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Research Paper

Development of a pulsating heat pipe with a directional circulation of a working fluid

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HIGHLIGHTS

- A pulsating heat pipe with two types of check valves was experimentally tested.
- Capillary barriers were ineffective as check valves.
- Ball valves allowed to create directional circulation of a working fluid.
- Directional circulation improved heat transfer characteristics of a pulsating heat pipe.

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ABSTRACT

The paper presents the results of development and experimental investigation of a pulsating heat pipe (PHP) with check valves (CV). The PHP was made of a copper capillary tube with an inside diameter of 1.25 mm and curved in the form of a flat spiral with a total of 40 turns. The PHP was joined to an aluminum plate, which served as a thermal interface for contact with the heat-load source and sink. The working fluid was freon R-152a. Tests were conducted to compare the efficiency of two types of CV: one was patterned after a capillary barrier, the other, after a floating ball valve. The tests were carried out in the horizontal mode and the top heat mode. The results of the experiments have shown the high efficiency of ball check valves and the inefficiency of capillary barriers for organizing a directional circulation of a working fluid. It was shown that ball check valves made it possible to organize a directional circulation of a working fluid. At the cost of this the isothermality of the PHP heating zone increases, and its thermal resistance and orientation sensitivity decrease. Besides, the value of the limiting heat load increases by 10–14%.

1. Introduction

Much attention has been given to PHPs, as a new type of heat pipes, since 1990, after the publication of Akachi's patent [1]. The interest of the developers of thermal-control systems in PHPs has not abated up to now owing to their simple design and excellent heat-transfer characteristics.

The process of heat transfer in a PHP is realized in a vapor-liquid/bubble-slug system at the expense of self-maintained chaotic pulsations, which arise if there is a temperature gradient. Such a system of liquid slugs and vapor plugs forms in a partially filled tube/channel of capillary dimensions.

The maximum value of the inside diameter of the tube (D_{cr}) follows from the balance of gravity forces and surface tension and is calculated by the following formula [2]:

$$D_{cr} = 2\sqrt{\sigma/g(\rho_l - \rho_v)}, \qquad (1)$$

where σ is the liquid surface tension, g is the free fall acceleration, ρ_l and ρ_v are the densities of liquid and vapor. In a simple case a PHP is a bundle of a capillary tube curved in the form of a serpentine.

In large part, investigations are connected with the optimization of PHPs in geometrical (pipe length/diameter/shape, number of turns, length of the adiabatic zone) and physical (type and amount of the working fluid, pipe material) parameters. Also, a considerable body of work is aimed at the improvement of the PHP heat-transfer characteristics at the cost of structural designs. Among them one can single out designs that create conditions for a directional circulation of the working fluid. For this purpose,

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either check valves (CVs) of different construction are built into the closed loop of the PHP, or the channels are made with a nonequal geometry of the cross-section. In the first case the circulation is ensured by the diode properties of the CVs, and in the second, by the introduction of additional unbalanced capillary forces.

Experimental investigations of a PHP with three floating-type ball valves and seven turns of a capillary tube with an inside diameter of 2 mm were carried out [3]. The working fluid was R-134a with a filling ratio of about 50%. The lengths of the heating and cooling zones were equal to 50 mm, and the length of the adiabatic zone was 500 mm. It was shown that CVs prevented a premature drying of the heating zone at the cost of delivering liquid there as a result of summation of the amplitudes of several oscillations. Besides, a PHP with CVs was also operable in the top heat mode. Investigations of a PHP with 40 turns and a variable number of ball CVs (0, 2, 5 and 8) were conducted in Ref. [4]. It was shown that the best heat-transfer efficiency was achieved at a number of CVs equal to 2.

Of interest is the use as a CV in a PHP of a Tesla-valve, which has no moving parts and is built into the channel containing the circulating liquid [5,6]. The unique geometry of a Tesla-valve facilitates the circulation of a flow in one direction by creating a larger pressure drop in the opposite direction. PHP channels with Tesla-valves were engraved and sealed up in a flat copper plate. Tests of a PHP with Tesla-valves have shown its higher efficiency in creating a directional circulation as compared to a conventional PHP. In this case the overall thermal resistance reduced by 15–20% depending on the value of the heat load. However, a Tesla-valve is rather complicated in itself, and it is difficult to combine it with a tubular PHP. Its location also requires an additional space, which is not always available.

In Ref. [7] it was shown that the desired flow circulation in a PHP might be achieved by joining adjacent channels. The interconnecting channels were located in the heating and cooling zones and were oriented at a certain angle with respect to the main channels. It was shown that the creation of a one-way flow made it possible to increase the heat transfer in a PHP by 24% at most as compared to a conventional PHP. However, the interconnecting channels had the maximum efficiency only at low and moderate heat-load values and filling ratios of 65%. The question of the geometry and the slope of the interconnecting channels remains topical.

A design that contributes to the flow circulation in a PHP and includes an alternation of channels of different geometry was studied in Refs. [8,9]. In Ref. [8] investigations were made of a flat-plate type PHP with alternating channels of rectangular section measuring 2 × 2 mm and 1 × 2 mm with water as a working fluid. Visual observations have shown that at a certain value of the heat load a pulsating flow becomes directional. In this case channels with larger cross-sections become primarily vapor-removal, and those with smaller cross-sections feeding. In Ref. [9] investigations were made of a PHP with 4 turns of a copper capillary tube, in which nonuniform channels were created by compressing the alternating channels to an oval shape. It has been found that the nonuniform design of a PHP contributes to the decrease in the thermal resistance and the value of the starting heat load. However, all these investigations were conducted only in the bottom heat mode and the horizontal mode, and it is not clear how efficient the PHP nonuniform configuration is for the top heat mode.

In recent years there have appeared a number of papers on the intensification of heat-exchange processes in PHPs by means of external physical fields of different nature: acoustic [10], magnetic [11] and electric [12]. On the whole, the first results of these investigations have shown a positive effect. However, the necessity of an additional expenditure of energy and the complication of the design are the drawbacks of this approach. Besides, it becomes much more difficult to choose working fluids, which must possess some peculiar properties. For instance, in the case of a magnetic field the working fluid must possess ferromagnetic properties [11]. For the interaction with an electric field the determining parameter proves to be the dielectric constant of the working fluid [12].

The practical applicability of one or another solution is determined by its applicability to the concrete conditions of a problem, such as orientation, the geometry of heating and cooling zones, and the means of supply and removal of the heat load. The present paper is part of a project on the creation of a combined heat-transfer system on the basis of a PHP and a loop heat pipe [13]. In this system the PHP is to ensure heat collection from a relatively large surface and concentrate it on the evaporator of the loop heat pipe, which transfers heat to a remote heat sink. A characteristic peculiarity of this PHP is the increased length of the heating zone with an aspect ratio to the length of the cooling zone of about 3. Some special requirements are imposed upon serviceability at different orientations. The aim of the previous investigations was the reduction of the PHP thermal resistance and the extension of the range of heat loads transferred for operation at any position of the device [14].

The aim of the present work was an experimental investigation of the effect of the directional circulation of the working fluid created by a couple of CVs on the PHP heat-transfer characteristics. Besides, it was necessary to evaluate the efficiency of using CVs of two different designs patterned after a capillary barrier and a ball valve.

2. Description of PHP and its modifications

The scheme of a closed-type PHP and its modifications created by inserting a couple of check valves of two different types are given in Fig. 1. The PHP was made of a copper capillary tube curved in the form of two flat spirals with 20 rectilinear sections and 10 turns on each side. Both spirals were brought into coincidence in a plane and joined to an aluminum plate. The ends of the spirals were connected in series with the formation of a closed loop with 20 turns on each side. One of the connecting elements had a branch for the filling tube. The working fluid was freon R-152a. The filling ratio was equal to 40% and was optimum for this PHP without CVs, which we had established in our previous investigations [14]. PHPs with CVs had the same filling ratio for the maintenance of identical experimental conditions. The general constructive parameters of the PHP are presented in Table 1.

The first PHP modification (PHP/CBCV) contained capillary barriers (CBs) which served as check valves. A capillary barrier was formed out of a stainless-steel net in the form of a cartridge with a bottom. In this case the edges of the cartridge were located in the cooling zone, and its bottom was in the adiabatic zone and faced the heating zone. It was assumed that a capillary barrier would prevent the movement of vapor bubbles into the cooling zone of the channel, and their growth would proceed in the opposite direction. Thus conditions for a directional circulation of the working fluid in the neighboring channels would be created.

The second PHP modification (PHP/BCV) was equipped with floating-type ball check valves (BCVs). A valve contained a steel ball whose movement was limited by a saddle of conic shape on one side, and by a limiter on the other.

3. Experimental setup and procedure

The general view of the experimental setup is shown in Fig. 2. The heat load was created by three flat electric heaters with a heating surface of 50 × 200 mm each. The value of the heat load