Design of CCD thermal control system for SuperView satellite remote sensor and its start debugging in-orbit

Tao Yang*, Shilei Zhao, Teng Gao, Zhenming Zhao, Qingliang Meng, Ping Zhang

Beijing Institute of space Mechanics & Electricity, China Academy of Space Technology, Beijing 100094, China;
*corresponding author, E-mail: yt20@mails.tsinghua.edu.cn (T.Y.)

Abstract. With the continuous improvement of the resolution of the space remote sensing camera, the temperature stability requirements of the remote charge coupled device (CCD) have gradually become more stringent. This paper presents and designs a distributed heat source precise temperature control Loop heat pipe (LHP) structure which is different from the traditional LHP structure, and realizes a unified and effective thermal management system which can accurately control the temperature of four heat sources. The results show that the LHP system has excellent heat carrying capacity and accurate temperature control effect on distributed heat source. In 2016, the LHP system was applied to the in-orbit temperature control of the remote CCD of SuperView satellite and has been run for nearly 48 months in orbit thus far. The temperature stability of the four CCD heat source devices controlled is superior to ±0.4℃. The design method and on orbit flight data of the distributed heat source precise temperature control LHP system in this paper will have a great reference value for the subsequent application of LHP system in the space temperature control field.

1. Introduction

As the most core photoelectric conversion device of the spatial optical remote sensor, the temperature control level of the charge coupled device (CCD) will greatly affect the imaging quality of the camera [1–5]. With the gradual improvement of the camera resolution, the temperature stability requirement of the CCD devices will also be improved accordingly [1-4]. The CCD devices have small heat capacity and high heat consumption, and the temperature is easy to fluctuate greatly during periodic operation. However, it is more difficult to control the focal plane of a phase machine which is composed of multiple CCD devices. Due to its small size, the space available for the installation of thermal control elements is very limited. At present, micro and small channel heat pipes (the section height is less than or equal to 5mm) are mostly used to transfer the heat power during CCD devices operation to the transfer collector plate, and then connect the transfer collector plate to the radiator for heat dissipation through the larger channel heat pipe. Due to the heat transfer capacity is insufficient, or the heat transfer resistance is too large, this method is difficult to meet the requirements of high precision temperature control [3-5].

Loop heat pipe (LHP) is a two-phase fluid loop device which transmits heats through circulation of working medium driven by the capillary force. It has many advantages, such as great transmission heats, long transmission distance, non-moving components, flexible layout of pipelines [6-10]. LHP was invented by Maidanik from the National Academy of Sciences of Russia in 1972 [11]. In 1989, Russian carried flight experiments of LHP on Gorizont spaceship and Granat satellite successively, which verified the starting and stable operation abilities of LHP in microgravity environment [12-13]. In 1994,
Russian applied 3 sets of LHP to participate in temperature control of optical system on the Obzor spaceship. This was the first official application of LHP to the thermal control system of spacecraft in the spatial microgravity environment. As an advanced precise thermal control technology, LHP has been extensively applied to thermal management system of spacecraft and possesses promising development prospects in future. The applications of LHP in space attract more and more attentions in the world. LHP also achieved some applications successively. For example, in 2011, ammonia LHP was adopted onto electronic device on TacSat-4 for heat dissipation. In the same year, LHP was adopted on the international space station for temperature control of the alpha magnetic spectrograph. Europe and Japan have been studying LHP technology successively since 1990s. In 1998, ESA built up a set of LHP in-orbit test platform and carried out in-orbit verification on SpaceHab in 2002. In 2006, Japan carried the LHP-based expansible radiator onto the ETS-VIII satellite and heat transmission capacity was 1000W. In 2010, Beijing Institute of Space Mechanics & Electricity launched a study on LHP study, aiming to solve the difficulties in constant temperature control of remote satellite focal circuit in national high-score special engineering. SuperView satellite is an optical remote satellite that great special technological project of China’s high-resolution earth observation system arranges. Main loads of satellite are full-color multispectral remote sensors and the maximum ground pixel resolution can reach the micrometer level. Heat dissipation each CCD device of the panchromatic multispectral remote sensor is 9W and the single orbit has to work for 0~15min. The single-orbit period is 90 min and the orbit height is about 500 Km. It requires that temperature stability and consistency of full-orbit 4 pieces of CCD devices are superior to ±2℃.

Due to the heat absorption position of the traditional LHP system is the evaporator of capillary pump and the single set of LHP is difficult to adapt to the uniform heat management of distributed heat source. Moreover, evaporator of capillary pump is generally a column-shaped structure and it has to add a heat resistance through the change-over structured thermal coupling heat source and evaporator. In addition, thermal radiation plates were used as the LHP condenser in the thermal control system of aerospace and it will be influenced by heat flows out of the spatial orbit. The condenser temperature fluctuates violently and it also leads to great fluctuation of temperature of the whole LHP. Meanwhile, for the periodically working heat sources, the repeated on and off of LHP make it difficult to assure temperature control accuracy of the controlled heat sources. Hence, this brings a great challenge against that how effective loads of SuperView satellite to realize accurate and effective temperature control.

To solve above problems, a temperature controlled LHP with distributed heat sources which is different from traditional LHP structure was proposed to overcome difficulties in our previous work. In this work, the heat carrying capacity and precise temperature control effect of distributed heat sources of the proposed LHP were tested. In 2016, the proposed LHP was applied successfully to in-orbit temperature control of remote CCD devices of SuperView satellite and launched successfully on September. The proposed LHP system was started successfully once after the in-orbit.

2. Design of CCD thermal control system
For heat source distribution in multi-heat source CCD devices of SuperView satellite and needs of precise in-orbit temperature control, a precise temperature controlled LHP structure with distributed heat sources which is different from traditional LHP structure was proposed as Fig.1 shows. A LHP structure that can realize simultaneous accurate temperature control of four heat sources was designed, which realized uniform effective heat management to distributed heat sources. It can be seen from Fig.1 that compared to the traditional LHP structure, the proposed LHP system involves an assistant condenser, a preheating plate and a cold plate component (series / parallel connection of multiple cold plates). Cold plates could couple with multiple distributed heat sources, respectively. The evaporator of capillary pump could be loaded with electric power to drive circulation of working medium. The gas-phase working medium is condensed into liquid firstly in the assistant condenser and liquid runs through cold plates to absorb heats and make phase transitions, and then liquefied in the master condenser to release heats, finally flowing into the liquid reservoir. Based on the upstream preheating plate, the...
temperature controlled LHP assures that working medium entered into the cold plate component is in two-phase state. Later, it controls the constant temperature of the reservoir to assure constant temperature of the two-phase working medium, thus assuring high temperature stability of the controlled heat sources [21].

The structural design of preheating plates and cold plate component of the proposed LHP system is shown in Fig.2. Specific materials and size parameters are listed in Table 1. The ontology is mainly composed of a capillary pump component, preheat plate, cold plate component, assistant condenser, master condenser and series welding of gas-phase pipelines and liquid-phase pipelines. The detailed design process is introduced in the above text. The cold plate component has 4 pieces of cold plates in series. The preheating plate and cold plate unit are plate-like structures, in which there’s a S-shaped channel to strengthen heat exchange. In practical application, cold plates contact with 4 pieces of CCD devices for heat conduction and coupling. The goal of temperature control of CCD devices is realized by controlling temperature of four pieces of cold plates precisely.

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Table. 1 Basic parameters of the proposed LHP system

| Name                        | Materials       | Physical description                  |
|-----------------------------|-----------------|---------------------------------------|
| Components of capillary pump |                 |                                       |
| Evaporator                  | Stainless steel | Φ19 mm                                |
| Capillary core              | Ceramics        | Pore diameter/porosity: 0.7um/70%     |
| Reservoir                   | Stainless steel | Outer diameter 36 mm                  |
| Pipelines                   |                 |                                       |
| Gas-phase pipeline          | Stainless steel | Φ3mm ×1.6m                            |
| Liquid-phase pipeline       | Stainless steel | Φ3mm ×1.6m                            |
| Preheating plates           | Stainless steel | 80mm×50mm×4mm                         |
| Cold plate component        |                 |                                       |
| Cold plates                 | Stainless steel | 108mm×20mm×4mm                        |
| Connecting pipelines        | Stainless steel | Φ2mm                                  |
By combining heat flow data out of the orbit of satellite, electric powers of different parts of LHP and condenser area can be further determined through a simulation analysis based on the heat equilibrium equation of LHP and SINDA/FLUINT two-phase flow analysis software (Table 2). Detailed process is shown in Reference [20].

Table. 2 Design state of temperature control components

| Name of components | Heating loop | Name of loop | Heating power | Temperature control threshold | Usage |
|--------------------|--------------|--------------|---------------|------------------------------|-------|
| Evaporator of capillary pump | Heating power | Driven heating loop | 50W | 30°C~31°C | Driving operation of LHP |
| Reservoir of capillary pump | Temperature controlled loop | 10W | 3°C~7°C | Constant temperature control of the reservoir |
| Preheating plates | Additional heating loop | 10W | 28°C~32°C | Assuring two-phase state of working medium in cold plates |
| Master condenser | Antifreeze heating loop | 10W | -41°C~40°C | 0.30m² |
| Assistant condenser | Antifreeze heating loop | 10W | -41°C~40°C | 0.32m² |

For multi-evaporator LHP systems in existing Chinese and foreign studies, evaporator refers to the evaporator of capillary pump, in which a capillary core is set. This not only has complicated structure, but also is difficult to be implemented in engineering and incurs a high cost. Moreover, temperatures of multiple evaporators are determined by their own reservoirs, showing poor temperature consistency. In the present study, a cold plate component is applied and its structure is closer to water cold plates which have simple structure, easy implementation and low cost. Moreover, temperature of multiple cold plate components is determined by reservoir of a capillary pump, showing high temperature consistency and high temperature control accuracy. Compared to traditional LHP structures developed by the United States and Russia, the proposed LHP system uses unique master and assistant condensers, preheating plates and multi-heat source distribution (cold plates). The cold plate components are formed by series connection of four cold plates which can couple with 4 pieces of CCD components. The proposed LHP system uses the capillary pump only for driving circulation of the working medium and gaseous working medium is liquefied fully in the assistant condenser. The liquid working medium is heated into two-phase state when it flows through the preheating plate. The two-phase working medium makes heat exchange with CCD devices after flowing through the cold plate component and then enter into the master condenser for secondary liquefaction. The liquid working medium finally flows into the reservoir to form a circulation. This capillary pump is made of porous material which is formed by sintering of ceramic powder. It has a small pore diameter, so that LHP can generate relatively high pumping capacity. In the proposed precise temperature controlled LHP system, the two-phase working medium that flows through the cold plate component and constant temperature of the controlled CCD device can be assured through precise control over temperature of the reservoir.
As Table 2 shows, the heating power above is 1.1 ~ 1.2 accompany margin. The heating loop is controlled by temperature controller, and the temperature is controlled by proportional switch with 6 second control period. The temperature cloud map of loop heat pipe condenser under low and high temperature condition as the Fig.3 and Fig.4 shown, respectively.

Fig. 3 Temperature cloud map of loop heat pipe condenser under low temperature condition

Fig. 4 Temperature cloud map of loop heat pipe condenser under high temperature condition
3. In-orbit flight data

3.1 Starting process

The proposed precise temperature-controlled LHP system with distributed heat sources is assembled onto CCD devices of SuperView satellite for thermal control after ground performance verification. The SuperView satellite was launched on 2016. In the process of satellite launch section and transfer in orbit, the LHP system is set as closed state, but the liquid reservoir, preheating plate and master/assistant condenser corresponding to the heating loop shall always ensure the closed-loop temperature control, so as to prevent the temperature of each part of the LHP system from being too low. It can be seen from Table 2, the settings of each part of the loop heat pipe.

After the satellite entered the predetermined orbit, the drive heating loop of evaporator is set as a closed-loop temperature control loop, and the LHP starts to organize and start. The temperature curves of each key part in the starting process are shown in Fig. 5. Before loading of additional heating power of the preheat plate, temperature of the reservoir was kept at 6.4°C, the temperature control threshold was within 3°C ~ 7°C and the evaporator temperature was -2.7°C, which was significantly lower than that of the reservoir. Under this circumstance, liquid working medium in the evaporator can be judged undercooling and the capillary core is infiltrated by liquid working medium. After the preheating plate is loaded with additional heating power, the temperature of preheating plate maintained at about 30°C, the temperatures of the evaporator and reservoir are increased by about 2°C ~ 8°C, indicating that undercooling liquid enters from the condenser into the capillary pump and the capillary core is further supplemented with liquid working medium. This indicates that LHP has startup conditions. Under this circumstance, temperature of the condenser is no lower than -45°C in the whole process.

![Fig 5. The temperature curves of each key part in the starting process](image)

After the evaporator is loaded with driving power, temperature of the evaporator increases quickly and it reaches to 7.7°C after about 96s, which is higher than temperature of the reservoir (about 1.3°C). Then the temperature of the evaporator increases stably. In the process, the temperature of preheating plate and CP1 of CCD inraeased sharply to 50°C and 16°C respectively at first, and then dropped sharply to around 6°C. Subsequently, the temperatures of four CP plates of CCD devices concentrate within 5.6°C ~ 6.2°C. At this moment, it can determine that the LHP has been started successfully.
3.2 Camera charging process
As the Fig.6 shows that after the camera is turned on, the temperature of the evaporator increased slowly and reached 7.4℃ after approximately 720 s, which was higher than the temperature of the liquid reservoir (approximately 1.6℃).

When the camera is charged, the temperature of the liquid reservoir in the LHP basically remains stable, the temperature of evaporator rises less than 0.2℃, the temperature rise of the four cold plates of CCD does not exceed 0.5℃, and the consistency of the four cold plates of CCD is always kept within 6±0.4℃.

![Variation curves of temperature at different parts of the LHP](image)

Fig 6. Variation curves of temperature at different parts of the LHP in the stable running process (12 minutes after the camera is turned on)

When the camera is turned on, the heat flow from the LHP to the condenser rises, the temperature of the liquid working medium returning to the capillary pump rises, the temperature of the liquid reservoir and evaporator rises, the saturation pressure inside the liquid reservoir increases, the overall pressure of the system rises, and the phase transition temperature of the working medium in the cold plates of CCD rises accordingly. At the same time, with the increase of gas phase pipeline in the condenser, the increase of system flow resistance and pressure difference, and the constant pressure of liquid reservoir, the saturation pressure and temperature of working medium in the CCD cold plate further rise, so the temperature of the cold plates of CCD rise greater.

It can be seen from Fig.5 and Fig.6 that temperature of the evaporator continues to increase after heating. Working medium which is gasified in the capillary pump enters into the assistant condenser along the gas-phase pipelines and finally arrives at CCD component along the liquid-phase pipelines after liquefaction and undercooling in the assistant condenser. The additional heating plate is cooled dramatically after undercooling liquid enters into it. Meanwhile, the liquid working medium is heated to the phase transition point by thermal compensation power consumption, thus triggering phase transitions. Hence, temperature of preheating plate is kept constant at about 7℃. The two-phase working medium runs through 4 CCD devices successively to realize accurate temperature control of cold plates. If CCD devices are working, heat dissipation is absorbed by working medium under the phase-transition temperature and temperatures of 4 CCD devices are controlled at about 6℃. Subsequently, phase-transition working medium enters into the master condenser and then is liquefied and undercooled, and finally returns to the reservoir.

3.3 In-orbit temperature regulation performance test
In the LHP system of this study, the temperature of two-phase working medium in any part of the loop pipeline is anchored on the liquid reservoir temperature, so the operating temperature of this LHP system
can be adjusted by adjusting the liquid reservoir temperature. The liquid working medium from the assistant condenser flows through the preheating plate and is heated into a two-phase working medium, which flows through the four cold plates of CCD assembly and absorbs or releases heat by adjusting the dryness. It is designed to ensure that the two-phase working medium flowing through the four cold plates of CCD has enough heat to compensate the CCD devices in the state of turning off the camera, and the two-phase working medium has enough latent heat to absorb heat when the camera is turned on.

It can be seen from Fig.7 that the temperature of the central control point of the liquid reservoir was set at 6°C, 13°C, 11°C and 9°C respectively, the temperature of key parts of the LHP system can be telemetered in orbit. The temperature of evaporator, preheating plate and four cold plates of CCD can keep a good consistency with the temperature of liquid reservoir, which fully verifies the temperature regulation characteristics of the LHP system in orbit.

Fig 7. Variation curves of temperature at different parts of the LHP system with the liquid reservoir

4. Conclusions

In this study, the precise temperature-controlled LHP system with a distributed heat source for the CCD devices has a good microgravity adaptability and temperature starting performance, coupled with a reasonable temperature control design, can ensure the remote sensing camera CCD devices in the space microgravity environment of ±0.4°C temperature control accuracy. Before the start of the LHP capillary pump, by loading the preheating plate to compensate the heating power, the liquid working medium in the condensing pipeline can be pushed into the capillary pump assembly, so that the liquid working medium can further infiltrate the capillary core, and the reliability of the LHP system starting under the orbit microgravity can be improved.

In 2016, the LHP system was applied to the in orbit temperature control of the remote CCD of SuperView satellite and has been run for nearly 48 months in orbit thus far. The design method and the in-orbit flight data of the proposed LHP system can provide references to the applications of the follow-up LHP system in the temperature-control fields in aerospace.

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