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# Experimental study of the thermal characteristics of a heat pipe

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ABSTRACT

The performance of a cylindrical heat pipe under various operating conditions was experimentally analyzed. The heat pipe consists of a copper tube with a diameter of 12.7 mm and 4 layers of copper screen mesh act as the wick. The heat pipe was equipped with a vacuum ball valve in order to charge the heat pipe with different amounts of working fluid. The effect of the working fluid fill volume, inclination angle, and heat input on the equivalent thermal resistance of the heat pipe were investigated. The results showed that in gravity-assisted orientations (condenser located above evaporator), the inclination angle has a negligible effect on the performance of the heat pipe. However, for gravity-opposed orientations (evaporator above condenser), as the inclination angle increases, the temperature difference between the evaporator and condensation increases which results in a higher thermal resistance. It was also found that if the working fluid in the heat pipe is under-filled, the capillary limit of the heat pipe decreases dramatically. However, overfilling of the heat pipe degrades the heat pipe performance due to excess liquid interfering with the evaporation-condensation mechanism. The results obtained from this experiment were also used to verify a previously developed numerical model. Very good agreement between the numerically predicted results and those from the experiment were obtained, thus validating the numerical technique developed and reported in authors' previous papers.

## 1. Introduction

A heat pipe is a heat transfer device that is capable of conveying large amounts of energy by cyclic evaporation-condensation processes. A heat pipe is comprised of a vacuumed-sealed container charged with an appropriate amount of working fluid. The inner surface of the container is covered with a wick material. When heat is applied to one end of container called the evaporator, the liquid working fluid is vaporized. The vapor then travels toward the other end of the container, called the condenser. In the condenser section of the heat pipe, the vapor condenses transferring energy to a heat sink. The resulting liquid is driven back to the evaporator by the capillary pressure provided by the wick structure. Using these mechanisms, heat pipes can exhibit heat transfer rates that are up to orders of magnitude higher than those seen in highly conductive metals. This feature makes the use of heat pipes desirable in many applications, such as thermal energy storage systems [1–3] and electronic cooling [4–6].

Experimental studies have been conducted to investigate the effects of different parameters on the thermal performance of heat pipes. These studies can be classified into different groups: studying the heat pipe operating conditions [7], investigating the type of wick structure [8], the effects of the working fluid type or the geometry of the heat pipe [9–11]. Some experiments have also been conducted with the aim of validating the numerical models used to simulate the complex multiphase heat transfer that occurs within heat pipes [12]. Faghri and Buchko [13] experimentally tested a copper-water heat pipe with the purpose of verifying their developed numerical model. The heat pipe was exposed to multiple heat sources and a screen mesh was used as the wick structure. In another experimental investigation, Faghri et al. [14] examined the transient and steady state operations of a high-temperature heat pipe with the main objective being the validation of their numerical results.

De Schampheleire et al. [15] investigated the effects of a novel wick material composed of metal fibers on the thermal operation of a water-copper heat pipe. The thermal resistance of the heat pipe with a fiber mesh wick was compared to those of a screen mesh and a sintered wick. Additionally, they also studied the effects of the thickness and porosity of the wick material on the performance of the heat pipe [16]. Kempers et al. [17] studied the effects of mesh layers and fluid loading on the performance of water-copper heat pipes. They concluded that the maximum heat transfer through the heat pipe increased as the number of mesh layers used for the wick increased. Wang et al. [18] conducted

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**Nomenclature**

| | |
|---|---|
| $A$ | area, $m^2$ |
| $c_p$ | specific heat, J/kg-K |
| $d$ | wire diameter, m |
| $d_o$ | heat pipe outer diameter |
| $h_{fg}$ | latent heat of evaporation, J/kg |
| $k$ | thermal conductivity, W/m-K |
| $k_c$ | thermal conductivity of copper, W/m-K |
| $L$ | heat pipe total length, m |
| $n$ | normal direction |
| $N$ | mesh number |
| $p$ | relative pressure, Pa |
| $p_0$ | reference pressure, Pa |
| $P_{v,c}$ | vapor pressure in the condenser, Pa |
| $q$ | heat flux, $W/m^2$ |
| $Q$ | heat transfer, W |
| $r$ | radial coordinate |
| $R$ | radius, m |
| $Res$ | total thermal resistance K/W |
| $T$ | temperature, K |
| $T_0$ | reference temperature, K |
| $t$ | thickness, m |
| $u$ | axial velocity, m/s |
| $v$ | radial velocity, m/s |
| $\vec{v}$ | velocity vector, m/s |
| $V$ | average velocity in vapor core, m/s |
| $z$ | axial coordinate |

*Greek*

| | |
|---|---|
| $\rho$ | density, $kg/m^3$ |
| $\mu$ | dynamic viscosity, $N\,s/m^2$ |
| $\varphi$ | viscous dissipation |
| $\varepsilon$ | porosity |

*Subscripts*

| | |
|---|---|
| a | adiabatic |
| c | condenser |
| e | evaporator |
| eff | effective |
| i | inlet |
| int | interface |
| $l$ | liquid |
| $o$ | outlet |
| v | vapor |
| w | wall |

experiments to study the effect of wick type on the performance of flat plate heat pipes. Two types of wicks were investigated. The first wick structure was made of intersected narrow grooves while interlaced channels was chosen as the second type. The thermal performances of heat pipes were obtained in both axial and radial directions at various heat fluxes. It was found that implementing the interlaced channels as the wick structure improved the heat conduction in axial direction and raised the capillary limit. Qu et al. [19] introduced a microgroove structure as the wick to an oscillating heat pipe and observed heat transfer improvement of the heat pipe. Huang [20] examined the enhancement in thermal performance of a heat pipe that resulted from using a composite wick. The wick was fabricated from a bi-porous structure composed of fine nickel metal powder sintered onto layers of a coarse pore copper mesh. Tharayil et al. performed a comprehensive analysis to study of the effects of different screen mesh size wicks on cylindrical and flattened heat pipes at various inclinations [21]. More studies that focus on the characterization of the effects that wick type has on the performance of heat pipes can be found in Refs. [11,22,23].

The effects of different working fluids on the performance of a dual diameter heat pipe were explored by Peyghambarzadeh et al. [24]. They used water, methanol, and ethanol as working fluids and reported that higher heat transfer coefficients were obtained for water and ethanol in comparison with methanol. Recently, water-based nanofluids have gained interest to be used as the working fluid in a heat pipe instead of a conventional working fluid due to their enhanced thermal conductivity. Asirvatham, et al. experimentally investigated the effects of silver nanoparticles on thermal behavior improvement of a copper water heat pipe [27]. More studies can be found exploring the effects of different Nano-fluids on heat pipe performance [25–27]. Experiments have also been conducted to study the performance of heat pipes that have unconventional geometries for use in specific applications. [11,28–30]. The performance of a heatsink with embedded L-type and U-type heat pipes was studied by Wang [31]. Wang et al. [32] developed a concentric condenser heat pipe array for application in waste heat recovery. The overall thermal performance of the heat pipe was investigated experimentally and the effects of heat input, inclination angle, and the length of evaporator section were studied.

Previously, the authors had developed a novel heat pipe network with the objective of improving the performance of a Stirling engine based concentrated solar power system [33]. The heat pipe array utilized a primary central heat pipe along with an array of secondary heat pipes. The solar energy received at the receiver is transferred to the Stirling engine via the primary heat pipe while the excess thermal energy is transferred to the phase change material (PCM) via the secondary heat pipes for storage and later use. A new steady-state numerical model that is capable of modeling the non-uniform condensation that occurs within the condenser section of the complex heat pipe network was developed [34]. The model was then employed to study the effect of various operating conditions as well as different geometrical features on the thermal performance of the heat pipe network in order to optimize the heat pipe array to achieve a uniform temperature distribution at the Stirling heat engine receiver [33,35]. After the development of the numerical model, a series of experiments were devised to validate the new numerical procedure. Due to the complexity associated with the manufacturing of heat pipes, an initial simplified laboratory case was investigated where a cylindrical water-copper heat pipe was designed and built. Additionally, a simulation of the heat pipes using the proposed numerical model was conducted and the results were compared to the experimental data. In addition to validation of the numerical model, the effects of the working fluid fill ratio and heat pipe orientation on the performance of the heat pipe were studied. Note that these effects were neglected in the original numerical model. The results of this investigation help to extend the uses of the numerical model in the design and optimization process of heat pipes as it can be used to predict the appropriate fill volume of the working fluid within a complex heat pipe geometry that would yield to optimal operation.

## 2. Experimental study

### 2.1. Heat pipe fabrication

The cylindrical heat pipe was made from a pipe with an inner diameter of 12.7 mm (0.5 in.), an outer diameter of 15.875 mm (0.625 in.), and a total length of 342 mm (16.46 in.). The heat pipe is made of 110 coppers. The top and bottom of the heat pipe container were tightly