Experimental investigation into storage of confined cryogenic liquids without evaporation venting

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Abstracts: In this study, a two-phase thermo-dynamical model was presented to evaluate the heat transfer and pressurization of cryogenic liquids in a closed container, and programs were formulated to predict the effects of various factors on the cryogenic storage performance. Experiments were carried out to verify the simulation. The experimental results agreed well with the theoretical prediction. The research helps to design long-term cryogenic vessels with minimum evaporation loss while abiding safety standards.

INTRODUCTION

Cryogenic liquids storage vessels are widely used in aerospace, transportation, and energy industries. Boil-off vapor is a great concern on cryogenic storage. It will concentrate in the vapor part of the inner tank, and will be eventually drained before causing tank overpressure. Substantial mass and cost savings could be achieved if evaporation venting can be avoided. Furthermore, inflammable, explosive or toxic liquids must be stored in a closed container without venting. Therefore, it is very important to study the storage feathers of confined liquids. Many researches dealt with the problem of thermal stratification and interface instability of propellants [1-2]. This study handles general cases of cryogenic liquid pressurization for engineering practice.

EXPERIMENTAL SETUP AND PROCEDURES

The experimental setup was schematically shown in Fig. 1. The setup consisted of a cryogenic vessel, a vacuuming system, data acquisition system and auxiliary facilities. The vessel was a 2-cubic meter, hi-vacuum multi-layer insulated (MLI) pressure vessel. The vacuuming system mainly included an oil diffusion pump and vacuum meter. Data acquisition system included computer, computer-based data logger, sensors and connection cables. All the sensors, viz. thermocouples, pressure transmitter, level meter, and flow meter, were linked to a Keithley data logger, whose voltage outputs were sent to PC computer via a GPIB bus.

Temperature profile of cryogenic liquids was recorded with copper-constantan thermocouples. In all the tests, the tank was initially filled with liquid nitrogen saturated at pressures close to local atmospheric pressure. The wall heat flux was then obtained from a boil-off calibration and the test begun immediately afterward. The experimental data was considered after the thermal equilibrium of system. During the test, a continuous record of the various sensors reading was made.

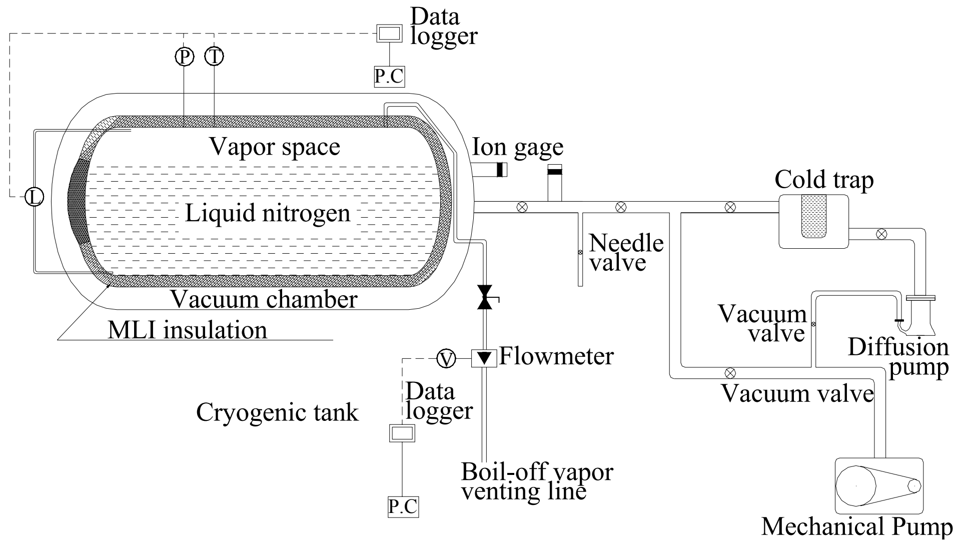

Figure 1 Experimental setup (L-level meter, P-pressure transmitter, T-thermocouples, V-flow meter)

RESULTS AND ANALYSES

Analytical models

The heating rate of MLI tank is usually less than 10 W/m², which is much too small for nucleate boiling to occur [3]. Confined cryogenic liquid is heated by inner shell. The liquid next to the container surface is warmed and move upward via a boundary layer causing slight circulation in the bulk liquid. A warmer stratified layer collecting around the vapor-liquid interface and continually thickness increasing result in a higher temperature at the surface than in bulk liquid. Some parts of the layer evaporate into vapor chamber; the other parts lose heat and move inward [4].

Confined cryogenic liquid storage can be divided into 2 successive phases: the steady expansion of cryogenic liquids, and the liquid pressurization at a constant volume. The initial cryogenic liquid in the tank is assumed as saturate and isothermal. Heat input to the liquid through the inner wall gives rise to the increase of temperature, pressure and enthalpy of the cryogenic contents. The liquid temperature rise results in its expansion. Taking the cryogenic contents as a control volume, we have energy equation 1.

$$Q = q\tau = M(u_f - u_i) \, . \tag{1}$$

Where, u_f, u_i is the final and initial enthalpy of cryogenic contents in the tank, respectively; Q is the heat leakage to the inner tank. Fluid density and inner energy can be derived from the pressure of cryogenic vessels. Hence, the final inner energy and density takes the forms of equation 2 and equation 3, respectively. Thus, enthalpy increase will be equation 4.

$$u_f = \rho_{lf}\phi_f u_{lf} + \rho_{vf}(1-\phi_f)u_{vf} \, , \tag{2}$$

$$\phi_f = {(\rho - \rho_{vf})}\Big/{(\rho_{lf} - \rho_{vf})} \, , \tag{3}$$

$$Q = V\left[\rho_{lf}u_{lf}\,{(\rho - \rho_{vf})}\Big/{(\rho_{lf} - \rho_{vf})} + \rho_{vf}u_{vf}\,{(\rho_{lf} - \rho)}\Big/{(\rho_{lf} - \rho_{vf})}\right] - V\left[\rho_{li}\phi_i u_{li} + \rho_{vi}(1-\phi_i)u_{vi}\right], \tag{4}$$

where, ρ and m is the density and mass of cryogenic contents, respectively; V is tankage, ρ is constant.

The confined liquid was heated in a constant volume when the tank was 100% full. The tank is assumed as a rigid body without deformation, the liquid enthalpy increase will be

$$\int_{\tau_0}^{\tau} qF_w d\tau = \rho \int_0^{V_L} c_v (T - T_0) dV \quad , \tag{5}$$

where, q is the heat flux to the cryogenic liquids; τ is the storage duration; F_w is the surface area of inner tank shell; C_v is the specific heat at constant volume; ρ is the liquid density; V_l is the tank volume and T is the liquid temperature. The above equations are numerically solved, and results are as follows.

<u>Results and discussion</u>

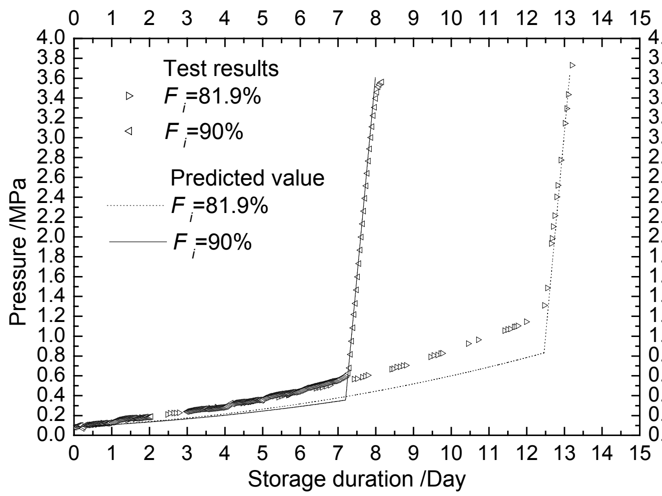

Figure 2 Pressure-time correlation

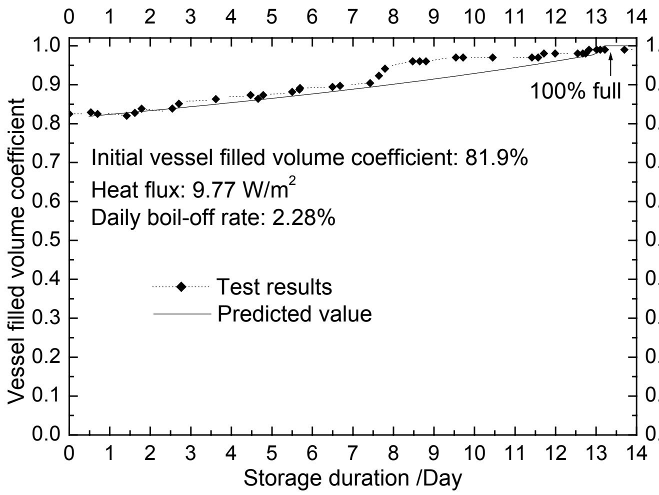

Figure 3 Variation of vessel filled volume coefficient

The pressure, the vessel filled volume coefficient, and the temperature of confined LN_2 is recorded as in Fig. 2, Fig. 3 and Fig. 4, respectively. In conformity with the former expectation, 100% full is the turning point of pressurization. Confined LN_2 expands steadily and tank pressure jumps after zero ullage. Furthermore, there is a clear temperature gradient in the LN_2, the maximum temperature difference is about 6 ℃. The interface temperature is higher than that of liquid core. The LN_2 temperature is lower than its saturate temperature corresponding to the tank pressure. The cryogenic contents are consumed as saturate and homogenous, so the predicted pressure is lower than the test pressure. However, the test vessel filled volume coefficient is higher than the predicted due to the surface flashing and instability.

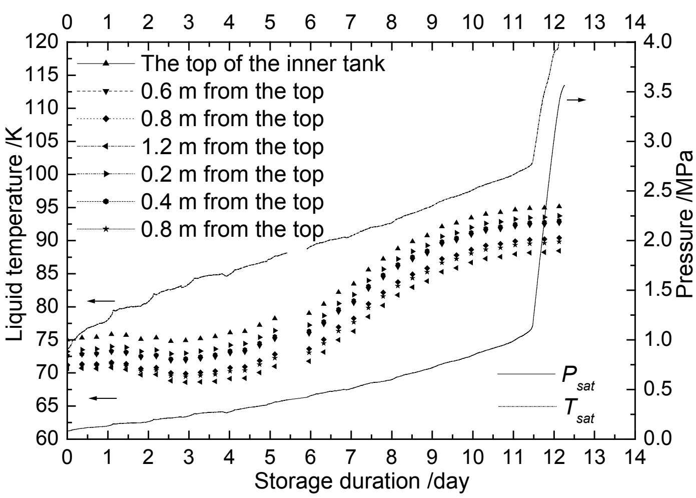

Figure 4 Temperature profiles of liquid nitrogen

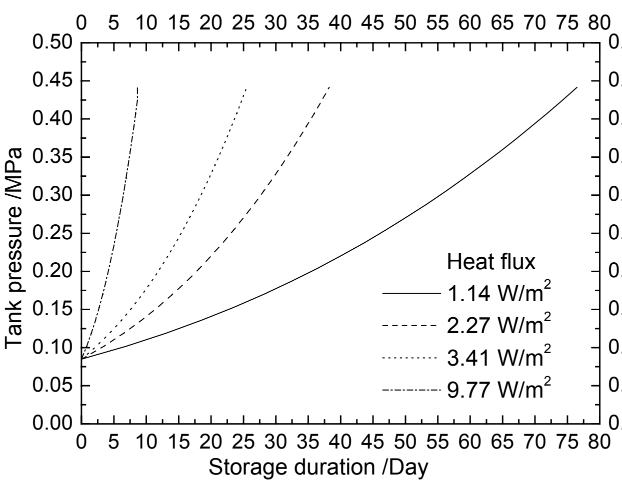

Figure 5 Heat flux effects on the pressurization

The confined cryogenic liquids pressurization is affected by various factors, viz. heating rate, initial vessel filled volume coefficient, and thermodynamic properties of cryogenic liquids. As shown in Fig. 5, the larger heating rate will lead to further pressure increase. The storage cycle will double if the heating rate halves. Therefore, insulation quality advance will effectively prolong storage cycle. As shown in Fig. 6, the cryogenic liquid temperature increase will cause its volume expansion. Higher Initial vessel filled volume coefficient will be quicker to reach the 100% full of cryogenic tank. However, if the initial vessel filled volume coefficient is low enough, the liquid content will decrease till the 100% full of vapor. Fig. 7 shows initial vessel filled volume coefficient and properties effects on storage cycle of cryogenic liquids. Given the heating rate is 9.77 W/m², the storage cycle fluctuates with initial vessel filled volume coefficient and liquid properties. The storage cycle will be the largest if the initial coefficient is 60%. Compared with liquid nitrogen, liquid oxygen, argon, and methane have longer storage cycle, while liquid hydrogen has much shorter storage cycle.

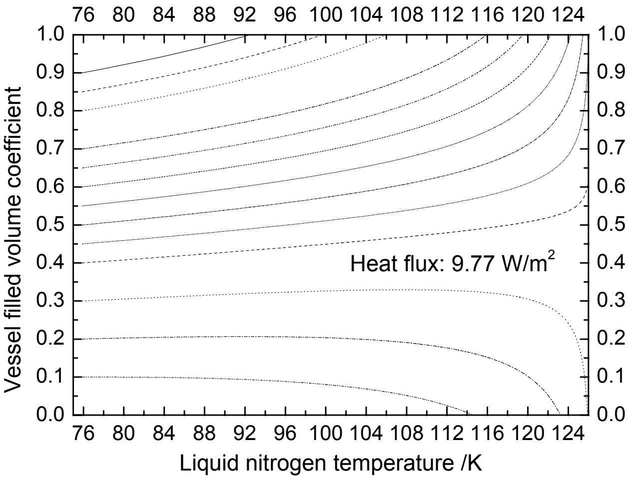

Figure 6 Vessel filled volume coefficient vs. T_l

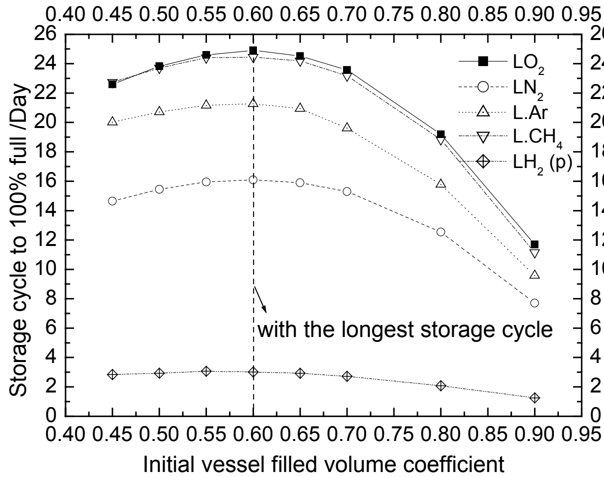

Figure 7 Property effects on liquid storage cycle

CONCLUSION

The 2-phases thermodynamic model can be used to predict the storage duration of cryogenic liquids with a fair agreement. Test tank pressure and ullage is slight higher than predicted value. Confined liquid temperature is lower than its saturate temperature, and the liquid-vapor interface temperature is higher than that of other parts.

Various factors affect the vent-less storage duration. The higher heating rate will cause shorter storage cycle. Vessel filled volume coefficient affects the storage duration of cryogenic tanks. For the experimental tank, its optimum Vessel filling volume coefficient is about 60%. Storage performance also varies with the properties of cryogenic liquids. Oxygen and methane have much longer storage cycle than nitrogen, while hydrogen storage cycle is quite shorter than that of nitrogen.

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