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Vaporization of cryogenic liquid stored in damaged vacuum-insulated tank

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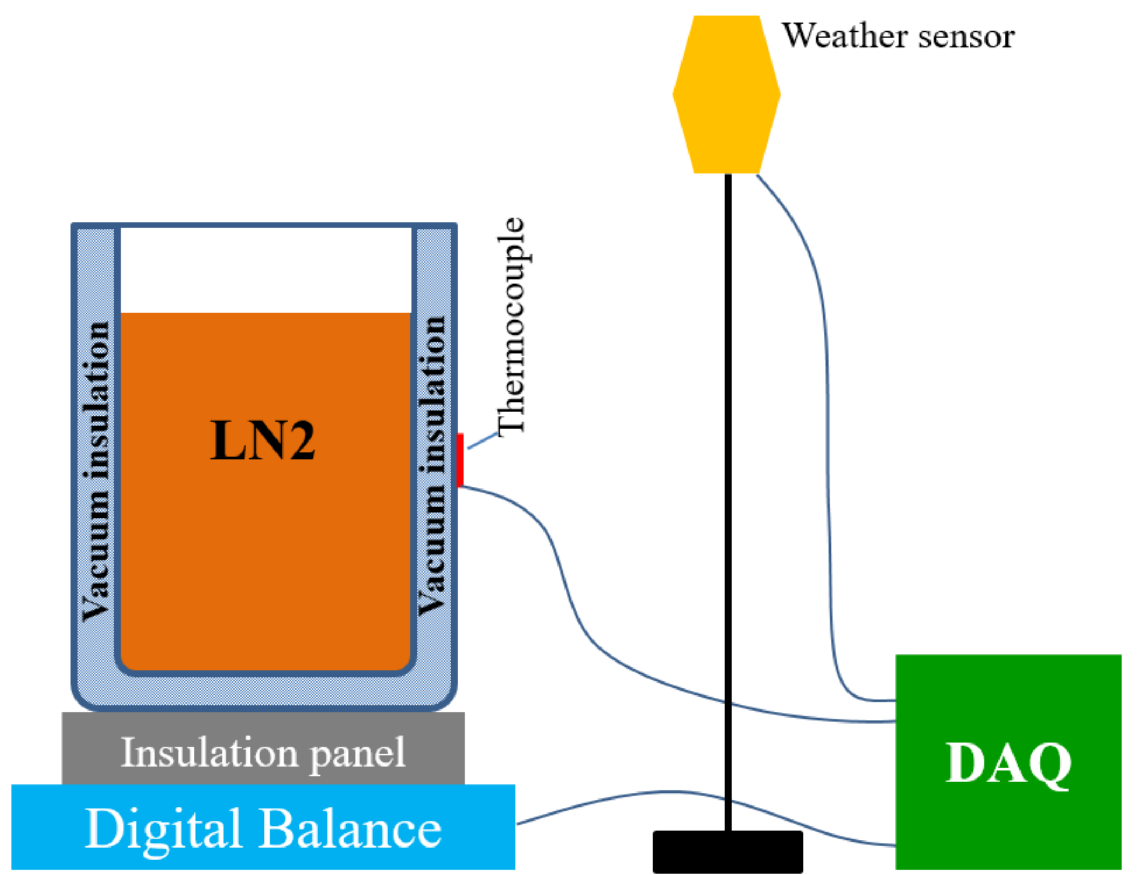
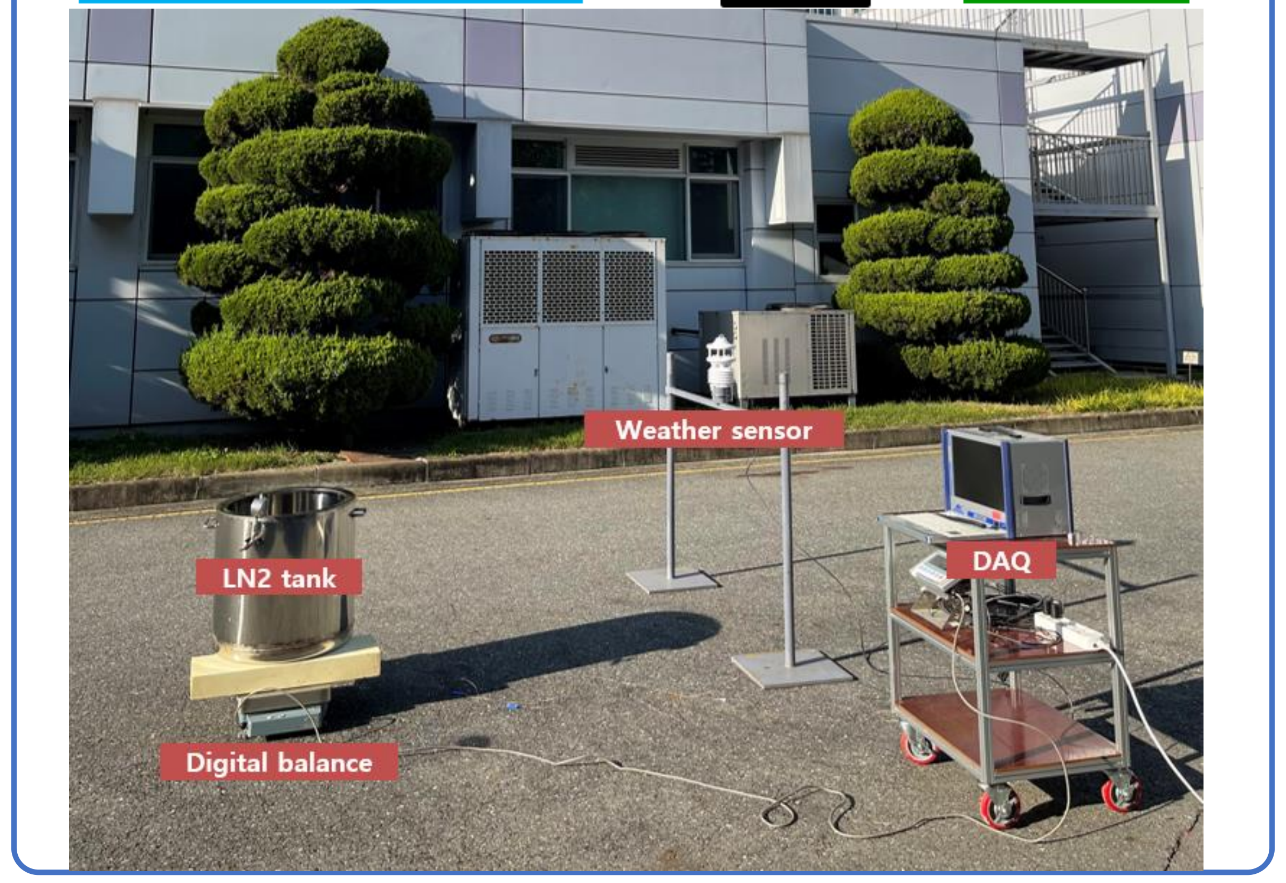
INTRODUCTION

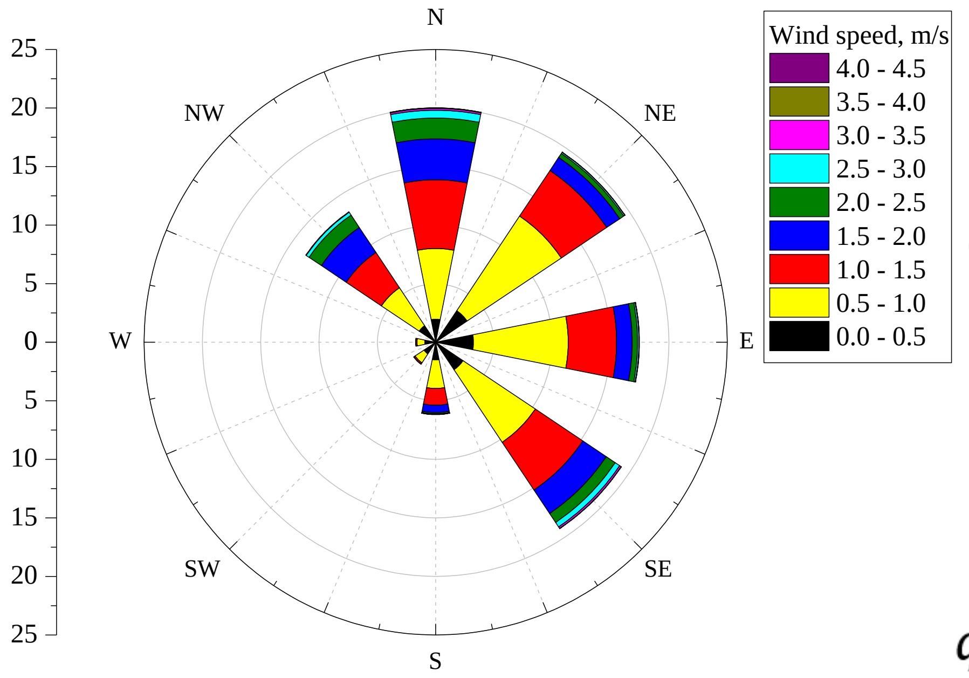
- Vacuum insulation is commonly used in cryogenic liquid storage because of its excellent insulation performance. However, the accidental loss of insulating vacuum might result in significant boil-off of the stored liquid. The loss of the stored liquid through boil-off not only impacts energy efficiency but also poses a serious safety concern. The hazards associated with the storage of cryogenic liquids must be thoroughly considered to protect humans, assets, and the environment.
- Quantitative risk assessment (QRA) is an essential tool for evaluating the risks. As a critical step in QRA, the consequence estimation process requires the evaluation of the boil-off rate of the liquid in the case of vacuum failure to analyze incident outcomes.
- In this study, the boil-off of liquid nitrogen stored in a double-walled vacuum-insulated tank in the case of vacuum loss was numerically and experimentally investigated.
- The findings of this study are expected to enhance the understanding of the boil-off behavior of cryogenic liquids in the case of the failure of vacuum insulation and also provide an efficient numerical tool for analyzing the incident outcomes for consequence estimation as a part of QRA.

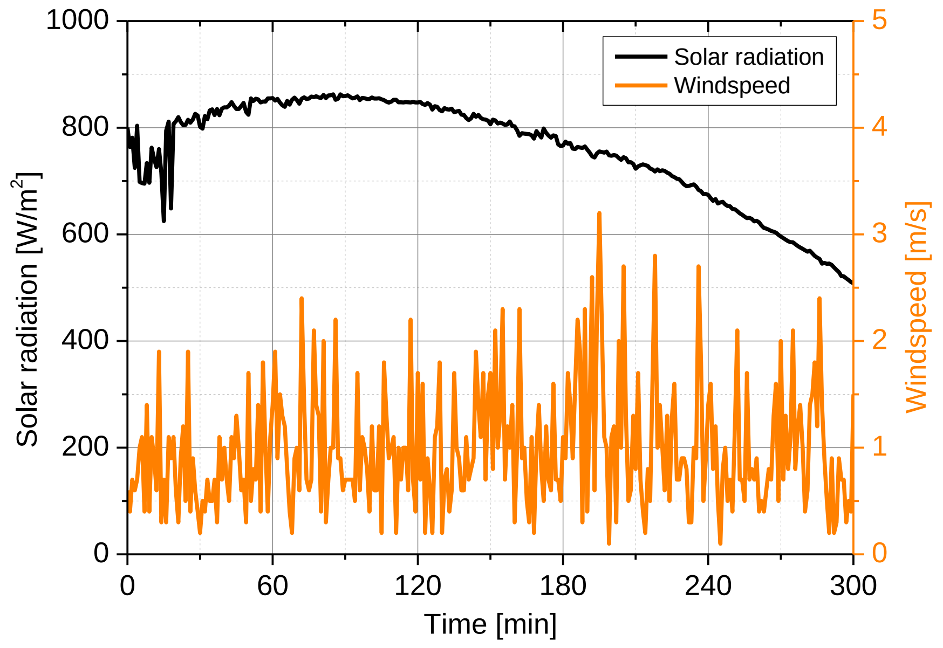
EXPERIMENTAL SETUP

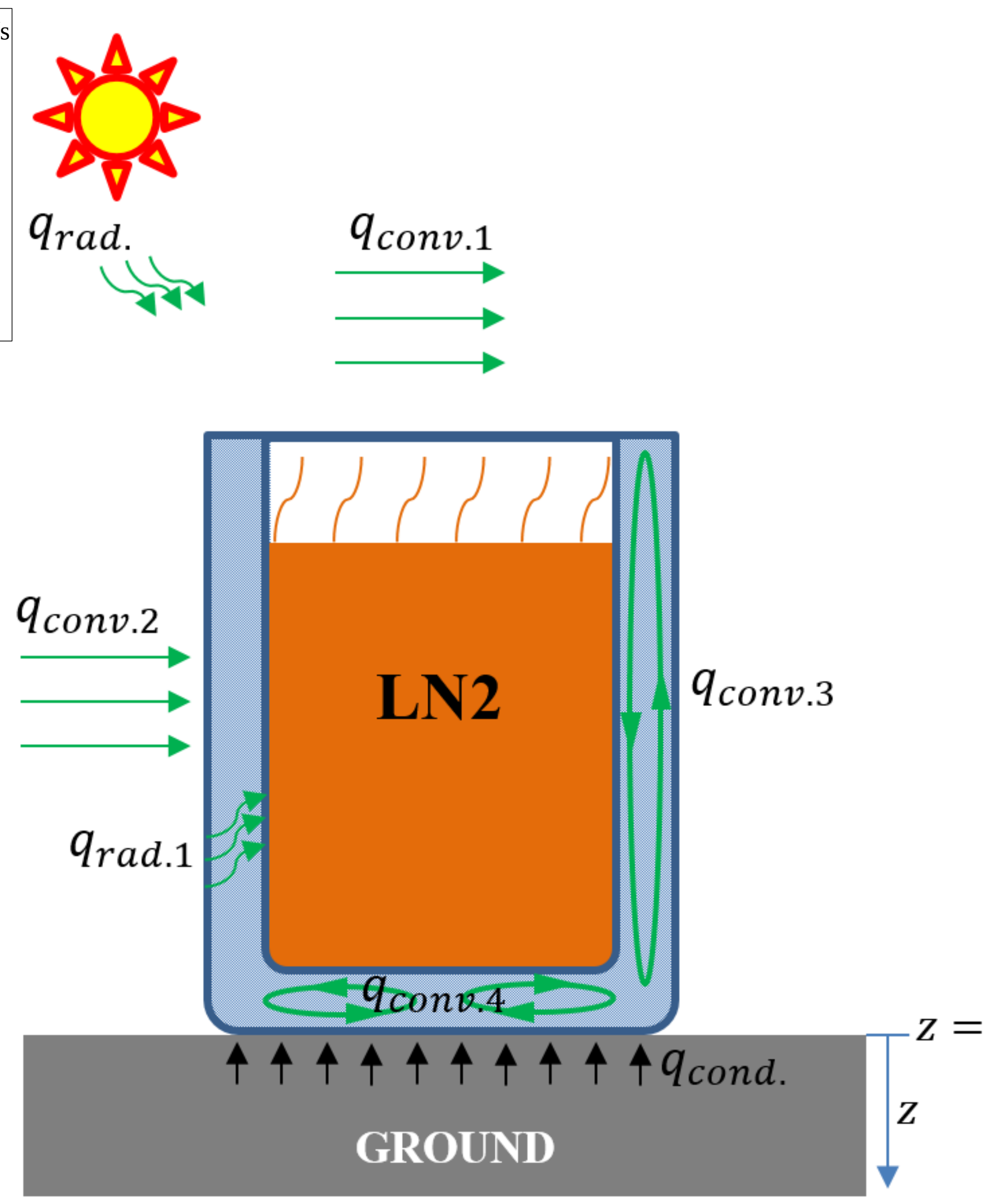




MODELING







$$q_{conv.1} = \frac{\pi d^2}{4} \times \frac{\lambda Nu}{d}(T_a - T_b)$$

$Nu = 0.664Pr^{\frac{1}{3}}Re^{\frac{1}{2}}$ if $Re < 320{,}000$ else $Nu = 0.037Pr^{\frac{1}{3}}(Re^{0.8} - 15{,}200)$

$Re = (u_{10}\rho d)/\mu;\ Pr = (c_p\mu)/\lambda$

$$q_{conv.2} = \frac{\pi DH}{2} \times \frac{\lambda Nu}{D}(T_a - T_w)$$

$$Nu = 0.3 + \frac{0.62Re^{1/2}Pr^{1/3}}{[1 + (0.4Pr)^{2/3}]^{1/4}}\left[1 + \left(\frac{Re}{282{,}000}\right)^{5/8}\right]^{4/5}$$

$Re = (u\rho D)/\mu$

$$q_{conv.3} = \pi d \times 0.364\lambda(T_w - T_b)Ra_h^{1/4}$$

$Ra_h = g\beta(T_w - T_b)h^3/(\alpha\nu)$

$$q_{conv.4} = \frac{\pi d^2}{4} \times \frac{\lambda Nu}{\delta}(T_{wb} - T_b)$$

$Nu = 0.069Ra^{1/3}Pr^{0.074}$

$Ra = g\beta(T_{wb} - T_b)\delta^3/(\alpha\nu)$

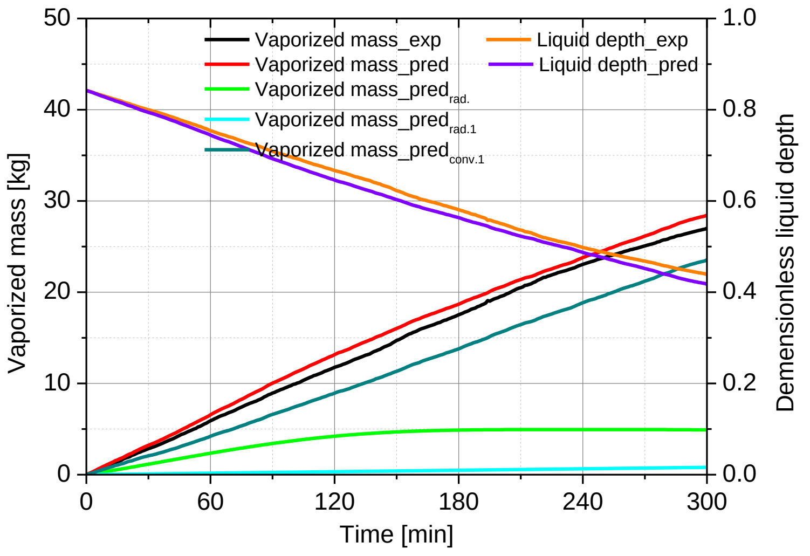
$$q_{cond.} = \frac{\pi d^2}{4} \times \lambda \left.\frac{\partial T}{\partial z}\right|_{z=0^+}$$

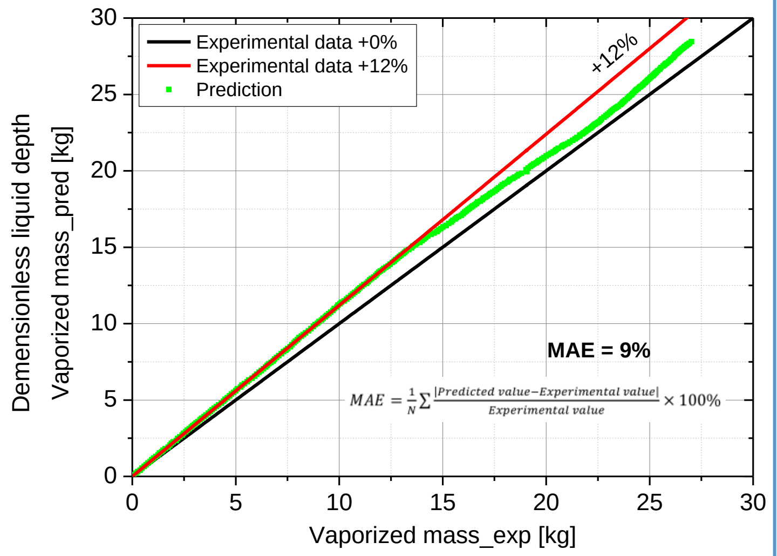
$$q_{rad.1} = \pi dh \frac{\sigma(T_w^4 - T_b^4)}{1/\varepsilon_w + 1/\varepsilon_b - 1}$$

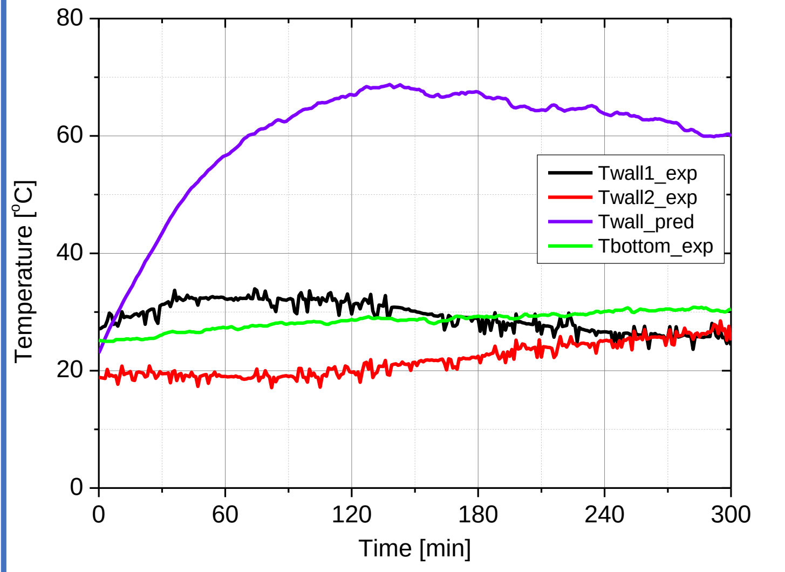
$$m_w c_w \frac{dT_w}{dt} = q_{rad} + q_{conv.2} - q_{rad.1} - q_{conv.3}$$

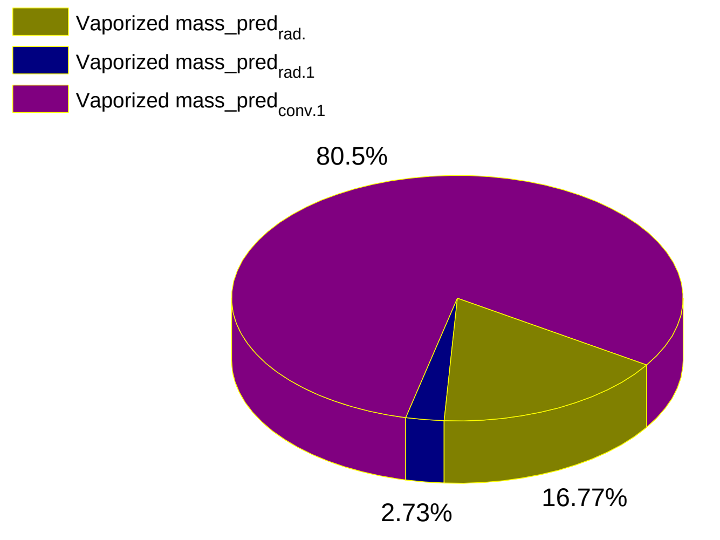
RESULTS

INTACT VACUUM-INSULATED TANK



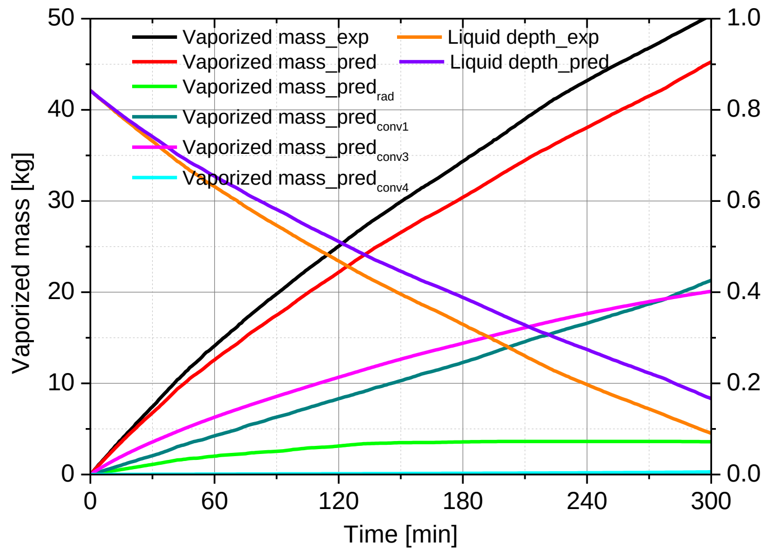


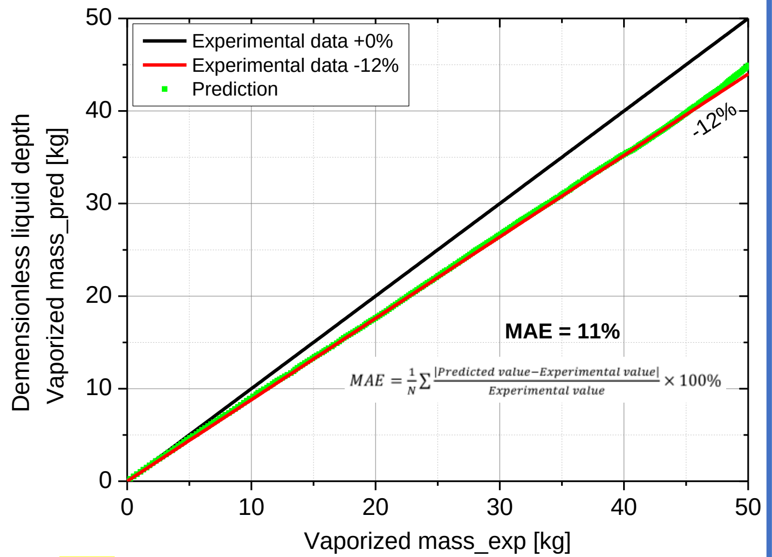


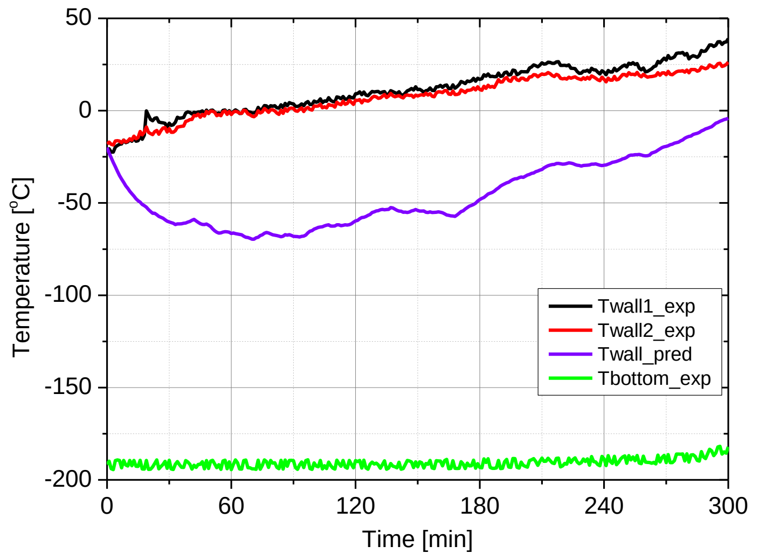


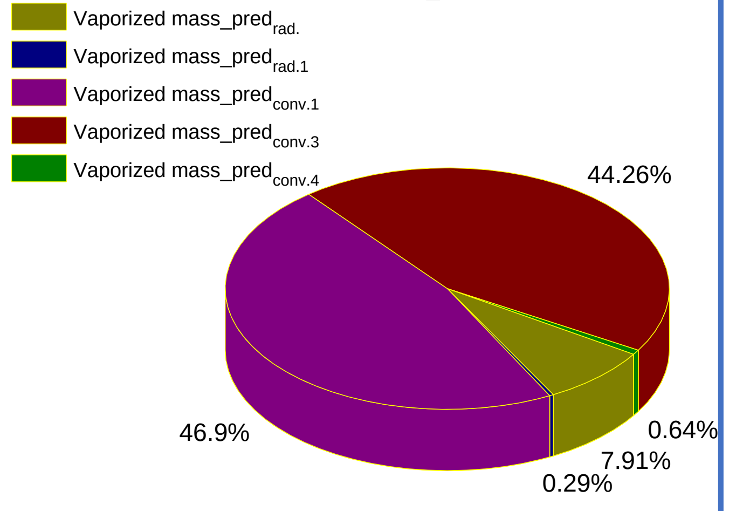
- The heat sources include $q_{conv.1}$, $q_{rad.}$, and $q_{rad.1}$ with the contribution of the former to the vaporization being significantly greater than that of the latter.
- The prediction agreed well with experiment, with the MAE of 9%.

DAMAGED VACUUM-INSULATED TANK



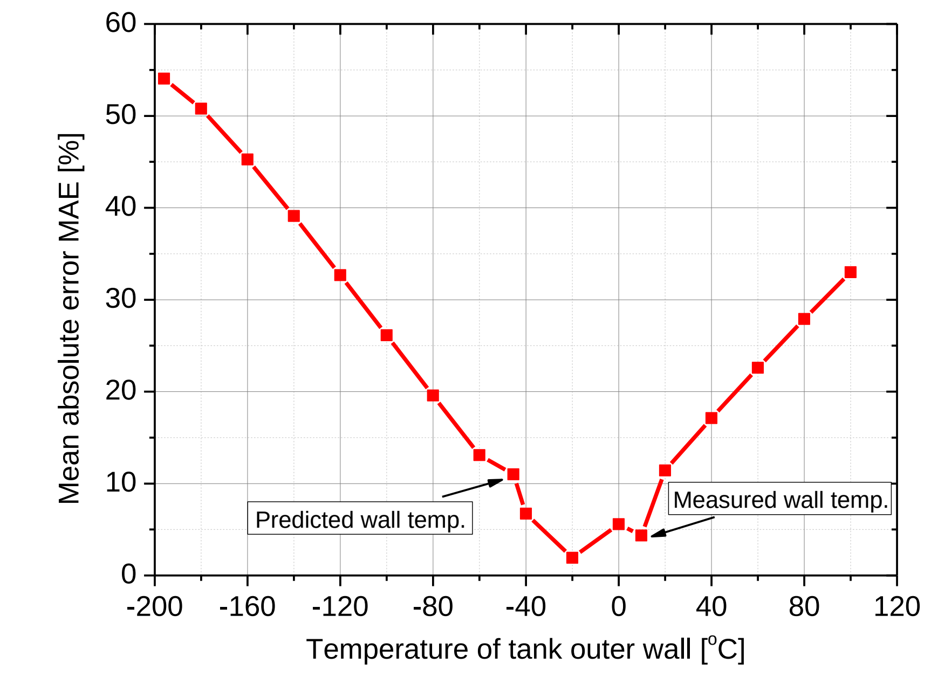






- The contributions of $q_{conv.1}$ and $q_{conv.3}$ to the vaporization were quite similar.
- The model significantly underestimated the tank wall temperature.
- The predicted vaporized mass agreed well with experiment, with the MAE of 11%.

RESULTS (cont.)



- The effect of outer wall temperature on the predicted vaporized mass in the case of damaged insulation was investigated.
- The neglect of convection heat transfer between tank walls resulted in the MAE of 55%.

CONCLUSIONS

- The heat sources for liquid vaporization, including radiation heats $q_{rad.}$ and $q_{rad.1}$, convection heat from the ambient air to the liquid surface $q_{conv.1}$, convection heat from the ambient air to the outer tank wall $q_{conv.2}$, and convection heats from the outer to the inner tank wall $q_{conv.3}$ and $q_{conv.4}$ were modeled.
- The prediction for vaporized mass agreed well with experiments. However, the discrepancies between predicted temperature of tank wall with measurements were observed.
- The contributions of $q_{conv.1}$ and $q_{conv.3}$ to the vaporization were quite similar.
- The heat transferred by radiation between two tank walls $q_{rad.1}$ was negligible compared to convection heat $q_{conv.3}$.

REFERENCES

- A. Bejan, 1995. Convective Heat Transfer, 2nd edition, John Wiley & Son, Inc., New York.
- J.P. Holman, 2010. Heat Transfer, 10th edition, The McGraw-Hill Companies, Inc., New York.

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