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The development and thermal analysis of a U-shaped pulsating tube operating in a rotating system of coordinates

Cezary Czajkowski, Przemysław Błasiak, Józef Rak, Sławomir Pietrowicz*

Department of Thermodynamics, Theory of Machines and Thermal Systems, Faculty of Mechanical and Power Engineering, Wrocław University of Science and Technology, Wybrzeże Wyspiańskiego 27 St., 50 -370, Wrocław, Poland

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ABSTRACT

A novel idea of heat transfer enhancement using a *U-shaped pulsating tube* in a rotating system of coordinates is presented and studied in the paper. The analyzed case consists of a U-shaped tube that rotates around the axis of revolution which is perpendicular to the tube axis. Similar to the classical *Pulsating Heat Pipe* (PHP), it is composed of an evaporation section, located at the ends of the U-tube, and a condenser section located in a tube bend. In the curved section of the tube a liquid slug is surrounded by two vapor plugs. Assuming laminar flow and ideal gas law for the vapor, the governing equations for the pulsating flow in a rotating system of coordinates are derived and non-dimensionalized, finally solved numerically using an explicit scheme. The goal of the analysis was to investigate the influence of the angular velocity and non-dimensional parameters on the thermal performance of the described device. It was found that the centrifugal force generated by rotational motion positively affects the thermal conductivity by increasing the pulsation frequency and decreasing the amplitude of the liquid slug displacement. The proposed buoyancy enhancement method may lead to new solutions during the cooling processes for the moving machinery elements.

1. Introduction

Commonly used passive or indirect cooling devices (for instance, radiators or heat sinks, which evacuate the heat from the system without additional external energy) to increase heat transfer are usually made of a material characterized by a high thermal conductivity. For example Ghosh et al. [1] examined the thermal properties of graphene, concluding that this material has extremely high thermal conductivity, reaching even 5150 W/(m K). Due to material limitations, engineers and scientists have been forced to seek other techniques for increasing the efficiency of the heat flux removal process [2,3]. One of the promising passive methods, called *indirect cooling techiques*, is the solution developed by Akachi [4] in 1996, called *Pulsating Heat Pipe* (PHP), in which the heat from a high temperature region is taken by an intermediate medium and transferred to a low temperature region. A PHP is a simple meandrical shaped pipe with a suitably small internal diameter which works on the basis of thermal, self-sustained, oscillations of the working fluid. Inside a capillary tube the phase change phenomena (both condensation and evaporation) occur. Unlike the conventional heat pipe, PHP is also a simple construction, because a porous structure called wick is unnecessary. As a result of the multiphase flow, accompanied by the continuous phase change phenomenon, the effective thermal conductivity reaches even up to 40 kW/(m K) [5]. Consequently, PHPs are able to transport high heat fluxes from small areas and provide an alternative for high efficiency conventional heat exchangers.

PHPs are a relatively recent invention whose foundation is based on the complexity of the heat transfer in the two-phase flow region. PHPs are attracting attention and have been studied by many researchers. The pulsating phenomena in a PHP and therefore the thermal efficiency of the device strongly depend on: the thermophysical properties of the working fluids [6,7], the orientation of a cooling section [7–9], the value of the heat load [10,11], tilt angles [12], channel layer [13], liquid filling ratio [14–16] and the inner diameter of the meandrical tube [17,18]. The above mentioned parameters are well established and being tested for different variables in experimental research. However, the impact of the variable external body force acting in a PHP is still unclear and requires more study. For this reason, the paper is intended to analyze the influence of the external force, which may have an effect on a PHP performance.

The operation of a PHP under a variable gravitational field (as gravity is the main source of body force acting on a PHP) has been already studied by some researchers. To achieve a variable gravitational force in a PHP, three experimental methods were carried out: on-orbit flight, parabolic flight or using a centrifuge. Kiseev et al. [19]

* Corresponding author.
E-mail address: slawomir.pietrowicz@pwr.edu.pl (S. Pietrowicz).

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Nomenclature

A_c	cross-sectional area of the tube, m^2
c_p	specific heat at constant pressure, J/(kg K)
c_v	specific heat at constant volume, J/(kg K)
C	integration constant, –
C_f	skin friction coefficient, –
d	inner diameter, m
F_g	gravitational force, N
F_o	centrifugal force, N
g	gravitational acceleration, m/s^2
G	overload, –
h	heat transfer coefficient, $W/(m^2 K)$
h_{fg}	latent heat of vaporization, J/kg
H	dimensionless heat transfer coefficient, –
k	specific heat ratio, –
k_{eff}	effective thermal conductivity, W/(m K)
l	axis of revolution, –
L	length, m
m	mass of vapor plug, kg
M	dimensionless mass of vapor plug, –
p	pressure, Pa
P	dimensionless pressure, –
$\dot{Q}$	transferred heat, W
Re	Reynolds number, –
r_h	distance from the center of rotation, m
r_x	position of the center of mass of the liquid slug, m
R	individual gas constant, J/(kg K)
R_h	dimensionless distance from the center of rotation, –
R_e	thermal resistance, K/W
z	thermal resistance per unit area, $(m^2K)/W$
t	time, s
T	temperature, K
x_p	displacement of the liquid slug, m
X_p	dimensionless displacement of the liquid slug, –

Greek symbols

ρ	density,
ζ	dimensionless parameter defined by Eq. (23)
ω	angular velocity, rad/s
Ω	dimensionless angular velocity, –
Ω_0	dimensionless angular velocity for validation, –
θ	dimensionless temperature, –
Θ	dimensionless temperature difference, –
ν_e	effective kinematic viscosity, m^2/s
τ	dimensionless time, –
τ_p	shear stress, N/m^2

Subscripts

0	reference state
1	left side
2	right side
l	liquid
v	vapor
h	heating
c	condensing section
e	evaporation section
m	minimum
M	maximum
I	lower range
s	center of the range
II	upper range
opt	optimal
p	liquid slug
1g	at centrifugal acceleration of $9.81 m/s^2$

Abbreviations

PHP	Pulsating Heat Pipe
HTC	Heat Transfer Coefficient

examined an overload of up to 12 g and experimentally proved that gravity has a strong influence on the efficiency of the heat transfer in a PHP. It has been shown that there is an increase in the average evaporator temperature from 160 ^oC at 0 g, up to 200 ^oC at 12 g level. Authors also reported that no evaporator dry out effect occurs for 12 g which makes the system more resistant to the transmission of large amounts of thermal energy. J. van Es et al. [20] experimentally investigated the effect of acceleration ranging between 1 g and 10 g on the phenomena occurring in the Flat Swinging Heat Pipe based on a PHP. It was noted that with an increasing of acceleration (up to 8.4 g) the efficiency of the device rises. In the experiment the PHP was mounted on a rotating disk thus the setup was analogical to the solution discussed in the current paper. Gu et al. [21] examined a PHP under micro, normal and hyper-gravity conditions. They revealed the possibility that micro-gravity has a positive effect on the thermal performance of the PHP. The same conclusion was described by Kawaji [22] within the range of acceleration between 0.02 g and 0.1 g. Mangini et al. [23] performed tests with a closed loop PHP in the bottom heating mode, which was positioned horizontally and vertically. The authors proved that under micro-gravity conditions, a horizontal PHP behaves similarly to the same, but vertical, PHP in the normal gravity. The authors also concluded that in gravity assisted cases the hyper-gravity period is able to eliminate partial dry-outs, restoring the correct operation until the occurrence of the next microgravity period during the parabolic flight. Ayel et al. [24] reported that in the vertical inclination, a PHP is rapidly influenced by variations in the gravity field. On the other hand, Thompson et al. [25] investigated hyper-gravity conditions (up to 10 g) and concluded that a PHP is gravity-independent. Lin et al. [6] experimentally analyzed a PHP and noticed that the gravitational acceleration negligibly affected the performance of the PHP. To conclude, the current state of experimental knowledge of the physical phenomena occurring in a PHP under variable external forces is poorly explored and its impact on a PHP performance requires further research.

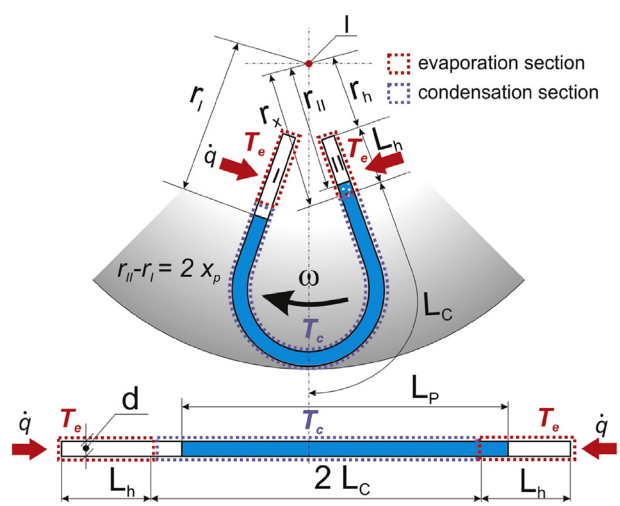

Fig. 1. Physical model of a U-shaped pulsating tube.