Heat transfer performance of an oscillating heat pipe under ultrasonic field with dual frequency

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Abstract. The oscillating motion and heat transfer capacity in an oscillating heat pipe (OHP) under the effect of ultrasound was investigated experimentally. Using the electrically-controlled piezoelectric ceramics, the ultrasonic sound was applied to the evaporating section of the OHP. The heat pipe was tested with or without the ultrasonic sound. The effect of ultrasound on the heat transfer performance was conducted with ultrasound of single frequency or dual frequency. The experimental results demonstrate that the OHP under the effect of the ultrasonic sound with dual frequency performs better than that one with single frequency.

1. Introduction
Extensive experimental investigations and theoretical analysis have been conducted, and show that the heat transfer performance of an OHP depends on many factors such as working fluid, tilt angle, dimension, filling ratio, turn number and heat flux level [1-10]. While these investigations have provided an insight into the mechanisms of oscillating motions and heat transfer occurring in the OHP, many factors affecting the heat transport capability have not been fully understood. Ma et al. [11] indicate that the temperature difference caused by the heat addition in the evaporator and heat rejection in the condenser is the primary reason for the oscillating motion. Pai et al. [12] presented a nonlinear thermomechanical finite-element model of U-shaped three-plug oscillating heat pipes (OHPs) and results show that an OHP is a parametrically excited nonlinear thermomechanical system. Ji et al. [13] and Hao et al. [14] improved the heat transfer capacity of the OHP by treating the inner surface. Most recently, Zhao et al. [15-16] demonstrated that ultrasonic sound can significantly reduce the startup power and enhance the heat transfer capacity of the OHP.

In this paper, the heat transfer performance of an oscillating heat pipe under the ultrasonic field with dual frequencies was investigated experimentally in order to find out whether ultrasonic sound with dual frequency can increase oscillating motion and enhance the heat transfer capacity of OHPs.
2. Experimental setup

![Figure 1. Schematic of the oscillating heat pipe with locations of the PZTs and thermocouples. (dimension unit: mm)](image)

Figure 1 illustrates a 6-turn closed-loop oscillating heat pipe. The size of the OHP has the overall dimensions of 15.5 cm by 15.5 cm. The OHP consisting of the condenser, adiabatic section, and evaporator was made of copper tubing with an inner diameter of 1.8 mm and an outer diameter of 3.0 mm. Six piezoelectric ceramics made of Pb-based Lanthanum-doped Zirconate Titanates (PZT) were placed on the evaporating section. Each piezoelectric ceramic has an inner diameter of 3.0 mm and an outer diameter of 10.0 mm. The OHP was instrumented with 32 T-type calibrated thermocouples. The maximum error of the calibrated thermocouples was ±0.1 °C.

![Figure 2. Schematic of the experimental system.](image)

The schematic of the experimental system is shown in figure 2. In order to reduce the thermal contact resistance, the copper tubing were laid into 1.5 mm deep semi-circular grooves machined into the 6.4 mm thick copper heat spreading plates for the evaporator sections, and 20.0 mm thick copper
plate in the condenser section. The evaporator plate was sized to match the strip heater’s dimensions of 38.0 mm by 155.0 mm while the condenser plate was sized to 64.0 mm by 155.0 mm. The adiabatic region was 53 mm long. The heat pipe was charged with high performance liquid chromatography (HPLC) grade water at the filling ratio of 50%. The OHP was encased in thermal insulation material and wrapped in aluminium foil to prevent the heat losses. The condenser section was cooled by a Julabo F34 temperature controlled circulator. Temperature data was collected via a NI SCXI-1600 DAQ at 100 Hz controlled by a computer. The ultrasonic sound was generated by the piezoelectric ceramics. A control circuit was used to adjust the ultrasound by varying voltage and frequency respectively. The operating temperature for all the tests were 40 °C.

3. Results and discussion

The same OHP was tested with and without the ultrasound to demonstrate the ultrasonic effect on the heat transfer performance of the OHP. The heat load tested was 25W, 40W, 60W, 80W, 100W, 150W and 200W respectively. The total power on the six PZTs was regulated to 0.1W no matter what frequencies were put on the PZTs. Figure 3 illustrates the ultrasonic effect on the thermal resistance of the OHP under different frequencies. As shown, the ultrasonic sound can effectively reduce the thermal resistance of the OHP no matter the power frequency on all the six PZTs were 14kHz or 474kHz. It also indicates that the thermal resistance was further reduced when the power frequency on one half of the PZTs was 14kHz and the other half of the PZTs was 474kHz.

Figure 3. Ultrasonic effect on the thermal resistance.

Figure 4 illustrates the ultrasonic effect on the effective thermal conductivity of the OHP under different frequencies. Same results were achieved that the effective thermal conductivity of the OHP performed best under the ultrasound with dual frequencies. Moreover, the ultrasonic effect works better when the heat load was less than 150W.

In order to better determine the ultrasonic sound effect on the heat transfer enhancement of an OHP, a relative enhancement, which is called the enhancement percentage, $E$, is defined as,

$$ E = \frac{(A - B)}{A} \times 100\% $$

(1)

where $A$ and $B$ are the thermal resistance of the OHP without and with the ultrasonic effect respectively. Figure 5 shows the ultrasonic effect on the enhancement percentage of the OHP. As shown, when ultrasound with dual frequency were added in the OHP, the heat transfer enhancement was the highest. In addition, it can be found that the enhancement percentage depends on the heat load. The highest enhancement percentage of the thermal resistance of the OHP was up to 42.8% when the heat load was 60 W with the effect of dual frequency ultrasound.
4. Conclusions
The heat transfer performance of an oscillating heat pipe under the ultrasonic field with dual frequencies was investigated experimentally. Results show that ultrasonic sound with dual frequencies performs better improvement on the heat transfer capacity of the OHP comparing to one frequency. In addition, the heat transfer enhancement of an OHP under the effects of ultrasonic sound depends on the heat load.

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