Project FORTE: Nuclear Thermal Hydraulics Research & Development

Thermal hydraulics for liquid metal fast reactors

Dr Xiaoxue Huang[1]

Prof. Shuisheng He[1]

Prof. J.D.Jackson[1,2]

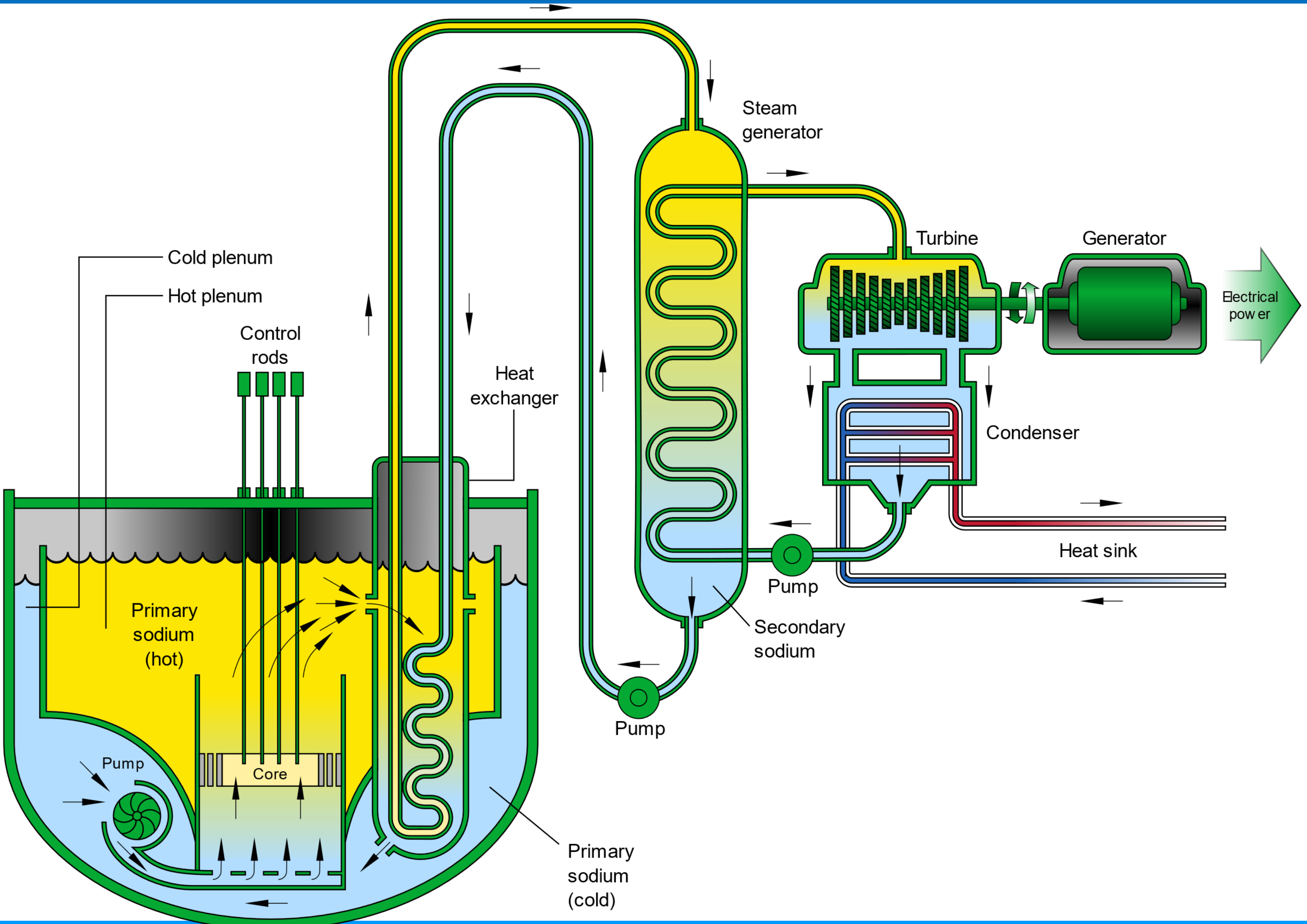
Mr Matthew Falcone[1]

[1]Department of Mechanical Engineering, University of Sheffield

[2]Department of Mechanical Engineering, University of Manchester

CONTENTS

Overview

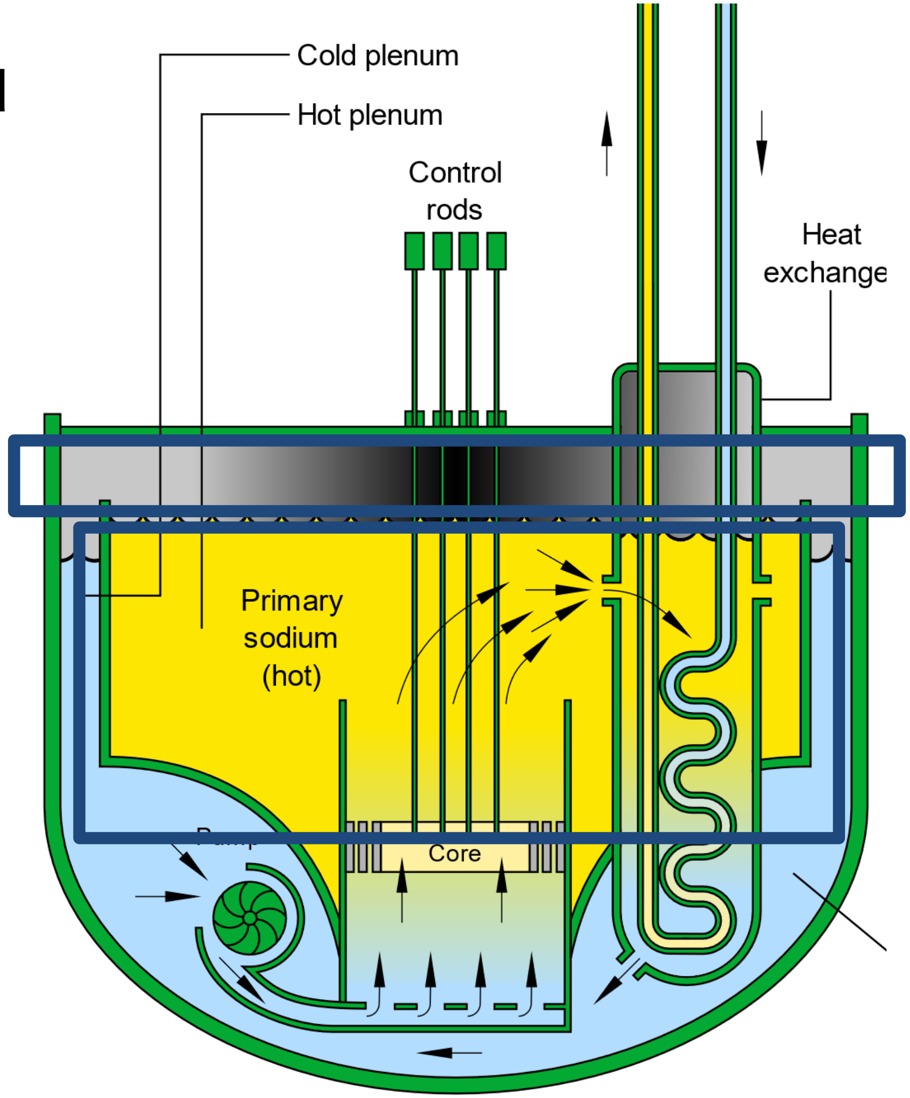

Steam
generator
Turbine
Generator
Electrical
pow er
Cold plenum
Hot plenum
Control
rods
Heat
exchanger
Condenser
Heat sink
Pump
Secondary
sodium
Primary
sodium
(hot)
Pump
Pump
Core
Primary
sodium
(cold)

❖ **The low Prandtl number of liquid metals**

- thermal boundary layer is much thicker than momentum boundary layer.
- the Reynolds analogy is no longer valid.

❖ **Challenges which require improved thermal hydraulic analysis:**

- high-speed sub-assembly jet mixing
- thermal stripping
- thermal stratification
- …



❖ **Heat transfer across the cover gas region**

- Natural convection + radiation + condensation

❖ **Deposition on penetrations and fission production retention**

Overview

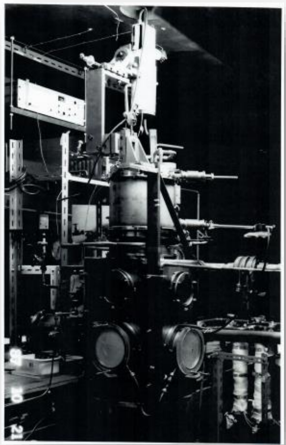
Task 1: **Historic data on heat transfer and aerosol characteristics in the cover gas region**
measurements of the emissivity of surfaces, experimental investigation of heat transfer and aerosol characteristics in the cover gas region carried out at University of Manchester in the 1990s.

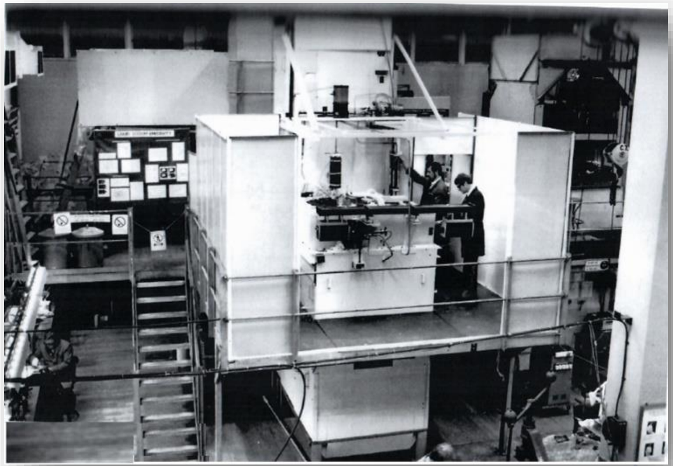
Task 2: **Numerical simulation of the cover gas region**
an numerical investigation into the aerosol dynamics, heat and mass transfer in the cover gas region.

Task 3: **Modelling of the upper plenum in LMFRs**
a thermal hydraulic modelling of liquid metal heat transfer in the upper plenum of a LMFR.

Task 1
Historic data on heat transfer processes within the aerosol-laden argon cover gas region

Historic data on heat transfer and aerosol characteristics in the cover gas region





Heat transfer across the aerosol laden cover gas
Aerosol characteristics

Emissivity of liquid sodium under different processes

Emissivity of stainless steel under different conditions

1980 sponsored by UKAEA

1985 sponsored by UKAEA

1988 sponsored by UKAEA and NNC Ltd.

1993 ceased

Emissivity measurements of

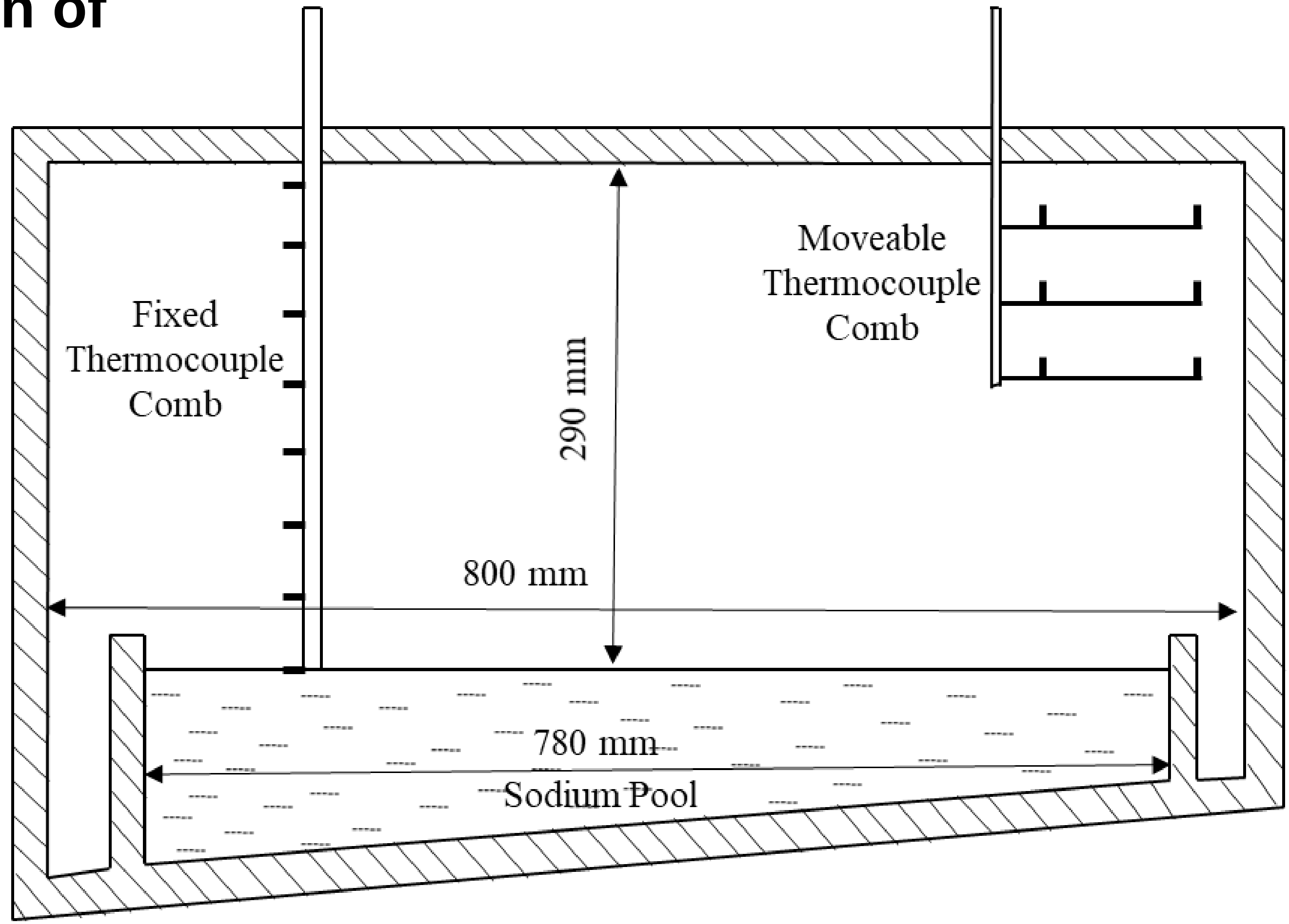
- stainless steel and other materials used in nuclear applications
- sodium contaminated stainless steel, stainless steel surfaces promoting dropwise condensation of liquid sodium
- surfaces during and after a heating process leading to evaporation and dryout
- liquid sodium, with and without ripples on it

Experimental investigation of

- characteristics of the sodium aerosol cloud in the argon cover gas above a sodium pool
- rate of heat transfer to the roof of the MUSAC test facility

Experimental investigation of

- ❖ aerosol concentration, size distribution and mean diameter
- ❖ cover gas temperature profiles
- ❖ heat transfer rate to the roof

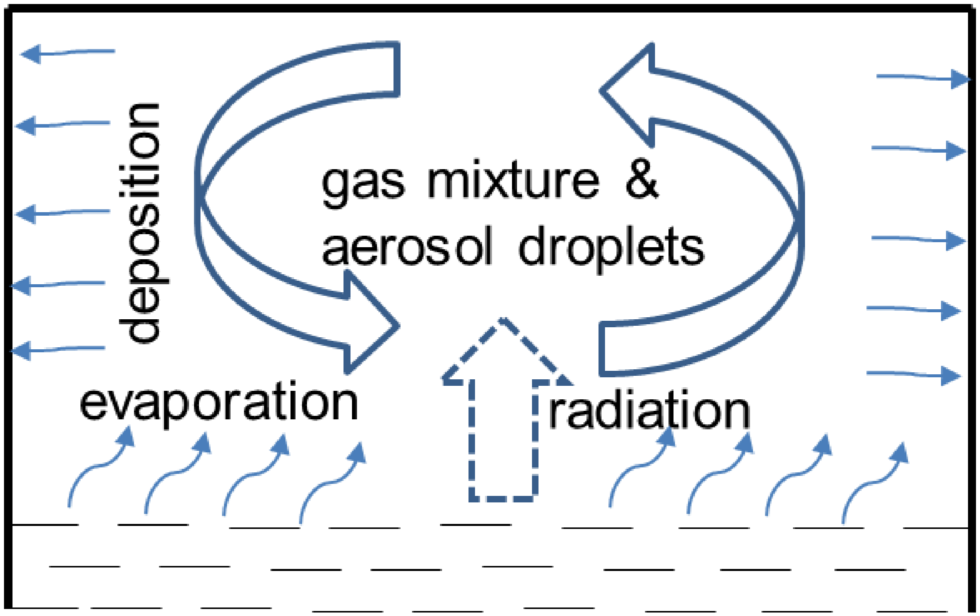


Schematic of the test section of MUSAC 3

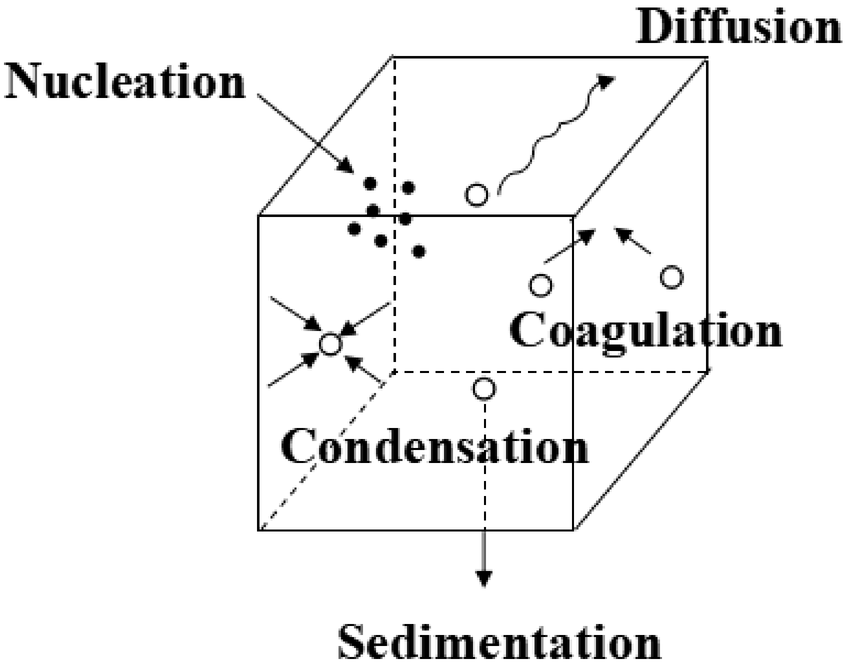
Task 2

Natural convection of a droplet-laden flow in a cylindrical enclosure above a hot sodium pool

Natural convection of a droplet-laden flow in the cover gas region

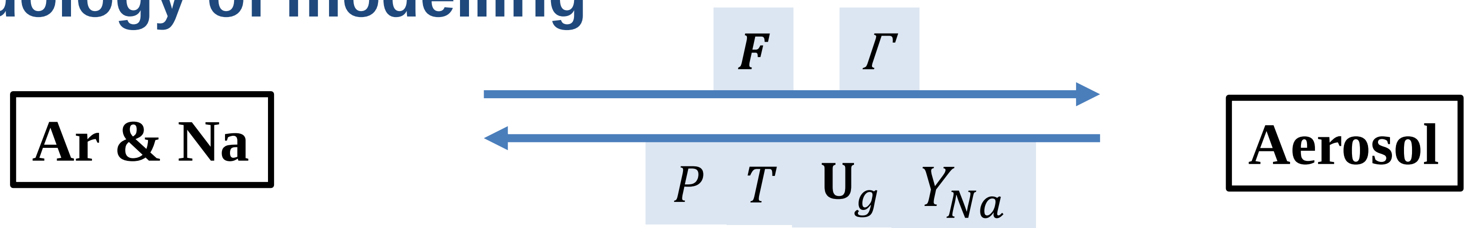


Multiphysics in the cover gas region



Physics of the aerosol dynamics

Methodology of modelling



Continuity equation for the mixture

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}_g) = -\mathit{\Gamma}$$

General dynamic equation

$$\frac{\partial n_j}{\partial t} + \nabla \cdot (n_j \mathbf{U}_{p,j}) + \frac{\partial}{\partial r_{p,j}} (n_j \dot{R}_{p,j}) = \nabla \cdot (D_{p,j} \boldsymbol{\nabla} n_j)$$

Energy equation

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot (\rho h \mathbf{U}_g) = \frac{dP}{dt} + \nabla \cdot (\lambda \boldsymbol{\nabla} T) + Q - \mathit{\Gamma} c_p T$$

Momentum equation

$$\frac{\partial}{\partial t}(\rho \mathbf{U}_g) + \nabla \cdot (\rho \mathbf{U}_g \mathbf{U}_g) = -\nabla P + \nabla \cdot \mu [(\nabla \mathbf{U}_g) + (\nabla \mathbf{U}_g)^T - \frac{2}{3} tr(\nabla \mathbf{U}_g) \boldsymbol{I}] - \boldsymbol{F} + \rho \boldsymbol{g} - \nabla \cdot (\rho \overline{\boldsymbol{u}' \otimes \boldsymbol{u}'})$$

Mass transfer equation for sodium vapor

$$\frac{\partial}{\partial t}(\rho Y_{\mathrm{Na}}) + \nabla \cdot (\rho Y_{\mathrm{Na}} \mathbf{U}_g) = -\nabla \cdot (\rho D_{\mathrm{Na}} \boldsymbol{\nabla} Y_{\mathrm{Na}}) - \mathit{\Gamma}$$

The equation of state

$$P = \rho R T \left(\frac{Y_{\mathrm{Na}}}{W_{\mathrm{Na}}} + \frac{Y_{Ar}}{W_{Ar}} \right)$$

temperature difference between roof surface and pool: 300~400 ℃

Rayleigh number: 1.6~2.1 $\times 10^7$

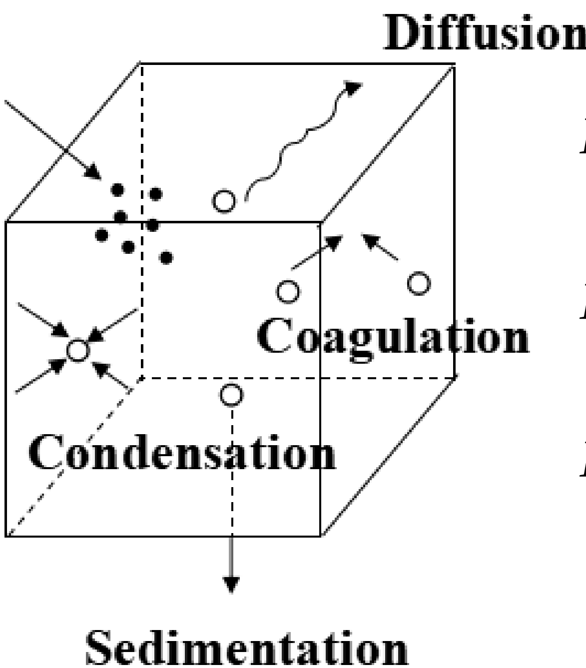
k–ω SST turbulence model with 2 scales wall function as a closure

Methodology of modelling

The general dynamic equation for aerosol populations

$$\frac{\partial n_j}{\partial t} + \nabla \cdot (n_j \mathbf{U}_{p,j}) + \frac{\partial}{\partial r_{p,j}}(n_j \dot{R}_{p,j}) = \nabla \cdot (D_{p,j} \nabla n_j)$$

convective t | growth by con | Brownian diffusion



Physics of the aerosol droplets

$$\dot{R}_{p,j} = \frac{D_{Na} M_{Na}}{\rho_p R T r_{p,j}}(P_{Na} - P_{sat}), \quad \dot{R}_{p,j} = \sqrt{\frac{M_{Na}}{2\pi R T}}\frac{C}{\rho_p}(P_{Na} - P_D),$$

$$\mathbf{U}_{p,j} = \mathbf{U}_g + \mathbf{U}_{G,j}, \quad D_{p,j} = \frac{RT}{N_A}\frac{1}{6\pi\mu r_{p,j}} C$$

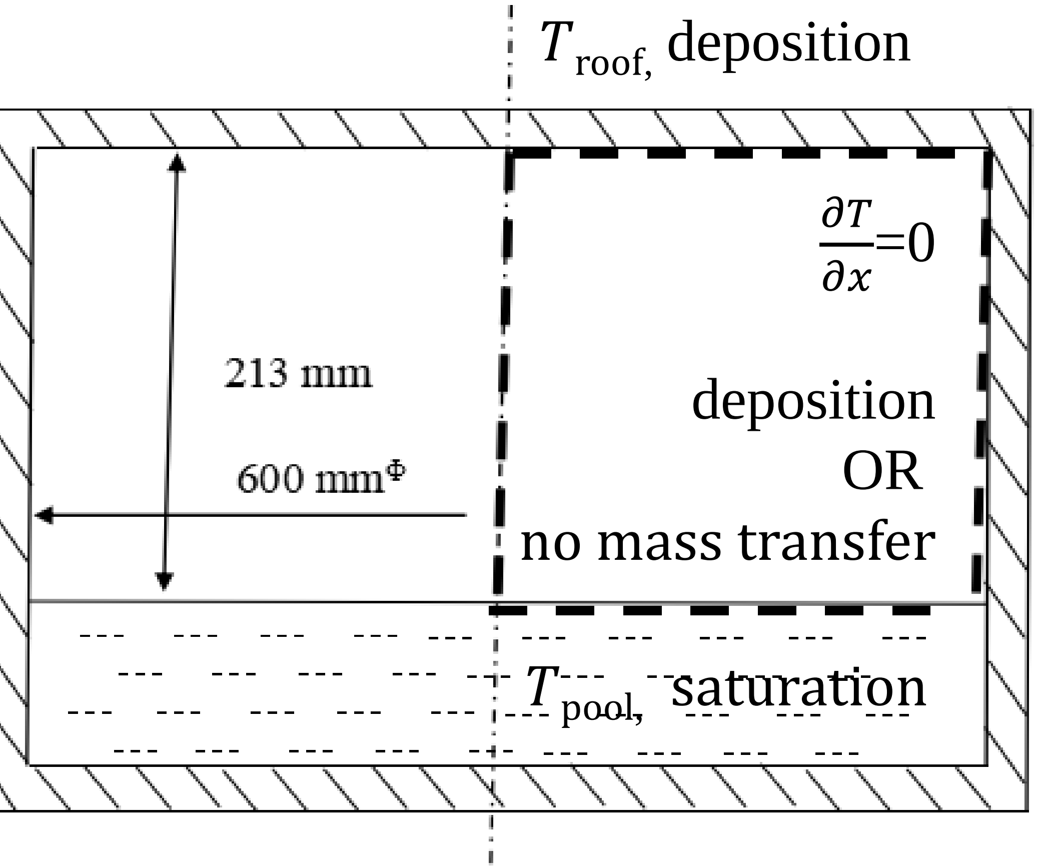
$$\mathbf{U}_{G,j} = \mathbf{U}_{TS,j}[1 - \exp(-\frac{t}{\tau})], \quad \mathbf{U}_{TS,j} = -\frac{2\rho_p r_{p,j}^2 \mathbf{g}}{9\mu} C$$

$$P_{Na} = P_{total}\frac{Y_{Na}}{W_{Na}} / (\frac{Y_{Na}}{W_{Na}} + \frac{Y_{Ar}}{W_{Ar}}), \quad P_D = P_{sat}\exp(\frac{2\sigma M}{R T \rho_p r_p})$$

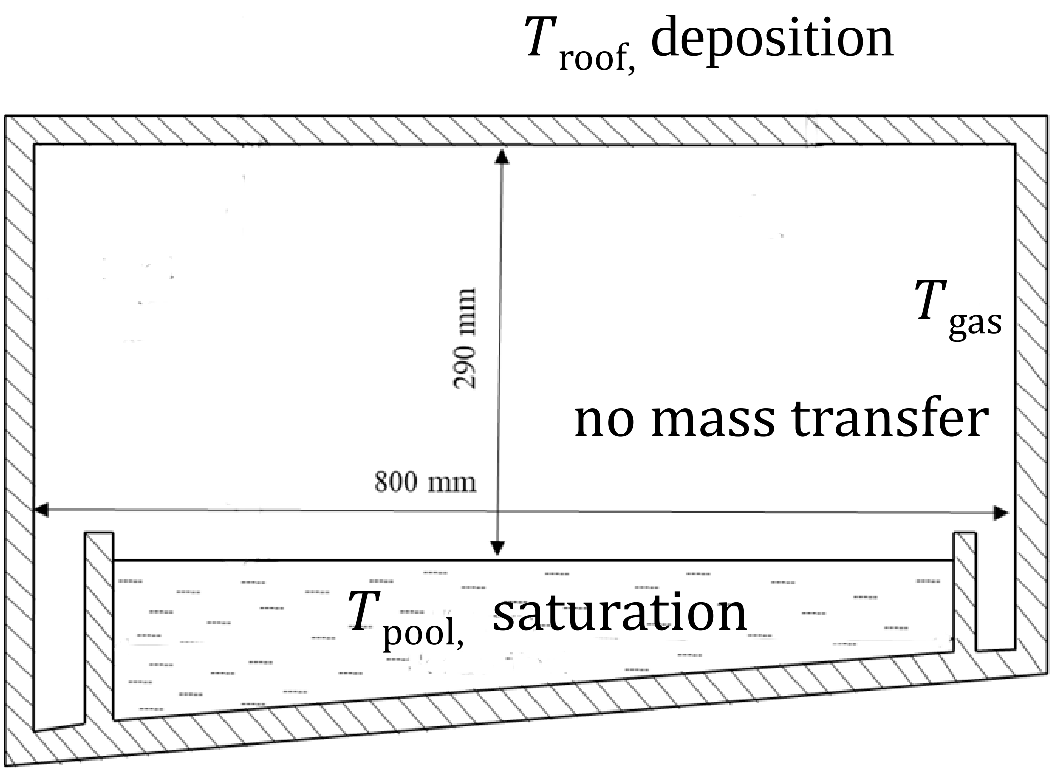
$$P_{sat} = \exp(18.832 - \frac{13113}{T} - 1.0948\ln(T) + 1.9777 \times 10^{-4} T)$$

size range : 10^{-9}~5×10^{-5} m.
The mathematical model is implemented in Code-Saturne.

Model setup



test apparatus in Ohira experiments



test apparatus in Manchester experiments

- development of numerical model
- evaluation of uncertainties of the model

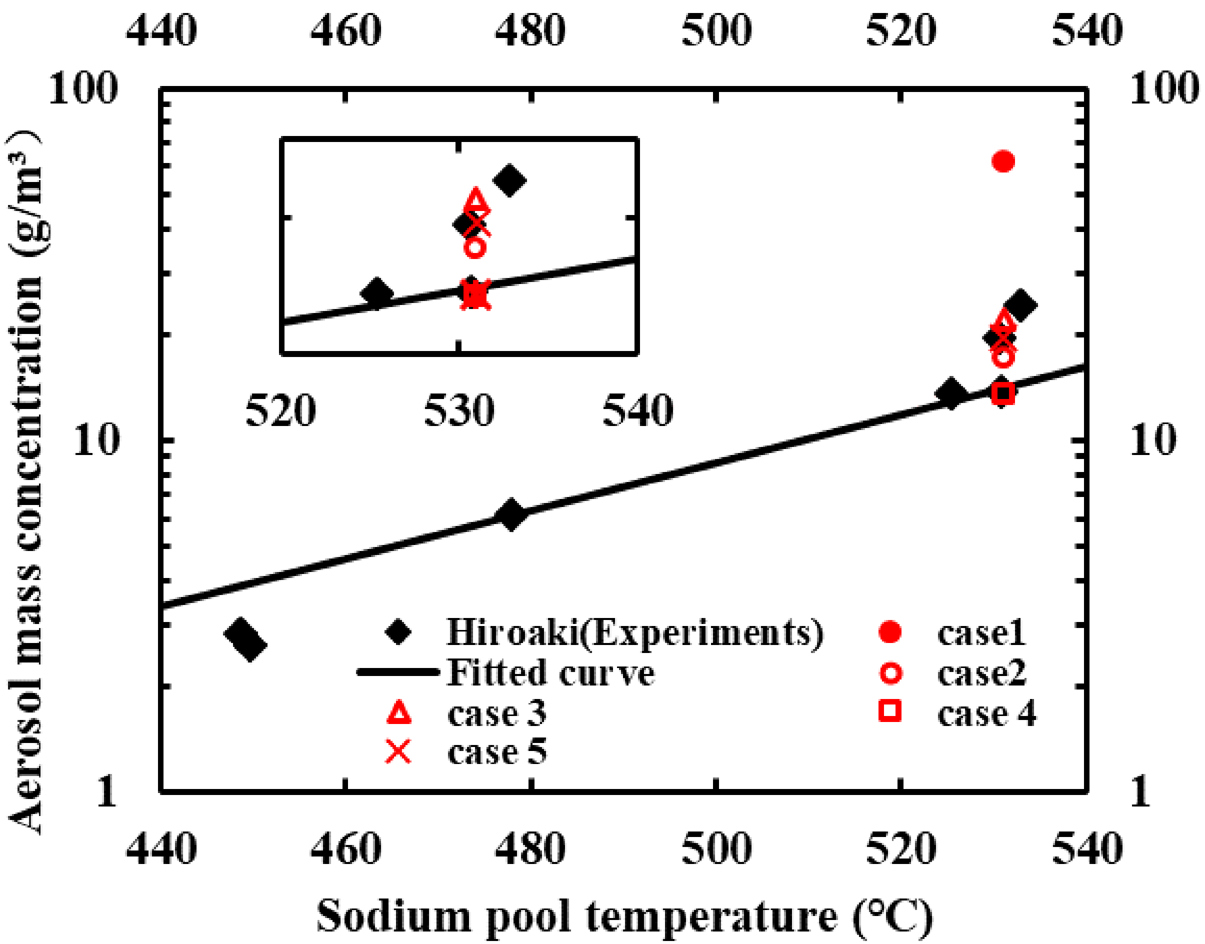
- validation of the model
- understanding of physics

Results and discussion- Simulation for the Ohira rig

Case No.	T_{pool} (℃)	T_{roof} (℃)	Nucleation rate (×10^8)	Deposition on side wall	Absorption coefficient(m^{-1})
1	531	205	2	N	N/A
2	531	205	0.35	N	N/A
3	531	205	0.35	N	0
4	531	205	0.35	N	0.3
5	531	205	0.35	Y	N/A

❖ Influences of nucleation rate (case 1 and 2), aerosol feedback, deposition on the side wall (case 5), heat radiation (case 3 and 4) are tested

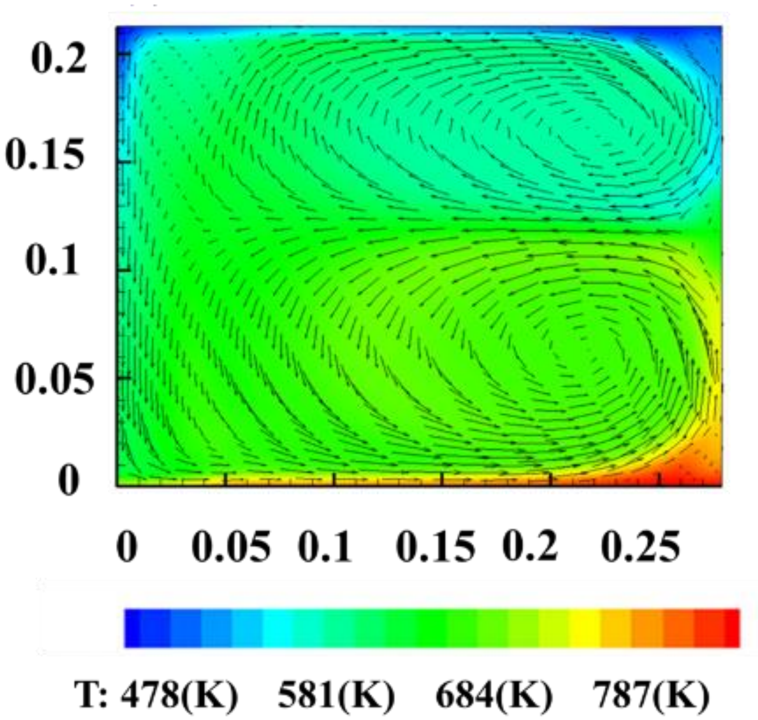
Results and discussion- Simulation for the Ohira rig

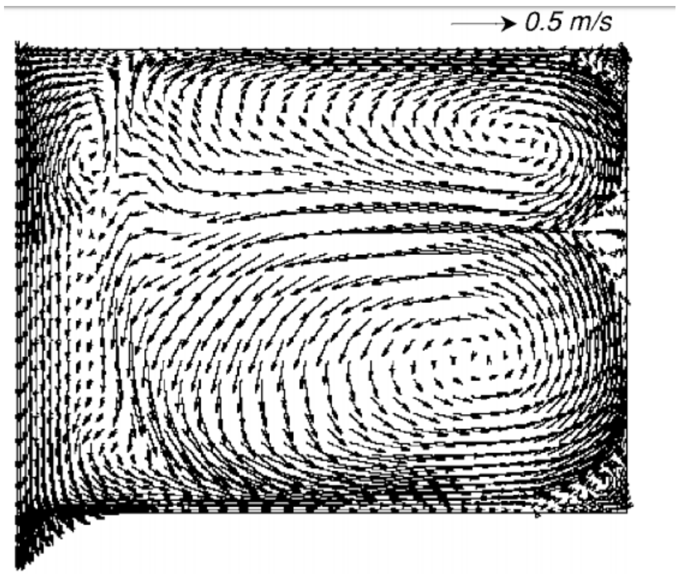


❖ Aerosol mass concentration is sensitive to the nucleation rate but not sensitive to the other model settings tested.

Results and discussion- Simulation for the Ohira rig

Without aerosol





Temperature and velocity distribution in this study

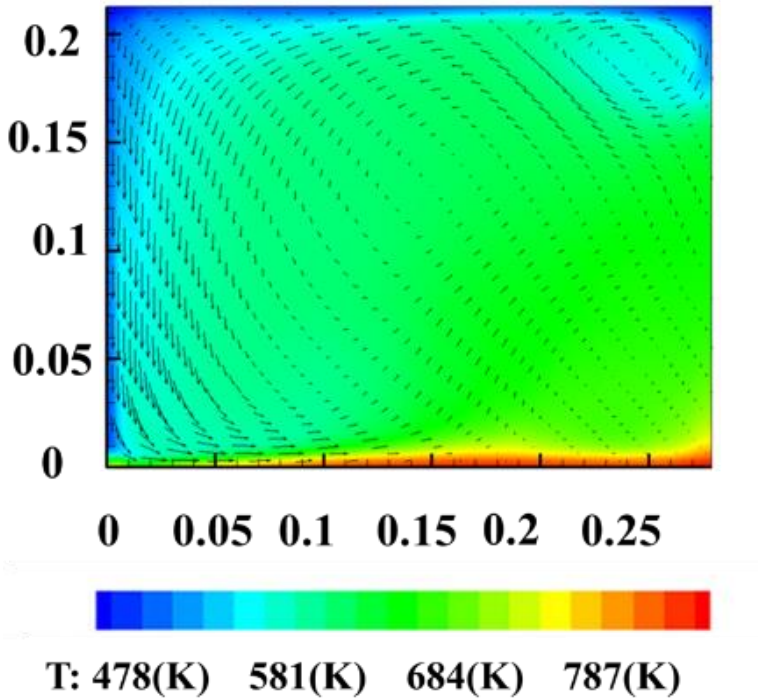
Velocity distribution in Ref [1]

❖ A pair of large vortices occupy a large part of the domain

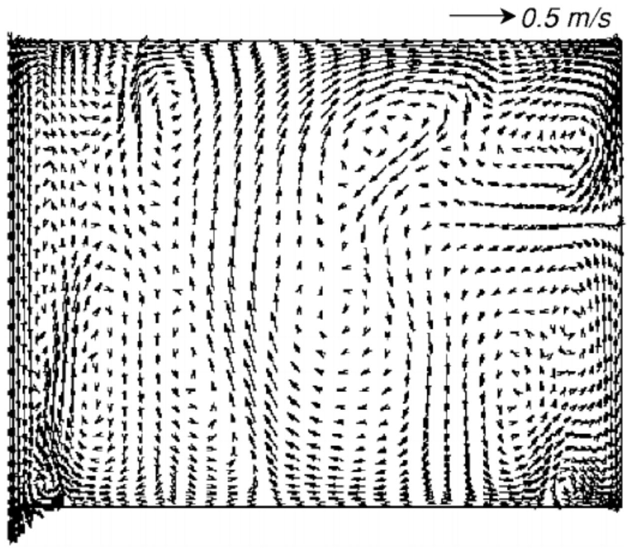
Ref [1]: Ohira H., 2002. Numerical simulation of aerosol behavior in turbulent natural convection. Journal of Nuclear Science and Technology, 39(7): 743-751.

Results and discussion- Simulation for the Ohira rig

With aerosol



Temperature and velocity distribution in this study



Velocity distribution in Ref [1]

- ❖ The vortices are split into small eddies
- ❖ The maximum velocity decreases from 0.436m/s in the previous slide to approximately 0.37m/s

Ref [1]: Ohira H., 2002. Numerical simulation of aerosol behavior in turbulent natural convection. Journal of Nuclear Science and Technology, 39(7): 743-751.

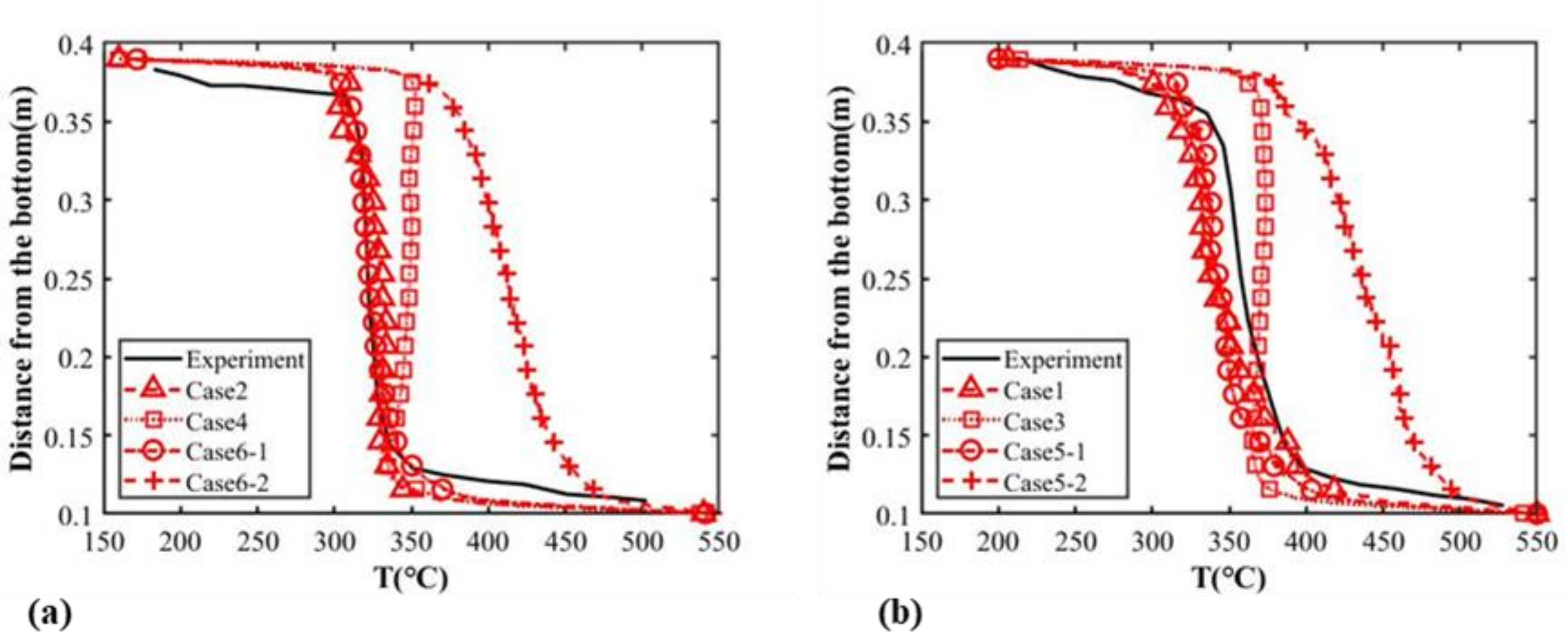
Results and discussion- Simulation for the Manchester rig

Case No.	T_{pool}(℃)	T_{roof}(℃)	Aerosol Feedback	Absorption Coefficient
1	550	200	Y	N/A
3	550	200	N	N/A
5-1	550	200	Y	0
5-2	550	200	Y	0.3

Case No.	T_{pool}(℃)	T_{roof}(℃)	Aerosol Feedback	Absorption Coefficient
2	550	160	Y	N/A
4	550	160	N	N/A
6-1	550	160	Y	0
6-2	550	160	Y	0.3

- Two series of boundary conditions: roof temperature of 160 ℃ or 200 ℃.
- Cases with (1 and 2) and without (3 and 4)aerosol, cases with radiation (5-1, 5-2, 6-1 and 6-2) are compared.

Results and discussion- Simulation for the Manchester rig

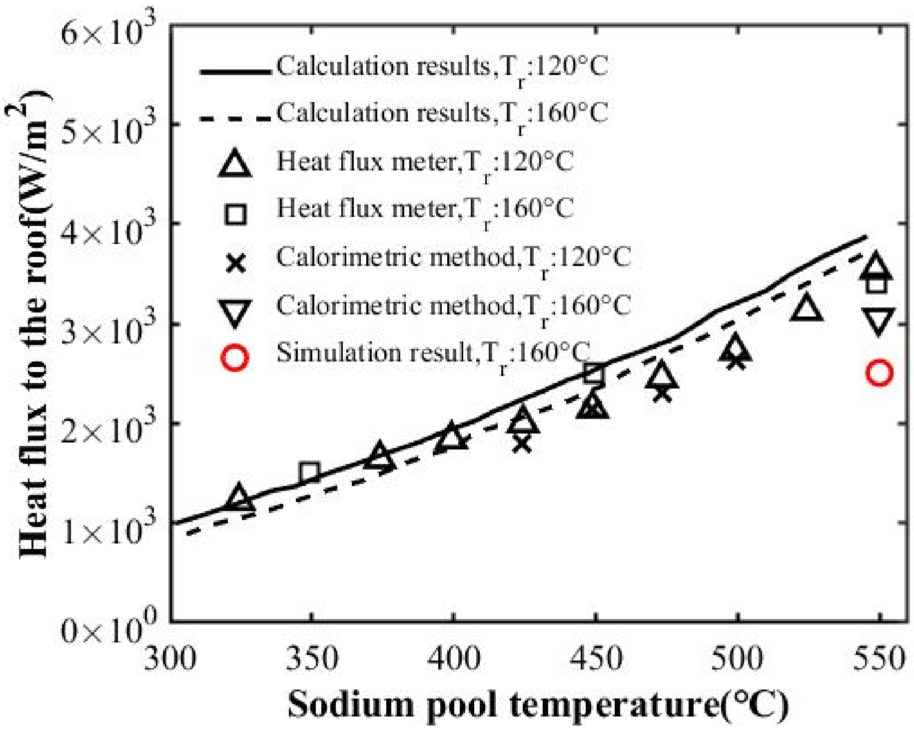


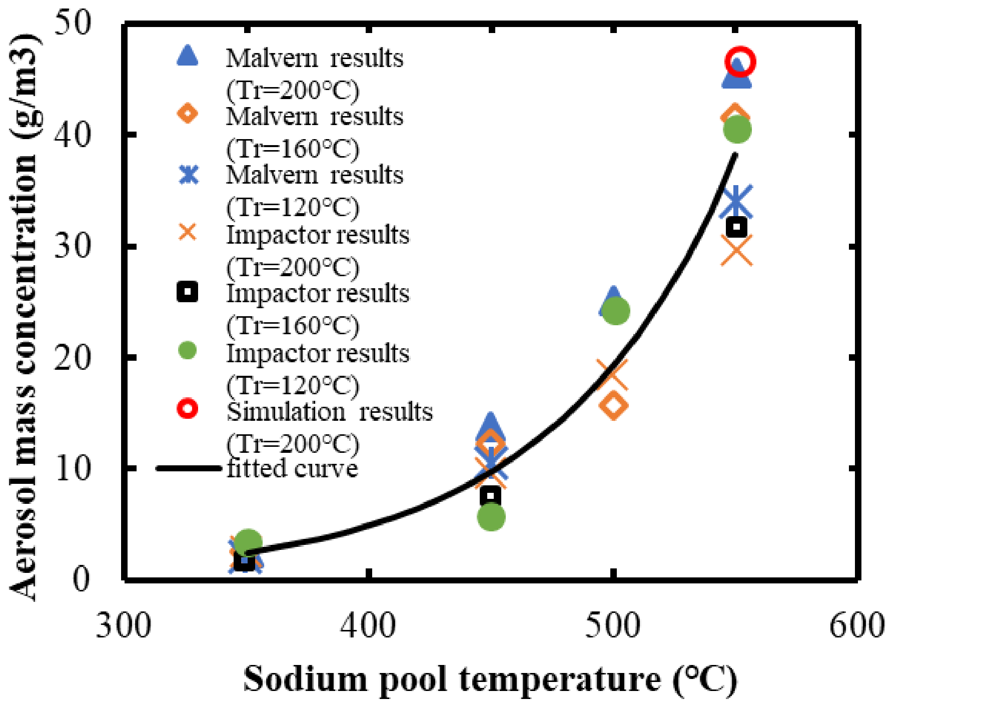
Vertical temperature distributions from simulations and from experiments

❖ Cases with aerosol and with heat radiation between surfaces agree well with the experimental observations

❖ The uniform absorption coefficient of 0.3 is not suitable

Results and discussion- Simulation for the Manchester rig



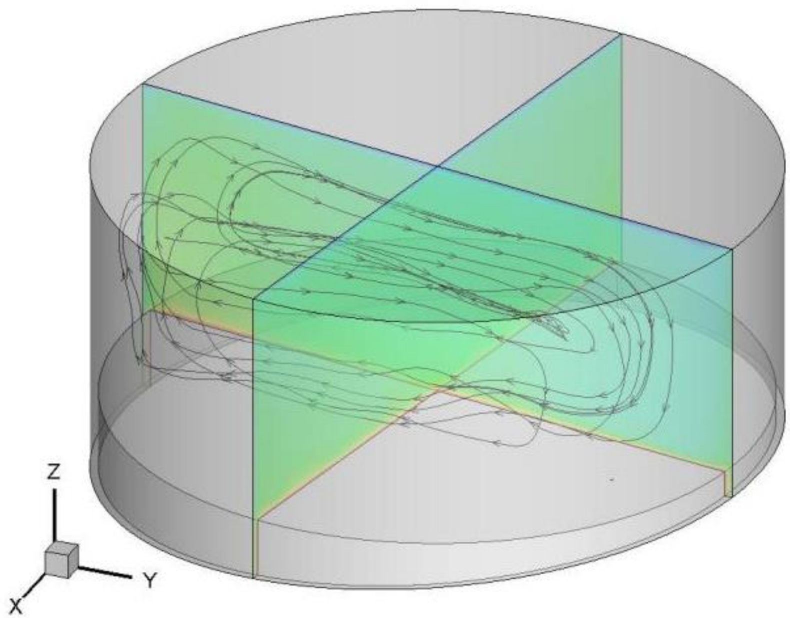


Heat flux and aerosol mass concentration variation with pool temperature and roof temperatures

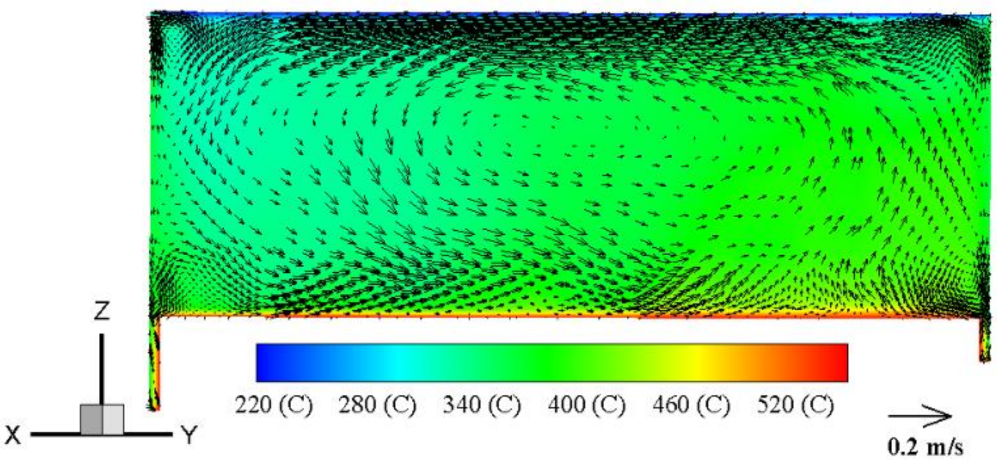
- Heat flux and mass concentration are mainly influenced by sodium pool temperature

- Fitted curve of aerosol mass concentration $m = 0.0204\exp(0.0137T_{Na})$

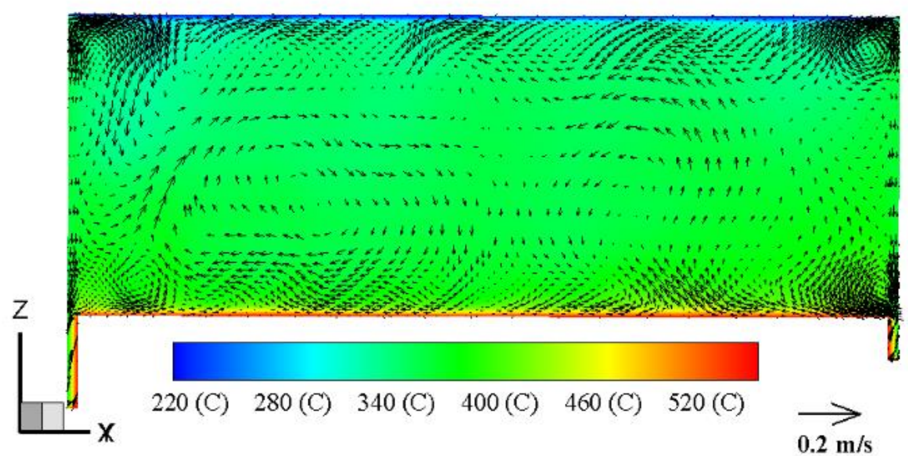
Results and discussion- Simulation for the Manchester rig



- A quasi-two-dimensional roll-like structure is observed, with one large circulation in one direction and several smaller vortices normal to that.
- A large structure is developed on the plane with main flow, whereas a few vortices with much smaller velocities are formed over the plane normal to it.

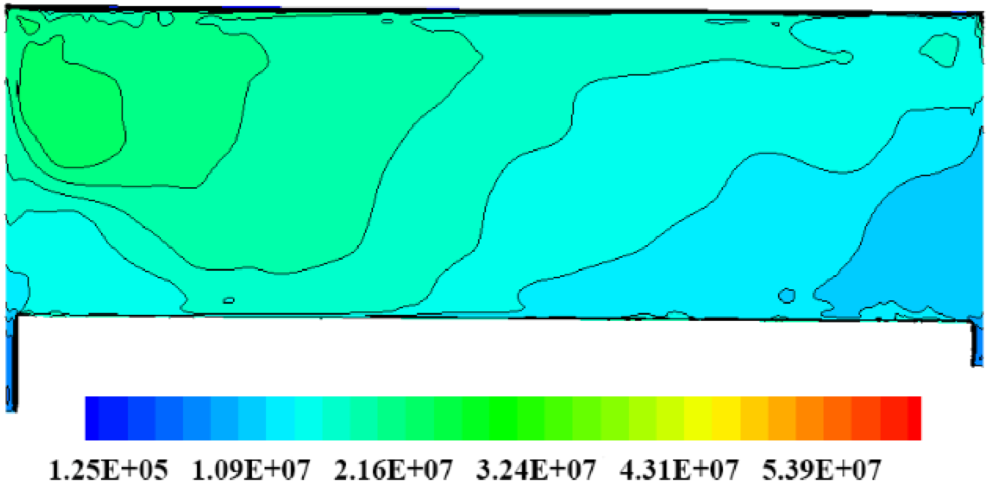


plane at (-π/18) from *yz*-plane in case 6-1

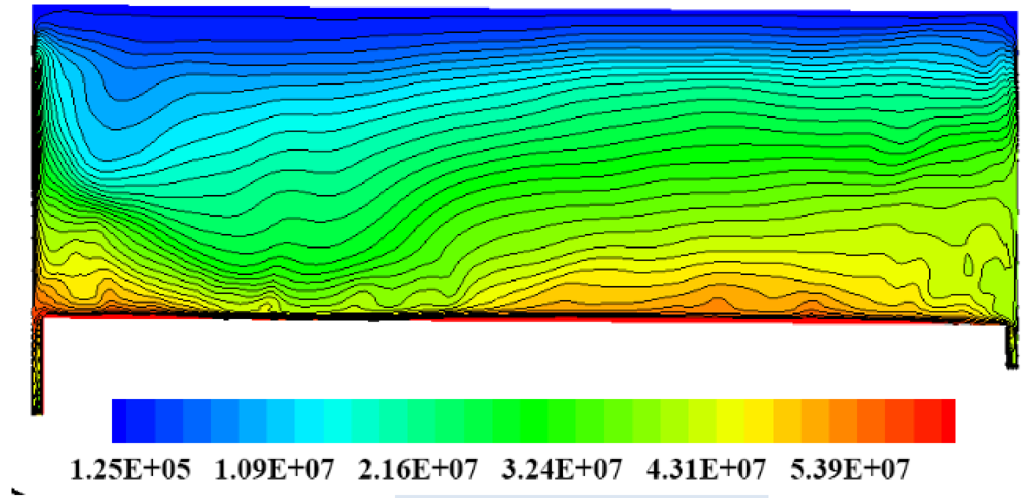


plane at (-π/18) from *xz*-plane in case 6-1

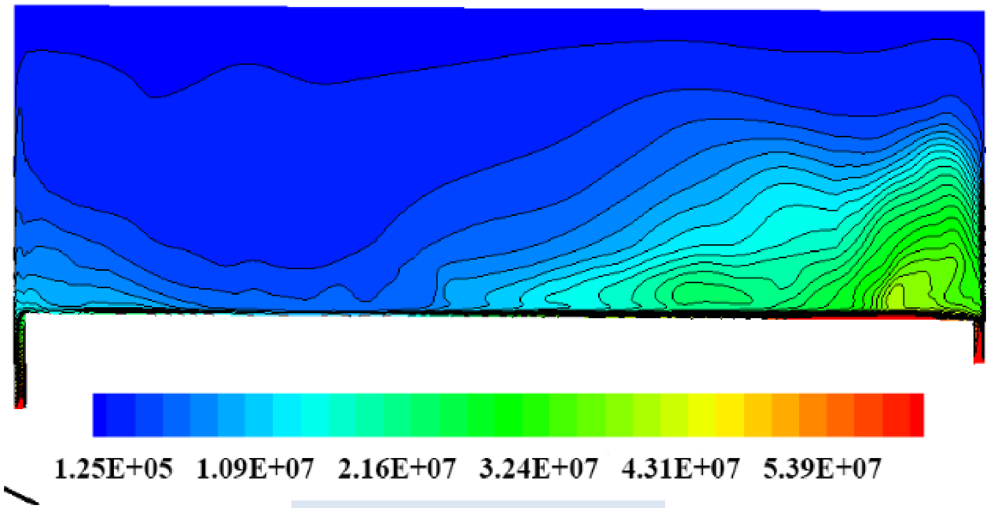
Results and discussion- Simulation for the Manchester rig



radius of 0.6 µm



radius of 24 µm

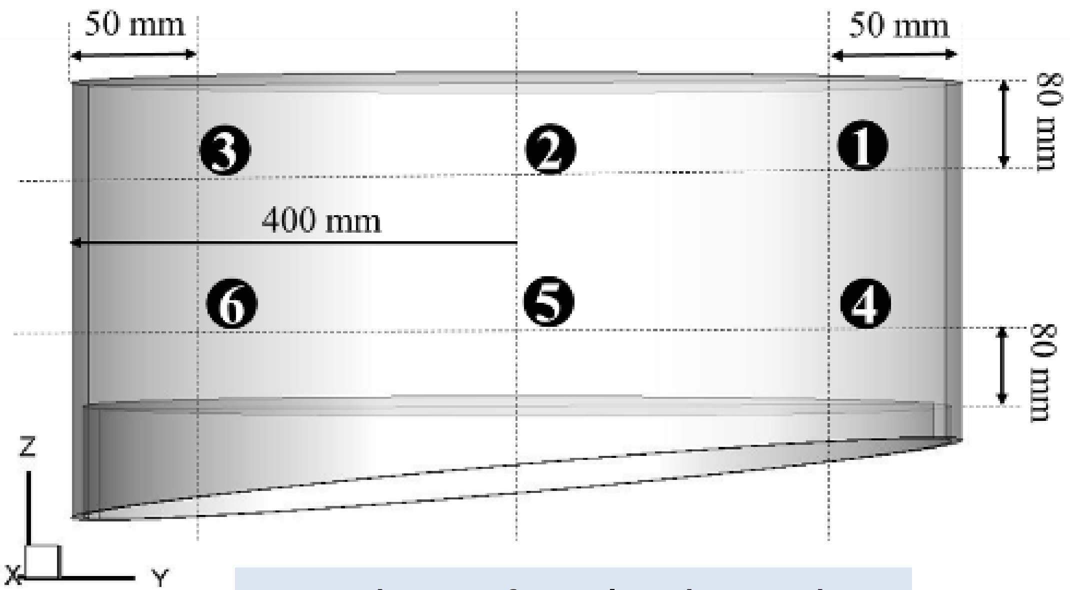


radius of 37 µm

- the aerosol volumetric concentration of the smallest droplet is lower on the side with higher temperature and higher on the other side.
- the smallest droplets exist in the whole cover gas region, while the larger ones do not exist both near the top surface and in the down flow region by the convection.

Aerosol volumetric concentration plane at (-π/18) from yz-plane

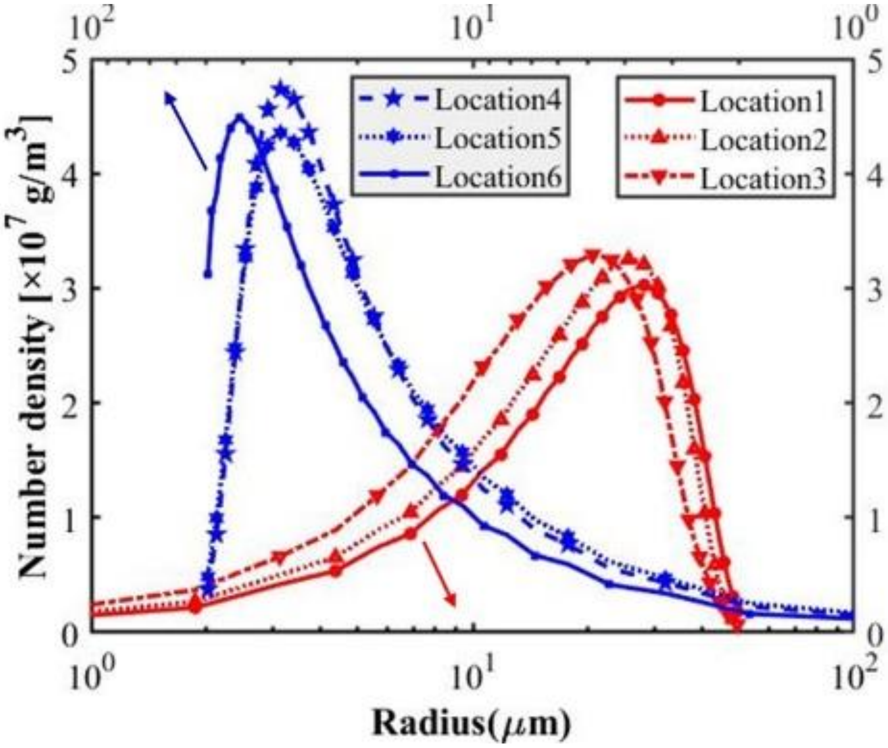
Results and discussion- Simulation for the Manchester rig



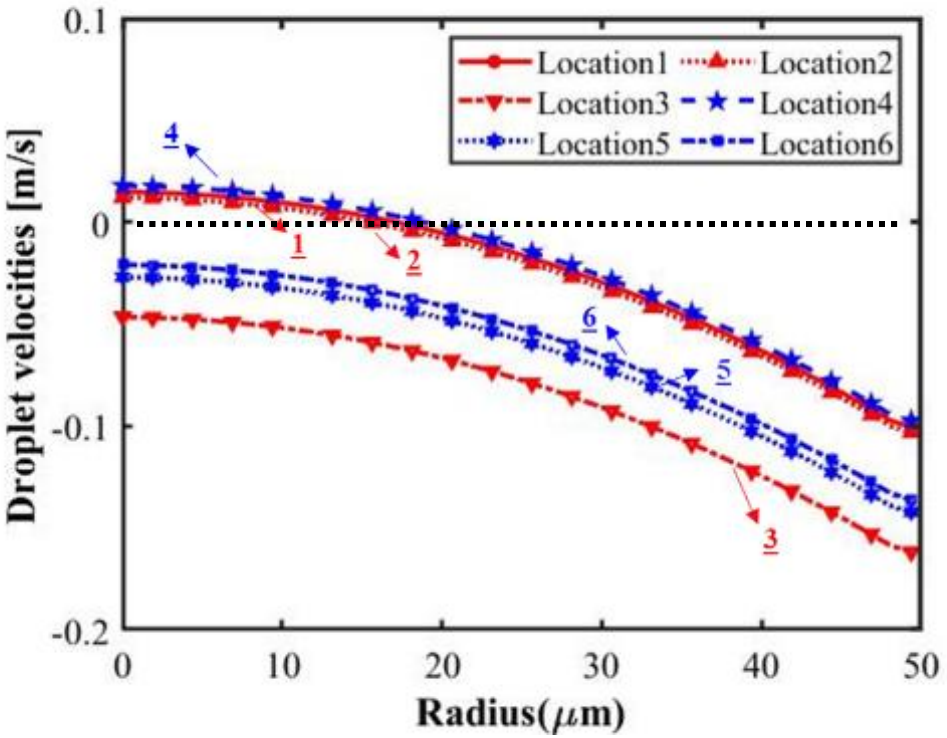
Locations of evaluation points

❖ The height of locations 1~3 is 80 mm below the top surface, while that of locations 4~6 is 80 mm above the pool surface.

Results and discussion- Simulation for the Manchester rig



Aerosol volumetric concentration



Droplet velocities

- ❖ At locations 1 and 2, the gas flows upward, but droplets larger than 18.0 μm flow downwards. Hence the droplet volumetric concentration reduce drastically when radius is above 18.0 μm.
- ❖ Among locations of 4, 5 and 6, only the droplets whose radius is smaller than 18.0 μm at 4 flow upwards. The number density distribution at location 4 peaks at 4.73×10^7 g/m^3.

Conclusions

- a model for the natural convection of a mixture of argon and sodium vapor and the aerosol dynamics in a cylindrical enclosure above a hot sodium pool is developed.
- A discrete-sectional model assuming homogeneous nucleation and isothermal droplet growth by condensation has been employed for the dispersed phase. This is coupled with the solution of the governing equations for the momentum, heat and mass transport.
- Simulations have been compared with experimental data in literature and in unpublished technical reports.
- A physical understanding of the natural convection of a droplet-laden flow is obtained.
- Stage II development: calibration of nucleation rate, improvement in radiation model, implementation of a high-fidelity simulation using LES

Task 3
Steady-state modelling of the upper plenum of the E-SCAPE test facility under normal operating conditions

Model development

Stage I

Development of the model using RANS simulation

→

Stage II

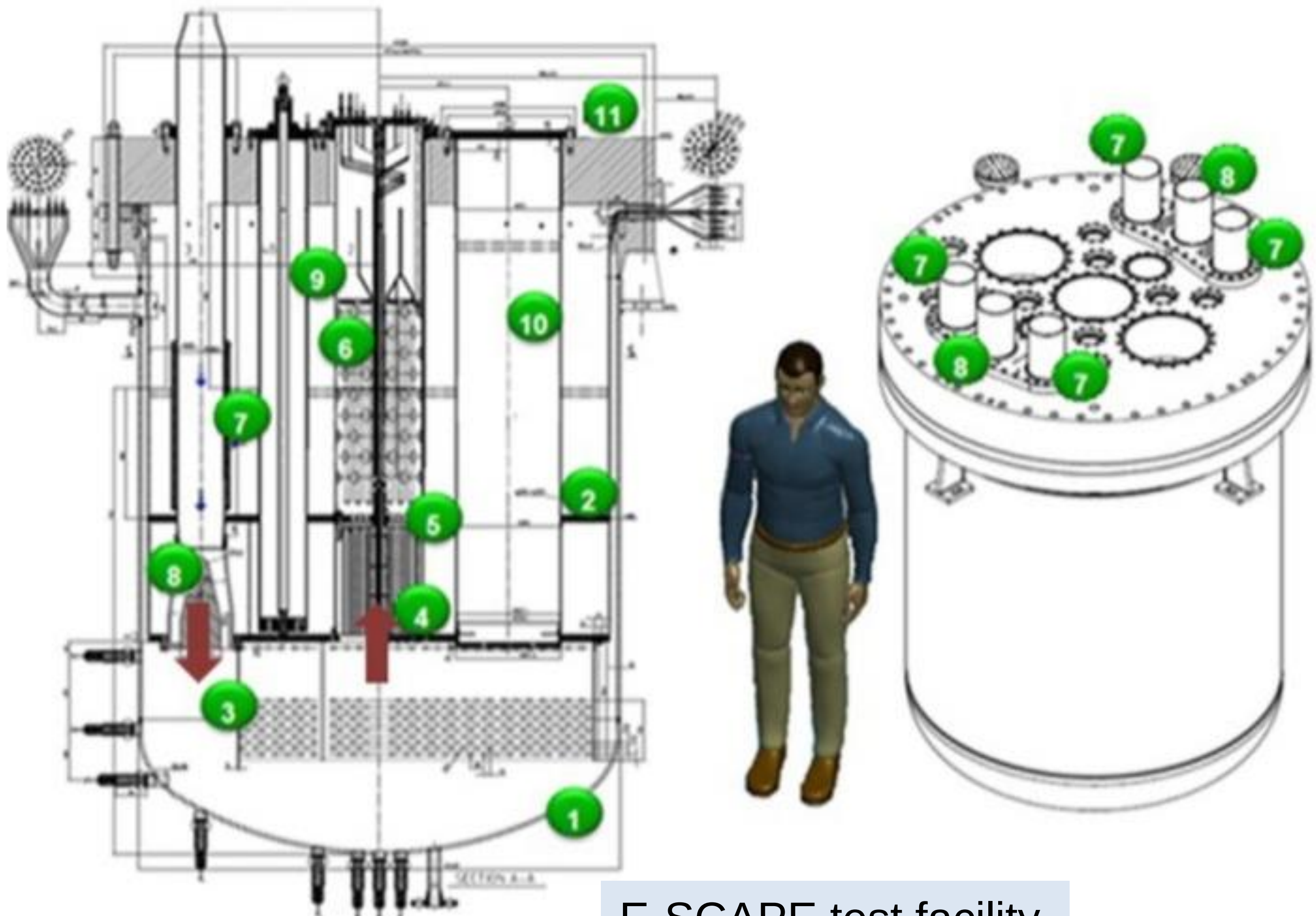
LES simulation

→

Numerical ‘experimental’ data for liquid metal test cases and to complement physical experiments

Model development

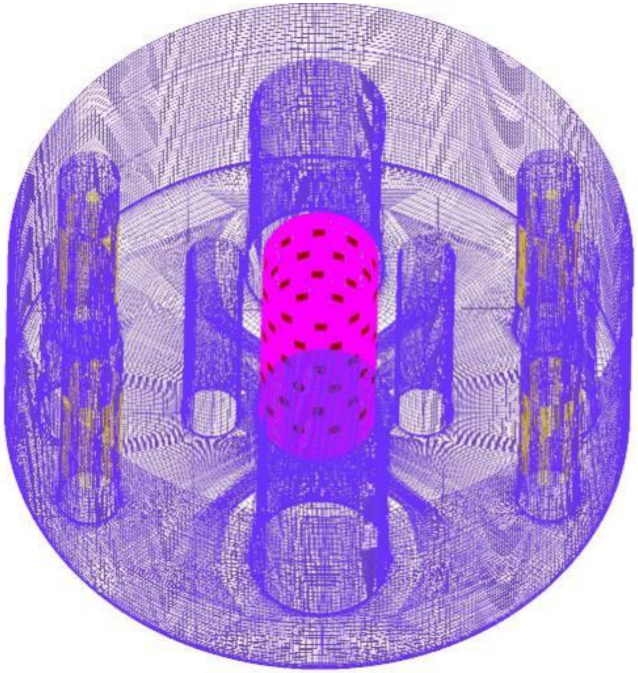
1 - main vessel
2 - diaphragm
3 - baffle
4 - core
5 - barrel
6 - control and safety rods handle
7 - heat exchangers
8 - pumps
9 - silicon doping devices.
10 - in-vessel fuel handling machines

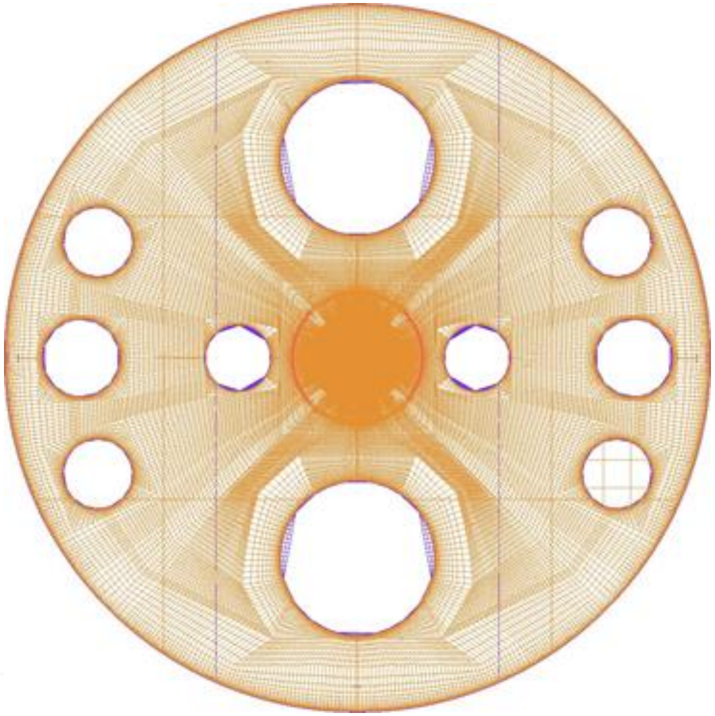


E-SCAPE test facility

- E-SCAPE (European SCAled Pool Experiment) test facility， a 1:6 scaled model of the research reactor MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) under design at SCK·CEN in Belgian

Model setup





Geometry

❖ small parts of instrument rigs and cover gas region are neglected

Mesh

❖ Block-structured hexahedral mesh is generated

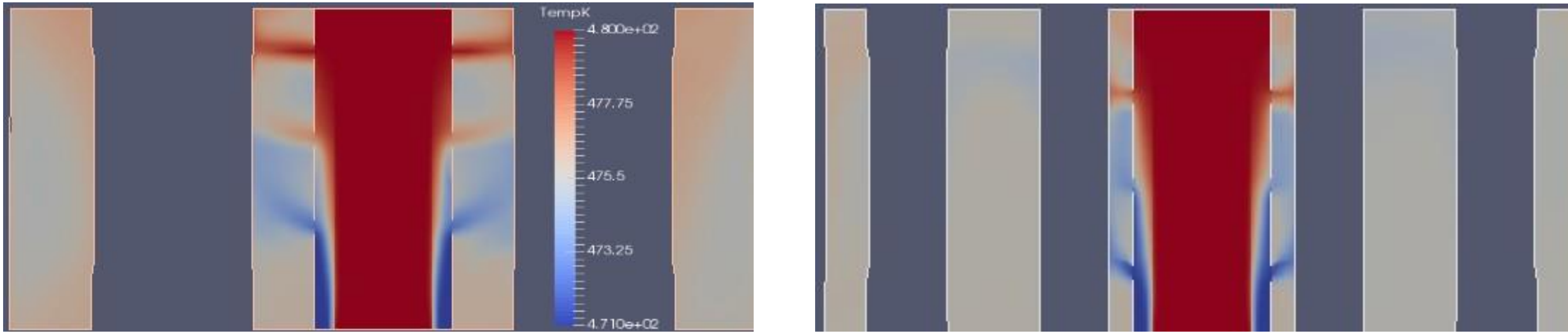
❖ a total number of elements of 4.4 million in the domain

Numerical method

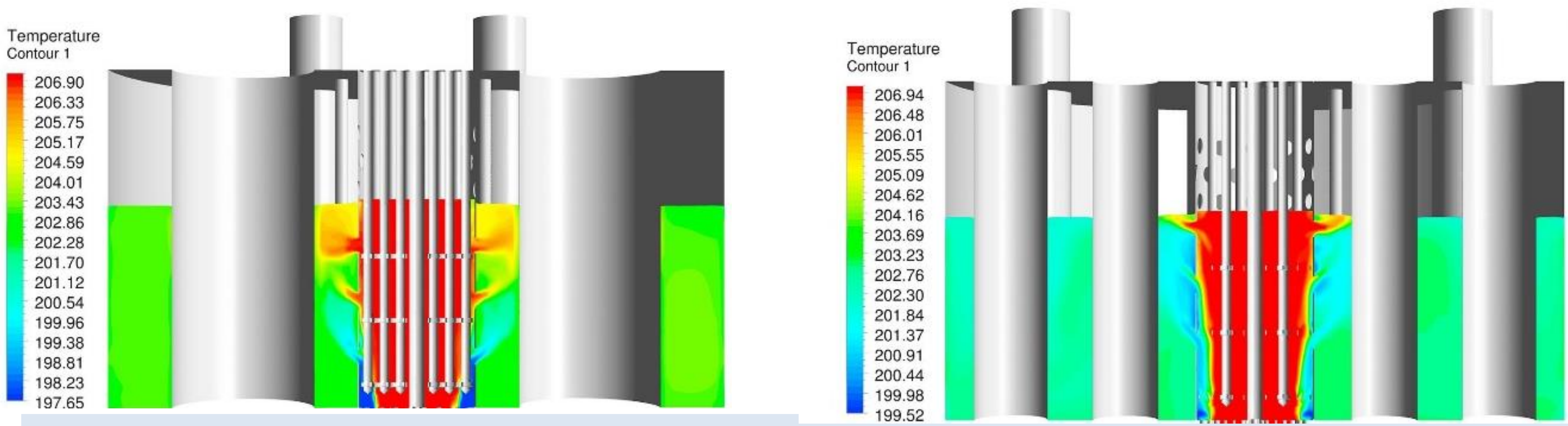
❖ low-Reynolds turbulence model k–ω SST

❖ pressure-velocity algorithm of SIMPLEC is selected

Results and discussion



Temperature profiles of sections through the (left) IVFHM and the (right) pumps in this study

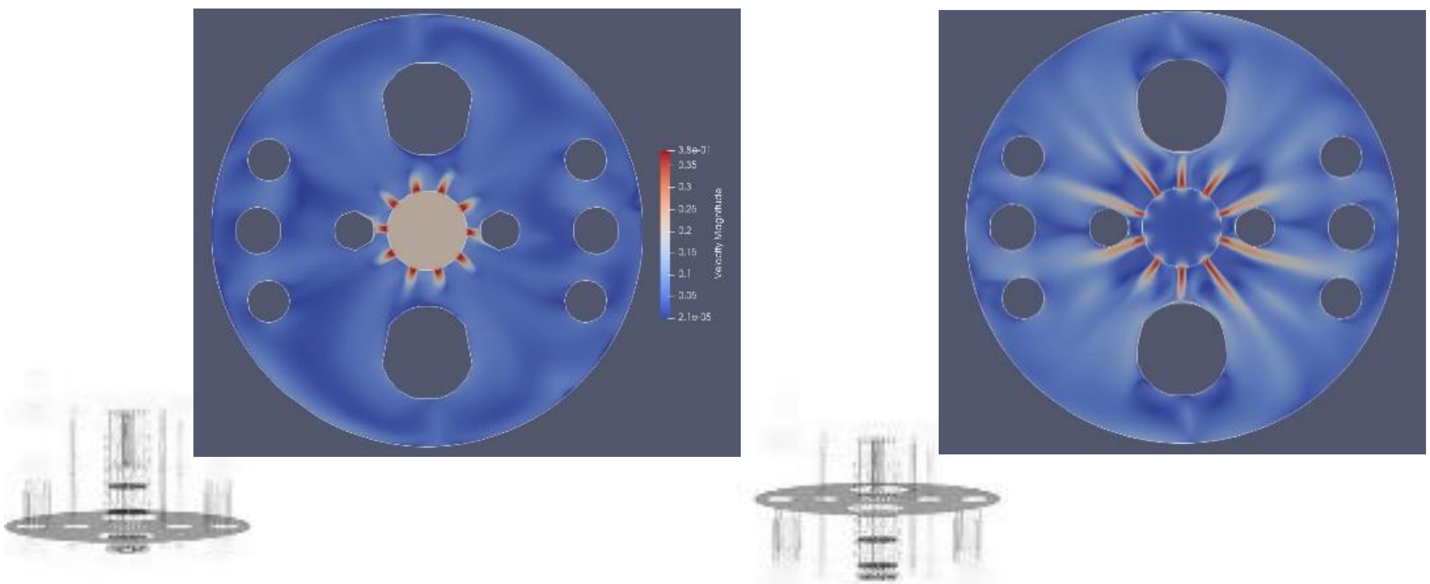


Temperature profiles of sections through the (left) IVFHM and the (right) pumps in Ref.[2]

Ref [2]: Toti A., Vierendeels J., Belloni F., Extension and application on a pool-type test facility of a system thermal- hydraulic/cfd coupling method for transient flow analyses. Nuclear Engineering and Design, 331:83 – 96, 2018.

Results and discussion

Velocity profiles of sections through the (left) IVFHM and the (right) pumps



Velocity profiles of sections at various height

- ❖ Low velocity in the plenum and velocity of 0.4 m/s in the barrel perforations
- ❖ The “jet” through the barrel perorations becomes stronger with height

Results and discussion

- a holistic model using a porous medium representation for the above core region and an explicit representation of the other components is developed.

- Simulation results are generally concordant with those in literature.

- Stage II improvements include:

(1) Adopting variable physical properties.
(2) Improving the mesh resolution in certain areas.
(3) Geometry of the model. i.e. the core bypass outlets
(4) High-fidelity turbulence modelling.
(5) Modification of boundary conditions for cover gas heat transfer.

This study will serve as the groundwork for more extensive investigation into the modelling of the upper plenum of a LMFR in the next phase of research.

Questions?