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Research Paper

Numerical and experimental investigation of pulsating heat pipes with corrugated configuration

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HIGHLIGHTS

- An improved pulsating heat pipe with corrugated configuration is proposed.
- The flow pattern observed from numerical and experimental method is compared.
- The start-up time is reduced up to 28.96% with corrugated configuration in evaporation section.
- The thermal resistance is reduced up to 37.57% with corrugated configuration in evaporation section.

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ABSTRACT

A single loop pulsating heat pipe with corrugated configuration in evaporation, adiabatic, and condensation section is numerically and experimentally investigated in present work. The investigation is carried out under the condition of varying input power ranged from 5 W to 40 W and filling ratio ranged from 30% to 60%. In the numerical investigation, VOF model is used to probe the feature of two-phase flow inside the single loop pulsating heat pipe. The present numerical results such as vapor–liquid flow pattern and variation trend of the thermal resistance show a good consistency with those of the experiments. It's found that the pulsating heat pipe with corrugated configuration in evaporation section has the best performance of start-up and heat transfer of present considered cases. The results show 28.96% decrease in start-up time and 37.57% in thermal resistance due to the application of corrugated configuration, which presents a remarkable improvement in the overall performance of pulsating heat pipe.

1. Introduction

In the last decade, increasing demand for the heat transfer device with higher efficiency has been appears in engineering application such as electronic cooling. Pulsating heat pipe (PHP) is an efficient heat transfer device which was first proposed by Akachi [1] in the 1990s. Typically, PHP consists of evaporation, adiabatic and condensation section [2–4]. Due to the temperature and pressure difference established inside the PHP, heat is transferred by an action of pulsation or circulation of the working fluid [5–8].

To understand the thermo-hydrodynamic behavior of PHP, numerous investigations have been conducted. It has been found that the features of PHP depend on the structure parameters, physical properties of working fluid and operation conditions [2,9–12]. The flow patterns, such as bubble flow, slug flow, and semi-annular/annular flow were observed by visual methods [6–7,13–14]. In the process of start-up of PHP, the sudden and the gradual are two common types [15].

Changing the geometrical structure of PHP has been proved to be a significant approach to enhance heat transfer performance of PHP. Due to the function of extending heat-transfer surface and thinning the boundary layer, the corrugated surface was an effective way to improve the heat transfer efficiency in practical applications [16]. Dizaji et al. [17] compared several arrangements of convex and concave corrugated tube in a double pipe heat exchanger. They found that the use of corrugated tubes was advantageous to increase the Nusselt number of heat exchanger in comparison with that of smooth one. The heat exchanger with a concave corrugated outer tube and a convex corrugated inner tube performed the best heat transfer efficiency. Moawed et al. [18] used a sinusoidal-shaped inner tube in a pipe heat exchanger, and investigated the effect of the sinusoidal pipe on the heat transfer characteristics and pressure drop. Compared with the smooth

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Nomenclature

C_p	specific heat, J/(kg K)
E	internal energy, kJ/kg
F	interface volumetric force, N/m^3
FR	filling ratio
L	length, m
p	pressure, Pa
Q	input power, W
R	thermal resistance, K/W
S_h	latent heat source term due to phase change, kg/(m^3 s)
S_m	mass source term due to phase change, W/m^3
T	temperature, K
t	time, s
$\vec{v}$	velocity vector, m/s

Greek symbols

α	volume fraction
μ	dynamic viscosity, kg/(m s)
ρ	density, kg/m^3
σ	surface tension coefficient, N/m
λ	thermal conductivity W/(m K)
κ	surface curvature, 1/m
η_R	the efficiency of thermal performance
η_t	the efficiency of start-up

Subscripts

a	adiabatic
c	condenser
e	evaporator
eff	effective
ex	experimental
l	liquid
nu	numerical
sat	saturation
v	vapor

tube, an up to 93% and 130% increase were achieved in heat transfer performance and friction factor, respectively. In addition, their results showed that the dimensionless exergy loss decreased with the increase of amplitude of the sinusoidal pipe.

As mentioned above, the corrugated configuration structure has been widely used in the heat exchanger devices. So far as the authors know, a few available data of corrugated configurations were applied in PHP. Therefore, the objective of present work is to investigate the effect of corrugated structure on the characteristics of PHP with corrugated configuration in different sections. Both experimental and numerical investigations on PHP with corrugated configuration are conducted.

2. Experiment description

The experimental apparatus of present work is shown in Fig. 1. The evaporation, adiabatic and condensation section are equal in length of 50 mm. For the purpose of visualization, the pulsating heat pipe is made of quartz glass with the inner diameter of 3.8 mm and outer diameter of 6 mm. The inner diameter of present pulsating heat pipe is small enough so that the working fluid water, will distribute itself naturally in the form of liquid–vapor slugs. The pulsating heat pipe apparatus is fixed in the vertical orientation with bottom-heating pattern. The surface of evaporation section is wrapped with heating wire of diameter 0.4 mm. The condensation section is immersed in a water cooler. The inlet temperature of water cooler maintains 25 °C and a constant mass flow rate at 4.77 g/s is set as well.

In order to probe the influence of corrugated configuration on the performance of pulsating heat pipe, three testing PHPs are manufactured. The corrugated configuration is adopted in evaporation, adiabatic and condensation section of three testing loops, namely test 1, test 2 and test 3, and detailed geometries are shown in Fig. 2. For the comparison of present PHP with corrugated configuration with regular PHP (without corrugated configuration), a regular PHP is manufactured as well. All the experiment conditions of testing PHPs such as the inner and outer diameter, the heating and cooling condition, and the filling ratio are consistent with that of the regular PHP.

The present PHPs are firstly evacuated to 0.084 MPa by a vacuum pump, and then filled the pipe with water through injection inlet as shown in Fig. 1 by a syringe. In present investigation, the filling ratios of PHPs are set to be 30%, 40%, 50% and 60%. The heating power varies from 5 W to 40 W by regulating the output voltage of transformer. As shown in Fig. 1, six T-type thermo-couples, labeled as Te1, Te2 for evaporation section, Ta1, Ta2 for adiabatic section, and Tc1, Tc2 for condensation section are attached at the outer wall of the PHP. The real-time temperature data is recorded by Agilent 34970A and then connected to a computer for scanning every 5 s. The experimental thermal resistance R_{ex} of PHP is calculated as follows

$$R_{ex} = (\overline{T_e} - \overline{T_c})/Q \tag{1}$$

where $\overline{T_e}$ and $\overline{T_c}$ is the average temperature of evaporation and condensation section, respectively, Q stands for the input heating power.

3. Physical and mathematical model

3.1. Physical model

In numerical investigation, a two-dimensional single loop PHP is modeled. The geometric structure of PHP adopted in numerical simulation is same as that of the experimental apparatus. To keep consistent with the experimental condition, the boundary condition in evaporation section is constant heat flux which depends on the input power. The condensation section of PHP is convective boundary condition, and the other parts of PHP are treated as adiabatic. For obtaining the initial two-phase distribution of working fluid, the temperature of 25 °C and subatmospheric pressure are assumed to be initial conditions in numerical simulation. The k–epsilon viscous model and standard wall function are adopted as well. The SIMPLE algorithm is performed for pressure–velocity coupling. The second-order upwind method is adopted for the momentum equation. The Geo-Reconstruct discretization method is performed for volume fraction. The contact angles of water and quartz glass is 20°.

3.2. Mathematical model and governing equations

The volume of fluid (VOF) model is adopted to simulate two immiscible free-surface fluids by solving one set of momentum equations in present numerical simulation. To track the interface between two phases, the definition of volume fraction α_v and α_l is necessary, where subscripts v and l represents vapor and liquid, respectively. In present numerical process, liquid water is defined