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Geometrical Shape of Pulsating Heat Pipe under Hyper Gravity Condition

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Abstract

The paper concerns a heat transfer characteristics for a pulsating heat pipe (PHP) under hyper-gravity condition. Two loops of pulsating heat pipe with the internal diameter of 1.5 mm were filled and tested with HFE-7000 as a working fluid. The experimental set-up allows for the investigation of two crucial parameters affecting the thermal process i.e. rotational speed (acceleration from 1 to 8g) and filling ratio (44 and 66, %). As a result, the dependences of the thermal resistance on the rotational speeds were obtained, thus declaring the optimal conditions for the heat transport process. The increase in filing ratio (FR) of the working fluid in hyper-gravity condition improves the thermal efficiency of PHP, as well as the direction of the evaporation section bending.

Keywords**:** Working fluid, Filling ratio, Rotary system, Pulsating heat pipe, Hyper-gravity

1. Introduction

Commonly used heat exchangers are based mostly on the heat conduction process, which in thermal technology management is less effective compared to the effective heat transport based on the phase change phenomenon. The aim of the proposed work is to examine the effect of changing the geometrical configuration of PHP subjected to a variable mass force on its thermal performance. The generated body force, acting along the normal to the axis of rotation, having a value higher than the value of gravity in the Earth's gravitational field, changes the conditions of the heat exchange process occurring inside the PHP capillary internal space. The inner diameter of the flow channel is one of the most important aspects of the construction of a PHP. During the energy transport, heat-flow phenomena must occur in the capillary force regime (in terrestrial conditions), which allows forming a two-phase structure (liquid slug and vapor plug train) of the working fluid. Above a certain value of internal diameter, called the critical diameter, the heat transport process will deteriorate significantly. The liquid phase will be completely separated from the vapor and the two-phase flow will disappear. In this case, the pulsating heat pipe will work as a thermosiphon, allowing energy to be transported only in the form of latent heat caused by evaporation phenomena. In connection with the above, the confinement criterion is one of the most frequently cited in the literature [1] [2]:

$$\frac{\Delta\rho g D^2}{\sigma} \leq 4 \qquad \text{Eq.1}$$

Recently, only a few studies of a PHP under high centrifugal force condition have been conducted. Therefore, only partial analysis can be provided with a literature overview. As a substitutive analysis, hyper-gravity studies can be applied with accuracy limited to only evaporator and condenser sections. Van Es et al. [3] in 2000 tested various designs of a PHP on a rotating table. It was noted that a set-up filled with acetone was operating stably up to a maximum acceleration of 8.4 g. In 2004 and 2005, Gu et al. [4] proved the possibility of PHP operation under a hyper-gravity of 2.5 g and with R-114 working medium. Ma et al. [5] in 2011 conducted experiments using a rotating table. The performance did not change up to a maximum acceleration of 10 g. Mameli et al. [6] and Ayel et al. [7] in 2015 tested the PHP during parabolic flight campaigns. They noted that hyper-gravity conditions of up to 2 g, resulted in the prevention of thermal instabilities after applying micro-gravity conditions. In 2014 Mameli et al. [8] conducted research on PHP under a varying gravity force. They proved that in microgravity conditions, due to the liquid phase dynamics, the confinement criterion based on the Bond number has no coincidence of results with the experiment (the condition for the capillary diameter for g striving to 0 represents the possibility of using any capillary diameter in space). Deng et al. conducted an experimental study of antigravity PHP heat efficiency determining that gravity has a significant impact on occurring heat-flow processes [9]. According to the conclusions of the work, such a device is subjected to a longer start-up process, and also exhibits more intense, in a quasi-steady state, temperature oscillations, with a higher value of thermal resistance.

Presented research have been conducted at Center of Applied Space Technology and Microgravity in Bremen. Experimental campaign was carried out on the basis of synthetic compound of the 3M^{TM} company under the trade name NOVECTM7000 with a very wide application [10].

2. Experimental Setup

The tested pulsating heat pipe under high centrifugal force is presented in Figure 1.

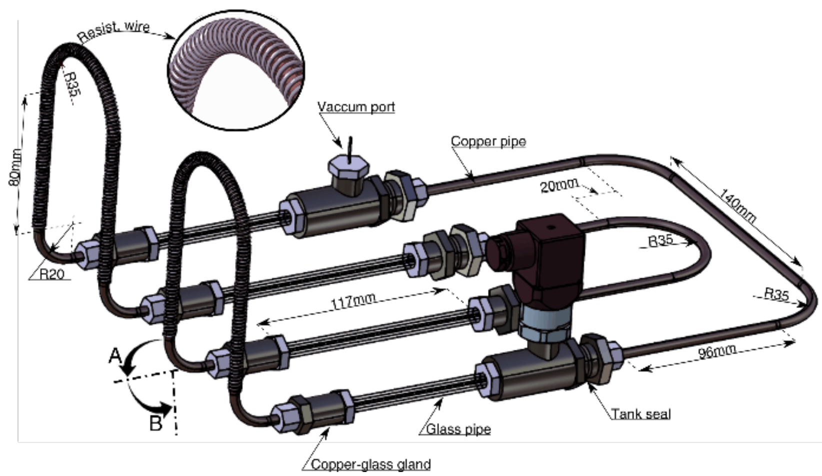

Figure 1 CAD model of tested PHP.

The main part of the experimental setup is a passive heat exchanger as for the standard design of a PHP. The capillaries are made of copper, with an inner diameter of d_{in} = 1.5 mm. The "quasi-adiabatic" section was made of 4 straight parts of the pipe, with a length of AL=145 mm each for visible field for camera and 115 mm long for left/right side arm of PHP. Then the capillaries were connected into a closed loop system by means of high vacuum glands. The bent elements of the device were created using a matrix that maintains the bending radius of each u-shape of 35 mm. The setup allows the position of bent elements to be changed (see: presented on Fig.1: "-B" position, and possible: "A" and "B"). It was successively tested in the direction opposite ("-B") and perpendicular ("A") to the mass force vector. The evaporation section was supplied with thermal energy through a jacketed resistance wire (Mi series Inconel600, 0.89 mm), additionally insulated with a double layer of mineral wool compressed by means of teflon tape, to which a DC power supply with GPIB port was connected. The condensing section was a flow tank made of PETG and connected to an external water supply that cools the entire campus. The inlet water temperature was maintained at 8℃ and the volumetric flow rate was $3.5\frac{l}{min}$. The exchanger was equipped with a port for measuring the pressure and a steel capillary port for seating a valve suitable for a high vacuum system. The individual dimensions of tested PHP are shown in Table 1.

Table 1 The selected operating parameters and geometrical configuration of the PHP.

Geometrical parameters of studied PHP	
PHP material	Copper
Internal diameter, mm	1.5
External diameter, mm	3.5
Number of bends, -	2
Total length, m	2.05
Evap./Cond. sec. length, m	0.54/0.70
Operating parameters	
Working fluid, -	HFE-7000
Heat flux, kW/m^2	25
Filling ratio, %	44 and 66
Acceleration, m/s^2	≤8g
Bent direction, -	A and B

3. Experimental Campaign

The set of planned tests provides for the change of two parameters such as rotational speed (and thus the gravitational field) and filling ratio. Each test envisages obtaining a steady state for the heat transfer process with a gradual change of the indicated parameters as the acceleration in the range from 1g to 8g and the filling ratio change from 44 to 66%.

The measurement campaign was performed on a rotating machine (Large Scale Centrifuge), which allows testing up to 24g (Fig.2c). The tests were carried out based on three main locations of the setup, the first one being a frame, so called swing, with a 10mm thick mounting plate. Here, the experimental setup (Fig.2a) was installed along with the cooling water supply system, the data acquisition system and the working fluid flow imaging system (Phantom Miro eX4 high speed camera and background LED panel). The second location was the center of the rotating device, where a DC power supply along with a control and measurement system, developed based on LabView software (Fig.2b), was placed. The last location is the control room, below the room with the rotating device, from which the test procedure was managed. The presented test results are for an acceleration range of up to 10g due to overpressure in the tank resulting from the machine's rotary motion and the resistances associated with hydrostatic pressure corresponding to the machine arm (approximately 6.5m).

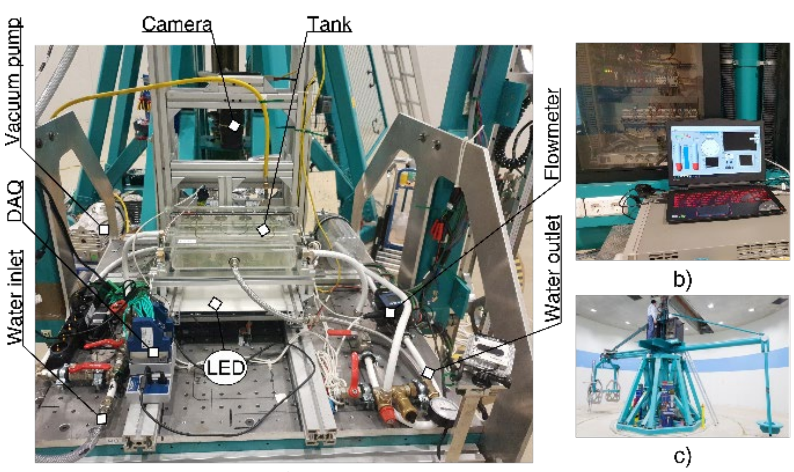

Figure 2 Main view of a)test stand, b) central control platform, c) Large Scale Centrifuge.

3. Summary

The test stand provides the ability to temperature and pressure measurement during the device operation in an axial rotating system. The condensation section could be successfully water cooled during campaign.

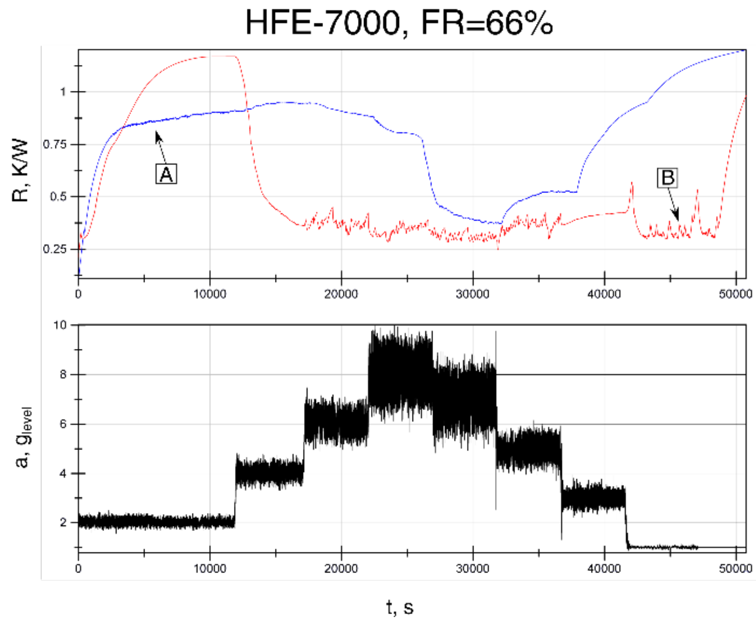

Figure 3 Thermal resistance and acceleration as a multiplication of normal acceleration in the Earth's gravitational field for low boiling point fluid with 66% of filling ratio..

The results confirm that the generated body force, acting along the normal to the axis of PHP adiabatic section, having a value higher than the value of gravity in the Earth's gravitational field, influences on the conditions of the heat exchange process. The tested parameters as filling ratio and bent direction of the evaporation section have a significant impact on the occurring thermal-flow phenomena.

Acknowledgements

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Nomenclature

g, m/s^2	-	Earth gravitational acceleration
$d_{in, mm}$	-	Internal diameter
AL, -	-	Adiabatic section length
DC,-	-	Direct current
FR, %	-	Filling ratio
GPIB,-	-	General purpose interface bus
LED,-	-	Light emitting diode
PETG,-	-	Polyethylene terephthalate glycol
PHP,-	-	Pulsating heat pipe

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