Paper Code: #466

Paper title: Estimation of mean charge on sodium metal aerosol in the bipolarly ionized argon and nitrogen gas

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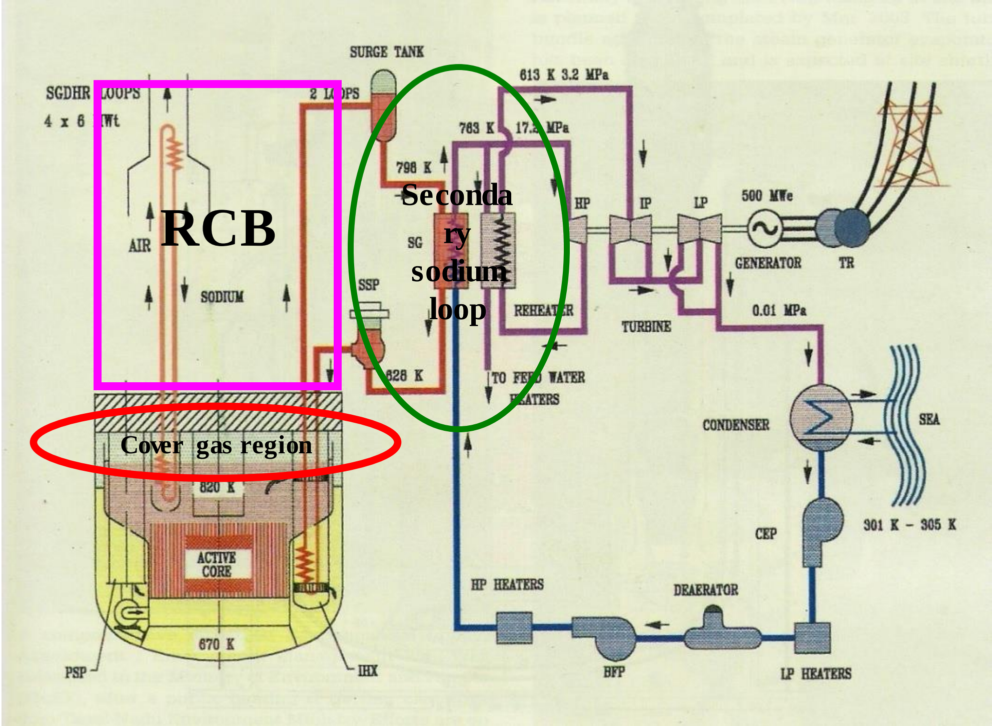
Content of the presentation

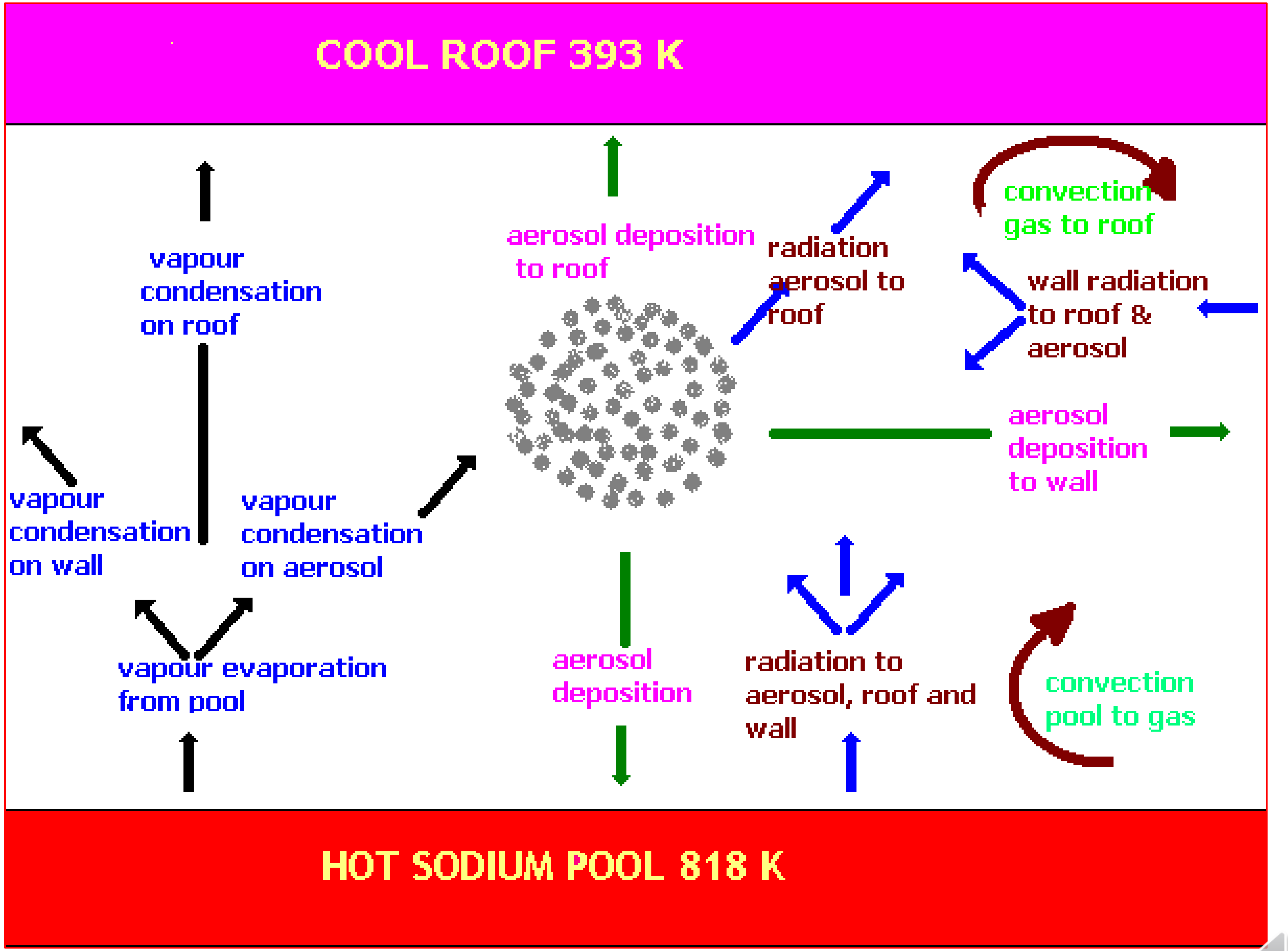
- BACKGROUND OF THE STUDY
- AEROSOL SOURCES, NATURE, CONSEQUENCES, AND EXPERIMENTAL FACILITY
- SCOPE AND OBJECTIVE OF THE STUDY
- THEORETICAL BACKGROUND
- RESULTS AND DISCUSSION
- SUMMARY AND CONCLUSION
- FUTURE SCOPE

Aerosol sources, nature, consequences, and experimental facilities



Source	Nature	Consequences	Exp. Facility
Sodium evaporation, nucleation, condensation and coagulation in argon cover gas	Radioactive sodium metal aerosols + FP (incase of clad rupture)	Influence of aerosol in heat and mass transfer to the rooftop structures, Deposition in the annular gap of top shield, Cover gas purification system, hinder the operation of instruments and In- containment source term estimation, etc.	Work carried out at SILVERNIA loop and Aerosol Test Facility

Aerosol dynamics in the cover gas region



Scope of the present study

Knowledge of sodium aerosol characteristics (size distribution and mass concentration) along with temperature distribution in the cover gas region would help:

- **Better estimation of thermal load to the rooftop structures,**
- **Mass transfer to the top shield, its narrow gaps, and penetrations,**
- **Coolant leakage detection systems that monitor aerosol concentration,**
- **Fraction of activity bound with sodium aerosol under failed fuel condition,**
- **Design of the cover gas purification system efficiency,**
- **Role of ionizing radiation on sodium aerosol characteristics and effect on sodium aerosol deposition and FP trapping, etc.**

Objective of the present work

Sodium aerosol characteristics in the cover gas region (size distribution, mass concentration) as a function of :

- **Sodium pool surface temperature,**
- **With and without gamma radiation field,**
- **Different cover gases,**
- **Estimation of electrostatic charge on aerosol,**
- **Consequences of charged aerosol inside the cover gas region.**

➢ **Temperature distribution inside the cover gas region,**

➢ **Deposition of the sodium aerosol on the inner surface.**

Details of the experimental facility

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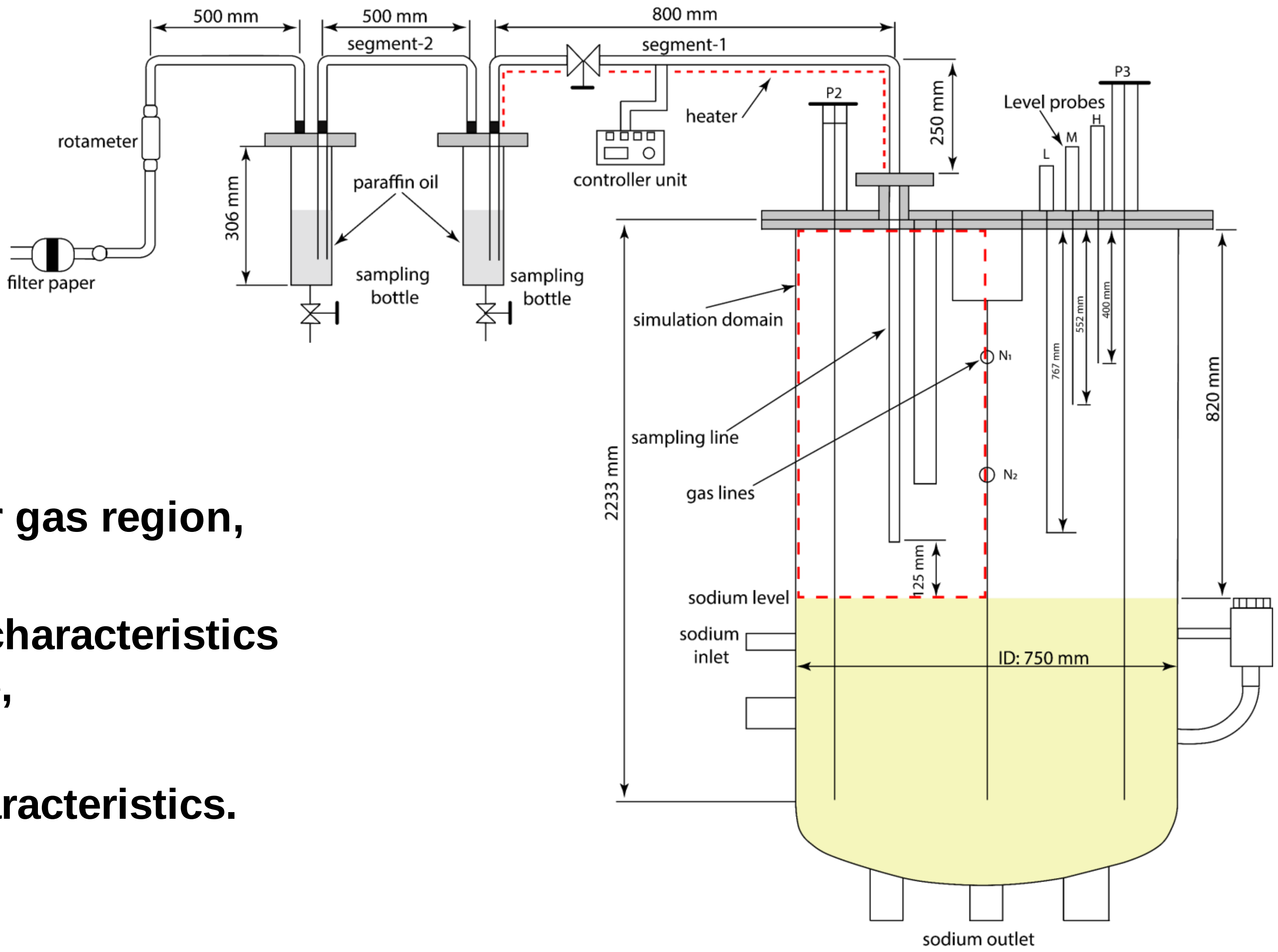
SILVERINA loop (TP-1) Facility is used for various experimental study

Present work consists of :

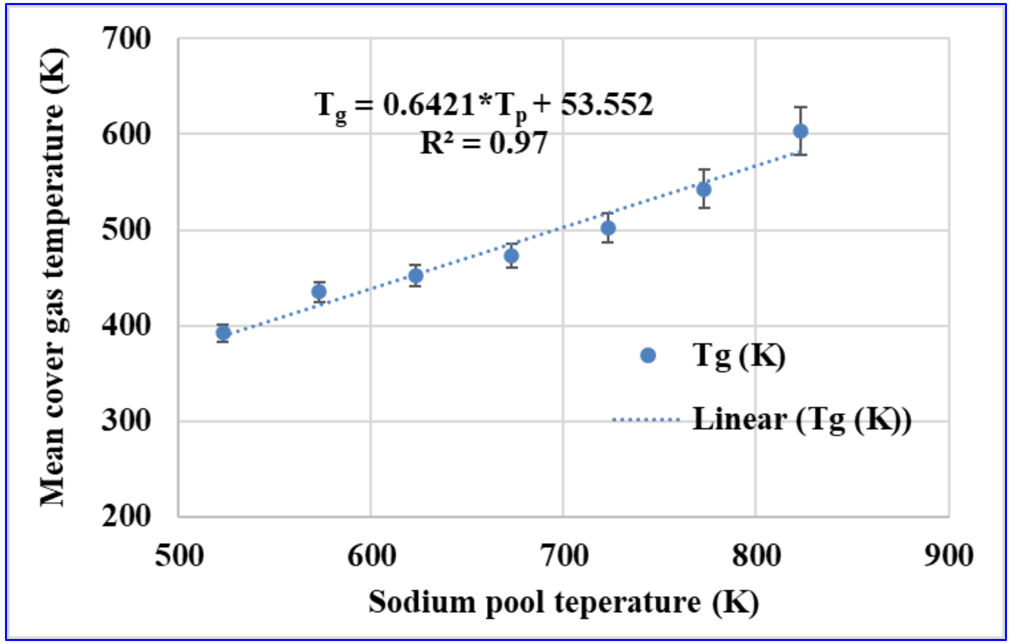
- **Temperature distribution inside the cover gas region,**
- **Determination of aerosol size and mass characteristics as a function of sodium pool temperature,**
- **Effect of gamma radiation on aerosol characteristics.**



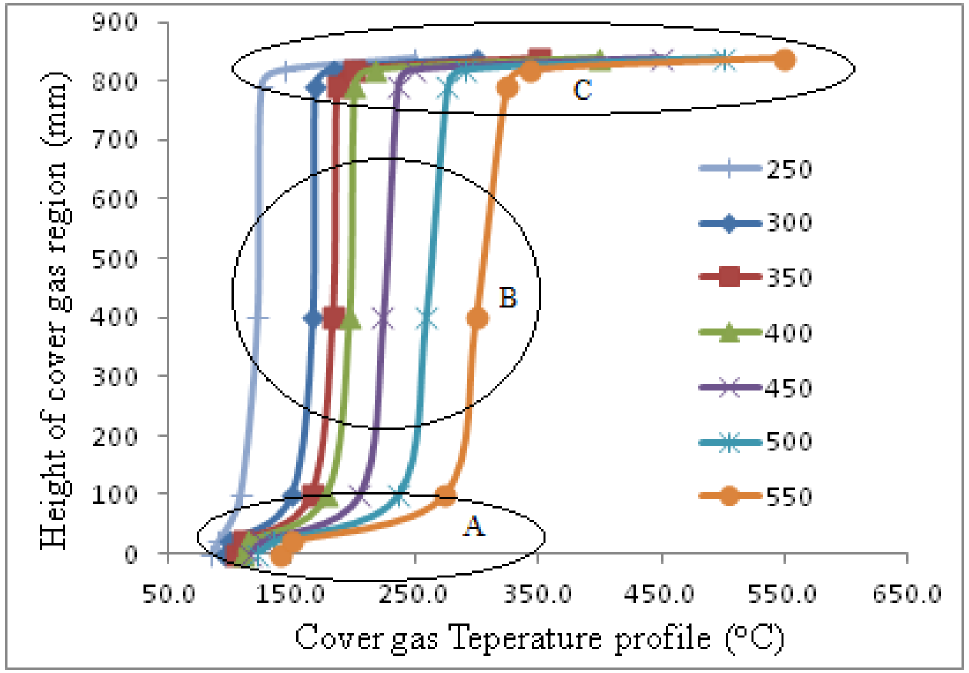
- Kumar et al., Development, and validation of a methodology for characterization of sodium aerosols in the cover gas region, Aero. Air Qua. Res., 14, 1534 -1541, 2014.
- Kumar A., Sodium metal aerosols characterization in the cover gas region, Ph.D. thesis, Homi Bhabha National Institute, Mumbai, 2017.

Results and Discussion

Temperature distribution inside cover gas space



Mean gas temperature vs sodium pool temperature



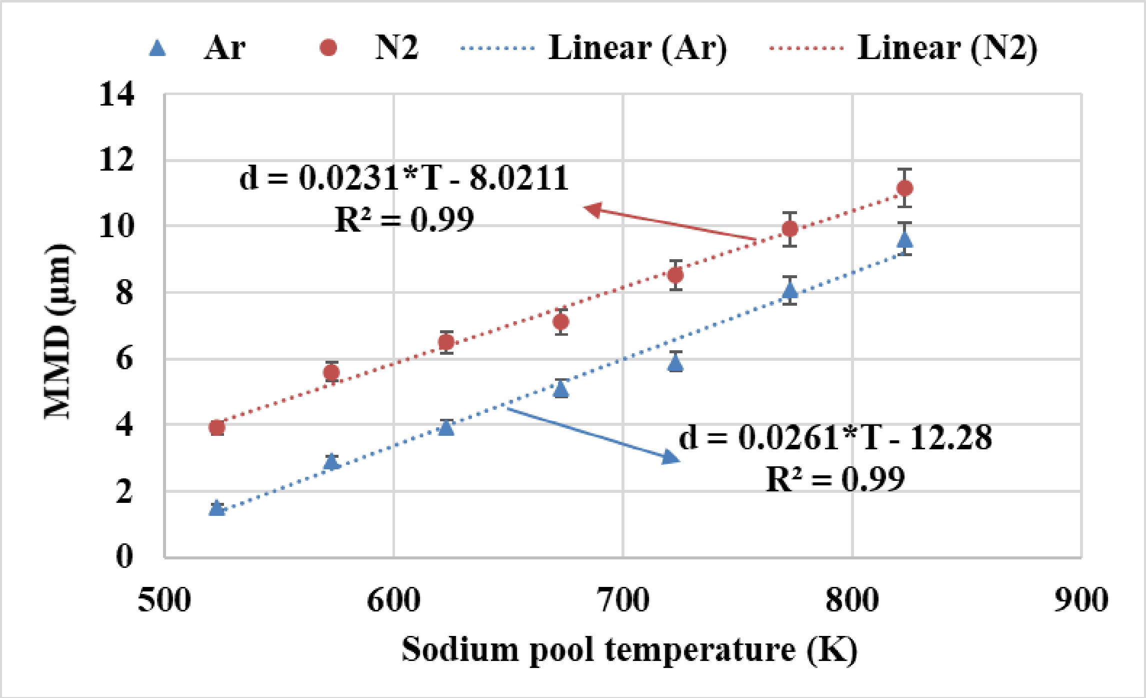
- **Steep temperature gradient exists near the roof (A) and pool surface (B) and it is higher for higher sodium pool temperature.**
- **Standard deviation of mean bulk gas temperature increase with pool temperature, i.e., SD ranges from ± 9 to 25%.**

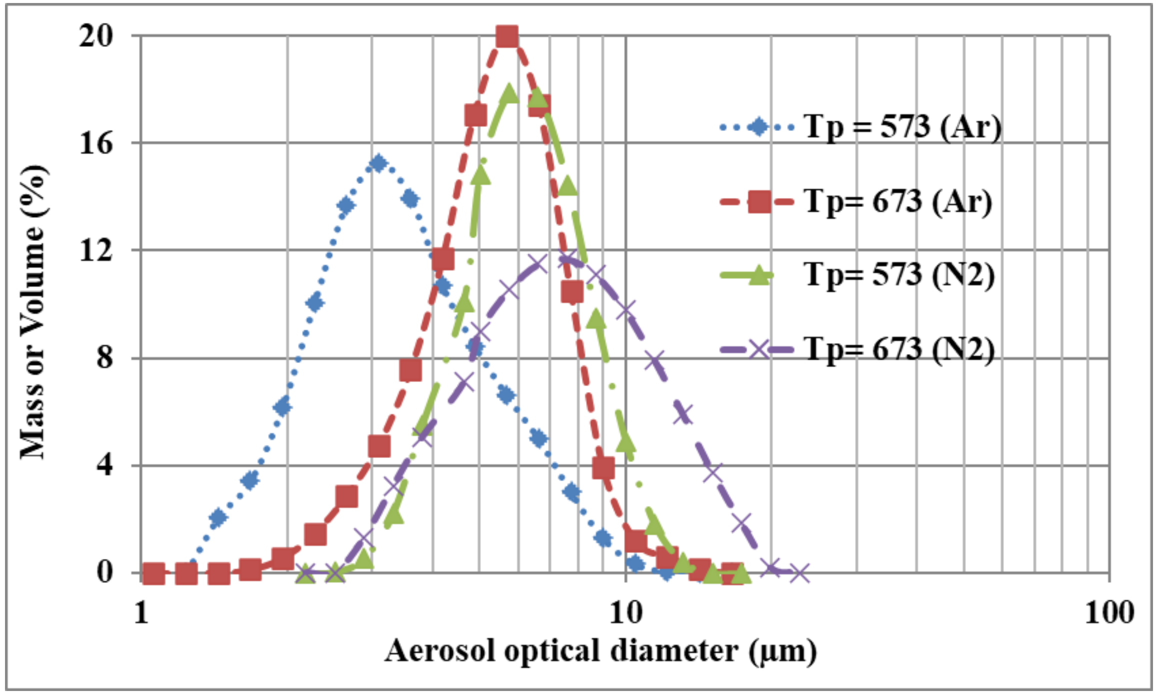
Kumar et al., Characterization of sodium aerosol in the cover gas region of SILVERINA loop, Aero. Air Qua. Res., 15 (2015) 1813 -1822.

Results and Discussion

Sodium aerosol size distribution & MMD

- Aerosol size distribution → mono-model and polydisperse.
- Mode of size - distribution → shifted to the higher size, and distribution has become broader for nitrogen gas when compared to the argon.
- Higher is sodium pool temperature, the more evaporation of sodium, and the higher is the mean diameter and polydispersity of aerosols.



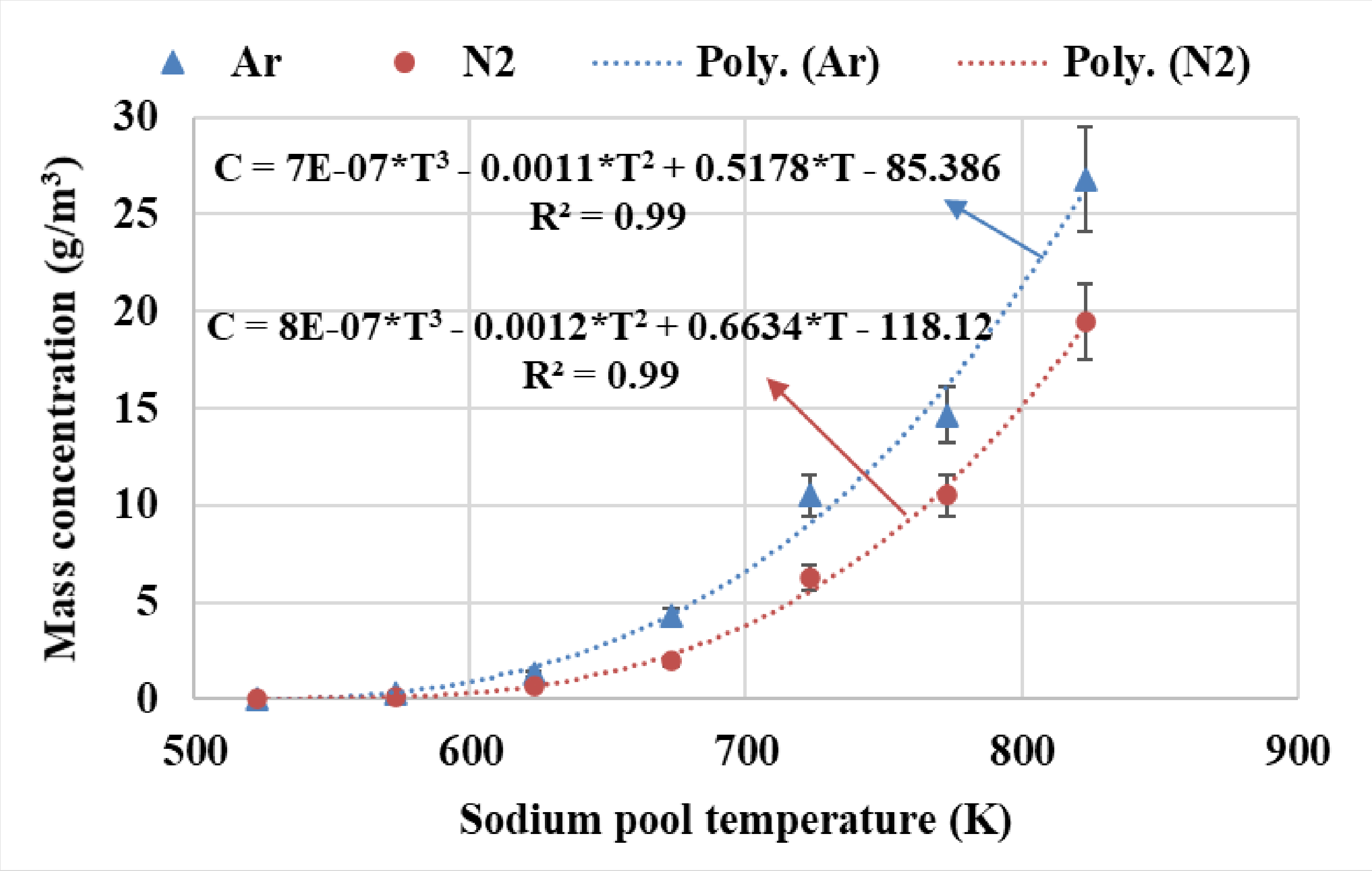


Kumar et al., Comparison of sodium metal aerosol characteristics in inert gas, IASTA -2018, at IIT Delhi, India.

Results and Discussion

Sodium aerosol mass concentration

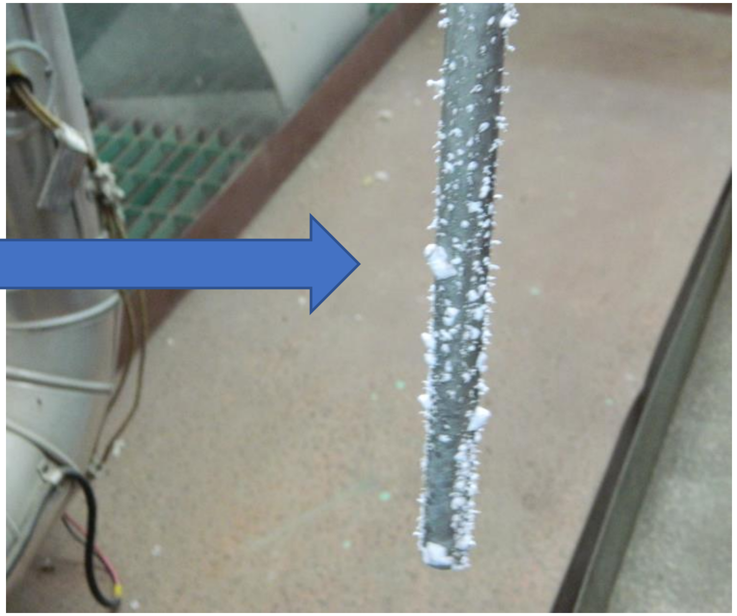
- Difference in aerosol mass concentration between argon and nitrogen gas ranges from 25 - 55% respectively for 523 to 823 K of pool temperature.
- Higher temperature gradient in the case of argon enhancing the convection, thereby resulting in higher aerosol concentration.

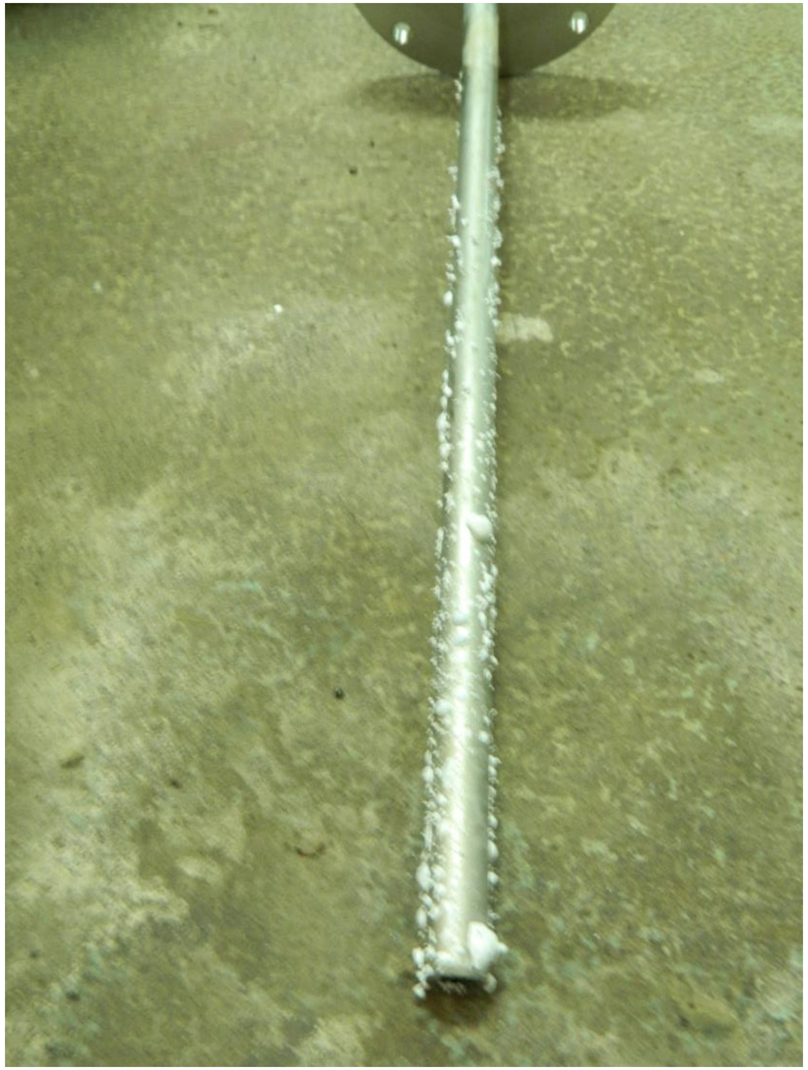


Kumar et al., Studies on Geometrical effect on sodium aerosol characteristics in the cover gas region, Aero. Air Qua. Res., 16 (2016) 1832-1840.

Results and Discussion

Sodium aerosol deposition in the surface of sampling tube





- **Deposition of aerosol on the outer surface to the cover gas is not uniform.**
- **Aerosol deposition density is found to be higher on the bottom side of the tube and decreases with height.**

Results and Discussion

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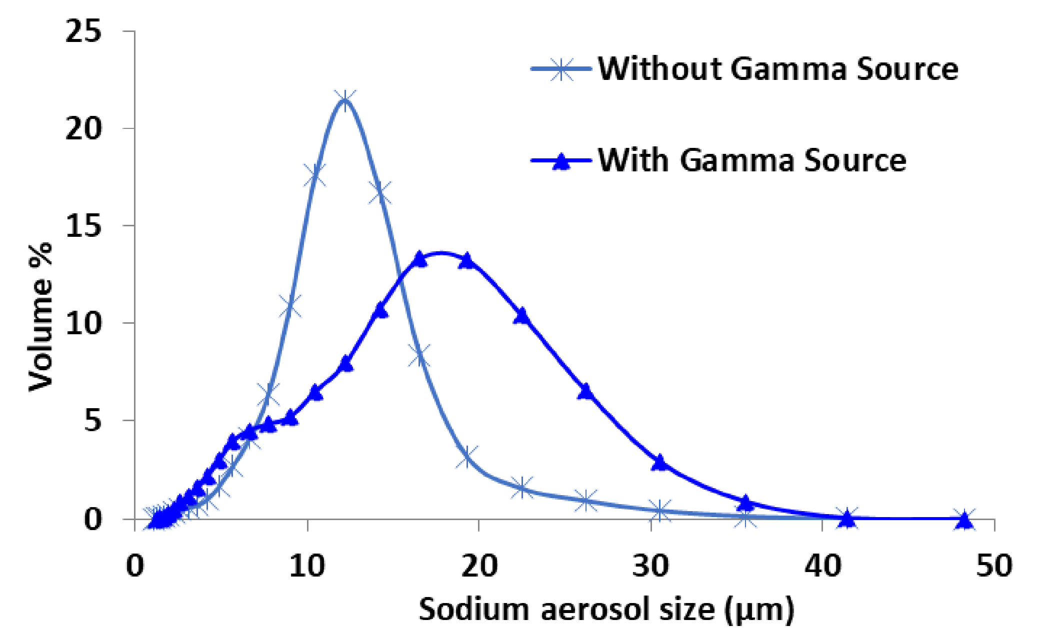
Effect of ionizing radiation on properties of sodium metal aerosol

- Co-60 source (Activity - 4.52 mCi) encapsulated in steel capsule → used for irradiation or ion-pair production.
- Absorbed dose in the cover gas region would be 1.69 mR which corresponds to the production of 1.75 x 10^9 ion-pairs/s.

(1R produces 2.08 x10^{15} ion-pairs/m^3)



Pool Temperature (K)	Without γ Source		With γ Source	
	MMD (µm)	C (g/m³)	MMD (µm)	C (g/m³)
723	6.5	13.6	9.7	9.9
773	8.7	18.1	12.1	14.6
823	10.6	30.6	13.8	27.4

Kumar et al., Influence of Gamma radiation on sodium metal aerosol characteristics in inert gas, IARPIC -2018, Mumbai, India.

Analytical equation for estimation of mean charge

Charging theories	Equation for charge distribution	Equation for mean charge
Boltzmann distribution	$N_j = N_t \frac{e}{(8\pi^2 \varepsilon_o akT)^{1/2}} \exp(\frac{-j^2 e^2}{8\pi \varepsilon_o akT}),$	$< j >= \frac{\sum_0^\infty j\, N_j}{\sum_0^\infty N_j} = \frac{\sqrt{8\varepsilon_o akT}}{e},$
Gaussian distribution	$N_j = N_t \frac{e}{(8\pi^2 \varepsilon_o akT)^{1/2}} \exp[\frac{-\{j - \frac{4\pi\varepsilon_o akT}{e^2} \ln\left(\frac{n_+\mu_+}{n_-\mu_-}\right)\}^2}{2(\frac{4\pi\varepsilon_o akT}{e^2})}],$	$< j >= \frac{\sum_{-\infty}^{+\infty} j\, N_j}{\sum_{-\infty}^{+\infty} N_j},$
Modified Boltzmann distribution	$\frac{N_j}{N_f} = [\frac{n_+\mu_+}{n_-\mu_-}]^j \frac{8\pi\varepsilon_o akT}{je^2} \sinh(\frac{je^2}{8\pi\varepsilon_o akT}) \exp(\frac{-j^2 e^2}{8\pi\varepsilon_o akT}),$	$< j >= \frac{\sum_{-\infty}^{+\infty} j\, N_j}{\sum_{-\infty}^{+\infty} N_j} = \frac{4\pi\varepsilon_o akT}{e^2} \ln\left(\frac{n_+\mu_+}{n_-\mu_-}\right),$

- **Charge on aerosol depends on (i) aerosol diameter, (ii) Temperature of the gas, and (iii) mobility and concentration of the ions.**

- **Mobility of ions also depends on the mass of ions, gas temperature and pressure, and type of gas of the environment.**

Mobility of ions can be extrapolated for any pressure and temperature condition → $\mu = \mu_0 \frac{P_0}{P} \sqrt{\frac{T}{T_0}},$

Estimated mean charge on sodium aerosol

Tp (K)	T_{bg} (K)	Argon gas (μ_+/μ_-=0.824)				Nitrogen gas (μ_+/μ_-=0.930)			
		MMD (µm)	Average charge (j)			MMD (µm)	Average charge (j)		
			Boltzmann	Gunn	MBD		Boltzmann	Gunn	MBD
523	392	1.52	3.37	-3.47	-3.65	3.91	5.41	-3.33	-3.46
573	435	2.92	4.91	-7.35	-7.49	5.60	6.80	-5.25	-5.39
623	452	3.95	5.84	-10.40	-10.51	6.51	7.50	-6.38	-6.52
673	473	5.10	6.78	-14.02	-14.10	7.11	8.01	-7.28	-7.42
723	502	5.92	7.53	-17.31	-17.36	8.52	9.04	-9.28	-9.41
773	543	8.07	9.14	-25.47	-25.45	9.91	10.13	-11.65	-11.77
823	603	9.62	10.52	-33.71	-33.08	11.15	11.32	-14.55	-14.63

- **Average charge calculated by Boltzmann's theory is the magnitude of the charge on aerosols.**
- **Average charge on aerosol is negative polarity and increases with the increase of aerosol diameter.**
- **Charge predicted by Gunn and MBD theory in good agreement and the variation between them is less than ± 5%.**

Approximations

- Sodium aerosol size distributed from 1 – 40 µm, the MMD of aerosols has been taken for the average charge estimated.
- Bulk cover gas temperature is used for estimation of mean charge; however, the temperature distribution is not uniform throughout the cover gas space.
- Positive and negative ions concentrations are equal. In an actual case, they may not be equal.
- Mobility of ions is a distribution function, but the average value has been taken for charge estimation.
- Mobility of ions is taken from literature, which is measured at room temperature and pressure. The same is extrapolated for high temperatures, the actual value is unknown or uncertain and may differ in the reactor conditions.

Consequences of the charge on aerosol

- The aerosol deposition to the sodium pool may be also enhanced because aerosol size distribution has become wider, and the mean aerosol size is also higher.

- The suspended equilibrium aerosol concentration is found to be lower than that of the non-ionic field.

- Deposition of aerosol to the cooler part and annular gap of the roof structures will be enhanced under the ionic field because charged aerosol deposits at a faster rate on conducting surfaces based on the electrostatic and dielectrophoretic force.

- Aerosols are found to be charged (based on MBD), and the mean charge is negative polarity. The FP vapors (Cs) may get enhanced trapping with sodium aerosols under charged conditions.

- FP (Cs) vapors are positively charged, and the magnitude of charge increases in lower charged aerosol concentrations. There will be additional trapping due to charged aerosols when compared to uncharged aerosols.

Conclusions

The average charge on sodium aerosol is negative and increases with the increase of aerosol diameter, i.e., the temperature of the sodium pool surface.

Charged aerosol inside the cover gas region will promote the aerosol size growth and enhances the depositions in the roof structure, annular gaps & sodium pool surface, which may reduce the equilibrium mass concentration.

The magnitude of the charge on aerosol is estimated based on the asymmetry of ion mobilities. Few other processes can modify the magnitude of mean charge, like charging induced by photon interaction with sodium aerosol, diffusion of ions to the walls surface of cover gas space, and if aerosol particle and inert gas (in case of argon) itself radioactive.

Scope of the further work

- **The theoretical study will be extended to assess the growth rate of aerosol size and deposition enhancement factor and their influence on aerosol characteristics and deposition in the annular/ narrow gaps.**

- **Fission products (Cs and iodine) trapping/ attachment to the aerosol inside cover gas space.**

- **Development of a theoretical model for aerosol dynamics to study the thermal-hydraulics inside the cover gas region and deposition in the various annular gaps.**

Acknowledgment

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- ✓ The authors wish to acknowledge Mr. S. Chandramouli, Head RIG Operation Section, and Mr. S. Krishnakumar for their help in conducting the experiments.

Thank you for your kind attention

- Any questions and valuable suggestions?