The ROSA-SA Project on Containment Thermal Hydraulics

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  - The CIGMA facility for integral testing
  - CFD analyses on
    - Erosion of density stratified layer by impinging jet
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Background and Objectives

- The Fukushima Dai-Ichi NPS accident re-emphasized the importance of severe accident research in Japan
- JAEA started the project on the containment thermal hydraulics related to:
  - Over-temperature Containment Damage
  - Hydrogen Risk
  - Aerosol Migration
- The ROSA-SA(Severe Accident) project
  - ROSA: Rig of Safety Assessment
  - A series of ROSA projects have focused on T/H issues, e.g.,
    - ROSA-III for BWR LOCA, ROSA-IV for PWR Small Break LOCA, etc.
  - Consists of integral tests, separate effects tests and analytical study for the LP and CFD codes
- Objectives
  - Obtain better physical understanding on the T/H phenomena
  - Validate and improve analysis methods for the LP and CFD codes

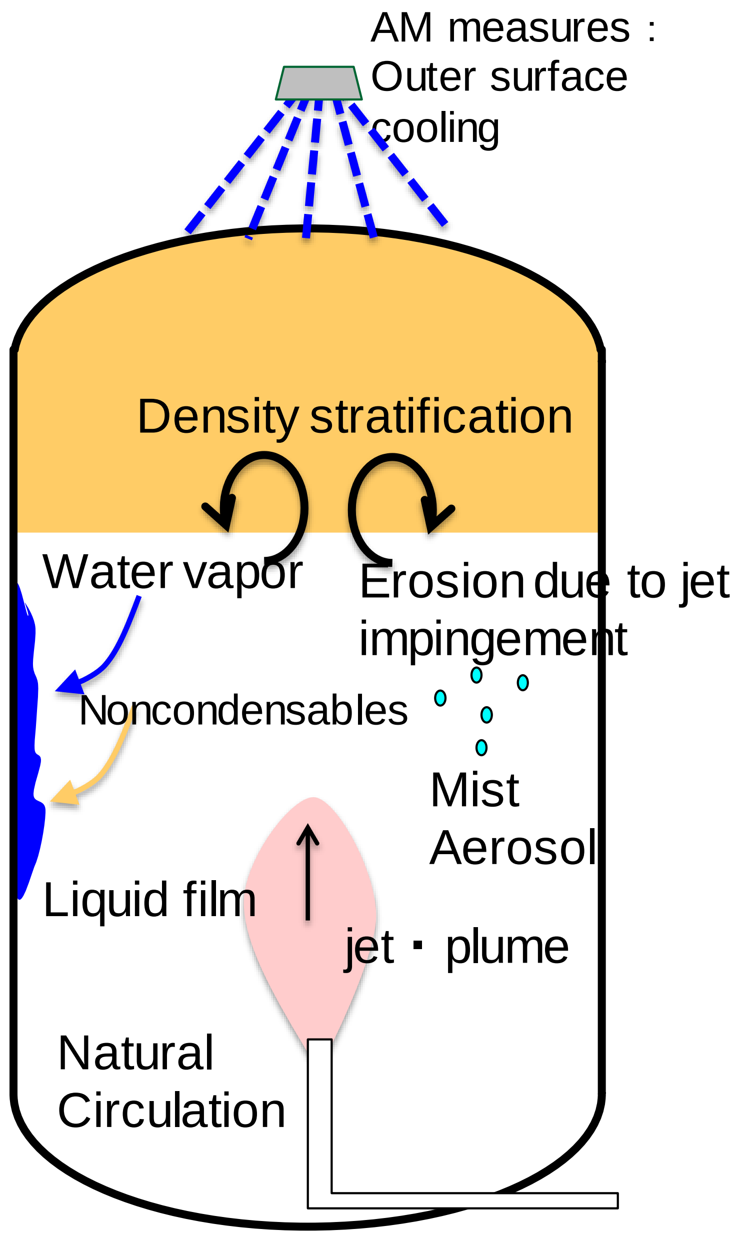
Technical Issues 1/2

- Over-temperature Containment Failure
  - Interaction of high-temp. gas flow and structure
- Hydrogen Risk
  - Thermal hydraulics of hydrogen-mixed gases

    SETH, SETH2, HYMERES, ISP-47 (stratification not predicted), PANDA, MISTRA, THAI, ….
- Aerosol Transport
  - Pool scrubbing

    relation with two-phase flow behavior, etc.
  - Behavior in large space

    water condensation on aerosol particles, etc.
- Effects on above phenomena of T/H behavior:
  - natural circulation, density stratification, jet, plume, cooling (spray, fan cooler, outer surface), mixing, phase change, heat transfer, mass transfer, etc.
  - scaling laws between test and reactor conditions



Technical Issues 2/2

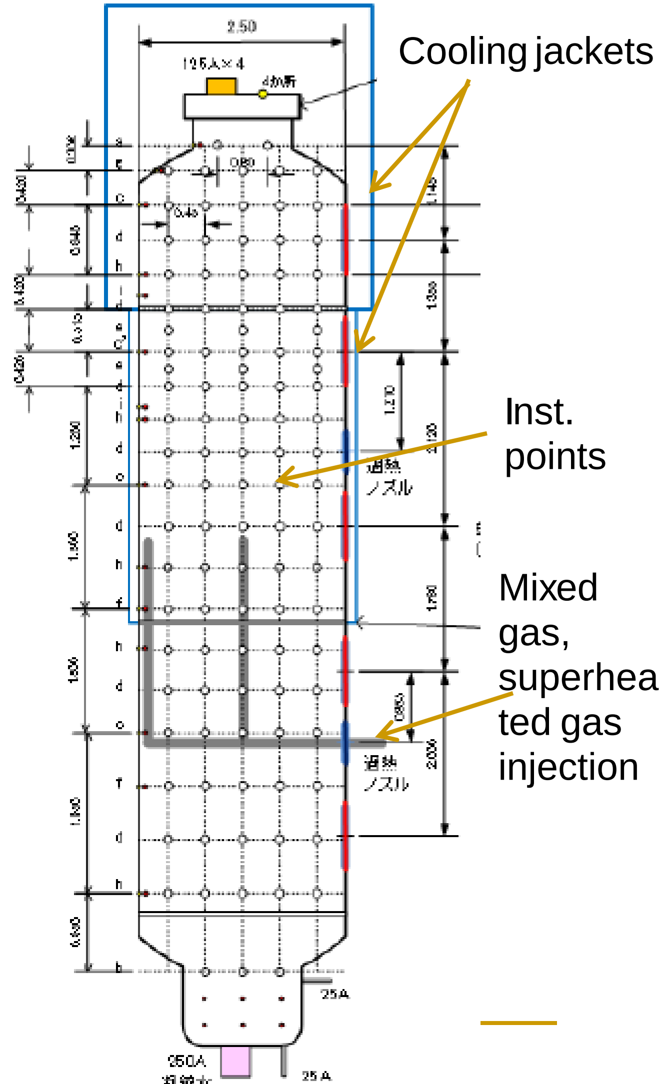
- Effectiveness of Accident Management (AM) Measures
  - Spray cooling, Fan cooler, Containment outer surface cooling
  - Containment vent, Nitrogen substitution
  - Performance outside the design conditions (e.g., low flow spray)
- Validation and improvement of prediction models
  - Lumped parameter (LP) codes such as MELCOR, RELAP5
  - CFD codes
    - To be used for technical support to the system analysis code being developed by Nuclear Regulation Authority(NRA), Japan
- Measurement technique
  - Detailed data for CFD model validation including distribution of gas molar fraction, velocity, turbulence, void fraction, etc.

Current Research Activities

1. Design of large-scale containment test facility CIGMA
2. CFD analysis on erosion of density stratified layer by impinging vertical jet
   - Turbulence model improvement for the RANS analysis based on the LES analysis
   - OECD/NEA PANDA benchmark test analysis
3. CFD analysis on steam condensation with noncondensables

1. Large-Scale Containment Test Facility

- Integral Test Facility: CIGMA
  - Containment InteGral Measurement Apparatus
- Characteristics
  - High design temperature & pressure
    - 573~773 K depending on pressure for boundary wall
    - Up to 973K for gas injection nozzle
    - Up to 1.5 MPa for pressure
  - Instrumentation with high space resolution & CFD-grade
    - Temperature (fluid 380, wall 240)
    - Gas sampling for QMS (118)
    - Velocity measurement using LDV, PIV through large windows of 650mm dia.
  - Testing on AM measures
    - Outer surface cooling
    - Vent, nitrogen substitution etc.
- First test scheduled in 2015

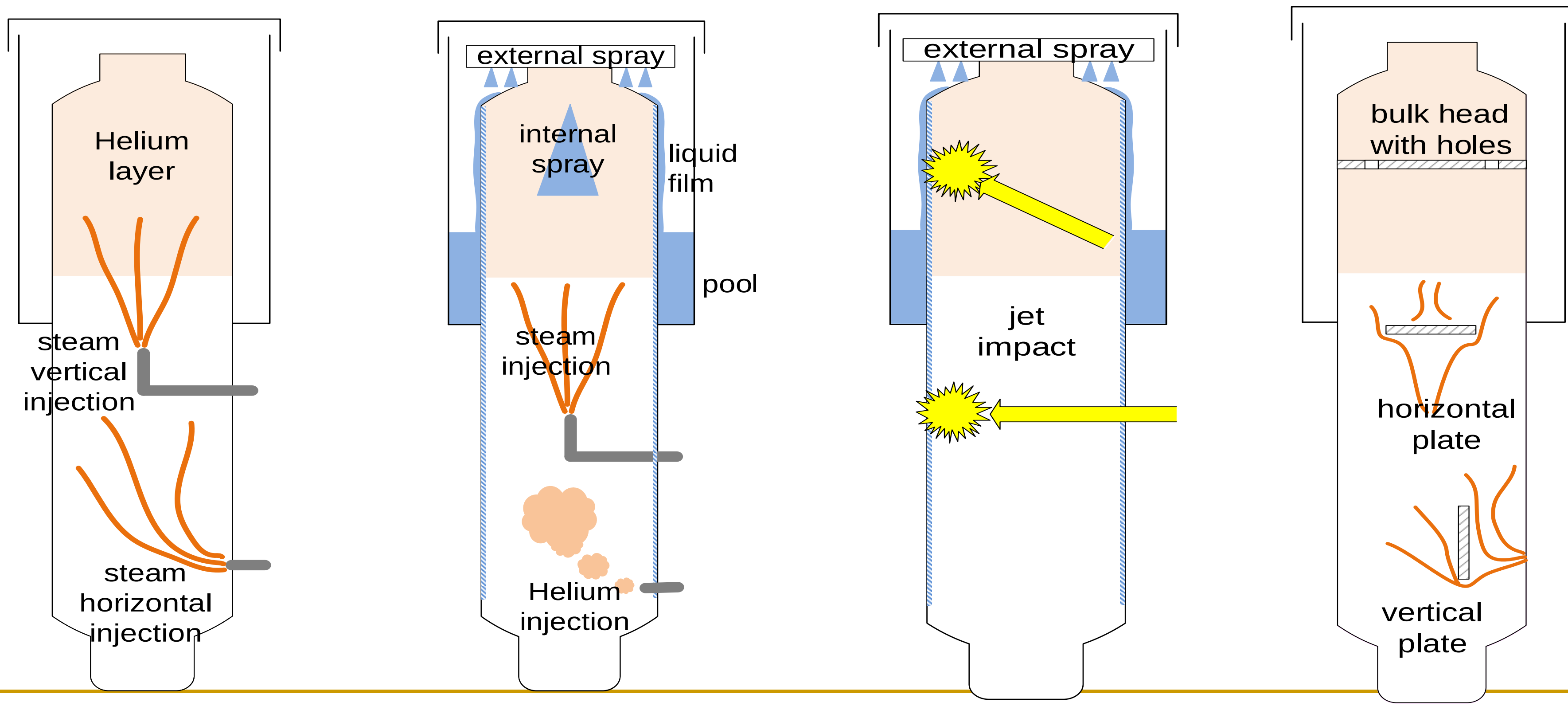


QMS: Quadrupole Mass Spectrometer
LDV: Laser-Doppler Velocimetry
PIV: Particle Image Velocimetry

The CIGMA facility is developed under the auspices of the Nuclear Regulation Authority (NRA), Japan.

Planned Experiments at CIGMA

- Erosion of density stratification due to Helium/Steam jet
- Effects of outer surface cooling on stratification, natural circulation
- Wall temperature behavior responding to impingement of high temperature jet
- Effects of internal structure, etc.



Comparison with Existing Facilities

- High design temperature and pressure
- Instrumentation with high space resolution

		THAI[4]	MISTRA[3]	PANDA[1,2]	CIGMA
Organization		GRS	CEA	PSI	JAEA
Height	m	9.2	7.3	25(total)	10
Diameter	m	3.2	4.25	4	2.5
Volume	m3	60	100	183*1	～50
Pressure	MPa	1.4	0.6	1.0	1.5
Temperature	K	453	473	473	573 (ave)*2
Power	MW	0.1		1.5	0.2
Instrumentation		~200	~370	~1000	
Thermocouple		>160	>300		~600
Concentration		~20	～50	～100	~100
Window		20		6	～15
Velocimetry		PIV/LDV	PIV/LDV	PIV	PIV/LDV

Notes
*1:
two vessel + interconnection pipe

*2:
573~773 K for boundary wall depending on pressure, and up to 973K at gas injection nozzle

Referemces
1. Paladino, D., Dreier, J., PANDA: A Multipurpose Integral Test Facility for LWR Safety Investigations, Scinence and Technology of Nuclear Installations , ID:239319, (2012).
2. Zboray, R., Paladino, D., Experiments on basic thermal hydraulic phenomena relevant for LWR containments: Gas mixing and transport induced by buoyant jets in a multi-compartment geometry, Nucl. Eng. Des., 240, 3158-3169, (2010).
3. Caron-Charles, M. et al., Steam Condensation experiments by the MISTRA Facility for field containment code validation, ICONE-10-22661, (2002).
4. OECD/NEA THAI Project, Final Report Hydrogen and Fission Product Issues Relevant for Containment Safety Assessment under Sever Accident Conditions, NEA/CSNI/R(23010)3.

Comparison with previous experiment conditions

- Pressure & Temperature
  - OECD/SETH-2, for example,

    Investigate hydrogen stratification break-up induced by heat and mass sources or by the actuation of a system (e.g. spray, …)

    - PANDA: $P < 2.6$ bar, $T < 130$℃, $T_{inj} < 150$℃
    - MISTRA: $P < 1.1$ bar, $T < 99$℃, $T_{inj} < 148$℃
- CIGMA tests will enlarge validation-range for models
  - Empirical correlations used in codes
    - Turbulent models, Similarity laws, etc.

    will be validated under enlarged T/H conditions

OECD/SETH-2 PROJECT PANDA AND MISTRA EXPERIMENTS FINAL SUMMARY REPORT, NEA/CSNI/R(2012)5 Table 5-17

2. Erosion of density stratified layer by jet flow

- RANS turbulence model improvement
  - Analysis using OpenFOAM for a containment
  - Model improved to include effects of jet-stagnation and buoyant
  - Compared with LES analyses
    - Using fine meshing, LES is believed to be more accurate.

Number of Cells: 0.54M for RANS, 5M for LES

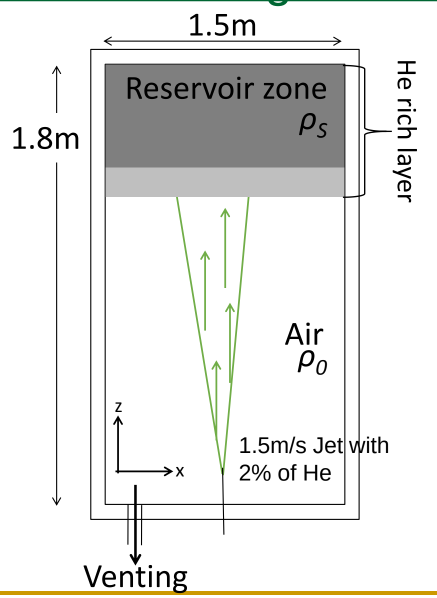
- Result
  - Erosion rates much larger for RANS than LES
  - <u>Modified model agrees well with LES.</u>

- **<u>Kato model</u> for kinetic energy production around flow stagnation region [3]**
- **<u>Katsuki model</u> for turbulence damping in stratification [4]**

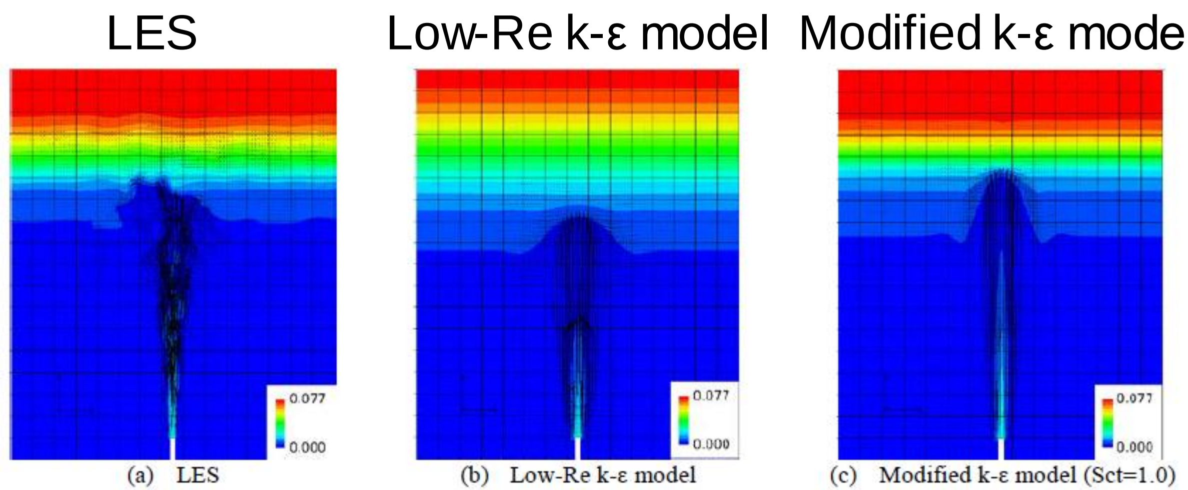
Note * : reprinted from those in Ref.2 with some changes.

rectangular parallelepiped of 1.5m x 1.5m x 1.8m

2% (7.7%) mass fraction = 13% (40%) molar fraction



Helium mass fraction at 60s*



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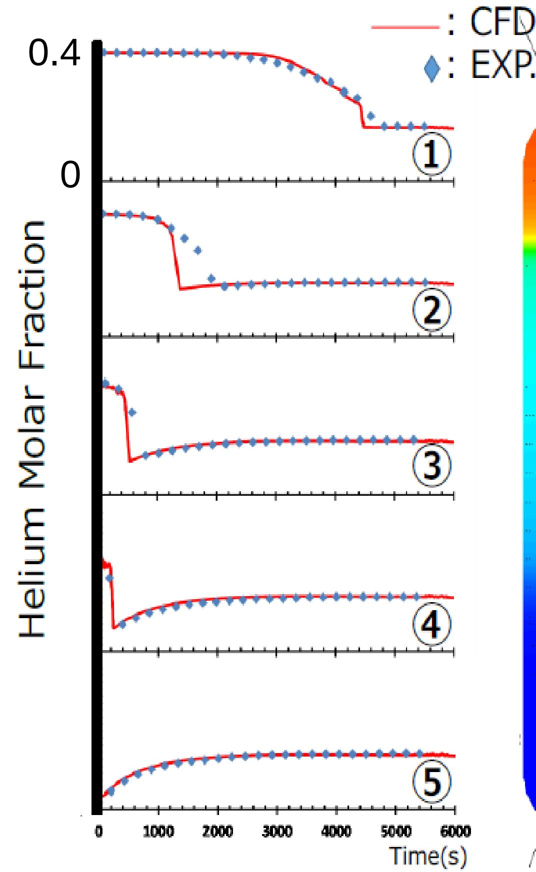
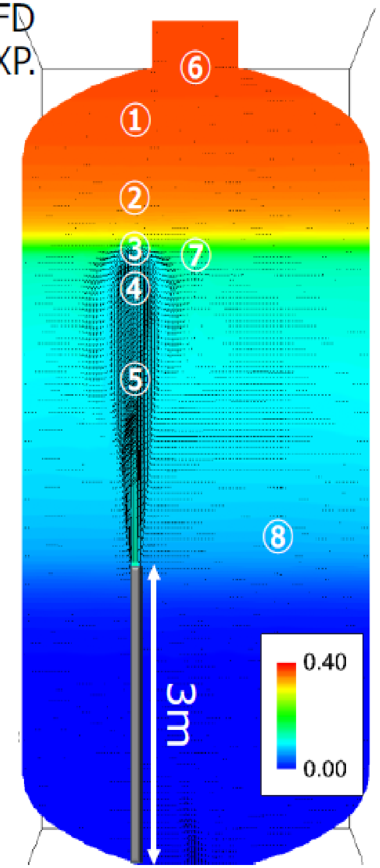
[1] S. Abe et al., RANS and LES analyses on a density stratified layer behavior of multicomponent gas by buoyant jet in a small vessel, ICONE-22, 2014. [2] S. Abe et al., A study on improvement of RANS analysis for erosion of density stratified layer of multicomponent gas by buoyant jet in a containment vessel, NUTHOS10-1181, 2014. [3] M. Kato, B. E. Launder, The modeling of Turbulent Flow around Stationary and Vibrating Square. 9th Symposium on turbulent shear flows,1993. [4] T. Katsuki, et al., Wind tunnel experiment and numerical simulation of atmospheric boundary layer under various atmospheric stability. Journal of Environmental Engineering, Architecture Institute of Japan. 74, 735-743, 2009. (in Japanese)

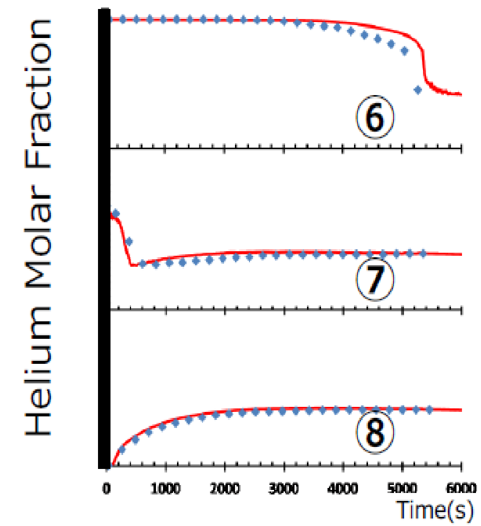
PANDA Benchmark Test Analysis

- OECD/NEA & PSI sponsored benchmark test
- Vertical jet effects on density stratified layer using PANDA
- 19 organizations
  - Test in 2013
  - Presentation CFD4NRS-5, 2014
- Post-test analysis using the improved RANS model agree well with the data

Tank : 4m dia. x 8m height

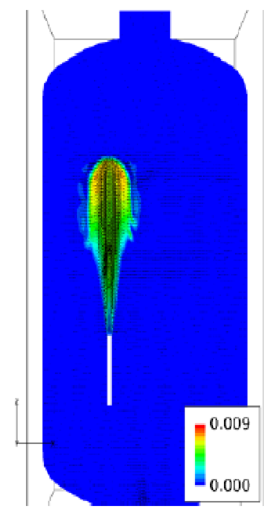






Helium molar fraction & velocity vector

Note : reprinted from Ref.1.



Turbulence diffusion coefficient & velocity vector

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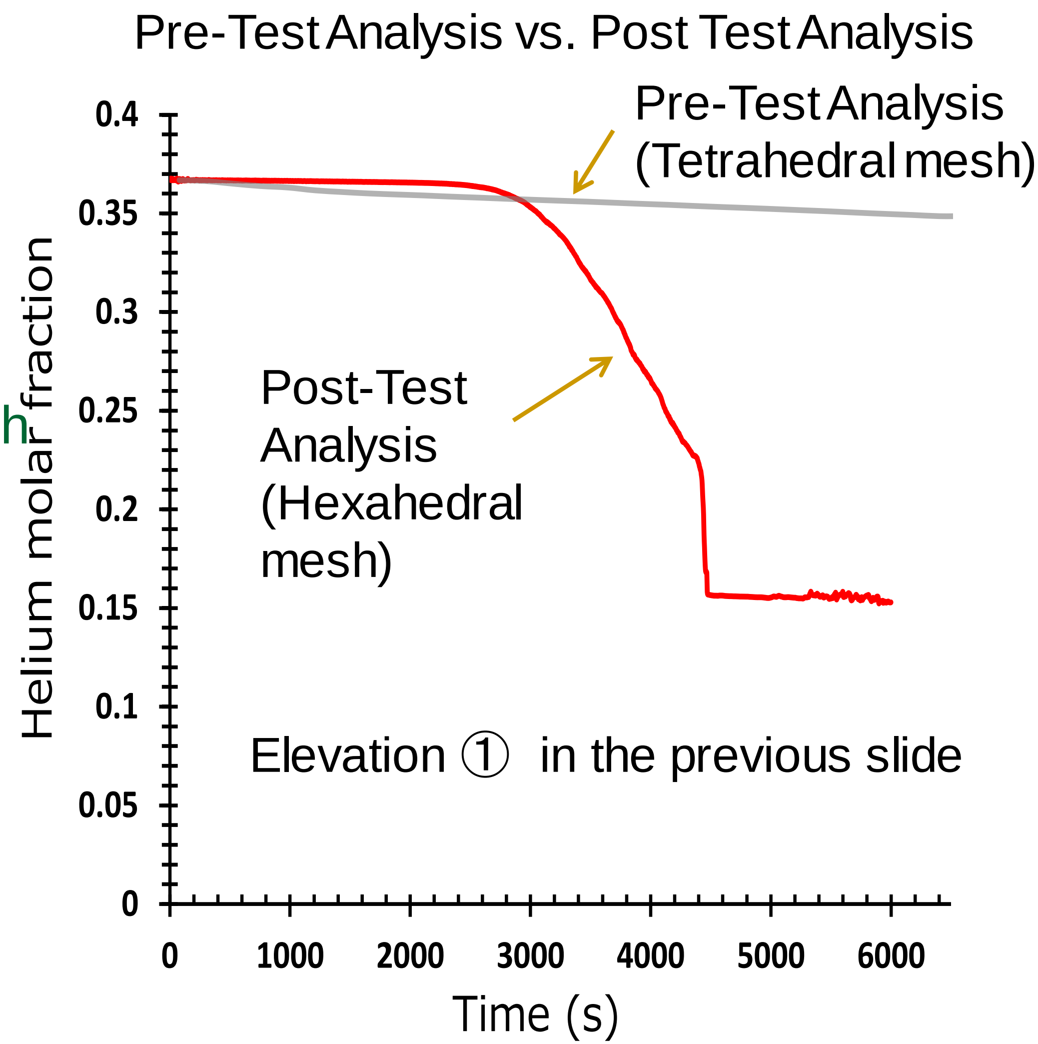
2. S. Abe et. al., RANS analyses on erosion behavior of density stratification consisted of helium-air mixture gas by a low momentum vertical buoyant jet in the PANDA test facility, the third International Benchmark exercise (IBE-3), submitted to Nucl. Eng. Des.

Future Plans for Stratified Layer Analysis

- Effects of mesh geometry*
  - Already identified
  - Hexahedral mesh recommended in some CFD Best Practice Guidelines
  - Several merits of tetrahedral mesh
  - Investigate a numerical scheme
- Models validation and improvement using exp. data from CIGMA and small-scale test facilities

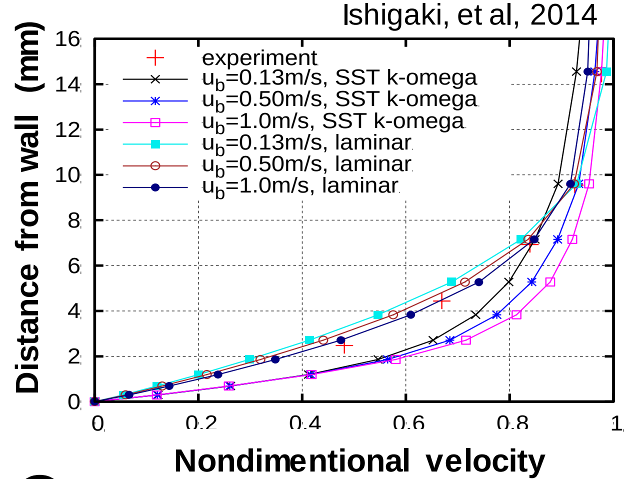


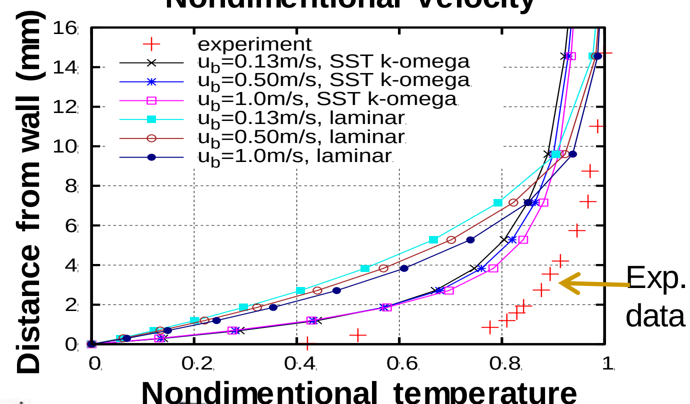
* The use of the hexahedral mesh was recommended by Dr. Studer of CEA to Dr. Abe, one of Authors, when he visited the CEA Saclay.

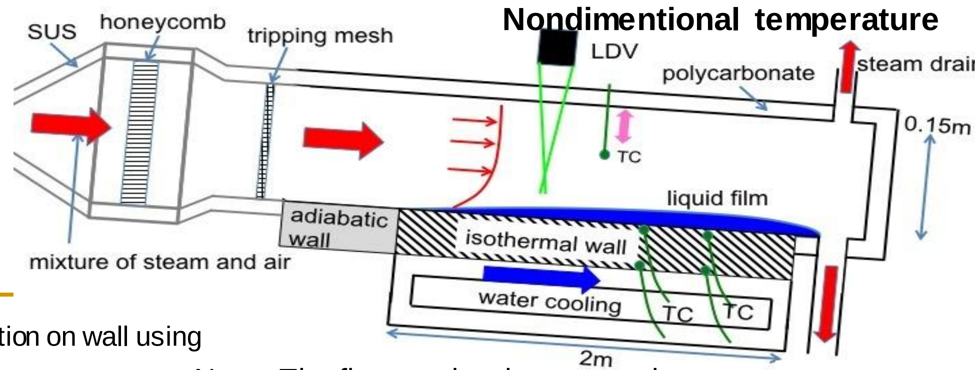
3. Wall condensation with noncondensables[1]

- CFD Analysis of test data in literature
  - Condensation of steam-air mixture on horizontal wall[2]
  - OpenFOAM : open source CFD code
  - Analysis models
    - Condensation rate determined by diffusion of steam
    - Thermodynamic equilibrium, No phase change
    - Liquid film not modeled
    - Liquid surface temp. given as a boundary condition
  - Results
    - Distribution predicted well for fluid velocity, but not for temperature, which suggests
      - Requirement in model improvement?
      - Problem in measurement?
- Planned experiments at JAEA
  - Atmospheric pressure
  - Slope changed: horizontal to vertical

Ishigaki, et al, 2014







1. M. Ishigaki, et. al., Numerical simulation of thermal flow with steam condensation on wall using the OpenFOAM code, CFD4NRS-5, 2014
2. H.C. Kang and M.H. Kim, *Int. J. Multiphase Flow*, **25**(8), 1601–1618, 1999.

Note : The figures showing comparisons are reprinted from Ref.1.

Summary

- The ROSA-SA project started in 2013 for research on containment thermal hydraulics related to:
  - Containment over-temperature damage
  - Hydrogen risk
  - Aerosol and gaseous FP transport
- The project has focused on :
  - Development of a large-scale containment experiment facility CIGMA & separate effects test facilities for condensation, density stratified layer, pool scrubbing, instrumentation testing, etc
  - CFD analyses of literature data to identify technical issues and improve analysis models
- The CIGMA tests will start in 2015

Acknowledgments : The CIGMA facility is developed under the auspices of the Nuclear Regulation Authority (NRA), Japan. We appreciate the technical discussions with the NRA staffs.