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Research Paper

A comparative study of launch canister thermal control systems using a liquid or gas working medium

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HIGHLIGHTS

- A thermal control system using a liquid working medium (L-TCS) in launch canister is proposed.
- The thermal control systems using a gas or liquid working medium are compared.
- The comparison is based on the same working medium's heat capacity flow rate.
- The L-TCS is better in both energy efficiencies and temperature control effects.

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ABSTRACT

A launch canister thermal control system (TCS) is important for the protection of the engine of a rocket and its electronic devices. Current TCSs using a gas working medium (G-TCS) have high energy consumption and unsatisfactory temperature control effects. Hence, in this study, a TCS using a liquid working medium (L-TCS) was proposed. The two systems were compared through verified simulation models and engineering calculations in different cases. The results of the loaded stable operation case showed that an L-TCS requires much less energy and has a much higher energy efficiency in all the analyzed seasons, namely, spring, summer, and winter, in comparison to the G-TCS. Moreover, an L-TCS is superior to a G-TCS in terms of the temperature control effects. In the unloaded start-up case, both the TCS types have their respective advantages, but their start-up durations are long. However, introducing a mixing fan can drastically decrease the start-up duration of the L-TCS.

1. Introduction

A launch canister can provide protection for a rocket during standby, and its thermal control system (TCS) can provide an appropriate temperature environment for the engine of the rocket and its electronic devices. However, current research on the thermal control of a launch canister is mainly focused on the launch phase [1–3], and studies on the thermal control during standby are rarely reported. Currently, TCSs using a gas working medium (G-TCS) are widely used because there is no leakage and requirement of any additional component in the canister. However, because of the small volumetric specific heat capacity of the air, a large volume flow rate is necessary to achieve the temperature control objective, which inevitably leads to a high flow energy consumption.

Presently, a TCS using a liquid working medium (L-TCS) is being used in buildings [4–6], space activities [7–9], batteries [10–13], and electronics [14,15]. Some studies have compared the G-TCSs and L-TCSs in the thermal management of batteries. Nelson et al. [11] found that the power demand for circulating air is approximately 55 times that for circulating liquid for the same Nusselt number. Sasmito et al. [12] observed that the pumping power in air cooling is approximately 24 times that in liquid cooling for the same net power output. Moreover, the simulation results of Chen et al. [13] showed that an air cooling system requires twice to thrice the pumping energy of a liquid cooling system at the same average temperature of the battery stack. In summary, all the studies similarly concluded that an L-TCS offers better energy savings.

Therefore, in this work, the adoption of an L-TCS in a launch canister was proposed. In the above-mentioned studies comparing a G-TCS and an L-TCS, there are considerable differences in the extents of energy saving evaluated because of the different preconditions. Moreover, those preconditions may not be appropriate as they cannot reflect the heat carrying capabilities of the working medium. Hence, a precondition based on the heat carrying capability was first proposed, i.e., comparing the working mediums at the

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Nomenclature

Mathematical symbols

c_p	specific heat capacity (J kg^{-1} K^{-1})
$\dot{C}_p$	heat capacity flow rate (W K^{-1})
D	diameter (m)
E	energy consumption in one day (kW h)
E_f	flow energy consumption in one day (kW h)
h	convective heat transfer coefficient (W m^{-2} K^{-1})
h_a	convective heat transfer coefficient between the outer wall and ambient air (W m^{-2} K^{-1})
k_i	thermal conductivity of the insulating material (W m^{-1} K^{-1})
L	pipe length (m)
$\dot{m}$	mass flow rate (kg s^{-1})
Δp	pressure drop (kPa)
Q	heat consumption in one day (kW h)
$\dot{Q}_{pipe}$	heat loss rate through the external pipe (W)
R_m	specific frictional resistance (Pa m^{-1})
t	integration time (one day)
t_a	ambient air temperature (°C)
t_w	average temperature of the working medium (°C)
ΔT_{max}	maximal temperature difference of the surface of the rocket (°C)
T	temperature (°C)
υ	wind speed (m s^{-1})
$\dot{V}$	volume flow rate (m^3 s^{-1})
Z	local resistance (Pa)

Greek symbols

Δ	difference
α	thermal coupling coefficient (W m^{-2} K^{-1})
η	energy efficiency
ρ	density (kg m^{-3})
σ^2	variance of the average temperature of the surface of the rocket
ϕ	diameter (m)
τ	time (s)

Subscripts

a	air
c	canister
he	heat exchanger
g	gas working medium
i	inlet or inner surface
l	liquid working medium
max	maximum
mean	mean value
min	minimum
o	outlet or outer surface
p	external pipe
total	total

same heat capacity flow rate. Having the same heat capacity flow rate implies the temperature difference between the inlet and outlet is the same for the same thermal requirement. Therefore, the temperature control effects of systems using different working mediums can be compared for the same thermal requirement. Moreover, external pipes and heat exchangers were considered in the calculations to provide a comprehensive understanding of the power consumptions of a G-TCS and an L-TCS, which is rarely reported.

In this work, the simulation models of a G-TCS and an L-TCS were constructed and experimentally verified, and used to compare the two systems in two cases under different seasons. In the loaded stable operation case, the energy consumptions, energy efficiencies, and temperature control effects of these two systems were compared in spring, summer, and winter. The unloaded start-up case was examined in the summer and winter seasons to compare their start-up performances.

2. Model

In the simulation of the launch canister, the shapes of the canister and rocket were simplified as cylinders. The effects of the connection, support, and other components were ignored in the thermal simulations of the G-TCS and L-TCS and flow simulation of the L-TCS. In the flow simulation of the G-TCS, the supporting structures were included for the accurate calculation of the flow resistance. As shown in Fig. 1, the TCSs consist of a main part within the canister and of a peripheral system including external pipes, a heat exchanger, and a fan or pump. The dimensions and materials of each part are also shown in Fig. 1. Table 1 lists the physical properties of the materials used in each part of the models, in which the liquid working medium, Therminol D-12, is a type of heat transfer fluid. The thermal conductivity and specific heat capacity of polyurethane were measured using a steady-state method and differential scanning calorimetry. The radiative properties of Al alloy and painted Al alloy were measured using a spectrophotometer.

The purpose of the thermal control is to maintain the surface temperature of the rocket at approximately 20 °C. The finite element analysis software, I-DEAS [16] was used for the simulation of the thermal and flow processes in the canisters. The outer surface of the canister convects heat to the ambient air, exchanges heat by radiating into the sky, and receives solar irradiation. The convective heat transfer coefficient is expressed as [17]

$$h = -0.0203\upsilon^2 + 1.766\upsilon + 12.263. \quad (1)$$

The thermal coupling coefficient between the thermal insulating layer and inner or outer wall is set as 50 W/(m^2·K), which was obtained from the experiments based on a steady-state method. The results of the experiments showed that this coefficient was between 44.47–107.82 W/(m^2·K) under pressures of 1584.68–3110.52 Pa. Through calculations, it was found that the specific value of the coefficient in this range hardly affected the thermal conduction in the canister. The inner surface of the canister and outer surface of the rocket exchange heat via radiation, and both convect to the air inside the canister. For the L-TCS, the liquid working medium is assumed to convect directly to the inner surface of the canister where a pipe is attached, reasonably ignoring the thermal resistance of the heat conduction inside the pipe wall and solder. The simulation results have been verified to be irrelevant to space steps.

To simplify the calculations, the structure of the external pipes of the TCSs was assumed to be straight with an elbow at each end. In the G-TCS, the straight pipe is 6.60 m long with an inner diameter of 200 mm, and the bend radii of both the elbows are 200 mm. In the L-TCS, the straight pipe is 9.94 m long with an inner diameter of 20 mm, and the bend radii of both the elbows are 30 mm. The absolute roughness of the inner wall of the external pipe is set as 0.15 mm [18] in the G-TCS and 0.002 mm [19] in the L-TCS. The pressure drop along the external pipe, Δp_p, can be calculated as