Experimental Thermal and Fluid Science 60 (2015) 290–298

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Dynamic test method to determine the capillary limit of axially grooved heat pipes

Jorge Bertoldo Junior *, Valeri V. Vlassov, Gino Genaro, Ulisses Tadeu Vieira Guedes

INPE – Instituto Nacional de Pesquisas Espaciais, Av. dos Astronautas 1758, Jd. Granja – CEP: 12227 – 010, São José dos Campos, Brazil

ARTICLE INFO

Article history:
Received 7 February 2014
Received in revised form 3 October 2014
Accepted 5 October 2014
Available online 12 October 2014

Keywords:
Dynamic test method
Capillary limit
Axially grooved heat pipe

ABSTRACT

The usual experimental method to detect heat pipe capillary limit under different inclinations includes submitting the pipe to a certain tilt and increasing the heat load at the evaporator zone until a sudden rise in temperature at this region (dry out) is observed. According to this method, for each heat load dwell imposed to the pipe, either the dry out phenomenon is detected or steady state temperature is achieved. The complete test is time consuming and the precision of the heat load detection needed to induce the dry out depends on the power step utilized. In addition, sometimes the dry out is difficult to detect accurately in axially grooved heat pipes due to the fact of the liquid phase is distributed in a non-homogeneous way at the evaporator zone. In fact, the grooves at the top of the heat pipe tend to dry faster. At the lower grooves of the evaporator forms a buildup of working fluid (puddle) due to gravitational effects and thus needing a higher heat flux to cause the drying. The dynamic method proposed in this paper to detect dry out in heat pipes consists in applying a given heat load on the heat pipe, which is initially kept in a horizontal position on a rotary table equipped with motor with reducer gearbox and digital inclinometer. After steady state is reached on the heat pipe, which is leveled horizontally, the table is driven causing the pipe to adverse tilt slowly until the dry out occurs. Once dry out initiates, the axial gravity force component, which is permanently increasing due to table rotation, provokes the liquid phase accelerated retreating from the evaporator, including the puddle liquid excess. It assists the fast overheating onset in the dried zone that in its turn allows a very clear detection of the dry out event by a temperature sensor. The pipe is then placed back in the horizontal position. The proposed test method besides requiring less time to obtain the capillary limit curve, permits to detect in a more precision way the exact time when the dry out occurs. The capillary limits obtained from this method were compared against those obtained from conventional methods for ammonia two-core axially-grooved heat pipe. The results show that dynamic test method can be adopted as an effective alternative to determine capillary limit for axially grooved heat pipes.

1. Introduction

Heat transport capability and thermal stabilization capacity are increasingly required in space applications. Axially grooved heat pipes have been widely used in space applications due to their high efficiency in thermal control satellites, providing temperature homogenization of structural panels in numerous middle and large-scale satellites [1].

Performance tilt test is part of HP qualification process [2] used by HP suppliers; this test may also be used by HP users, as part of incoming inspection. In these tests the capillary limit is detected as a function of the HP adverse tilt (inclination at which the HP evaporator zone is above to the condenser zone). It is desirable that the test procedure be capable of detecting the dry out with high precision and without excessive time consumption.

The conventional method includes investigation of the heat transport limit under different HP inclinations. The basic procedure consists of detecting the heat pipe capillary limit (Q_{max}) by increasing the heat rate input until the temperature at the evaporator zone starts suddenly to increase [2–10].

Conducting such experiments is time/labor consuming and bothersome, since all experimental data must be collected at steady state condition for each heat load dwell and each HP inclination [8]. The result precision obtained for Q_{max} depends on the heat load increase step ΔQ. When a small ΔQ is needed to achieve a desired precision, it causes excessive test time consumption. For the next tilt the process shall be repeated starting from the lowest

* Corresponding author. Tel.: +55 12 3208 6234.
E-mail addresses: jorge.bertoldo@inpe.br (J. Bertoldo Junior), valeri.vlassov@inpe.br (V.V. Vlassov), gino.genaro@inpe.br (G. Genaro), ulisses.guedes@inpe.br (U.T.V. Guedes).

http://dx.doi.org/10.1016/j.expthermflusci.2014.10.002
0894-1777/

power. The time needed to obtain the steady state varies with the size of the heat pipes and with the thermal capacity of the supports and test setup. The higher the HP length and test setup thermal capacities, the longer the time needed to reach the steady state condition.

The ESA HP standard first issue PSS-49 [2] establishes two criteria for the dry out occurrence. The first looks rather a convention: the dry out is assumed when the maximal temperature difference over evaporator zone overpasses 5 °C. The second is related to the linearity behavior of the temperature distribution between evaporator and adiabatic zones as a function of the heat load applied. Thus when linearity is broken, it is assumed that dry out has occurred. Such criteria have drawbacks related to some uncertainty in the exact dry out detection and an extended testing time is needed to achieve the required accuracy. In the ESA extended standard last issue [3] these specific criteria were eliminated (relaxed) in favor of a general statement: "Maximum performance shall be declared when temperature excursions in the evaporator indicate the beginning of a non-nominal operational condition, observed when the maximal temperature difference over evaporator zone overpasses 5 °C. NOTE temperature excursions are characterized by peak temperatures normally caused by dry out conditions". Basically, in order to recognize the occurrence of the dry out based on these criteria, an HP expert interpretation is needed.

Indeed, the dry out instant is not usually precisely detectable underground conditions due to partial dry out phenomenon, observed when temperature at the beginning of the evaporator zone starts to increase, and bottom liquid puddle influence, when the bottom grooves are fed with liquid formed at the bottom of the vapor channel along the HP length. The dryer the upper grooves the more liquid the artery receives.

Several studies have been published to evaluate the whole effect of the liquid puddle phenomenon on the HP performance at 1G testing (ground condition) as a function of the tilt (HP slope). Authors in [1,11–13] have developed numerical methods to identify the portion of dry grooves from temperature measurements of the HP external surfaces. They also confirmed that for axially grooved HP, the upper grooves are more likely to suffer dry out than at the bottom or lateral grooves. The effect is more pronounced for HPs with larger diameters. Moreover, under such circumstances, HP may operate stably in partial dry out condition, so the beginning of the phenomenon is not precisely detectable when only a small portion of the evaporator is dry.

Usually the dry out is determined when the temperature at the beginning of the evaporator zone (i.e. at the hotter HP end) starts to increase at a higher rate. However, some investigators observed that some evidence of partial dry-out is detected first at the middle of the evaporator zone while at the beginning of evaporator the temperature increases very slowly. This particular phenomenon, as explained in [1,11], is related to the capillary effect at the proximity of the HP end cup. Before partial dry out is reached at the middle of the evaporator, liquid is continuously transferred from the flooded bottom part of the pipe to the upper grooves through a technological ring gap at the end of the cup. The presence of this technology gap depends on soldering technology. From one hand, this effect can improve capillary limit especially underground testing, and from other hand, may increase uncertainty on the dry out detection during inclination performance test carried out by the conventional method.

There are many experimental studies focused on determining heat pipe maximum heat transfer limit under adverse tilts [4,5,8]. The evolution of data acquisition software and new high precision inclinometers with digital output make it possible to develop a more effective HP tilt performance test method to determine the capillary limits under adverse tilts.

The proposed method uses a motorized test table, where a very slow and controlled rotation speed can be set. First, the heat pipe shall reach the steady state condition for selected input power at horizontal position. When the motor is switched on, providing slow HP adverse inclination under specified rotation speed. The dry out phenomenon is very evident and its occurrence is well determined when compared with conventional methods. Synchronized temperature data acquisition and angle variation yield the exact moment at which the dry out takes place. It should be pointed out that the data acquisition system should provide precise inclination angle registration, which is time-synchronized with the temperature reading.

The dynamic test proposed in this work lasts much less than conventional ones, because the power steps and multiple steady-state soaks at each angle in order to identify the dry out phenomenon are not necessary anymore.

2. Test set-up

The heat pipe used as test specimen is a two-core aluminum axially grooved heat pipe filled with ammonia. Such an HP profile is used in many space applications for thermal stabilization of structural panels. The HP cross section profile is 19 mm height × 19 mm width, with 730 mm long. Each core has 8 mm effective external diameter and 5.8 mm diameter of vapor channel. The HP profile is extruded from 6063 aluminum alloy, with each core formed by 20 trapezoidal grooves.

The HP is equipped with two skin heaters and two cooling radiators, as shown in Fig. 1.

Heaters are connected electrically in parallel and the cooler is connected hydraulically in series from upper to bottom side of the radiator (Fig. 1). The ethylene–glycol coolant circuit is controlled by thermostat, which provides 3.3 L/min volumetric flow rate. The enter/exit coolant temperature difference at each radiator is 0.48 °C under maximal heat load of 47 W per core. Foam insulation is applied on the heat pipe to minimize parasitic heat losses or gains from ambient.

Fig. 2 shows the HP cross section and thermal couples positioning on the two cores. Liquid puddle that can form during ground test is also shown schematically. Heating of the two cores is provided by electrical skin heaters positioned upper and down along the flat surface of the HP at evaporator zone. At the other end of the pipe, cooling is provided by two reservoirs interconnected to each other and filled with cooler fluid. Evaporator zone is 207 mm long (L_e) and condenser zone is 180 mm long (L_c).

The heat pipe is fixed on a motorized-rotational table and precisely leveled in an horizontal position on the table's surface, (Fig. 3). The pipe is fixed to the table by two rigid insulation supports made of phenolic textolite.

The motorized-rotational table is built in extruded aluminum profile and equipped with a DC motor–reduction gearbox. An electronic controller provides adjustable rotational velocities with a minimum magnitude of 0.2 deg/min.

The test setup instrumentation includes an Agilent Data Acquisition System 34970A; 19 T-type AWG-30 thermocouples within 0.3 °C precision and 0.1 °C resolution; a DC stabilized power supply of 500 mV ± 0.001% output voltage; two skin heaters MINCO HK5285 R3.3L12E, 10% resistance tolerance, and one thermostat Nova Ética to control bath temperature within 1 °C precision and 0.1 °C resolution. Angle is monitored by a Mitutoyo PRO3600 inclinometer and acquired by the Data Acquisition System with specified precision of 0.05° and sensitivity of 0.01°. The data acquisition rate is 2 s for both temperature and table tilt.

The experimental setup is shown schematically in Fig. 4.