International Journal of Heat and Mass Transfer 119 (2018) 496–507

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Investigation of heat transfer mechanism of low environmental pressure large-space spray cooling for near-space flight systems

Ji-Xiang Wang [a], Yun-Ze Li [a,*], Xi-Kui Yu [b], Guang-Chao Li [a], Xin-Yan Ji [a,c]

[a] School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, PR China
[b] Shenyang Aircraft Design and Research Institute, AVIC, Shenyang 110035, PR China
[c] Beijing Institute of Spacecraft Environment Engineering, Beijing 100094, PR China

ARTICLE INFO

Article history:
Received 3 May 2017
Received in revised form 15 October 2017
Accepted 27 November 2017

Keywords:
Spray cooling
Flash boiling
On-board thermal management
Aerospace application

ABSTRACT

There is an imperative need to employ the on-board electro-driven equipment since the concept of all-electric and more-electric technology has been applied in the design of near-space flight systems. This application will inevitably bring a dramatic increase in the waste heat because of incomplete energy conversion, which will easily cause an overheating in the electrical device. What's worse, the near-space flight system will encounter extremely tough thermal environment where the atmosphere is rarefied due to the high altitude and the temperature of the introduced air into the plane is awfully high owing to the aerodynamic heat, both of which will pose a great challenge for the near-space thermal control system. Aiming to design an efficient thermal protection strategy of the on-board permanent magnet synchronous motor for the steering of major flight control which operates constantly in the near-space cruise stage, this paper proposes a novel low environmental pressure large-space spray cooling system. Revolving the scheme, a small-scaled experimental prototype was designed and established, upon which thermal tests were conducted to estimate influence of several parameters such as environmental pressure, nozzle inlet temperature and spray volumetric flow rate upon the cooling performance. Both flash boiling and subcooled spray phenomena were discussed, results of which suggests the former is more desirable due to the temperature uniformity and high coolant utilization. In addition, capable of providing performance predictions and guidances for future full-scaled tests, an empirical experimental correlation with the relative error of only ±8% was acquired on the basis of the data in the flash boiling region.

1. Introduction

Recently, the boundary between aerospace and aviation systems has become vague, accelerating the historic integration of the astronautic and aeronautic sciences. Therefore the near space connecting the astrospace where conventional spacecrafts commonly operate and the stratosphere where traditional airplanes fly has increasingly been paid attention to in the last decades [1]. Novel near-space vehicles (NSV) such as commercial space flight systems, hypersonic vehicles (HVs) and manned two-stage-to-orbit reusable vehicles will intend to operate in or get across the near space, bringing huge strategic significances in economic development, national defence and deep-space exploration. [2] Many industrially developed countries such as the USA and Russia have set up programs of developing NSVs as a top priority where the on-board propulsion, aerodynamics, energy management and attitude or altitude control [3] should be further investigated since the operation of the NSVs differs from that of either conventional aircrafts or spacecrafts [1].

For example, the HV is a reusable plane that can execute horizontal take-off and landing on the ground, fly through the edge of Earth's atmosphere, cruise in the near space which is defined as the range of Earth altitude from approximately 20 km to 100 km [4], implement the in-orbit tasks in the space environment and flexibly re-enter into the atmospheric layer. Such wide flight envelope determines that the HV will be exposed to complicated thermal environment [5], especially for the near-space cruise stage where the atmosphere is rarefied due to the high altitude and the temperature of the introduced air into the plane is awfully high owing to the aerodynamic heat. In this stage a function failure in the common cold-air-assisted convective heat removal technology will be occurred. Hence the on-board thermal management for the hypersonic technologies need to be reconsidered as well.

To date, great efforts has been made towards the thermal performance analysis and protection technology dealing with the high

---

[*] Corresponding author.
E-mail address: buaalyz@163.com (Y.-Z. Li).

https://doi.org/10.1016/j.ijheatmasstransfer.2017.11.128
0017-9310/

Nomenclature

T	temperature (°C)
T_{in}	nozzle inlet temperature (°C)
T^*	dimensionless temperature of SPMSM
$\overline{T}$	average temperature (°C)
ΔP_{sn}	pressure drop across nozzle (MPa)
d_{sn}	nozzle orifice diameter (mm)
g	gravitational constant (m/s^2)
P_e^*	dimensionless environmental pressure
v	velocity (m/s)
R	gas constant (8314 N·m/(kmol·K))
H	height (m)
L	length (m)
P	heat generation rate (W)
V	volume (m^3)
U	voltage (V)
I	electricity (A)
c_p	sensible heat ($J \cdot kg^{-1}K^{-1}$)
V'	spray volumetric flow rate measured by the flow meter (L/h)
h_{lg}	latent heat (kJ/kg)
x	portion of the evaporated coolant (%)
M	molar mass (g/mol)
d_{32}	sauter mean diameter (μm)
P_e	environmental pressure (kPa)
D	spray distance (m)
$d_{E-SPMSM}$	hydraulic diameter of the cross section of SPMSM (m)
d_s	diameter of the spray cone area (m)
h	heat transfer coefficient ($W/m^2 \cdot K$)
$\overline{h}$	heat transfer coefficient based on the average temperature ($W/m^2 \cdot K$)
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
Kn	Knudsen number

Greek symbols

λ	thermal conductivity (W/m·K)
α	molecule mean free path (m)
ε	dimensionless characteristic geometric size
σ	surface tension (N/m)
μ	dynamic viscosity (Pa·s)
ς	uncertainty (%)
ρ	density (kg/m^3)
υ'	practical Spray volumetric flow rate (L/h)
γ	spray cone angle
τ	dimensionless total heat generation rate

Subscripts

sat	saturated state
l	liquid phase
g	gas phase
a	air
cu	copper
PMSM	permanent magnet synchronous motor
SPMSM	simulated PMSM
*g*0	gas-phase under atmospheric pressure
dro	droplet

aerodynamic heating rate generated on the external surface structure during the hypersonic flight through the atmosphere. Persova et al. [6] developed a numerical scheme based on the finite-element-method for efficiently calculating the aerodynamic heat flux at the non-zero angle of attack. Temperature field and stress–strain behaviour of the focused HV's nose cap can be mapped using the solution of the coupled 3D-problem. The calculated heat flux at stagnation point can be larger than 1000 kW/m^2. Thermal protection strategies such as internal liquid coolant cooling and gas cooling are proposed in references [7] and [8] respectively. With all these scientific breakthroughs and discoveries, thermal protection system for the aerodynamic heating has become a relatively mature technology.

In addition to the external aerodynamic heating phenomenon, the increasing internal heat load generated by incomplete energy conversion in the on-board electro-driven equipment will also pose great risks during the execution of flight missions, which is intolerable for the aerospace engineering. To guarantee the reliability of the on-board equipment which is extremely significant for the implementation of the near-space mission and even the safety of the entire vehicle, the on-board thermal management arranged to provide indoor thermal protection should be studied as well especially for the fact that the concept of more-electric or all-electric systems have been extensively applied in the design of modern vehicles [9].

Since the more-electric/all-electric aeroplane has been running high in recent years, traditional hydraulic, pneumatic and mechanic on-board modules will be gradually replaced by electro-driven equipment (EDE). For example, permanent magnet synchronous motors (PMSMs) are replacing hydraulic actuators due to their simple structure, light mass and high operation efficiency [10] for the action of major flight control surface such as wing flag and aileron. Simultaneously, waste heat generated from the incomplete energy conversion inside the PMSM will cause a dramatic increase in the temperature of the PMSM's subassemblies such as stator winding, insulation layer and bearings which are vulnerable thermal-sensitive components if the thermal control system fails to remove the equal heat to the outside space. Thermal overloading of the PMSM is the primary trigger to cause irreversible demagnetization, bringing an unfavourable degradation or even a permanent damage of the PMSM. It is reported that the energy conversion efficiency of the PMSM could be within the range of 70–90% [11] which can be listed top among EDE. As the total power of the EDE system could be more than 50 kW [12], at least 5–15 kW will be produced inside the machine as the form of the waste heat. What's worse, accommodating the PMSM in a hermetic casing for the purpose of providing a relatively nonintrusive environment is one of the common packaging methods and developing permanent magnet micro-motors is a tendency in almost all areas of technologies especially in aeronautical and astronautical field where space and mass savings should be the priority, both of which will enhance the operation reliability, but meanwhile deteriorate the heat removal condition unavoidably. The stator winding, which is the main heat generation component due to the copper and iron loss, is attached tightly to the inside wall of the casing, which means that heat conduction is involved in the heat dissipation process. Then, convective heat transfer is engaged in transferring the heat from the casing to the outer space with the assistance of fins as shown in Fig. 1.

Researchers have done extensive works in the area of the heat dissipation technique regarding the thermal control of the EDE. An air-cooling method with a centrifugal impeller for the motor was proposed by Li [13]. However, the air-assisted cooling technology is very difficult to deploy in the near-space cruise operation