Energy Conversion and Management 176 (2018) 194–208

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

A hybrid cooling system combining self-adaptive single-phase mechanically pumped fluid loop and gravity-immune two-phase spray module

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ARTICLE INFO

Keywords:
Space thermal control
Multiphase flow
Spray technology
Phase change material
Hybrid cooling system

ABSTRACT

Although single-phase mechanically pumped fluid loop (MPFL) and two-phase spray cooling technologies have been investigated independently for decades, there is a lack of understanding on the combined operation of these two modules. The MPFL has been extensively utilized in the space thermal control system due to its technological maturity and gravity immunity. The spray cooling, which is characterized by the speciality in thermally dealing with the high heat flux equipment, has not gone that far owing to its complexity in the management of the two-phase flow in the space environment. It is also acknowledged that the MPFL, as an overall cooling strategy in the space thermal control system, will not be replaced completely in the foreseeable future because the primary on-board electronic devices require normal heat dissipation demand and only a few equipment such as on-board laser diode and multi-chip modules demand extreme high heat removal technologies. Therefore, a combination of the MPFL and spray cooling technologies, which constitutes the biggest innovation in this paper, is imperatively needed. A hybrid cooling system (HCS) combining the single-phase self-adaptive MPFL and gravity-immune two-phase spray module which satisfies various cooling demands is proposed in the present study. A validating system as a prototype was established on the basis of the optimal design method. Three test cases were conducted to verify the coordinated operation between the single-phase module and two-phase one and investigate thermal performances of both modules. In all the experiments, the controlled temperature of the cold plate in the MPFL remains within a range between 35.9 °C and 41.9 °C under the heat load from 50 W to 150 W. The highest heat flux acquired by the spray cooling module can be up to 468.8 W/cm^2 with the superheat level being 70.0 °C. Results can be drawn that the two modules can be operated simultaneously and independently. Systematic operation efficiency of the proposed HCS is calculated to be 17.7 which displays a high economy of the proposed system.

1. Introduction

Unprecedented evolution of global space industries in exploration scope, vehicle complexity, task variety and duration has been taking place in the last decade. For example, as the flight plan of space shuttle was terminated in 2011 [1], more attention has been paid to the reusable aerospace plane which can implement horizontal take-off and landing, fly across the Earth's atmosphere, cruise in the near space and release satellites or other deep space explorers in the orbit operation stage. It is acknowledged that such space missions will inevitably lead to a boost in both the variety of the on-board electrical and electronic devices and the power requirement since the concept of the more-electric or all-electric vehicle has been running high recently [2]. Due to the incomplete energy conversion, a large amount of heat will be generated during operation [3], which should be handled properly by the thermal control system otherwise the on-board devices or even the entire vehicle will be at risk because of the overheating caused by the accumulated heat [4,5].

Since the heat dissipation demand has been increased greatly, active thermal control strategy is preferred to be the overall spacecraft thermal control system although passive cooling method such as heat pipe, and radiation will be indispensably deployed locally. Possessing several advantages such as gravity immunity, high reliability, technological maturity, the single-phase mechanically pumped fluid loop (MPFL), as an active thermal control approach, has been widely utilized in many famous space vehicles [6]. For instance, an MPFL-based

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https://doi.org/10.1016/j.enconman.2018.09.010
Received 6 July 2018; Received in revised form 27 August 2018; Accepted 2 September 2018

Nomenclature

A	area (cm^2)
c	specific heat (W/kg·K)
h	heat transfer coefficient (W/m^2·K)
m'	mass flow rate (kg/s)
M_p	maximum overall shoot (°C)
P	pressure (kPa)
p_{input}	input power (W)
p_{I}	input power of pump I (W)
p_{II}	input power of pump II (W)
P_{spray}	spray pressure (kPa)
p_{SPM}	heat dissipated by the SPM (W)
q	heat flux (W/cm^2)
Q_{diss}	total quantity of the waste heat dissipated by the HCS (W)
T	temperature (°C)
T_{spray}	SIT (°C)
$\overline{T}$	average temperature (°C)
V	VFR (L/h)

Greek symbols

λ	thermal conductivity (W/m·K)
η	efficiency (%)
τ	time (s)
κ	maximum percent overshoot
χ	distance (m)

Subscripts

cp	cold plate
cp, out	outlet of the cold plate
cp, in	inlet of the cold plate
cu	copper
EO	ejector outlet
eje	ejector
i	location of i in the cold plate (i = 1, 2, 3, 4)
j	location of j in the test heater (j = $c1$, $c2$)
PF	PF
s	settling
sat	Saturation condition
SC	spray chamber
SF	SF
$spray$	spray flow
sys	system
tar	target surface
$tar-c1$	target surface - Location c1
$tar-c2$	target surface - Location c2
w	water

Abbreviations

CP	cold plate
HCS	hybrid cooling system
MFR	mass flow rate
MPFL	mechanically pumped fluid loop
PF	primary flow
SIT	spray inlet temperature
SPM	single phase module
ST	surface temperature
SF	secondary flow
TCV	thermal control valve
TPM	two-phase module
TS	target surface
VFR	volumetric flow rate
VFR-CP	volumetric flow rate through the CP
VFRS	volumetric flow rate of the spray flow
VFRP	volumetric flow rate of the PF

thermal control system for Curiosity which is a USA Mars Science Laboratory was described. Approximately 2000 W waste heat generated from the Radioisotope thermal generator and electronics was designed to be rejected by the MPFL [7]. The primary mechanism of the on-board MPFL is to use thermal control valves (TCVs) to control the flow rate of the coolant according to the comparison between the real-time temperature and the set-point. If the real-time temperature is higher than the set-point, the TCV will allow more coolant to come in to remove the waste heat using the sensible heat of the coolant to level down the real-time temperature. If the real-time temperature is lower than the set-point, less coolant will be allowed to come. Several drawbacks of the traditional MPFL have also been spotted such as a high energy consuming, systematic complexity and low reliability. Efforts towards a novel self-adaptive MPFL in our previous study to overcome the issue above was devoted. Detailed information of the traditional MPFL and the self-adaptive one is provided in the Section 2.

An inherent disadvantage of the single-phase MPFL is that it hardly takes the advantage of the latent heat of the coolant. It means that the MPFL alone can barely dissipate the extreme high heat flux efficiently [8]. As all-electric and more-electric vehicle design concept has been running high in the recent years, higher electrical power demand for the vehicle operation will be inevitable which will lead to a huge boost in the generation rate of waste heat (several hundred kW [9]) due to the incomplete energy conversion [10,11]. What's worse, miniaturization and integration of the electronic device will reduce the surface for heat dissipation clearly which will level up the dissipation requirement ($\geq$500 W/cm^2 [12]). It means thermal control strategy using single-phase MPFL alone will definitely fail to satisfy the heat removal demand, which will pose great risks in the operation of the electronic device and even the flight system [13].

Aiming to deal with the high heat flux equipment, the two-phase spray cooling technology is illustrated to be an appropriate one and believed the next-generation thermal control strategy [14] because liquid-vapour phase change is an efficient and vigorous energy transfer process [16,17]. It has been extensively researched and applied in the cooling of ground-based apparatus [18,19]. In contrast, the space-oriented spray cooling is still in its infancy [20] as few articles were published to disclose the space-oriented spray cooling application. Among the limited literature concerning the space spray cooling technology, great efforts have been devoted to studying the heat transfer and flow condition of the spray in the space environment (low environmental pressure and various gravitational field). Wang et al. [21] investigate the spray cooling performance of an electronic equipment cabin under the low pressure. Acceleration effects upon the spray cooling performances was investigated by Zhang et al. [22] and Michalak et al. [23] respectively. The former one reported that the acceleration effect may boost the cooling capacity for a given surface temperature while the latter concluded that the increasing acceleration would increase the surface superheat. A Comparative study of spray cooling performance under various gravities was carried out by Yoshida et al. [24] under series of parabolic flight and ground experiments. Performances under minus g ($-1g$) cases were generally better than those under positive g ($1g$) cases in the nucleate region. Additionally, no clear effect of gravity was observed in the relatively low spray volume flux (1.4×10^{-4} m^3/(m^2·s)) before the occurrence of CHF, but for cases of relatively large spray volume flux, significant influence of it was