THERMAL PERFORMANCE ESTIMATION TECHNIQUES FOR LIQUID HYDROGEN CONTAINMENT SYSTEMS

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ABSTRACT

A principal challenge of large-scale liquid hydrogen (LH_2) transport and storage is to limit the amount of boil-off gas (BOG) generated due to heat ingress. The low temperature and low latent heat of LH_2 necessitate advanced cryogenic storage technologies to address this challenge. To this end, a number of different storage concepts have been proposed, including, for large-scale systems with tank capacity of several thousand cubic meters: a suspended, glass bubble-insulated system for on-land storage by NASA [1], a membrane-type system for ship transport by Shell and GTT [2], and spherical-type systems, also for ships, by Moss Maritime [3] and Kawasaki Heavy Industries [4]. Still, no consensus on the optimal concept for neither stationary nor in-transit storage has been reached. All the while, a recent review has pinpointed differences in assumed heat ingress and resulting boil-off as driving a wide spread of conclusions in existing value chain efficiency analyses [5]. This observation underscores the need for accurate thermal performance estimation techniques in design and optimization of LH_2-based hydrogen value chains and their constituent components.

In the present work, two approaches to thermal performance estimation will be compared: a high-fidelity modelling framework based on the finite-element method (FEM), and a thermal resistance network model. Emphasis will be placed on their respective merits, limitations, and recommended use-cases. Additionally, the two approaches are compared in a case study concerning a ship-borne, LH_2 containment system with a capacity of approximately 160 000 m^3.

At the core of the FEM-based framework is a numerical solver (implemented in the open-source FEM-library NGSolve [6]) of the steady heat equation:

$$\nabla \cdot (k \nabla T) = 0.$$

Here, k is (material- and temperature-dependent) thermal conductivity. Given k, a tetrahedral mesh representing the geometry of the containment system (not including the contained LH_2), and appropriate boundary conditions, the solver predicts the temperature T everywhere within the containment system. On the inner tank surface, a uniform Dirichlet boundary condition of 20 K can be used to represent a full tank, or a position-dependent temperature profile computed using a separate fluid simulation software may also be prescribed. A standard convective boundary

condition is appropriate on the containment system's exterior surface. The total heat ingress can readily be estimated using the computed temperature field.

A main strength of the FEM framework is its accurate representation of the system geometry. This provides great flexibility, since it enables effects of geometric details and of spatial variations in, e.g., cargo temperature and material properties, to be captured by the model. Moreover, the model can readily be coupled to a thermal stress model using the same tetrahedral mesh, as has been done by the authors. The computed temperature field is then used to estimate thermal stresses in the structure. Moreover, through a simple coupling scheme, the effect of thermal contraction on heat ingress can be estimated. Preliminary investigations suggest this effect only causes a minor adjustment to the heat ingress estimate.

Contrary to the FEM framework, a thermal network model generally does not provide spatially resolved temperature fields. Instead, it models the containment system as a collection of discrete temperature nodes separated by thermal resistances. For a spherical, double-walled LH_2 tank with a support skirt, one could use nodes to represent, e.g., the following: 1) the contained LH_2, 2) the outside of the inner wall, 3) the cold spot where the support skirt meets the outer wall, 4) the outer wall far away from the cold spot, and 5) the ambient. Then, for example, the thermal resistance between 3) and 5), and 4) and 5), will be given by the exterior convective boundary condition, the resistance between 2) and 3) by the thermal conductivity of the skirt material, and that between 2) and 4) by the thermal conductivity of the insulation material. We find that including a thermal resistance between 3) and 4) (based on the analytical solution of a simplified case) improves the network model's ability to estimate the cold spot temperature. This improvement, which we refer to as a cold-spot correction, in turn yields a more accurate heat ingress prediction.

Given its simpler and more approximative nature, it is to be expected that a thermal network model is less accurate than FEM (assuming that the underlying system description, including geometry and material properties, is accurate for both). However, the loss of accuracy need not be of practical significance. To investigate this matter, a case study was conducted for a spherical, skirt-supported, double-walled, perlite-insulated LH_2 tank with a capacity of approximately 40 000 m^3 and geometric dimensions based on a previous conceptual study [7]. In this case study, both the FEM framework (*excluding* coupled effects of thermal contraction) and the thermal network model (*including* the cold-spot correction) were used to estimate the thermal performance of the tank. The models' heat ingress predictions differed by roughly one percent, and the cold spot temperature predictions by even less. For the price of this marginal accuracy reduction, the thermal network model reduces computational time by many orders of magnitude compared to FEM.

In light of the above, the thermal network model appears well-suited for on-design performance predictions of skirt-supported LH_2 tanks. Its low computational cost makes it particularly attractive for use within value chain optimization frameworks. FEM, on the other hand, is a valuable tool for more specialized studies of the containment system itself, for example concerning geometry optimization, or off-design performance estimation. Additionally, FEM is highly useful for validating thermal network models.

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