

Comparative performance assessment of multilayer insulation (MLI) systems for liquid hydrogen vessels in fire scenarios

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SUPPLEMENTARY MATERIAL

S.A Tank thermal model comparison with experimental results

The current literature lacks sufficiently detailed experimental data concerning LH₂ tanks featuring MLI systems under fire exposure. For this reason, the effectiveness of the proposed model (see Section 3.2 of the main document) in predicting the pressure build-up within cryogenic tanks was verified by comparison with experimental tests performed by Xie et al. [1,2] on a liquid nitrogen (LN₂) tank experiencing a sudden loss of vacuum within the MLI systems. Such a condition impairs the insulation performance and must be considered when addressing the safety of LH₂ tanks.

As reported by Xie et al., 50% of the tank volume was initially filled with liquid nitrogen at atmospheric pressure, in equilibrium with its vapor. The system featured an aluminum-based MLI with layers number varying from 10 to 30. Further details regarding the LN₂ tank geometry and MLI system characteristics are provided elsewhere [2]

At the beginning of the test, the pressure within the MLI system was increased by inflating gaseous nitrogen in the insulation gap, and the subsequent pressure build-up inside the tank was recorded. Three different tests were performed by varying the number of MLI layers between 10 and 30. Moreover, during the tests involving 30 MLI reflective layers, the temperatures of the 10th, 20th, and 30th layers were measured.

The model proposed in the present study was adapted to the specific tank geometry, MLI characteristics, and nitrogen physical properties of the case considered. In particular, the heat transfer coefficient from the inner wall of the tank to the liquid nitrogen (h_L) was here calculated as suggested by Kida et al. [3].

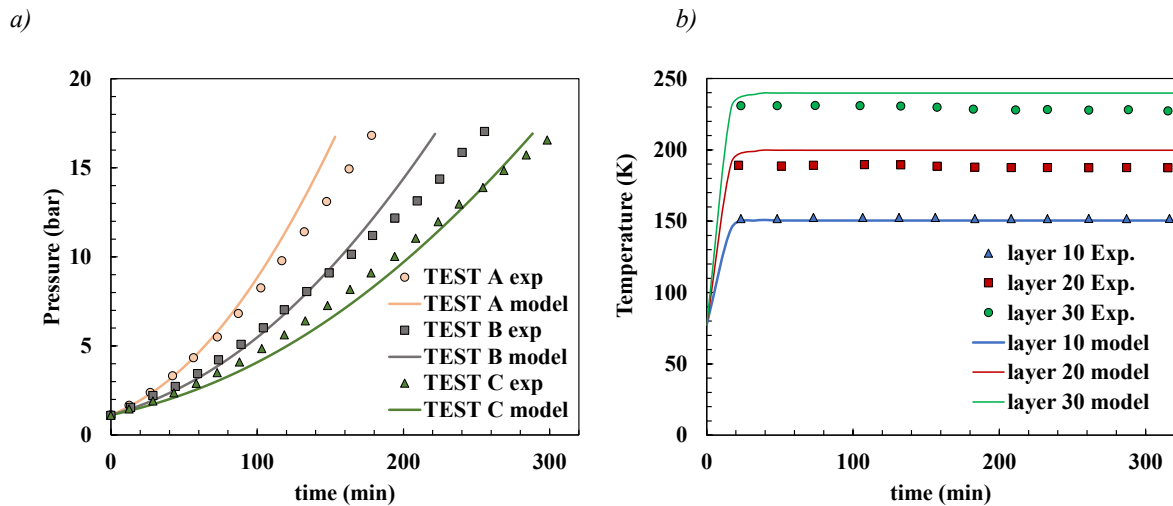


Figure A.1. Modelling (continuous lines) versus experimental (dots) results : (a) pressurization curves for the LN₂ tank with 10 (TEST A), 20 (TEST B), and 30 (TEST C) MLI reflective layers under loss of vacuum conditions; (b) temperature distribution within the MLI system of TEST C during the loss of vacuum experiment performed by Xie et al. Experimental data from [1,2].

Figure A.1a presents a comparison between experimental data and modeling results for the self-pressurization of the LN₂ tank in the tests addressing MLIs with 10 (referred to as TEST A), 20 (referred to as TEST B), and 30 reflective layers (referred to as TEST C). In all the cases, the model simulates well the experimental results, offering a slightly conservative prediction of the total time of pressurization. For this reason, the model is considered as conservative in the context of fire safety assessment of cryogenic tanks.

Figure A.1b compares the temperature distribution within the MLI with 30 layers measured in the tests by Xie et al. with the model predictions. Over the entire simulation time, the maximum difference between measured and simulated temperatures comes from the 30th layer and stands at 10 K. This result suggests that the heat flux towards the inner tank wall is well caught during the simulation.

Overall, the model predicts both the tank self-pressurization and the insulation temperature with sufficient precision under normal boundary temperatures. However, additional research is required to validate its performance under fire conditions, which is currently not feasible due to the absence of sufficiently detailed experimental benchmarks in the present literature.

S.B Supplementary results of the case-study

Figures B.1 and B.2 present the pressure history within the LH₂ tank and the maximum inner shell temperature during the eight fire scenarios considered in the present study (see Section 3.3 of the main document) for the aluminum-based and polyester-based MLI respectively. These results are complementary to those shown and discussed in the results section of the main document (see section 5.1) and here presented for the sake of completeness.

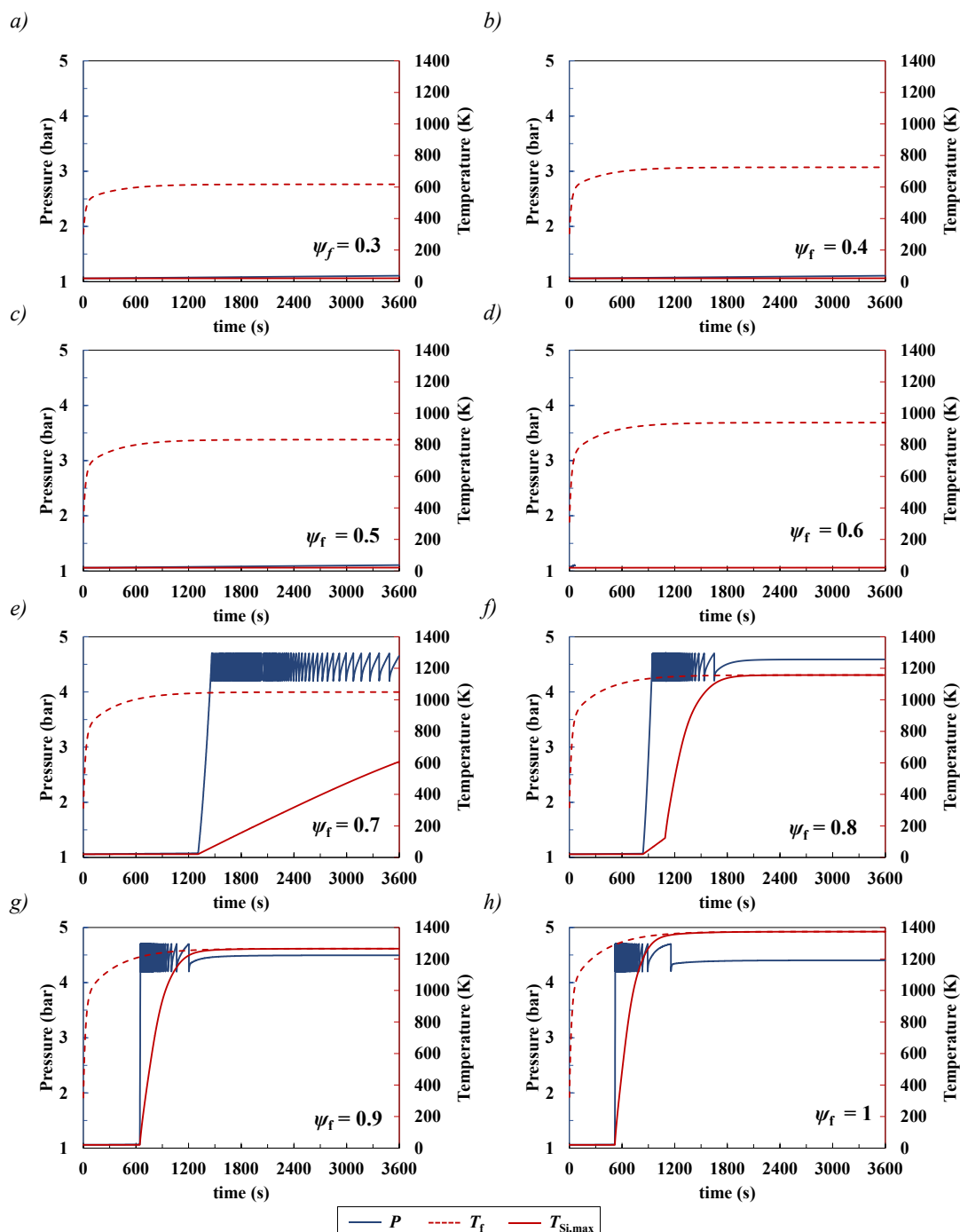


Figure B.1. Complementary case-study results: Pressure (blue line), flame (dashed red line), and maximum inner shell (continuous red line) temperature history obtained for the case study addressing aluminum-based MLI, (see Section 3 of the main document). Panels (a) to (h) refer to flame temperature factor (ψ_f) varying from 0.3 to 1 with a step of 0.1.

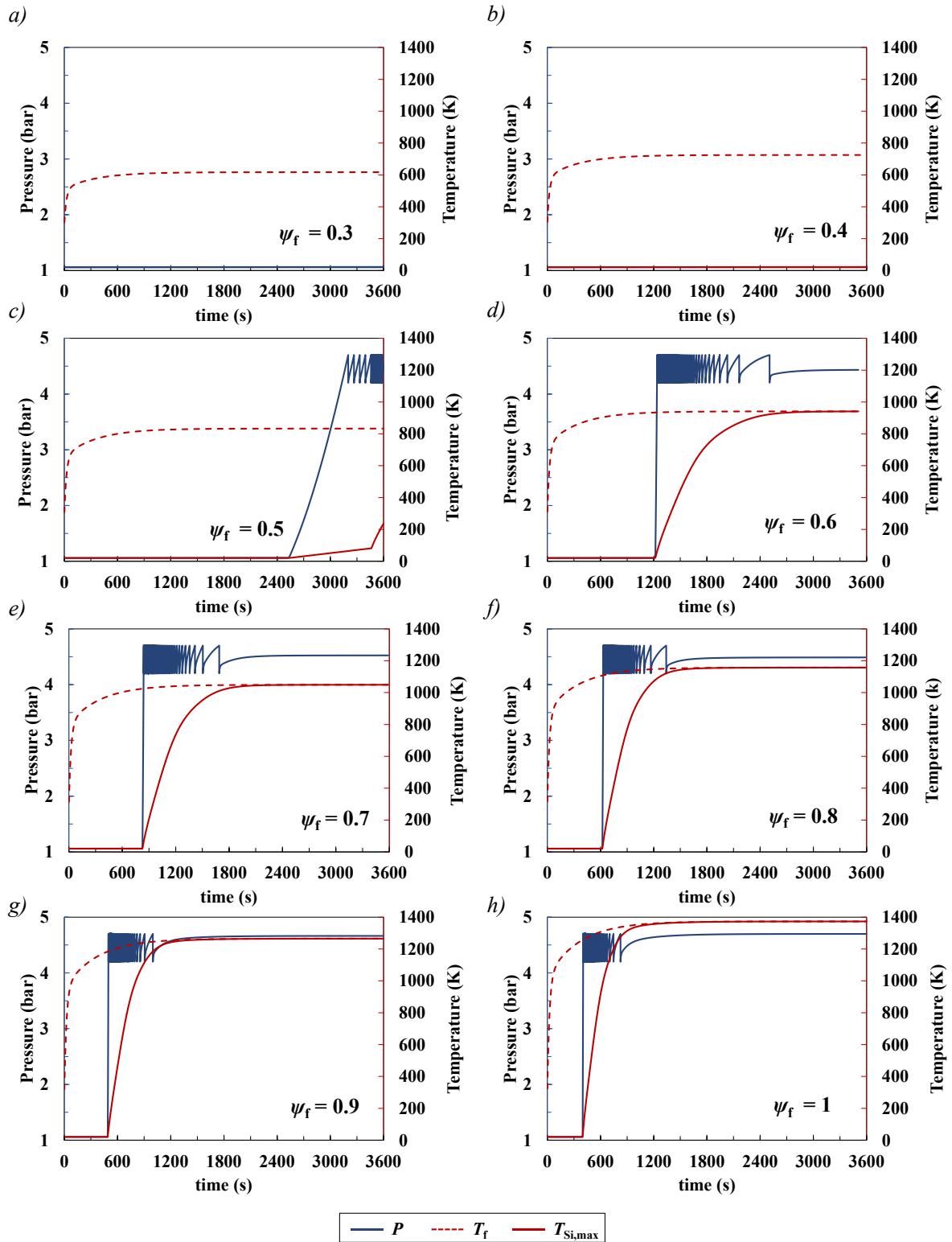


Figure B.2. Complementary case-study results: Pressure (blue line), flame (dashed red line), and maximum inner shell (continuous red line) temperature history obtained for the case study addressing polyester-based MLI, (see Section 3 of the main document). Panels (a) to (h) refer to flame temperature factor (ψ_f) varying from 0.3 to 1 with a step of 0.1.

Figure B.3 depicts the modeled temperature of MLI reflective layers over time vs the flame temperatures (dashed red line) under the fire scenarios corresponding to $\psi_f = 1, 0.7$ and 0.5 . Panels a, c and e refer to aluminum-based MLI, while Panels b, d, and f to polyester-based one. For the sake of clarity, only 10 out of 80 layers are reported as representative of the overall behaviour. The temperature of each layer increases following the flame one with a delay becomes longer the closer the layer is to the inner shell of the tank. If the degradation thresholds are reached (see Table 2 in the main text), the layer is assumed as destroyed and removed from the simulation. At the end of the most severe fire scenario (i.e., $\psi_f = 1$), all the MLI layers are degraded regardless of the insulation material. For $\psi_f = 0.7$, the complete degradation still occurs in polyester-based MLI while one layer remains intact in aluminum-based MLI. Moving to $\psi_f = 0.5$, all the aluminum-based layers remain intact at the end of the simulation but only one layer survives in polyester-based MLI.

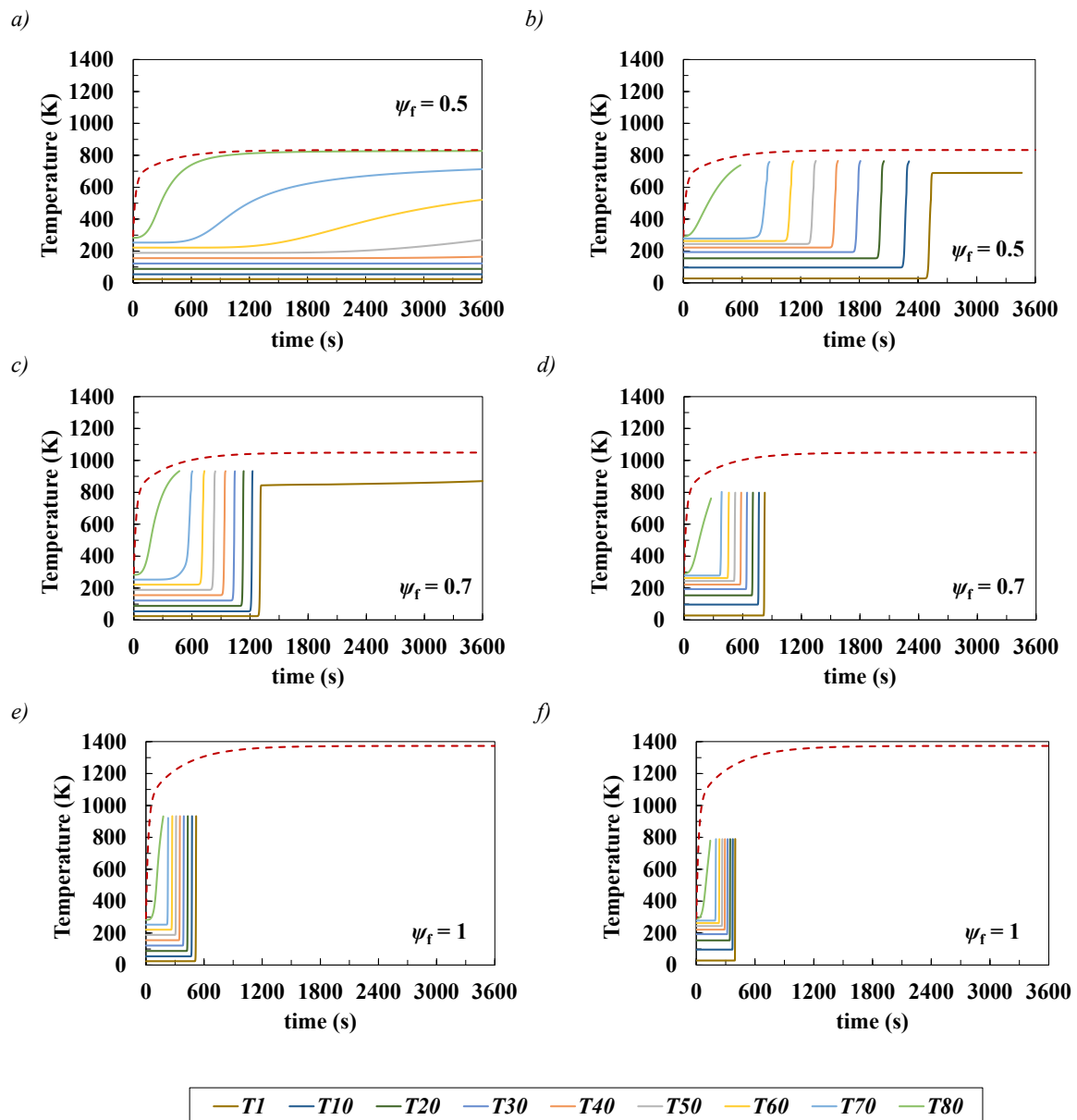


Figure B.3. model temperatures of the radiative layers over time considering flame temperature factors (ψ_f) equal to 0.5, 0.7 and 1. Panels (a), (c), and (e) refer to aluminium-based MLI; Panels (b), (d), and (f) refer to polyester-based MLI. According to Figure 2 of the main text, layers 1 and 80 face the inner and outer shell of the tank, respectively.

These outcomes highlight the superior fire resistance features of the aluminum-based MLI under milder fire conditions, as confirmed by observing the calculated heat flux values to the inner shell of the tank, depicted in Figure B.4. Figures 4a and b refer to aluminum-based (Panel a) and polyester-based (Panel b) MLI, respectively. The values of the heat fluxes were calculated according to the set of equations presented in Table 1 of the main text and vary between 0.2 and 65000 W/m^2 , depending on the fire intensity and insulation material considered. As a general behaviour, the heat flux reaches the peak value as soon as the MLI is completely degraded, before decreasing due to rise in inner shell temperature (please, see Figure 4 in the main text). The higher the flame temperature the higher the maximum heat flux received by the tank and the less the time to reach this peak value. Overall, these results are closely linked to that of tank pressurization, furtherly explaining the reasons for the different pressurization rates obtained in the present study (see Figure 4 of the main text).

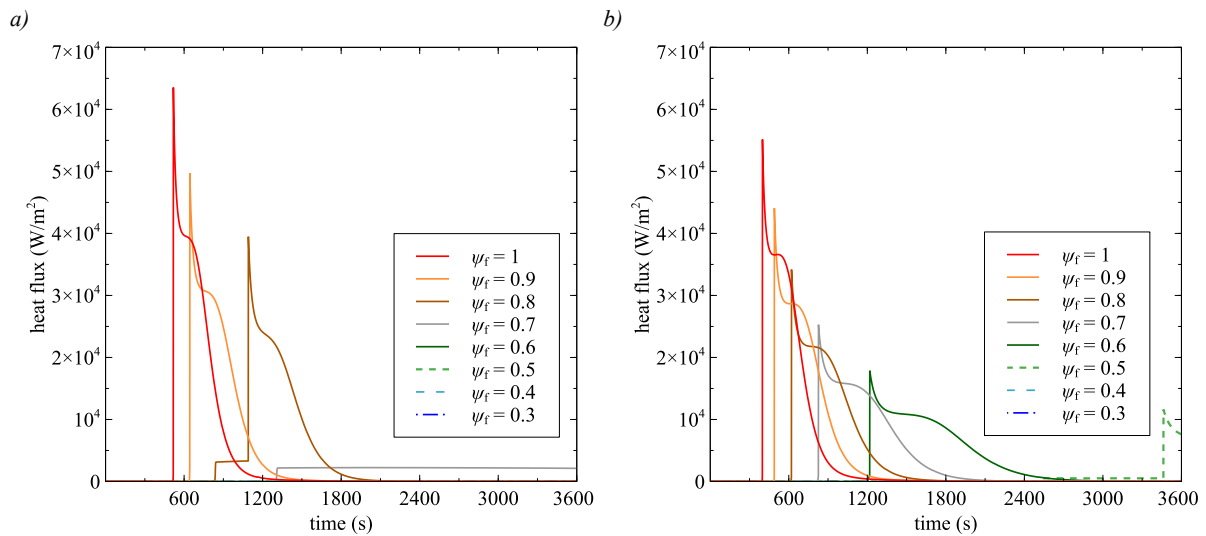


Figure B.4. Complementary case-study results: heat fluxes through the inner tank wall during fire exposure for flame temperature factors (ψ_f) varying from 0.3 to 1 with a step of 0.1. Panel (a) refers to aluminum-based MLI; Panel (b) refers to polyester-based MLI.

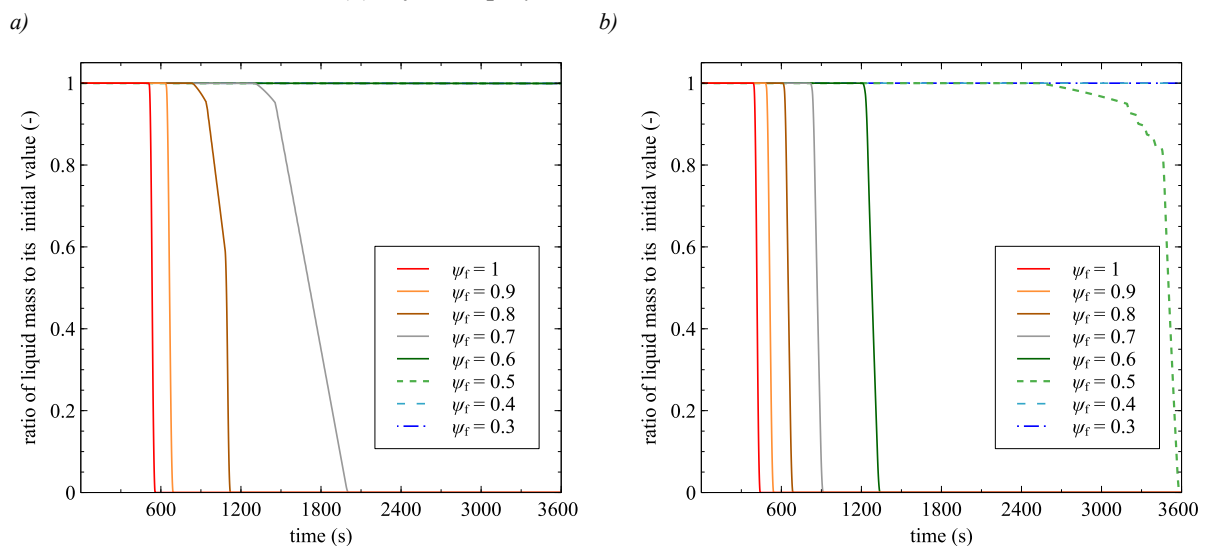


Figure B.5. Complementary case-study results: liquid hydrogen mass variation inside the tank during fire exposure for flame temperature factors (ψ_f) varying from 0.3 to 1 with a step of 0.1. Panel (a) refers to aluminum-based MLI; Panel (b) refers to polyester-based MLI.

Figure B.5 presents the ratio of the liquid hydrogen mass inside the tank to its initial value for the fire scenarios analyzed as simulated by the model. Panel a refers to aluminum-based MLI, while Panel b refers to the polyester-based one. The results show that complete liquid evaporation occurs under intense fire for both MLIs considered, while this happens only for the polyester-based material under mild conditions (i.e., flame factors equal to 0.6 and 0.5). For low fire intensities (i.e., flame factors equal to 0.6 and 0.5) no appreciable liquid mass variation are observed.

S.C Results for 80% filling degree

Figures C.1 and C.2 depict the pressure and the maximum inner shell temperature increase in within the LH₂ tank 80% filled with liquid hydrogen for the eight fire scenarios considered in the present study (see Section 3.3 of the main document). Figure C.1 and C.2 refer to aluminum-based and polyester-based MLI, respectively.

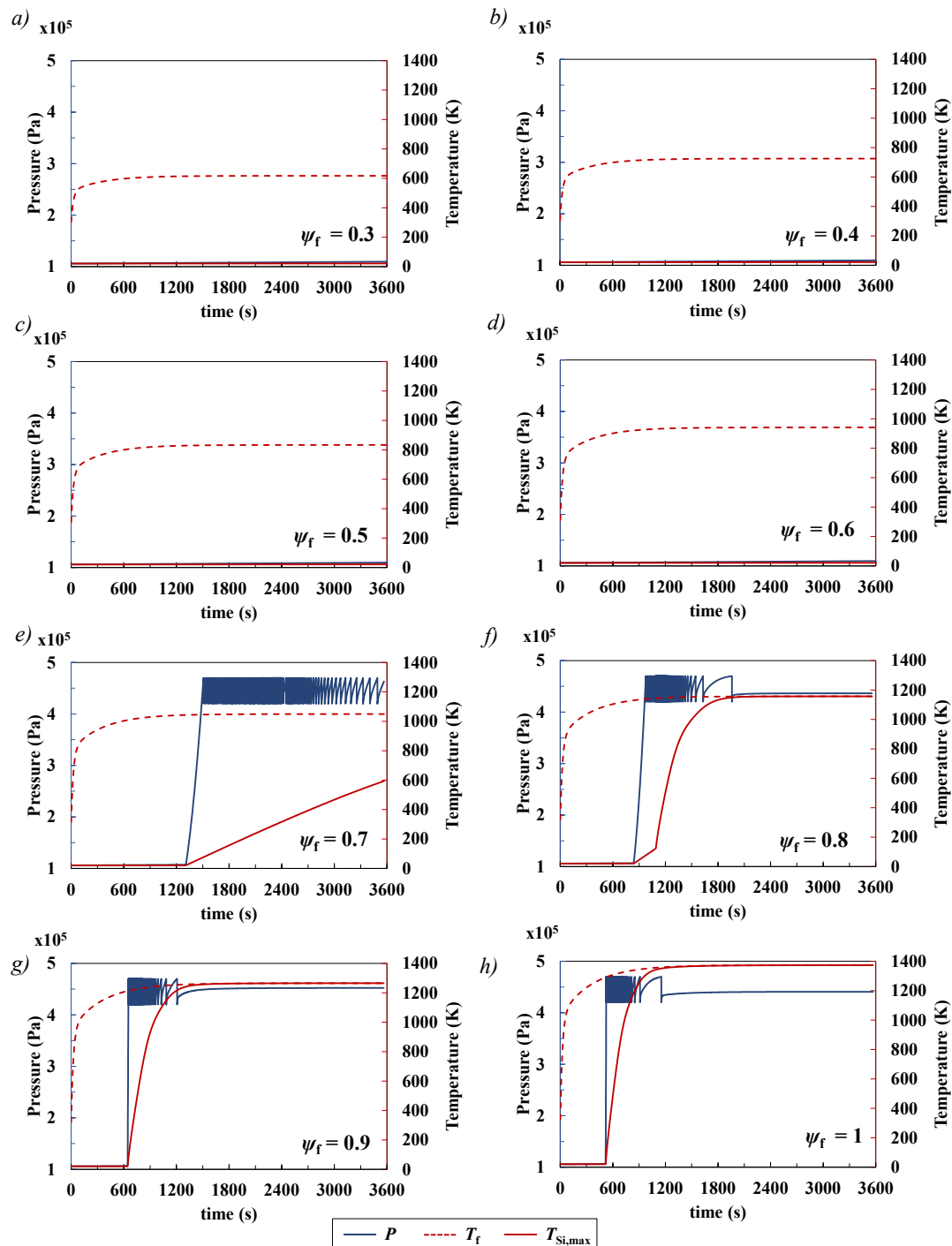


Figure C.1. Results for a LH₂ tank filled with liquid hydrogen up to 80% of its volume: Pressure (blue line), flame (dashed red line), and maximum inner shell (continuous red line) temperature history obtained for the case study addressing aluminum-based MLI, (see Section 3 of the main document). Panels (a) to (h) refer to flame temperature factor (ψ_f) varying from 0.3 to 1 with a step of 0.1.

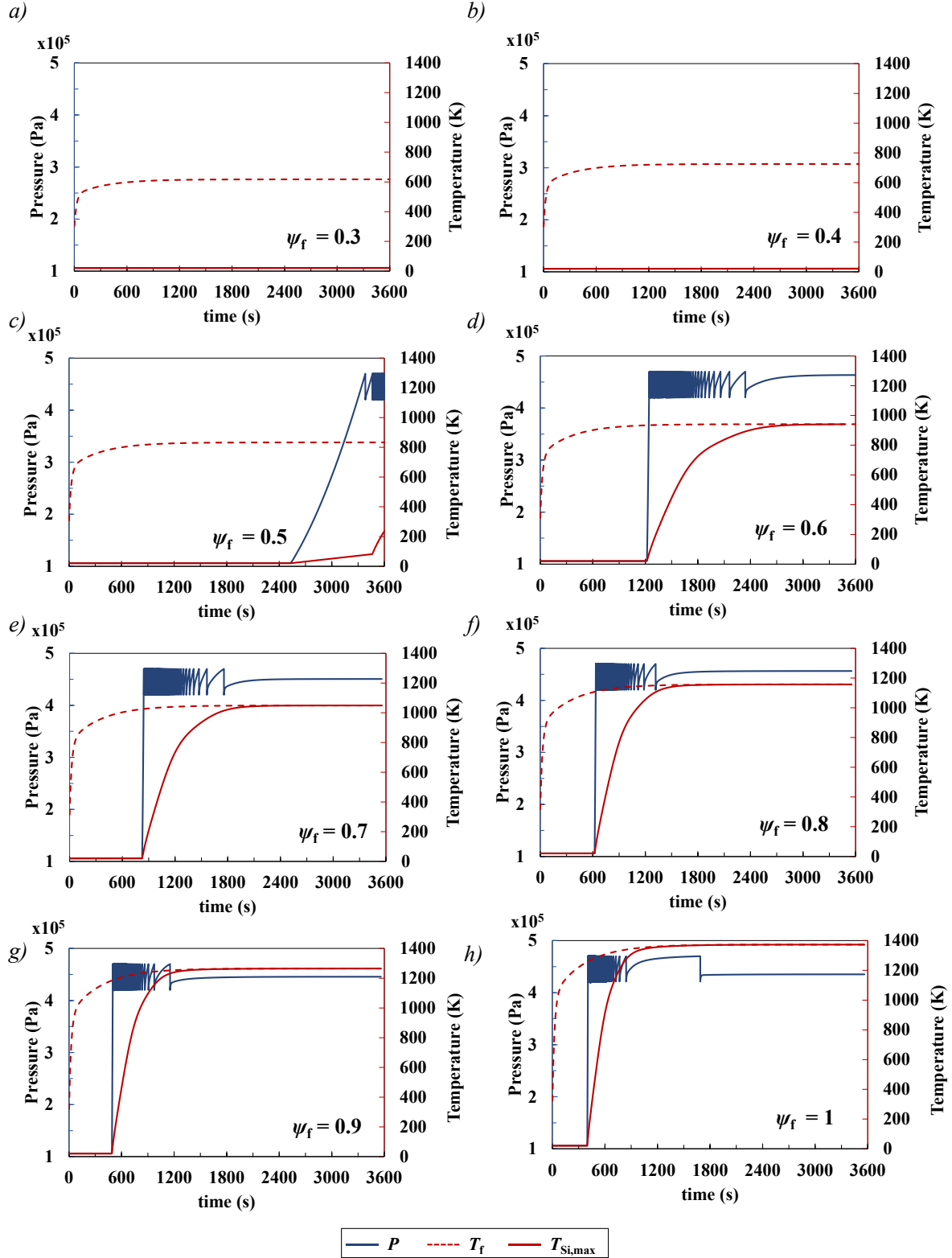


Figure C.1. Results for a LH₂ tank filled with liquid hydrogen up to 80% of its volume: Pressure (blue line), flame (dashed red line), and maximum inner shell (continuous red line) temperature history obtained for the case study addressing polyester-based MLI, (see Section 3 of the main document). Panels (a) to (h) refer to flame temperature factor (ψ_f) varying from 0.3 to 1 with a step of 0.1.

S.D Model sensitivity analysis

A sensitivity analysis was performed to assess the influence of selected model parameters on the final computational results. The analysis evaluates the robustness of the model and provides detailed insights into the uncertainty associated with parameter selection. The parameters are grouped into three main categories: empirical parameters, insulation system parameters, and tank operating parameters, as listed in Table 6 of the main text. The empirical parameters considered include all those introduced in the study, except for the convective heat transfer coefficient of the gas inside the insulation system. This exclusion is justified by the low vacuum pressure within the insulation, which prevents convective heat transfer. Notably, the overall convective heat transfer coefficient of hydrogen (h) accounts for variations in both the vapour and liquid phases, as it is computed as a weighted average (see Eq. 30 in Table 3 of the main document). The insulation system and tank operating parameters were chosen based on their susceptibility to variation across different tanks. These parameters depend on the specific application and technical requirements, such as insulation performance at normal operating conditions (e.g., the number of MLI layers), space and weight constraints (e.g., insulation gap thickness), and installation methods (which influence layer compression and spacer thickness). Conversely, other tank design parameters were excluded from the analysis as they are strictly defined by standards. Finally, this section does not address changes in liquid filling levels, which are analysed in Section S.C. Similarly, the effect of flame characteristics and of the related parameters are extensively analysed in the main document.

The sensitivity analysis was performed by carrying out model simulation runs varying each of the selected parameters within a range of $\pm 10\%$ with respect to the reference value (reference values are reported in Sections 4.1 and 4.2 of the main document) while keeping the values of the other parameters constant. The effect of these variations is assessed on basis of the final results obtained for the time to MLI degradation (t_{id}), the time to first PRV activation (t_{PRV}) and the time to failure (t_{tf}).

The results of the sensitivity analysis considering a fire scenario with a flame factor, ψ_f , equal to 1 are presented in Figure D.1 for both of the two MLI types.

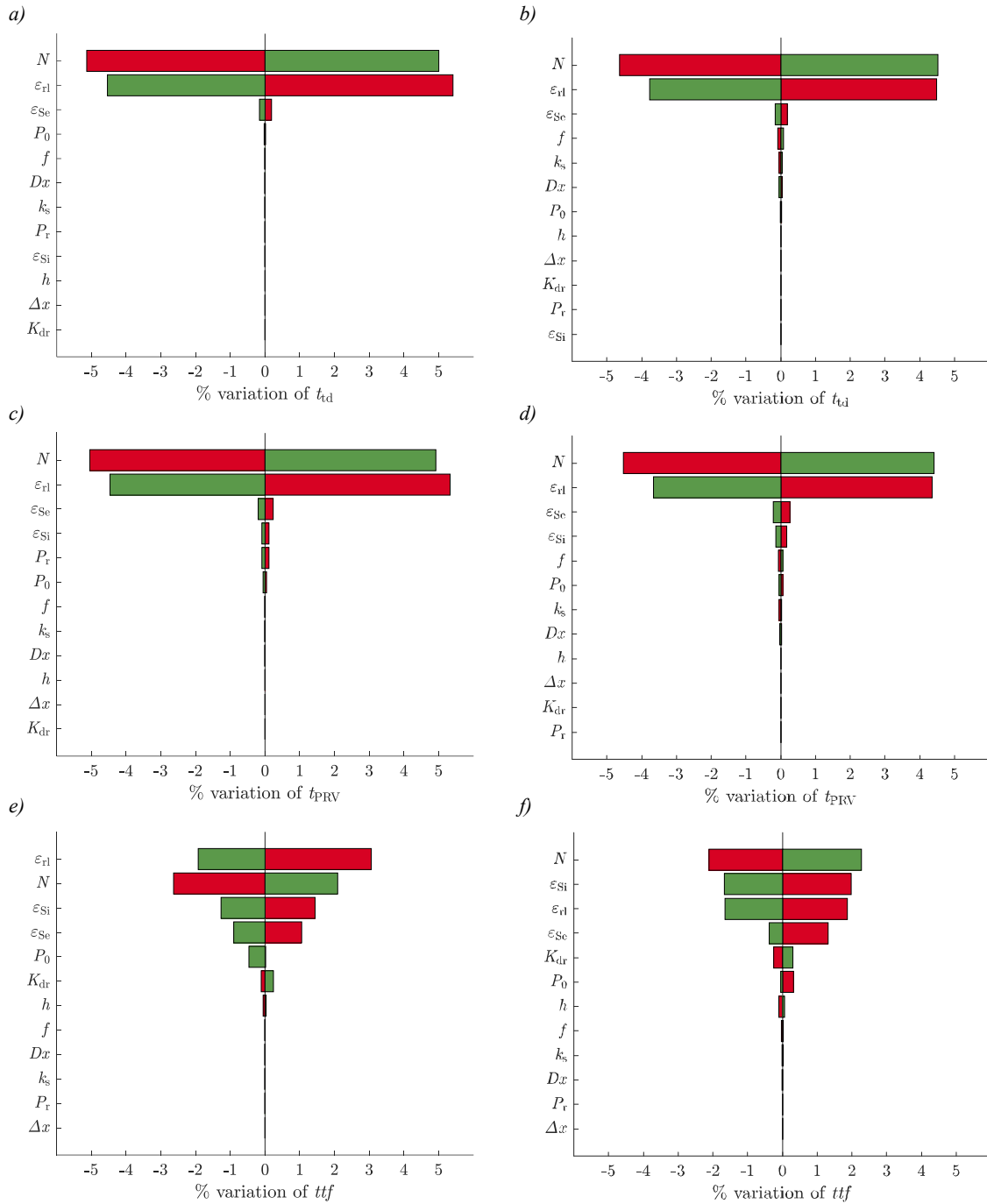


Figure D.1. Sensitivity analysis results when the model is applied to an LH₂ tank filled with liquid hydrogen up to 50% of its volume and considering a fire scenario with a flame factor ψ_f equal to 1. The parameter description is provided in Table 6 of the main text. The green bars shows the effect of a +10 % variation of the input parameter with respect to the reference value, while the red bars show a -10 % variation of the input parameter with respect to the reference value. Panels (a), (c), and (e) refer to aluminium-based MLIs, while Panels (b), (d), and (f) refer to polyester-based MLIs.

The x-axis represents the percentage variation in the output variables, while the y-axis lists the parameters in a decreasing order of influence. A filled green bar means that the input was varied by +10 % with respect to the reference value, while a red bar indicates a variation of -10 %. The results show that the output variation scored a ± 5 % maximum difference, with the number of layers (N) and surface emissivity having the stronger influence, while the effect of the other parameters is negligible, with variations lower than 1 %.

The results also show the importance of the characteristics of the MLI system in terms of number of layers and of the construction material, highlighting the role of the surface emissivity, that may have a significant effect in the scenario evolution, as reported in previous studies [4].

Overall, the results of the sensitivity analysis demonstrate that the outcome of the case study is robust: the uncertainty related to reasonable assumptions concerning the input parameters have a limited effect on the values of the RTs.

References

- [1] Xie GF, Li XD, Wang RS. Study on the heat transfer of high-vacuum-multilayer-insulation tank after sudden, catastrophic loss of insulating vacuum. *Cryogenics (Guildf)* 2010;50:682–7. <https://doi.org/10.1016/j.cryogenics.2010.06.020>.
- [2] Xie GF, Li XD, Wang RS. Experimental study on the storage performance of high-vacuum-multilayer-insulation tank after sudden, catastrophic loss of insulating vacuum. *Heat Mass Transf Und Stoffuebertragung* 2012;48:757–66. <https://doi.org/10.1007/s00231-011-0928-z>.
- [3] KIDA M, KIKUCHI Y, TAKAHASHI O, MICHIOYOSHI I. Pool-Boiling Heat Transfer in Liquid Nitrogen. *J Nucl Sci Technol* 1981;18:501–13. <https://doi.org/10.1080/18811248.1981.9733284>.
- [4] Campese D, Scarponi GE, Eberwein R, Hajharir A, Otremba F, Cozzani V. Modelling Fire Response of Cryogenic Liquid Hydrogen Tanks Equipped with Multilayer Insulation (MLI) Systems. *Chem Eng Trans* 2024;111:451–6. <https://doi.org/10.3303/CET24111076>.