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Research paper

Optimal design of a Thermodynamic Vent System for cryogenic propellant storage

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ABSTRACT

Future operations in space exploration require to store cryogenic liquids for long duration. Residual heat loads, due to heat conduction in the launcher structure or solar radiation, induce cryogenic propellant vaporization and tank self-pressurization. The Thermodynamic Vent System (TVS) permits to control self-pressurization using the following procedure: a fraction of liquid propellant is removed from the tank by a pump, cooled down by a heat exchanger and re-injected inside the tank as a jet or a spray. As no natural heat sink is available in space, the cold source is created by removing another fraction of liquid propellant which is expanded in a Joule-Thomson valve and vented to space. The sub-cooled injection is followed by vapor condensation and liquid bath destratification due to mixing. In this work, an optimization method is applied to an extended homogeneous thermodynamic model to design a TVS system maximizing the storage duration under various heat load and tank size assumptions.

1. Introduction

Refueling with cryogenic propellants in Earth orbit is an option currently considered to send rockets on deep space missions since it provides a significant increase of the delivered payload mass [1]. The ability to transfer liquid in a micro-gravity environment must be however demonstrated and the capacity to store cryogens for a long duration remains a key issue [2]. The present work is precisely focused on this second technological barrier. Residual heat loads, due to heat conduction in the launcher structure or residual solar fluxes, induce cryogenic propellant vaporization and tank self-pressurization. Due to the extended duration of the mission, an un-controlled tank self-pressurization is bound to lead to storage failure.

The first technical solution to tackle this issue is the implementation of a relief valve (see Fig. 1). This type of pressure control system is known as Direct Venting (hereafter denoted DV) [3]. The main advantages of DV are its straightforward implementation and sizing. As can be observed in Fig. 2, the tank pressure level remains constant during a DV regulation and is fixed by the relief valve venting pressure. Considering ideally a perfect DV system which vents only pure vapor cryogen, the expelled vapor flow rate is adjusted, depending on the heat load induced liquid evaporation, to maintain a constant tank pressure. Consequently, the cryogen liquid mass linearly decreases, from an initial 90% liquid filling (*initial condition of all runs presented in this study*), until the tank is emptied. From now on, a so-called empty tank will actually correspond to the state where the liquid volume in the tank goes below 10% of the tank volume. This state is achieved after roughly 90 h for a 137 L tank. Fig. 2 also displays (see green dash) the life expectancy of the same tank without any pressure control: after 23 h only, the tank pressure reaches its maximum allowable value ($p_{max} = 3.5 \times 10^5$ Pa). In this example, DV regulation thus permits to multiply the tank life expectancy by a factor close to four. Unfortunately, in micro gravity, the liquid phase distribution in the tank is such that it is likely DV will lead to venting out cryogens as a liquid phase. Liquid venting drastically increases the tank emptying speed as observed in Fig. 3 where the time t_{DV} needed to empty the tank is plotted as a function of the prescribed venting pressure, for various liquid mass fraction θ of the expelled propellant - $\theta = 0\%$ corresponds to the previously considered ideal (pure vapor) DV. One can observe in Fig. 3 that the performance of an ideal DV system ($\theta = 0\%$ curve) increases when the venting pressure decreases. This behavior is due to the fact that the density ratio $\frac{\rho_{liq}}{\rho_{vap}}$ between the liquid hydrogen and its vapor increases when the pressure decreases. When the liquid mass fraction of the vented fluid is no longer zero, the venting time dramatically

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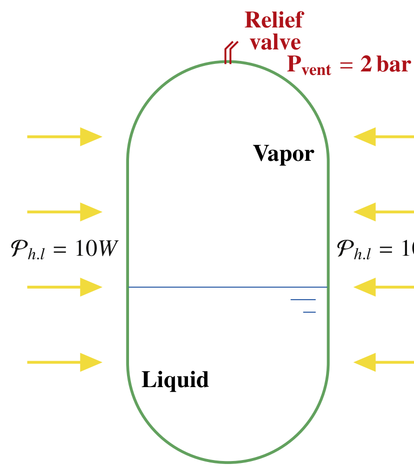

Fig. 1. Schematic view of a LH_2 tank submitted to a 10 W heat load and regulated thanks to a relief valve triggered at 2 bar.

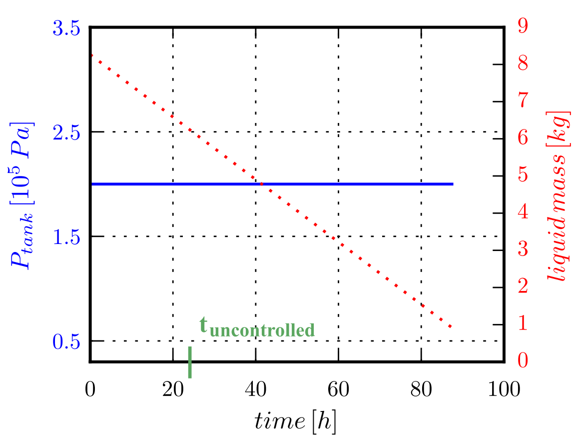

Fig. 2. Pressure (blue) and liquid mass (red) evolution in 137 L tank initially filled at 90% during a DV pressure regulation. The un-controlled tank life expectancy is specified by the green dash. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

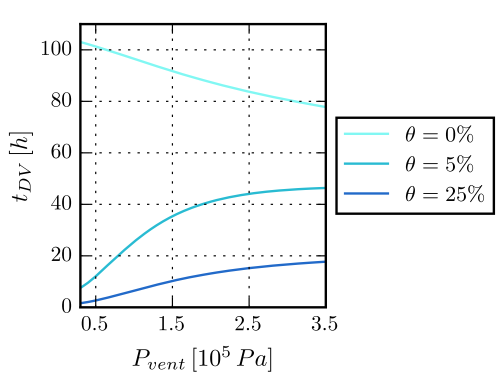

Fig. 3. Influence of the relief valve venting pressure (p_{vent}) and the liquid mass fraction of the expelled propellant (θ) on the DV venting time for a 137 L tank submitted to 10 W heat load.

decreases (see $\theta = 5\%$ or 25% in Fig. 3). Since no device ensures pure vapor removal from the tank in micro-gravity environment, the DV regulation system appears inappropriate to manage tank pressure for long-duration space missions. However the venting time computed for an ideal DV system provides a target performance (depending on tank volume, heat load and operating pressure) for an alternative regulation strategy designed to operate in space conditions.

Such a pressure regulation system adapted to microgravity space condition has been developed at NASA in the nineties and is called Thermodynamic Vent System (see [4–7]). The TVS control strategy is based on the following process: a fraction of liquid propellant is removed from the tank by a pump, cooled down by a heat exchanger and re-injected inside the tank as a jet or a spray (see Fig. 4). As no natural heat sink is available in space, the cold source is created thanks to the vented branch. The subcooled injection is followed by vapor condensation and liquid bath destratification due to mixing resulting in a tank pressure reduction.

Recently, Barsi [8–10] and Demeure [11] have studied TVS control systems using on-ground small scale experiments with simulant fluids. These works evidenced some difficulties that need to be overcome for properly managing the thermal boundary condition at the tank wall for on-ground laboratory experiments. This issue was recently tackled in [12] using an active wall insulation technique. Despite non-ideal adiabatic conditions, Barsi and Demeure were both able to demonstrate that measured trends for tank pressure and temperature could be correctly predicted with an homogeneous thermodynamic model. Such a model describes the physical phenomena occurring in the tank during self-pressurization and TVS injection from thermodynamic balance equations. Liquid and vapor phases are assumed to remain in thermal equilibrium during the regulation history. It is further assumed that both phases remain at the saturation temperature corresponding to the tank ullage pressure. This model yields an accurate prediction of tank temperature and pressure evolution during self-pressurization and TVS regulation when compared with available on-ground experiments (see [13] and Section 3.4 of the present paper). However, the model does not take explicitly into account gravity effects as it relies on global balance equations inside the tank. Experimental data being currently unavailable for space conditions, the future validation of the model for low or zero gravity conditions will rely on high-fidelity numerical simulations, still in development at this stage (see for instance [14]).

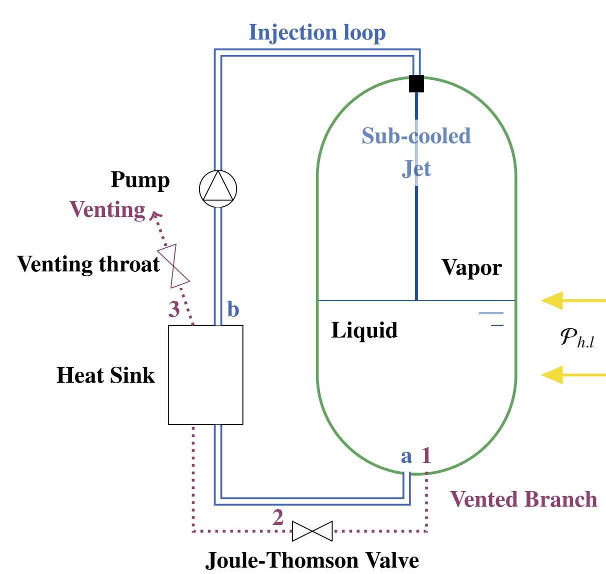

Fig. 4. Schematic view of a TVS controlled tank. The (blue) injection loop drives directly a subcooled jet inside the ullage. The (violet) vented branch creates the cold source heat sink. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)