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Research Paper

Performance of thermodynamic vent system for cryogenic propellant storage using different control strategies

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HIGHLIGHTS

- The gas-liquid throttle mode and smaller valve opening contribute to reduced fluid mass loss.
- The control strategy which operates the pump and vent valve through separate methods is preferred.
- The TVS operation is more challenging with helium pressurization than without helium pressurization.

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ABSTRACT

The performance of the thermodynamic vent systems (TVS) is significantly influenced by the operating parameters, initial condition, and geometry of the tank. This paper presents an experimental investigation on the effects of operating parameters on liquid nitrogen tank pressure control including different throttling modes and control strategies. Two control strategies were implemented experimentally on a TVS-equipped LN_2 tank. The first strategy involves starting the pump and vent valve simultaneously once the ullage pressure increases to the upper limit of the control band. The second strategy involves operating the pump based on the ullage pressure, while the vent valve is controlled based on both the ullage pressure and bulk-liquid temperature. The results showed that the pressure-drop rate under the gas–liquid throttling mode was found to be approximately 1.95 times higher than that under the liquid-only throttling mode. The temperature increase rates of the ullage and liquid in the first strategy are slightly slower than those in the second strategy, whereas the average mass lost in the first strategy is approximately 3.25 times that in the second strategy for the same operation time. In addition, the effect of a non-condensable gas on the TVS performance was comparatively investigated.

1. Introduction

The cryogenic propellant pair LH_2–LO_2 is widely used for space exploration because of their high specific impulse and health hazards reduction when compared to hypergolic fuels and oxidizers. Because of continuous radiation, the cryogenic tank pressure will increase eventually, which can be hazardous [1,2]. As long-term storage of such cryogens in space is important for future space missions, some effective pressure control measures have been proposed [3,4] such as resettling venting and surface tension control technology. Employing auxiliary system to accelerate or rotate the tank is an effective way of separating the liquid from the vapor to be vented under zero gravity. However, the tradeoffs are the additional mass as well as increased mission complexity. A thermodynamic vent system (TVS) was proposed as a potentially competitive technology to control the pressure of cryogenic tanks containing liquid–vapor mixtures in low-gravity environments [5].

In the past 20 years, many theoretical and experimental analyses on TVS have been conducted. In 1993, Fazah et al. [6] proposed a spray-bar TVS concept by replacing the compact heat exchanger and introducing a mixing pump to accomplish better destratification effect. The thermal energy was extracted from the tank while minimizing the propellant boil-off. Nguyen [7] developed a homogeneous integrated method of predicting the TVS performance to investigate the pressure-control effect of a spray-bar TVS in a liquid hydrogen (LH_2) tank with a volume of 18.09 m^3. The predicted ullage-pressure drop rates were in good agreement with the measured values during the mixing/venting cycles; however, in the pressure–increasing stages, the prediction was inaccurate. Lopez et al. [8] developed a CFD model to simulate an ellipsoidal-shaped LH_2 tank-pressure control using an axial jet TVS under

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Nomenclature

C1,2,3,4,5,6	cases 1, 2, 3, 4, 5, and 6
ECFSTP	efficient cryogenic fluid storage test platform
GHe	gaseous helium
GN_2	gaseous nitrogen
GRC	Glenn Research Center
MSFC	Marshall Space Flight Center
J–T valve	Joule–Thomson valve
LCH_4	liquid methane
LH_2	liquid hydrogen
LN_2	liquid nitrogen
LO_2	liquid oxygen
MHTB	multipurpose hydrogen test bed
TVS	thermodynamic vent system
h_{fg}	latent heat of liquid nitrogen ($J \cdot kg^{-1}$)
p_{max}	upper limit of pressure (kPa)
p_{min}	lower limit of pressure (kPa)
p_l	liquid saturation pressure (kPa)
p_u	ullage pressure (kPa)
q	heat leak (W)
t_d	duration time of TVS cycle(s)
t_c	current time of TVS cycle(s)
t_s	starting time of TVS cycle(s)
$\dot{V}$	boil-off gas flow rate ($m^3 \cdot s^{-1}$)
ρ	density of the nitrogen gas at the inlet of the flow meter ($kg \cdot m^{-3}$)

various fill levels and heating conditions. The predictions showed that the higher filling height and larger heat leak require a greater spray flow to ensure that the tank pressure is controlled within a specified range. The TVS-performance experiments related to LH_2 [9,10], liquid nitrogen (LN_2) [11,12], and liquid methane (LCH_4) [13,14] were conducted successively on a multipurpose hydrogen test bed (MHTB) at the Marshall Space Flight Center (MSFC). In addition, a TVS performance test was performed at the Glenn Research Center (GRC) [15] with liquid oxygen (LO_2) filling levels of 97%, 80% and 63% at background temperature of 233 K. In these studies, the pressure and temperature evolutions in the ullage and liquid were obtained when the TVS was in operation. They proved that the tank pressure could be well controlled using the TVS for the different types of cryogenic propellants. During 2014–2016, Thibault et al. [16] and Mer et al. [17] designed and fabricated a room temperature TVS apparatus to assess the performance of the pressure-control cycles. Fluoroketone, whose normal boiling point is 322 K, was used as the storing fluid in the experiment, which was thought to have similar behavior as cryogenic propellants. The temperature distribution and pressure dynamics within the tank were obtained. The effects of initial tank filling and injection mass flow rate on the cooling time were analyzed. However, the different TVS operation modes were not compared with the different pressure-control bands in these studies. Such aspects are important for understanding the characteristics of the TVS control of tank pressure and optimizing the TVS design. More recently, Liu et al. [18] presented a quasi-steady state model to optimize the heat-transfer performance of a concentric tube heat exchanger using a TVS. Different factors such as circulating mass flow, external heat leakage, and pipe size were analyzed and compared. Mer et al. [19] proposed an extended homogeneous thermodynamic model for designing the TVS to maximize the storage duration of a LH_2 tank with a volume of 137 L and a heat load of 10 W. The TVS operation parameters were optimized to yield maximum efficiency with various heat loads and tank sizes.

The implementation and optimization of a spray-bar TVS for space applications develop slowly as on-orbit testing and technology demonstration are rare. Although these experimental and theoretical studies have helped in significantly understanding the pressure-control effect of the TVS, only a few studies report on optimizing the TVS parameters, thus requiring more experimental studies. In our previous experiments [20], the behaviors of the TVS operating parameters in the mixing-only mode and mixing-venting mode were compared. The effect of different pressure-control bands on the performance of the TVS was examined. However, the effects of the operating parameters on the TVS performance were unclear, which is critical in understanding the TVS performance. In the present study, different TVS experiments with LN_2 as the test fluid were performed with different throttle modes and control strategies. The pressure variations and key performance-evaluating index (liquid mass loss) under different operation conditions were compared and were analyzed in detail. In addition, the effect of a noncondensable gaseous helium (GHe) on the TVS performance was comparatively investigated.

2. TVS operation principle and control strategies

The spray-bar TVS comprises a concentric tube spray-bar heat exchanger, spray-bar assembly, a Joule–Thomson (J–T) expansion valve, and a circulation pump. Fig. 1a shows the schematic of the spray-bar TVS. When the ullage pressure p_u reaches the allowed upper limit pressure p_{max} for the tank, the mixing-only operation mode is activated. A stream of propellant is extracted from the bulk fluid in the tank using the circulation pump, and subsequently, sprayed back into the tank through the spray bar. The spraying process helps in mixing the fluid regardless of the liquid and ullage positions, i.e., the destratification and minimum pressure rising rate are ensured because of the large heat capacity of the liquid. Only the circulation pump is activated in this mode during which the bulk fluid is still subcooled. It should be noted that as the pump situated inside the tank is activated, heat generated by the pump due to friction and dissipation also enters the system. However, when the bulk-fluid temperature reaches the saturation temperature corresponding to the lower limit p_{min} of the tank pressure, the increase in pressure can no longer be controlled via mixing alone because the liquid and ullage are at largely the same saturation conditions. The TVS operation should be switched to the mixing-venting mode. When the saturation pressure p_L of the liquid corresponding to the liquid temperature increases to p_{min} (state 1), both the circulation pump and J–T valve are activated. Thereafter, the flow driven via the pump is split into two streams. The smaller stream passes through the J–T valve where it isenthalpically expands to a two-phase state at lower pressure and temperature (state 1 → state 2), whereas the larger stream at a relatively higher temperature flows into the inner channel of the heat exchanger (state 1 → state 4). The pressure and temperature of the fluid reduce via two throttle modes of the J–T valve: the liquid-only throttling and gas–liquid throttling. Thereafter, in this recuperative heat exchanger, the two-phase mixture absorbs heat from the recirculation flow (i.e., induces cooling effect) and turns into a superheated gas (state 2 → state 3). The superheated gas at state 3 is vented out of the tank, while the cooled fluid at state 5 is sprayed back into the tank. When the ullage pressure p_u reduces