Simulation of Sloshing-Induced BOG/BOR in Cryogenic Fluid Storage Tanks

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Series of workshops on safety of cryogenic hydrogen transfer technologies
Workshop No. 4

Understanding of heat and mass transfer for cryogenic and liquid hydrogen

4th December 2024, Virtual event

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LVHYS

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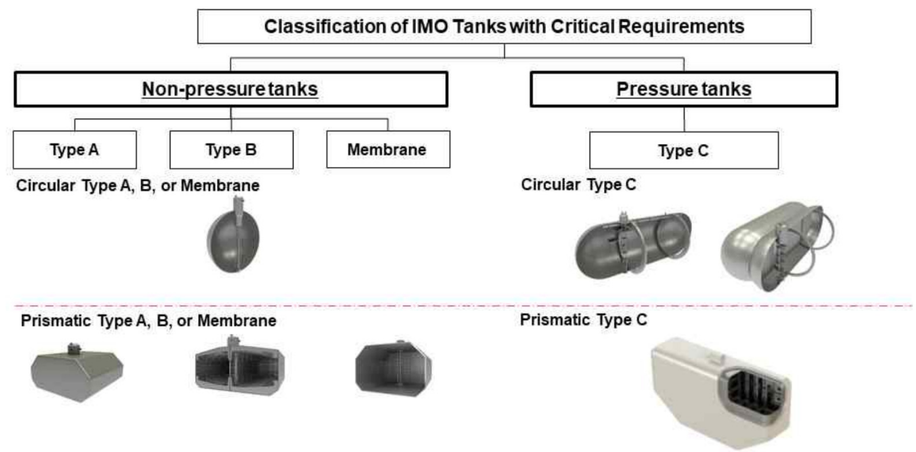
01 Introduction

LNG carrier

LH2 carrier

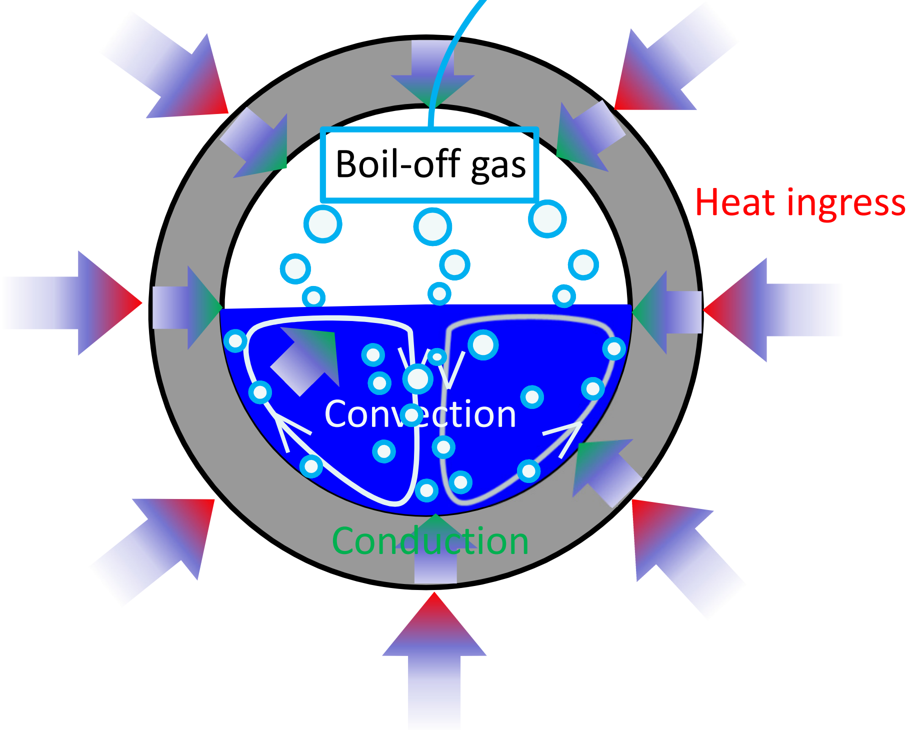


* Source

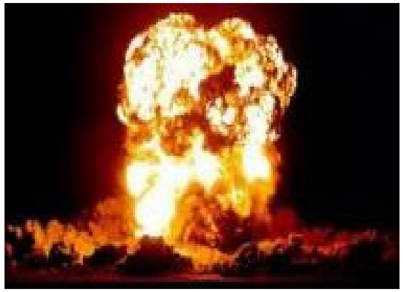
https://www.maritime-executive.com/article/liquefied-hydrogen-bunker-vessel-designed

Jang, D. J., Kim, J. U., & Park, H. J. (2020). 액화수소 (LH2) 저장 탱크 및 안전 기준 개발. *Superconductivity and Cryogenics*, *22*(1), 4-8.

01 Introduction



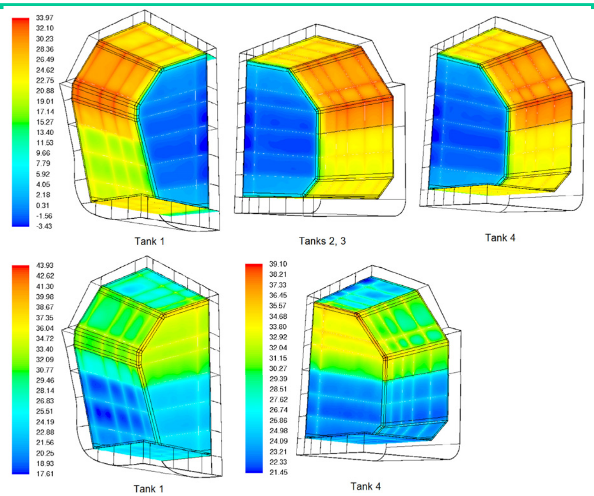
- Vaporization of liquefied gas
- Unavoidable
- Related with cost and safety
- Minimization (Zero Boil-off, ZBO)



- **Boil-off Rate (BOR)**
  - The amount of liquid that is evaporating from a cargo due to heat leakage and expressed in % of total liquid volume per day
  - ***Parameter of design performance***

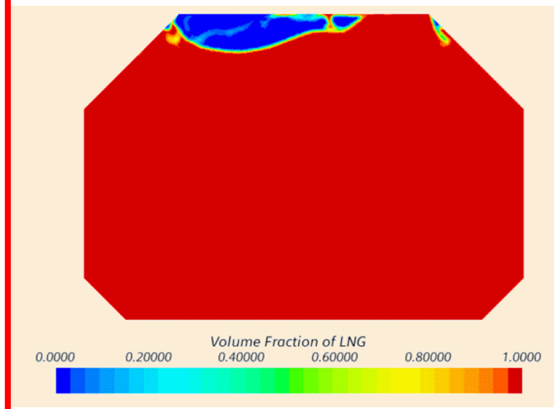
01 Introduction

- BOG inside Cryogenic Fuel Tank in Static and Dynamic Status



- Mutiphase-thermal analysis in equilibrium status
- Real boil-off gas
- Different filling ratio

Static condition



- Motion of tank (=sloshing)
- Partial cooling
- Vaporization

Dynamic condition

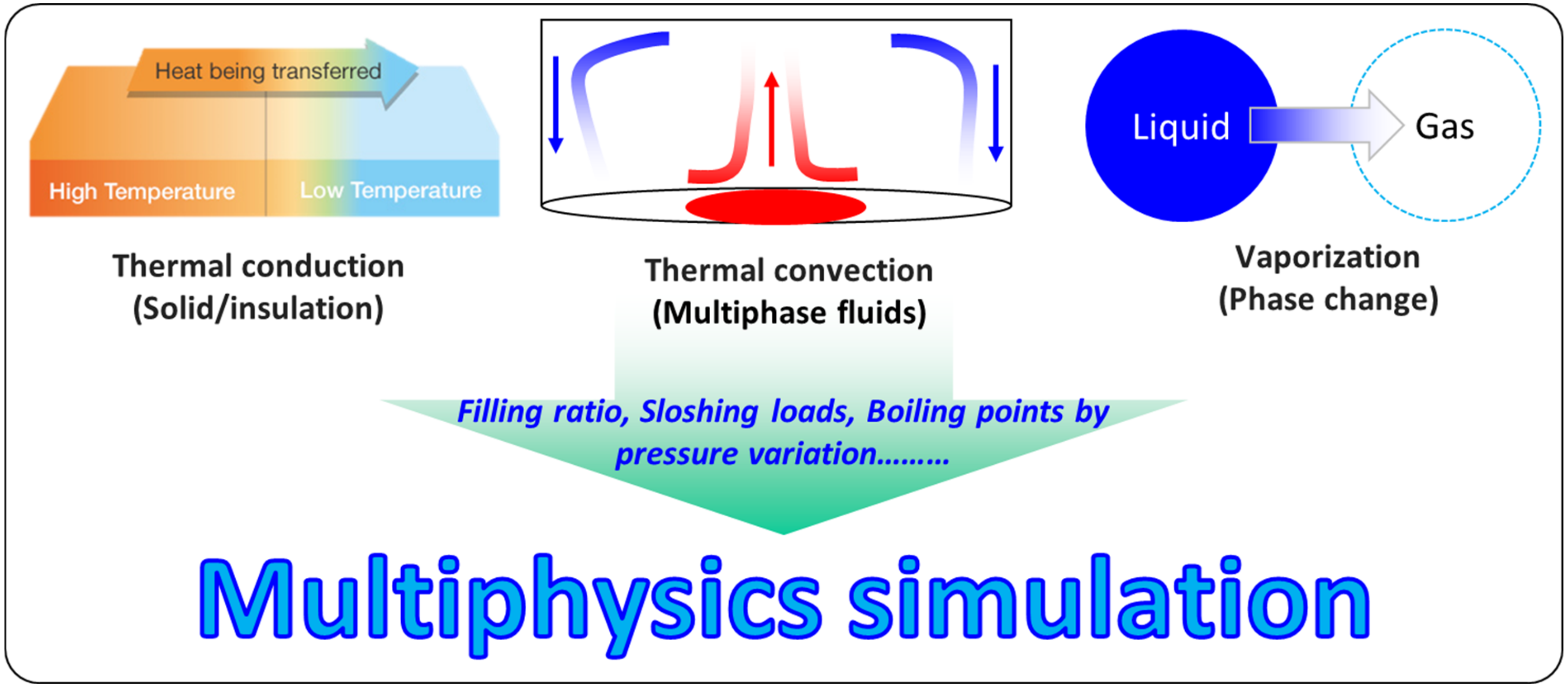
*Source

1) Miana, M., Legorburo, R., Díez, D., & Hwang, Y. H. (2016). Calculation of boil-off rate of liquefied natural gas in mark III tanks of ship carriers by numerical analysis. *Applied Thermal Engineering*, *93*, 279-296.

01 Introduction

- ## Objectives

To study the BOG/BOR changes affected by dynamic characteristics of multiphase-thermal flow with phase change in insulated cryogenic fluid tanks during sloshing motions



- https://www.daikin.com/corporate/why_daikin/benefits/heatpump/

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02 Numerical Simulation Method

- Governing equations in control volume approach
  - Mass conservation law:

$$\frac{\partial}{\partial t}\int_V \rho dV + \oint_A \rho \mathbf{v}\cdot \mathbf{da} = \int_V S dV$$

$$\sum_{i=1}^{n} \alpha_i \rho_i = \rho \qquad \sum_{i=1}^{n} \alpha_i = 1 \qquad S = \sum_i S_{a_i} \cdot \rho_i$$

α_i: volume fraction of phase i
ρ_i: density of phase i
$\mathbf{a}$: surface area vector
$\mathbf{v}$: mixture velocity
S: mass source term

  - Momentum conservation law:

$$\frac{\partial}{\partial t}\left(\int_V \rho \mathbf{v} dV\right) + \oint_A \rho \mathbf{v}\otimes \mathbf{v}\cdot \mathbf{da} = -\oint_A p\mathbf{I}\cdot \mathbf{da} + \oint_A \mathbf{T}\cdot \mathbf{da} + \int_V \rho \mathbf{g} dV + \int_V \mathbf{f}_b dV$$

p: pressure
$\mathbf{I}$: identity tensor
$\mathbf{g}$: gravity
$\mathbf{T}$: stress tensor
$\mathbf{f}_b$: vector of body forces

  - Energy conservation law (for fluid):

$$\frac{\partial}{\partial t}\int_V \rho E dV + \oint_A \left(\rho H \mathbf{v} + p\mathbf{I}\right)\cdot \mathbf{da} = -\oint_A \dot{\mathbf{q}}'' \mathbf{da} + \oint_A \mathbf{T}\cdot \mathbf{v} \mathbf{da} + \int_V \mathbf{f}_b \cdot \mathbf{v} dV + \int_V S_E dV$$

E: total energy
H: total enthalpy
$\dot{\mathbf{q}}''$: heat flux vector
S_E: energy source term

  - Energy conservation law (for solid):

$$\frac{\partial}{\partial t}\int_V \rho_s C_p T_s dV = -\oint_A \dot{\mathbf{q}}'' \mathbf{da} + \int_V S_u dV$$

ρ_s: total energy
C_p: specific heat
T_s: solid temperature
S_u: volumetric heat source

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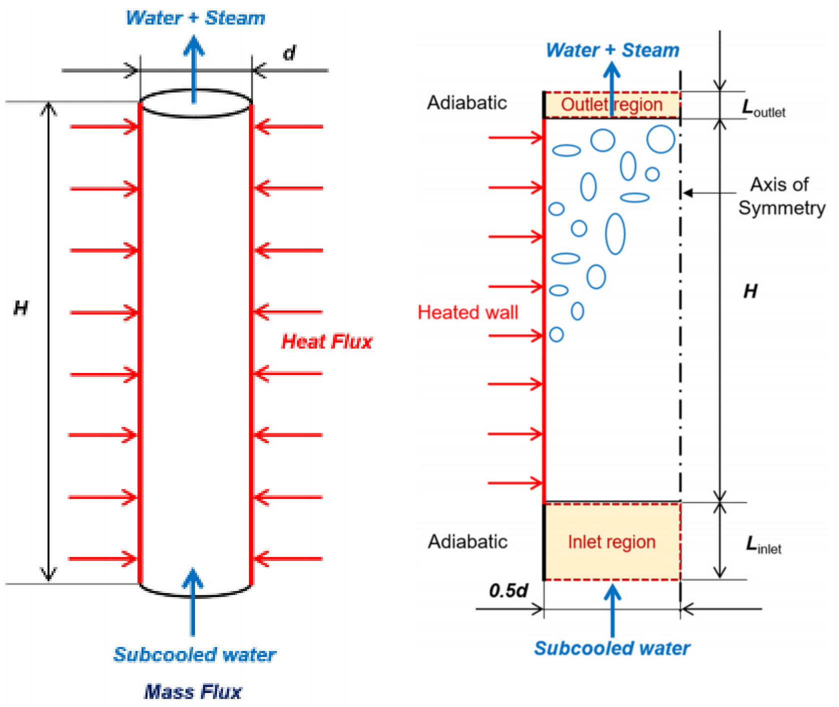
02 Numerical Simulation Method

- Governing equations in control volume approach
  - Multi-physics CFD simulation by STAR-CCM+ (v.15.02)

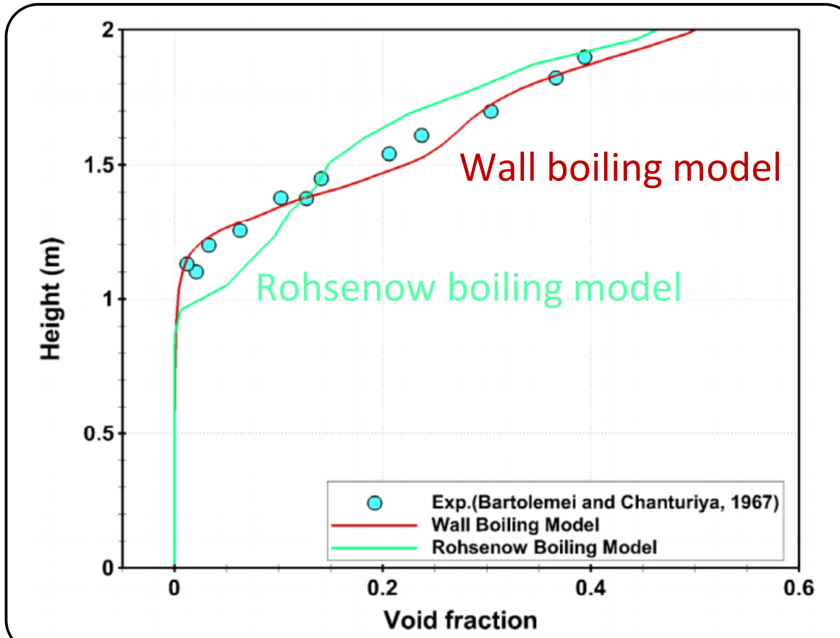
Numerical modeling	
Discretize	FVM (Finite volume method)
Multiphase model	VOF (Volume of fluid)
Time	2nd-order implicit
Convection	2nd-order upwind scheme
Courant-Friedrichs Lewy (CFL)	<0.25
Thermal boundary layer	Buoyancy-Driven Two-Layer
Turbulence	Realizable k-ϵ
Phase change model	Rohsenow boiling model

02 Numerical Simulation Method

- Boiling Model



< Definition of problem (Bartolemei & Chanturiya, 1967) >



< Generation of void fraction along height >

< Computational time consumed >

	Rohsenow boiling model	Wall boiling model
Iterations	Total solver elapsed time (s)	
10000	2,086	4,278
20000	4,165	8,669

Sloshing motion

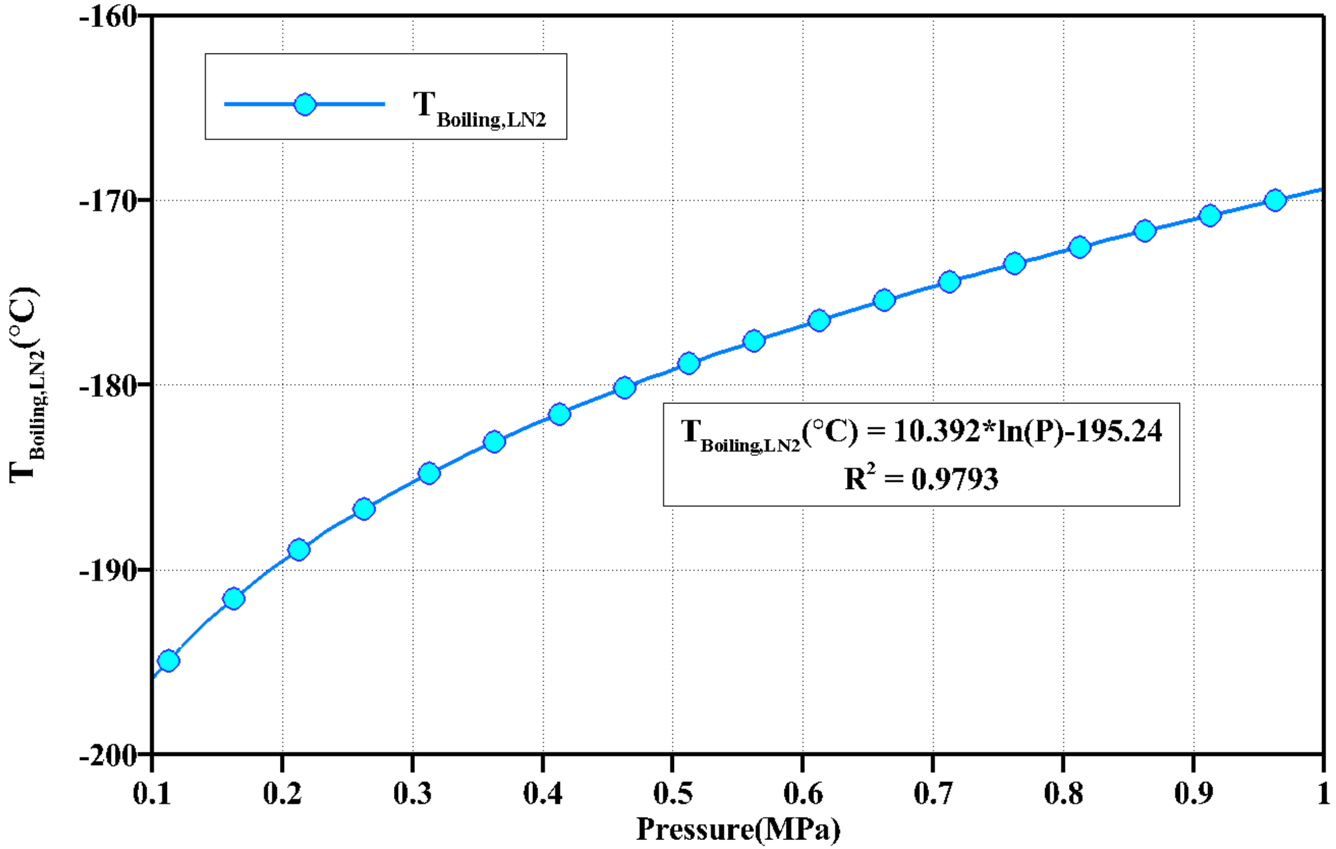
Natural convection

Calculation time

Rohsenow's boiling model

02 Numerical Simulation Method

- Boiling Point of LN_2 as a Function of Pressure



Span, R.; Lemmon, E.W.; Jacobsen, R.T.; Wagner, W.; Yokozeki, A., A Reference Equation of State for the Thermodynamic Properties of Nitrogen for Temperatures from 63.151 to 1000 K and Pressures to 2200 MPa, J. Phys. Chem. Ref. Data, 2000, 29, 6, 1361-1433, https://doi.org/10.1063/1.1349047

Contents

Jeon, G. M., Jeong, S. M., & Park, J. C. (**2024**). Experimental and numerical investigation of the influences of sloshing motion on the change in boil-off gas/boil-off rate in a cryogenic liquid tank. ***Ocean Engineering***, 298, 117173.


Ocean Engineering

Research paper

Experimental and numerical investigation of the influences of sloshing motion on the change in boil-off gas/boil-off rate in a cryogenic liquid tank

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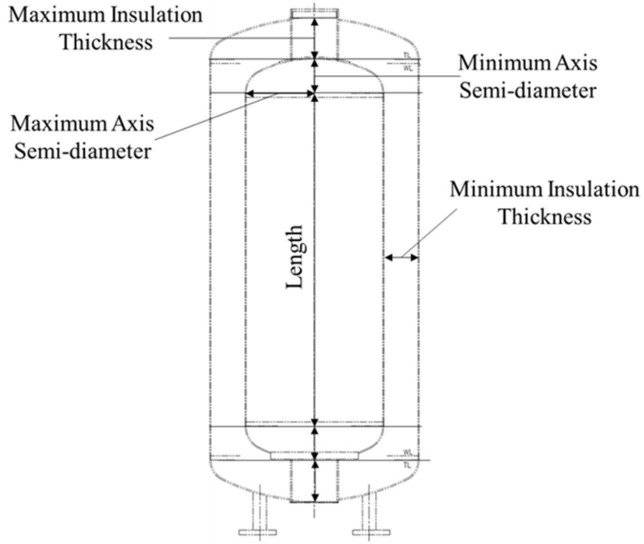
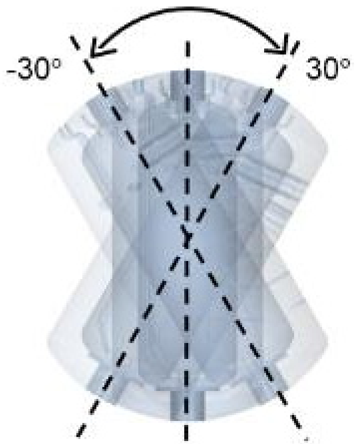
BOG Estimation under Dynamic Condition : LN2 Vertical C-type Tank

- Experiments



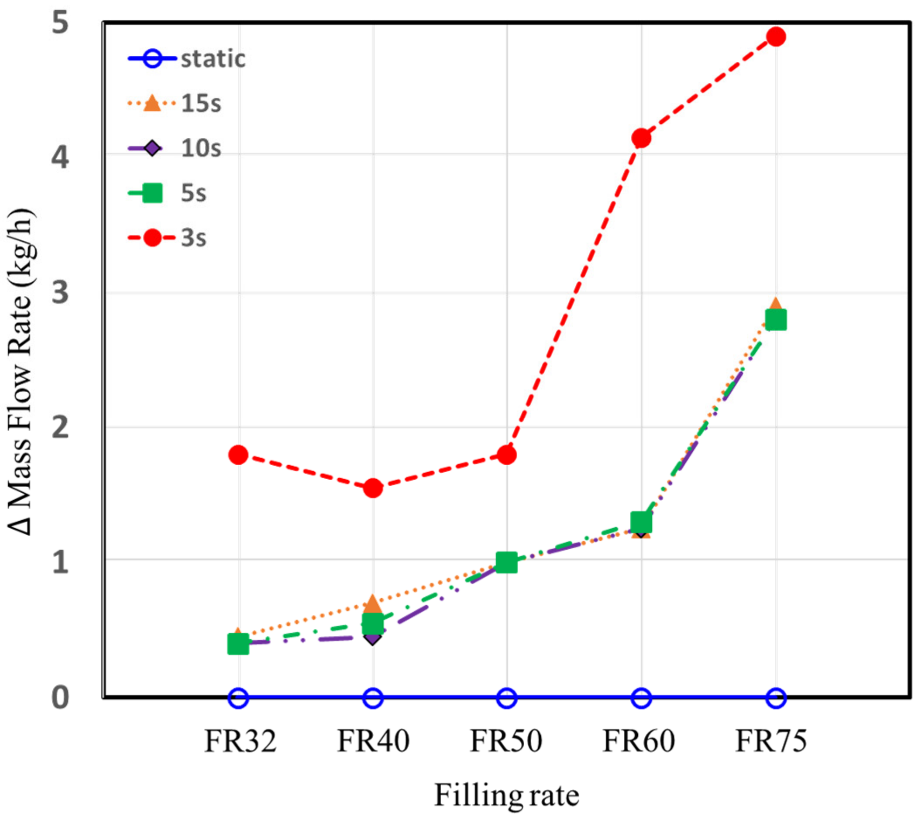


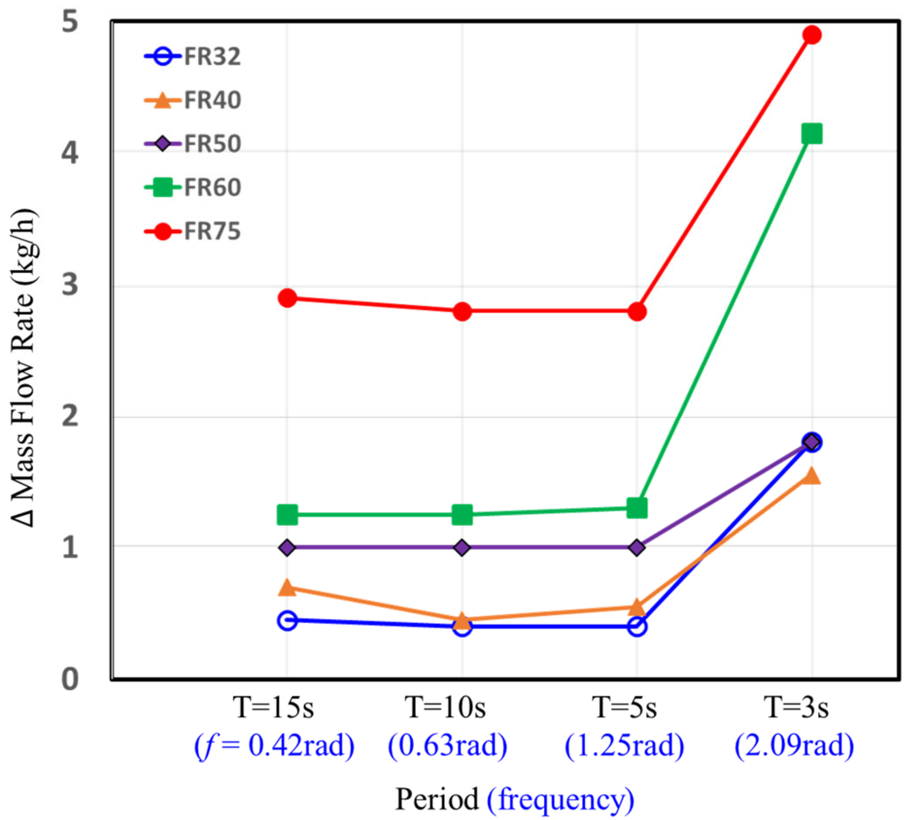
- Filling level (%): 75, 60, 50, 45, 32
- Sloshing period (sec): 15, 10, 5, 3
- Experiment data obtained:
  - **Temperature** from 50 thermocouples
  - **Mass flow rate** from outlet
  - **Pressure** from outlet

< Outlines of experiment with sloshing motion >

BOG Estimation under Dynamic Condition : LN2 Vertical C-type Tank

- Experiments



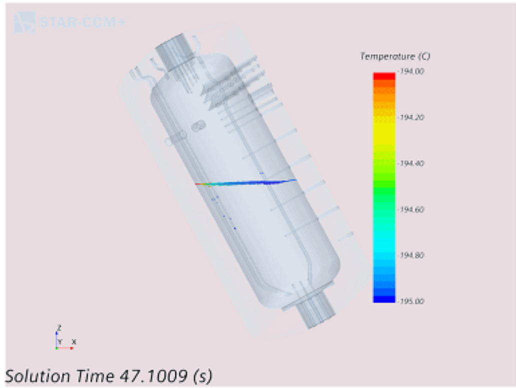


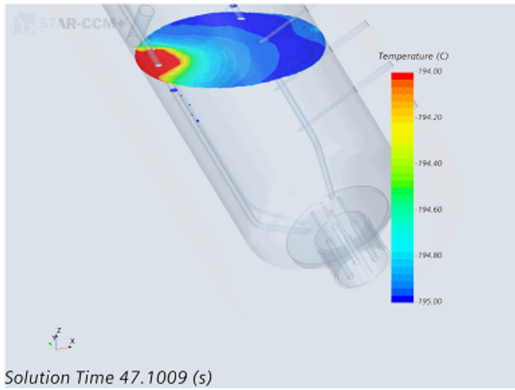
Comparison of relative mass flow grouped by filling ratio to sloshing period

BOG Estimation under Dynamic Condition : LN2 Vertical C-type Tank

- Effect of Physical Models

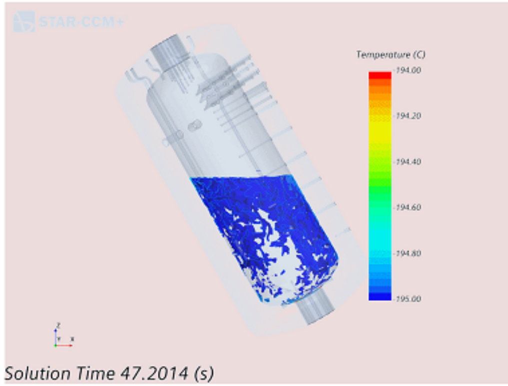
VOF + noPC

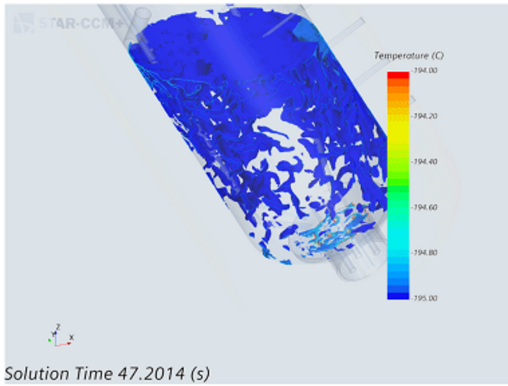




- No phase change (PC) model
- No vaporization
- Constant boiling point (BP)
- Higher temperature near interface

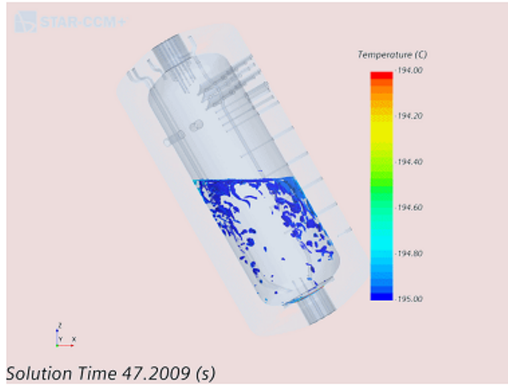
VOF + PC + constantBP

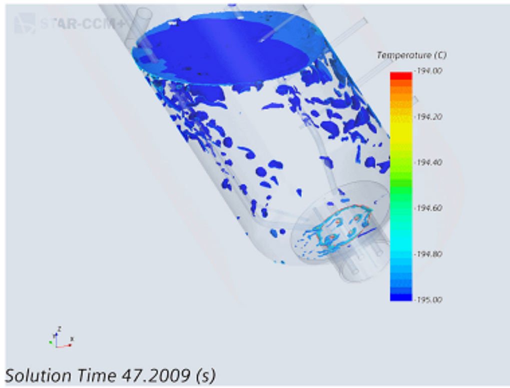




- Phase change model
- Constant boiling point (−195°C)
- Excessive vaporization
- Subcooled LN_2

VOF + PC + variableBP

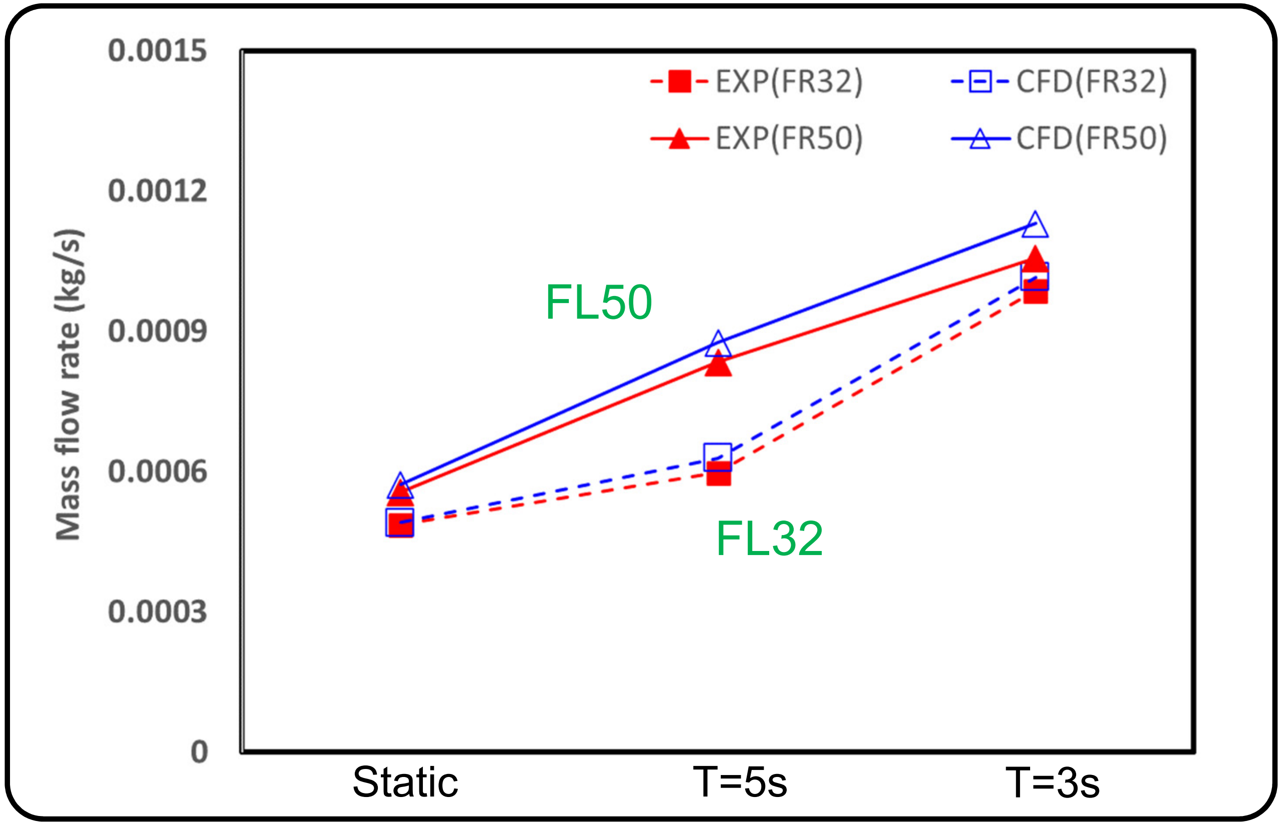




- Phase change model
- Pressure dependent boiling points
- Proper vaporization

BOG Estimation under Dynamic Condition : LN2 Vertical C-type Tank

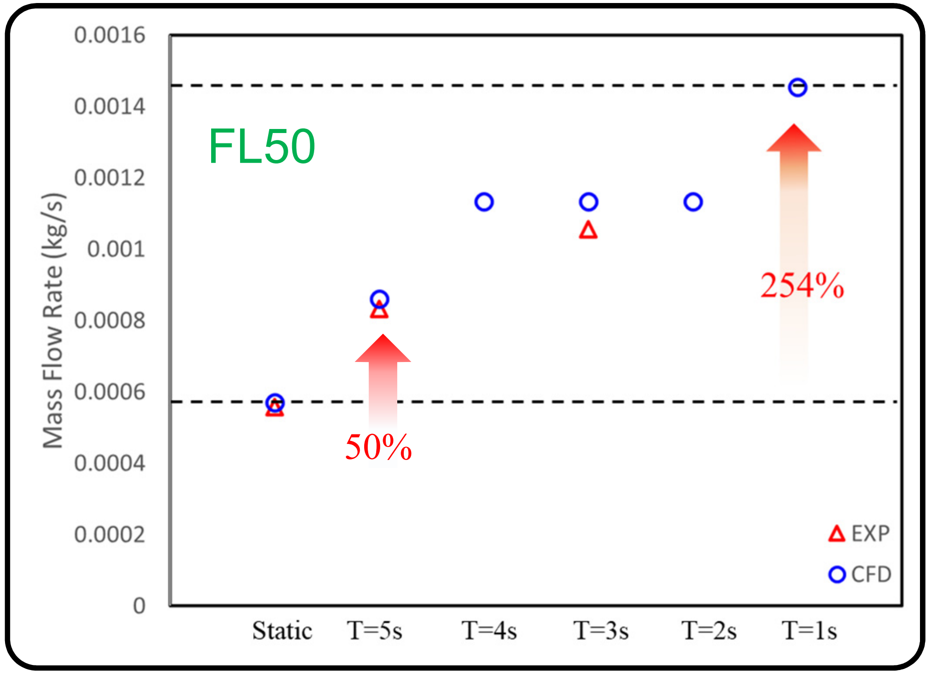
- BOG (Expressed by Mass Flow Rate at Outlet)



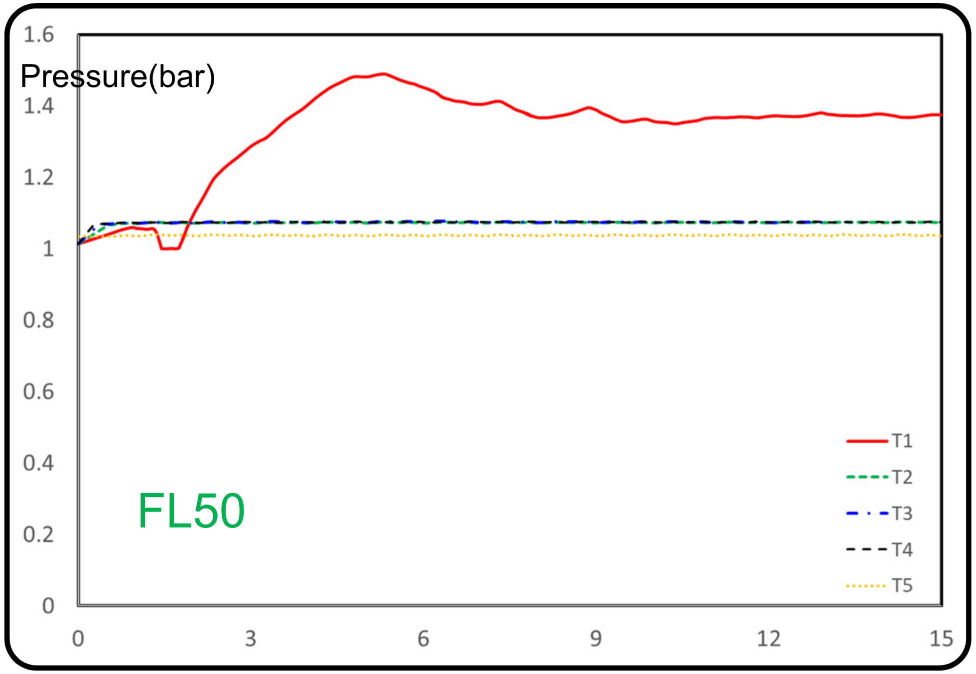
< Comparison of BOG at different filling levels and sloshing periods >

BOG Estimation under Dynamic Condition : LN2 Vertical C-type Tank

- BOG and Pressure at Outlet



< Comparison of BOG at sloshing periods >



< Time-series of pressure at outlet >

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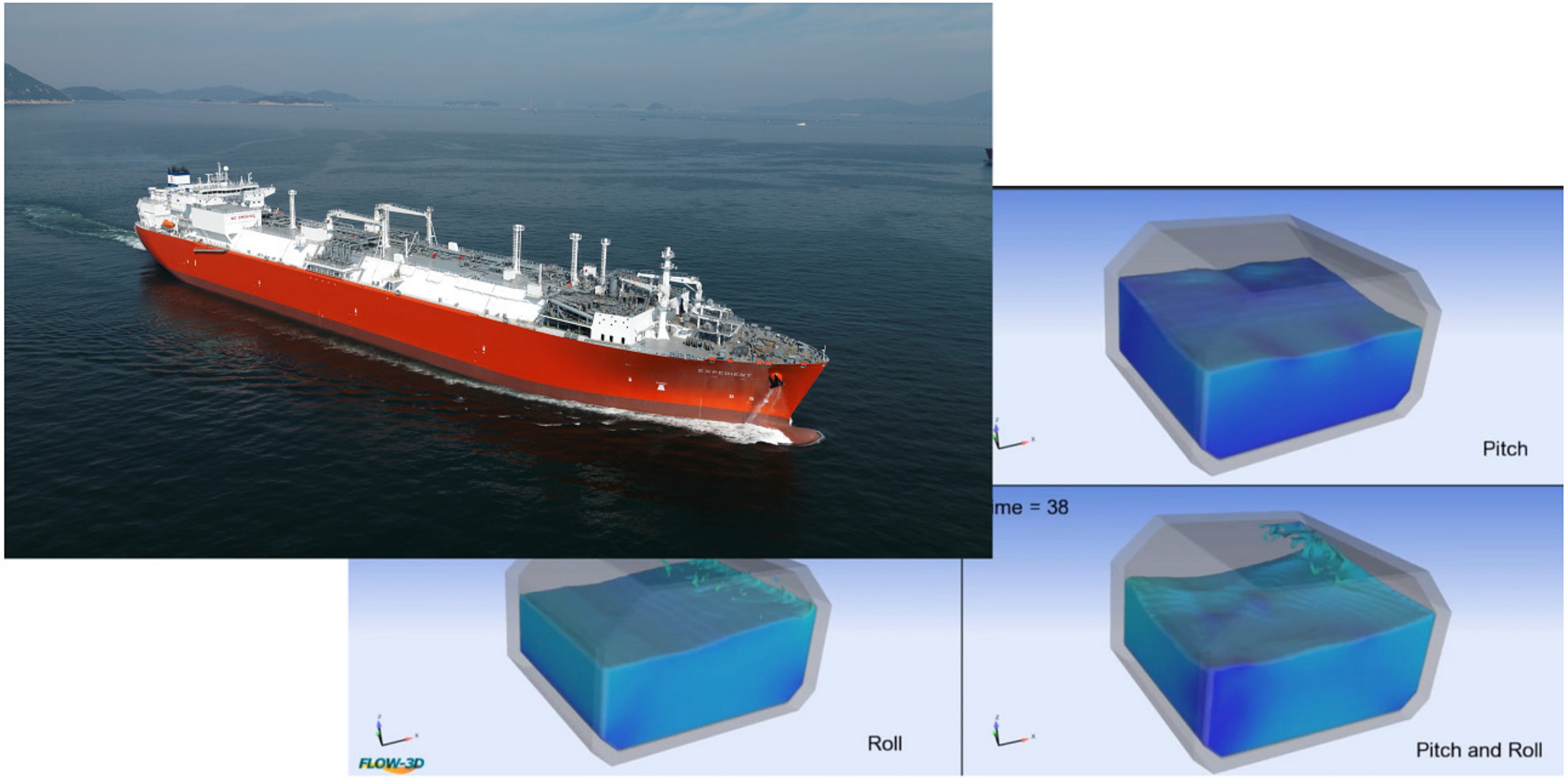
BOG Estimation under Dynamic Condition : LNG Membrane Tank

- Motion Data



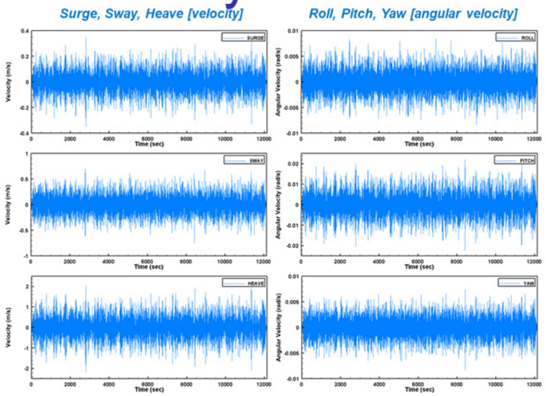
Example of LNGC Sloshing

*Source - FLOW 3D

ELVHYS

BOG Estimation under Dynamic Condition : LNG Membrane Tank

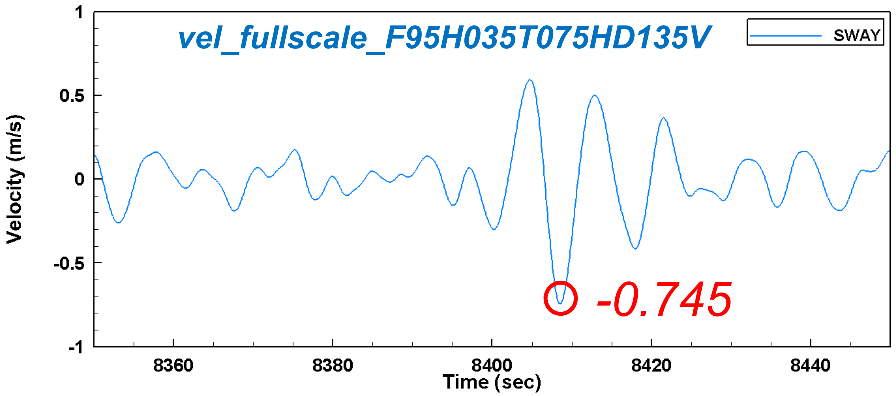
- Forced Sway Motion from Motion Analysis

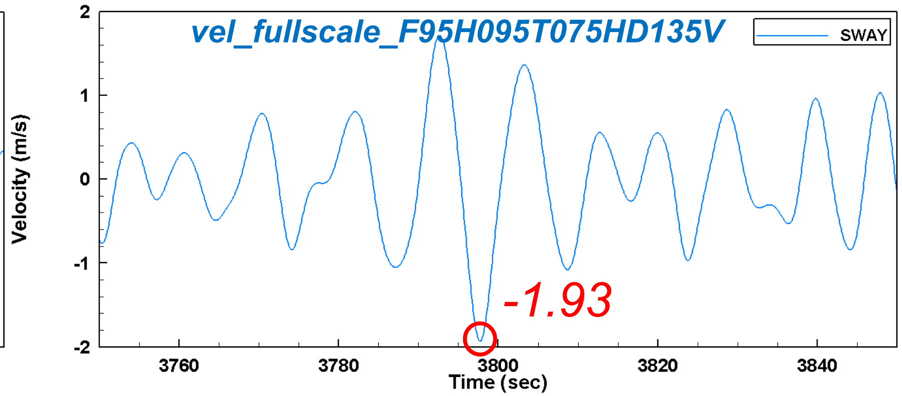


Estimated 6-DOF Motions in Real Sea Status

$$\dot{X} = \omega A \cos\left(\frac{2\pi}{T} t\right)$$

ω : angular velocity
A : amplitude
T : Sloshing period
t : time





- ✓ Regular small sway case $\omega A = 0.745$
- ✓ Regular large sway case $\omega A = 1.93$

BOG Estimation under Dynamic Condition : LNG Membrane Tank

- Forced Sway Motion from Motion Analysis
  - Sloshing (Sway Motion) Period :T
  - **DNV**, Sloshing Analysis of LNG Membrane Tanks, 2014
    - ➢ Resonance Period for longitudinal liquid motion(Lamb, 1932)

$$T_n = \frac{2\pi}{\sqrt{\frac{\pi}{L} g \tanh\left(\frac{\pi h}{L}\right)}}$$

L : Length of the Tank

h : Height of water filled in the Tank

	Amplitude (m)	Sloshing period (s)				
Regular	0.745	5.262	6.262	7.262	8.262	9.262
	1.93					

Contents

05 Conclusion

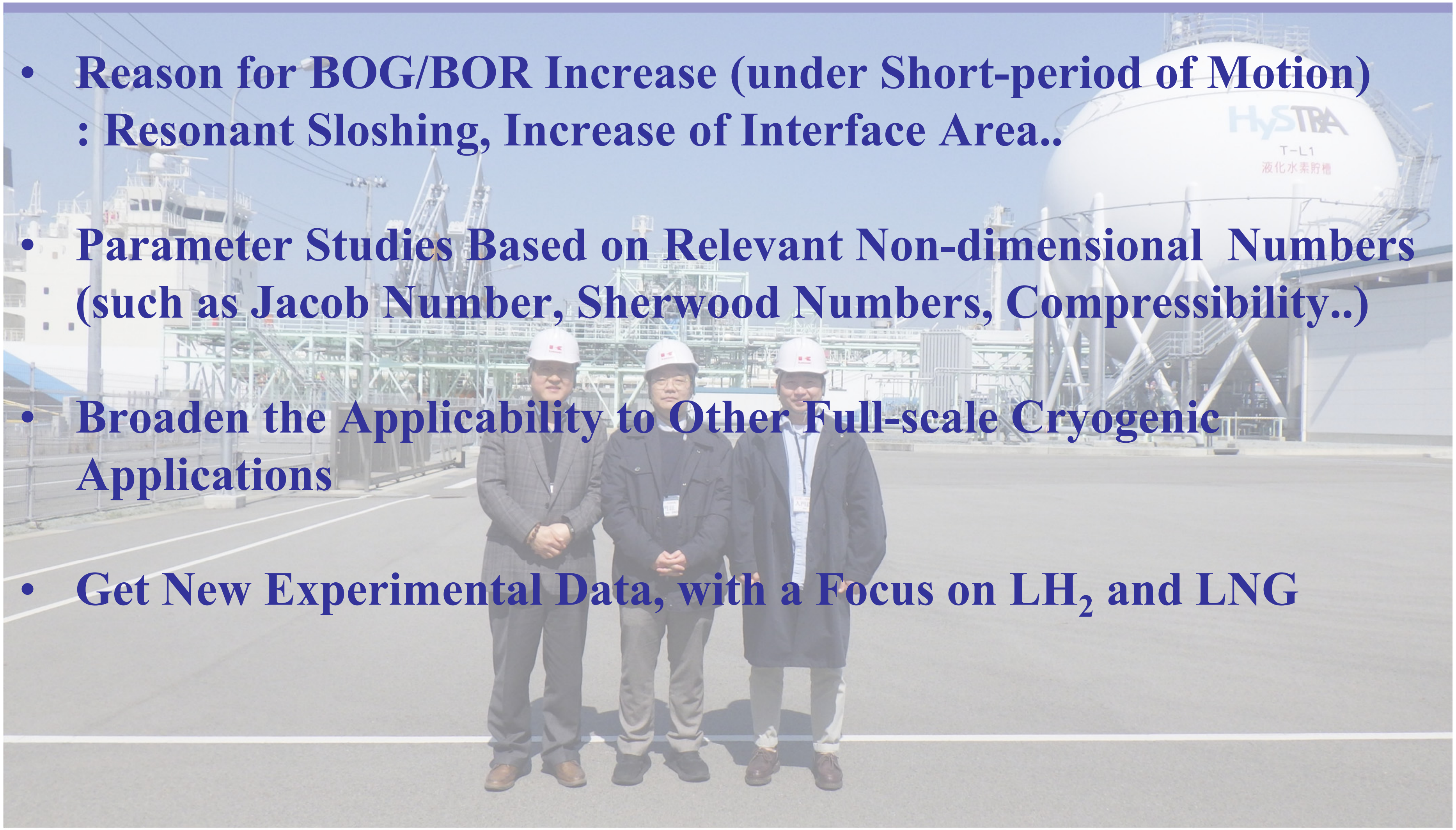
- **To Estimate BOG/BOR in Cryogenic Liquid (LN_2, LNG) Tanks under Dynamic Motion [Real Scale & Real Liquid]**

- Multi-physics Simulation Technique was Developed
- Comparisons with Experiments Show Good Agreement

- Sloshing Effect Should be Considered.
- Negative Pressure Occurrs around the Corners of the Tank Affects the BOG/BOR

- Multi-physics Simulation is a Useful Tool for Complex Physical Phenomena

Topics for On-going and Future Works



- **Reason for BOG/BOR Increase (under Short-period of Motion)**
  : Resonant Sloshing, Increase of Interface Area..

- **Parameter Studies Based on Relevant Non-dimensional Numbers (such as Jacob Number, Sherwood Numbers, Compressibility..)**

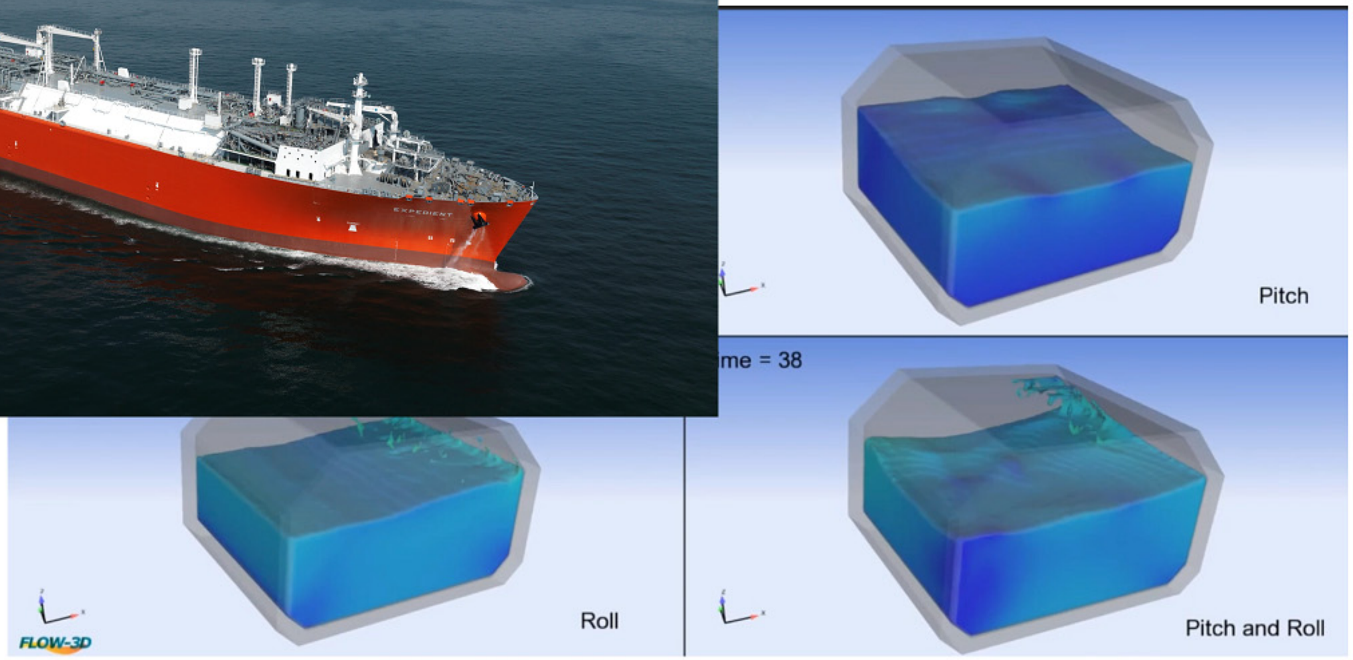
- **Broaden the Applicability to Other Full-scale Cryogenic Applications**

- **Get New Experimental Data, with a Focus on LH_2 and LNG**

Relevant Articles by the Authors

- Seo, Y. S., Chung, S. M., & Park, J. C. (**2024**). Multiphase-thermal flow simulation in a straight vacuum-insulated LH_2 pipe: Cargo handling system in LH_2 carrier. ***Ocean Engineering***, 297, 117030.
- Seo, Y. S., Chung, S. M., & Park, J. C. (**2024**). Multiphase-Thermal Flow Simulation in a Straight Vacuum-Insulated LH_2 Pipe: Fuel Gas Supply System in a LH_2-Fueled Ship. ***Journal of Marine Science and Engineering***, 12(6), 914.
- Jeon, G. M., Jeong, S. M., & Park, J. C. (**2024**). Experimental and numerical investigation of the influences of sloshing motion on the change in boil-off gas/boil-off rate in a cryogenic liquid tank. ***Ocean Engineering***, 298, 117173.
- Chung, S. M., Ahn, H. J., & Park, J. C. (**2024**). Numerical approach to analyze fluid flow in a type C tank for liquefied hydrogen carrier (part 2: Thermal flow). ***Journal of Energy Storage***, 76, 109599.
- Jeon, G. M., Park, J. C., Kim, J. W., Lee, Y. B., Kim, D. S., Kang, D. E., ... & Ryu, M. C. (**2022**). Experimental and numerical investigation of change in boil-off gas and thermodynamic characteristics according to filling ratio in a C-type cryogenic liquid fuel tank. ***Energy***, 255, 124530.
- Chung, S. M., Jeon, G. M., & Park, J. C. (**2022**). Numerical approach to analyze fluid flow in a type C tank for liquefied hydrogen carrier (part 1: Sloshing flow). ***International Journal of Hydrogen Energy***, 47(8), 5609-5626.
- Chung, S. M., Seo, Y. S., Jeon, G. M., Kim, J. W., & Park, J. C. (**2021**). Parameter study of boiling model for CFD simulation of multiphase-thermal flow in a pipe. ***Journal of Ocean Engineering and Technology***, 35(1), 50-58.
- Jeon, G. M., Park, J. C., & Choi, S. (**2021**). Multiphase-thermal simulation on BOG/BOR estimation due to phase change in cryogenic liquid storage tanks. ***Applied Thermal Engineering***, 184, 116264.

Acknowledgements



Example of LNGC Sloshing

*Source - FLOW 3D