Numerical investigation of thermal distribution and pressurization behavior in helium pressurized cryogenic tank by introducing a multi-component model

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Background

Accurate prediction of pressurant gas requirement or pressure history is of importance to the design and optimization of pressurization system.

Various thermodynamic phenomena my occur simultaneously during pressurization including heat transfer, mass transfer, and species transport.

A completed CFD which could consider these thermodynamic phenomena is beneficial to the pressurization analysis and design.

Objectives

An improved CFD model is introduced to investigate the thermal performance and pressurization behaviors for pressurized discharge process.

Multi-component ullage including helium and propellant vapor is considered and an improved phase change effect is involved in the CFD model.

Thermodynamic phenomena as well as the pressurization behaviors are obtained and analyzed through the new CFD model.

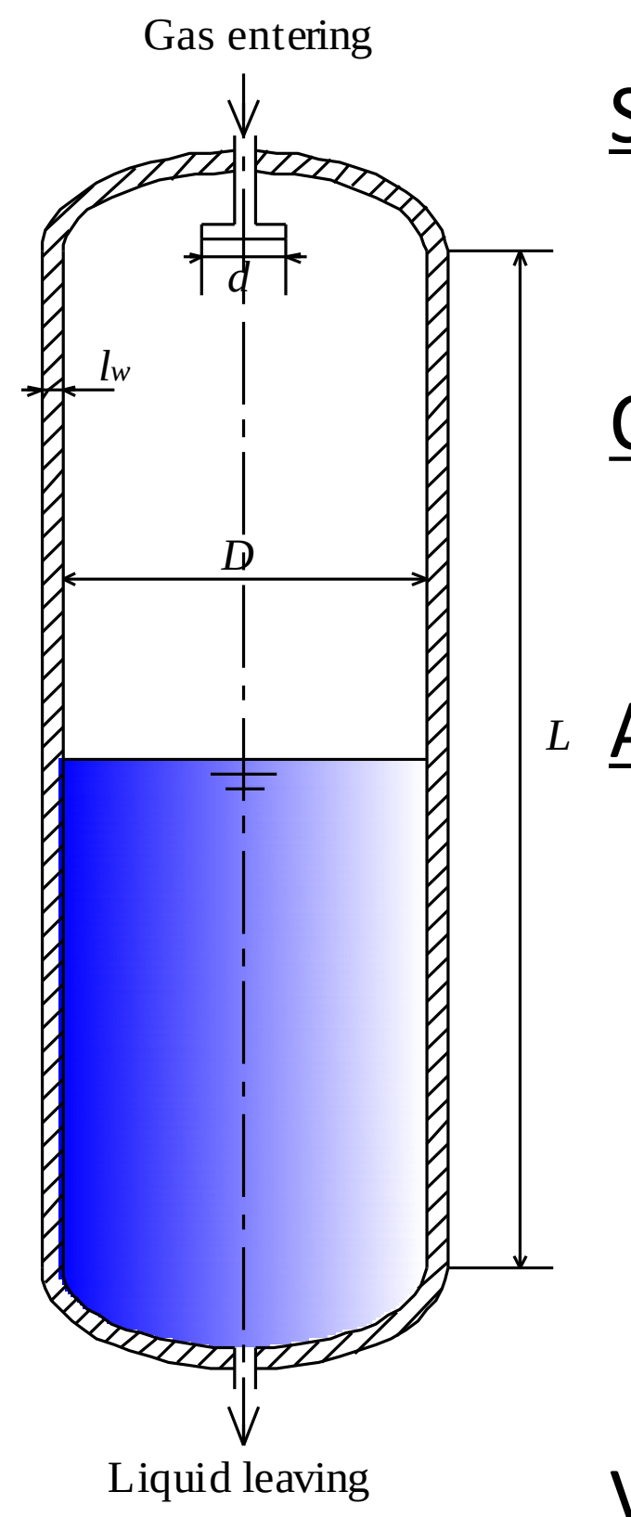
Conclusions

◆ Compared to the helium-only ullage model, the present model produces a weaker fluid-wall heat transfer rate, and further resulting in a higher ullage temperature as well as the pressurization behaviors.

◆ The multi-component ullage will affect the property variation within the ullage, leading to an observable radial temperature distribution, especially for the liquid oxygen tank.

◆ The phase change mode of LH_2-He case is liquid evaporation, while the LO_2-He case experiences first the vapor condensation and then the liquid evaporation process during the whole discharge. On the whole, the phase change effect is very small and has a slight influence on the pressurization performance.

CFD model



Solver

Fluent14.0 (double precision, axial symmetry)

Computing domain

liquid region + ullage region + wall region

Activated models

Ideal-gas model → calculate ullage density

VOF model → calculate phase distribution

low-Re k-ε model → calculate fluid-wall heat transfer

species transport model → consider multi-component effect

Variable properties of fluids and solid wall

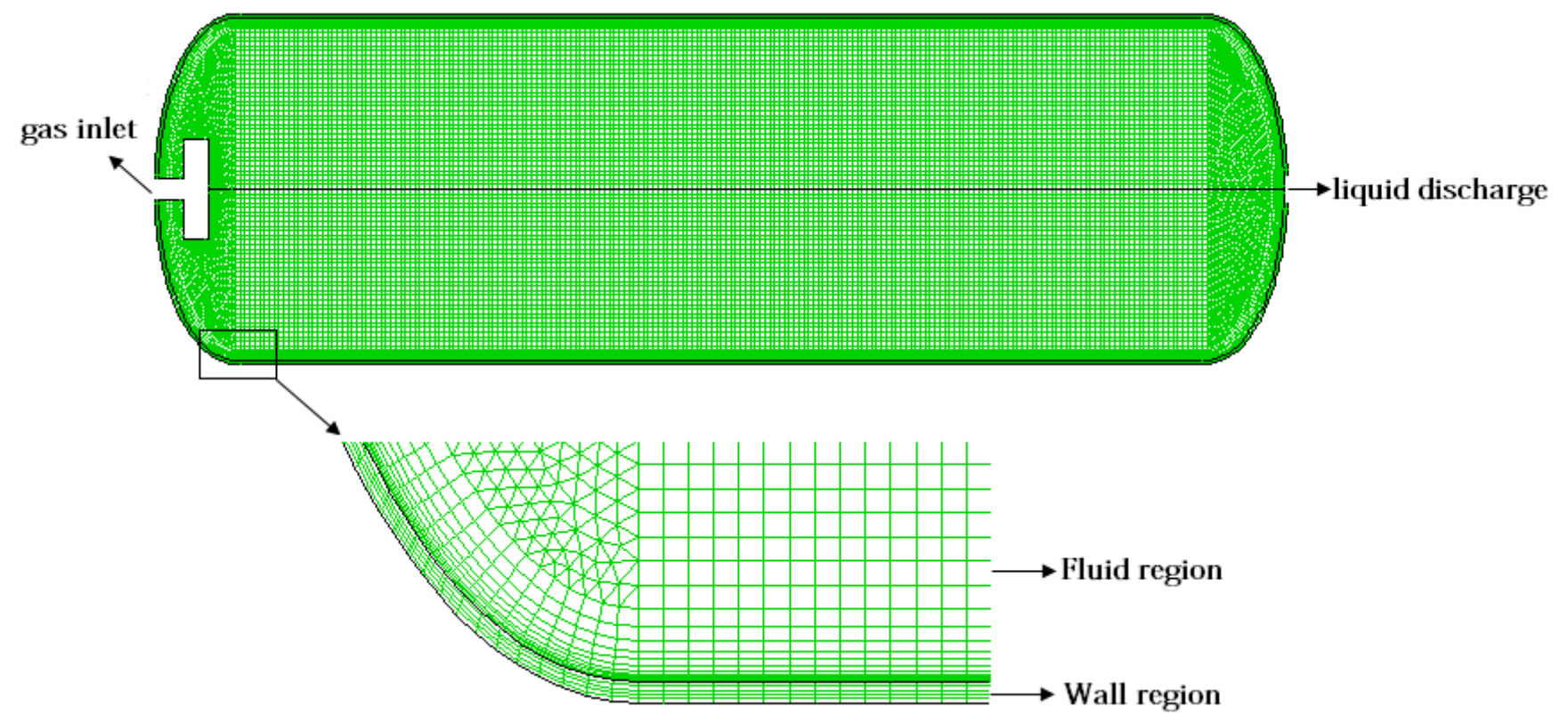
Boundary conditions

gas inlet and liquid outlet: mass-inlet-flow

exterior wall: adiabatic boundary

Initial conditions

To obtain a reasonable initial field distribution, a pre-pressurization operation is conducted by the CFD model in advance.



Phase Change model

A quasi-steady thermodynamic condition is supposed and the difference between propellant fluid temperature, *T*, and the saturation temperature, T_{sat}, corresponding to the vapor partial pressure, P_{vapor}, is taken as the driving force of phase change

For $T \geq T_{sat}$(evaporation)

$$\dot{m}_{vl} = -\dot{m}_{lv} = C\alpha_v \rho_v \frac{|T - T_{sat}|}{T_{sat}}$$

For $T < T_{sat}$(condensation)

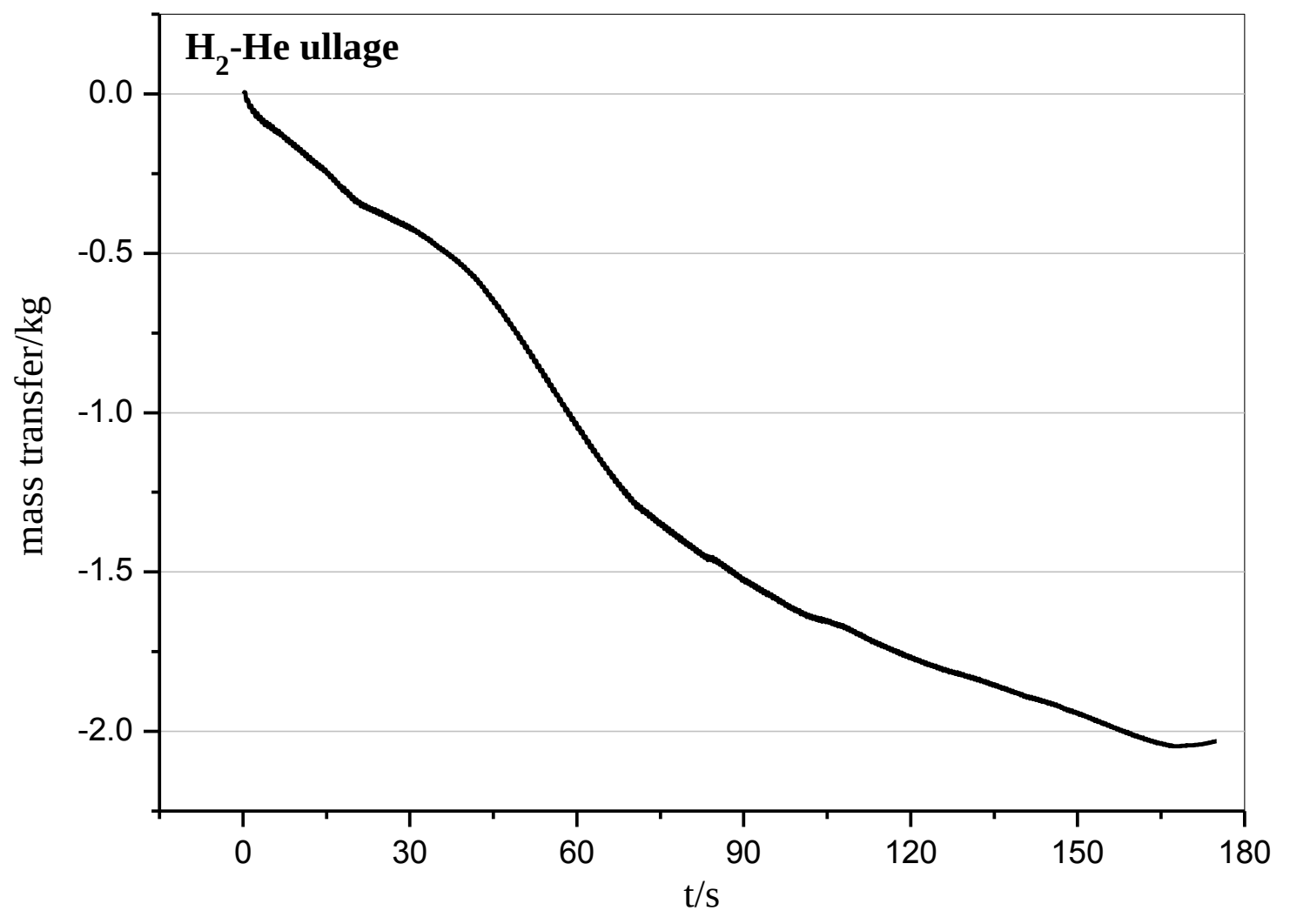
$$\dot{m}_{lv} = -\dot{m}_{vl} = -C\alpha_l \rho_l \frac{|T - T_{sat}|}{T_{sat}}$$

T_{sat} is calculated as follows:

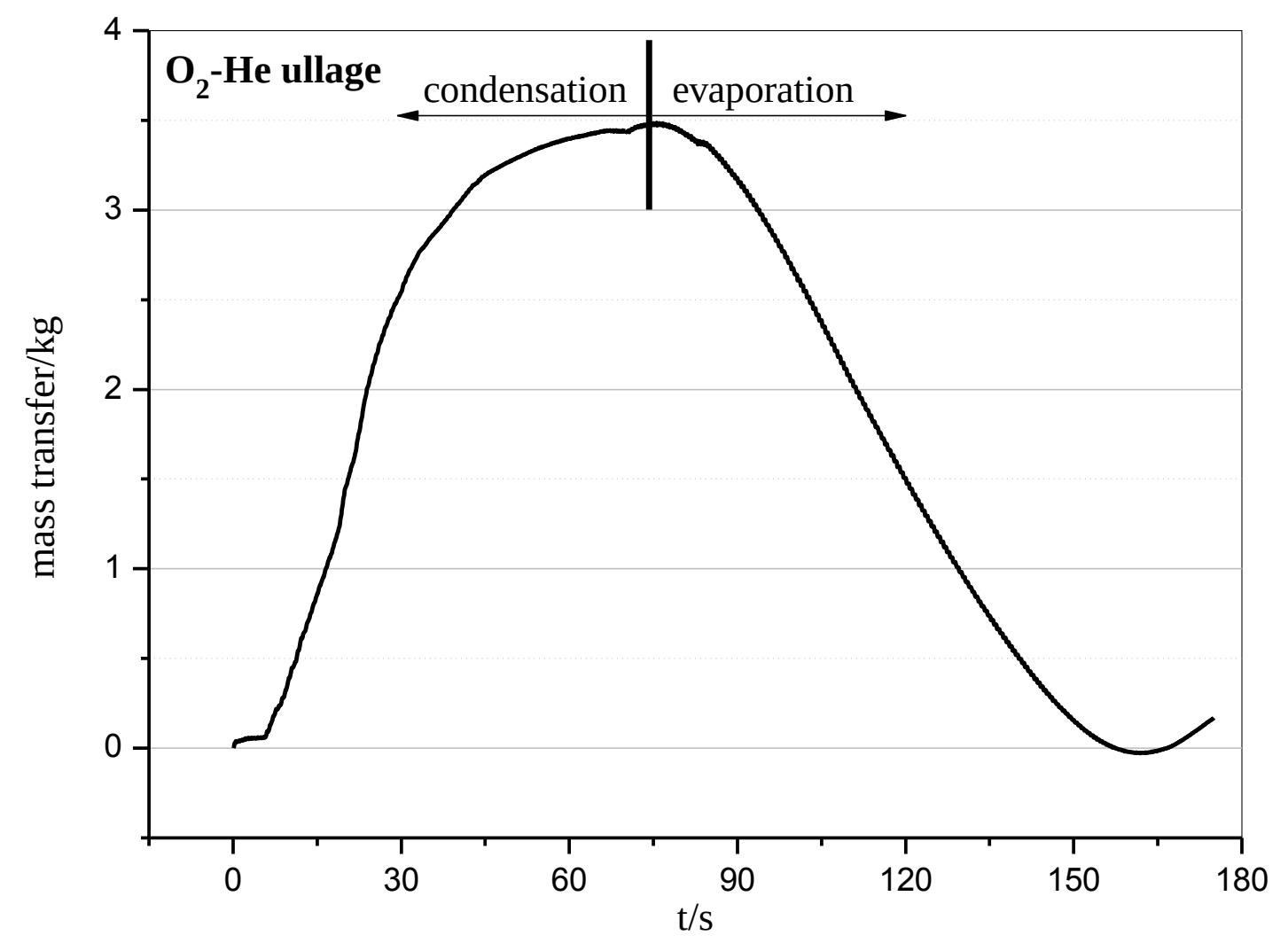
$$T_{sat} = T_{sat}(P_{vapor})$$

$$P_{vapor} = P_{total} \cdot x_{vapor}$$

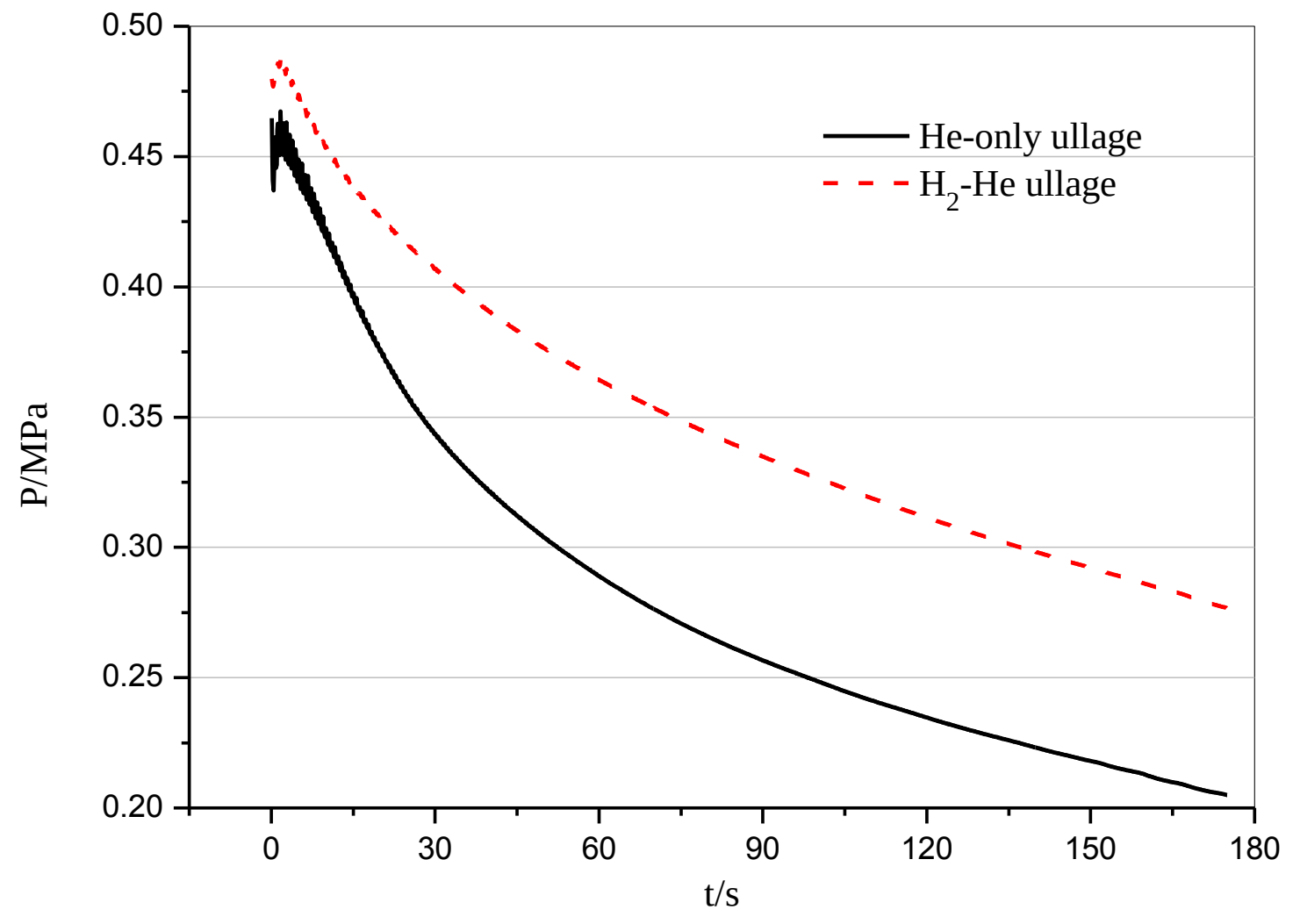
Results



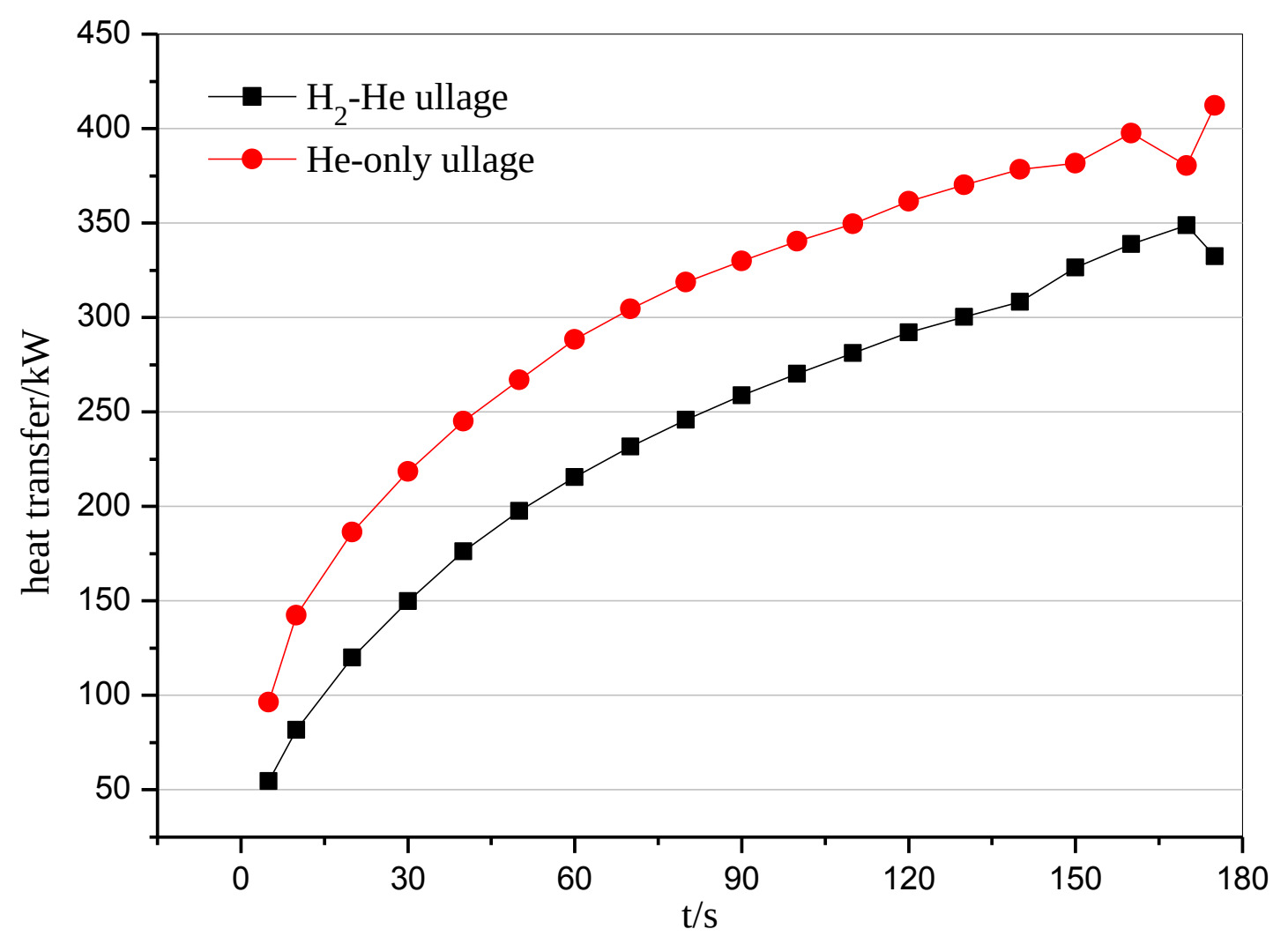
For LH2-He case, the phase change model during the whole discharge process is evaporation. The ratio of mass transfer amount to discharging liquid mass is about 0.03%.



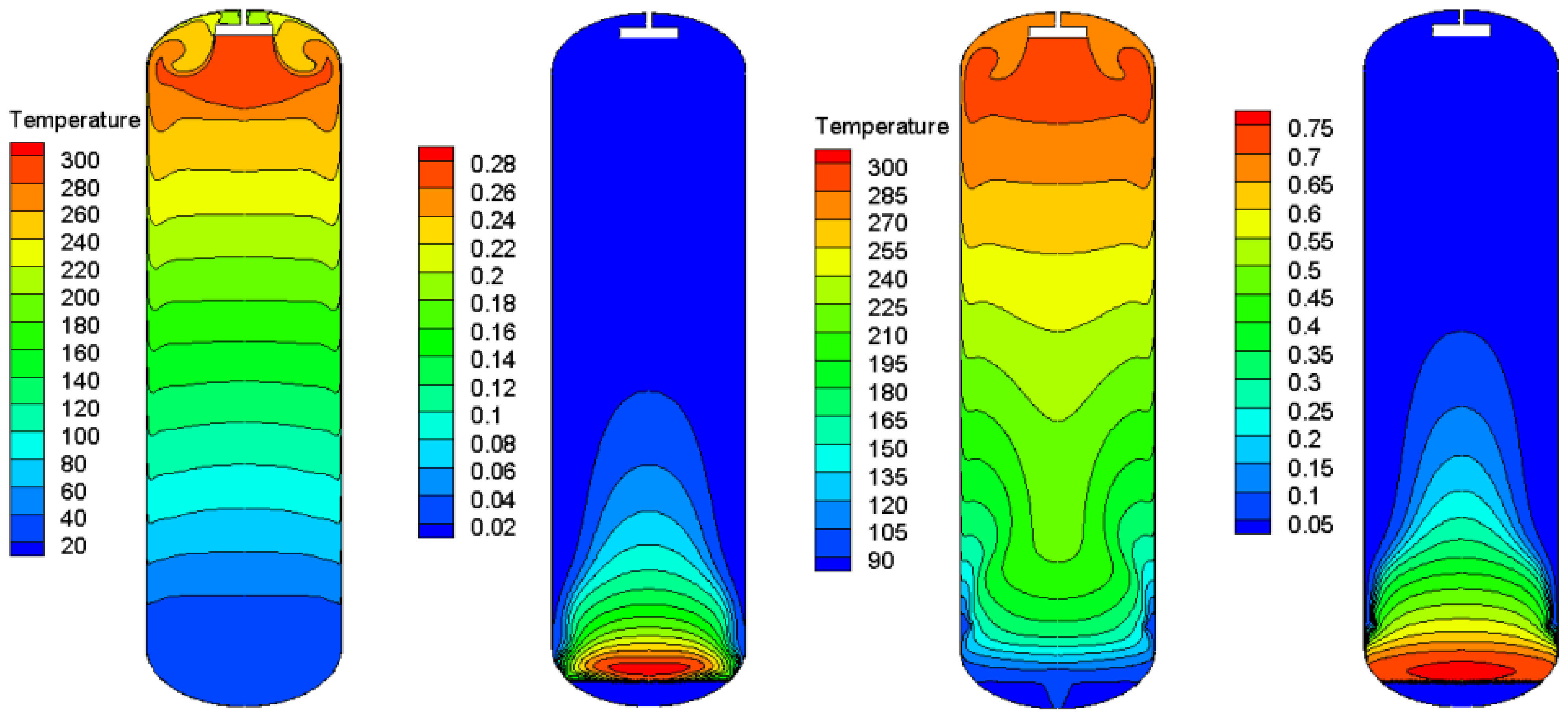
For LO2-He case, fluid first experiences a continuous vapor condensation and then a liquid evaporation for the remainder of discharge.



The improved CFD model produces a remarkably higher pressure values compared to the previous model.



Ignoring the propellant vapor effect in the computation will overestimate the ullage-wall heat transfer. The average deviation of the predicting values is approximate 33.4%.



Different propellant tanks have different temperature distributions, and the gas concentration distribution exert a significant effect on the temperature distributions.

For LH2-He case, gas temperatures at the same height are approximately equal.

For LO2-He case, a significant radial temperature distribution exists in the lower ullage region.

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