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Research Paper

Analysis of chaotic flow in a 2D multi-turn closed-loop pulsating heat pipe

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HIGHLIGHTS

- Chaotic flow in a 2D multi-turn PHP was investigated.
- Non-linear temperature oscillations were analyzed.
- Optimal filling ration and minimum thermal resistance were obtained.

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ABSTRACT

Numerical study has been conducted for the chaotic flow in a multi-turn closed-loop pulsating heat pipe (PHP). Heat flux and constant temperature boundary conditions have been applied for heating and cooling sections respectively. Water was used as working fluid. Volume of Fluid (VOF) method has been employed for two-phase flow simulation. Volume fraction results showed formation of perfect vapour and liquid plugs in the fluid flow of PHP. Non-linear time series analysis, power spectrum density, correlation dimension and autocorrelation function were used to investigate the chaos. Absence of dominating peaks in the power spectrum density was a signature of chaos in the pulsating heat pipe. It was found that by increasing the filling ratio and evaporator heating power the correlation dimension increases. Decreasing of the autocorrelation function with respect to time showed the prediction ability is finite as a result of chaotic state. An optimal filling ratio of 60% and minimum thermal resistance of 1.62 °C/W were found for better thermal performance of the pulsating heat pipe. It is notable that two dimensional simulations in current study lead better understanding of the mechanism and validating the numerical method for full three dimensional modeling.

1. Introduction

Downsizing of personal computers and advancing performance of processors has called for the development of micro and miniature heat pipes to transport heat from chips to heat sinks. The Pulsating or Oscillating Heat Pipe (OPH or PHP) is a very promising heat transfer device. Due to the pulsation of the working fluid in the axial direction of the tube, heat is transported from the evaporator section to the condenser section. The heat input, which is the driving force, increases the pressure of the vapour plug in the evaporator section. In turn, this increased pressure will push the neighboring vapour plugs and liquid slugs toward the condenser, which is at a lower pressure [1]. Although a variety of designs are in use, the fundamental processes and parameters affecting the PHP operation still need more investigation. Shafii et al. [2] presented analytical models for both open and closed-loop PHPs with multiple liquid slugs and vapour plugs. Heat transfer in both looped and unlooped PHPs was due mainly to the exchange of sensible heat and higher surface tension resulted in a slight increase in total heat transfer.

Zhang and Faghri [3–5] investigated heat transfer process in evaporator and condenser sections of the PHP. They developed heat transfer models in the evaporator and condenser sections of a pulsating heat pipe with one open-end by analyzing thin film evaporation and condensation. Results showed the frequency and amplitude of the oscillation is almost unaffected by the surface tension after steady oscillation has been established. The amplitude of oscillation was decreased with decreasing diameter of the pulsating heat pipe and decreasing wall temperature of the heating section, but the frequency of oscillation was almost unchanged.

Researchers have conducted many experimental and theoretical studies to investigate complicated behaviors and unsolved issues

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Nomenclature

F	body force (kg m/s^2)	S	source term
g	gravity acceleration (m/s^2)	V	volume of cell
α_q	void Fraction of phase q	f	frequency (Hz)
v_q	velocity of phase q (m/s)	λ	Lyapunov exponent
ρ_q	density of phase q (kg/m^3)	PSD	power spectrum density (W/Hz)
μ	dynamic viscosity (kg/m s)	ACF	autocorrelation function
T	temperature (°C)		
k	thermal conductivity (W/m K)		

of the pulsating heat pipes [6–12]. Recent studies have suggested the existence of chaos in PHPs under some operating conditions [13–16]. The approach in these studies is to analyse the time series of fluctuation of temperature of a specified location on the PHP tube wall (adiabatic section) by power spectrum calculated through Fast Fourier Transform (FFT). The two dimensional mapping of the strange attractor and the subsequent calculation of the Lyapunov exponent have been performed to prove the existence of chaos in PHP system. By calculating Lyapunov exponents, it was shown that the theoretical models are able to reflect the characteristic chaotic behavior of experimental devices.

Although several theoretical and experimental studies of the chaotic behavior of pulsating heat pipes have been carried out, there has been no detailed numerical simulation for PHPs. Pouryoussefi and Zhang [17] recently conducted a numerical simulation of the chaotic flow in the closed-loop pulsating heat pipe with two turns. Constant temperature was the boundary condition for both evaporator and condenser. Chaotic behavior of the PHP was investigated under different operating conditions. In this paper, the authors have extended their previous work [17] by applying heat flux boundary condition and thermal behavior investigation in addition to chaotic behavior investigation. Heat flux and constant temperature boundary conditions have been used for evaporator and condenser, respectively. The PHP structure is two-dimensional and water is the working fluid. Thermal resistance, axial wall temperature distribution and chaotic parameters have been investigated under different operating conditions.

2. Physical modeling

The two dimensional structure of the PHP were the same for all different operating conditions in this work and water was the only working fluid. Different evaporator heating powers, condenser temperatures and filling ratios were tested for the numerical simulation. The pulsating heat pipe structure consists of three sections: heating section (evaporator), cooling section (condenser), and adiabatic section. The tested heating power range in this study is from 10 W to 65 W. Fig. 1 illustrates a schematic configuration of the PHP which has been used in this study. The three different sections have been distinguished by two horizontal lines. The length and width of the tube are 870 mm and 3 mm respectively. The span of the PHP was considered 1 m as a 2D simulation. Fig. 2 shows meshing configuration used in this study. Only a part of evaporator section has been depicted to show the quadrilaterals mesh which were employed for simulation. The quadrilaterals mesh was used for the entire pulsating heat pipe. Effects of the surface tension are remarkable in pulsating heat pipes behavior and performance. Calculation of surface tension effects on triangular and tetrahedral meshes is not as accurate as on quadrilateral mesh. The region where surface tension effects are most important should therefore be meshed with quadrilaterals [17].

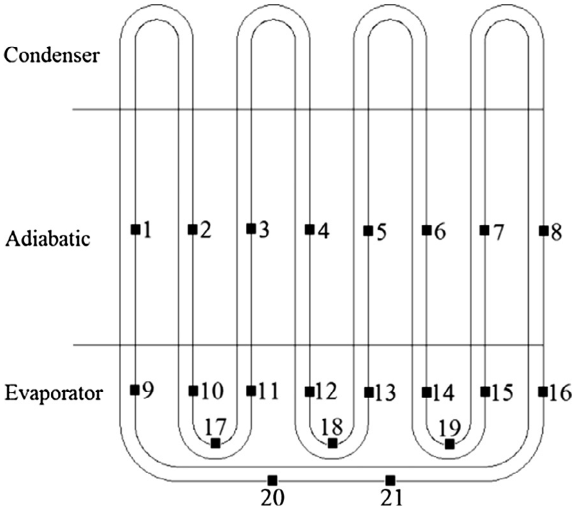

Fig. 1. Pulsating heat pipe structure.

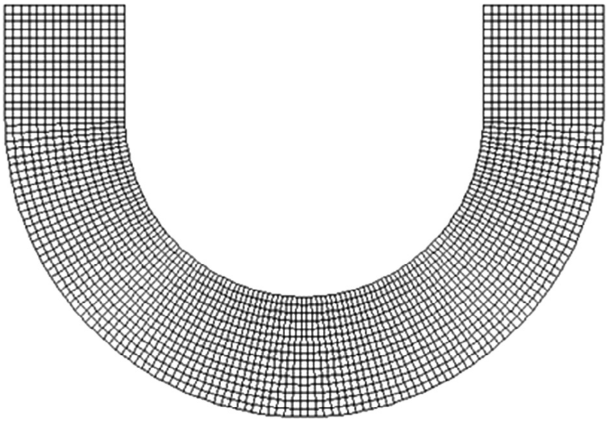

Fig. 2. Meshing configuration.

Volume of Fluid (VOF) method has been applied for two phase flow simulation. The VOF model is a surface-tracking technique applied to a fixed Eulerian mesh. It is designed for two or more immiscible fluids where the position of the interface between the fluids is of interest. In the VOF model, a single set of momentum equations is shared by the fluids, and the volume fraction of each of the fluids in each computational cell is tracked throughout the computational domain.

Applications of the VOF model include stratified flows, free-surface flows, filling, sloshing, the motion of large bubbles in a liquid, the motion of liquid after a dam break, the prediction of jet

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