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# Experiment investigation on thermal performance of a large-scale oscillating heat pipe with self-rewetting fluid used for thermal energy storage

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A B S T R A C T

The maximization of oscillating heat pipe (OHP) has important significance on OHP based large-scale thermal energy storage (TES) system. In order to understand the thermal performance of OHP with long heat-transport distance for thermal energy storage (TES) application, a large-OHP testing platform was constructed. The influence of working medium type, heating load, cooling condition on the thermal efficiency, thermal resistance and effective thermal conductivity of OHP were investigated and analyzed. The results mainly showed that the OHP with self-rewetting fluid (SRWF) has greater heat transfer limit and can work normally under larger heating load compared to that with water or ethanol as working medium. The OHP with filling ratio (FR) of 40–80% can endure higher heating load compared to the case of FR = 30%. It can be concluded that the best FR is about 40% under large heat load (the effective thermal conductivity reaches 5676 $\mathrm{W\,m^{-1}\,{}^{\circ}C^{-1}}$ at 700 W). The SRWF based OHP with long heat-transport distance in this paper has lower thermal resistance and larger heat density compared to those of some other research groups.

## 1. Introduction

Thermal energy storage and utilization technologies have great significance to the demand of energy saving and emission reduction and these technologies are widely used in those fields, like waste heat recovery, solar heat utilization and so on. The performance of thermal transport medium directly affects the efficiency of thermal energy storage (TES) system. There are several kinds of heat transport medium commonly used, such as metal, single phase fluid, liquid-vapor phase change heat transport medium. Heat pipe (HP), acted as thermal transport medium with high efficiency, received much attention in recent years [1].

Nowadays, HP has been utilized in thermal energy recovery or TES skillfully by many researchers. Qiu et al. [1,2] designed a high-temperature solar energy storage and power generation system investigated the thermal performance of HP with complex geometric structure used in it through numerical method and found that the thermal resistance of HP shows negative correlation with temperature and vapor radius while shows positive correlation with the heat input which agrees well with the existing experimental data. Liu et al. [3,4] designed a kind of HP based heat exchanger used for latent heat TES and experimentally studied the heat transfer characteristics under charging only mode, discharging only mode and simultaneous charging/discharging modes, respectively. The heat exchanger realizes the function of heat storage and heat release at the same time. Khalifa et al. [5,6] designed two other high-temperature TES systems curiously based on axially finned HP and suspended finned HP, respectively. Experimental results and numerical results were both obtained and compared. The results showed that the energy extracted of the axially finned HP system increases by 86% and the HP effectiveness increases by 24% compared to bare HP.

Those HPs mentioned above are convectional HP, capillary force driven HP or gravity driven HP. Different from the conventional HP, oscillating heat pipe (OHP) has great potential in heat transport and has the advantage of low cost, flexible geometry, large heat transfer limit, simple design, followed by more superior performance and better design [7]. OHP with different sizes can be used in different fields. Miniature and micro OHP has been a hot spot of research since the date of its birth, mainly including the innovation of working medium, structural innovation, changing the external force field, and so on.

Karthikeyan et al. [8], Nine et al. [9] and Wang et al. [10] used function thermal fluids (copper and silver colloidal nano-fluid, $Al_2O_3$ nano-fluid and microcapsule fluid) as working medium to

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**Nomenclature**

| | |
|---|---|
| $R$ | thermal resistance [°C W$^{-1}$] |
| $T$ | temperature [°C] |
| $Q$ | heat [W] |
| $K$ | thermal conductivity [W m$^{-1}$ °C$^{-1}$] |
| $\sigma$ | surface tension[N m$^{-1}$] |
| $\eta$ | thermal efficiency |
| $p$ | pressure [Pa] |
| *Subscripts* | |
| *ave* | average |
| *cap* | capillary |
| *s* | substrate material |
| *e* | evaporation |
| *c* | condensation |
| *w* | water |
| *ohp* | oscillating heat pipe |
| *eff* | effective |
| *Acronyms* | |
| *EF* | enhancement factor |
| *TES* | thermal energy storage |
| *FR* | filling ratio |
| *SRWF* | self rewetting fluid |
| *RCW* | rate of cooling water |

improve the performance of OHP, respectively, and proved that the heat transport capability can be enhanced relative to water under specific conditions. Ma et al. [11,12] designed two novel 3-D flat OHPs which can manage the heat flux of 20 W/cm$^2$ and 300 W/cm$^2$, respectively. Burban et al. [13] designed an OHP with novel structure and applied it in thermal management of hybrid electric vehicle electronic device innovatively. Mameli et al. [14–16] studied the influence of gravity on the thermal performance of the flat plate OHP and tube OHP systematically, mainly including the magnitude of gravity acceleration and the direction of gravity field. The thermal performance of OHP is rapidly influenced by the magnitude of gravity acceleration when placed vertically. Qu et al. [17,18] established the heat transfer correlation model and the lower limit prediction model of the pipe diameter. The lower limit prediction model of the pipe diameter was verified through a visualization experimental investigation. In order to enhance the heat transport among OHP, Xian et al. [19] proposed a method of pulsing heating. Pulsing heating can enhance the temperature fluctuation effectively, and then decreases the temperature difference between the heating section and cooling section. In the previous work of our group [20], we built a small TES experimental platform based on small OHP/phase change material (PCM) coupling structure and found that the starting temperature of the OHP should be lower than the phase change temperature. The thermal response time of the PCM was quite short, and the oscillating and the temperature variation had good synchronization.

The maximization of OHP has important significance in OHP based large-scale thermal energy storage system. Liu et al. [21] designed an OHP with long heat transport length used as solar energy collector and confirmed the possibility for OHP application in solar thermal energy collection. Rittidech et al. [22,23] designed solar thermal collector based on closed-end OHP and closed-loop OHP/check valve, respectively. However, those researches mentioned above were mainly focus on the thermal efficiency of both collectors and the thermal characteristics of OHP itself, such as thermal resistance, effective thermal conductivity, were not studied.

Self-rewetting fluid (SRWF), the concept of which raised by Abe can prevent the dry out phenomenon on the heated surface and improve the thermal performance of heat transfer devices, such as OHP. Hu et al. [24–26] studied the mechanism of heat and mass transfer of SRWF and the application in heat-transport enhancement of micro OHP systematically. It was found that the thermal resistance can be decreased comparing with water as working medium.

In this paper, aimed to understand the thermal performance of OHP and long heat-transport distance for large-scale TES application, a large-OHP is manufactured which is about two times longer than that in Liu's work [21]. The thermal performance and heat transport efficiency under different operation conditions are compared and analyzed, including different working mediums (water, ethanol and SRWF), different filling ratio (FR), different heating powers and different rates of cooling water (RCW).

## 2. Experiment description

### 2.1. Experiment set-up

Fig. 1 shows the photograph of the experimental system, relevant parameters of geometry and materials and the experimental conditions. As can be seen in it, the experimental system mainly includes liquid injection system, OHP, pressure transducer, DC power, heating system, flow adjustable pump, low-constant temperature bath and data acquisition system (Agilent 34970A acquisition/switch unit, 34901 module and OMEGA K-type thermocouples). The condenser section is placed in a sealed water box, which is made up of two pieces of organic glass plate clamped around the welded square frame. The OHP passes through the square frame and is welded into it. The evaporation section is twined round with heating wire with insulating treatment. The adiabatic section is wrapped with thick insulation ceramic fiber cotton. Fig. 2 exhibits the photograph of the OHP and the schematic of temperature measuring points clearly. The condenser section is connected to the OHP though flared type two-way connectors. The pressure transducer and the liquid injection pipe are connected to the OHP though flared type three-way connectors. Liquid injection and vacuum pumping are controlled by a three-way valve. The OHP is sealed by the two-way valve after the injection. Therefore, the OHP can be charged repeatedly. The measuring points include the temperature of the evaporation section ($T1$–$T5$) and the condensation section ($T6$–$T10$), the temperature of inlet cooling water ($T11$) and the temperature of outlet cooling water ($T12$).

The table in Fig. 1 summarizes the relevant parameters of the OHP and the experiment conditions. The FR ranges from 30% to 80% with an interval of 10%. The whole height and inner diameter of the OHP are 1200 mm and 4 mm, respectively. With regard to the inner diameter ($Di$) range of OHP, there are the following empirical formulas (1)–(3) [27,28].

$$Di_{min} \leqslant Di \leqslant Di_{max} \tag{1}$$

$$Di_{min} = 0.7\sqrt{\frac{\sigma}{(\rho_{liq} - \rho_{vap})g}} \tag{2}$$

$$Di_{max} = 1.84\sqrt{\frac{\sigma}{(\rho_{liq} - \rho_{vap})g}} \tag{3}$$