Applications and Prospects of Fluid Cooling Systems for Solar Arrays in Solar Exploration Missions Postprint

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Abstract

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Full Text

Preamble

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Application and Prospect of the Fluid Cooling System of Solar Arrays for Probing the Sun

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Abstract: The Solar Close Observations and Proximity Experiments (SCOPE) mission, proposed by the Yunnan Observatories, Chinese Academy of Sciences, aims to operate at a distance of 5 to 10 solar radii from the Sun to conduct in situ detection of solar eruption processes and observe magnetic field structure responses. The solar flux received by the satellite ranges from 10^3 to 10^6 $\mathrm{Wm^{-2}}$, posing significant challenges for thermal management of the solar arrays. In this work, we discuss the solar array cooling system of the Parker Solar Probe, review developments in fluid loop techniques, and propose a research plan for a next-generation solar array cooling system. This paper provides a valuable reference for novel thermal control systems in spacecraft for solar observation.

Keywords: In situ detection of solar eruption; Solar array cooling system; Pumped fluid loop; High heat flux dissipation

1. Introduction

Solar activity profoundly impacts Earth's space environment and human life, causing interference with orbiting satellites and onboard electronic equipment. Detection of solar activity is essential for understanding and minimizing potential interference with satellites, thereby ensuring their successful orbital operation. Solar activity also disrupts Earth's magnetic field, leading to "magnetic storms" that affect terrestrial electronic communications and information service equipment.

Humanity's exploration of the Sun has been relentless since ancient times. Thanks to gradually developing scientific exploration capabilities, we have created and utilized solar telescopes, magnetometers, coronal observers, X-ray imagers, and other detectors to photograph coronal loops, solar flares, and other phenomena [1]. In recent years, national and international space agencies have launched numerous solar exploration spacecraft, including the Solar Dynamics Observatory (SDO, 2010), Parker Solar Probe (PSP, 2018), Solar Orbiter (2020), Chinese Hα Solar Explorer (CHASE, 2021), and Advanced Space-based Solar Observatory (ASO-S, 2022). However, many scientific questions remain unresolved, such as why the coronal temperature is much higher than the photosphere temperature, the origin of the solar wind, the source of energetic particles, and the mechanisms of acceleration and transport [2].

Although humanity's desire to explore the Sun has persisted for millennia, excessive solar radiation poses a formidable challenge to spacecraft design during close-proximity solar exploration. Managing extremely high external heat flux, spacecraft thermal protection, and solar array thermal management are critical technologies for ensuring the successful completion of scientific missions by solar probes. The Sun-facing surface of a spacecraft approaches 1,400 °C at a solar distance of 0.046 AU [3]. NASA's PSP employs a carbon-carbon composite sandwich structure for efficient thermal protection and utilizes a pumped single-phase water loop system to dissipate heat from the solar arrays while protecting internal payloads and equipment from high temperatures.

The Chinese Solar Eruption Approach Probe, first proposed by the Yunnan Observatories, Chinese Academy of Sciences, aims to orbit the Sun for extended periods at distances of 5 to 10 solar radii. The probe intends to conduct close-up detection of solar eruption processes and observe magnetic field structure responses [4, 5]. The perihelion altitude of its designed orbit is smaller than that of PSP, placing correspondingly higher demands on spacecraft thermal protection and thermal control technology [4, 6]. In response to the high heat dissipation requirements of solar exploration missions, this paper discusses the solar array cooling technology developed by NASA for PSP, reviews the current development and application status of pumped fluid loop techniques, and proposes a research plan for a next-generation solar array cooling system.

2. Thermal Control Technology of the Parker Solar Probe

The PSP's orbit perihelion is approximately 0.046 AU, where solar intensity reaches about 7$×10^{5}$ Wm^{-2}. The Sun-facing side of the spacecraft surface experiences temperatures of approximately 1,400 °C. To ensure proper functioning of PSP's instrumentation, the satellite interior must be maintained near room temperature (approximately 30 °C). The Thermal Protection System (TPS) developed by Johns Hopkins University Applied Physics Laboratory employs a sandwich structure with a carbon-carbon composite surface material and nearly 4.5 inches of carbon foam with 97% porosity for highly efficient thermal insulation [7, 8]. The TPS structure has a diameter of 2.4 m and weighs approximately 73 kg.

[Figure 1: see original paper] shows the structural distribution of the PSP thermal control system. The TPS is located atop the spacecraft, and the Truss Structure Assembly (TSA) is mounted behind the TPS to connect it to the satellite platform [9].

In addition to Sun-facing thermal protection materials, the solar arrays—key components of PSP—are subjected to extremely high external heat flux variations. As solar distance decreases from 1.02 to 0.046 AU, solar intensity on the solar arrays varies from the order of 10^3 Wm^{-2} to 10^5 Wm^{-2}, posing a significant challenge to normal operation. To alleviate this extremely high external heat flux at perihelion, PSP incorporates a solar array cooling system that uses a fluid loop to dissipate heat absorbed from the solar arrays into the Cooling System Primary Radiator (CSPR), ensuring the arrays remain at proper operating temperatures to supply power under intense solar heat flux.

The solar array cooling system, shown in [Figure 2: see original paper], consists of one reservoir, one dual pump set, two pump motor controllers, two cooling plates, four CSPRs, and three isolation valves (ISOs). The system operating temperature must be maintained within 10–125 °C. For the required operating temperature range and heat transfer capacity, the working medium is deionized water with a filling volume of approximately 3.7 L. The system is pressurized to increase the boiling point of deionized water above 125 °C to prevent pump cavitation. The system uses single-phase centrifugal pumps supplied by Hanson, USA, providing a pressure head of 48–62 kPa and a total flow rate of 4–6 L/min [3]. Maximum power consumption of the solar array cooling system is approximately 49 W, with a total weight of 86 kg.

During PSP's launch and gradual orbital changes, ensuring the working fluid remains within safe temperatures (between water's triple point and boiling point) is a critical design consideration. According to mission requirements, prior to launch, PSP uses ground equipment to maintain closed-loop temperature control of 45–50 °C for the deionized water in the reservoir. During launch, this fluid is isolated from the rest of the system by ISO1, and the deionized water is kept within a safe temperature range through proper insulation and its own thermal capacity.

Incorporating solar array thermal control requirements, major in-orbit events, orbital locations, and orientations of the PSP solar array cooling system are shown in [Figure 3: see original paper]. Major events include: (1) After spacecraft attitude adjustments cause the temperature of the solar arrays, CSPR1, and CSPR4 to increase to a safe range, isolation valve ISO1 opens to start the fluid loop; (2) During orbit correction maneuvers, all four CSPRs are in shadow, and to prevent CSPR2 and CSPR3 temperatures from dropping below –150 °C, orbital correction duration is limited to 3 hours; (3) At a solar distance of 0.94 AU, after PSP attitude adjustment, CSPR2 and CSPR3 are warmed by solar radiation to above 20 °C, opening isolation valves ISO2 and ISO3 to start the full fluid loop; (4) When solar distance exceeds 0.82 AU, external heat flux on the solar array is low, requiring CSPR2 and CSPR3 to face the Sun to maintain suitable operating temperatures; (5) Upon arrival in Venus orbit, the TPS is oriented to the Sun and the solar array cooling system remains in normal operation; (6) When PSP experiences Venus eclipses, CSPR2 and CSPR3 are oriented toward the Sun before the eclipse to store thermal energy in advance and avoid large temperature drops; (7) During a Venus eclipse, the cooling system must remain above the minimum safe temperature for at least 11 minutes; (8) When approaching the Sun (<0.7 AU), the solar arrays are folded, and the detector relies only on solar cells at the tip of each array to receive light and supply power, reducing heat input [10].

PSP arrived at its first perihelion in November 2018. [Figure 4: see original paper] shows the variation of inlet and outlet temperatures of the solar array cooling plate with solar distance, demonstrating that the temperature difference between inlet and outlet is approximately 5 °C, with outlet temperature below 70 °C, meeting the thermal design requirements of the solar arrays [10].

3. Spacecraft Fluid Technology

The Solar Close Observations and Proximity Experiments (SCOPE) spacecraft will reach much closer solar distances than PSP, facing higher external heat flux (about 2.5$×10^{6}$ Wm^{-2}), which poses a greater challenge to the heat dissipation capability of the solar array cooling system. Pumped fluid loop technology and vapor compression heat pump technology may be suitable for high heat flux cooling, as discussed below.

3.1 Pumped Fluid Loop Systems

Currently, pumped fluid loop technology has gradually matured and has seen on-orbit applications, providing important technical methods for: (1) heat dissipation from spacecraft near the Sun with heat flux on the order of MWm^{-2}; (2) temperature control for Transmitter and Receiver (T/R) modules of space-borne phased array radar and laser payloads [11]; (3) high-power thermal control of large crewed spacecraft at the tens of kilowatts level [12]; and (4) precise temperature control of payload instrumentation [13]. Pumped fluid loop systems can be classified into pumped single-phase fluid loops and pumped two-phase fluid loops, depending on whether phase change occurs in the fluid.

3.1.1 Pumped Single-Phase Fluid Loop System As shown in [Figure 5: see original paper], the thermal control system of Chang'e-5 consists of a pump module, flow resistance adjustment valve, fluid loop separation module, working fluid discharge valve and radiator, water sublimation heat exchanger module, and pipelines. The thermal control system provides integrated heat collection and dissipation for the lander and ascender, ensuring flow path separation and reconfiguration before the ascender takes off from the lunar surface through the flow path separation module [14–16].

A two-stage fluid loop is adopted for temperature control in the Destiny module of the International Space Station (ISS), as shown in [Figure 6: see original paper]. Based on different working temperatures inside and outside the cabin, water is used as the working medium for the interior, and heat is exchanged with an ammonia loop outside the cabin through an intermediate heat exchanger, facilitating heat collection inside and dissipation outside [17,18].

The core module of China's space station (Tiangong) adopts a three-stage circuit for temperature control, including a ventilation circuit system, an internal fluid loop system, and a radiated outer loop system, enabling the collection, transfer, and dissipation of heat from personnel and instruments within the space station [19,20].

A fluid loop cooling technique based on micropumps is used in the Pujiang-1 satellite, launched in 2015. As shown in [Figure 7: see original paper], the system includes micropumps and their controllers, a fluid reservoir, check valves, and three-way valves and pipes. The micropump is a centrifugal pump driven by a DC brushless motor with a rated flow rate of 1.3 L/min, a rated head of 7.7 m, and a rated power of 10.3 W [21]. Based on continuous on-orbit test results of two micropumps running for 90 days and 9 days, the Shanghai Institute of Satellite Engineering considers the system to meet requirements for long-term orbital use.

In conclusion, pumped single-phase fluid loop technology has been applied in spacecraft both nationally and internationally in recent years, demonstrating good on-orbit performance, high-efficiency heat dissipation, and long-term stable operation, capable of meeting the high-power-density heat dissipation demands of next-generation spacecraft.

3.1.2 Pumped Two-Phase Fluid Loop Systems Currently, the pumped two-phase fluid loop technique is less commonly used in spacecraft. Its main difficulties include: (1) Compared with single-phase flow, the flow and heat transfer stability of a two-phase loop system is somewhat inferior, resulting in significantly increased system complexity; (2) The two-phase system operating under high pressure is not as safe and reliable as a single-phase fluid loop; (3) Due to microgravity effects on bubble dynamics, heat transfer characteristics at boiling point change in orbit [22]; and (4) Vapor quality at the pump inlet must be strictly controlled in a two-phase system to avoid pump lifetime degradation due to cavitation [23].

The Alpha Magnetic Spectrometer (AMS02) on the ISS adopts a pumped two-phase CO_2 loop to precisely control the temperature of tracker instruments in the detector, as shown in [Figure 8: see original paper], with temperature control stability verified at $±$0.2 °C in orbit [13, 24–27]. The gear pump (GA-HT23.PVS, flow rate of 8.5–506 ml/min, maximum head of 5.2 bar) manufactured by MICROPUMP, USA, is used for the pumping unit [26]. The instrument was launched in 2011, and its cooling system reportedly requires periodic in-orbit maintenance, including cooling pump replacement, system leak detection, and fluid charge [28].

The pumped two-phase fluid loop remains in an experimental stage for Chinese spacecraft. The Beijing Institute of Spacecraft System Engineering designed a pumped two-phase fluid loop system using R134a (1,1,1,2-Tetrafluoroethane) as working fluid with a flow rate of 514 L/h for 3 × 3 m surface source blackbody temperature control. Test results show system temperature uniformity can achieve $±$0.8 °C with stability of $±0.2°C/15minatroomtemperatureabove30°C, helpingimprovetheaccuracyofsatelliteinfraredandhyperspec phaseloopsysteminvolvingamicrochannelevaporator, two−phasepump, highheatsourcesimulator, andsystem hourflight.Testresultsshowedtheevaporator′sflowboilingheattransfercoefficientreached7.8–9.1W/(cm^{2 with a flow rate range of 0.18–0.65 L/min, and its maximum heat dissipation capacity can reach 271 W/cm^2 [30].

A ground-based test of a mechanical pumped two-phase fluid loop for a space-based remote sensing camera, built by the Beijing Institute of Space Mechanics & Electricity, uses a shielded pump as the driving source. The system features a two-phase, temperature-controlled reservoir with passive cooling as the temperature-control component and nine heat sources to simulate distributed instruments on a spacecraft. The feasibility and stability of the two-phase fluid loop system were verified based on data monitoring during experiments, including preheater startup, heat source startup and shutdown, normal heat source operation, and power change conditions [31, 32].

3.2 Vapor Compression Heat Pump Systems

For thermal management of large spacecraft platforms such as future space stations, vapor compression heat pump systems can enhance the heat transfer temperature difference between evaporator and condenser sides compared with pumped two-phase fluid loop technology, further improving system heat transfer efficiency and reducing required radiator area [33]. However, significant scientific and technical challenges remain for space application of vapor compression heat pump systems, including bubble dynamics in the evaporator during boiling under microgravity conditions, oil-gas separation in the compressor, enhancement of the condensation process, and ground equivalent simulation methods [34].

4. Technology Prospects for SCOPE Solar Array Thermal Control

Based on analysis of the PSP solar array cooling system and current development of pumped fluid loop thermal control technology, we propose the following prospects for technological development of the thermal control system for the SCOPE spacecraft:

(1) Flexible fluid loop thermal control technology provides important tools for spacecraft-stage thermal management. Pumped single-phase loop active thermal control technology can increase heat dissipation capacity by one order of magnitude compared with conventional cooling methods [35]. It is also more reliable than both two-phase fluid loop systems and vapor compression heat pump systems, making it suitable for small and medium-sized spacecraft with long lifetime requirements. Meanwhile, leveraging the improved heat transfer capability of the pumped fluid loop, a spacecraft-level pumped single-phase water loop can be designed. A

multi-level coupling heat transfer layout between the fluid loop and solar arrays, radiators, and platform heat exchangers has been developed to achieve efficient heat transfer, thermal compensation, and waste heat dissipation. Highly dynamic heat management can be achieved by switching flow paths and controlling flow rates at various levels within the fluid loop to maintain optimal operating temperature ranges for each component.

(2) The importance of adaptive thermal control methods is increasing. Adaptive control of the solar array cooling system is essential because signals from the solar detection spacecraft at perihelion take approximately 8 minutes to return to Earth, making it difficult for ground crews to address on-board thermal control anomalies in a timely manner. The adaptive control method requires multi-level fusion of temperature, flow, and position data information, a mathematical model for temperature field prediction, and quantification of temperature sensitivity of controlled objects to different parameters under large heat flux density. Through data analysis and machine learning, optimal temperature control strategies can be planned, enabling adjustable thermal management through tracking, collecting, distributing, and dissipating heat from multiple components such as spacecraft equipment, payloads, and solar arrays.

(3) Adaptive thermal control integrated analysis systems for complex tasks should have the ability to optimize multiple interfaces with various parameters. An adaptive thermal control flow chart is shown in [Figure 9: see original paper]. The adaptive thermal analysis system will conduct integrated analysis of the solar approach detection mission from the main aspects of physical field simulation, intelligent control algorithms, parametric fitting, and system visualization. Self-programming and various types of analysis software will be jointly developed to achieve data interaction, control, and analysis between different modules to achieve the required characteristics of advanced integration and analysis.

5. Summary

This article summarizes the cooling system of PSP solar arrays, as well as the development and application of efficient heat dissipation technology on different spacecraft, and proposes research prospects for future development of thermal control technology for the SCOPE spacecraft. The following insights are obtained:

(1) With the advancement of space exploration missions, high heat flux cooling technology has taken on greater significance. Conventional cooling methods have difficulty meeting the thermal control requirements of solar close-up exploration missions, and development of technologies with higher heat dissipation capabilities is urgently needed.

(2) Compared with pumped two-phase fluid loop systems and heat pump technology, a pumped single-phase fluid loop ensures a balance between

efficiency and reliability, making it an important means of high heat flux cooling for future spacecraft. The SCOPE vehicle may use pumped single-phase fluid loop technology for cooling solar arrays, and detailed design work needs to be carried out in the future.

(3) There are many parameters that can be controlled in a pumped single-phase loop, such as flow rate, flow path, temperature, and radiator area. Coordinating the various parameters relevant to heat transfer performance is a key issue. Therefore, it is necessary to develop an on-orbit adaptive thermal control method for pumped fluid loop systems to allow real-time adjustment of the heat dissipation capacity of the SCOPE spacecraft.

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Author Contributions

Kangli Bao conceived the idea, provided investigation support, and wrote the original draft. Xiaofei Zhu and Jianchao Feng provided investigation support and wrote the original draft. Liu Liu provided investigation support, reviewed and edited the manuscript. Xiaofeng Zhang reviewed the manuscript, performed project administration and supervision. Zhiming Cai reviewed the manuscript and performed supervision. Jun Lin reviewed the manuscript and supported funding acquisition. Yonghe Zhang performed supervision. All authors read and approved the final manuscript.

Declaration of Interests

Xiaofeng Zhang, Zhiming Cai and Yonghe Zhang are editorial board members for *Astronomical Techniques and Instruments*, and Jun Lin is the executive editor-in-chief for *Astronomical Techniques and Instruments*. They were not involved in the editorial review or the decision to publish this article. The authors declare no competing interests.

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