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Design and operation of a Tesla-type valve for pulsating heat pipes

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ABSTRACT

A new Tesla-type valve is successfully designed for promoting circulation in a pulsating heat pipe (PHP) and improving the thermal resistance. Its functionality and diodicity is tested by laminar single-phase modelling and by steady two-phase flow experiments. The valve is symmetrically integrated in a single-turn PHP, which reduces variabilities to give a more thorough understanding of the behaviour in PHPs. Two transparent bottom-heated PHPs, one with and one without valves, are manufactured and the flow behaviour and thermal performance is studied. The valves produced a diodicity which lead to a difference in velocity of 25% for the different flow directions. Furthermore, a decrease of 14% in thermal resistance was observed due to the addition of the valves.

1. Introduction

The demand for faster and smaller micro-electronic systems continues to increase and consequently, the amount of produced heat per volume increases. Therefore, the need for novel efficient cooling devices is vast [1]. Heat pipes are effective passive heat spreaders that can be used to solve this problem. Due to the combined convection and phase transition, a high heat exchanging efficiency can be achieved [2]. A drawback of the traditional heat pipe is that it requires an intricate wick structure and cannot be easily miniaturised due to the capillary limit [3]. Therefore, a new heat pipe called the Pulsating (or Oscillating) Heat Pipe (PHP) was introduced by Akachi in 1990 [4]. The main benefits of the PHP are that it has a very simple shape with no wick structure, which can be easily miniaturised. This makes it a very inexpensive and easy-to-integrate heat spreader which can be beneficial for many, also non-electronic, applications [5].

A PHP generally consists of a simple meandering capillary tube or channel which alternatingly passes through evaporator (heating) and condenser (cooling) zones as schematically shown in Fig. 1. Due to the capillary size of the channel a series of liquid slugs and vapor plugs is formed by the working fluid. The constant heat exchange triggers phase-change phenomena which result in pressure variations inside the device that consequently trigger movement of the liquid slugs and plugs. The overall heat transfer is mainly determined by the sensible heat transfer and the latent heat contributes mostly to the movement of the slugs and plugs [6]. The performance of a PHP thus relies on the continuous non-equilibrium conditions throughout the system and an intricate interplay of physical phenomena. Depending on the specific conditions, the liquid slugs are stagnant, pulsating, circulating with a superimposed pulsation or purely circulating [7,8]. Furthermore, the flow pattern can vary from the normal bubble–liquid slug flow to annular flow [9]. The PHP has received large interest in the scientific community, however, due to the complexity and chaotic behaviour, no fully comprehensive theory or model and no general design tools are available [10,11].

It is known that circulation of the working fluid contributes to a better performance of the PHP [12–14]. The liquid contact in the evaporator is increased when the working fluid is circulating, which increases the heat transfer. This makes it interesting to investigate methods to promote circulatory motion in a PHP [9,15]. Moreover, directional promotion could increase the stability and predictability of the PHP.

Circulatory motion has been induced inside PHPs using asymmetrical heating [16], floating-ball check valves [17], a variation of channel diameters [9,18,19] and Tesla-type valves [20]. Although being of scientific interest, promoting the circulation using asymmetrical heating is not practically applicable. Similarly, using floating-ball check valves inherently contradicts the benefits of the PHP by having a moving part and being difficult to manufacture when integrated and/or miniaturised.

A more practical solution is to utilize asymmetrical flow resistance to promote directional circulation. Holley and Faghri [18] were the first to suggest this by varying the channel diameter. It was demonstrated that this could theoretically improve a directional flow in a single-turn PHP and also improve the heat transfer. These phenomena were attributed to the fact that a bubble in an

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Nomenclature

a	D-valve geometry radius, mm
b	D-valve geometry radius, mm
CW	clockwise
CTR	circulation tally ratio
CCW	counter-clockwise
D	channel diameter, m
Di	diodicity
e	D-valve geometry radius, mm
F	field of view
g	gravitational acceleration, 9.81 m/s^2
I	identity matrix
IG	gas inlet
IL	liquid inlet
I/O	inlet/outlet
J	channel junction
l	entrance length, m
L	D-valve geometry length, mm
O	outlet
P	pressure evaluation line
p	pressure, Pa
Q	flow rate, m^3/s
q	heat rate, W
R	D-valve geometry radius, mm
Re	Reynolds number
T	thermocouple location
u	velocity, m/s
V	volume, m^3
W	channel width, mm

Greek symbols

α	D-valve geometry angle, °
β	D-valve geometry angle, °
γ	Surface tension, N/m
ϵ	D-valve geometry angle, °
μ	Viscosity, $Pa \cdot s$
ρ	Density, kg/m^3
ϕ	Air–water volume ratio

Subscripts

av	average
$cond$	conduction
$conv$	convection
f	forward
hyd	hydraulic
in	input
l	liquid
m	main channel
r	reverse
rad	radiation
s	side channel
$transfer$	transferred
v	vapor

expanding channel will move in the diverging direction due to unbalanced capillary forces. When the tube diameter is varied in the condenser and the evaporator, i.e. having alternating channel diameters per turn, this effect is exploited to promote a circulatory flow. Kwon and Kim [19] performed experiments on several single-turn closed loop PHPs with a varied channel diameter. Besides the diameters, the heat input and inclination angle were also varied. It was concluded that a dual-diameter helps to generate a circulating flow at a lower input power and a maximum decrease in thermal resistance of 45% was found. Also it was shown that an optimum of diameter difference exists due to the fact that the smaller tube increases the flow resistance and therefore reduces the mass flow rate of the fluid. Liu et al. [9] performed experiments on three different PHPs with four turns of which one had alternating channel diameters and another had a single section in the adiabatic section which had a larger diameter. These modifications both induced the circulatory motion and improved the thermal performance compared to the standard PHP. Although these variations in channel diameter can promote circulatory flow significantly, the effect is substantially dependent on gravity. The bubble movement will cause the larger channel to contain more vapor than the smaller channel. This causes an unbalance in gravitational force which is the main driving force that promotes the circulating flow [19]. This influence is believed to be reduced when the overall size decreases and the number of turns increases [19,21].

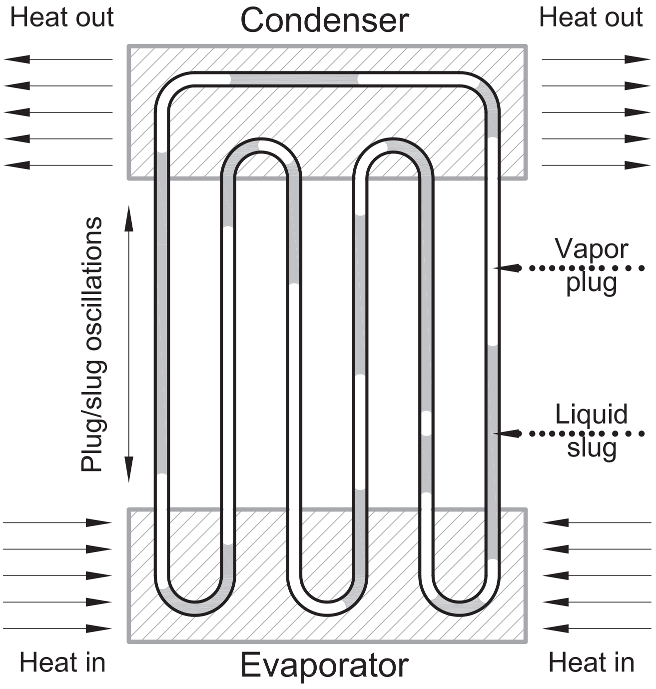

Fig. 1. Standard schematic configuration of a closed-loop PHP. At the evaporator section heat is added to the system while at the condenser section heat is removed. Due to the capillary size of the channel the working fluid naturally distributes itself into liquid slugs (grey) and vapor plugs (white). Pressure variations inside the system trigger movement of the working fluid which transfers heat from the evaporator to the condenser.

A second option of creating an asymmetrical flow resistance is to utilize flow rectification structures or ’no-moving-parts’ passive valves. Proven to function for micro-pumps, these valves have received great interest in the field of microfluidics due to the fact that they are easy to manufacture, durable and can transport fluids containing particles [22,23]. The valves are structures that have a higher pressure drop for the flow in one direction (reverse) than the other (forward). This difference in flow resistance causes a net directional flow rate in the forward direction in oscillating flows. The efficiency is often expressed in diodicity Di, being the ratio of pressure drops for identical flow rates [24]:

$$Di = \left(\frac{\Delta p_r}{\Delta p_f}\right)_Q \tag{1}$$