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Studies on Geometrical Effect on Sodium Aerosol Characteristics in Cover Gas Region

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ABSTRACT

Sodium aerosol characteristics in the cover gas region of sodium cooled fast reactor is important for determining the heat and mass transfer phenomena from the hot sodium pool surface to the roof slab of the reactor vessel. In this study, experiments are carried out in the Test Pot-3 (TP-3) of SILVERINA loop and sodium aerosol characteristics are compared with that of Test Pot-1 (TP-1) carried out in our earlier work and with previous similar type of work available in the literature to understand the geometrical effect of sodium aerosol characteristics. The bulk cover gas temperature and sodium aerosol diameter are required as input parameters for the theoretical simulation of sodium aerosol mass concentration. An empirical relation for bulk cover gas temperature is derived and validated with our experimental results and used for other geometries. Similarly, an empirical relation for sodium aerosol diameter is arrived based on our experimental results and available published works. The theoretical model developed earlier for the prediction of sodium aerosol mass concentration is used for calculating the aerosol mass concentration for various geometries, by incorporating new relation for particle diameter and bulk cover gas temperature. The simulated mass concentration of sodium aerosol in cover gas region of various studies showed good agreement with the experimental results. The sodium aerosol mass concentration and Mass Median Diameter (MMD) increases with increase of sodium pool temperature. However, the values are strongly dependent on the aspect ratio (L/D) of cover gas geometry. It is also observed that MMD of sodium aerosols increases with increase of aspect ratio (L/D) while mass concentration increases with decrease of aspect ratio of the cover gas region. The modeling is found useful in predicting the sodium aerosol mass concentration for similar type of geometries and pool temperature.

Keywords: Sodium aerosol characteristics; Cover gas region; Geometrical effect; Particle radius and bulk cover gas temperature.

INTRODUCTION

In pool type sodium cooled fast reactor (SFR), reactor core, primary sodium pumps, intermediate heat exchange systems, decay heat exchangers etc. are immersed in sodium pool in the reactor vessel. Argon is used as cover gas, which serves as blanket above the sodium pool in the reactor vessel. The reactor vessel is closed by using a top shield above the cover gas region. The sandwiched region between the surface of hot sodium pool and the top shield (called as roof slab) of the reactor vessel is called as cover gas region (Sinai *et al.*, 1993). The schematic diagram of cover gas region (cylindrical in shape) is shown Fig. 1. Fig. 1 describes diameter of the sodium pool (D) and height of the cover gas region (L) having boundary on the bottom side with sodium pool, on top side with roof slab and at the side with wall of the reactor vessel. The temperatures of the corresponding regions are described as Tp, Tr, Tm and Tw as sodium pool temperature, bottom of roof slab temperature, bulk cover gas temperature and wall temperature respectively. In the cover gas region, there exist pool boundary layer near the sodium pool and roof boundary layer near the roof slab due to temperature gradient near the sodium pool and roof slab respectively. The roof slab supports, rotatable plugs, control plug, in-vessel fuel handling machine, primary sodium pumps, intermediate heat exchangers, and decay heat removal systems. In the normal operating condition of SFR, the temperature difference between the sodium pool and the bulk gas temperature leads to considerable evaporation of sodium from the pool surface and subsequent condensation results in the formation of sodium aerosol within the cover gas region (Ford *et al.*, 1993) either by heterogeneous

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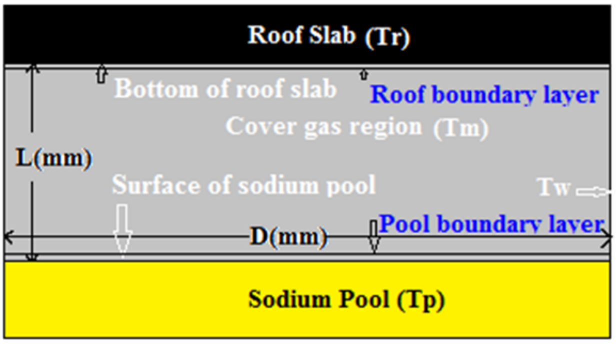

Fig. 1. Schematic diagramme of cover gas region, sodium pool and roof top.

nucleation or self-nucleation (homogeneous nucleation). When these aerosols have sufficient concentration, they would modify the total heat transfer to the cooled roof structure by absorption and scattering mechanisms. Further, the mass transfer occurs due to condensation of sodium aerosols on the cooler surfaces like annular gaps, roof top, control plug, rotating plugs and fuel handling machine resulting deposition of aerosols, which hinders the rotational movement of rotating plug and operation of fuel handling machine (Roberts, 1995). The aerosol mass concentration influences the operation of cover gas purification system and reduces its efficiency (flow through cold trap circuit). Also, the aerosols with sufficient concentration reduce the visibility of cover gas region [Core inspection facility in RAPSODIE, France and Fast Breeder Test Reactor (FBTR), India].

In the reactor design, conservative approach without taking into account of aerosols characteristics has been considered for the heat and mass transfer phenomena. However, it is at most important to know the aerosol mass concentration and aerosols size distribution in order to predict effectively the heat and mass transfer phenomena, which may get changed due to interaction of thermal radiation with aerosols and mass transfer due to condensation of aerosols. Towards this, as a part of aerosol studies related to fast reactor program, characterization of sodium aerosols in the cover gas region has been initiated in Radiological Safety Division (RSD) Indira Gandhi Center for Atomic Research (IGCAR), India. The studies are performed in one of the sodium test pot (TP-1) of sodium loop facility called SILVERINA loop in Fast Reactor Technology Group (FRTG), IGCAR (Chandramouli *et al.*, 2006) and significant results have been obtained. The study began by sampling metal aerosol without exposing to atmosphere in Aerosol Test Facility (ATF) and characterization techniques is validated in SILVERINA Loop (Kumar *et al.*, 2014), followed by, experimentation in TP-1 of SILVERINA loop to determine sodium aerosol mass concentration and size distribution for various pool temperatures (250–550°C). The salient results of the experiments are summarized as: (i) the mass concentration in cover gas region is found to vary in the range of 0.026–35.6 g m^{-3} and the MMD is found to vary in the range of 1.5–11.5 µm for pool temperature 250–550°C respectively, (ii) the sodium aerosol mass concentration increases with increase of sodium pool temperature according to polynomial function and the MMD of sodium aerosol increases linearly with increase of sodium pool temperature, (iii) the mass concentration and MMD of sodium aerosol is found to be larger near the pool surface than near the top flange and middle region of cover gas (Kumar *et al.*, 2015a). The temperature profile of the cover gas region was measured at various heights viz. 0, 10, 35, 100, 300, 700, 800 and 820 mm from the top flange. The temperature profile is found to follow similar pattern in accordance with available literature. A theoretical simulation has been developed to predict the sodium aerosol mass concentration in cover gas region by taking input from experimental value of sodium aerosol diameter and dimension of cover gas region of TP-1. A good agreement has been observed for the sodium aerosol mass concentration between theoretical prediction and experimental measurements (Kumar *et al.*, 2015a).

At this juncture, it is inferred from the literature that, the dimension of cover gas region influences the aerosol characteristics. It is observed from the studies by Himeno and Takahashi (1980), Himeno and Yamagishi (1982), Frukawa *et al.*, (1984), Glockling (1991), Minges and Schutz (1991), Yamamoto *et al.* (1991), Minges and Schutz (1993), Newson *et al.* (1993) and Roberts (1995), the sodium aerosol characteristics (size distribution and mass concentration) are different for different geometries. The variation of sodium aerosol characteristics in the cover gas region for different geometries for different pool and roof temperatures are shown in Table 1. It is noted from the Table 1 that, the sodium aerosol characteristics depend on geometry of the vessel (L/D ratio, where L - height of cover gas region and D - diameter of sodium pool), in addition to the pool and roof temperatures. To confirm the above experimental observations, experiments have been carried out in another Test Pot (TP-3) of SILVERINA loop and sodium aerosols characteristics are determined. The L/D ratio of TP-3 is 1.875, which is higher than that of TP-1 (1.075) i.e., smaller vessel than TP-1. (The description of TP-3 given in Materials and Methods section). Further, in this work, an empirical relation is derived from our experimental results of TP-1 and TP-3 to predict the temperature of the bulk cover gas region and applied for predicting the bulk cover gas temperature for other studies. The sodium aerosol diameter (MMD) is arrived through an empirical relation based on our experimental results of TP-1 and TP-3 of SILVERINA loop and for the available published work by Himeno and Takahashi (1980),

Table 1. Variation of sodium aerosol characteristics in the cover gas region for different geometries.

	L/D	Pool Temp. (°C)	Roof Temp. (°C)	MMD (µm)	Mass Conc. (g m^{-3})
TP-1	1.076	250–550	85–140	1.5–11.5	0.6–30.6
Yoshiaki	4.516	300–550	120	6.0–26.0	0.2–20.0
Glockling	2.333	300–550	150	3.3–13.5	0.5–36.5
Minges	0.55	350–550	120	3.5–8.5	1.5–40.0

Glockling (1991) and Minges and Schutz (1991). It is to be noted that all the above experiments were carried out by varying sodium pool temperature only. In this paper, the details of the experimental results obtained from TP-3 of SILVERINA loop, the empirical relations for bulk cover gas temperature and the sodium aerosol diameter are presented. The validation of our theoretical simulation on aerosol mass concentration with the experimental results of TP-1, TP-3 and the experimental results published by Himeno and Takahashi (1980), Glockling (1991) and Minges and Schutz (1991) are also presented.

MATERIALS AND METHODS

A detailed description on SILVERINA Loop system with test pot-1 (TP-1), sampling system and experimental procedure are described in our earlier work (Kumar *et al.*, 2015a). In this paper, a brief note on test pot-3 (TP-3), sampling system and experimental procedure pertaining to current experiments are given in the following section.

Test Pot (TP-3) of SILVERINA Loop

SILVERINA loop is a dynamic sodium loop facility with an electromagnetic pump, cold trap, plugging indicator, sodium sampler, heater vessel, interconnecting pipe lines, bellows sealed valves, flow meters and cover gas purification circuit. Sodium is filled in to the loop from a storage tank with a capacity of 1300 kg (Chandramouli*et al.*, 2006; Kumar *et al.*, 2014). A schematic diagram of sodium aerosol sampling system installed in TP-3 along with TP-3 vessel is shown in Fig. 2. The vessel is made with SS316. Sodium heating is provided by four number of Expanded Cold Region (ECR) heaters fixed on the surface of vessel to keep the sodium in liquid state. In this vessel two heaters will be in service and two will be spares. The height and internal diameter of the TP-3 vessel are 1600 mm and 400 mm respectively and the height of the cover gas region is 750 mm. The total volume and quantity of sodium holdup in TP-3 are 0.208 m^3 and 0.11 m^3 respectively. The top flange of TP-3 is provided with three nozzles for sodium level indication (low, middle and high levels) and a spare nozzle. The spare nozzle is used for aerosol measurement.

Sampling System

The aerosol sampling system consists of (a) Aerosol sampling tube, (b) Aerosol sampling bottle, (c) Line Heaters and controller and (d) Aerosol flow controlling device. [The detailed description of the above systems is described in our earlier work (Kumar *et al.*, 2015a)]. In the present experimental set-up, the portion of the sampling tube which goes inside TP-3 has been fabricated with a length of 385 mm to enable the sampling at the middle level. Before starting the experiment the sampling tube is attached with the flange and inserted into TP-3. The aerosol sampling tube is made of SS316 with internal diameter of 10 mm (1.5 mm wall thickness). The maximum particle diameter that can be collected is 20 µm, without having bias due to wall deposition by impaction for a flow rate of 2 L min^{-1} (Hinds, 1982).

The sampling bottle is filled with paraffin oil (~600 mL) and maintained at ambient temperature. The sodium aerosol laden cover gas is made to pass through the bottle, thus solidification of aerosol particles would occur as the cover gas enters into the paraffin oil. The residence time of the cover gas is increased due to baffle arrangement, which ensures that all sodium aerosols get trapped from the cover gas before it goes out of the bottle. The cover gas coming out from the sampling bottle # 1 is made to pass through sampling bottle # 2 so as to remove aerosols escaped if any, from the 1st bottle. After sampling, the sample bottles are removed from the loop and paraffin oil is drained for analysis. To prevent sodium aerosol solidification within the sampling tube during experimental measurements, the wall temperature of the sampling tube is maintained above 110°C. The gas flow through the sampling bottles is regulated by using a rotameter. A glass fiber filter of 25mm was used to prevent aerosols escaped, if any, after the 2nd bottle.

Before the experiment, pressure holdup test for sampling tube and gate valve has been carried out by pressurizing TP-3 up to 0.5 kg cm^{-2} above atmosphere. The functioning of surface heaters, temperature controller and thermocouples (fitted in the sampling line) has been checked by heating the heater up to 150°C.

Temperature Measurement System

A photograph of the sampling system along with temperature measurement system is shown in Fig. 3. The pool, roof and bulk cover gas temperatures are important parameters for the theoretical simulation of aerosol mass concentration in cover gas region of SILVERINA loop. Hence a similar type of temperature measurement system as described in Kumar *et al.* (2015a) for TP-1, has been fabricated with matched top flange for the aerosol port. It consists of vertical cylindrical shaft welded below the top flange with six grooves to insert 6 thermocouples which are terminated at six different heights. Temperature was measured by using chromel-aluminium K-type thermocouples at the six locations in the cover gas region. The temperature measurement locations from the top of flange are (i) roof surface (0 mm), (ii) one location near to the roof surface (90 mm), (iii) three locations on the middle of the cover to gas region (200 mm, 300 mm and 500 mm) and (iv) one

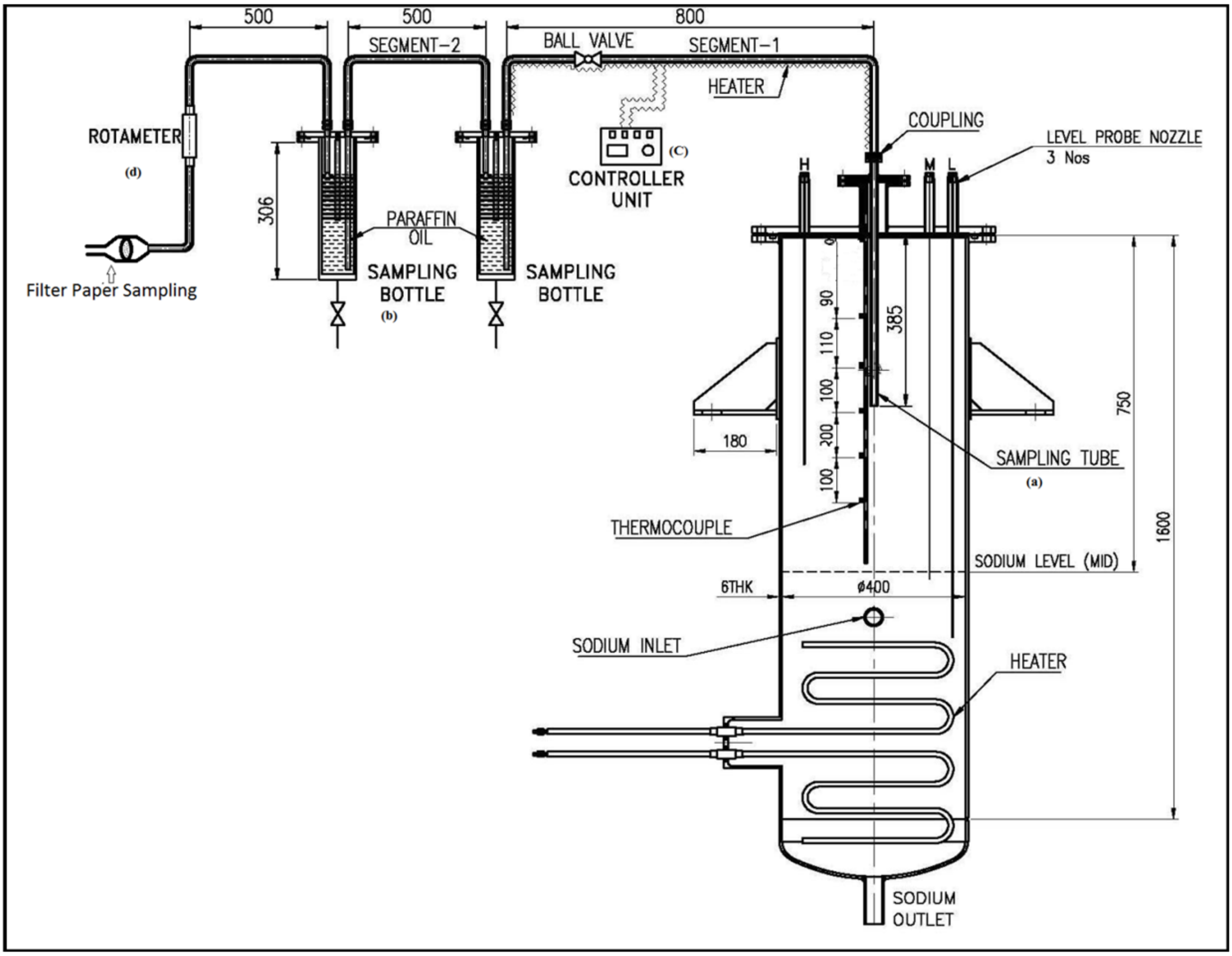

Fig. 2. A schematic diagram of sodium aerosol sampling system installed in TP-3 of SILVERINA loop.

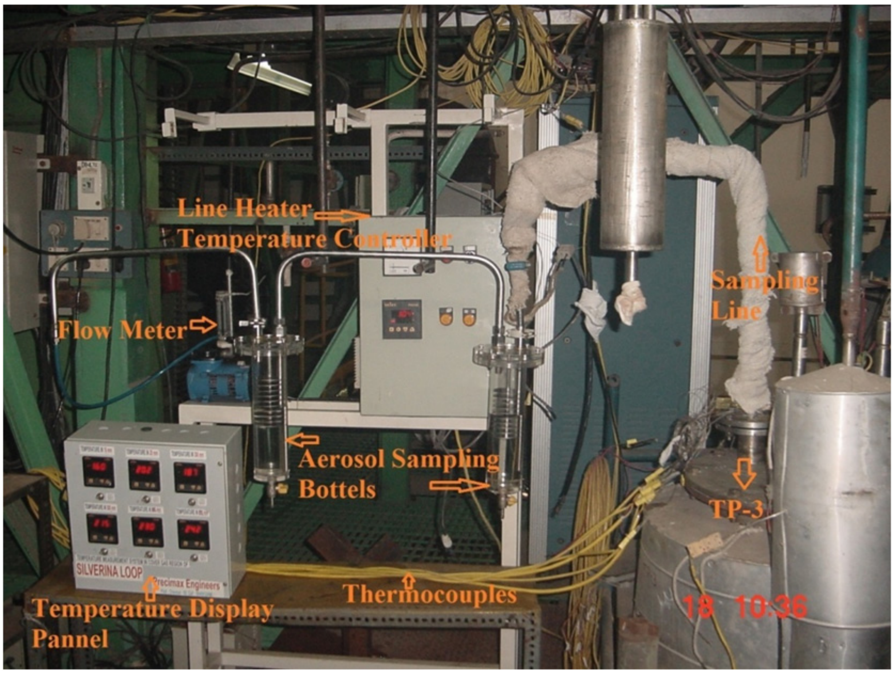

Fig. 3. A photograph of the aerosol sampling system along with temperature measurement system.

location near the sodium pool surface (600 mm). Sodium pool temperature is measured separately. Accordingly, the thermocouples were terminated at 600 mm, 500 mm, 300 mm, 200 mm, 90 mm, and 0 mm from bottom surface of the top flange. Each thermocouple is connected with 3½ - digit digital indicator.

SAMPLING AND ANALYSIS

Aerosols are drawn from the cover gas region and allowed to get trapped in liquid paraffin oil medium without exposing them to atmosphere. After isolating the bottles from the system the sampling bottles were taken for analyzing the samples. The size distribution of sodium aerosols is determined by using Mastersizer (M/s Malvern Instruments, UK). The measurement of sodium aerosol mass concentration is carried out by conductivity method (M/s Metrohm, 856 conductivity module, Switzerland). The details are described in Kumar *et al.* (2014).

The sodium pool temperature was varied from 250–550°C in step of 50°C. The cover gas (argon gas) is made to bubble through liquid paraffin oil at a flow rate of 2 L min^{-1}. The sampling time is varied from 10 minute to 2 minute according to sodium pool temperature. Since the sodium aerosol mass concentration increases with increase of sodium pool temperature and in order to avoid coagulation of aerosol trapped in the paraffin oil, the sampling time was kept for 10 minutes for the pool temperature 250°C and progressively reduced to 2 minutes when pool temperature is 550°C. Test runs showed that, up to 50 mg of trapped sodium aerosol mass in the bottle, the coagulation of aerosols was not noticed for next 24 hrs after sampling.

RESULTS AND DISCUSSION

Temperature Profile in TP-3

The temperature profile in TP-3 of cover gas region is measured by varying sodium pool temperature from 250–550°C. The temperature profiles of the cover gas region with cover gas height for various pool temperatures are shown in Fig. 4. It is observed that, temperature profile is found to follow a similar pattern as found in the literature (Roberts, 1995) and the results obtained in TP-1 (Kumar *et al.*, 2015a). The temperature started decreasing from the pool surface (750–600 mm) - region C, then has almost uniform temperature region (600–90 mm) for about 500 mm height - region B, and decreases towards roof temperature (90–0 mm) - region A. The temperature of the roof top found to vary from 90 to 160°C for the sodium pool temperatures from 250 to 550°C respectively.

Determination of Bulk Cover Gas Temperature

Bulk cover gas temperature is an important parameter for theoretical prediction of aerosol mass concentration. In order to arrive bulk cover gas temperature, an empirical relation is derived based on area and temperatures of sodium pool, roof and wall surface and it is given as:

$$Tm = \left(\frac{Tp \times Ap + Tr \times Ar + Tw \times Aw}{(Ap + Ar + Aw)} \right) \quad (1)$$

where Tm - is the bulk cover gas temperature,
Tp, Tr and Tw are the sodium pool, roof and wall surface temperatures respectively,
Ap, Ar and Aw are the area of sodium pool, roof and wall surface respectively.

The above empirical relation is validated with the experimentally measured temperature from 250–50°C of the cover gas region of TP-1 and TP-3 and it is given in Table 2. It is noted from Table 2 that, the predicted cover gas temperature is always higher compared to the experimentally measured cover gas temperature for TP-1 and TP-3. The variation in the experimental and estimated bulk cover gas temperature is well within 10%. Since, the bulk cover gas temperature is not available in the published other works,

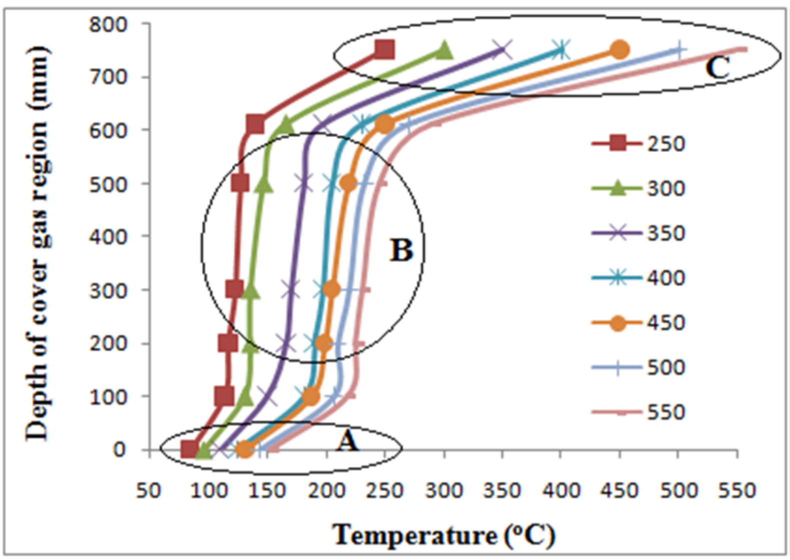

Fig. 4. The variation of temperature in cover gas region with cover gas height for various pool temperatures for TP-3.

Table 2. Comparisons of predicted and experimentally measured cover gas temperature (Tm) for various pool temperatures of TP-1 and TP-3.

Tp (°C)	TP-1				TP-3			
	Tr (°C)	Tw (°C)	Tm (°C) Exp.	Tm (°C) Estimated	Tr (°C)	Tw (°C)	Tm (°C) Exp.	Tm (°C) Estimated
250	85	120	120	135	85	120	120	130
300	95	160	160	172	95	140	140	152
350	105	180	180	195	110	170	170	182
400	110	200	200	217	125	190	190	205
450	120	230	230	247	130	210	210	226
500	130	270	270	284	145	230	230	249
550	140	330	330	335	160	260	260	279

this empirical relation [Eq. (1)] is used for predicating the bulk cover gas temperature for the geometry of other works.

Aerosol Characteristics in TP-3

The MMD obtained for middle level of cover gas region for various pool temperatures of TP-3 is shown in Fig. 5 and it is found to vary from 2.1 to 16 µm. It is observed from Fig. 5 that, MMD found to increase linearly with increase of sodium pool temperature. Fig. 5 also includes linear fitted equation for MMD with temperature of the sodium pool for TP-3. The mass concentration of the sodium aerosols is found to vary from 0.04–21.98 g m^{-3}. The variation of sodium aerosol mass concentration for various pool temperatures is shown in Fig. 6. It is observed that, the mass concentration increases with increase of sodium pool temperature and found to fit polynomial regression.

In the cover gas region, there exists convection current due to thermal gradient between hot pool surface and bottom of the roof slab. The aerosols, formed due to evaporation of vapor for a particular temperature of the pool surface, are carried by the convection current, undergo coagulation and reaches steady state value. Further, the cover gas region is being maintained at a positive pressure of 0.5 kg cm^{-2} before starting of every sampling. The positive pressure ensures the uniform distribution of aerosols through-out the region and sampling flow rate of 2 L min^{-1} without any pump. Besides, aerosol deposition does occur on colder roof slab when the particles enter into the upper boundary layer. We have noticed in our experiment in TP-1 and TP-3, for a given difference in temperature between pool surface and roof slab, the steady state condition is reached in about 20–30 minutes. The measured values of concentration and diameter are after this period. Hence, hydrodynamic condition in cover gas region viz., convection current, aerosol deposition and sampling flow rate are taken care once steady state values are reached.

Theoretical Simulation

A theoretical simulation for the aerosol mass concentration in the cover gas region is formulated in our earlier work (Kumar *et al.*, 2015a, b) using mass and number concentration decay equation by including the effect of continuous source term and various removal mechanisms (Sheth *et al.*, 1975). A first order differential equation is formulated to predict the equilibrium mass and number concentrations of the sodium aerosols in cover gas region. In this model, the input parameters are (i) temperature of sodium pool surface, roof and bulk cover gas, (ii) geometry of the vessel (diameter of the pool surface and height of the cover gas region) for a given cover gas region and (iii) initial radius of aerosol. In our earlier work, the initial radius is taken from the linearly fitted equation derived from the actual measurement in that cover gas region. This approach requires sampling of sodium aerosol from the cover gas region.

To improve theoretical modeling for predicting the sodium aerosol characteristics in cover gas region for different geometry, an empirical relation has been derived to predict the particle size of aerosols and validated with the experimental results obtained from our works in TP-1 and TP-3 (Himeno and Takahashi, 1980; Glockling, 1991; Minges and Schutz, 1991). The empirical relation includes variation of L/D ratio and sodium pool temperatures. The empirical relation for aerosol radius is arrived as:

$$R = \left(\frac{Ro}{2}\right) \times \left(0.5046 \times \frac{L}{D} + 1.0634\right) \times \left(\frac{Tp}{\mathrm{Tpi}}\right)^{2.5} \quad (2)$$

where R - radius of aerosol at Tp (µm),
Ro - 1.0 µm, (radius of aerosol at Tpi)
L- height of cover gas region (mm),
D - diameter of the sodium pool (mm),
Tp - Sodium pool temperature (°C),
Tpi - Temperature at which measurable aerosol mass concentration is observed which is 250°C.

It is observed in our study (in TP-1 and TP-3), sodium aerosol mass concentration is measurable at sodium pool temperature of 250°C. The average aerosol diameter (MMD) measured is around 2.0 µm. Hence, we have taken radius R_0 as 1.0 µm. By using this empirical relation, the sodium aerosol radius is estimated for any geometry and for all pool temperatures (250°C–550°C). The estimated and experimentally measured sodium aerosol diameter (MMD) for various pool temperatures of TP-1, TP-3 (Himeno and Takahashi, 1980; Glockling, 1991; Minges and Schutz, 1991) are given in Table 3. The variation of MMD versus sodium pool temperature for various L/D ratios for both experimentally determined values and empirically fitted equation is shown in Fig. 7. It is observed from Fig. 7 that, for a given pool temperature the value of MMD is found to

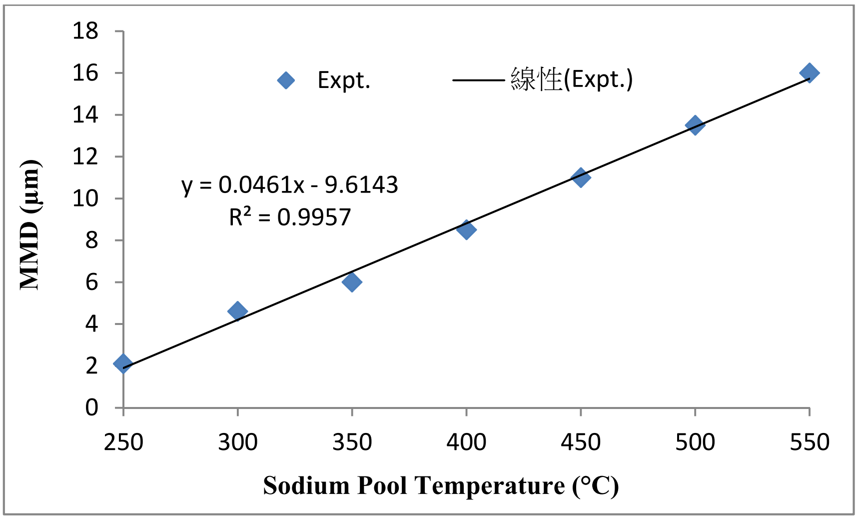

Fig. 5. MMD of sodium aerosol in the middle region of the cover gas of TP-3 for various pool temperatures.

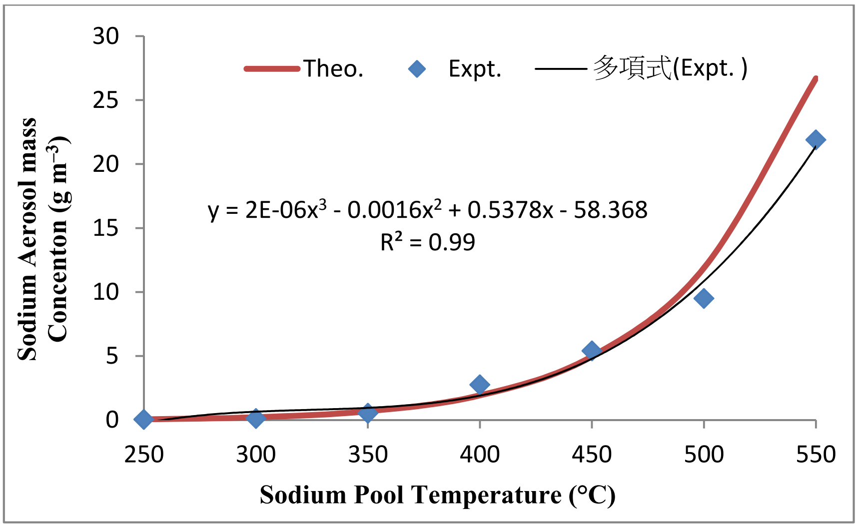

Fig. 6. Sodium aerosol mass concentration (simulated and expt.) in the middle region of cover gas of TP-3 for various pool temperatures.

Table 3. Comparison of estimated and experimentally measured sodium aerosol diameter (MMD) for various pool temperatures of TP-1, TP-3 (Himeno and Takahashi, 1980; Glockling, 1991; Minges and Schutz, 1991).

Pool Temperature (°C)		250	300	350	400	450	500	550
Minges (L/D-0.55)	Exp. MMD (µm)			3.5	4.5	6	7.2	8.5
	Theo. MMD (µm)			3.11	4.34	5.83	7.58	9.63
	Variation (%)			11.14	3.55	2.83	5.27	13.29
TP-1 (L/D-1.076)	Exp. MMD (µm)	1.5	2.89	4.33	5.44	6.47	8.86	11.5
	Theo. MMD (µm)	1.61	2.53	3.73	5.2	6.98	9.09	11.53
	Variation (%)	7.33	12.45	13.85	4.41	7.88	2.59	0.26
TP-3 (L/D-1.875)	Exp. MMD (µm)	2.11	3.95	5.62	7.59	10.81	12.85	15.79
	Theo. MMD (µm)	2.01	3.17	4.66	6.51	8.75	11.37	14.43
	Variation (%)	4.73	19.74	17.08	14.22	19.08	11.51	8.61
Glockling (L/D-2.333)	Exp. MMD (µm)		3.43	6.45	8.58	9.72	11.24	13.55
	Theo. MMD (µm)		3.53	5.19	7.25	9.73	12.67	16.07
	Variation (%)		2.91	19.53	15.5	0.1	12.72	18.59
Yoshiaki (L/D-4.516)	Exp. MMD (µm)		6	7.9	11	14.6	19.5	26
	Theo. MMD (µm)		5.27	7.75	10.82	14.53	18.91	23.99
	Variation (%)		12.16	1.89	1.63	0.47	3.02	7.73

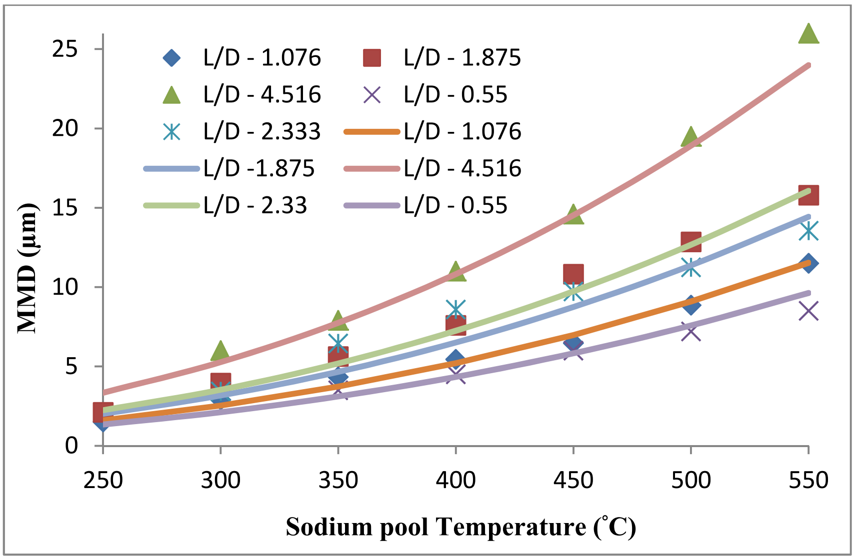

Fig. 7. Variation of MMD (Expt. and Theo.) with sodium pool temperature for various L/D ratio.

Table 4. Comparison of theoretically predicted and experimentally measured sodium aerosol mass concentration for of TP-1, TP-3 (Himeno and Takahashi, 1980; Glockling, 1991; Minges and Schutz, 1991).

Pool Temperature (°C)		250	300	350	400	450	500	550
Minges (L/D-0.55)	Exp. C (g m^{-3})			1.52	5.39	11.86	20.39	40
	Simulated C (g m^{-3})			1.31	3.73	8.72	18.02	33.39
	Variation (%)			13.81	30.79	26.47	11.62	16.52
TP-1 (L/D-1.076)	Exp. C (g m^{-3})	0.06	0.33	1.85	4.95	12.02	18.12	30.62
	Simulated C (g m^{-3})	0.06	0.33	1.31	3.75	9.59	17.89	34.11
	Variation (%)	0	0	29.18	24.24	20.21	1.26	11.39
TP-3 (L/D-1.875)	Exp. C (g m^{-3})	0.04	0.17	0.69	2.01	5.12	11.97	21.98
	Simulated C (g m^{-3})	0.05	0.21	0.89	2.61	6.45	14.46	28.67
	Variation (%)	25	23.52	28.98	29.85	25.97	20.8	30.43
Glockling (L/D-2.333)	Exp. C (g m^{-3})		0.47	1.24	5.22	11.12	22.41	36.13
	Simulated C (g m^{-3})		0.34	1.39	3.83	8.92	18.33	33.87
	Variation (%)		27.65	12.09	26.62	19.78	18.2	6.25
Yoshiaki (L/D-4.516)	Exp. C (g m^{-3})		0.21	1.39	2.45	6.51	12.14	20
	Simulated C (g m^{-3})		0.26	0.98	2.52	5.79	11.51	20.89
	Variation (%)		23.8	29.49	2.85	11.05	5.18	4.45

increase with increase in L/D ratio. Moreover, the MMD is found to increase with increase of pool temperature for a given geometry (L/D) of the cover gas region and found to follow super-linear pattern with increase of L/D value, i.e., for smaller diameter vessel. The large MMD value and super-linearity can be the result of enhanced coagulation of the aerosols during convection motions in the smaller cover gas region. It is also observed from Fig. 7, for L/D ratio of 0.55, the MMD follows linear pattern. The condition of super-linearity is observed for L/D values of 2.33 and 4.516. Hence, empirical relation is formulated with exponent 2.5 to accommodate the increment of size with increase of pool temperature for different geometry starting from 0.55 to 4.516. It is noted from the Table 3 that, the deviation of estimated and experimentally measured sodium aerosol size (MMD) is within ± 20% for all cases. The empirical relation is found useful in predicting all the conditions satisfactorily.

Once we know the radius of aerosol, temperature of the sodium pool, roof, and wall and geometry of cover gas region (diameter of the sodium pool and height of cover gas region), the sodium aerosol mass concentration in the cover gas region is estimated using the theoretical model developed earlier. Based on the theoretical formulation, sodium aerosol mass concentration is predicted for our experiment TP-3 and it is included in Fig. 6. Further the theoretical simulation for mass concentration is carried out for our works in TP-1, TP-3 and from available in literature i.e., works from Himeno and Takahashi (1980), Himeno and Yamagishi (1982), Glockling (1991) and Minges and Schutz (1991, 1993) and it is given in Table 4. It is noted from the Table 4 that, the maximum variation of theoretically simulated sodium aerosol mass concentration and experimentally measured aerosol mass concentration is found to be ± 30%. The theoretical modelling is found useful to predict the sodium aerosol mass concentration with respect to pool temperature for a given geometry of the vessel. The present study helps to predict the aerosol mass concentration for any similar geometry.

SUMMARY

A new set of experiments are carried out in TP-3 of SILVERINA loop and compared with results of TP-1 (our earlier study) and with published literature works to understand the geometrical effect on sodium aerosol characteristics. The bulk cover gas temperature and sodium aerosol diameter are used as an input parameter for theoretical simulation of sodium aerosol mass concentration. An empirical relation for bulk cover gas temperature is derived and validated with our experimental results and used for other geometry. Similarly, an empirical relation for sodium aerosol diameter is derived based on our experimental results and from available published works. The theoretical model developed earlier is used for predicting the sodium aerosol mass concentration in which, the particle radius and bulk cover gas temperatures are replaced with present empirical relation for calculating particle radius and bulk cover gas temperature taking in to account of aspect ratio (L//D) and area of the cover gas region respectively. The simulated mass concentration of sodium aerosols in cover gas region of various studies showed good agreement with the experimental results. The sodium aerosol mass concentration and MMD increases with increase of sodium pool temperature. However, the values strongly depend on the aspect ratio (L/D) of cover gas geometry. It is also observed that MMD of sodium aerosols increases with increase of aspect ratio (L/D) while mass concentration increases with decrease of aspect ratio of the cover gas region. The modeling is found useful in predicting the sodium aerosol mass concentration for any similar type of geometry and pool temperature.

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