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Temperature oscillation of loop heat pipe for AMS cryocooler

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Abstract

Temperature oscillation characteristics of loop heat pipes (LHPs) for alpha magnetic spectrometer (AMS) cryocoolers during thermal vacuum and thermal balance (TVTB) testing were determined. Temperature oscillation only occurred for only one of eight LHPs. Temperature oscillations normally occurred at high sink temperature and/or heat load. Inclusion of a bypass valve was an effective measure to suppress temperature oscillations, because vapor at the condenser was not saturated when the bypass valve was open.

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Keywords: Loop heat pipe; bypass valve; temperature; alpha magnetic spectrometer

1. Introduction

The alpha magnetic spectrometer (AMS) is one of the greatest scientific projects, with the main aim of searching for dark matter and anti-matter [1]. AMS uses four Stirling cryocoolers (CC) to extract parasitic heat from the shield around the helium-cooled magnet. Loop heat pipes (LHPs), with propylene as the working fluid, transfer heat from the cryocoolers. Each cryocooler has two redundant LHPs, a left and a right LHP, and the heat dissipates from the LHPs to deep space through condensers integrated with the dedicated zenith radiator (Fig. 1). Each LHP consists of an evaporator connected to the cryocooler, a compensation chamber, liquid line, vapor line, bypass valve, bypass line, and a condenser (Fig. 2). LHPs with bypass valves work to ensure the cryocooler performs normally within its temperature limits: [-20 ^{o}C, +40 ^{o}C] [2, 3].

Wang et al. [2] studied the bypass valve characteristics of LHPs experimentally, while Xin et al. [3] built a model of LHPs for AMS cryocoolers with SINDA/FLUENT. The LHP operating temperature is dependent on the load and the sink temperature. As the operating conditions change, the evaporator

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temperature will change during the transient phase and reach a new steady state. However, under certain conditions, the LHP never really reaches a steady state, but instead displays oscillatory behavior [4-9]. Three types of temperature oscillation have been reported [4,5]. The first type is ultra-high frequency temperature oscillations lasting seconds, caused by formation of liquid slugs in the condenser or the vapor line. This type of temperature oscillation is not significant due to the very low oscillation amplitude. The second type is high frequency temperature oscillations lasting seconds to minutes, caused by the inability of the vapor front to find a stable position about the condenser exit. The amplitude of temperature oscillations in the liquid line can be higher than 10K, whereas the amplitude in the evaporator is very small, of the order 1K or less. The third type is low frequency temperature oscillations lasting hours, which may appear with specific conditions such as large evaporator thermal mass, low heat load and cold sink temperature. The amplitude can be as high as tens of K. To date, however, there is a lack of knowledge of temperature oscillation behavior of LHP with a bypass valve. This study investigated the oscillation characteristics of LHPs for AMS cryocoolers during thermal vacuum and thermal balance (TVTB) testing in the Large Space Simulator (LSS) at the European Space Research and Technology Centre (ESTEC).

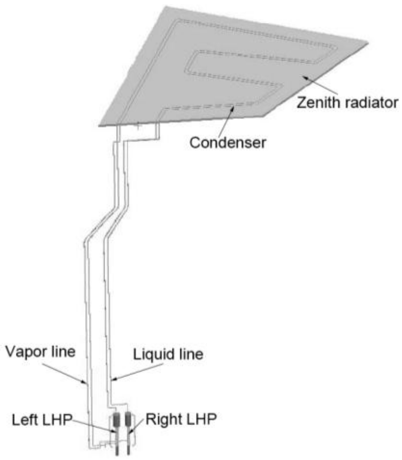
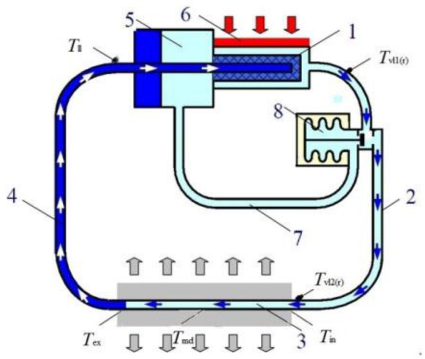


Fig. 1. Loop heat pipe layout



1. Evaporator; 2. Vapor line; 3. Condenser; 4. Liquid line;
5. Compensation chamber; 6. Cryocooler body;
7. Bypass line; 8. Bypass valve.

Fig. 2. Schematic diagram of loop heat pipe

2. Experiments

The AMS was installed horizontally in the LSS chamber (Fig. 3). The cryocoolers and the LHPs (except the condensers) were wrapped with multi-layer insulation (MLI). During the test, the LSS shroud temperature was changed from -90°C to +45°C and the pressure was less than 2.2×10-6 Pa. The vapor line and liquid line of LHPs for CC1 (Wake upper) and CC3 (Ram upper) are longer than those for CC2 (Ram lower) and CC4 (Wake lower). The LHPs of CC1 and CC3 are thus filled with 13% more propylene than those of CC2 and CC4.

The temperature of vapor line inlet T_{vl1}, vapor line exit T_{vl2}, and liquid line exit T_{ll} was measured with type T thermocouples (accuracy 0.5°C) (Fig. 2). In the diagram, (r) denotes the corresponding temperature of right LHPs. The temperature of the condenser inlet, middle, and exit (T_{in}, T_{md}, and T_{ex}) was measured with Pt1000 thermal resistance, with accuracy of 0.3°C. The mean of T_{in}, T_{md}, and T_{ex} was defined as the sink temperature of the LHPs, T_{sk}. The temperature of the reject collar, cryocooler body, and evaporator (T_{rc}, T_{bd}, and $T_{evp(r)}$) was measured with DS18S20 dallas sensors, with accuracy of ±0.5°C. Data on the shroud temperature, Tshr, was collected from the LSS data acquisition system, with accuracy of 0.3°C.

The main steps in TVTB testing of AMS are: (1) pump down, (2) bake out, (3) initial cooling down, (4) switch on in cold environment, (5) AMS complete switch on, (6) AMS temperature gradient, (7) cold thermal balance, (8) cold to hot transit, (9) hot thermal balance, (10) hot power outage and switch on, and (11) return to ambient. LSS shroud temperature variations during this process are illustrated in Fig. 4. During the experiment, both LHPs of CC1, CC2, and CC4 operated mormally but only the left LHP of CC3 was successfully put into operation.

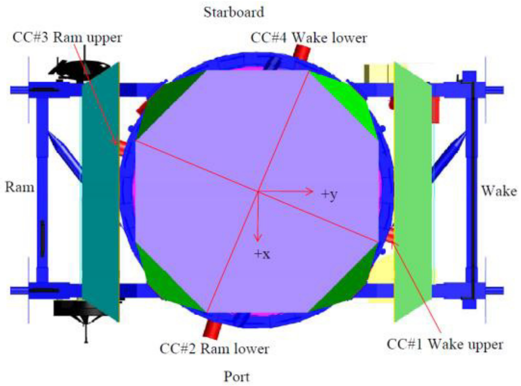


Fig. 3. Overview of the AMS in the LSS chamber

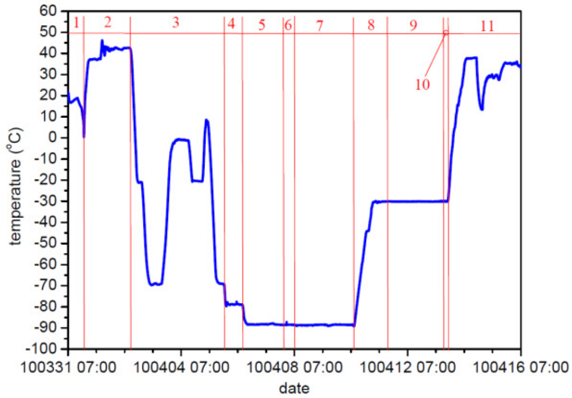
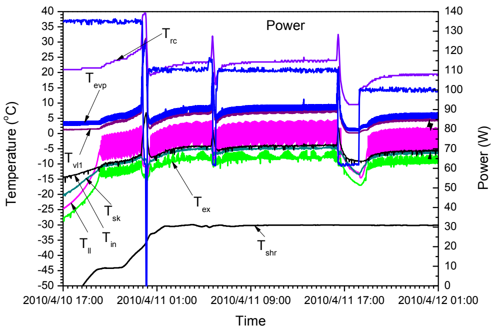


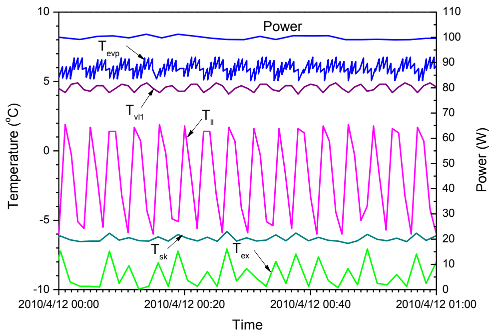
Fig. 4. Shroud temperature history during TVTB testing.

3. Results and discussion

During our TVTB test, temperature oscillations appeared only for the left LHP of CC3 after the bypass valve was closed at 20:07 on April 10, 2010 (Fig. 5).



(a)



(b)

Fig. 5. Temperature oscillations in the left LHP of CC3 (a) general graph; (b) enlarged graph

As stated above, if the evaporator temperature is lower than the lower limit (-20°C), the bypass valve opens. Part of the vapor then flows through the bypass line directly to the compensation chamber instead of the condenser. The degree of sub-cooling of liquid going inside the compensation chamber will be very high to compensate for vapor flow from the bypass line. As the shroud temperature T_{shr} increased, the bypass valve closed gradually and shut off at 20:07 on April 10, 2010. Fluid from the condenser exit was saturated, as confirmed by the similar temperatures of the condenser inlet T_{in} and exit T_{ex} (Fig. 5).

As T_{shr} increased continuously, the condenser could not condense all the vapor and bubbles escaped from the condenser to the liquid line. The temperature of the fluid at the condenser exit increased, as can be seen from the trend in T_{ex}. Because the shroud temperature was lower than the liquid line temperature, vapor bubbles escaping from the condenser exit condensed inside the liquid line at the beginning. After a delay of about one minute, vapor bubbles began to accumulate in the liquid line. The temperature of liquid line exit T_{ll} increased sharply. A slug of liquid was rapidly pushed into the compensation chamber. The temperature of the evaporator T_{evp} dropped due to the cold liquid forced into the compensation chamber.

As the heat leakage increased and T_{evp} dropped, vapor generated in the evaporator decreased. The condenser was able to dissipate the heat load and the vapor front receded back into the condenser and T_{ll} and T_{ex} decreased. Liquid flow into the compensation chamber decreased at the same time. The temperature of the compensation chamber and the evaporator increased accordingly. The heat leakage decreased due to less liquid flow to the compensation chamber.

As the heat leakage decreased and the evaporator temperature increased, vapor in the evaporator increased. The condenser could not accommodate all the vapor again. This process was repeated indefinitely and manifested itself in the form of temperature oscillations. The temperature oscillation phase shift between *T*evp (T_{vl1}) and T_{ll} was 180 degrees (Fig. 5 (b)). In contrast, Chen [5] found the temperature oscillations of the evaporator to be 180 degrees out of phase with the condenser exit. In that experiment, heat was dissipated to the liquid line because the ambient temperature was higher. Once vapor escaped from the condenser exit, it could not condense but propelled the liquid flow into the compensation chamber immediately.

Temperature oscillation is not a stable equilibrium but a metastable equilibrium condition. This transit from a metastable equilibrium to unstable conditions occurred three times during the test: 1) When the shroud temperature increased to -35ºC, at 23:45 on April 10, 2010, with cryocooler power 135 W; 2) when the power fluctuated from 110 W to 116.5 W with shroud temperature -30ºC at 05:28 on April 11, 2010; and 3) with no significant disturbance of the heat load or the sink temperature at 20:33 on April 12, 2010. At the latter time, T_{evp}, T_{vl1}, and T_{rc}, increased sharply because when there was any increase in disturbance of heat power and/or sink temperature, the condenser could not condense the vapor and the vapor content at the condenser exit exceeded a critical value, so the vapor bubbles accumlated to form a vapor slug. With the assistance of the buoyant force, vapor instead of liquid moved through the liquid line to the compensation chamber, the amount of liquid inside the compensation chamber decreased and could not provide the evaporator with enough liquid, so evaporation declined. The evaporator temperature and that of the reject collar increased sharply, the reject collar temperature reached the upper limit (40ºC), and the cryocooler tripped.

The oscillation frequencies were the same for T_{ll}, T_{evp}, and T_{vl1} (0.0058Hz @ 135 W, 0.0053Hz @ 110 W respectively). The oscillation amplitude of T_{ll}, T_{evp}, and T_{vl1} was 8K, 1.5K, and 0.6K, respectively. The decrease in the temperature oscillation amplitude was caused by heat transfer between the liquid line and the sink, and by the thermal inertia of the compensation chamber and the evaporator. The temperature oscillations disappeared when the power of the cryocooler was decreased to 60 W. We can thus conclude that temperature oscillations normally occur at high sink temperature and/or heat load. This is the reason why no temperature oscillations occurred for the LHPs of CC1, CC2, and CC4, with both LHPs in operation. The heat load of each LHP of CC1, CC2, and CC4 was only half that of the left LHP of CC3. When the bypass valve was open, it was impossible for temperature oscillations to arise because vapor at the condenser was not saturated.

4. Conclusions

Temperature oscillation characteristics of LHPs for AMS cryocoolers during TVTB test were determined. Oscillation only occurred for the left LHP of CC3 of which only one LHP was in operation. Temperature oscillations normally occurred at high sink temperature and/or heat load. Inclusion of a bypass valve was an effective measure to suppress temperature oscillations, because vapor at the condenser was not saturated when the bypass valve was open. This study of transient behaviors of LHPs for AMS crycoolers can be used as reference for similar large-scale scientific instruments in space. Further visual experiments would help understand the LHP oscillation process.

Acknowledgements

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Biography

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