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Heat transfer in the evaporation zone of aluminum grooved heat pipes

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ABSTRACT

The paper deals with the results of experimental study of heat transfer and visualization of transport processes in the evaporation zone of aluminum heat pipes. Heat pipes had an external diameter equal to 10.0, 12.5, 14.0 and 17.0 mm and a capillary structure shaped as axial grooves of Ω-shaped cross section at their inner surface. Different heat transfer regimes and their emergence as a function of coolant type, geometry of capillary structure shaped as grooves, effective length and heat load level are found. The obtained generalized formulas enable one to calculate heat transfer coefficient in the evaporation zone of ammonia-, acetone- and pentane-fuelled aluminum heat pipes with Ω-shaped longitudinal axial grooves over the range of the heat flux from 0.1 W/cm^2 to 8.0 W/cm^2. The physical model of thermal and hydraulic processes in the evaporation zone of aluminum heat pipes is proposed.

1. Introduction

Heat pipes (HPs) [1] are known as high-performance passive heat transfer devices that allow improving heat transfer characteristics and decreasing the mass and size of thermal control systems of on-board electronic equipment (EE) of spacecrafts. Aluminum heat pipes (AHPs) with a capillary structure shaped as axial grooves at their inner surface have come into common use [2–4]. AHPs are being manufactured by aluminum alloy extrusion [5], allowing one to make a grooved capillary structure (CS) as a whole with a HP body. In this case, geometric sizes of both the CS and the HT body can be widely ranged, allowing one to provide their optimum operation under different conditions. As a rule, AHPs are being made of aluminum alloys of 6060/6063 grades, ammonia is used as coolant; in some cases, acetone, pentane, methane, ethane or propylene may be applied. The design of AHPs provides their high heat transport ability under zero gravity, unlike HPs with powder, net and metal-fiber CSs [1]. AHPs of low mass can be densely packed and to a large extent correspond to the compactness characteristics of modern satellite systems. Moreover, AHPs are often used as a component of solar panels of spacecrafts [6,7] designed for installing on-board equipment or as a heat removal radiator. Solar panels operate both as load-bearing and thermal control systems. AHPs have also found wide use in ground-based resource-saving systems, for example, in solar collectors [8] and lighting LED devices [9,10].

Fig. 1 depicts the types of capillary structure grooves used in AHPs. The triangular groove (Fig. 1, a) is less efficient and is usually made on small-diameter AHPs, when a groove of another shape cannot be made technologically. There are also AHPs with trapezoidal (Fig. 1, b), rectangular (Fig. 1, c), and Ω-shaped grooves (Fig. 1, d). AHPs with such grooves were tested under space conditions and ensured a stable operation of the EE. The analysis revealed that trapezoidal grooves have a smaller hydraulic resistance than rectangular ones (the lower part of a trapezium serves as an artery). Owing to this, larger heat flows may be transferred. On the other hand, rectangular grooves operate steadily in the zone of limiting heat flows due to a constant radius of a meniscus. AHPs with Ω-shaped grooves provide higher heat flows thanks to a cylindrical part of grooves – arteries. But the Ω-shaped CS is characterized by a sudden onset of a crisis (evaporation zone draining) when the meniscus decreases while approaching the limiting heat flows. "Double grooves" are also promising (Fig. 1, e), since they can constantly transfer significant limiting heat flows. This effect is due to the presence of the zone where a groove is separated into two parts. At a low liquid level in the groove corresponding to the range of limiting heat flows, the meniscus radius can decrease, which in turn increases capillary head.

At present, AHPs with trapezoidal and Ω-shaped grooves have found most use in space technology.

Although a large number of firms and institutes are involved in the development and manufacture of space-related aluminum grooved heat pipes (AGHPs), the available literature lacks the generalized relations meant to calculate heat transfer intensity in the evaporation and condensation zones of such HPs. Typically, the publications give data on the maximum heat transport ability,

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Nomenclature

s	groove width (m)
h	groove depth (m)
d	diameter (m)
Q	heat flow (W)
t	temperature (°C)
F	area (m^2)
L	length (m)
q	heat flux (W/cm^2)
n	number
C	coefficient of hydraulic and thermal processes

Greek symbols

α	heat transfer coefficient (W/m^2 K)
Σ	total value
λ	thermal conductivity (W/m K)
σ	liquid surface tension coefficient (N/m^2)
ν	liquid kinematic viscosity coefficient, m^2/s
ρ	vapor density, kg/m^3

Subscripts

eV	evaporation zone
ex	external
g	groove
v	vapor space, vapor
l	liquid
m	material
b	boiling
ef	effective
A	heat transfer regime A
B	heat transfer regime B
C	heat transfer regime C
D	heat transfer regime D

Abbreviations

HP	heat pipe
AGHP	aluminum heat pipes with a capillary structure shaped as axial grooves
AHP	aluminum heat pipes
CS	capillary structure
LA	laboratory autotransformer
EE	electronic equipment
PI	Igor Sikorsky Polytechnic Institute
DHP	Department of Heat and Power

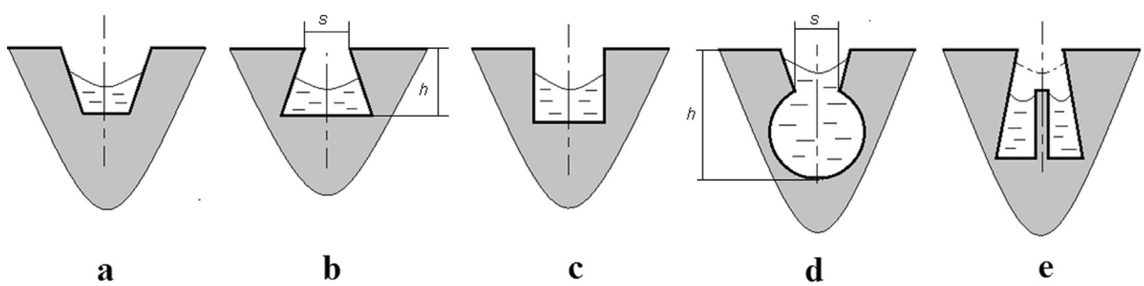

Fig. 1. Types of grooves in AHPs: a – triangular, b – trapezoidal [9,10]; c – rectangular [11,3]; d – Ω-shaped [12,13]; e – "double groove" [14].

temperature fields, thermal resistances, and in very rare cases numerical values of heat transfer intensity in the evaporation and condensation zones [4,15].

It should be noted that the heat transfer intensity in the evaporation zone is one of the most important factors responsible for the thermal resistance of HPs and their temperature field. This is the zone where heat transfer crises occur under certain conditions and actually cause the AGPH operation to cease. The conditions and mechanism of occurrence of crises in the evaporation zone of AGHPs are insufficiently studied.

The urgent character of a detailed analysis of thermal and hydraulic processes in AGHPs is also characterized by the fact that currently, a large number of studies are concentrated on developing mini HPs with CSs in the form of longitudinal axial grooves [16,17], HPs with CSs in the form of grooves [18], and thermal siphons with grooves at the HP inner surface [19,20].

2. Experimental techniques

2.1. Designs and geometric sizes of the investigated AGHPs

AHPs with Ω-shaped grooves, developed and manufactured at the Laboratory of Heat Pipes of the Department of Heat and Power [3,21], were experimentally investigated. In Table 1 and Fig. 2, a–d, the general view and geometric sizes of the cross sections of the studied AGHPs are shown.

The sizes of the cross section of longitudinal grooves of the HP capillary structure are usually based on the choice of the main principle of the HP operation, meaning that capillary pressure should be greater than viscous pressure losses in vapor and liquid flows. For Ω-shaped grooves, to fulfill this requirement is problematic, since their narrowest part connecting the artery with the vapor space provides a maximum capillary head and, at the same time, causes viscous pressure losses to be high in the coolant liquid flow. Therefore, the CS geometric sizes of the investigated AGHPs have been chosen using the analytical and mathematical models [21] based on the analysis of heat and mass transfer processes in such CSs. External diameters and profile shapes have been determined on how much they can be used in space technology. More than 70 AGHPs with different CS configurations (Table 1) and different evaporation and condensation zone lengths have been examined. The AGHP length has been ranged from 400 mm to 3 200 mm, the evaporation zone length – from 30 mm to 750 mm, and the condensation zone length – from 100 mm to 1 200 mm.

2.2. Experimental set-up

The experimental set-up included the systems to measure temperatures, power supply, cooling, and heater power, as well as the arrangements to alter the orientation of AGHPs in the force field.

In experiments on the external surfaces of the investigated AGHPs, the following conditions were made: