



RESEARCH ON AEROSOL AND MULTIPHASE FLOWS IN THE NTUA NUCLEAR ENGINEERING SECTOR (NES)

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OUTLINE

- Our research areas and focus
- Aerosol flows modelling
- Homogeneous nucleation
- Containment flows
- Boiling flows
- Other studies in progress

RESEARCH FOCUS

- Our research is focused on nuclear safety applications; however, the developed models and codes have broader applicability
- Our goals
 - Understand better the **fundamental mechanisms**
 - **Develop or improve models**
 - Extend the use of **CFD in nuclear safety** applications
- Computational tools
 - **General purpose CFD + in-house** models
 - **Lumped or 1-d in-house codes**

AEROSOL FLOWS MODELING

- Transport, Diffusion, Deposition (slip velocity), Nucleation, Growth/Evaporation, Coagulation, Agglomeration
- **General Dynamic Equation (or Population Balance Equation)**

$$\frac{\partial \rho n_{m,i}}{\partial t} + \nabla \cdot (\rho(\mathbf{u} + \mathbf{c}_i)n_{m,i}) - \nabla \cdot (\rho D_{p,eff,i} \nabla n_{m,i}) = S_{i,nucl} + S_{i,cond} + S_{i,coag}, i = 1, \dots, n_{bins}$$

- Coupled with the **condensable vapors transport equation**

$$\frac{\partial \rho C_{m,j}}{\partial t} + \nabla \cdot (\rho \mathbf{u} C_{m,j}) - \nabla \cdot (\rho D_{v,eff,j} \nabla C_{m,j}) = - \left. \frac{\partial \rho C_{m,j}}{\partial t} \right|_{nucl} - \left. \frac{\partial \rho C_{m,j}}{\partial t} \right|_{growth}, j = 1, \dots, n_{species}$$

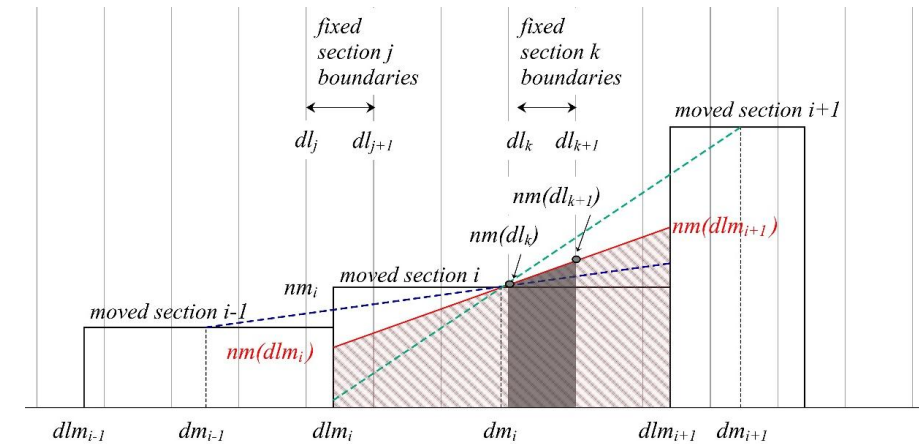
- **Multispecies:** The transport equation for the species mass fraction in the particulate phase

$$\frac{\partial \rho C_{p,j}}{\partial t} + \nabla \cdot (\rho \mathbf{u}_m C_{p,j}) - \nabla \cdot (\rho D_{p,eff,m} \nabla C_{p,j}) = \left. \frac{\partial \rho C_{p,j}}{\partial t} \right|_{nucl} + \left. \frac{\partial \rho C_{p,j}}{\partial t} \right|_{cond}, j = 1, \dots, n_{spec}$$

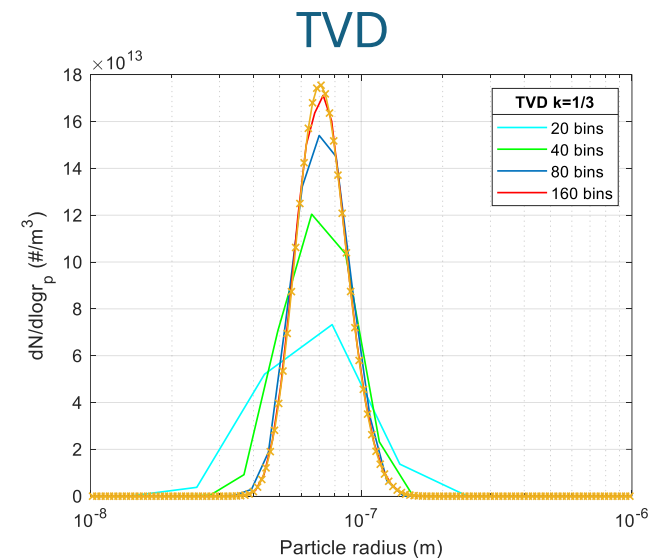
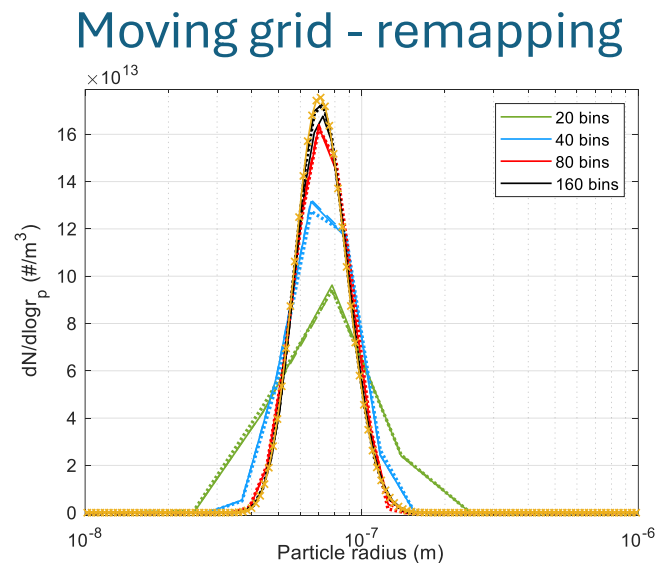
- **Sectional method**
- **Eulerian**

GROWTH/EVAPORATION NUMERICAL SOLUTION

- A **moving grid – remapping** method has been developed
- Stable and robust (e.g. compared with TVD)



**Transport,
nucleation,
condensation**



HOMOGENEOUS NUCLEATION STUDIES

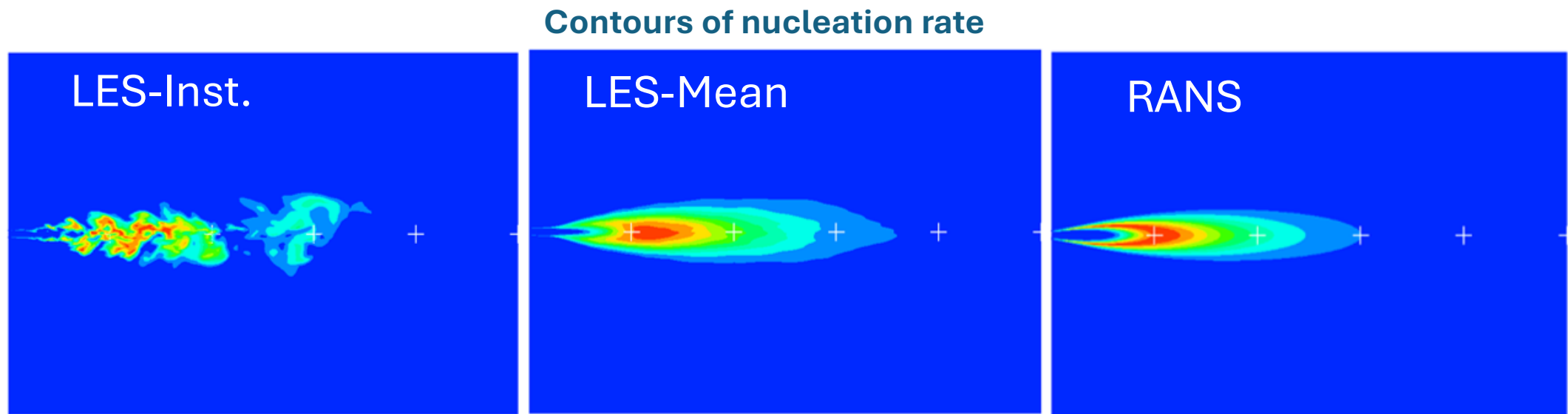
- The Classical Nucleation Theory (CNT) is the most often used formula
- CNT is very useful; however, it may be orders of magnitude off
- The goal:
 - assess the performance of CNT for practical applications
 - laminar and turbulent flows

HOMOGENEOUS NUCLEATION STUDIES

- A new modification of the CNT was developed, based on the introduction of the Tolman length in the kinetic version of the CNT
- The new modification was found to be more reliable than other CNT versions compared with experimental isotherms of DBP

EFFECT OF TURBULENCE MODELLING

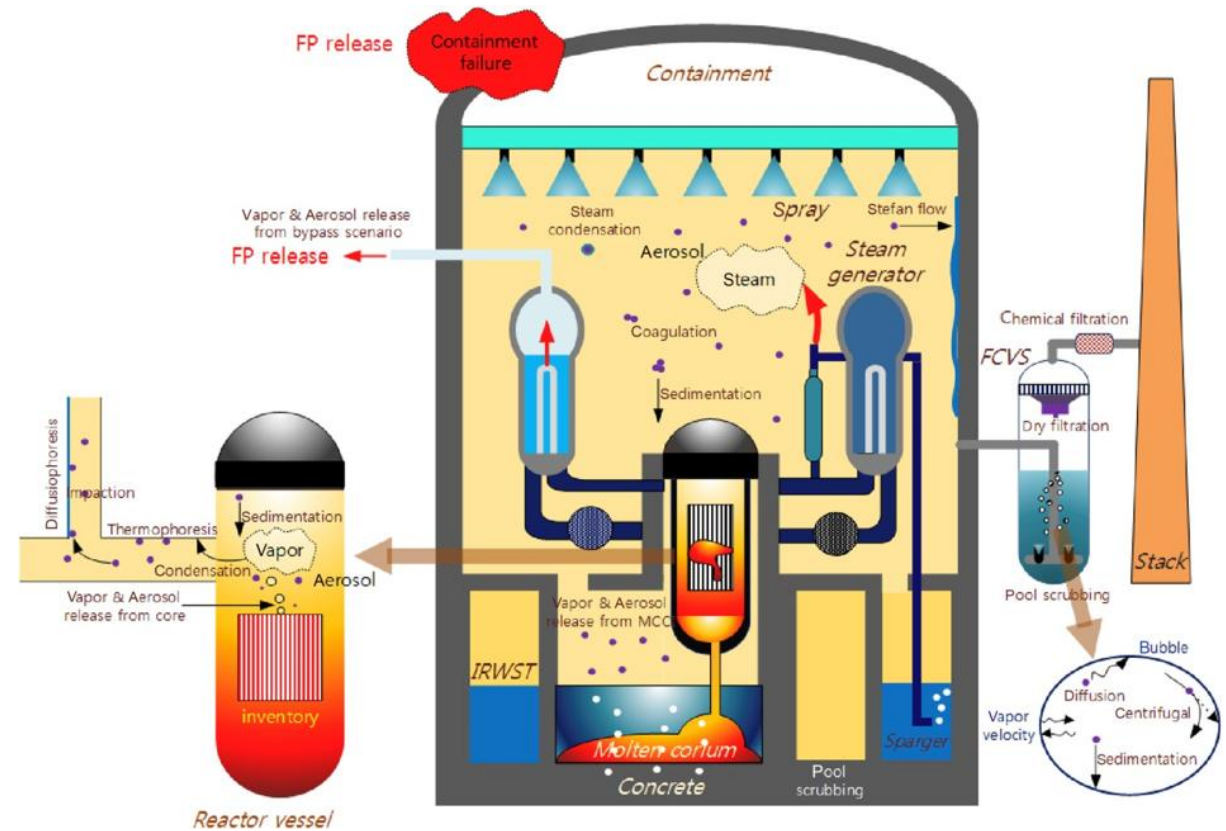
- Nucleation rate is extremely sensitive to temperature and saturation ratio



- ✓ In terms, however, of the final number concentration of the formed particles, RANS provided results comparable to LES

CONTAINMENT AEROSOL FLOWS

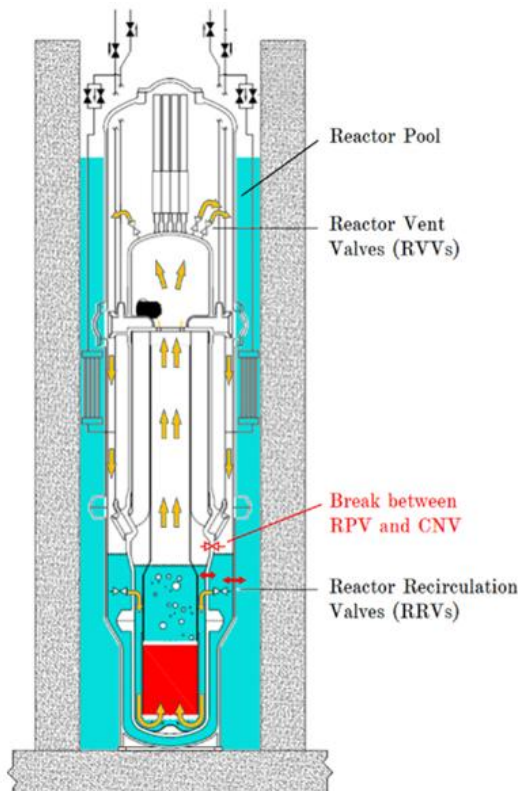
- If the *reactor core* (i.e. the fuel) is not continuously cooled, it will melt!
- During a core melt accident, **radioactive materials** are released to the **containment** as **aerosols**
- To estimate the atmospheric releases, we need to simulate **aerosol dynamics and deposition (retention)** in the containment
- This is relevant for existing or new reactor designs (e.g. iPWR)



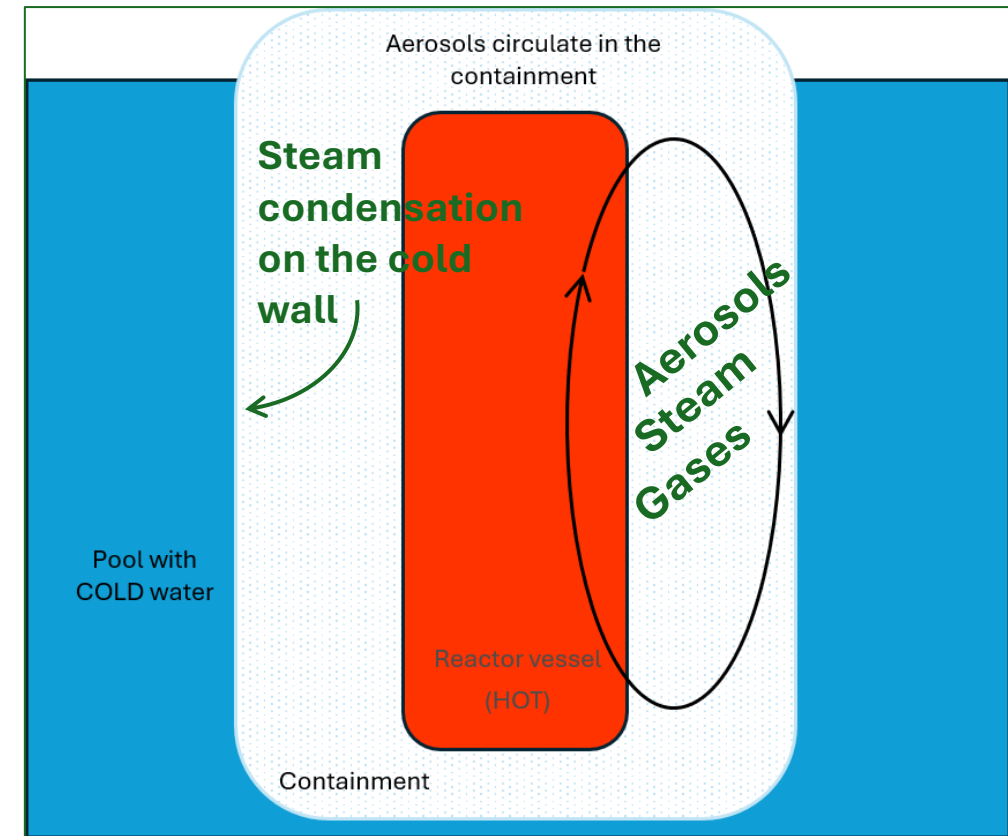
EXPANDING THE AEROSOL MODEL FOR CONTAINMENT FLOWS

- Natural circulation
- Steam condensation
- Internal aerosol processes
 - Gravity
 - Thermophoresis
 - Diffusiophoresis
 - Turbophoresis
 - Inertia
 - Diffusion

Integral Pressurized
Water Reactor (iPWR)
design

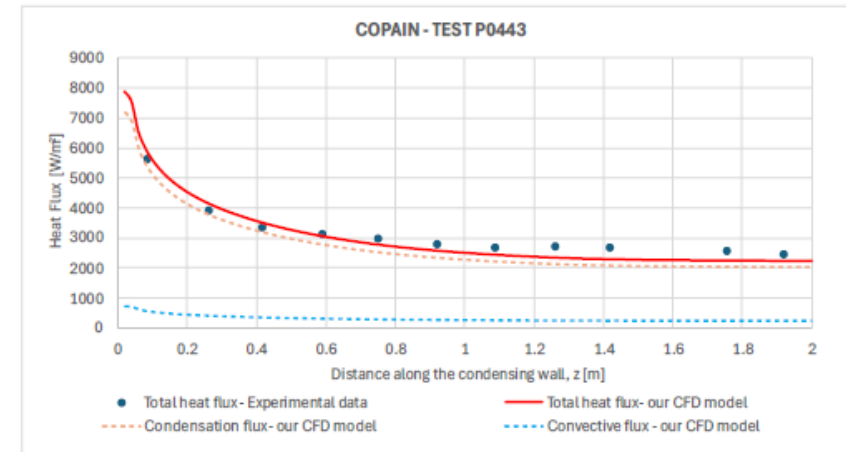
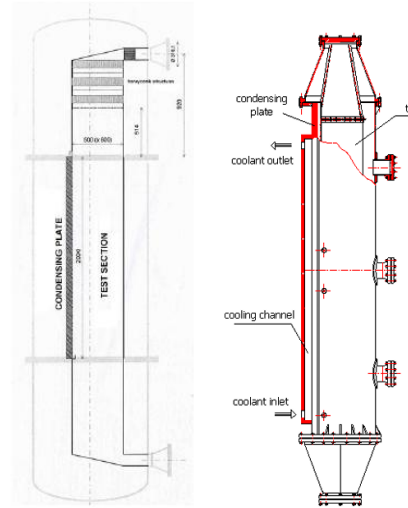


A simplified representation

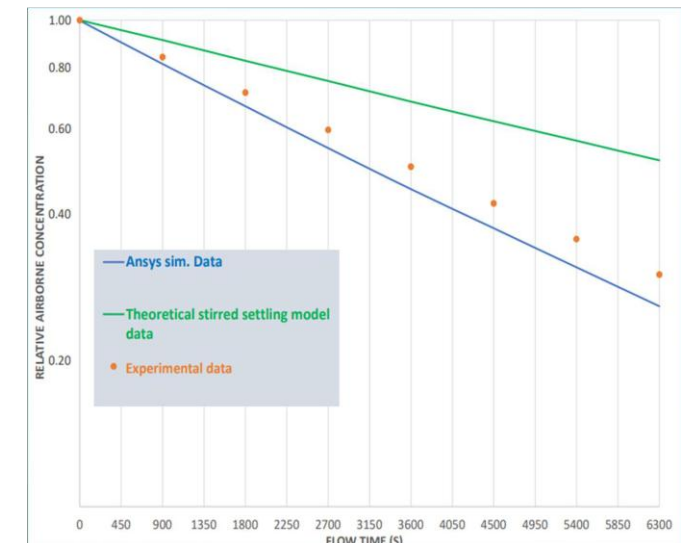
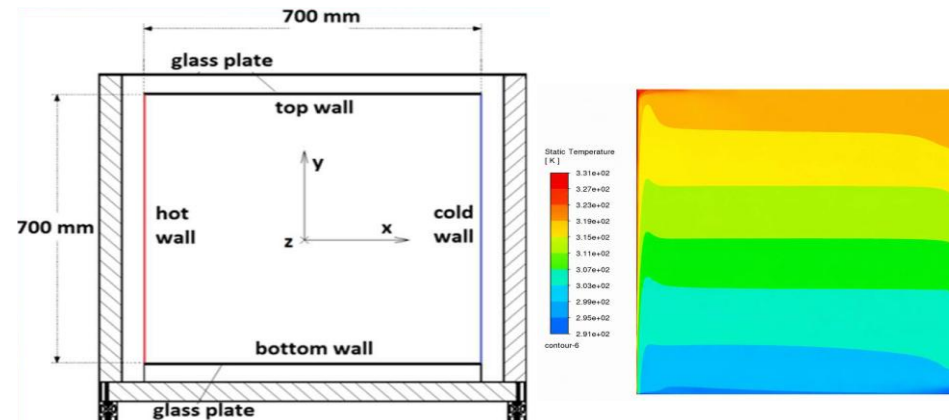


EXPANDING THE AEROSOL MODEL FOR CONTAINMENT FLOWS

Steam condensation in presence of non-condensable gases
(simulation of COPAIN and CONAN experimental facilities)



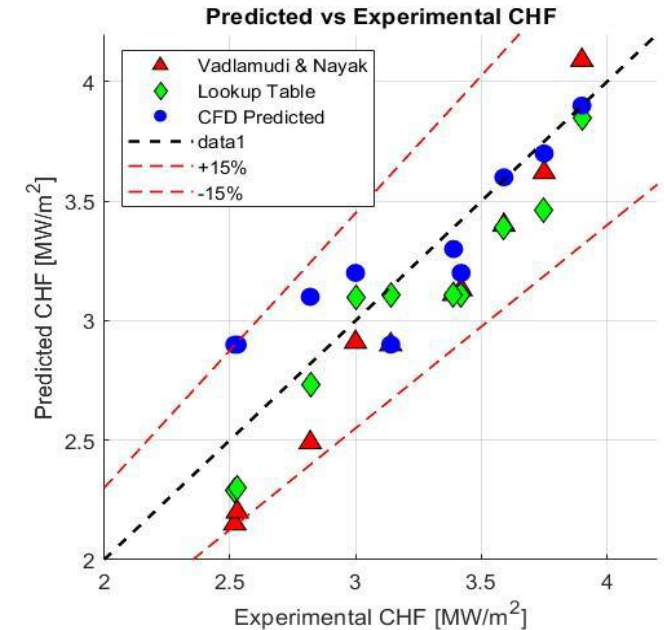
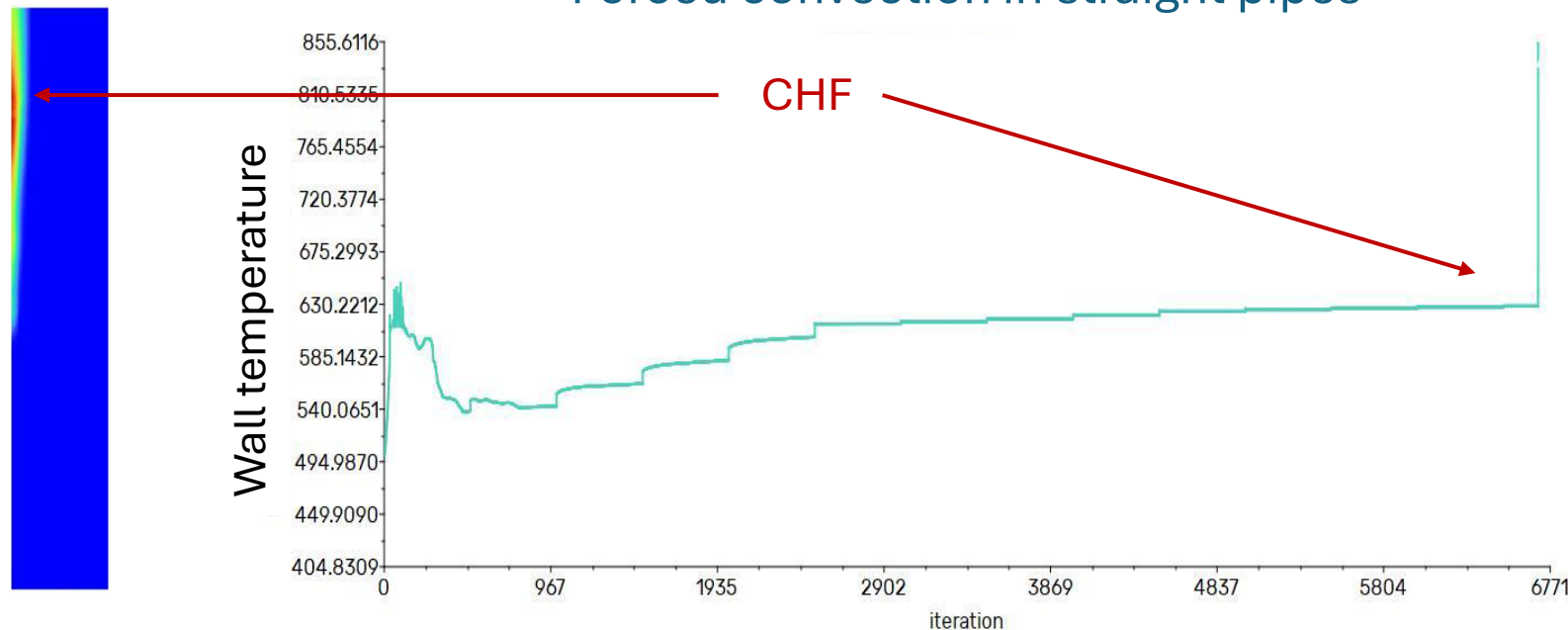
Particle deposition in a cavity under natural circulation (simulation of DIANA experimental facility)



BOILING FLOWS

- **Nucleate boiling:** Use of mechanistic models for the components of the wall boiling model
- **Critical Heat Flux (CHF):** Straight pipes, Curved surfaces

Forced convection in straight pipes



CRITICAL HEAT FLUX IN CURVED SURFACE, UNDER NATURAL CIRCULATION

- Prevent damage of the vessel by the molten fuel (corium) by cooling the vessel externally

e.g. Large LWR

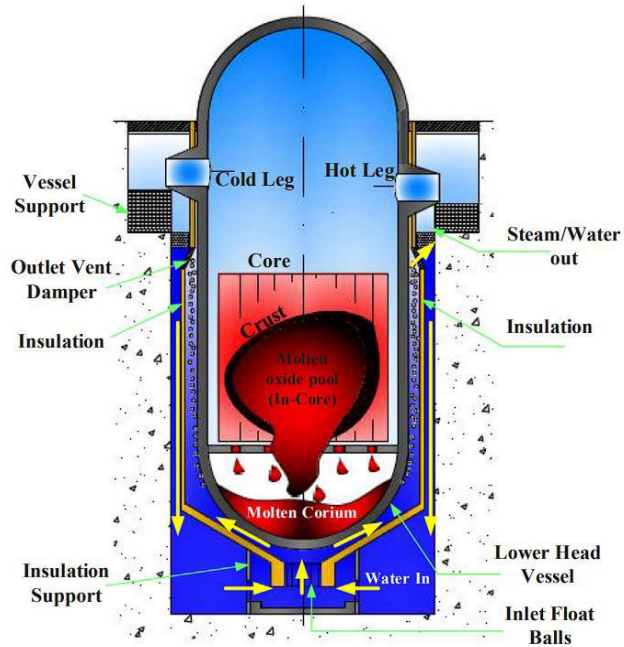
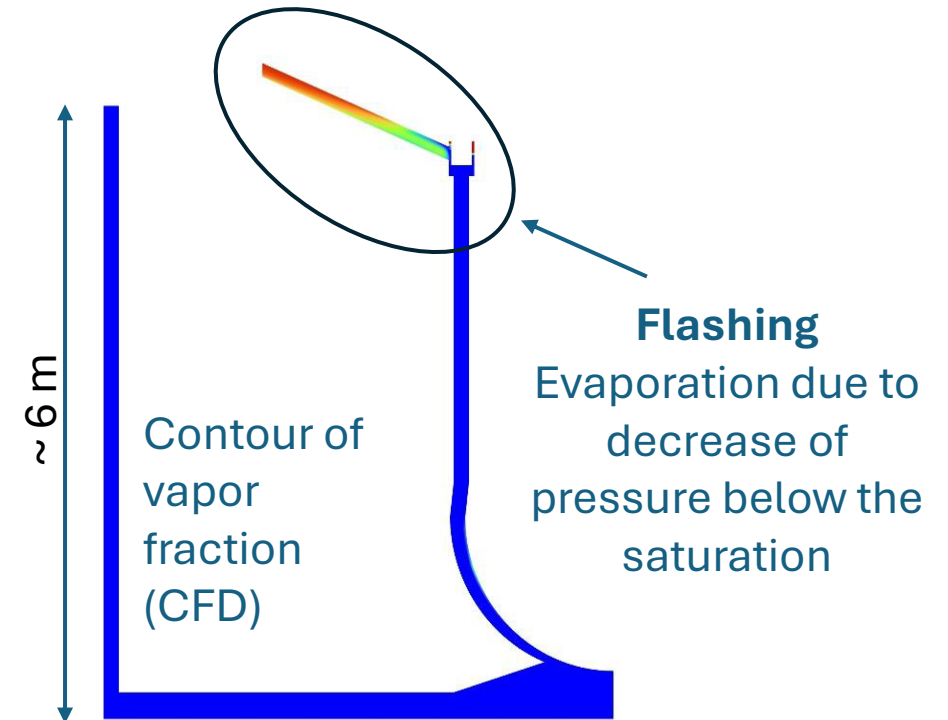
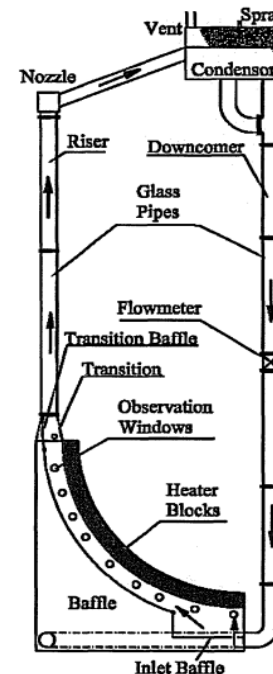


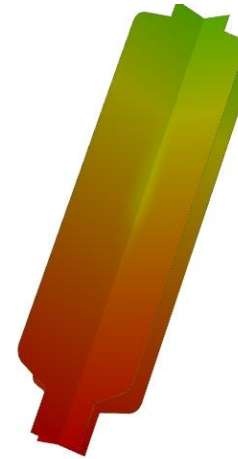
Figure from Zhang et al., 2019, Applied Thermal Engineering, 149, pp.881–888

ULPU test facility

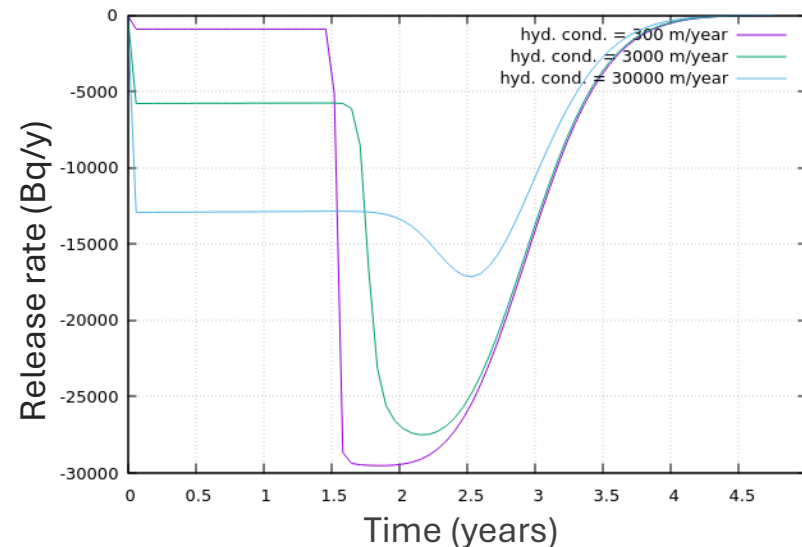


OTHER ON-GOING TASKS

1. Spray removal of aerosol in the containment
 - Eulerian modelling for all phases
2. Turbulent deposition of particles
 - Turbophoresis
3. Two-phase flow (air, water) in porous media and migration of radionuclides
 - Disposal of radioactive waste in cementitious materials



Particle removal by spray in THAI facility (CFD results)



Radium release rate from radioactive waste disposal facility (initial water content $x=0.5$)



THANK YOU!