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Optimization of a vapor compression heat pump for satellite cooling

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ABSTRACT

In recent years the heat fluxes that must be removed from aerospace electrical systems have been steadily increasing, motivating the use of vapor compression heat pumps to cool the electrical components.The heat pump system considered here is a conventional four-component heat pump that uses an oil-free scroll compressor in place of the oil-lubricated compressor that is more often employed for terrestrial applications.The first part of this study considers the fluid selection, and refrigerant R152a is found to be a good choice. This study then delves into the detailed performance analysis of the oil-free scroll compressors that are envisaged to be used in this 12 kW system, with predicted COP over 4.0. Finally, the entire operating envelope of the heat pump system is considered, including variations in electrical load and seasonal variations in the radiative environmental temperature.The source code for the analysis presented here and that of PDSim are provided as supplemental information.

Optimisation d'une pompe à chaleur à compression de vapeur pour le refroidissement de satellite

Mots clés : Pompe à chaleur ; Compresseur à spirale ; Refroidissement de satellite

1. Introduction

Satellites are deployed into low earth orbit (LEO) or geosynchronous orbit (GEO) in order to provide a platform for a wide range of missions, including telecommunications systems, surveillance systems, and astronomical systems, amongst others. For terrestrial electronics systems, the last few decades have brought with them a large increase in electrical component power density. Aerospace applications have seen a similar increase in electrical power density of their electrical payloads, which results in a commensurate need in cooling for the electronic components.

For many past and present satellites, cooling of components was achieved through traditional heat pipes connecting electrical components and large radiators. As electrical

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cooling demands have increased, radiator surface area has not increased at the same pace. Therefore, to reject more heat for a given radiator area, the surface temperature of the radiator must increase. Alternatively, the heat rejection rate can be further increased through the use of deployable radiators.

If the desired radiator surface temperature is above the working temperature of the electrical components to be cooled, it is necessary to employ active cooling through the use of a heat pump to boost the temperature of a working fluid above the desired radiator surface temperature. Through condensation of the working fluid, the heat can be rejected through the radiator.

The heat pump systems required for aerospace applications share many commonalities with those of terrestrial applications. In the simplest case, both terrestrial and aerospace heat pump units are composed of the conventional four-component system – compressor, condenser, expansion device and evaporator.

In some ways, design and optimization of heat pumps for aerospace applications differs from that of terrestrial applications. Some of the most important considerations are:

- Satellites must be delivered to orbit by rocket engines, which costs approximately USD \$25,000/kg^{-1} (EARSC, 2011).
- The satellite will operate in a low-gravity environment, making oil-refrigerant separation difficult.
- There is no possibility of servicing the system during its lifetime.
- The maximum working temperatures of the electrical components is specified

There is a relative paucity of published literature on the design of heat pumps for aerospace and low-gravity applications. Woolley (1993) patented an oil separator that it is claimed would be well-suited for application in zero-gravity environments. St. Pierre (1987) patented a heat pump system that can operate in zero-gravity environments. Messaros and Verstracte (1994) describe the development process for a multi-stage piston compressor for a Joule—Thomson cooler. This compressor uses a forced oil lubrication system, and has a specified failure rate of less than 1.42 failures per million hours. It employs the oil separator described in the patent of Woolley. Nikanpour et al. (1997) investigated a range of system designs for an aerospace heat pump system with cooling capacity between 300 W and 2 kW and evaporation and condensation temperatures of 276 K and 343 K respectively. They find an optimal radiator temperature that minimizes the system mass. Domitrovic et al. (2003) carried out an experimental campaign to characterize the performance of a heat pump prototype at terrestrial gravity. Cole et al. (2006) described preliminary work on a development project for a 5 kW–15 kW cooling capacity heat pump that would achieve a COP of 1.7 with evaporation and condensation temperatures of 4.44 °C and 60 °C respectively.

Nomenclature

A_{rad}	Radiator area (m^2)
f	Rotational frequency (Hz)
h_i	Inlet enthalpy (J kg^{-1})
h_i	Internal height of channel (m)
l	Segment length
L	Length (m)
$\dot{m}$	Mass flow rate (kg s^{-1})
N	Number (–)
p	Pressure (Pa)
$\dot{Q}$	Heat transfer rate (W)
q'	Heat transfer per unit length (W m^{-1})
q''	Heat transfer per area (W m^{-2})
R	Thermal resistance (m^2 K W^{-1})
T	Temperature (K)
ΔT	Temperature difference (K)
α	Heat transfer coefficient (W m^{-2} K^{-1})
ω	Rotational speed (rad s^{-1})
ω_r	Reduced rotational speed (–)
η	Efficiency (–)
COP	Coeff. of Performance (–)
w_i	Internal width of channel (m)
w	Width (m)
$\dot{W}$	Power (W)
ε	Radiator emissivity (–)

Subscripts

∞	Ambient
1,2,3,4	State point index
c	Radiator area
c	Condensing
cr	Reduced condensing
crit	Critical
circuit	Circuit
channel	Channel
e	Evaporation
evap	Evaporator
e,i	Evaporator inlet
e,o	Evaporator outlet
er	Reduced evaporation
i	Inlet
flow	Flow
r	Refrigerant
rad	Radiator
pass	Pass
o	Outlet
oi	Overall isentropic
v	Volumetric
mc	Microchannel
pass	Radiator pass
s	Surface
sh	Superheat
sc,target	Subcooling target
triple	Triple point
total	Total
TIM	Thermal Interface Material