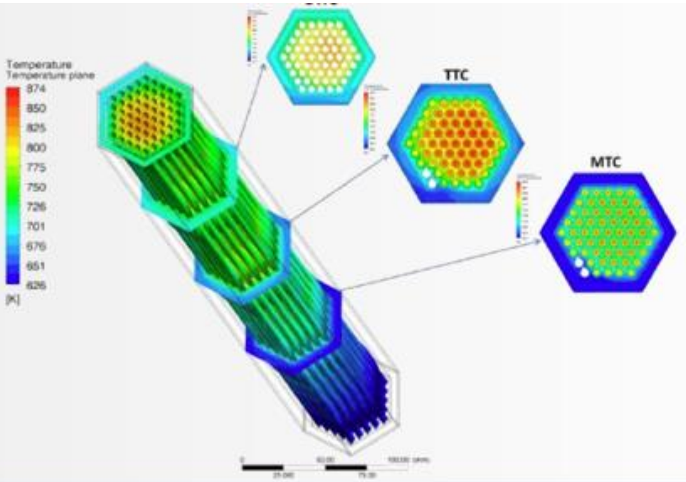
Technical Meeting on State-of-the-art Thermal Hydraulics of Fast Reactors



Paper Code: #101

Paper title: Spatio-temporal evolution of sodium combustion aerosol and temperature distribution during sodium pool fire in a confined environment

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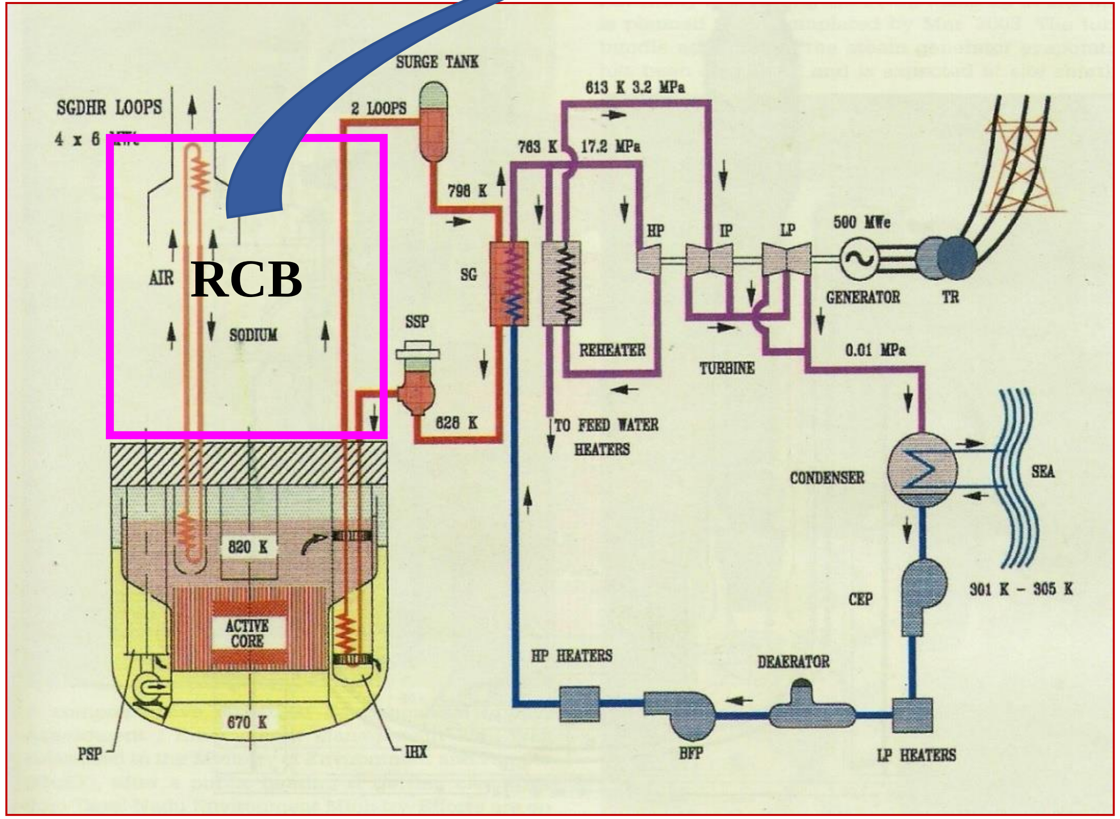
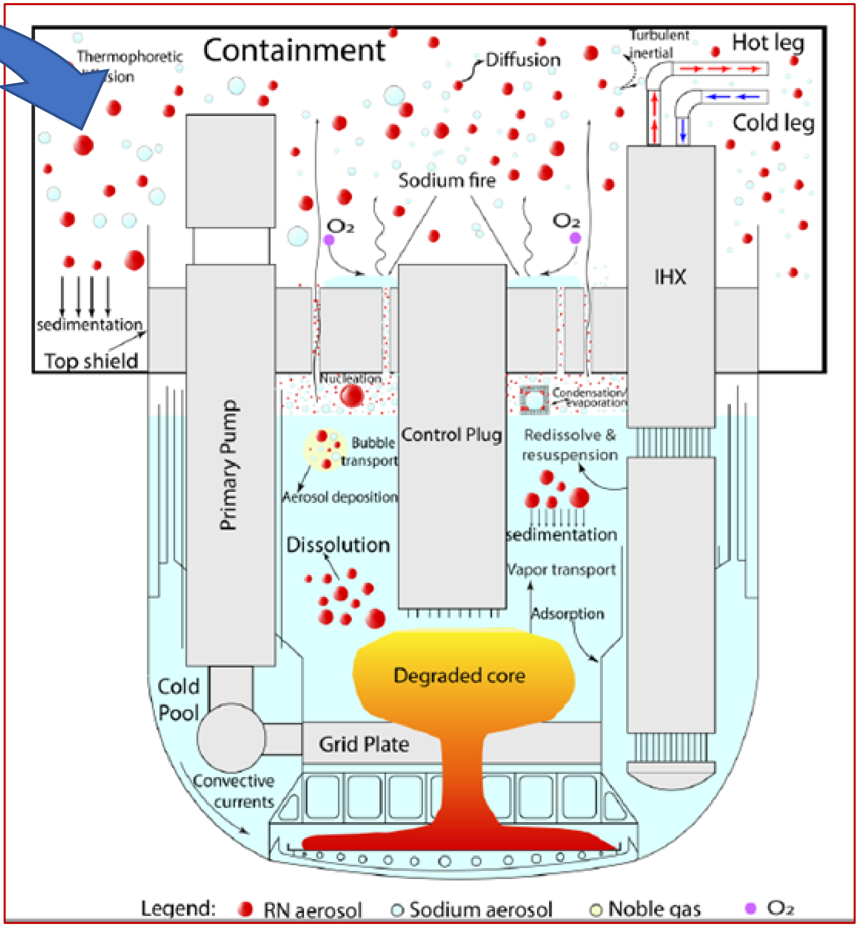
Content of the presentation

- Aerosol sources, nature, and consequences
- Background or Introduction
- Scope and Objective of the study
- Experimental facility and Aerosol metrological devices
- Results and discussion
- Summary and conclusion
- Future Work

Aerosol sources, nature, and consequences





Source	Nature	Consequences
Under Severe Accident (CDA) condition of SFRs	Coolant, fuel and FP aerosols generated inside RCB, transport through leak paths	In-containment and Environment source estimation, Radiation and chemical hazard to the public & occupational workers,

Introduction

In case of CDA in SFRs, sodium will be ejected from the reactor vessel into the RCB and resulted in sodium fire.

Released sodium in RCB vigorously reacts with the containment atmosphere leading to temperature and pressure rise.

Reaction products (Na2O and Na2O2), starts to nucleate, condensate and coagulate, leading to the formation of sodium aerosol.

The oxides aerosol reacts with moisture and converted to the hydroxide instantaneously. The hydroxide aerosol gets converted to sodium carbonate upon reaction with CO_2 then it further converts to bicarbonate.

The generated aerosol gets dispersed and suspended in RCB based on geometry of the building and degree of turbulence.

These sodium aerosols along released RN (fuel & FP) remains suspended in containment till they settle down or leak to the environment.

EST primarily depends on the dynamics of sodium aerosols inside the containment and leak rate of the containment.

Introduction

It is essential to carry out a safety analysis of SFRs using computational tools and models shall be validated with experimental data, particularly aerosol dynamics inside the containment along with thermal hydraulics.

Most codes assume uniform aerosol concentration in large containment buildings and the evolution of suspended aerosol characteristics was predicted.

In actual case a non-uniform concentration is expected, which leads to stratification of aerosols inside the containment.

Towards assessment of aerosol dynamics in realistic scenario, spatial-temporal characteristics of sodium aerosol and temperature distribution were studied by conducting sodium pool fire experiments in a large chamber.

Scope of the study

Knowledge of sodium and fission product aerosol dynamics along with temperature distribution in the containment would help:

- **Better analysis of thermal loadings on the containment,**
- **To evaluate the amount of aerosol suspended in the containment (available for release with time) and activity associated with it, considering sodium burning scenarios and aerosol behaviour,**
- **Behavior of mixed (Na + FP) aerosol in closed containment at higher temperature & pressure,**
- **To decide containment functional requirement in terms of allowable leak rate,**
- **Estimation of Environment Source Term.**

Objective of the present work

Study on spatio-temporal sodium aerosol characteristics and temperature distribution in the large chamber:

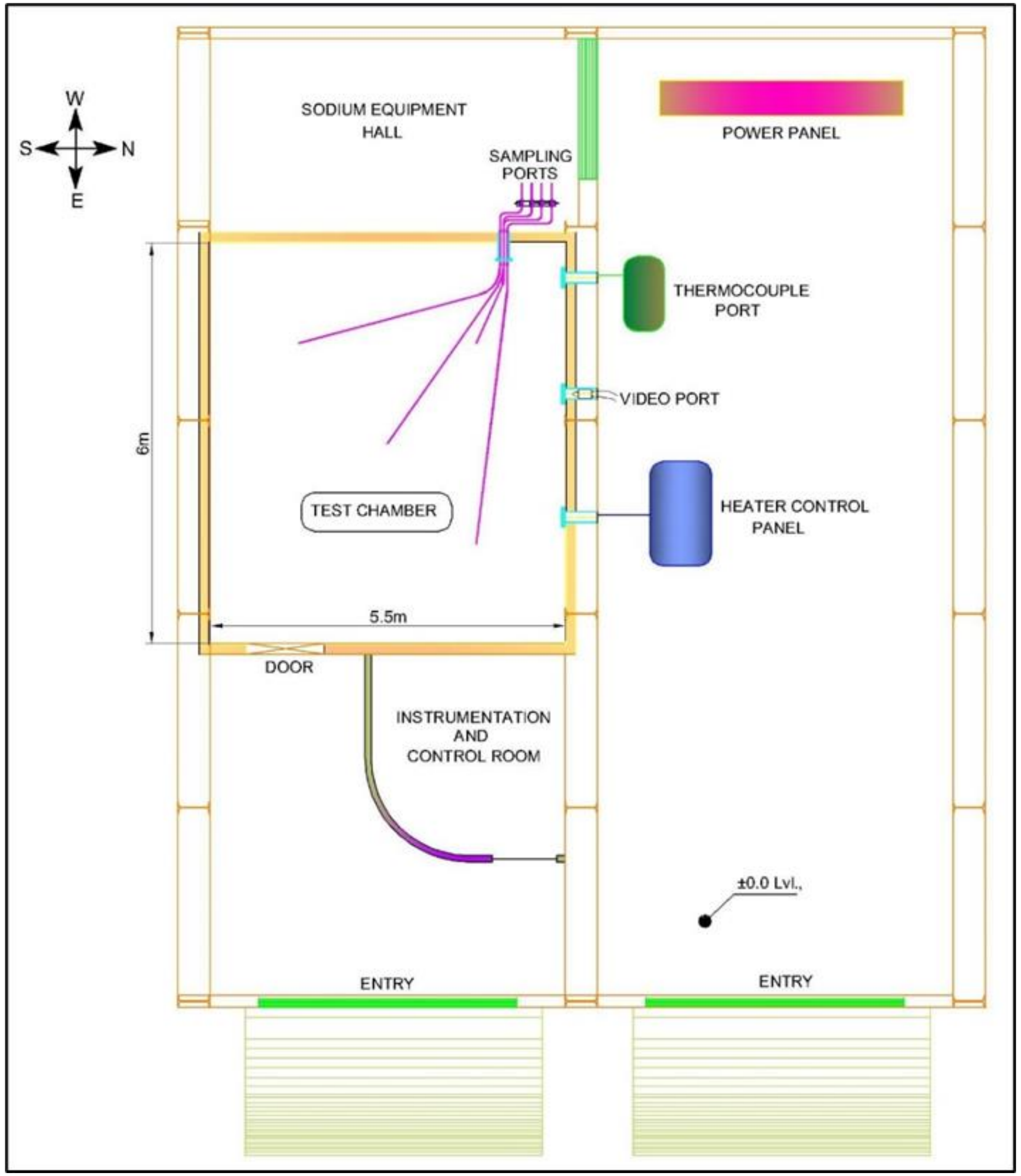
- **Burning characteristics of sodium pool fire,**
- **Temperature distribution inside the facility,**
- **Multi-elevation sampling to study stratification of aerosol,**
- **Evolution of sodium aerosol size distribution and size growth,**
- **Deposition of the aerosol on the inner surface of the chamber,**

- **To produce representative experimental data for the evolution of spatial-temporal characteristics of sodium aerosol produced inside a closed enclosure.**
- **Applicability of a zero-dimensional numerical model for evolution of aerosol characteristics & compared with the experimental observations.**

Details of the experimental facility

MINA facility consists of

- A closed rectangular steel chamber of size 6.0 m x 5.45 m x 4.6 m (~ 150 m^3),
- Designed to withstand pressure of 1 bar at 300 ºC,
- Chamber is provided a leak-tight door of 2.0 m x 1.5 m,
- Facility has a dedicated sodium supply system, instrumentation and control room,
- Facility has state-of-the-art equipment's and instruments to monitor dynamic pressure, spatial gas, and wall temperature distribution, data acquisition, and two viewing ports for the high-speed video imaging system.

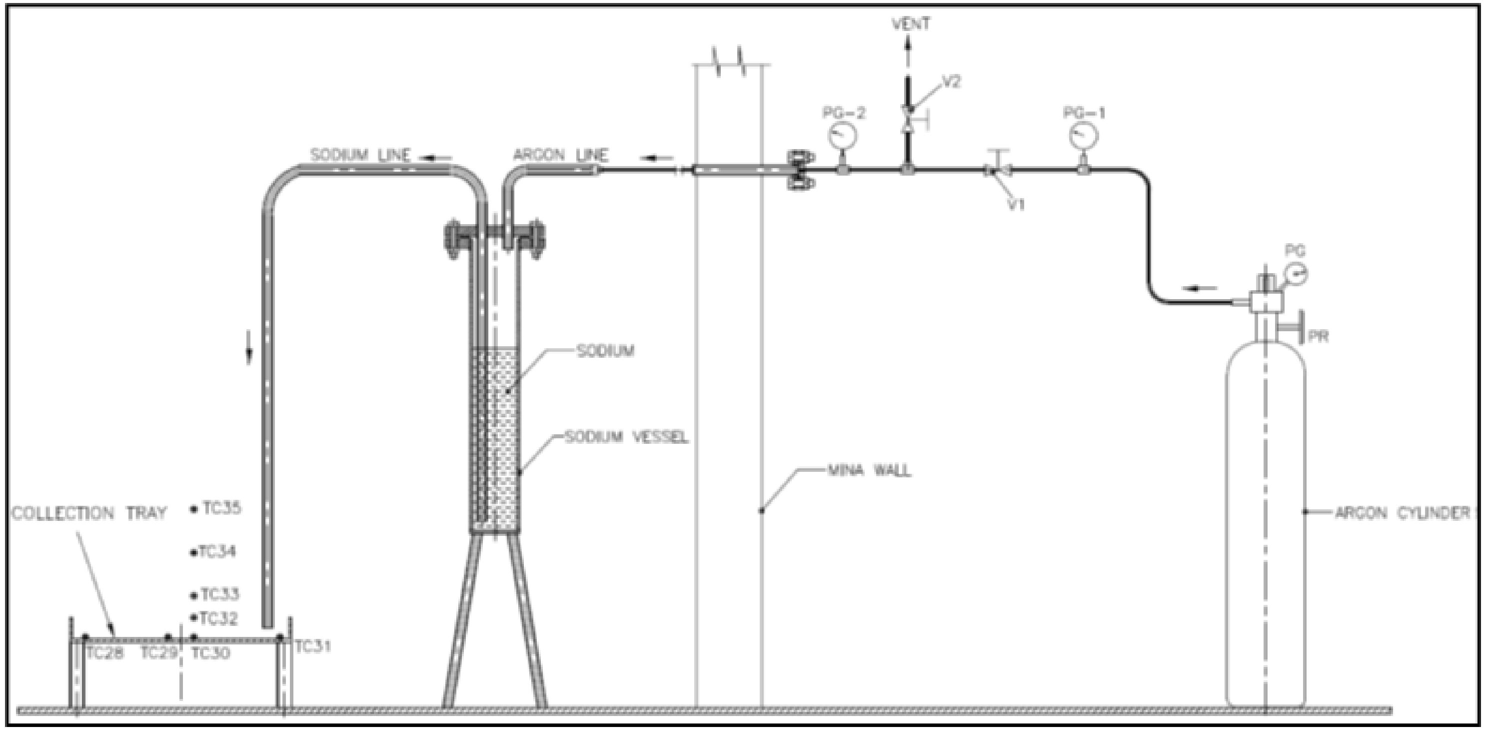


Schematic of the MINA facility.

Design of sodium pool fire experiments (1/3)

- SS tray of 0.5 m x 0.5 m x 0.05 m and pool area → 0.25 m^2.
- Tray and sodium supply tank were heated to ~ 350 ºC by using surface heaters while maintaining the argon pressure in the vessel at ~ 0.05 bar.

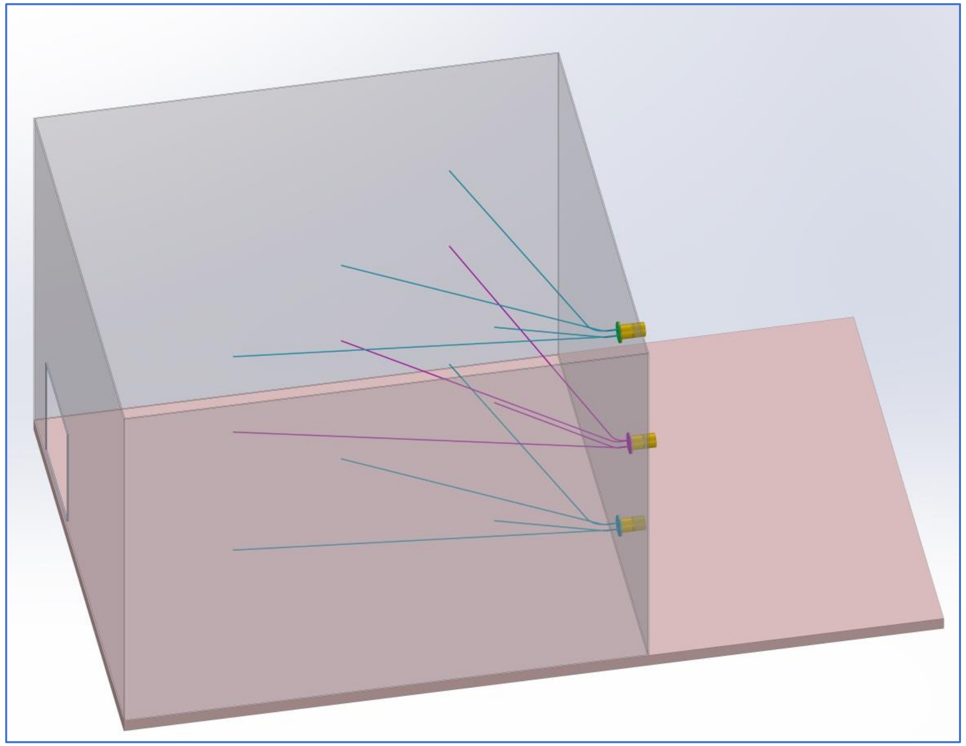
Sodium pool fire set-up



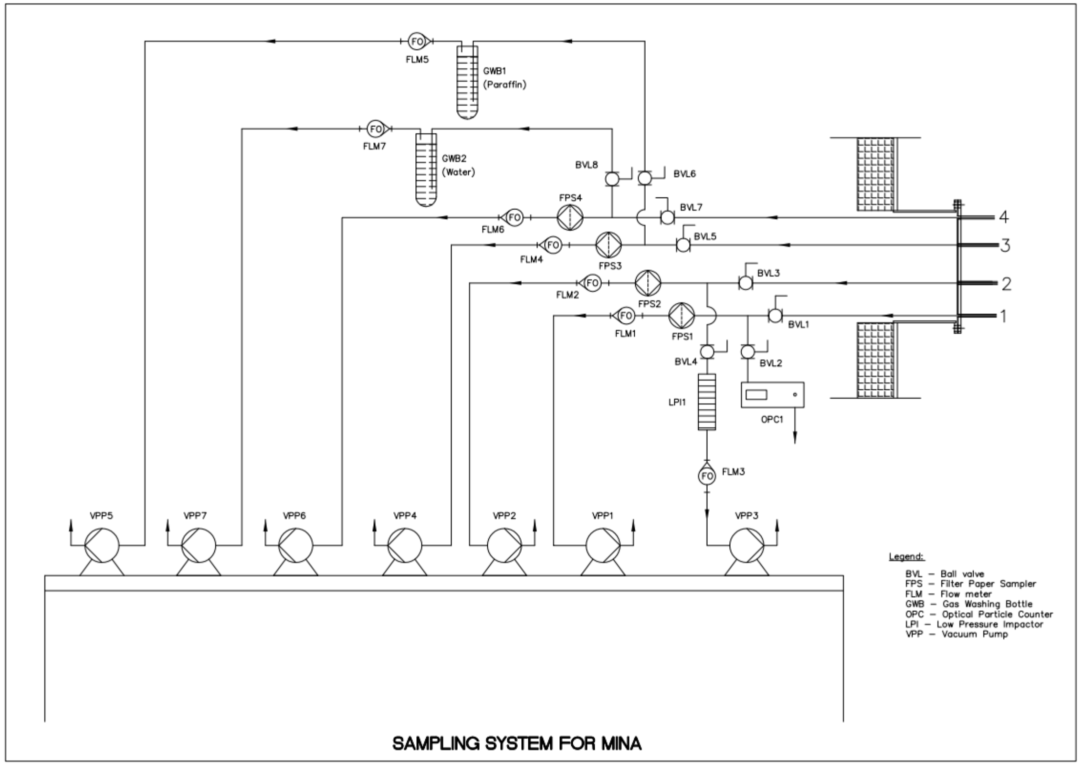
Schematic of sodium and argon supply system.

Design of sodium pool fire experiments (2/3)

- Multi-elevation (1.2, 3.0 3.9 m) sampling for characterization of aerosol.
- Total sampling positions 12 → 4 Nos. in each elevation.



3-D View of MINA chamber and sampling layout.

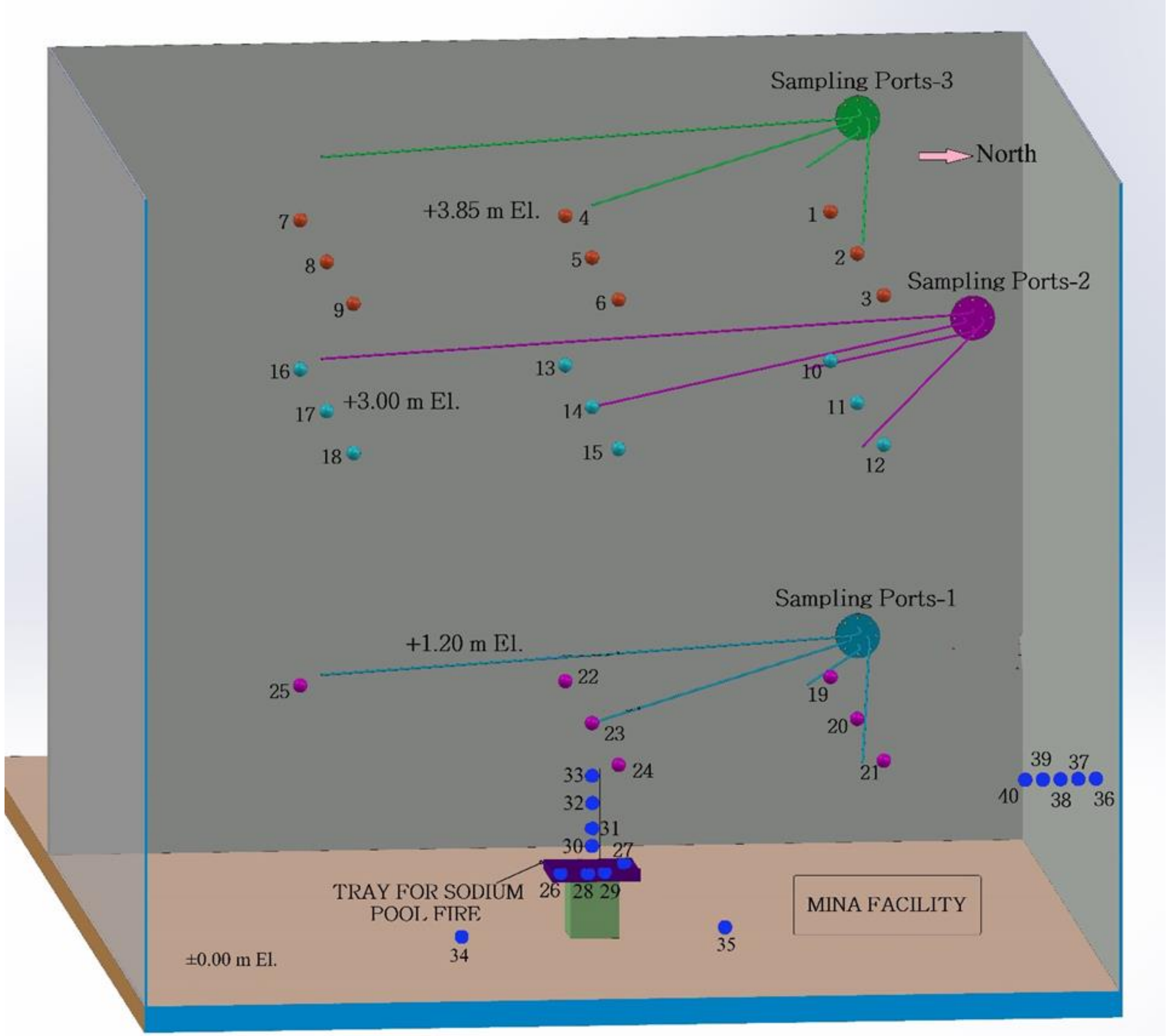


Schematic of aerosols sampling for BE.

Design of sodium pool fire experiments (3/3)

Matrix for monitoring the spatio-temporal temperature distribution during pool fire.

- **Total 40 Nos. → K – type thermocouples,**
- **TE and ME → 9 Nos., BE → 7 Nos.**
- **Pool area → 4 No. and Above the pool → 4 Nos.**
- **Near the chamber wall → 5 Nos. and Floor → 2 Nos.**



3-D isometric view of the sampling positions & temperature monitoring locations

Aerosol metrological devices

Both off-line and real-time sampling techniques were employed.

Instrument	Principle	Measured Characteristics	Measuring Range	On-line/ Off-line
Filter paper sampler	Gravimetric + chemical	Mass concentration	--	Off-line
Low-Pressure Impactor	Impaction + Gravimetric	Mass-size distribution	0.08 - 35 µm	Off-line
Aerosol Spectrometer	Light Scattering	Number/ mass-size distribution	0.3 – 20 µm	On-line
Turn Table Technique	Mass deposit	Deposition flux/ velocity	--	Off-line
SS collection plates	Chemical	Aerosol fallout	--	Off-line

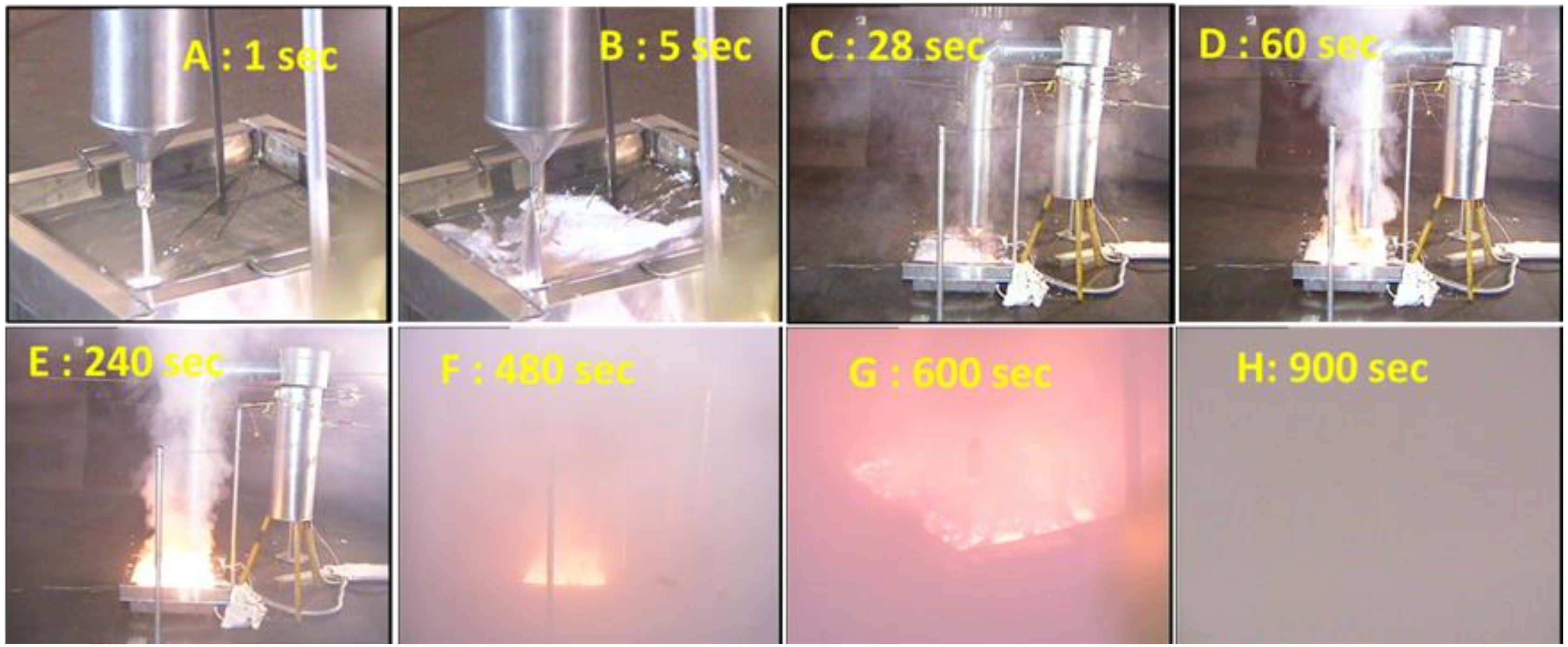
SS collection plates of 10 cm x 10 cm were placed on the floor, pasted on the sidewall and downward-facing surface of the chamber to collect cumulative aerosol deposition mass.

- MISRA, J., SUBRAMANIAN, V., KUMAR, A., Investigation of Aerosol Mass and Number Deposition Velocity in a Closed Chamber, Aero. Air Qua. Res., 13 2 (2013) 680-688.
- SUBRAMANIAN, V., KUMAR, A., PUJALA, U., Studies on sodium aerosols dispersion in open environment for fast reactor safety. Annals of Nuclear Energy, (2019) 125, 63-73.

Results and Discussion (1/12)

Sodium combustion and aerosols generation

- 2 kg sodium was drained into the tray in ~ 15 s.
- Visibility has been entirely lost 15 minutes from the start of the experiment.
- As soon as the liquid sodium is drained into the SS tray, a sodium pool was formed and burning started instantaneously.

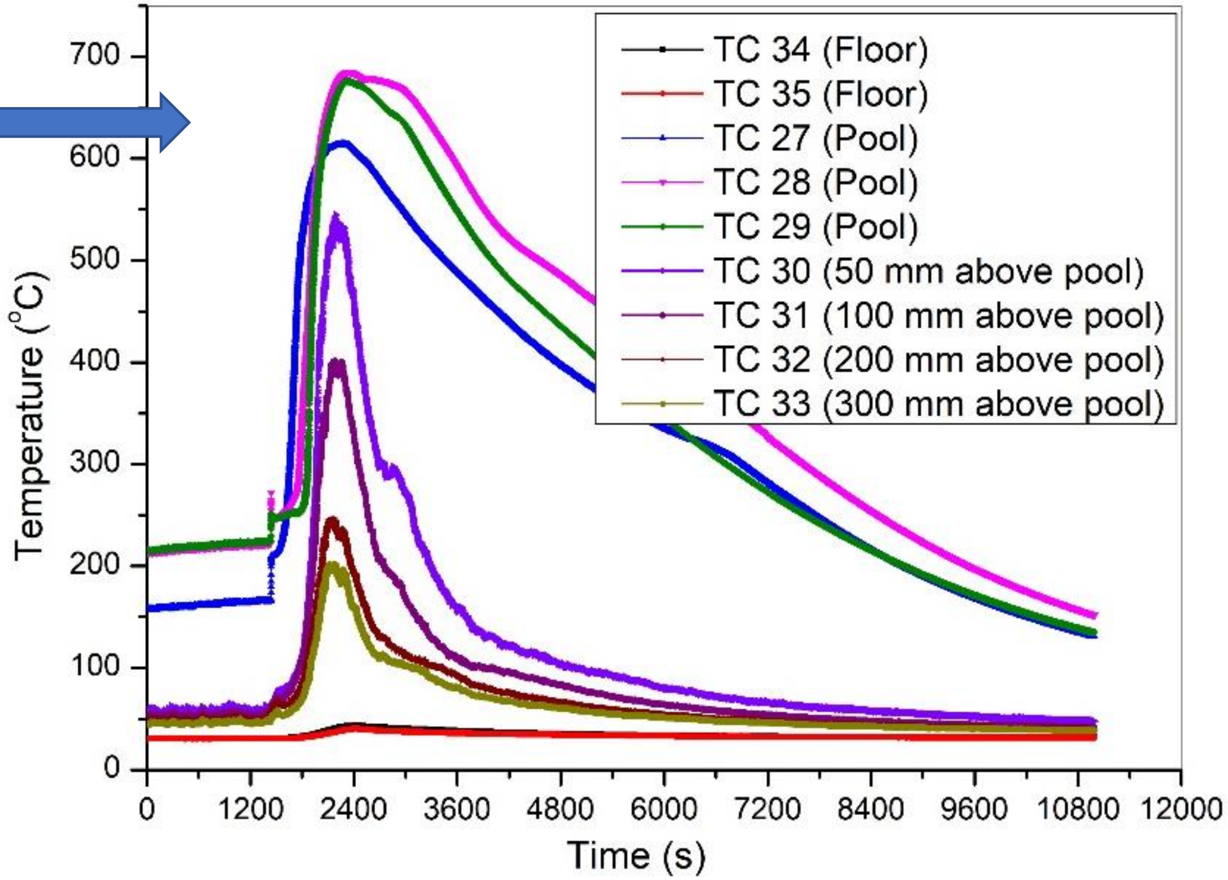


Optical images show the upward movement of aerosol inside the chamber during combustion period due to a strong thermal gradient in the vertical direction.

Results and Discussion (2/12)

Temperature distribution in pool and above the pool region

- Sodium pool temperature increased to a maximum of 685 ± 5.2 ºC in ~ 10 minutes and remained at ~ 660 ± 5.0 ºC until the completion of sodium combustion (~25 minutes).
- Temperature near the sodium pool surface was ~ 550 ± 4.1 ºC (at 50 mm above the collection tray) and decreased with vertical distance.
- In about 3 hours, the temperature of the sodium pool decreased to less than 150 ± 1.1 ºC.

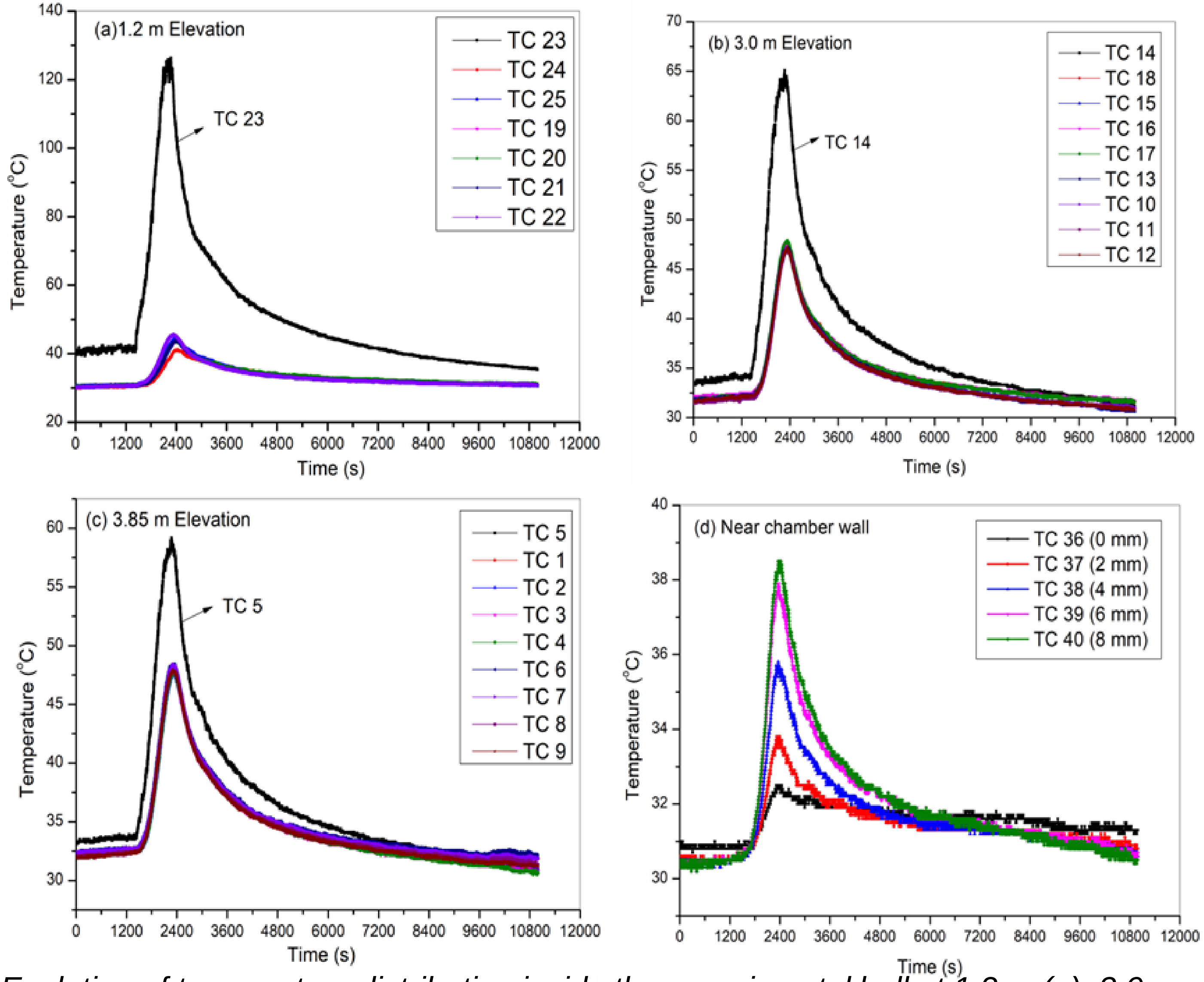


Evolution of temperature during sodium pool fire.

Results and Discussion (3/12)

Temperature distribution inside the experimental chamber

- **Maximum recorded temperature near the centre sampling points at 1.2 m is 126 ºC.**
- **Maximum difference in temperature between the chamber wall and air at 8.0 mm distance inside the chamber is about 6.0 ºC.**
- **Temperature gradient near the chamber wall → 7.5 ºC/cm.**
- **Vertical temperature distribution has two steep gradients,**
  - **Temperature decreases from 685 ºC to 200 ºC at a 0.3 m distance,**
  - **Temperature decreases from 200 ºC to 59 ºC over a 3.40 m distance.**

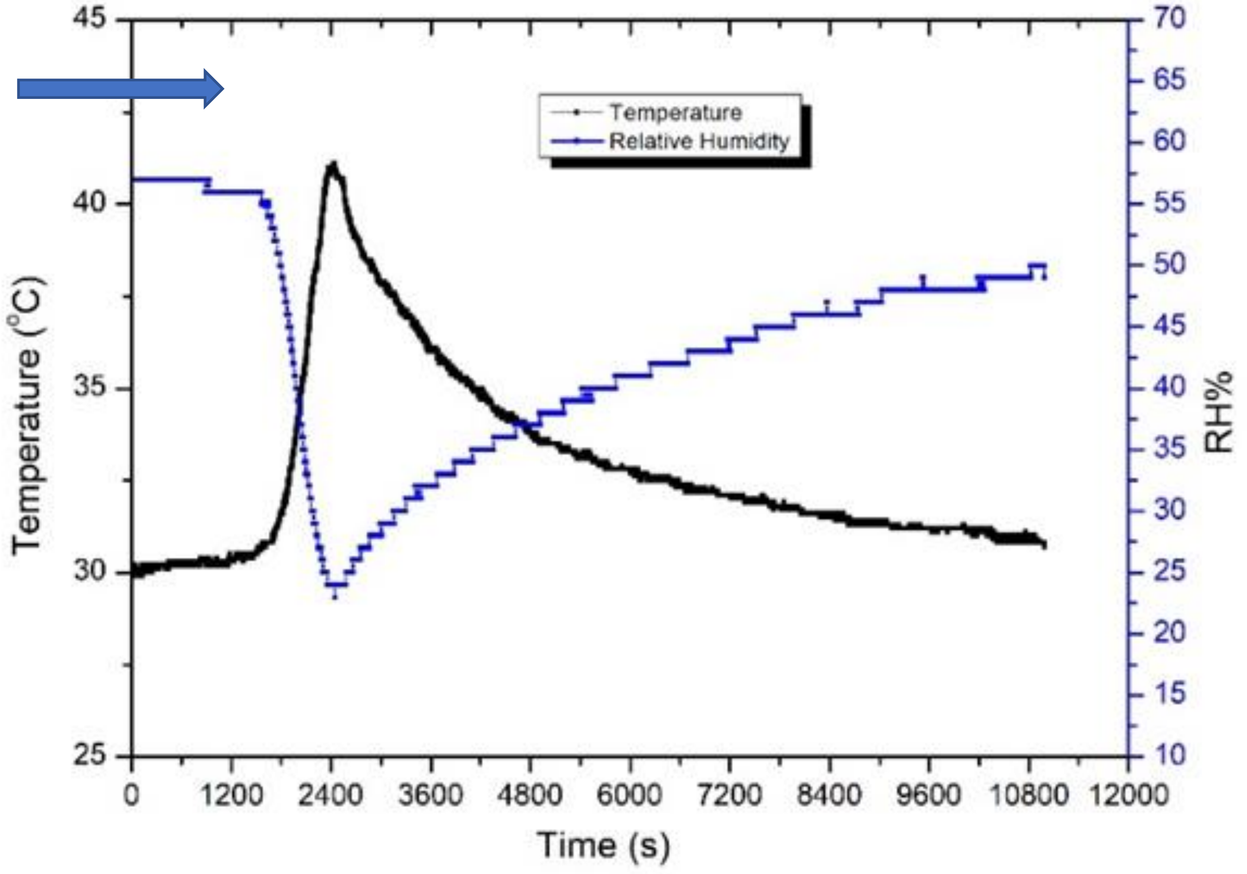


Evolution of temperature distribution inside the experimental hall at 1.2 m (a), 3.0 m (b) and 3.85 m (c) elevation and near the wall region (d) at the bottom elevation

Results and Discussion (4/12)

Evolution of Relative humidity

- RH% was observed to reduce from the initial value of 56 ± 0.5 % to 24 ± 0.2 % in 20-min (during pool fire).
- The change may be attributed to the chemical reaction between sodium/ sodium aerosols with moisture and temperature-dependent variation in RH%.
- The degree of change of moisture saturation also depends on temperature of the air in the chamber.
- The gradual increase in humidity after 20 min is due to decrease in temperature of the chamber when sodium burning is in quenching stage.



Temporal change of RH% along with gas temperature.

Results and Discussion (5/12)

- After 24 hours of the experiment, the sample was taken from the residue of the tray for determining un-burnt sodium.
- Post residue analysis by hydrogen displacement method reveals that about 10% of sodium was left un-burnt.
- From the burnt sodium mass and duration of the fire, the average burning, and aerosol release rates are calculated.
    - Estimated average burning rate → 17.3 kg/m^2*hr
    - Aerosol release rate are → 0.24 g/s.

Sodium burning characteristics and aerosol generation rate

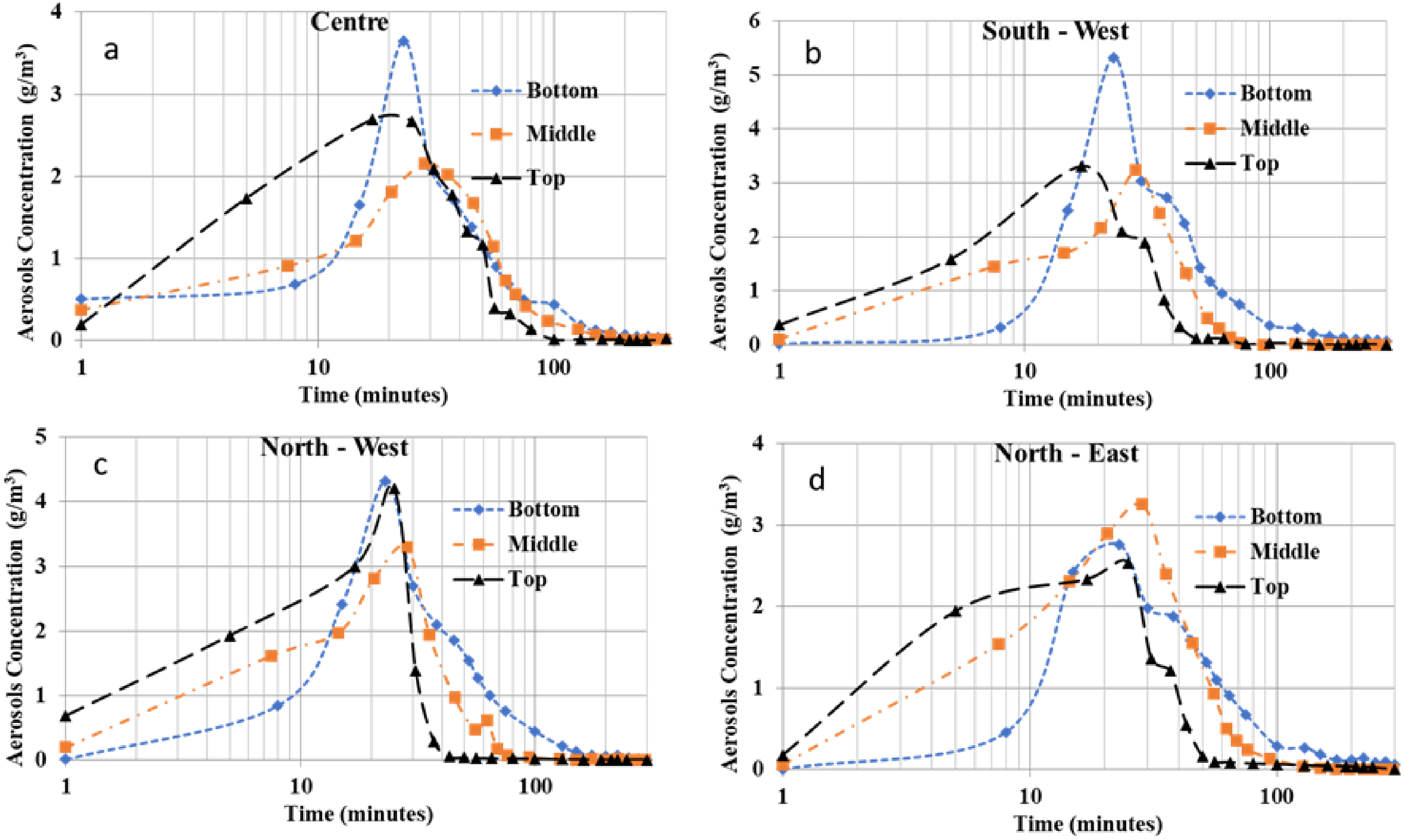
Experimental parameters	Units	Values
Quantity of sodium used	kg	2.0
Sodium pool area	m^2	0.25
Duration of pool fire	hr	0.42 (25 min)
Quantity of un-burnt sodium	kg	0.2
Quantity of burnt sodium	kg	1.8
Burning rate	kg/m^2*hr	17.28
Aerosol generation rate*	kg/hr	0.86 (0.24 g/s)

*Assume 20 % of the burned sodium manifested as an aerosol.

Results and Discussion (6/12)

Spatio-temporal distribution of sodium aerosols concentration

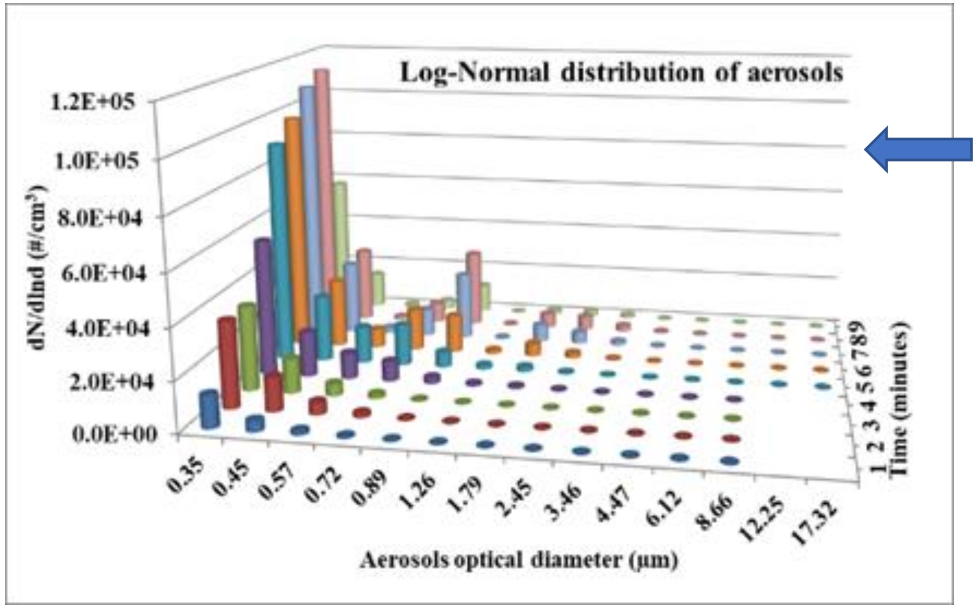
- **Maximum average suspended aerosol concentration at the bottom, middle and top elevation is 4.01 ± 1.08, 2.42 ± 0.52 and 2.87 ± 0.92 g/m^3.**
- **Average suspended concentration shows that the concentration is higher at the TE than at the middle and bottom in the first 20 minutes.**
- **After cease of the fire, the BE concentration increased due to settling of the suspended aerosols from higher elevations.**
- **Based on the aerosol concentration measurements, it is understood that the aerosol distribution is not well mixed throughout the experimental periods.**



Aerosol mass concentration as a function of time.

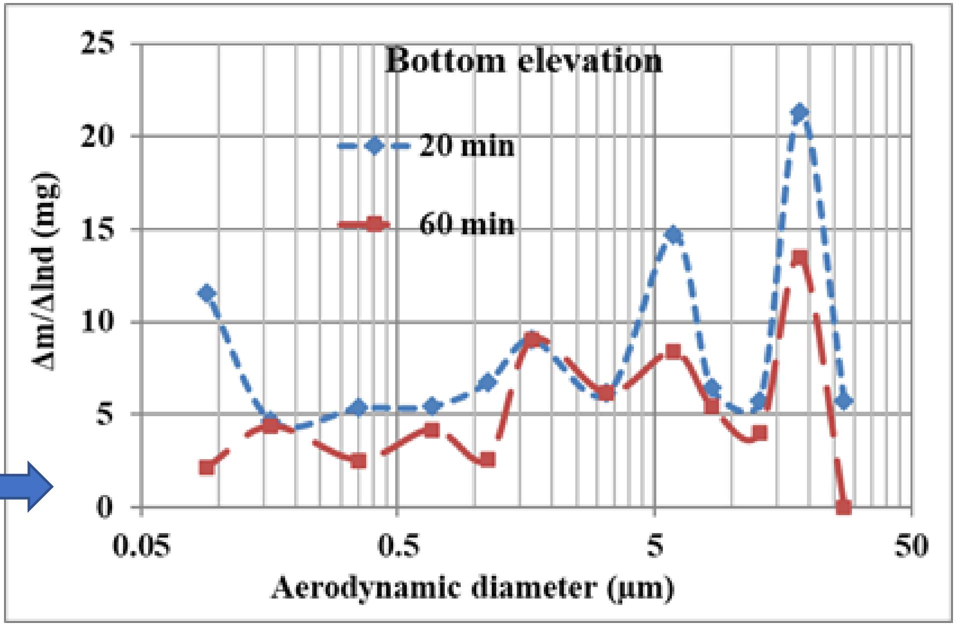
Results and Discussion (7/12)

Evolution of sodium aerosol size distribution



Log – normal number size distribution as a function of time.

Log – normal mass size distribution as a function of time.



- Higher fraction of particles is formed in the sub-micron size (< 0.5 μm) at the start of the experiment with single-mode, and with the progress of time, aerosols size distribution became multi-mode characterized by a dominant peak in the sub-micron region (< 0.5 μm) and a small peak in the range of 0.57 – 1.26 μm, 1.26 – 4.47 μm and few particles also found greater than 5.0 μm.
- During the initial period, the aerosol size ranged from 0.1 μm to 25 μm with five modes (0.15, 0.75, 1.65, 6.0 and 19.0 μm), and at a later stage, samples have four size modes (0.35, 1.25, 6.0 and 19.0 μm).
- Overall, the aerosol generated during the sodium pool fire varied in three orders in size and ranges from 0.1 μm to 25 μm.

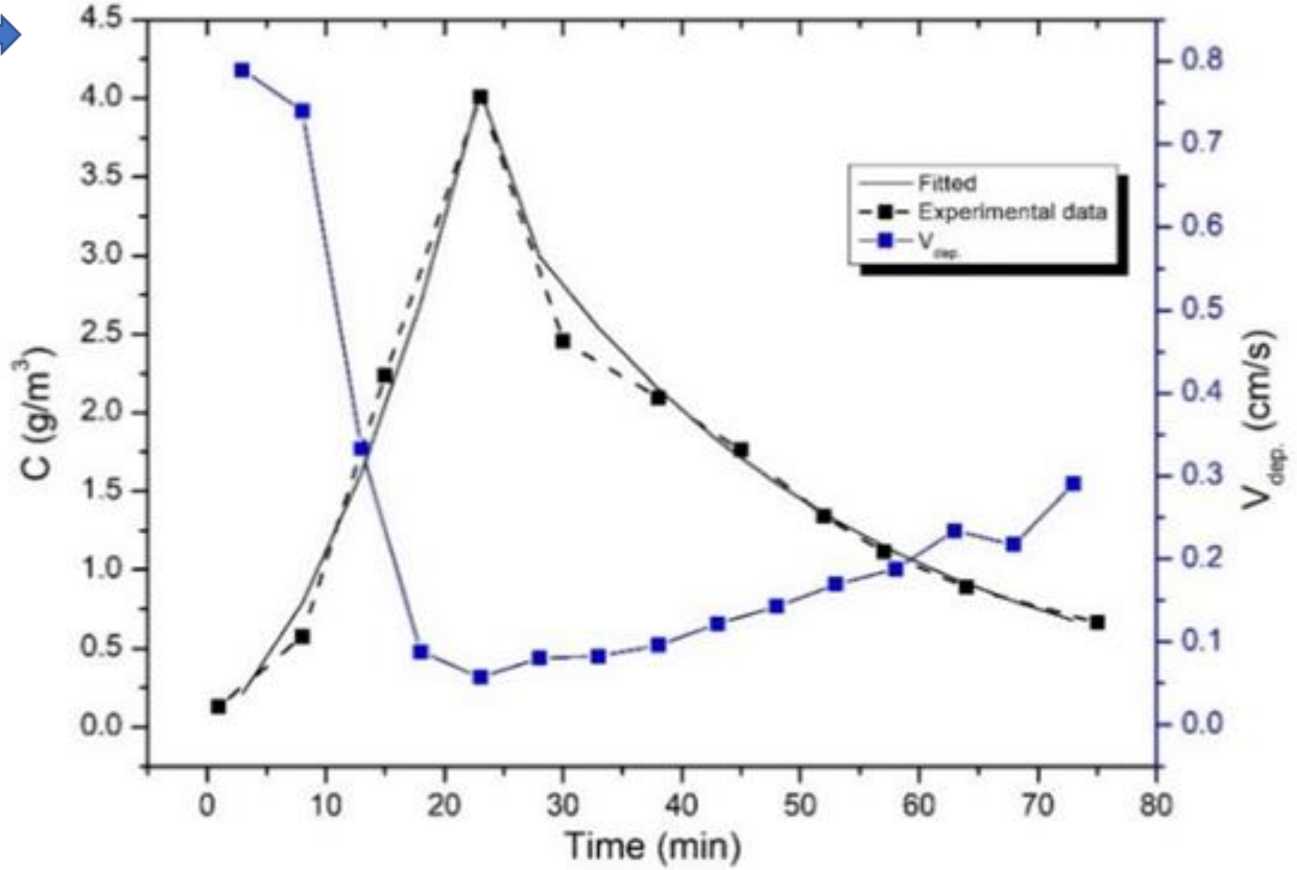
Results and Discussion (8/12)

Aerosol mass deposition velocity

- **Turntable equipment was used to determine the aerosol mass flux (J) and mass deposition velocity (Vdep).**
- **The deposition velocities were estimated by using the formula given below:**

$$V_{dep.}(\mathbf{m/s}) = \frac{J\ (g/m^2 * s)}{C\ \ (g/m^3)},$$

- **The aerosol deposition velocity ranged from 0.059 ± 0.005 to 0.289 ± 0.025 cm/s as time increases from 25 – 75 min.**
- **The lowest deposition velocity for sodium aerosols is 0.06 ± 0.01 cm/s when the aerosol mass concentration is 4.01 g/m3.**
- **The measured deposition velocity is increased from 0.06 cm/s up to 0.29 cm/s and the average deposition velocity of the sodium aerosols is observed to be 0.15 ± 0.07 cm/s.**



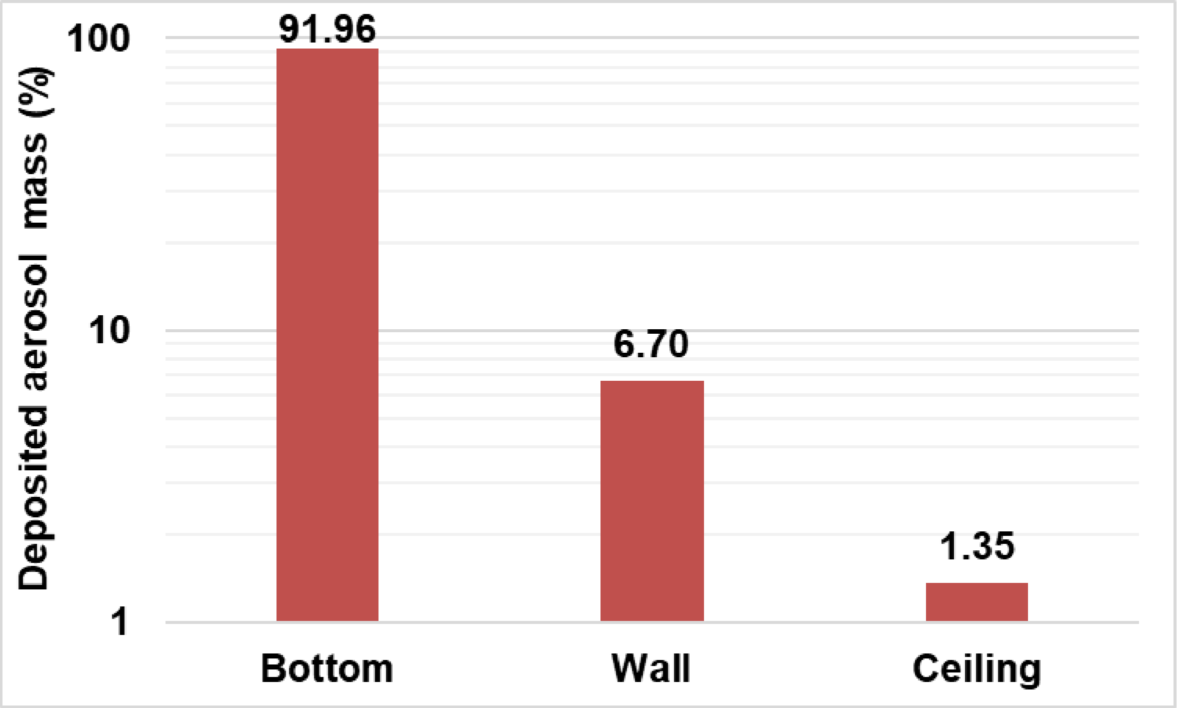
Aerosol deposition velocity as a function of time.

Results and Discussion (9/12)

Distribution of deposited aerosol mass

- **The fraction of total deposited sodium aerosol mass is dominant on the floor (91.96 %) than the side walls (6.70 %) and downward facing surface (1.35%).**

- **The aerosol deposited in the horizontal surfaces (floor of the chamber) is dominated by gravitational settling, while vertical surfaces are diffusion and thermophoretic forces.**



Deposited aerosol mass distribution.

Results and Discussion (10/12)

Aerosol modelling and comparison with observations

- **Theoretical model used in the present simulation is based on the first-order differential equations solved by the finite difference method to predict the aerosol characteristics as a function of time in a confined environment.**

- **In the present simulation,**
  - **Coagulation due to Brownian motion,**
  - **Polydispersity of aerosol,**
  - **Coagulation correction factor for the entire range of particles.**

- **Deposition mechanism considered are:**
  - **Gravitational settling,**
  - **Wall plating,**
  - **Thermophoretic and,**
  - **Ventilation.**

- KUMAR A., Sodium Metal Aerosol Characterization in Cover Gas Region, PhD thesis, https://shodhganga.inflibnet.ac.in/handle/10603/274246.
- LEE, K.W., & CHEN, H., Coagulation Rate of Polydisperse Particles, Aerosol Sci. Technol., 3 (1984) 327-334.

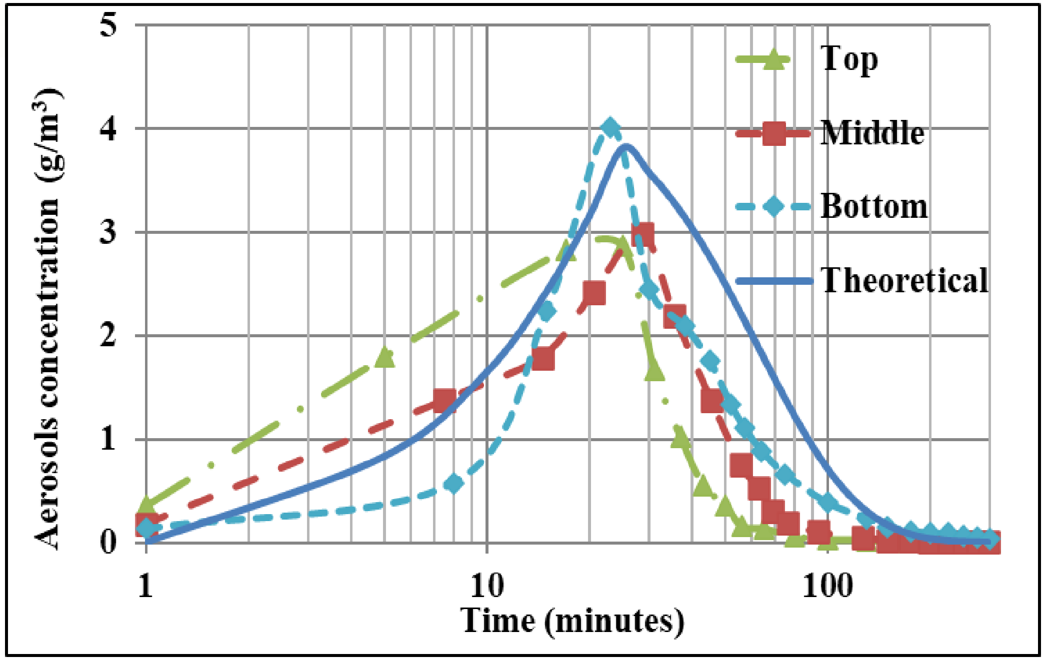
Results and Discussion (11/12)

Input parameter for simulation

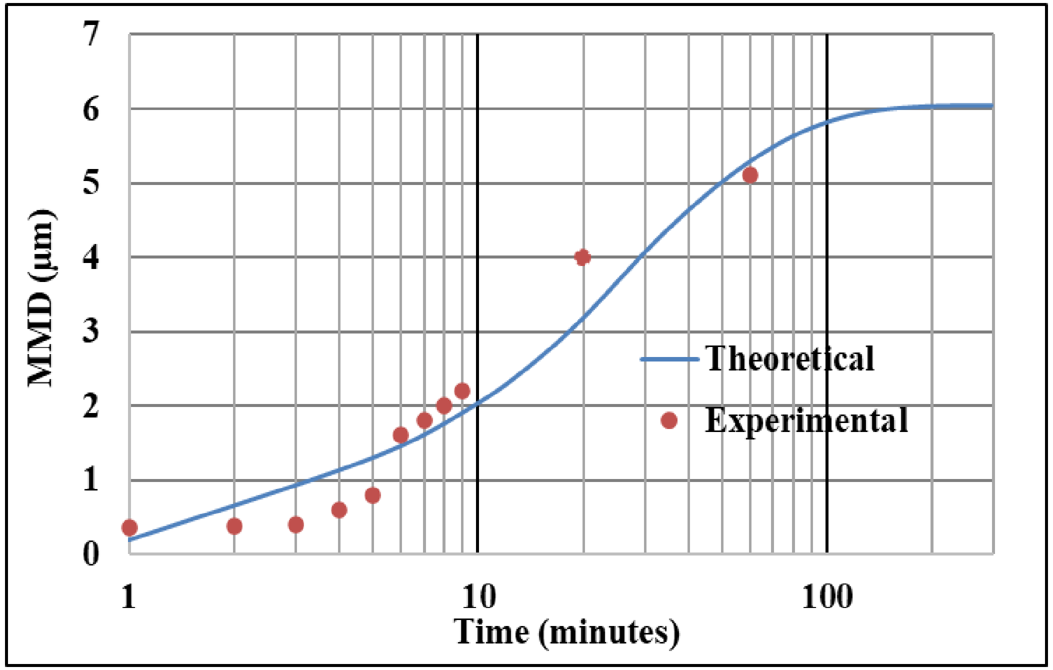
- **Most of the input parameters were derived from the present experimental results.**
- **Shape factor and boundary layer values are taken from literature.**
- **The initial aerosol diameter (MMD) and GSD are 0.2 µm and 2.0 respectively and have been taken from present measurements.**

Experimental parameters	Units	Values
Aerosol source rate	g/s	0.42
Aerosol source duration	S	1500
Mass Median Diameter (MMD)	µm	0.2
Geometric Standard Deviation (GSD)	--	2.0
Density of aerosol	g/cm^3	2.13
Shape factor	--	1.0
Diffusion boundary layer thickness	µm	1.0
Bulk gas temperature	ºC	50
Chamber wall temperature	ºC	31
Temperature gradient between gas and wall	ºC/cm	7.5

Results and Discussion (12/12)



Temporal change of concentration of aerosol.



Evolution of aerosol median size growth.

Average suspended aerosol concentration is well matched for peak concentration.

Experimentally observed decay of aerosol concentration is faster than simulated maybe because of Turbulent deposition and coagulation, extra surface available in the chamber, etc.

After about 100 min, the aerosol concentration deposits ~ 98%, 96% and 90% of maximum suspended concentration at the top, middle and bottom elevation, respectively. While it is 82% as per the prediction.

Assumptions

- The spatial distribution of aerosol characteristics was not considered for theoretical calculation.

- The gas bulk flow is zero and the particles are homogeneously distributed over the simulation domain.

- The impaction process (which may be significant only at high convection velocities) is neglected.

- Turbulent deposition and coagulation are not included in the simulation.

Conclusions

A zero-dimensional model predicts the overall trend of evolutions of aerosol mass concentration but notably deviated from the data in all specific values.

The evolutions of aerosol median size by theoretical simulation capture the overall trend reasonably.

After about 100 min, the suspended aerosol concentration is ~ 2%, 4% and 10% of maximum concentration at top, middle and bottom elevation, respectively, while it is 18% as per the prediction.

About 92 % of aerosol is deposited on the floor of the chamber, and the remaining aerosol is deposited on the chamber walls and downward-facing surfaces.

The effect of hygroscopic growth, turbulent and gravitation agglomeration is not considered in the present simulation. The above parameters will also influence the predictions.

The present experimental study has given significant insight into understanding the heterogeneous distribution of aerosols along with temperature distribution in closed containment.

Future work

The experience gained from the experiment will be used to improve the methodology and instrumentation for capturing the thermal-driven turbulent phenomenon.

The sodium fire dynamics, aerosols behaviour, chemical kinetics and thermal hydraulics are challenging problems that can be addressed with 3-D CFD or fire dynamics codes, which will be taken up.

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Thank you for your kind attention

- Any questions and valuable suggestions?