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Investigation of a gravity-immune chip-level spray cooling for thermal protection of laser-based wireless power transmission system

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ABSTRACT

Aiming to enhance the on-board thermal protection platform for the space laser-based wireless power transmission (WPT) system which is essential for the development of distributed space systems, an improved gravity-immune closed-loop spray cooling system with an ejector loop is proposed in this paper. The gravity-immunity features its design of the novel fluidic loop, uncovering the reliability of the future in-orbit test and potential of the practical deployment of the spacecraft thermal management. The biggest innovation of the fluidic loop lies in the integration of the spray cooling loop and an ejector loop which is to create a local low pressure area without any rotary mechanical components for the purpose of consistently removing the liquid–vapor mixture from a relatively high pressure in the spray chamber guaranteeing a relatively high operation efficiency. Ground-based experimental set-up was established to test the feasibility of the system's operation mechanism, based on which thermal tests were organized to study the practical heat dissipation capability in both continuous and periodic operating tasks. The largest critical heat flux (CHF) could go or be up to 705 W/cm^2 and optimal efficiency at CHF was calculated to be 9.34% in the continuous mode. Additionally, nozzle inlet temperature with high subcooling degree is preferred in the periodic mode.

1. Introduction

The distributed space system (DSS), a concept of distributing the functionality of a single spacecraft among several closely-flying satellites, where spacecrafts fly in formation are involved has been revolutionising the pattern of our human space-oriented explorations. Compared with the former single function-centralized space vehicle, several advantages concerning the newly proposed technology, such as mass and expense reduction, high reliability and modularity improvement, risk mitigation etc. are spotted by aerospace scientists [1]. However, similar to other applications in the field of industry, the lack of power supplement has become a critical challenge for the development of DSS. Schemes of the power supplementary components for the traditional space plane are mainly self-powered systems (for example, nuclear sources, solar array-battery systems, fuel cells and so on). As the proposal of DSS has been running high in recent years, it is impossible and impractical to install such power generation unit in each spacecraft, which would lead to resource waste and budget crisis. What's worse, the overall volume, mass and complexity of the vehicles in formation would reach an extremely high level that is unacceptable especially in the aerospace engineering.

Fractionation of the power subsystem accompanied with wireless power transmission (WPT) technology, in which a resource vehicle collects solar energy and distribute it to mission vehicles (MVs) wirelessly [2], has shed light on the solution of power supply issue for DSS. Since the space power generation system is a mature technology as stated above, the implementation of WPT is critical for DSS to manoeuvre MVs in a cluster.

Several approaches regarding electromagnetic radiation WPT which is applied to space long-distance transmission have been intensively investigated by scientists for decades. The space-to-space power transfer mission was firstly proposed in as early as 1985 using microwave power transmission (MPT) [3]. The MPT consists of four modules: Solar cell arrays where the direct current (DC) is generated from solar energy, DC-to-RF device where the DC is converted into radio frequency (RF), antennas where the beam microwave energy is produced and rectenna arrays located in the power receiving spacecraft where the received microwave is converted into useful DC power feeding the whole operation of the MVs. Although the overall ideal end-to-end efficiency is estimated

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Nomenclature

T	temperature (°C)
T_{in}	nozzle inlet temperature (°C)
h	heat transfer coefficient (W/m^2 K)
q	heat flux (W/cm^2)
ΔP	pressure drop across nozzle (MPa)
d_0	orifice Diameter (mm)
μ	dynamic viscosity (Pa/s)
d_{32}	Sauter mean diameter (μm)
g	gravitational constant (m/s^2)
V	volumetric flow rate (L/h)
m'	mass flow rate (kg/s)
A	area (m^2)
d_H	hydraulic diameter of the micro-channel (m)
Greek symbols	
ρ	density (kg/m^3)
λ	thermal conductivity (W/m K)
η	efficiency (%)
σ	surface tension (N/m)
χ	distance (m)
Subscripts	
i	location of i ($i = 1, 2$)
sur	target surface
l	liquid phase
cu	copper
v	vapor phase
sat	saturation condition
CHF	critical heat flux
$s-2$	target surface - Location 2
$s-1$	target surface - Location 1

to be 43% [4], higher than that of other methods, the value is impractical because the efficiency is highly dependent on the rectenna array size and relative location between antennas and rectenna arrays. The efficiency will reduce dramatically by the antenna misalignments [5]. Other disadvantages such as low energy density, prohibitive costs, disturbance of communication etc. have restrained its extensive deployment in the space. Turner [6] discussed an efficient method of distributing high energy–density beams of unconverted concentrated sunlight towards the high-temperature MVs' receivers where heat engines operate to generate power from the stored heat in the receivers of MVs. Although energy conversion only occurs at the heat engine eliminating multiple intermediate energy conversions, indicating that a huge increase in the end-to-end efficiency (exceed 20%), technological immaturity and skyrocketing launch cost of reflective optics for sunlight concentration, collimation and emission still prohibit it from space application.

With advantages of higher energy density and more available and flexible devices, which facilitate space long-range power transmission, there has been a boom in the development of laser-based WPT technology [7]. The laser power beaming system (LPBS) which is schematically shown in Fig. 1 is the most critical component in laser-based WPT. High energy laser is generated via laser diodes which are powered by the electrical power originally coming from the solar power cells. Then assisted by the beam director, the laser beam is projected to the remote photovoltaic (PV) receivers of the MVs. Finally, a conversion from light back to electricity is occurred in PV arrays to power the subsystem of the MVs [8]. In fact, this technology has also been considered as a clear candidate for the foundation of the space power station where the collected energy is transported to the ground.

Although the LPBS theoretically enables the resource vehicle to transmit large amount of available power (several hundred kW [9]) to any location in space, the efficiency, which is determined by two conversion processes, must be considered in assessment of performance systematically. The efficiency of electro-optical conversion which takes place in laser diodes was calculated to be 50% [10], while that of the reverse conversion which occurs in PV arrays was estimated to be 20–30% [11]. It indicates that only 10–15% of the original energy is able to be utilized by the power-consumption devices and correspondingly the large majority of it is left as waste heat remaining in the interior structures of either

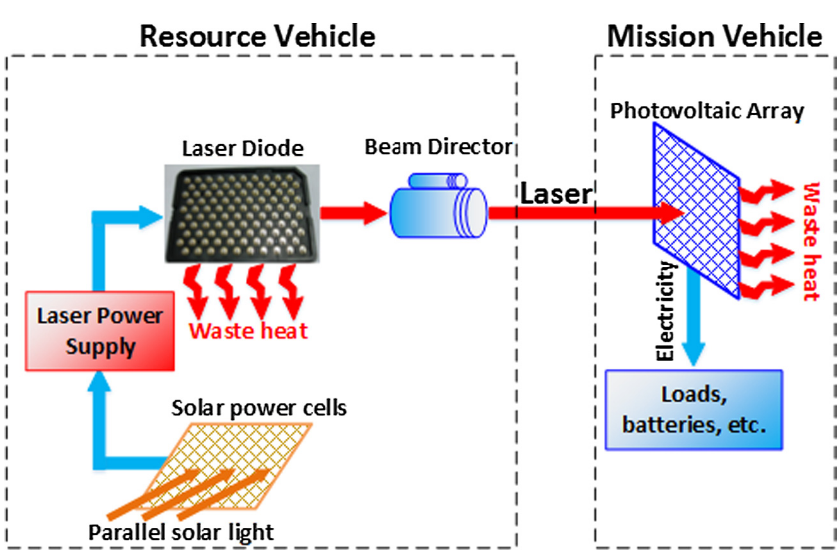

Fig. 1. General description of the laser power beaming system.