Regulative Characteristics of Methanol – Copper Heat Pipes for Asteroid Lander “MASCOT”

Volodymyr Baturkin[1], Vitali Feidelheimer[2], Kaname Sasaki[1], Eugen Mikulz[1] and Tra-Mi Ho[1]

[1]*DLR – Institute of space systems, Bremen, 28359, Germany*
[2]*FH Aachen – University of Applied Sciences, Aachen, 52064, Germany*

Abstract

Variable conductance heat pipes (VCHPs) are the main part of MASCOT (Mobile Asteroid surface SCOuT) lander passive thermal control system (TCS). They provide variable conductivity by utilizing the physical heat transfer limitations. This allows the heat pipes to act as thermal switches without additional constructive elements. The advantage is the simplicity and compactness of a conventional heat pipe design. Two cylindrical copper-methanol heat pipes with shell length 0.482 m and 0.438 m and external diameter of 0.006 m, having copper discrete metal fiber wick and copper shell were constructed and verified in the temperature range −75…+60 °C. The purpose is to apply this design into the MASCOT project and to investigate their regulative characteristics and longitudinal physical heat transfer limitations. VCHPs show a change of thermal resistance from 70 K/W, at a sink temperature of −60 °C, to 0.8 K/W at a sink temperature of +60 °C; with an obtained maximal heat transfer rates of 5 W and 16 W, respectively. It is found, that the switching effect of the heat pipes is governed by the sonic velocity limitation, the saturation vapor pressure of the working fluid and the maximal capillary pressure of the fibrous capillary structure.

Keywords: Heat pipes; Copper-Methanol; Metal fiber wick; Heat transfer limitations; Variable conductance.

VCHPs are used as thermal control devices on the MASCOT lander. This lander (300 × 300 × 200 mm³, mass 10 kg) was jointly developed by the German Aerospace Centre (DLR) and the Centre National d'Etudes Spatiales (CNES) to investigate the asteroid (162173) Ryugu. It is equipped with a sensor suite with four scientific instruments to examine the surface structure, composition and physical properties including its thermal behavior and magnetization of asteroid. It is capable to lift itself over asteroid surface to dislocate for further measurements.

The lander is affixed to the main spacecraft Hayabusa-2 built by the Japan Aerospace Exploration Agency (JAXA). It is since December 2014 on its way to the asteroid Ryugu, reaching it in July 2018. During the mission phases, Mascot is facing contrary requirements to the thermal control system. In the cruise phase, the radiator is exposed into the deep space where the VCHPs should limit the heat exchange from inner electronics into space. On the asteroid, the hot phase begins, the Lander must get rid of the internally generated heat. For this purpose, two VCHPs were developed by the Heat Pipe Laboratory of the National Technical University of Ukraine “Kyiv Polytechnic Institute” and tested intensively as a heat transfer unit and as a flight hardware for MASCOT mission at the DLR Institute of Space Systems in Bremen/Germany [1].

The variable conductance of Mascot’s heat pipes is achieved due to decrease of longitudinal heat transfer intensity, appeared in VCHPs at low heat sink temperature -70…0 °C. Three main factors are identified as the cause. The first limitation is the sonic limit of vapor. It is identified by a CFD analysis of the vapor flow. Choked condition is approached at the end of the adiabatic section. At heat sink temperatures below −60 °C, sonic velocity is reached at temperature about −42 °C in the evaporator.

The second heat transfer limitation is connected with values of maximal capillary pressure $\Delta p_{cap,max}$ and saturation pressure in vapour p_{sat}. For the case, when $\Delta p_{cap,max} > p_{sat}$ in the evaporator, the heat transfer is defined by the saturation pressure, for $\Delta p_{cap,max} < p_{sat}$ - by the capillary pressure drop. The first point of transition is found by the condition $\Delta p_{cap,max} = p_{sat}$. For the investigated heat pipes, it is calculated to be at −27 °C ± 2 °C in the beginning of the evaporator.

The third limitation relates to the classical hydrodynamic limitation: the sum of the liquid (Δp_l) and vapor (Δp_v) pressure drop must be lower than the maximal capillary pressure drop ($\Delta p_{cap,max} \geq \Delta p_l + \Delta p_v$). Limitation of maximal transferred heat power Q_{max} is calculated by [2]:

$$Q_{\max} = \frac{\Delta p \cdot h_{fg}}{(\nu_l / (A_w K_w) + 8\nu_v / (\pi r_v^4)) L_{eff}}, \qquad (1)$$

whereby ν_l, ν_v - kinematic viscosities; h_{fg} - latent heat of vaporization; A_w, K_w - wick cross section and permeability; r_v - vapor core radius; and L_{eff} - effective heat pipe length.

The pressure difference Δp in Eqn. (1) is the maximal capillary pressure in case of temperatures above the second transition point or the maximal saturation pressure below this point.

To identify the transition temperatures two tests are conducted with two different shapes of heat pipes, having 2D geometry (four and five bends with radii 0.015 m in the same plane, L_{eff} = 0.37 m and 0.347 m): (1) startup tests with a stepwise heat input and a constant sink temperature; (2) thermal cycling tests with a constant heat input and a stepwise variable sink temperature. They are carried out in a vacuum with a pressure below 1×10^{-6} mbar. Sink temperature (mounting plate, used as basis for HP set up) are regulated with a running-liquid cryostat Huber 385. A measurement system YOKOGAWA DC100 and twelve custom-made PT100 sensors with constantan wires records the temperature along the heat pipe shell. Power supply (HAMEG HP4040) is remote controlled with LabVIEW for powering of heaters and recording of voltage, current and power values.

The first transition temperature at −27 °C is confirmed by startup tests. The sink is kept at a constant temperature (−75 °C, −70 °C, −60 °C and −40 °C) while the heat input at the evaporator is 1 W, 5 W and 10 W in each test run with a uniform initial temperature profile. Reaching the first transition point T_{tr}, the heat pipe begins to change its temperature distribution (Fig. 1).

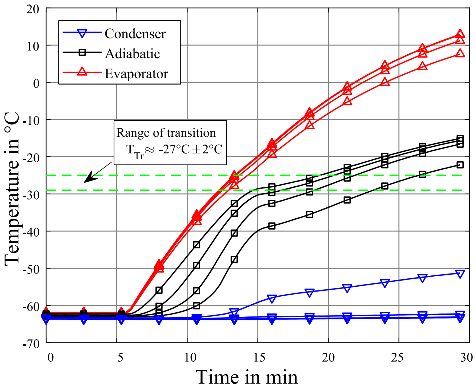

Fig. 1. Startup test with step heat input of 5 W at time =6 min and a constant sink temperature of −60 °C.

Below this point, the temperature change in the adiabatic section is nearly linear, and it becomes uniform, reaching the capillary limit. After this point, a dry-out in the evaporator happens, increasing the temperature in the evaporator further. The transition point temperature saves the value −27 °C±2 °C at heat sink temperature −75….−40 °C and the applied heat 5...10 W. As soon as the evaporator reaches the first transition point, the temperature distribution changes along the heat pipe. The temperature profile is not affected by the sonic limit during the startup of VCHPs. This transition point is validated by a test with an inclined gravity assisted heat pipe where the maximal allowable capillary pressure drop is higher and condition $\Delta p_{cap,max} = p_{sat}$ is reached at higher T_{tr}.

To find the second transition point, the sink temperature is changed stepwise from 60 to −60 and to 60 °C at a constant heat input of 1 W, 5 W and 10 W. In additional cycling tests the sink temperature changes 20→−40→20°C; 20→−10→20°C. The temperature profile during the thermal cycling test is shown in Fig. 2. Approaching the capillary limitation, the heat pipe switches from isothermal temperature profile into profile with a large temperature difference between the evaporator and the condenser. A dry-out of the evaporator is indicated by the rise of its temperature at about 100 min. First, the heat pipes encounter the capillary limitation and then the sonic limit. The approached sonic limitation is identified by a constant temperature at the end of the adiabatic section. It is not affected by the further temperature change in the condenser. In the cycling test 20→−40→20°C with a heat input of 5 W, the heat pipe shows that the switching point occurs at the same sink temperature. The heat pipes repeated their resistance values after being in essential overheating of the evaporator above the condenser, reaching 110 °C, that is important for practical application.

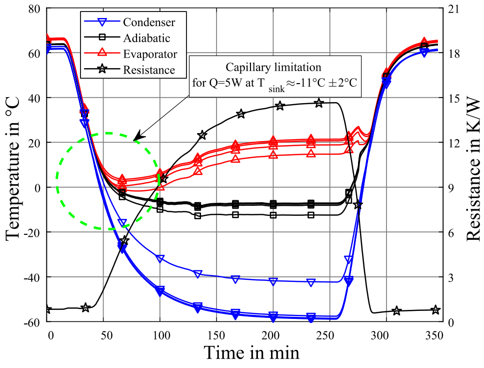

Fig. 2 Thermal cycle at constant 5 W heat input from 60 °C to −60 °C and back after steady state.

Longitudinal variable conductance of methanol heat pipes with cooper fibrous capillary structures is achieved by using the physical limitations in inner heat transfer. VCHPs having the simple geometry of a conventional heat pipe, have demonstrated an essential variation of thermal resistance in range of two orders, operating inside wide heat sink temperature −70 …+60 °C, with input heat values from 0.25 W to 10 W. Inner heat transfer change prevents MASCOT electronics from overcooling below the survival temperature at low power generation and radiator temperatures −70…−20 °C. This was confirmed in thermal vacuum tests on unit and system levels and in MASCOT flight operation in 2014 − 2017.

REFERENCES

[1] Kravets, V.; Alekseik, Ye.; Alekseik, O. et al. (2017): „Heat pipes with variable thermal conductance property for space applications“. DOI: 10.1007/s12206-017-0503-8.

[2] Faghri, Amir (1995): *Heat pipe science and technology*. Washington [etc.]: Taylor & Francis.