air-firing conditions being obviously higher than that under O26 conditions. The adiabatic flame temperature of the wet cycle was slightly higher than that of the dry cycle. The maximum heat load appeared on the waterwall around the burner area, decreasing gradually along the furnace height upward and downward in the burner area. The heat absorption capacity of the furnace under O26 conditions was lower than that under air-firing conditions. The heat absorption capacity of the platen heating surface under O26 conditions was equal to that under air-firing conditions, and the heat absorption capacity of the waterwall under O26 conditions was about 7% to 12% less than that under air-firing conditions.

Full Text

Preamble

Experimental Study on Heat Transfer Performance of Pulsating Heat Pipe with Refrigerants

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The effects of different refrigerants on heat transfer performance of pulsating heat pipe (PHP) are investigated experimentally. The working temperature of pulsating heat pipe is kept in the range of 20℃–50℃. The startup time of the pulsating heat pipe with refrigerants can be shorter than 4 min when heating power is in the range of 10W–100W. The startup time decreases with heating power. Thermal resistances of PHP with filling ratio 20.55% were obviously larger than those with other filling ratios. Thermal resistance of the PHP with R134a is much smaller than that with R404A and R600a, indicating that the heat transfer ability of R134a is better. In addition, a correlation to predict thermal resistance of PHP with refrigerants was suggested.

Keywords: R134a, pulsating heat pipe, heat transfer performance, non-dimensional correlation

Introduction

As a potential heat transfer component for micro/mini scale cooling devices with high heat flux, pulsating heat pipe (PHP) has been investigated extensively by scholars worldwide since its introduction by Akachi [1]. Nowadays, PHP has been deployed in practical engineering applications due to its advantages [2-3].

Numerous researchers have investigated the effects of various factors on startup and heat transfer performance of PHP with conventional working fluids [4-8]. However, the working temperatures of PHP with conventional working fluids are higher than room temperature, making them difficult to apply in electronic cooling applications. The removal of heat dissipation from electronic apparatus at room temperature represents an important challenge, necessitating the study of PHP with new working fluids to achieve suitable operating temperatures for electronic cooling.

Zhi Li and Li Jia et al. [9] experimentally studied the thermal performance of PHP with acetone for LED cooling and found that the working temperature could exceed 70℃ at high heating power. Gu J.J. and Kawaji M. et al. [10] investigated the effects of gravity on pulsating heat pipes with refrigerant (R-114), confirming that pulsating heat pipes with refrigerant can operate satisfactorily under reduced gravity and are suitable for space applications. Naik Rudra and Pinto Linford et al. [11] proposed a simplified theoretical model of pulsating heat pipe employed in a vapor compression refrigeration system, obtaining the best results with R-12 as the working fluid. Li Xuejiao and Jia Li et al. [12] experimentally studied the thermal performance of plate pulsating heat pipe with low-boiling point fluids, finding that pulsating heat pipes with low-boiling point fluid start up more quickly with lower startup temperature compared to acetone at different heat powers. Lu Qianyi and Jia Li et al. [13] experimentally studied plate pulsating heat pipe application in rack cooling systems using R600a as working fluid, with start-up temperature in the range of 18–27℃.

Although thermal performance of PHP has been studied extensively, the relationship between heat transfer performance of PHP and refrigerant working fluids has not been investigated in detail. Based on previous research [14-16], this paper experimentally investigates the heat transfer performance of a tube-type pulsating heat pipe with refrigerants R134a, R404A, and R600a. The working temperature of PHP was maintained in the range of 20℃–50℃, and a non-dimensional correlation to predict the thermal resistance of PHP with refrigerants was suggested.

Experimental Setup and System

The investigated pulsating heat pipe was made of red copper and bent into a coil with 18 turns, with an inner diameter of 2 mm and outer diameter of 3 mm. The lengths of evaporator, condenser, and adiabatic sections are 50 mm, 100 mm, and 100 mm, respectively. The PHP was tested vertically, with the evaporator section heated by electrical resistance heater wire. The working fluids were R134a, R404A, and R600a, respectively. Fourteen T-type thermocouples were fixed on the PHP to measure temperature across the three sections. Specifically, six thermocouples were fixed on the evaporator section on every other straight tube, with the same arrangement for the condenser section, and two thermocouples were fixed on the adiabatic section. The six thermocouples on the evaporator section were covered by the electrical resistance heater wire. The experimental system is shown in Fig. 1 [Figure 1: see original paper].

The experimental system includes a heating system, cooling system, steady flow system, data acquisition system, and evacuation system. The evaporator section was heated by an electrical resistance heater, while the condenser section of the tested PHP was cooled by cooling water from a water tank. The inlet and outlet temperatures were measured by three T-type thermocouples at the inlet and three at the outlet. To obtain stabilized cooling water, a steady flow system was equipped with an overflow port on the top and an outlet at the bottom. The flow rate of cooling water was maintained between 1.5 g/s and 2.5 g/s. Experimental data were collected by an Agilent 34970A data acquisition unit with a 1 Hz collecting frequency and a personal computer. The tested PHP was evacuated by a vacuum pump (V-i120SV).

Results and Discussion

In this research, the influence of filling ratio and working fluid on startup and heat transfer performance of pulsating heat pipe were studied. The temperature of the evaporator section was maintained between 20℃–50℃, and the heating power in the experiment was kept in the range of 10W–100W. In this paper, the thermal resistance is defined as:

Where, cp is the specific heat of cooling water; ṁ is the mass flux, and Tout and Tin are the average temperature of three thermocouples fixed in the outlet and inlet of the cooling tank. TH and TC are temperature of evaporator section and condenser section respectively.

Influence of Filling Ratio

The PHP was charged with R134a working fluid at filling ratios of 20.55%, 35.2%, 49.89%, and 74.84%, respectively. The heating power was maintained in the range of 10W-100W to keep the evaporator section temperature in the range of 20℃-50℃. The startup times of the PHP with four filling ratios at different heating powers are shown in Fig. 2 [Figure 2: see original paper].

In general, the startup time of the PHP with four filling ratios decreased with heating power. At 10W heating power, the startup times reached maximum values, with the longest startup time of 220s for filling ratio Φ=20.55%. When heating power exceeded 20W, all startup times remained below 50s. The shortest startup time was 11s for Φ=49.89% at 60W. Additionally, when heating power was in the range of 40W-100W, the startup times with four filling ratios did not change significantly with heating power.

Figure 3 [Figure 3: see original paper] shows the influence of filling ratio on thermal resistance of the PHP. The thermal resistance curve for PHP with 20.55% filling ratio was higher than the other three curves. The thermal resistance of PHP with 20.55% filling ratio was in the range of 0.64℃/W-1.44℃/W, indicating that the PHP with R134a is not suitable for operation at low filling ratio. The difference among thermal resistances of the other three filling ratios was not very apparent at the same heating power, suggesting that the effect of filling ratio on thermal resistance may not be significant. The minimum thermal resistance value was 0.27℃/W when Φ=74.84% and heating power P=100W.

As shown in Fig. 4 [Figure 4: see original paper], all working temperatures for PHP with four filling ratios were in the range of 20℃-50℃ when heating power was in the range of 10W-100W. The temperature of the evaporator section increased significantly with heating power, and larger filling ratio could achieve higher evaporator section temperature. However, for Φ=49.89% and Φ=74.84%, the two curves almost overlapped, meaning the evaporator section temperature did not increase with filling ratio. For higher filling ratio, the evaporator section could achieve lower temperature at the same heating power. High filling ratio means more working fluid is in the PHP, which can transport more energy from evaporator section to condenser section, leading to greater heat dissipating capacity at the condenser section. In this research, the evaporator section temperature for Φ=20.55% and Φ=35.27% exceeded 50℃ when heating power exceeded 50W and 60W, respectively. However, the evaporator section temperature for higher filling ratios stayed below 50℃, allowing higher heating power input up to P=100W.

Influence of Working Fluid

To investigate the effect of working fluid on thermal performance of PHP, refrigerants R134a, R404A, and R600a were tested at different heating powers with filling ratio Φ=74.84%. Figure 5 [Figure 5: see original paper] shows the startup time of R134a, R404A, and R600a with heating power. At the same input heating power, the startup time of PHP with R134a was shorter than that with R404A and R600a. However, as heating power increased, the difference between startup times of the PHPs with three refrigerants decreased, becoming very small when heating power exceeded 80W.

The thermal resistances of the PHPs with R134a, R404A, and R600a are given in Fig. 6 [Figure 6: see original paper]. The results indicate that the thermal resistance of the PHP with R134a was much smaller than that with R404A and R600a. The difference between thermal resistances of the PHPs with refrigerants decreased with heating power. Thermal resistance of the PHP with R600a was 0.88℃/W at 20W heating power, which was bigger than that with R134a, with the difference approaching 50%. At higher heating power, the difference was more than 20%. The heat-transfer capability of R134a is apparently better than R404A and R600a in this research.

The working temperatures of the PHPs with R134a, R404A, and R600a are given in Fig. 7 [Figure 7: see original paper]. All temperatures were in the range of 20℃–50℃ and can be applied in heat transfer at room temperature. The working temperatures of PHPs increased with heating power. R404A exhibited the lowest working temperature among the three refrigerants, suggesting that refrigerant R404A is more suitable for operation under room temperature conditions.

Correlation about Thermal Resistance

Based on non-dimensional analysis, a non-dimensional correlation for thermal resistance can be written:

Φ (4)

The above equation can be transformed into non-dimensional form:

$\cdot \Phi$ (5)

Some non-dimensional parameters were introduced. Non-dimensional thermal resistance is written as:

Non-dimensional surface tension is written as:

Non-dimensional heating power is written as:

Non-dimensional dynamic viscosity is written as:

The coefficient and exponents in Eq. (5) can be determined from experimental data. More than 200 experimental data points were applied in this research, and the coefficient and exponents in Eq. (5) were obtained.

The comparison between the prediction of the suggested non-dimensional correlation and experimental results is given in Table 1 . The average relative error is less than 25%, which indicates that the suggested non-dimensional correlation provides good prediction for the thermal resistance of PHP with refrigerant.

Table 1 The comparison between non-dimensional correlation and experiment on thermal resistance

Filling ratio Φ=85.17%

Heating power (W)	Experimental result (℃/W)	Predict value (℃/W)	Relative error (%)

Conclusions

In this paper, the thermal performance of PHP with refrigerants R134a, R404A, and R600a was investigated, and a non-dimensional correlation for thermal resistance was suggested. The following results were obtained:

1. Startup times of PHP with four filling ratios reduce with heating power. Thermal resistances of PHP with filling ratio 20.55% were obviously larger than those with other filling ratios. Thermal resistances of PHP with the other three filling ratios differ not too much at the same heating power. Working temperatures of PHP increase with input heating power.

2. Thermal resistance of the PHP with R134a is much smaller than that with R404A and R600a, which means the heat transfer capability of R134a is much better. Working temperatures of the PHP with R404A are lower than those with R134a and R600a at the same heating power.

3. A correlation to predict thermal resistance of PHP with refrigerants was suggested based on non-dimensional analysis.

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