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Simple predictive heat leakage estimation of static non-vacuum insulated cryogenic vessel

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Abstract

The diminishing of heat leak into cryogenic vessels can prolong the storage time of cryogenic liquid. With the storage of cryogenic liquid reducing, the heat leak decreases, while the actual storage time increases. Regarding to the theoretical analysis, the obtained results seems to be constructive for the cryogenic insulation system applications. This study presents a predictive assessment of heat leak occurring in non-vacuum tanks with a single layer of insulation. A Radial steady-state heat transfer, based on heat conduction equation, is taken into consideration. Graphical results show the thermal performance of the insulation used, they also allow us to choose the appropriate insulation thickness according to the shape and diameter of the storage tank.

Keywords: cryogen, heat leak, prediction, non-vacuum, insulation

Nomenclature

D	Tank diameter	[m]
e_i	Insulation thickness	[m]
L	Length of the cylinder	[m]
$\dot{Q}$	Heat flux	[W/m^2]
$\dot{Q}_1$	Cylinder side heat flux	[W/m^2]
$\dot{Q}_2$	Lateral side heat flux	[W/m^2]
S_b	Tank side surface	[m^2]
S_L	Total lateral surface	[m^2]
T_{ext}	External temperature	[K]
T_{cry}	Liquefaction temperature	[K]
λ_i	Insulator thermal conductivity	[W/(m·K)]
ΔT_{eq}	Equivalent thermal gradient	[K]
Ψ	Specific technical financing parameter	[(€·m^{-1})/(€·m^{-3})]
Ψ'	Specific technical financing parameter	[(€·m^{-2})/(€·m^{-3})]

1. INTRODUCTION

Principles of insulating vessels for the storage and transportation of liquefied gases were discussed since the 50s of the previous century. General principles relating to the thermal design of low-loss vessels and analyses of methods that can be used to improve the performance of an insulated vessel by utilizing the refrigerative effect of the escaping vapor were presented and discussed [1, 2].

Li et al. [3] contribute significantly in the design, usage and selection of cryogenic vessels. They analyzed effects of liquid volume fraction, temperature and work pressure on the pressure rise rates in cryogenic vessels. The non-loss storage time was calculated through non-dimensional criterion such as non-dimensional pressure, non-dimensional thermal load and primal liquid volume fraction.

Effective results are obtained for examining the non-contact cooling of high-temperature superconductors. Tanaka et al. [4] measured the heat transfer characteristics in cryogenic and low-pressure environments, and found out the heat transfer mode from the comparison between experimental results and theoretical values.

Li et al. [5] shows the important role that the two-phase flow plays on thermal stratification in the cryogenic tank. Experimental and numerical investigation contribute to the understanding of the transient process of thermal stratification in liquid nitrogen (LN$_2$) induced by lose of vacuum in a multi-layer insulated cryogenic tank.

The influence of a sudden, catastrophic loss of insulating vacuum on the heat transfer characteristics in a high-vacuum-multilayer-insulation cryogenic tank has been researched experimentally. Xie et al. [6] analyzed and discussed the effects of the insulation and the initial liquid level on venting rate and heat flux leaking into the liquid nitrogen (LN$_2$). The maximum value of the heat flux leaking into the liquid is higher than the steady value of it. The number of insulation layers is the most important factor effecting on the heat flux.

Li et al. [7] analyzed the steady state heat leak into cryogenic vessels with different liquid level height using a finite element model. A liquid nitrogen boil-off method was adopted in experiments to validate the result of numerical simulation. The effect of liquid level on heat leak into the cryogenic vessel can be considered in calculation of storage time and structure design.

Rubeli et al. [8] proposed an experimental technique to precisely measure in real time the temperature and the heat exchanged to the bath of a quenched resistive

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superconducting fault current limiter tape immersed in liquid nitrogen. The current and the associated voltage are measured, giving a precise knowledge of the amount of energy dissipated in the tape.

A research work assessed the efficiency of a cryogenic energy storage system in order to identify if and how it can achieve an acceptable round-trip efficiency [9]. For this purpose, a thermodynamic analysis of such system, based on air liquefaction and storage in an insulated vessel was presented.

Hamdy et al. [10] reviews and evaluates concepts of cryogenic energy storage systems and reports the results from exergy analysis. They considered two cold exergy recovery cycles: direct expansion of liquid air and expansion of liquid air in combination with an organic Rankine cycle. The exergetic efficiency of the overall system configuration and the round-trip efficiency are considerably improved.

A new test method based on the pressure changes over time in cryogenic vessel to determine heat insulation performance requirements is designed [11]. The volume of instantaneous evaporated gas and heat leakage are calculated by the current standard corresponding to the maximum allowable daily evaporation rate of cryogenic vessel.

Garceau et al. [12] observes the sudden vacuum break in beam-line tubes of liquid helium cooled superconducting particle accelerators. Basing on extended previous experiments, a new theoretical model that systematically describes the gas dynamics and condensation is presented.

Previous studies gave physical insights to prevent the heat loss that occurs in pressurized vacuum insulated vessels (PVIVs). Information is scarce on cryogenic storage using non-vacuum insulated vessels (NVIVs). The present work paves the way for a theoretical understanding of the thermal conduction processes involved in such cryogenic systems. A facile approach is proposed to estimate the heat flux leaking into the cryogenic liquid in the case of static non-vacuum insulated tank with different initial liquids and two insulation types.

2. STEADY STATE HEAT LOSS CALCULATION

Storing a gas in liquefied form considerably reduces the volume occupied. The liquid form allows to store up to 230 times more fluid in the same volume. There are two storage ways of cryogen: pressurized at ambient temperature or at low temperature (Cryogenic storage).

Sphere and hollow cylinder are the two geometric shapes used in the chemical industry because of their storage capacities. The cylindrical will be studied first, and then the results will be extended for the sphere. The studied tank, of 2 m measurement lengthwise, is a cylindrical container with elliptical bottoms insulated at atmospheric pressure and non-vacuum, made of stainless steel (Fig. 1).

Assuming the tank wall thermal resistance negligible and a perfect contact between the insulation layer and the wall, the steady-state conduction heat flux through the cylinder can be written merely, in the form:

$$\dot{Q}_1 = \frac{2\pi\lambda_i L}{\ln(1+\frac{2X_i}{D})}\,(T_i - T_o) \qquad (1)$$

An approximate equation [14] through an average surface can be written:

$$\dot{Q}_1 = \frac{\lambda_i\,\bar{S}}{\ln(1+\frac{2X_i}{D})}\,\Delta T_{eq}\,\frac{1}{\bar{R}} \qquad (2)$$

ΔT_{eq} is the equivalent thermal gradient given by Buhler [15], as:

$$\Delta T_{eq} = 0{,}9\left(T_{ext} - T_{cry}\right) \qquad (3)$$

Heat conduction flux through the side faces of the container:

$$\dot{Q}_2 = \frac{\lambda_i}{e_i} S_L \Delta T_{eq} \qquad (4)$$

With,

$$S_L = 2S_b = 0.69\pi D^2 \qquad (5)$$

Whence:

$$\dot{Q}_2 = \frac{\lambda_i}{e_i} 0.69\pi D^2 \Delta T_{eq} \qquad (6)$$

The overall heat loss:

$$\dot{Q} = \dot{Q}_1 + \dot{Q}_2 \qquad (7)$$

Finally, the expression of heat dissipation through the cylindrical vessel:

$$\dot{Q} = 2\pi\lambda_i \Delta T_{eq}\left[\frac{L}{ln\left(1+\frac{2e_i}{D}\right)} + \frac{0.69D^2}{2e_i}\right] \qquad (8)$$

In terms of cryogen temperature:

$$\dot{Q} = 1.8\pi\lambda_i (T_{ext} - T_{cry})\left[\frac{L}{ln\left(1+\frac{2e_i}{D}\right)} + \frac{0.69D^2}{2e_i}\right] \qquad (9)$$

Similar reasoning leads to the expression of the heat loss in a sphere:

$$\dot{Q} = 2\pi\lambda_i \Delta T_{eq}\left[1 + \frac{D}{2e_i}\right] D \qquad (10)$$

Whence:

$$\dot{Q} = 1.8\pi\lambda_i (T_{ext} - T_{cry})\left[1 + \frac{D}{2e_i}\right] D \qquad (11)$$

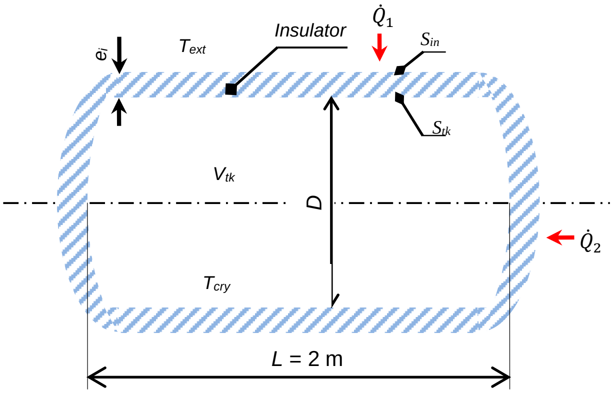

Fig. 1. Cylindrical tank scheme.

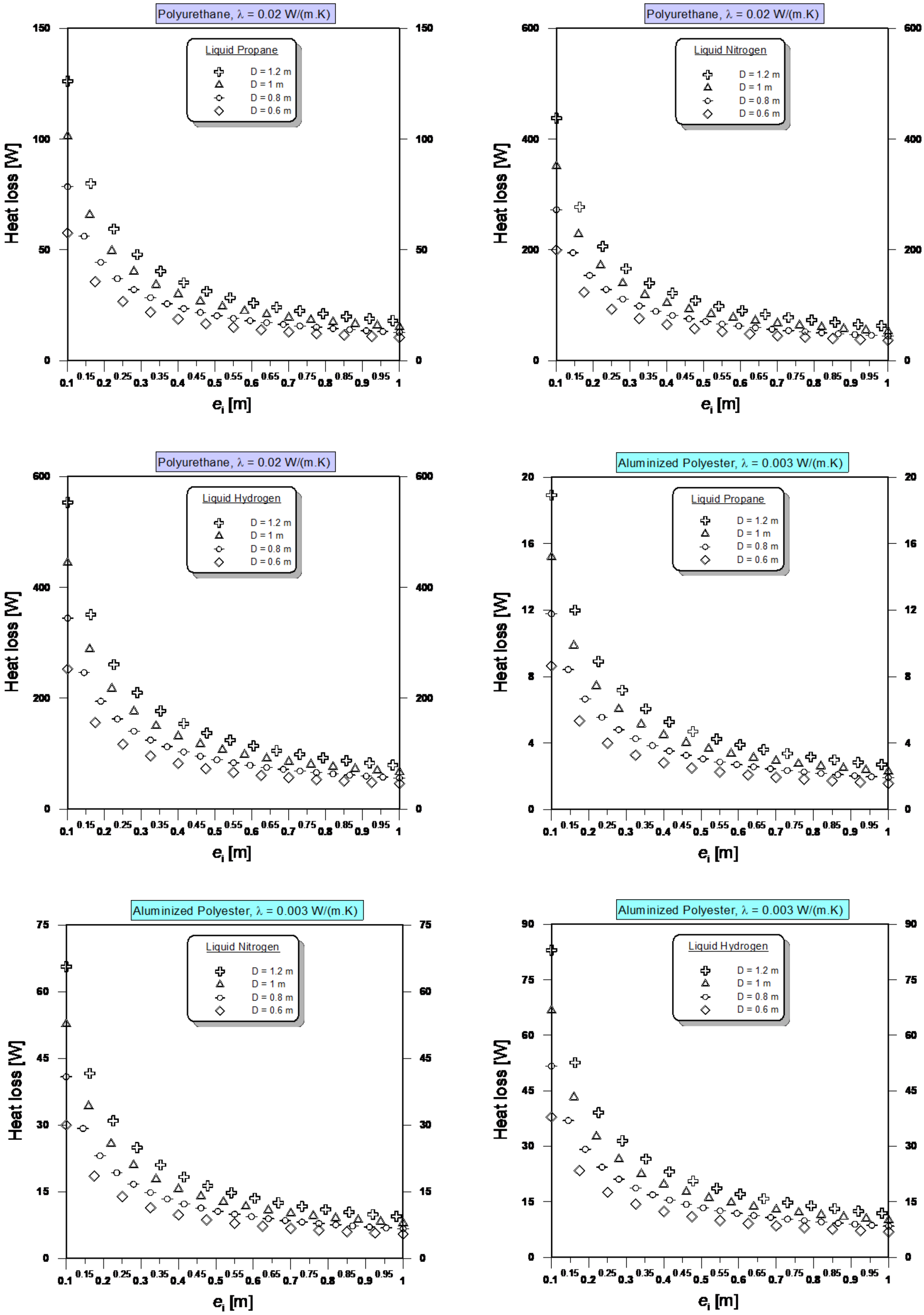

Fig. 2. Cylindrical tank: Cryogen heat loss vs insulation thickness.

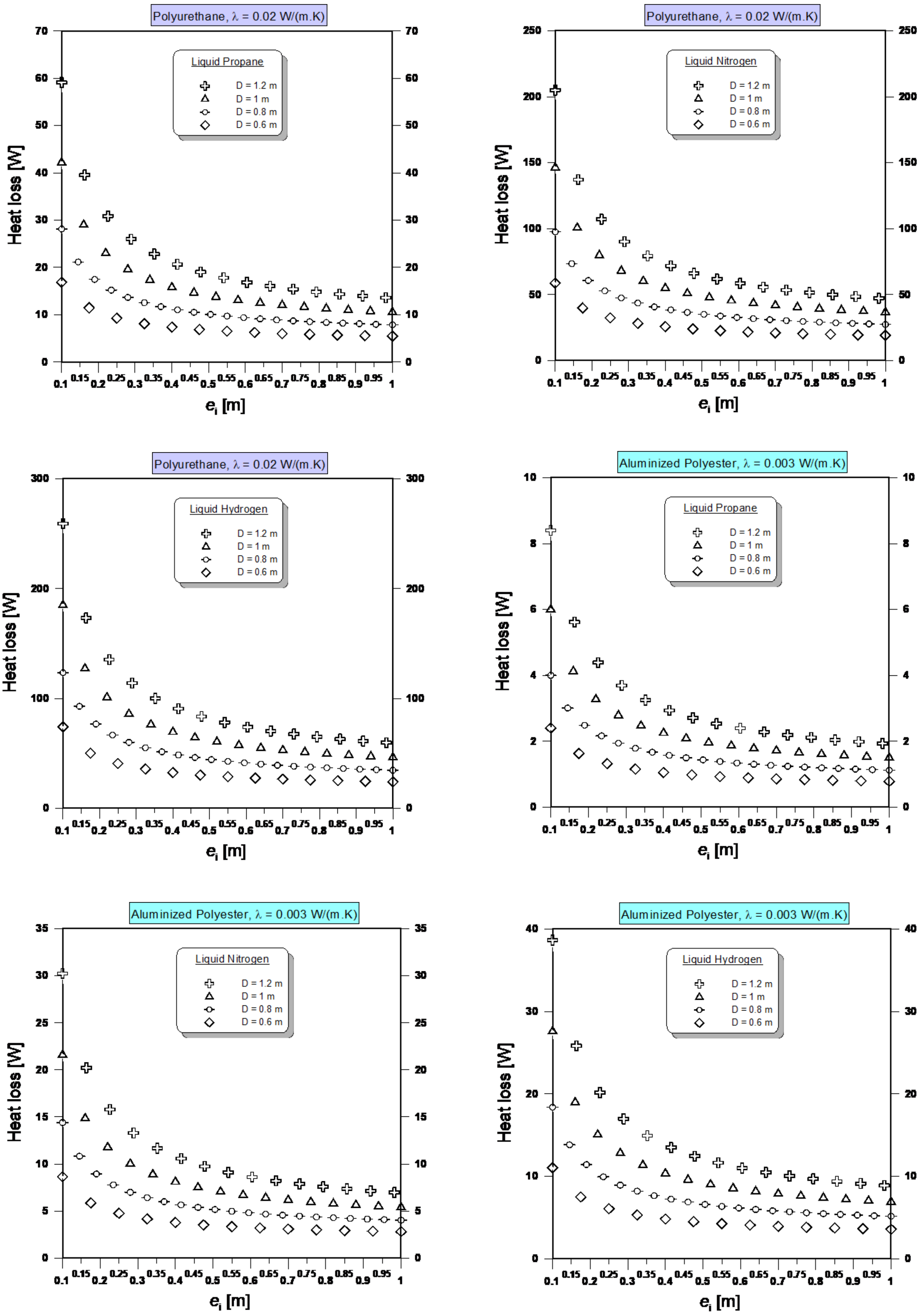

Fig. 3. Spherical tank: Cryogen heat loss vs insulation thickness.

TABLE 1
THERMAL PROPERTIES OF INSULATION MATERIALS

Material	Thermal conductivity W/(m.K)	Specific heat J/(kg.K)	Density kg/m^3	Thermal diffusivity m^2/s
Polyurethane foam	0.02	1674	40	0.3×10^{-6}
Aluminized polyester	0.003	1171	1390	0.2×10^{-8}

Selection of insulation material should be based on initial cost, effectiveness, durability, the adaptation of its shape and the installation methods available in each particular area [13].

The main advantage of polyurethane foam in comparison with other thermal insulation materials is possibility to cover this material on the complicated shape metal surfaces by spraying method, which leads to significant cost savings.

From an economic point of view, it may be better to choose an insulating material with a lower thermal conductivity rather than increase the thickness of the insulation. With highly reflective surface of polished aluminium, aluminized polyester offers the glossy metallic appearance of an aluminium foil at a reduced weight and cost.

Using polyurethane and aluminised polyester (Tab. 1) as insulation materials, heat leak calculations are represented graphically while storing at cryogenic temperatures (Figs 2 and 3). The thermal insulation performance of these two materials is tested at the environmental temperature of 293.15 K in a particular range of temperature. Three storage types are considered: liquid propane (T_{cry} = 230.95 K), liquid nitrogen (T_{cry} = 77.36 K), and liquid hydrogen (T_{cry} = 20.28 K).

3. RESULTS DISCUSSION AND SUGGESTIONS

Below, the thermal efficiency of two types of insulation will be discussed, namely a foam (Polyurethane) and a superinsulator (Aluminized polyester). Insulation is applied to both cylindrical and spherical tank.

From the analysis of figure 2, it can clearly be deduced that insulation with polyurethane is not recommended for the storage of cryogenic fluids such as nitrogen (LN2) and hydrogen (LH2). Indeed, heat leakage of 50 to 150 W occurs for an insulation layer varying from 0.55 to 1 m thick in a cylindrical tank with a length of 2 m. Nonetheless, it would possible to consider LNG product storage such as liquid propane in the studied cylindrical tank respecting an insulation thickness limit of 0.55 m. In this case, the smallest diameter (0.6 m) must be chosen with instantaneous monitoring of the liquid temperature.

On the other hand, an aluminized polyester insulation offers better thermal performance. Such kind of insulator provides an acceptable insulation efficiency of the considered cylindrical tank containing a cryogenic liquid below 100 K. Lower heat leaks are observed, less than 30 W with the condition that $e_i \geq 0.33$ m. For LNG products such as liquid propane, the heat loss recorded in this case is in the range [2-7] W corresponding to superinsulation thickness $e_i \geq 0.33$ m. Although the cylindrical shapes allow better integration in a crowded environment, they can be used for intermediate storage in production units.

Regarding the sphere storage (Fig. 3) insulated in polyurethane, the losses exist despite a smaller volume compared to the above cylindrical shape. However, if there is a useful margin between the normal operating pressure of storage and its maximum allowable pressure, such tanks can be used for temporary cryogen storage at a temperature around 80 K. In fact, heat transfer from tank surrounding will cause a slow increase in its temperature and pressure.

On the other hand, using aluminized polyester insulation, some cryogenic fluids can be stored in a spherical tank of small diameter, $D \leq 0.8$ m. In this case heat loss is less than 5 W for $e_i \geq 0.45$ m. Heat leakage due to storage of liquid propane are negligible regardless of insulation thickness, ie less than 1 W for a container diameter of 0.6 m and [2-4] W for a diameter of 1.2 m.

Identification of the different heat loads on the system would tell us the maximum range of insulation layer thickness, which is of great practical significance. Comparison of the tanks with insulation of various types should be carried out for the same holding capacity of the tanks to avoid the effect of the scale factors; optimum thickness must be determined for each type of insulation. Based on an energy cost balance, a recent published work [13] allowed the optimization of insulation thickness of cryogenic shells. The optimum thickness is estimated according to the equation:

$$e_{opt} = D\left\{\left(\frac{3.19\,\Psi}{0.19\,\Psi + 8.76D\,\Psi' + 3.25D^2}\right)^{-0.4259} + 0.3008\right\}^{-1.1737} \qquad (12)$$

The parameter Ψ represents the ratio of energy cost per 1 m of insulation on the insulation cost of 1 m^3. Ψ' is the ratio of shell cost per 1 m^2 on the insulation cost of 1 m^3.

The optimal thickness must satisfy a compromise between tank diameter and layer thickness, i.e. $e_{opt} \leq \frac{1}{3}D$. In the present case study, independently of the volume of cryogenic storage, from low capacity container (0.6 m) to the biggest tank (1.2 m), polyurethane is the suitable insulator when storing at low temperatures, around 230 K, like liquid propane. Indeed, the maximum insulation thickness would be $e_{max} = \frac{1}{4}D$. Concerning storage at very low temperature in the vicinity of 90 K like liquid nitrogen, a multilayer insulation (MLI) made of aluminized polyester is recommended. In this case the necessary maximum insulation thickness is $e_{max} = \frac{1}{2}D$. Concerning storage at extreme temperatures near 20 K, like hydrogen liquid, the present investigated reservoirs needs a maximum insulation thickness of $e_{max} = \frac{4}{3}D$.

For optimal stabilization, a thermal insulation with a thickness adapted to the operating conditions has to be used. It specifies operational requirements for static non-vacuum insulated cryogenic vessels, designed for a maximum allowable pressure greater than 0.5 bar.

4. CONCLUSIONS AND PERSPECTIVE

Through heat leakage estimation of static non-vacuum cryogenic vessel by simple predictive method, two major conclusions come out:

- Polyurethane foam, also known as cellular plastic or expanded plastic, offer both a high strength-to-weight ratio and low thermal conductivity. Opaque to thermal radiation, this category of unevacuated insulation is reasonably competitive in thermal effectiveness at low temperatures. Omitting the degradation of insulating properties with time, the principal disadvantage highlighted in this paper is low maximum temperature limits. Indeed, polyurethane is not recommended for cryogenic storage at very low temperatures, particularly below 200 K. However, its use is strongly advised in large liquefied natural gas (LNG) storage tanks and LNG ship tankers.
- Proper isolation clearly improves the efficiency of cryogenic devices and minimizes cryogenic losses as a result of evaporation. The use of the superinsulation made of aluminized polyester allows the cryogenic system to increase efficiency while reducing the size and weight. In such case, the appropriate temperatures are around 80 K like liquid nitrogen (LN2). For extreme temperatures near absolute zero (0 K), such as liquid hydrogen and helium, an oversized insulation thickness will be required. Therefore, we need to use Multi-layer insulation (MLI) which is composed of multiple layers of thin sheets.

Results presented in this article can be easily extended to obtain a huge graph database (GDB) regrouping all the cryogenic fluids as well as the LNG products stored at low temperature. Abacuses can be created, useful for engineers working in process industries where insulation is a key parameter.

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