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Transient and isothermal characteristics of a particular heat pipe☆

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ABSTRACT

This paper presents a simple and rapid mathematical model to calculate the non-steady-state startup process and study the isothermal characteristics of a particular heat pipe. The model takes into consideration the special structure and usage conditions, where vapor temperature in the heat pipe changes only over time. This vapor temperature change correlation is calculated numerically and is set as the temperature boundary condition for the working well. The temperature, velocity and pressure distribution in the working well are then solved using FLUENT. The results manifest that the time required for approaching steady condition are 450 s, 550 s and 600 s with water bath temperatures of 330 K, 340 K and 350 K, respectively. The comparison of the calculations and experimental data shows good agreement, and the maximum deviation is 3.7 K.

1. Introduction

Semiconductor material growth, standard blackbody furnace, and temperature calibration are all needed in an isothermal environment. Through the application of heat pipe, we can get better isothermal performance. Due to the simple structure, low cost, and excellent heat transfer properties, two-phase closed thermosyphons (TPCTs) have been successfully used in electronics cooling, heat recovery, solar energy development and utilization of geothermal resources, etc. [1–5]. The behavior of the TPCT in steady state situations is well known. However, literature about their transient behavior or isothermal characteristics is surprisingly scarce. Several research works on numerical models of heat pipe have been already reported [6,7]. The models range from one-dimensional steady-state analytical solutions to three-dimensional numerical methods. A review of numerical models and solution methods for various heat pipe operations including steady-state, continuum transient and frozen start-up has been provided by Faghri [8–10]. Some of his work with Harley [10] presented a transient thermosyphon model. This work used two-dimensional compressible ideal gas, and laminar flow equations to model the vapor. They also used a two-dimensional model for the wall temperature profile. Vafai et al. [11–15] have developed comprehensive pseudo-three-dimensional analytical models for asymmetrical flat-shaped, including both disk-shaped and flat-plate, heat pipes. They incorporated liquid flow, secondary vapor flow and the effects of liquid–vapor hydrodynamic coupling and non-Darcian transport in their models. Reed and Tien [16] presented a theoretical investigation of the TPCT response time with a model describing the behavior of the whole system in both transient and steady regimes. The authors indicate that, for most TPCTs, the governing time scale was the "film residence time". The authors use a one-dimensional vapor flow model to indicate the effects of annular flow. One drawback was that this model did not include the effect of the thermosyphon wall. Generally, previous theoretical models consisted of a set of highly nonlinear partial differential equations. To obtain solutions to these equations, numerical techniques such as finite-difference and finite-element methods must be incorporated, and significant programming efforts and computational time were required. Faghri [17,18] summarized a "network" model of the steady-state heat pipe operation. The heat pipe was divided into nine components each with a specific thermal resistance. Estimation of the thermal resistance of each component was noted. The network model provided a simple way to calculate temperatures and heat fluxes in the heat pipe.

The research on isothermal characteristics of the heat pipes has mainly focused on experimental studies. Li [19] has made a study on the uniformity of vertical temperatures on the glass-water heat pipe. He tested the vertical temperature profile with heat pipe temperatures at 323 K, 333 K, 348 K and 353 K. The results show that the heat pipe exhibits high temperature uniformity. He also analyzed the factors that impact on vertical temperature distribution. Yan [20] studied the glass-water heat pipe performance with respect to internal temperature stability, uniformity and different amounts of working fluids. Studies have shown that in the range of 273 K to 303 K, the temperature stability inside the heat pipe is, within 16 h, better than 0.1 mK.

The isothermal characteristics and its application were seldom mentioned in the former literature. To study the transient and isothermal characteristics of a particular heat pipe through a simple, rapid and accurate method, a mathematical model to calculate the non-steady-state startup process of the heat pipe with working well is presented

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Nomenclature

D	Diameter, m
e	Specific energy, kJ/kg
h_{fg}	Latent heat, kJ kg^{-1}
m	Mass, kg
M	Total mass of working fluid, kg
Q	Heat rate, W
S^*	Dimensionless numbers
T	Temperature, K
V	Total volume, m^3

Greek symbols

ρ	Density, kg m^{-3}
α	Heat transfer coefficient, W m^{-2} °C^{-1}
τ	Time, s
δ	Thickness of pipe wall, m

Subscripts

i	Input
j	Evaporation
l	Liquid phase
o	Condensation
v	Vapor phase

in this paper. The vapor temperature in the tube changes only over time, and this change correlation is calculated by numerical calculation and is set up as the temperature boundary condition of the working well. The temperature, velocity and pressure distribution in the working well are then solved using FLUENT.

2. The structure of the heat pipe

A schematic diagram of the heat pipe with a working well modeled in this work is shown in Fig. 1. It can be seen from this figure that there is a working well in the heat pipe. The working fluid of the heat pipe in this work is high purity water, and the material of the heat pipe wall is glass. The research objective is the temperature distribution within the working well. The research purpose of the heat pipe with a working well is to achieve a constant temperature environment in the working well, to provide the necessary conditions for calibration of temperature measuring devices or the reproduction of temperature scales. The heat pipe is surrounded by heating sources while at use; therefore, it does not have any adiabatic section. The evaporation section of the heat pipe is the whole external surface and the condensation section is the working well.

In addition, Fig. 1 shows the structure and size of the thermometer well, which is 0.12 m in diameter and 0.25 m in length. Four points in the working well are simultaneously monitored to observe the temperature, velocity and pressure distribution as shown in Fig. 1. The locations of the four monitoring points are distributed equidistantly along the axis. Their coordinates are (0,0), (0.07,0), (0.14,0) and (0.21,0) respectively.

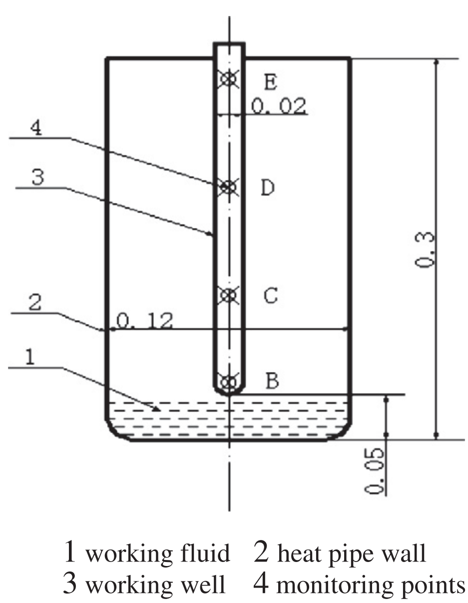

Fig. 1. The schematic diagram of heat pipe.

3. Computational model

3.1. Model assumptions

Some characteristics of the heat pipe would be obtained through experimental observation as follows:

The heat pipe was immersed in water bath with a constant temperature of 353 K. No boiling and bubbles appeared in the gas–liquid interface; it is a natural evaporation process. No gaseous flow could be seen in heat pipe. The temperature of the heat pipe increased in a short period of time. Meanwhile, there were small droplets in the bottom of the working well, but no significant condensate liquid film could be seen in the heat pipe wall.

The following assumptions were made in the development of the simple model [21]:

(1) The entire liquid and vapor content are at respective temperatures which stay uniform throughout the given phase at any given time.
(2) The liquid and vapor phases are, at their corresponding temperatures, in a saturated state at any given time, meaning that the system goes through a quasiequilibrium process.
(3) There is no liquid film on the walls of the heat pipe.
(4) The effect of phase-change occurs at the liquid–vapor interface.
(5) The heat transfer coefficient at the condenser wall is uniform and constant.

3.2. Model

The development of a simple transient model for the heat pipe is discussed in this section. The model is developed using a control volume formulation of the energy balance. The heat pipe is divided into two control volumes. The first control volume corresponds to all the liquid present in the heat pipe, while the other control volume encloses the entire vapor content of the heat pipe.

The conservation of mass and volume for the entire heat pipe leads to Eqs. (1) and (2) given below:

$$m_l + m_v = M \tag{1}$$

$$m_l v_l + m_v v_v = V \tag{2}$$

Eqs. (1) and (2) can be expanded as:

$$m_v = (V - M v_l)/(v_v - v_l) \tag{3}$$