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A highly self-adaptive cold plate for the single-phase mechanically pumped fluid loop for spacecraft thermal management

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ABSTRACT

Aiming to improve the conventional single-phase mechanically pumped fluid loop applied in spacecraft thermal control system, a novel actively-pumped loop using distributed thermal control strategy was proposed. The flow control system for each branch consists primarily of a thermal control valve integrated with a paraffin-based actuator residing in the front part of each corresponding cold plate, where both coolant's flow rate and the cold plate's heat removal capability are well controlled sensitively according to the heat loaded upon the cold plate due to a conversion between thermal and mechanical energies. The operating economy enhances remarkably owing to no energy consumption in flow control process. Additionally, realizing the integration of the sensor, controller and actuator systems, it simplifies structure of the traditional mechanically pumped fluid loop as well. Revolving this novel scheme, mathematical model regarding design process of the highly specialized cold plate was entrenched theoretically. A validating system as a prototype was established on the basis of the design method and the scheduled objective of the controlled temperature (43 °C). Then temperature control performances of the highly self-adaptive cold plate under various operating conditions were tested experimentally. During almost all experiments, the controlled temperature remains within a range of ±2 °C around the set-point. Conclusions can be drawn that this self-driven control system is stable with sufficient fast transient responses and sufficient small steady-state errors.

1. Introduction

In the past few decades, not only National Aeronautics and Space Administration (NASA) but also China Aerospace Science and Technology Corporation (CASC) have set up programs of developing high-quality thermal control system as an urgent priority. One of the primary goals of the advanced spacecraft thermal control technology is to stabilize the temperature of the on-board sensitive electronics well within the acceptable range during space task execution.

With the purpose of accommodating the multiple requirements of flight task, the next-generation spacecraft will face the ever more complicated space thermal environment, such as constantly varying external heat flux, which is caused by not only the space vehicle's attitude alteration during the on-orbit flight but also the dramatic diurnal temperature changes (greater than 100 °C on Mars [1]) when landing on other planets. Additionally, the indoor heat source caused by on-board electrical system, proportion system, weapon system and other flight components will experience a great alteration across the entire flight stages. How to keep a safe operating temperature of the spacecraft-loaded electronics when confronting the coupled effects of the ever-changing external and internal heat loads will post a major challenge for future spacecraft thermal management. Capable of handling increasingly complex heat dissipation issue, the forced liquid cooling [2] is regarded as one of the promising candidates to address the thermal control concerns.

The conventional strategy of the forced liquid cooling for space-based thermal control system is the Single-Phase Mechanically Pumped Fluid Loop (MPFL) [3], which consists of a pump, connection tube system, a radiator heat exchanger and payload heat exchangers called cold plates (CPs) [4]. The CPs are attached tightly to the heat generation components, rejecting their heat directly. It is known that the performance of the MPFL depends on the components mentioned above [5]. Many scientists have done tremendous efforts to improve the traditional single-phase MPFL system from different aspects. Yamada et al. [6] invented a honeycomb-cord

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Nomenclature

T	temperature
V_0	initial volume of solid-phase paraffin, m^3
f	defection generated by the actuator, m
m'	mass flow rate, kg/s
T_{ob}	objective of the controlled temperature, °C
Q_{in}	heat load, W
V	volume of the paraffin, m^3
V_{cp}	volumetric flow rate of water through the cold plate, L/h
T_m	melting point, °C
d	diameter of the paraffin seal boot, m
c	specific heat, J/(kg °C)
A_c	surface area involved in convection, m^2
h_c	convection heat transfer coefficient, W/(m^2 °C)
M_p	maximum overshoot, °C
R	thermal resistance

Greek symbols

α	volume expansivity of the paraffin
β	isothermal compressibility of the paraffin
η	effectiveness of a heat exchanger
ε_f	fin efficiency
κ	maximum percent overshoot

Subscripts

p	paraffin
0	initial state
cp	cold plate
max	maximum value
in	inlet water
out	outlet water
w	water
s	steady state

CP that can acquire a significant mass reduction without deteriorating heat rejection capability. A high-temperature, low-power, electrochemically-driven fluid cooling pump was proposed by Boeyen et al. [7]. This more efficient, lighter cooling fluid pump met the increasing thermal management demands of future spacecraft. A transient simulation of a single-phase MPFL using ESATAN/FHTS was implemented by Kotlyarov et al. [8]. The simplified analytical model in parallel with the special scenario of thermal performance tests have enabled studying many respects of the MPFL transient behavior. In order to modulate pressure and accommodate changes in the working fluid volume within the loop efficiently, a MPFL integrated with a gas charged accumulator is typically disclosed. The design description of the specialized accumulator accompanied with sophisticated EXCEL based spreadsheets were developed to gain the accurate sizing and charging parameters of the accumulator [9]. With all these breakthroughs, the single-phase MPFL nowadays has possessed several advantages compared to the two-phase loops: mechanical and electrical compatibility with spacecraft, strong flexibility of ground-based tests and inherent high robustness of in-orbit operation. Holding such outstanding superiorities, the single-phase MPFL has been utilized in many famous spacecraft. For example, the Mars Pathfinder Spacecraft which launched on Mars in December 1996 used a MPFL system to transfer the waste heat from the lander electronics to an external radiator [10]. Besides, heat rejection system of the International Space Station is equipped with the MPFL as well [11].

The general thermal control strategies of the MPFL are familiar. The key approach is to regulate the flow through the heat generating and rejecting components, which is achieved by either splitting or mixing the fluid stream pumped from different branches. The splitting or mixing valve is actually a three-way valve which can be driven to a position between 0% and 100%, able to balance the flow through the various fluidic branches. Taking the splitting valve as example, as shown in Fig. 1 temperature sensors detect the varying temperature of the point A, conveying the temperature information to the controller. Based on the active control logic philosophy, the controller sends the driving signal to the motor of the three-way valve, regulating the mass flow rates of the bypass line and the main fluid line linking to the radiator. The valve position will be quickly adjusted in response to the comparison between the point A's temperature and the referenced temperature. By changing the ratio between these two sub-flows, the heat dissipation capacity is well controlled and hence the temperature of the controlled objects [12]. The primary advantage of the temperature control process is that the entire flow driven by the pump remains constant which will maximize the life of the pump to enhance the reliability of the MPFL system. However it has three main problems as well: (1) a high energy consumption [13] applied in the flow control system would post a significant limitation in space application; (2) the precision of the temperature control cannot be guaranteed for each CP as a centralized thermal control strategy is adopted; (3) the function of the MPFL system totally depends on the reliability of the critical three-way valve, which leads to an essential redundant deployment of the three-way valves and thus it will inevitably increase the whole system's size and weight. How to maintain the clear advantage while solve these three issues mentioned above will became the core task for the space thermal engineers in the future.

Phase change materials (PCMs) that melt and solidify at a variety of temperature has been widely used in various thermal management applications due to their outstanding thermal properties. There are numerous organic and inorganic chemical materials that can be classified as PCMs. Inorganic materials (salt hydrates and metallics) have larger energy storage density and higher thermal conductivity but undergo supercooling and phase segregation [14]. Organic materials such as paraffins are able to melt and freeze repeatedly without phase segregation and degradation of latent heat [15]. Therefore the latter ones demonstrated a strong preference for being applied in the space-based system where high reliability is the top priority. Three primary approaches revolving the application of PCMs have been proposed by scholars:

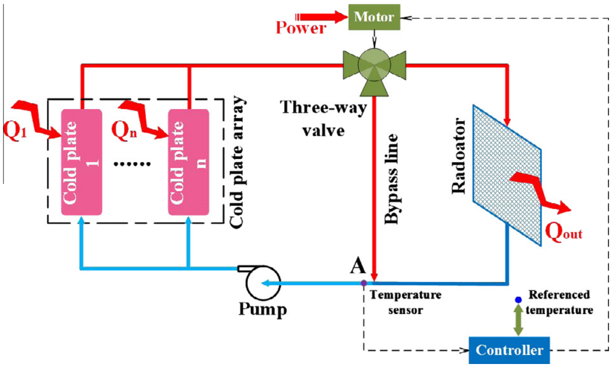

Fig. 1. Simplified structure of the traditional MPFL using the splitting valve.