Applied Thermal Engineering 118 (2017) 82–89

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Feasibility analysis and application consideration of a rapid method to obtain subcooled cryogenic propellants

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HIGHLIGHTS

- A rapid method to obtain subcooled cryogenic propellants is proposed.
- The thermodynamic model of temperature dropping rate is developed.
- The subcooled time of the present method can drastically shorten.
- The cooling way is changed into active cooling with passive cooling.

ARTICLE INFO

Article history:
Received 31 October 2016
Revised 13 January 2017
Accepted 16 February 2017
Available online 22 February 2017

Keywords:
Subcooled cryogenic propellants
Rapid obtaining subcooled degree
Pumping decompression method
Subcooled time
Liquid consumption

ABSTRACT

Subcooled cryogenic propellants that can significantly improve its own thermodynamic performances have attracted more and more attentions. To shorten subcooled time, a rapid method to obtain subcooled degree is proposed. To illustrate the thermodynamic essence of the method proposed as a whole process system, the thermodynamic analysis is carried out to explain the throttle cooling process. To quantitatively compare and explain the rapid feature, the thermodynamic model of cooling rate is developed to calculate the subcooled time and liquid consumption, and nonlinear equations are solved numerically. The effects of several key parameters are then analyzed. The results show that the method presented in this paper is feasible and effective. Compared with the conventional pumping decompression method, the subcooled time used the rapid method can drastically shorten, and even cut down on more than one half in some cases. The cooling way is changed from a conventional type of passive cooling to the novel type which combines active cooling with passive cooling. Subcooled time and liquid consumption are inversely proportional to the pumping speed, linearly positively correlated to the inlet pressure of the throttle valve, and exponentially positively correlated to the inlet temperature of the throttle valve. The proposed method can be applied at the launch site of large cryogenic launch vehicles in the future.

1. Introduction

Cryogenic propellants applied to large launch vehicles have become one of the most widely used fuels due to the advantages of non-toxic, pollution-free, low-cost, high-specific impulse and large thrust. The specific impulse of cryogenic propellants can be 30–40% higher than that of propellants at normal atmospheric temperature [1,2]. At present, the temperature of cryogenic propellants is mostly close to the normal boiling point, representing thermal physical performances that remain insufficient, especially for liquid hydrogen. Many studies have demonstrated that subcooled cryogenic propellants can significantly improve its own thermodynamic performances in engineering applications [3–23]. For instance, when the liquid hydrogen temperature decreases from normal boiling point temperature (20.39 K) to triple-point temperature (13.8 K), its density and sensible cooling capacity per unit volume increase by 8.8% and 20%, respectively [5]. When the densities of liquid hydrogen and liquid oxygen increase by 8% and 10%, respectively, the total take-off weight of launch vehicles is reduced by as much as 20% [6].

Many investigators [24–33] have discussed various methods to obtain subcooled degree, which is a prerequisite of using subcooled cryogenic propellants. For instance, Mustafi [7,8] proposed a novel method to implement cryogenic propellant cooling called the thermodynamic cryogen subcooled (TCS). Baik [25] identified the most cost effective densification system. Several liquefaction/refrigera-

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http://dx.doi.org/10.1016/j.applthermaleng.2017.02.088
1359-4311/

Nomenclature

c_{pg}	specific heat at constant pressure for gas, W/(kg K)
c_{pL}	specific heat at constant pressure for liquid, W/(kg K)
c_{ps}	specific heat for solid, W/(kg K)
m_L	liquid mass, kg
$\dot{m}_p$	gasification rate by pumping decompression formation, kg/s
$\dot{m}_t$	mass flow of throttle cooling, kg/s
$\dot{m}_c$	mass flow of vacuum pump, kg/s
h_{gs}	enthalpy of saturation gas, kJ/kg
h_{Ls}	enthalpy of saturation liquid, kJ/kg
h_{in}	enthalpy of throttle valve inlet, kJ/kg
h_{out}	enthalpy from diffuser flowing out, kJ/kg
i	grid node
h_g	gas enthalpy per unit mass, kJ/kg
h_L	liquid enthalpy per unit mass, kJ/kg
u_s	solid internal energy per unit mass, kJ/kg
dm_g/dt	change of gas mass in ullage per unit time, kg/s
dm_L/dt	change of liquid mass per unit time, kg/s
dE_g/dt	change of gas total energy per unit time, W
dE_L/dt	change of liquid total energy per unit time, W
dE_s/dt	change of solid total energy per unit time, W
Q_c	external heat leakage, W
Q_p	cooling capacity of pumping decompression, W
S	pumping speed of vacuum pump, m^3/s
Q_t	throttling cooling capacity, W
V_t	total volume of the subcooler, m^3
V_L	liquid volume, m^3
T	temperature, K

Greek symbols

ζ	evaporation rate of day and night
ρ_g	gas density, kg/m^3
$d\tau$	time step
ϕ	vapor fraction, kg/kg

tion combinations were considered for densifying hydrogen and oxygen propellants. Schmidt [31] verified the practicability of subcooled cryogenic liquids by injecting non-condensable gas into the liquid. Through the above massive literature investigations, it is found that these methods to obtain subcooled cryogenic propellants mainly include a heat transfer method, a pumping decompression method and a helium injection method. For large or heavy launch vehicles in the future, when subcooled cryogenic propellants are used as fuels, there are two key characteristics: (1) the subcooled degree need to be sufficiently large (approaching the triple-point temperature); (2) the subcooled requirement is also very large for each launching task in excess of 1000 m^3 (e.g., the maximum loading volume of liquid hydrogen for American Saturn V have reached 1200 m^3 [34]). Therefore, the pumping decompression method is one of most sensible and feasible options for engineering applications. However, its disadvantages are that the subcooled time is too long, and cannot be controlled arbitrarily.

With the rapid development of aerospace technology, the demand for launching tasks associated with launch vehicles have also increased quickly, so preparation period for each launching task has to be shortened correspondingly. Although the cooling system used to obtain subcooled cryogenic propellants is only a sub-system, it still occupies a lot of preparation time for the ground loading system. Moreover, the longer subcooled time, the more heat leakage, so the waste of cryogenic propellants is even greater correspondingly. Therefore, the rapid method to obtain subcooled cryogenic propellants is proposed to ensure intensive launch for future launch vehicles, shorten preparation period of each launching task and enhance cryogenic propellants utilization. To gain a better understanding on the present method, theoretical feasibility is analyzed, the thermodynamic model of cooling rate is developed, and effects of several key parameters are discussed. The results of this study may further supplement knowledge hierarchy of cryogenic propellants cooling, and provide theoretical basis and technology support for launching large or heavy launch vehicles in the future.

2. Configuration and feasibility analysis

2.1. Fundamental configuration

Fig. 1 displays the subcooler that consists of tank components, baffle components, throttle components and pumping decompression components. The tank components include an inner tank, an outlet tank, insulation materials, pipelines, valves and instruments. The baffle components are used to prevent liquid from being pumped out directly. The pumping decompression components include a heat exchange device, valves, pipelines and evacuated devices. The throttle components include pipelines, valves, a cryogenic liquid pump, throttle devices, a heat exchanger and a diffuser.

2.2. Theoretical feasibility analysis

The rapid method presented in this paper can be realized by a combined system including the pumping decompression cooling and the throttle cooling. Fig. 2 shows the p–T diagram to illustrate the pumping decompression cooling process. It can be clearly seen that the corresponding saturation temperature gradually declines with reducing of the ullage pressure, as shown in curve a–b in this figure. Then thermodynamic equilibrium state at gas-liquid interface is being changed due to the change of pressure, the gasification of liquid continuously occurs to absorb a great deal of latent heat, resulting in the decline of the bulk liquid temperature. The area of phase-change heat transfer is the gas-liquid interface in the subcooler.

The throttle cooling is to utilize the Joule-Thomson effect to achieve cooling capacity. It is well known that the adiabatic throttle process through J-T valve is an isenthalpic expansion of the fluid, in which the specific enthalpy of the fluid at entrance and exit of valve must be equal. It follows that differential cooling can only be achieved if the constant enthalpy curve in p–T space has a positive slope. This requirement can be explained in more common terms by the introduction of what is called the Joule-Thomason coefficient μ, which is simply the slope of a constant enthalpy curve in p–T space:

$$\mu = \left(\frac{\partial T}{\partial p}\right)_h \tag{1}$$

To achieve cooling by the Joule-Thomson effect, this coefficient must be positive. For real gases, μ can be either positive or negative depending on the state of the fluid. However, for liquids formed two-phase flow in cooling system presented in this paper, μ can be positive. For further understanding the physical process, the Joule-Thomason coefficient using a theorem of partial differentiation can be rewrite as

$$\mu = -\left(\frac{\partial T}{\partial h}\right)_p \left(\frac{\partial h}{\partial p}\right)_T \tag{2}$$