16th International Heat Pipe Conference (16th IHPC)
Lyon, France, May 20-24, 2012

Experimental performance comparison of axially grooved heat pipes charged with acetone and ammonia

Jorge Bertoldo Junior, Valeri V. Vlassov, Pedro Antônio Cândido, Gino Genaro
Instituto Nacional de Pesquisas Espaciais – INPE,
São José dos Campos – SP, Brasil.
jorge.bertoldo@inpe.br

Valery M. Kiseev
Ural State University - USU
Ekaterinburg, Russia

ABSTRACT

To validate proposed axially grooved heat pipe, designed to work with acetone, comparative characterization tests have been conducted for two heat pipes, having the same profile height of 19.1 mm, and length of 730 mm. First heat pipe is charged with acetone and has unique core however the second heat pipe, charged with ammonia, has two cores. Both heat pipes are directed to Space application and have profiles with similar flat interfaces to fit inserting in honeycomb satellite panels. Two different characterization tests were performed. First, an inclination test conducted by means of a motorized table; second, a dry-out test in horizontal position at different temperatures. The characteristic curves were obtained for both HP profiles under symmetrical heating/cooling

KEY WORDS *:heat pipe, thermal stabilization of satellite panels, HP performance test, ammonia, acetone.*

1. INTRODUCTION

Historically, when heat pipes (HPs) first were recognized in 1960's as promising devices for thermal control in space applications, aluminum HPs with different fluids began to be developed and tested. The fluids were mainly freons, ammonia, methanol, and propylene. Soon after the aluminum-ammonia HP demonstrated best heat transport capability, which allowed the producing of light HPs with very small diameter (about 10 - 20 mm); the technology was space-qualified and other technologies were restricted for special applications. Traditionally, aluminum-ammonia HPs are used in thermal control systems, because ammonia has appropriate temperature range and high Liquid Transport Factor.

There are two main kinds of heat pipe aplications in satellites: (i) for tranferring heat to radiator over large distances from areas where are equipment with high heat dissipation or; (ii) for spreading heat over a structural panel to minimaze the thermal gradients over it and finally reduce the equipment temperature. In many cases where HPs are embedding in honeycomb panels, larger diameter tubes are quite desirable because they can provide higher area of thermal contact with the panel face-sheet and fits the panel thickness.

In such applications the acetone heat pipes can comepetite with ammonia HPs; their lack of performance can be compensated by a particular design, as increasing the cross section area of the tube. Also, other criteria may be adopted on working fluid choice, in terms of vapor pressure, toxicity and dangerousness.

As quoted by Nakamuro et al, 1984, amonnia heat pipe need to have a wall thickness high enough to endure the vapour pressure at temperature of ~120oC which is the imbedding process temperature to cure adhesive. Acetone heat pipe would not have this problem because the pressure inside the tube don’t offer explosion risks during imbedding process.

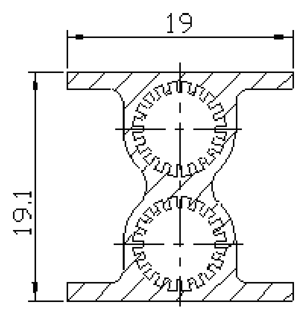

Figure 1.a) Ammonia Heat Pipe Profile

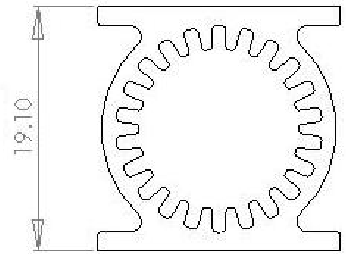

Figure 1.b) Acetone Heat Pipe Profile

Acetone-copper heat pipes already have been used in thermal control of the Mageon 4 and 5 satellites, which was in operation for more than 4 years (Baturkin et al, 2002); flat aluminium-acetone mini HPs are produced to cool electronics for domestic and industrial applications. Al-acetone groove HPs have never designed no produced and qualified for Space applications up to now, as we can monitor through available publications.

In order to exploit the advantages and disadvantages of heat pipes charged with low-pressure fluids, INPE adopted a research program CONTER (when PJHPACETONA), which includes the development of two phases technologies employing low-pressure and low hazardous working fluids (Vlassov, 2008).

Finally, a HP axially groove profile was designed and optimized to have the acetone as a working fluid and to fit the honeycomb satellite panels of 20 mm thickness, see Fig. 1b. This profile is suitable for a low-pressure fluids and is a less dangerous alternative of ammonia HPs (Fig. 1a) used in CBERS series satellites.

2. EXPERIMENTAL SETUP

The HP thermal performances are investigated using the classical test setup, presented in the Fig. 2.

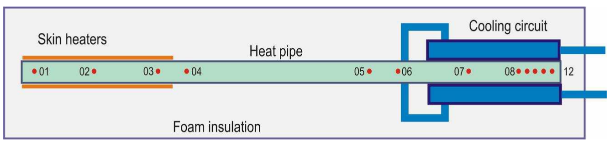

Figure 2. Heat Pipe test setup

The heat pipe is held with a supporting insulation fixture. Heat is applied to one end symmetrically from above and from below of heat pipe with a skin eletrical heater and is removed from the oposite end by a coolant circuit controlled by thermostat. Thermocouples are attached along the lenght of the heat pipe to measure the axial vapour temperature along the heat pipe at different positions, see Figure 2. An insulation system is used over the heat pipe to minimaze the parasitic heat losses or inputs, see Figure 3 (Brennan P. & Kroliczek, E., 1979).

The heat pipe is fixed firmly through insulation supports on structure of a motorized table (see Figure 3). Motorized test table can rotate in very slow angular velocity, 3.40 deg./min. Inclination angle is measured by a digital inclinometer, within 0.1 degree accuracy. Performace tests is conduceted under different inclination angles and cooling liquid temperatures -20oC, 0oC and 20oC,

During preliminary tests, two types of dry-out were detected, like was purposed by Busse and Kemme, 1979, analysing the physical mecanism of the dry out in gravity assist heat pipes. There are two different types of dry out; first is when power is set at a fixed value and the motorized test table is rotated in very slow angular velocity, until the dry-out phenomenon occurs. This dry-out is characterized as complete, once the condenser temperature gets fast drop down following the fast rising up at evaporator end. Second type is when HP is set at horizontal position and power is gradually increased. In this case the dry-out is partial, which is detected following the PSS-49 standard criteria, where was take in consideration that partial dry out phenomena occurs when the difference between two consecutive points of the evaporator is at least five degrees.

Figure 3. Both heat pipes installed on rotation table

The heat transport characteristics, including maximum heat transfer capability and conductance, are determined through the measuring temperature distribution along both heat pipes under same heat load conditions.

We believe that the 1st type of dry-out (fixed power and increasing angle) corresponds the dry-out mechanism that could take place under microgravity (0-G) condition, when the Marangony effect does the same work as the dynamic liquid moving, driven by slow test table rotation, which provokes a complete drying of the evaporation area. Busse & Kemme, 1979, proposed this way of dry-out conditions, keeping heat flux, temperature and all other design and operating parameters.

The 2nd mechanism, of partial dry-out, may only take place under 1-G condition, when the gravity effect on the excess liquid pool contributes to the liquid return. This phenomenon arises from a lack of hydrostatic driving force in grooves and appears when the heat flux increases (Busse & Kemme, 1979).

3. SIMPLIFIED ANALYTICAL MODEL FOR PERFORMANCE EVALUATION

We developed a simplified analytical model to predict basic HP performance, used well-known relationships for axially grooved HPs, presented in (Chi and (Faghri, 1995). The basic system of equations, used to compare with experimental data, is presented below.
Under maximal heat load, the capillary pressure must sustain hydraulic lost of liquid flow in grooves and vapor flow in HP core, as well as hydrostatic tilting component because of possible HP inclination. The capillary balance is expressed by

$$\Delta P_c^{\max} = \Delta P_l + \Delta P_v \pm \Delta P_g \qquad (1)$$

Other components of pressure balance like interfacial shear pressure drop are neglected. Assuming the Darcy flow and conception of effective HP length to account variable mass flow rate in evaporator and condenser zones, the balance can be expressed as following

$$\frac{2\sigma Cos\theta}{w} = \frac{\mu_l Q_{\max} L_{eff}}{K\lambda\varepsilon\delta_p \pi D_v \rho_l} + \frac{128\mu_v Q_{\max} L_{eff}}{\lambda\pi D_v^4 \rho_v} \pm \rho_l g L Sin\beta \quad (2)$$

The simplified geometry presented in Fig. 4 was adopted.

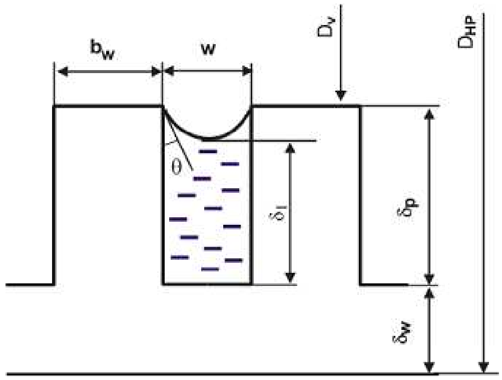

Figure 4. HP cross section parameters.

Permeability is expressed by

$$K = \frac{d_{hg}^2}{2(f\,\mathrm{Re})} \qquad (2)$$

Shah and Bhatti in 1987 have found that for the rectangular channels

$$(f\,\mathrm{Re})_l = 24(1 - 1.3553a + 1.9467a^2 - 1.7012a^3 + 0.9564a^4 - 0.2537a^5) \qquad (3)$$

This equation is applicable to the configuration shown in Figure 4 (Faghri, 1995).

The equation components are:

$$a = \frac{w}{\delta_p}; \quad \varepsilon = \frac{w}{w + b_w}; \quad \delta_l \cong \delta_p - \frac{w}{2};$$

$$L_{eff} = \frac{1}{2}(L_e + L_c) + L_a;$$

The groove hydraulic diameter expression is modified to account the average meniscus recession under maximal heat load:

$$d_{hg} = \frac{4\delta_l w}{(2\delta_p + w)} \qquad (4)$$

Finally we have the expression for maximal heat transport capability:

$$(QL) = Q_{\max} L_{eff} = \frac{2\sigma Cos\theta \mp w\rho_l g L Sin\beta}{w\left(\dfrac{\mu_l}{K\lambda\varepsilon\delta_p \pi D_v \rho_l} + \dfrac{128\mu_v}{\lambda\pi D_v^4 \rho_v}\right)} \qquad (5)$$

This expression is used to compare with experimental data for both acetone and ammonia

HP; the last is factored by 2 in order to account two-core performance.

4.RESULTS

Fig 5 and 6 show the axial temperature distribution along the length for both HPs analysed, ammonia and acetone, at horizontal HP position and under different heat loads. It is possible to observe, that acetone HP presents elevated temperature differences between evaporator wall and vapor temperature and between vapor temperature and condenser zone. At the same time the temperature differences along the adiabatic sections are very small.

It can explained by the following. Because of relatively wide grooves of acetone HP profile, the liquid phase does not fill all upper grooves, which provokes the liquid pool at the bottom of HP of significant volume. Such phase redistribution forms additional thermal resistances from both sides: liquid pool from the bottom and empty grooves from the above. Finally, this phenomena makes the temperature differences between evaporator and condenser sections to be significantly higher than for ammonia HP.

The heat pipe performance curve, that is the relation of average temperature difference between the evaporator and condensor zone to the maximal heat transport capability (QL), are presented in Figs. 7 and 8 for tests in horizontal position. The maximum heat transfer rate Q_{max} is defined as the heat load when dry- occurs. The maximum heat transfer capability (QL) is defined as the product of Q_{max} and L_{eff}, L_{eff} is the effective length of the heat pipe (Nakamaru et al, 1984).

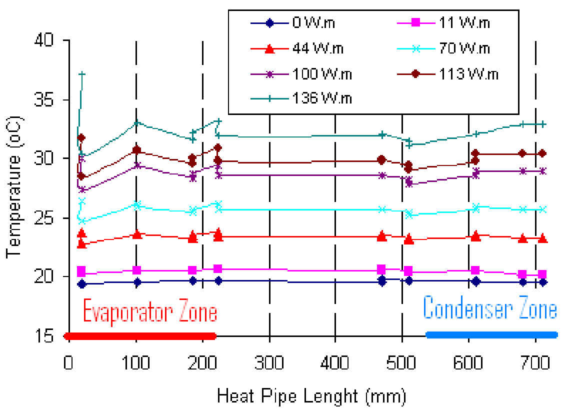

Figure 5. Temperature distribution along the ammonia heat pipe lenght.

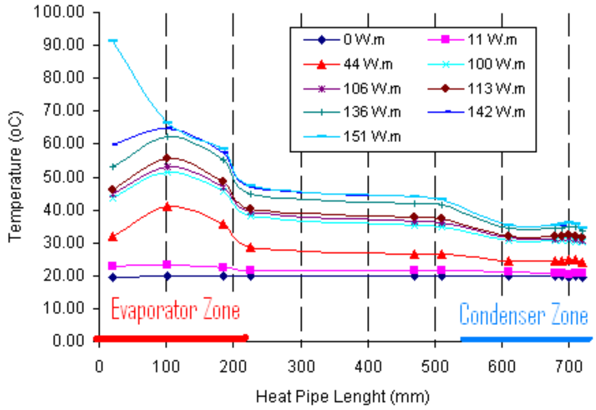

Figure 6. Temperature distribution along the acetone heat pipe lenght.

Predicting the maximum heat transfer capability under 0-G condition would be possible by a measurement of (QL) under different inclination angles. It is generally conducted for reason of the theoretical linear relation between the maximum heat transfer capability and the inclination of the heat pipe (Brennan P. & Kroliczek, E., 1979) (Nakamaro et al, 1984)..

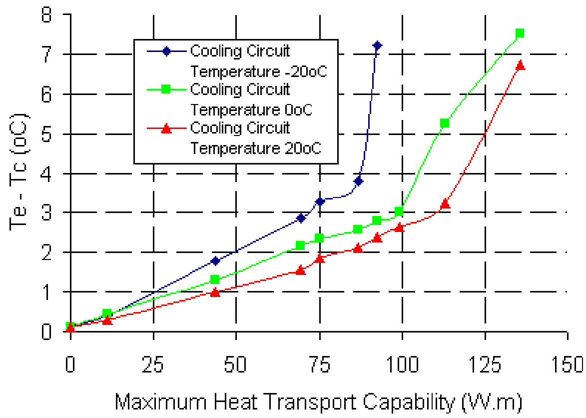

Figure 7. Ammonia Heat Pipe performance curve

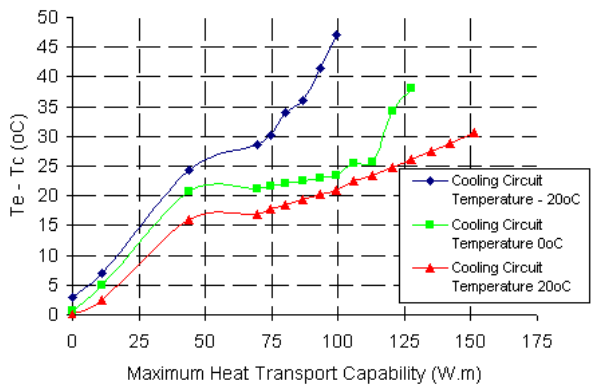

Figure 8. Acetone Heat Pipe performance curve

The characteristics curves of the inclination test are presented in Figs 9 and 10 under different vapor temperatures. The tendency performs as expected: ammonia HP is less sensitive to inclination, then acetone HP. Acetone HP becomes still more sensitive to inclination under lower temperatures. .

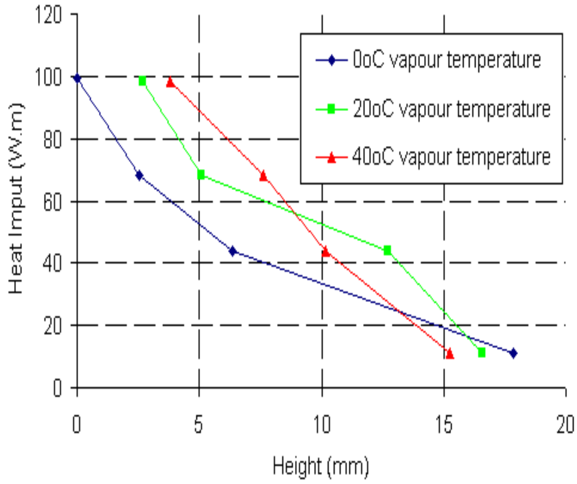

Figure 9. Ammonia Heat Pipe Inclination Test

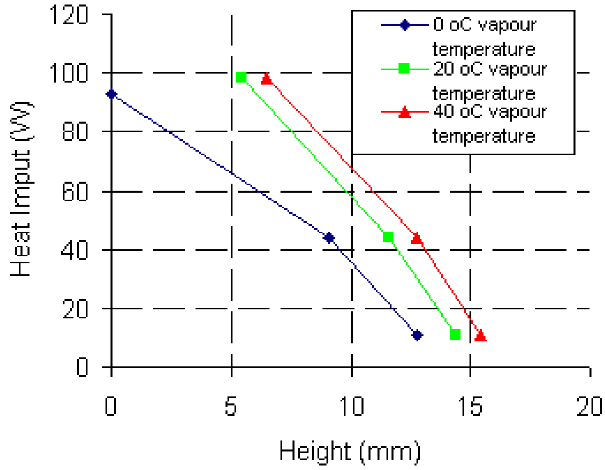

Figure 10. Acetone Heat Pipe Inclination Test

Next, the maximum heat transfer capability is taken up as function of vapor temperature. In figure 11 it is possible to see the theorectical and experimental results for both HPs. Obtained magnitudes of maximal heat transport capability (QL) are similar within about ±30% for both HPs, having acetone HP QL better values under higher temperatures (above +30C) and vise-versa in lower temperatures

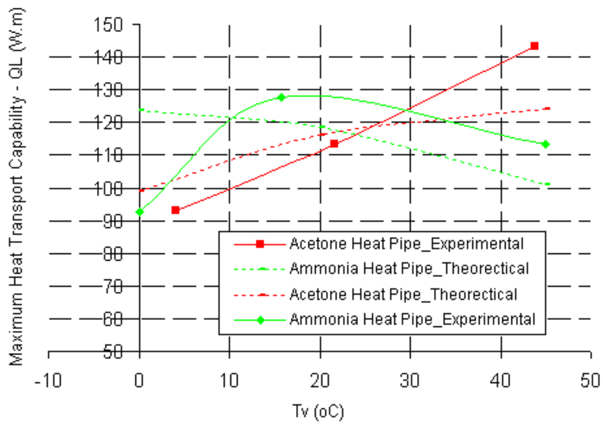

Figure 11. Comparison between theorectical and experimental maximum heat transport capability

In case of axial grooved heat pipes, in higher temperature ranges, the execess of liquid of the working fluid forms liquid puddle at lowest point of the heat pipe because of the variation of liquid density and non connection between groove. Probably not all upper groves are filled with liquid, that contributes to the volume of the puddle. The bottom grooves, which are partially submerged, shows a reduction in their effective transport length and the actual effective elevation increases the maximum heat transfer capability (Nakamaru, et al, 1984). This situation partly explains the observed discrepancies between the theorectical and experimental results.

5. CONCLUSIONS

The conducted tests confirm that two-cores ammonia HPs can be substituted with one-core acetone HP for the application in honeycoms satellite panels of specified thickness of 20 mm.
Obtained magnitudes of maximal heat transport capability (QL) are similar within about 30% for both HPs, having ccetone HP QL better values under higher temperatures (above 30C) and vise-versa in lower temperatures, that is expected through fluid properties.

At the same time, acetone HPs presents additional difficulties for testing in 1G conditions as well as to interpret the test results. Because of relatively wide grooves, the liquid phase does not fill all upper grooves, which provokes the liquid pool at the bottom of HP of significant volume. Such phase redistribution forms additional thermal resistances that make the temperature differences between evaporator and condenser sections to be significantly higher than for ammonia HPs. In inclination test the Acetone HP presents more sensitivity to tilting that establishes more exigent requirement for leveling when testing at 1G conditions.

Anyway, in 0G conditions it is expected all grooves of acetone HP being filled with liquid, and these thermal resistances do not appear.

NOMENCLATURE

σ – surface tension
μ - dynamic viscosity
ρ - density
λ -latent heat
ε - porosity
β - inclination angle
δ - thickness
θ - contact angle

ACKNOWLEDGEMENT

Authors would like to acknowledge the support of CNPq organization, Brasil, through Research Project 560092/2010-5, Edital MCT/CNPq/AEB 33/2010.

REFERENCES

Baturkin, V., Zhuk, S., Vojta, J., Lura, F., Biering, B., Lötzke, H – G (2003) *Elaboration of thermal control systems on heat pipes for microsatellites Magion 4, 5 and BIRD.* Applied Thermal Engineering 23, p.1109–1117.
Brennan, P., Kroliczek, E. (1979) *Heat Pipe Design Handbook.* B&K Engineering, Inc., Contract No NAS5-23406, June 1979.
Busse, C. A., Kemme, J. E. (1980) *Dry-Out Phenomena in Gravity – Assist Heat Pipes with Capillary Flow.* International Journal of Heat Mass and Transfer, 23, p. 643 – 654.
Chi, S. W. (1976) *Heat pipe theory and practice*, McGraw-Hill Book Company, London.
Faghri, A. (1995) *Heat pipe science and technology.* Taylor & Francis, London
Fleischman, G. L., Chiang, T. C., Ruff, R.D. (1991) *Oxigen Heat Pipe 0 – G Performance Evaluation Based on 1 – G Tests.* AIAA 26th Thermophysics Conference, Honolulu.
Hoa, C., Demolder, B., Alexandre, A. (2003) *Roadmap for developing heat pipes for ALCATEL SPACE's satellites.* Applied Thermal Engineering 23, p. 1099–1108.
Nakamaru, K., Kanamori, Y., Kimura, H., Masumoto, H., Ogushi, T. (1984) *Development of Fixed Conductance Heat Pipe for Spacecraft Application.* 5th International Heat Pipe Conference, Tsukuba, p. 465 – 472.
Qualification requirements to heat pipes (1983) *ESA PSS-49 (TST-01).* Issue 2.
Shah, R.K., Bhatti, M.S. (1987) *Laminar Convective Heat Transfer in Ducts*, in: S. Kakac, R.K. Shah, W. Aung (Eds.), Handbook of Single-Phase Convective Heat Transfer, Wiley, New York, Chapter 3, pp. 3.1–137.
Vlassov, V. V. (2008) *Analysis of Heat Spreading Performance of Acetone-Filled Heat Pipe at Low Temperatures for using in Satellite Honeycomb Panels.* Journal of Aerospace Engineering, Sciences and Applications, 1, p. 1 – 17.