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Research Paper

Design and thermal analysis of a segmented single-artery heat pipe

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HIGHLIGHTS

- A single-artery heat pipe using the meniscus coalescence technique was presented.
- The sizing of the venting hole diameter and distance separating holes were explained.
- An arterial heat pipe satisfying the presented sizing criteria was tested.
- The test results obtained at horizontal and adverse elevation were analyzed.

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ABSTRACT

A segmented single-artery heat pipe was studied. The work specifically focused on venting of the noncondensable gas-supported vapor blockage in the liquid artery. The successful operation of the heat pipe requires a careful sizing of the venting holes placed on the fine arterial mesh. The two important design parameters, namely, the venting hole diameter and the distance separating the holes, were analyzed by taking into account the required trade-offs. An arterial heat pipe satisfying the sizing criteria was tested at horizontal and adverse elevations at varying heat loads. The measured heat transfer limit and thermal resistance of the pipe demonstrated effectiveness of the design. The pipe performance continuously degraded at adverse elevations.

1. Introduction

The thermal control of modern spacecraft with increasing power density levels is becoming more challenging. Therefore, there is an increasing demand for high-capacity heat pipes. Heat pipes with an axially grooved cross section (AGHP) have been used as standard thermal control hardware in several spacecraft. Because of the limited heat transfer capability of AGHPs, arterial heat pipes (AHPs) have been extensively investigated since the 1970s. The main idea was the introduction of separate vapor and liquid passages or arteries to minimize viscous losses. These pipes nearly doubled the heat transfer capacity with respect to an AGHP of the same diameter and length. However, many of the AHP developments were later abandoned due to their susceptibility to arterial blockage as a result of noncondensable gas (NCG)-supported vapor bubbles.

Among the early AHP developments, two interesting and representative developments are the Communication Technology Satellite (CTS) and monogroove heat pipes as shown in Fig. 1. The CTS heat pipes had two circular cross-section stainless-steel mesh arteries spot-welded to a felt wick in the middle of the pipe as shown in Fig. 1(a). They were developed to cool the traveling wave tube amplifiers (TWTA) aboard the CTS [1]. The felt wick in the middle provided the liquid flow to the circumferential wall grooves on the inner surface of the pipe from the felt wick. Methanol was used as working fluid. Although ammonia would have been more efficient, it was found to be riskier for arterial deprime because of the ammonia's lower superheat, higher vapor pressure and slope of the vapor-pressure curve (dP_{sat}/dT) [2]. A mixture of 90% nitrogen and 10% helium was used to control the pipe conductance. Helium was introduced for leak detection. As the fine mesh wick forming artery can wet faster than the artery (glazing effect), vapor blockages can easily be formed in the artery, leading to a pipe deprime. To avoid this problem, a separate priming foil proposed in Reference 3 was introduced to take advantage of the meniscus coalescence technique. This technique will be discussed later in detail in the paper. The CTS pipes experienced failures in space. These failures were explained by the formation of small bubbles as a result of the freeze/thaw cycle of the working fluid [4]. In spite of its relative success, this pipe design was not further developed for other missions.

In the monogroove AHP, as shown in Fig. 1(b), the liquid artery consisted of a single axial reentrant groove connected to the vapor space through a narrow longitudinal slot [5]. Circumferential wall grooves were manufactured on the inside wall of the pipe around the vapor space in the evaporator and condenser. The capillary

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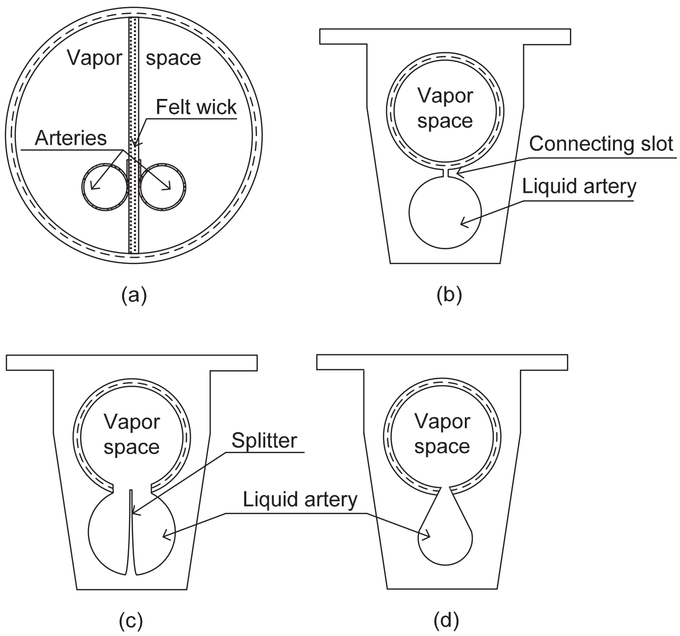

Fig. 1. Cross section of different arterial heat pipes: (a) CTS, (b) monogroove, (c) graded groove, and (d) tapered.

pumping pressure necessary for the pipe operation was provided by the meniscus formed in the narrow connecting slot. Therefore, the monogroove heat pipe had to be charged carefully to ensure that the meniscus remained in the narrow slot. In a later design, a mesh wick was introduced to the evaporator and adiabatic sections to ensure that the circumferential wall grooves were always wetted in the event that an NCG-supported vapor bubble blocked the liquid artery. Another difficulty was the venting of NCG-supported bubbles through this narrow slot [6]. A graded groove arterial heat pipe, as shown in Fig. 1(c), was also developed to prevent the arterial blockage caused failures [7]. In this design, a larger slot with a splitter was introduced between the liquid artery and vapor channel in the evaporator section. The larger channel facilitated the venting of large vapor bubbles, and the splitter reduced the slot width to maintain a relatively high capillary pumping capability.

The tapered AHP, as shown in Fig. 1(d), was mostly based on the monogroove heat pipe design [8]. As the liquid artery was tapered, the NCG-supported bubbles were vented by the meniscus coalescence method. In the event that a vapor bubble was ingested into the liquid artery, the receding meniscus and the growing bubble due to the reduced evaporation from the circumferential wall grooves would coalesce, leading to venting of the bubble to the vapor space. The tapered heat pipe operated successfully in ground but the pipes were not used in a space mission.

A flexible high-performance variable conductance AHP was presented in a more recent work [9]. This pipe was based on the graded single groove design. The pipe included two flexible sections and multiple bends. It was shown that a 1-cm outer diameter pipe had a maximum heat transport limit of 150 Wm and heat flux limit of more than 50 W/cm^2. A summary of other AHP designs can be found in References 10 and 11.

The freeze/thaw cycle of the working fluid is not the only reason for arterial blockage. The inevitable presence of NCG in a heat pipe will promote the formation of bubbles in the liquid artery. NCG may come out of the working fluid if the NCG partial pressure above the arterial liquid is suddenly decreased, for example due to a sudden increase of the heat load. Regardless of the mechanisms, the NCG-supported bubbles in the artery may eventually cause a partial or full arterial blockage as investigated in Reference 12. Without an appropriate design, the AHP will sooner or later experience dryout.

In this work, a segmented single-artery heat pipe proposed in Reference 13 was studied. Further development efforts and some of the thermal performance characteristics can be found in References 14–16. The main objective of this work is to investigate two important design trade-offs in sizing the mesh forming the artery, and specifically the venting hole for meniscus coalescence (hole diameter and distance separating subsequent holes), and to optimize the pipe design to vent an arterial blockage. An AHP manufactured according to these design specifications was experimentally investigated. The heat transfer limit and evaporator thermal resistance were obtained at horizontal and adverse elevations.

2. Design of the venting hole

A cross section of the segmented single-artery heat pipe is shown in Fig. 2. The artery is formed using a stainless steel mesh by contact spot welding. Circumferential screw grooves on the inside wall run along the entire length of the pipe. The circumferential grooves distribute the working fluid from the artery along the circumference of the heat pipe. Thus, they provide a large uniform thin film for more efficient evaporation. As the liquid and vapor flow is separated, the liquid-vapor countercurrent flow does not set off an entrainment limitation as it would be experienced by a more traditional non-arterial heat pipe. The venting holes are carefully placed on a sufficiently thin mesh wick to vent a potential arterial blockage as explained in the next section.

2.1. Calculation of the venting hole size

Fig. 3 shows a longitudinal cross section of the liquid artery along the venting holes with a bubble blockage. For the two menisci on opposite sides of the liquid bridge in a venting hole to coalesce, the sum of depths of both menisci, $(d_i + d_e)$, should be larger than the wick thickness, t, as illustrated in Fig. 3. To vent the arterial blockage, the venting hole diameter needs to be carefully chosen for a given thickness of the mesh wick forming the artery.

Considering that the liquid in the artery and wick, including the liquid bridge plugging the artery should be at the same pressure, the internal meniscus radius, r_i, will be equal to the artery meniscus radius, r_a. From the geometry, the meniscus coalescence condition can then be written as

$$r_e\left[1-\sqrt{1-\frac{D_{vh}^2}{4r_e^2}}\right]+r_a\left[1-\sqrt{1-\frac{D_{vh}^2}{4r_a^2}}\right]\geq t \qquad (1)$$

Solving for (r_e/r_a) will lead to

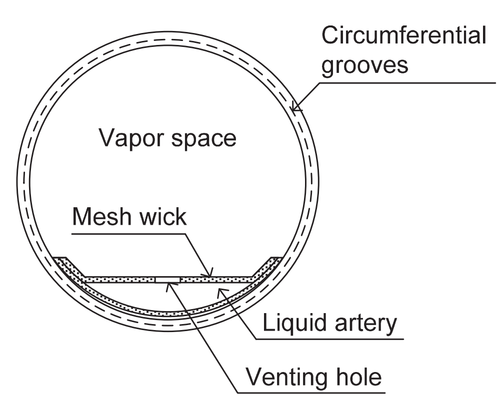

Fig. 2. Cross section of the arterial heat pipe (not-to-scale).