Investigation on the chill-down behavior and thermal stress distribution of a cryogenic tank during fill processes

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Background

During the fill process of a cryogenic tank, the tank wall is chilled down by the inflowing liquid hydrogen and vaporization-induced hydrogen gas. The multiple heat transfer types imposed on the tank wall at different phases of the fill process result in a non-uniform temperature distribution along the axis, which causes the emergence of thermal stress within the tank wall. The tank undergoes different chill-down behaviors under different filling procedures, resulting in distinct thermal stress distributions.

Objectives

- Chill-down characteristics of the tank during GH2 and LH2 fill processes under different inflow rates.
- Evolutions of thermal stress distributions within the tank wall during GH2 and LH2 fill processes under specific restricting conditions.

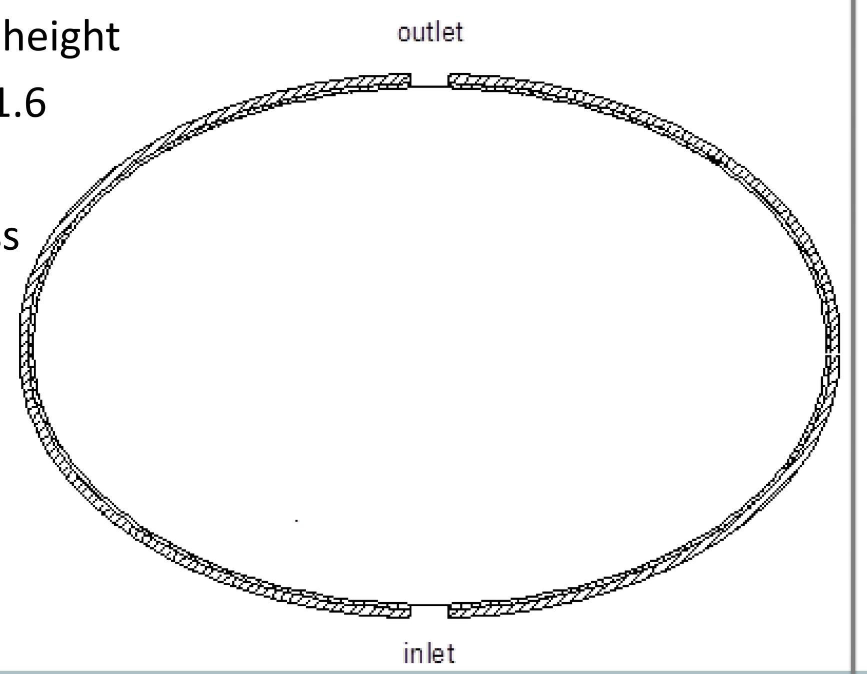
Conclusions

- In GH2 fill processes, the chill-down behavior of the tank is controlled by the combined action between the inflowing forced convection and gas free convection along the tank wall, whose intensities change with the inflow rate.
- In LH2 fill processes, the chill-down behavior of the tank is dominated by phase change and gas free convection along the wall.
- During the GH2 fill process, thermal stresses concentrate at the two ports under three different restricting conditions.
- During the LH2 fill process, the tank is subjected to a significant thermal stress within the bottom elliptic head in the former 400 s of the whole fill process under an inflow rate of 7.5 kg/s, and the maximum thermal stresses appear at regions in contact with LH2 within the former 20 s and those in contact with the liquid-gas interface in the following time.

Object

Structural Parameters

Cylindrical section: 8.5 m in diameter,
0.09 m in height
Elliptic headers: aspect ratio 1.6
Tank wall: 4 mm in thickness
Insulation: 35 mm in thickness



Filling Conditions

GH2 fill processes:
- initial conditions: 300 K, 0.11 MPa, filled with pure helium
- inflow temperature: 25.02
- inflow rates: 1 kg/s, 2 kg/s, 3 kg/s, 4 kg/s
- the venting valve is kept closed before the pressure reaches 0.322 MPa

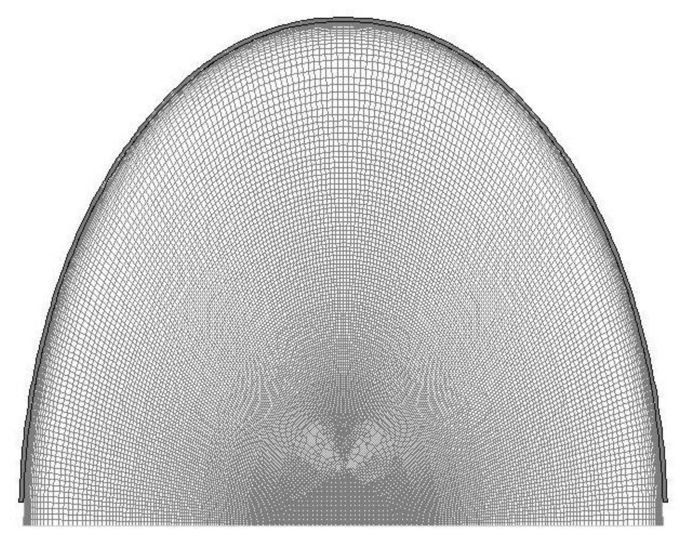
LH2 fill processes:
- initial conditions: 300 K, 0.11 MPa, filled with pure hydrogen
- inflow temperature: 19.65 K (2 K under saturation temperature of 0.11 MPa)
- inflow rates: 5 kg/s, 7.5 kg/s, 10 kg/s, 12.5 kg/s
- The vent valve is kept open throughout the fill process

Methods

CFD Method

Two dimensional axisymmetric model is employed.

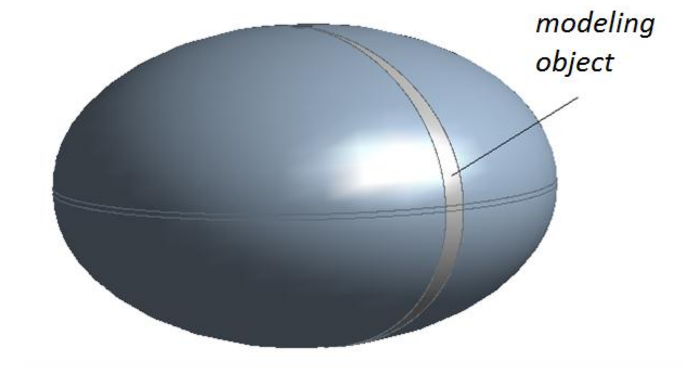
GH2 fill process: species transport model to represent the mixing between GH2 and GHe.



LH2 fill process: VOF model to capture the liquid-gas interface and phase change model to represent vaporization and condensation

Finite Element Method

The tank wall region within a circumferential interval of 1 degree is modeled

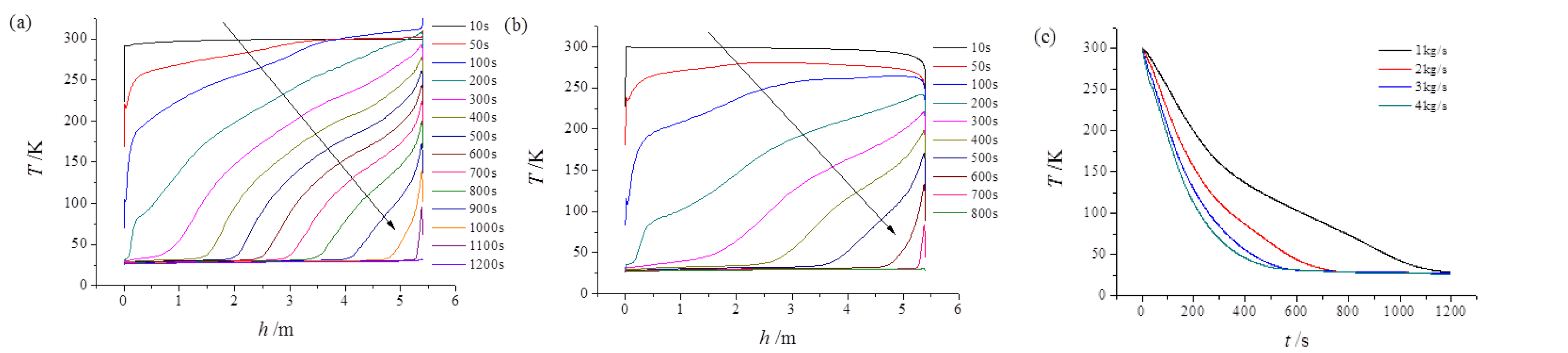


The temperature distribution data at different time instants are inputted to the structural analysis

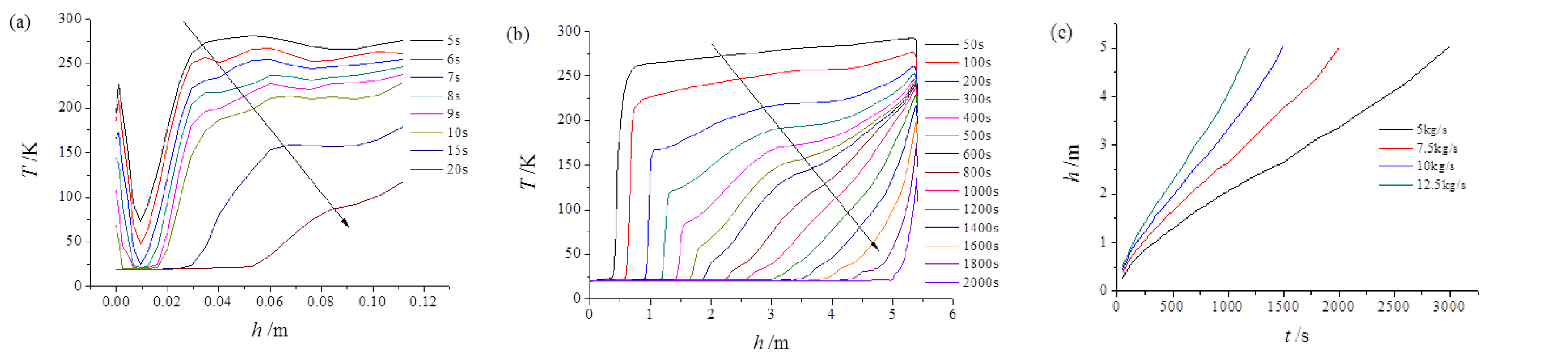
Restricting conditions at the inlet and outlet: radially free, rigid and elastic

Results

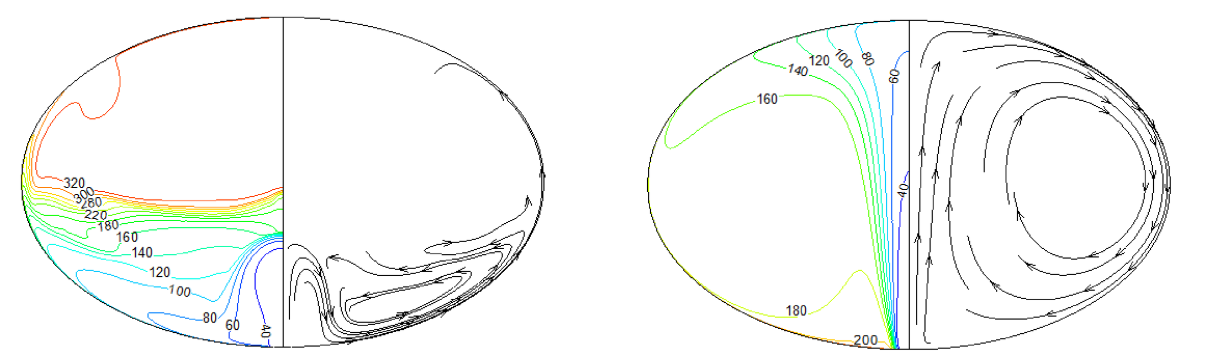
Chill-down Characteristics of the tank



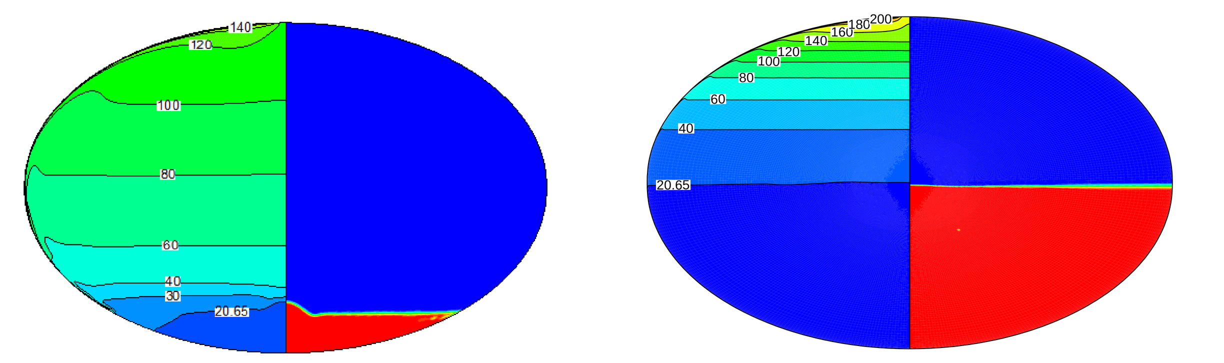
Time histories of the wall temperature during GH2 fill processes: (a) 1 kg/s; (b) 2 kg/s; (c) average temperature.



Time histories of the wall temperature and liquid level during LH2 fill process: (a) (b) 7.5 kg/s; (c) liquid level

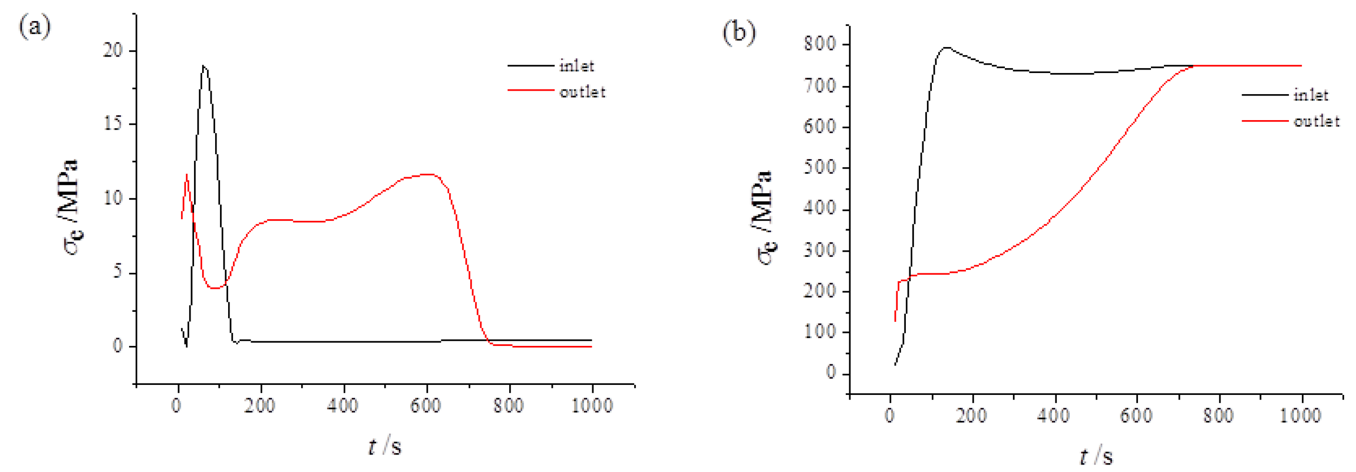


Temperature and flow field at 20 s during GH2 fill processes: (a) 1 kg/s; (b) 2 kg/s.



Temperature and phase field during LH2 fill process (7.5 kg/s):(a) 100 s;(b) 1000 s

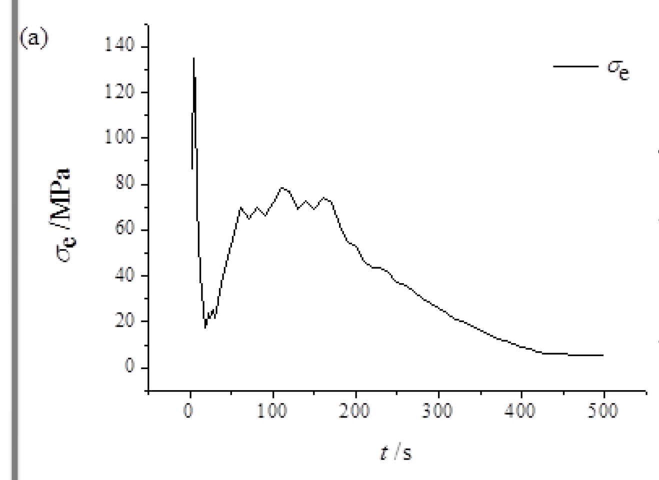
Evolutions of Thermal Stress Distribution



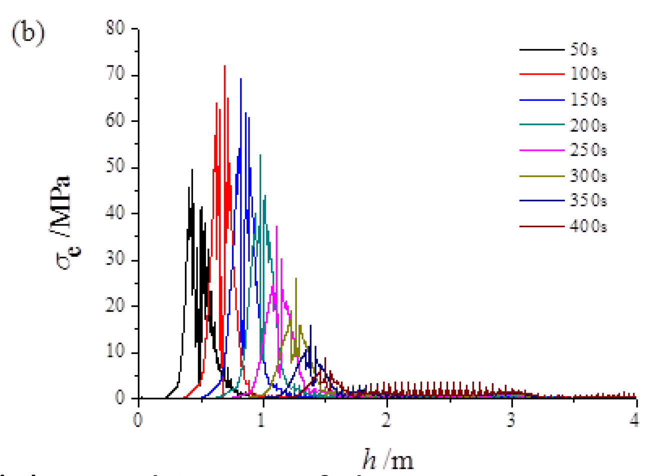
Thermal stresses at inlet and outlet are affected by the type of restricting conditions as well as local temperature distributions.

Radially rigid restricting condition causes largest thermal stress.

Time histories of thermal stress under different restricting conditions during GH2 fill process (2 kg/s) :(a) radially free; (b) rigid.



The tank wall suffers significant thermal stress concentration due to the remarkable temperature gradient



The location where thermal stress concentration occurs varies with the rise of the liquid level.

Thermal stress within tank wall during LH2 fill process (7.5 kg/s): (a) time history of the maximum value; (b) axial distribution.

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