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Research Paper

Experimental and numerical investigation of the thermal performance of a novel sintered-wick heat pipe

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HIGHLIGHTS

- A novel type of sintered wick heat pipe (one-third wick) was fabricated and tested.
- Thermal resistance of the novel heat pipe is lower than that of the annularly one.
- This heat pipe has simpler manufacturing procedure compared with the annularly one.
- This heat pipe is a good candidate for applications at zero gravity conditions.
- The Florez model provides satisfactory results for the calculations of k_{eff}.

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ABSTRACT

Thermal performance of a novel sintered wick heat pipe was investigated in this study. Two types of sintered wick heat pipes were fabricated and tested at different filling ratios of water, and their thermal resistances in different modes were compared. In the first type, wick was sintered annularly (conventional type), and in the other one (novel type of sintered wick) it was sintered only in one third of cross-section. Results showed that dry-out occurs at higher heat input by an increase in the filling ratio. Moreover, the best filling ratio is 20% for both heat pipes. Thermal resistances of the partly sintered wick heat pipe are approximately 28%, 17% and 47% lower than those of the annularly sintered one at 20% filling ratio in the vertical, horizontal and reverse-vertical modes, respectively. Gravity has a slight effect on partly sintered wick heat pipe performance in the horizontal mode. This novel type of sintered wick heat pipe has simpler structure, and its manufacturing is more affordable compared with the annularly sintered wick. Hence, the use of this type of novel heat pipe (partly sintered wick) rather than the conventional type (annularly sintered one) is recommended in most applications, especially in space conditions where the gravity is negligible. In addition, experimental results were compared with numerical ones, and it was shown that the Florez orthorhombic and Alexander models can provide reasonable predictions for the effective thermal conductivity of water-saturated sintered powder-metal wicks.

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1. Introduction

Shrinkage of electronic devices is possible by components compression, which increases heat flux density per unit area. Hence, equipment with a high heat transfer capability becomes more important. Heat pipes are two-phase heat transfer instruments [1] that can transfer heat at lower temperature differences between the evaporator and condenser. These devices benefit from high heat transfer coefficients of two-phase flows to transfer a relatively large amount of heat from the evaporator to the condenser without consuming electrical energy. Heat pipes are composed of three sections: an evaporator, an adiabatic section and a condenser. Heat flux, Q, is applied to the evaporator. The part of the liquid that is in equilibrium with the surrounding vapor evaporates, and then moves to the condenser, where condensation takes place. This movement occurs as a result of the pressure difference between the evaporator and the condenser sections. Heat pipes use capillary structure to return the condensed working fluid from the condenser to the evaporator [2,3]. The capillary force caused by the capillary structure pumps liquid to the evaporator. Because of the capillary force, heat pipes can be used in locations where gravity is negligible (such as satellites) or even against gravity (where the evaporator is above the condenser).

The three important properties of wicks in heat pipe design are thermal conductivity, capillary pressure, and permeability [4]. The four common wick structures used in the heat pipes are grooved, wire mesh, sintered powder metal, and fiber/spring. Each structure has its own benefits, drawbacks, and capillary limitations [5]. Sintered wick has been widely used in the heat pipes, since the

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gravity has a minor effect on its performance. These wicks have smaller pores and higher thermal conductivity, for they are made of fused metal powders that stick together perfectly. In addition, these powders stick to the wall and have an intimate contact with the heat pipe wall, so that there is low thermal resistance between the pipe and the porous wick. Hence, the effective thermal conductivity is high. The sintered wick is located in the interior part of the pipe wall, and the center of the pipe is considered to be empty where vapor passes through it.

Sintered wicks are manufactured in two ways. In the first method, wick is sintered in the main tube in one step, and in the second method wick is sintered separately and inserted in the tube afterwards. Some special conditions are necessary for metal powder sintering procedure, so as a sealed furnace that is needed to increase the temperature near metal powder melting point (approximately 100–200 °C below the metal powder melting point) [6]. Moreover, a reducing atmosphere is necessary to prevent powder oxidation and reduce oxide layers already present on metal powders. Some reducing atmosphere is mentioned in the literature, for example, semi-burnt hydrocarbons such as methane, butane, and propane, dissociated ammonia, mixture of nitrogen and hydrogen with predetermined ratios, and pure hydrogen. Pure hydrogen is the best reducing atmosphere for copper powder sintering [7]. A typical sintering process is described by Reay et al. [6].

In the literature, two distinctive types of sintered wick heat pipes are investigated from the geometric perspective: one is the tubular heat pipe and the other is the flat plate heat pipe. Tubular heat pipes are more common and consist of a closed pipe with a capillary structure in its wall. These types of heat pipes transfer the heat along the pipe. As is evident from the name of the flat plate heat pipe, this type of heat pipe has a flat surface, and its cross-section is often rectangular, which makes it possible to be located over flat plates such as thermoelectric coolers or other electronic instruments [8]. The objective of fabricating this type of heat pipes is heat spreading and temperature flattening over the surface. Flat plate heat pipes, which are sometimes called vapor chambers (in which the only role of the wick is to distribute the liquid inside the evaporator), are usually made of sintered wick structure [6]. In the flat plate heat pipe, the evaporator and condenser are located opposite to each other, and the distance between them is very short and the direction of the heat transfer is often perpendicular to the device [9].

Research studies on improving thermal performance of sintered wick heat pipes can be divided into two categories: studies that examined different working fluids and those that investigated wick structures. Kumaresan et al. [10] tested the performance of a sintered heat pipe filled with CuO nanoparticles. Their results showed that the utilization of such surfactant-free nanofluids (CuO/DI–water mixture) increases the heat transfer performance. Kang et al. [11] reported that adding silver nanoparticles to water decreases the temperature differences between the pipe walls of a sintered wick heat pipe compared with the pure water as the working fluid. Li et al. [12] studied a heat pipe with sintered grooved composite wick. Their results showed that higher heat load prolongs the time required to reach an equilibrium state. Liou et al. [13] tested flat-plate sintered mesh-wick heat pipes. They showed that small values of wick permeability hindered the decrease in evaporation resistance and resulted in dry-out. Wong et al. [14] reported that in flat-plate sintered heat pipe, the presence of fine powders in wick causes further reductions in the values of minimum evaporation resistance. The effects of mixing wick powder with space-holder on the properties of the porous wick have been studied in different works [15–20]. Li et al. [21] tested the effect of fabricating parameters on properties of sintered porous wicks for loop heat pipe, and their results showed that when porous wicks with equal porosity are manufactured for LHPs, small compacting pressure (low space-holder addition) should be applied in order to achieve a desirable capillary pumping capability. Jiang et al. [22] and Li et al. [23] investigated the effects of metal powder size range and sintering parameters on porous wick properties and its heat transfer capabilities. Those parameters were temperature, time, atmosphere and position of sintering process.

Based on the literature, it can be concluded that different types of sintered wick structure affect the thermal performance of sintered wick heat pipe. In this study, a novel type of sintered wick heat pipe was fabricated, tested, and compared experimentally and numerically with a conventional cylindrical sintered wick heat pipe. The current research is mainly focused on the thermal performance of these two heat pipes at several filling ratios of water as the working fluid and at different orientations.

2. Experimentation and numerical analysis

2.1. Heat pipe specifications and numerical analysis

In general, the typical wick pattern in conventional wick heat pipes is annular. But manufacturing of this kind of heat pipe wick has its own difficulties and requires special attention. In this work, two types of sintered wick heat pipe were fabricated. One of the wicks was sintered annularly (conventional type), with a thickness of approximately 1.3 mm, and the other one (partly sintered wick) with only one third of the cross-section to benefit from the advantages of thermosyphon heat pipes. Moreover, it had circumferential grooves (twenty four per cm), with a depth and width of 0.15 mm in the evaporator and condenser sections.

In manufacturing the sintered capillary structure (wick) of both heat pipes, the same amount of copper powder was used. For this purpose, 0.75% wt. mixture of lithium stearate and 53–63 μm spherical copper powder was used, and its sintering procedure was similar to that given by Reay et al. [6], described as follows: First, the tube was filled with powder while mandrel was located inside. Afterwards, it was heated in a furnace at a temperature of 850 °C and 50% vol. hydrogen and 50% vol. nitrogen atmosphere for 30 minutes. After the tube was cooled and removed from the furnace, mandrel was brought out and the tube was resintered for another 30 minutes at the same conditions.

The outer diameter, length and the casing thickness of both heat pipes were 15.87 mm, 250 mm and 0.68 mm, respectively. The length of the evaporator and condenser sections was one fourth of the total length, and the rest of it was allocated to the adiabatic section. The cross-sectional view of the annularly sintered wick heat pipe is shown in Fig. 1. Fig. 2a and b present the circumferential grooves of the partly sintered wick heat pipe before sintering and the cross-sectional view of it after sintering, respectively.

Based on Archimedes' and imbibition's principle, the effective porosities of the annularly sintered and the partly sintered wicks were 36.2% and 38.1%, respectively [24,25]. These values are relatively close to each other and their difference is within 5%. In addition, to calculate the approximate value of permeability, the Kozeny–Carman equation is used [25,26]:

$$K = \frac{D^2 \varepsilon^3}{180(1-\varepsilon)^2} \tag{1}$$

where K, D, and ε are the permeability (m^2), the average diameter of the copper powder particles (m), and the wick porosity, respectively.

Before fabrication of these types of heat pipes, following a series of simplifications, two-dimensional simulations have been conducted by a free, open source CFD software package to calculate the approximate average thermal resistances for both types of heat pipes and for different wick thicknesses, and the simulation results were compared together. For the sake of comparing the thermal resis-

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