ACOUSTIC AND TURBULENT AGGLOMERATION OF SODIUM AEROSOLS

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Abstract

The suitability of 6 packing materials for removal of sodium fire aerosols in a wet cell scrubber was evaluated experimentally by measuring the efficiency and flow resistance of two 10.2 cm deep cells in series at air face velocities of 185 and 289 cm/sec, water flow rates of 0.210 and 0.387 cm³/sec/cm², with and without aerosol prehumidification. The most satisfactory material was found to be 50 µm diameter stainless steel fibers at a packing density of 30 kg/m³ (porosity = 0.99). Two 10.2 cm deep cells in series gave a removal efficiency of 85% for typical sodium fire aerosols at a face velocity of 289 cm/sec. Measurement of efficiency as a function of particle size indicated a reduction in efficiency in the 0.4 to 1.1 µm size range for all packing materials.

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Introduction

One of the proposed safety systems for the LMFBR is an aerosol filtration system through which the reactor containment building atmosphere would be vented in the event of an accidental release of burning sodium. A proposed filter system consists of two stages: the first, a scrubbing system, containing a humidifying section, a wet cell washer, a water separator or demister, and a heater/dryer, and the second, consisting of a prefilter, a high efficiency particulate filter (HEPA), a zeolite bed, and another HEPA filter. Burning sodium metal in a normal oxygen atmosphere produces a dense aerosol composed of a mixture of sodium oxides, hydroxide, and carbonates. When combustion occurs at a relative humidity greater than 35%, the resulting agglomerated aerosol particles absorb water vapor and form sticky droplets that create difficult clogging and crusting problems for high efficiency air cleaning equipment.⁽¹⁾ Therefore, the scrubbing section would have to maintain greater than 90% removal efficiency without clogging for a period of many hours. The present study was conducted to develop performance data for the first stage scrubbing system.

Wet cell washers utilize beds of coarse fibers and are characterized by low pressure drop, high efficiency for particles above 5 μm , and the ability to recirculate the scrubbing water for long periods. A principal advantage of this device for the application described above is its ability to resist clogging by sticky water soluble sodium aerosol particles.

Experimental Apparatus and Procedures

Figure 1 is a diagram of our experimental wet cell washer. It consisted of a humidification section followed by three cells, the first two wetted and the last, a non-wetted mist eliminator. A downstream centrifugal blower drew the aerosol from the chamber through the humidification section and the scrubber unit. A Venturi meter, located downstream of the scrubber unit, measured air flow rate and liquid manometers were used to measure pressure drop across the cells. The upstream sampling port was located between the 90 m^3 aerosol generation chamber and the humidification section and the downstream sampling port was located after the mist eliminator cell. Cells up to 4" thick were mounted in a support frame sealed to the scrubber unit at a 45 degree angle to provide a 12" x 12" (30 cm x 30 cm) scrubber cross section. System air flow rates were 0.151 and 0.236 m/sec, giving filter face velocities of 185 and 289 cm/sec.

Experimental variables were cell construction, cell face velocity, spray water flow rate, option of prehumidification, and aerosol concentration. Experiments were conducted using a factorial design for each filter medium and two levels for system variables. A total of 30 runs were made providing 151 efficiency and pressure drop measurements. Tests were done in a random order and analyzed statistically to show the significance of each variable or combination.

Cells were filled with the packing materials at the porosities indicated in Table 1. In addition to packed cells, a Neva-clog* screen was tested. It is constructed from two thin perforated stainless steel plates each having an array of 0.025 cm diameter holes on 0.075 cm centers with the holes in one plate offset from the other so that aerosol flow must bend twice. This induces

*Buffalo Forge Co., Buffalo, N.Y.

interception and impaction of aerosol particles on and between the plates.

Two Spraying Systems 1/4 J atomizing nozzles, each spraying $45 \text{ cm}^3/\text{min}$, were used to humidify the sodium aerosol before it entered the first wet cell. These are two-fluid nozzles that use water and air pressure to produce a fine water spray with a high concentration of droplets in the $1\text{--}10 \text{ }\mu\text{m}$ range.⁽²⁾ Retention time in the humidification chamber was 1 sec.

Each wet cell is sprayed with a single Spraying Systems type 3/8" HH27W nozzle that produces a wide angle (120 degrees) solid cone spray that covered the entire cell face. Water flow rates were 170 and $320 \text{ cm}^3/\text{sec}/\text{cm}^2$. Water drained to a sump at the bottom of each cabinet from which it could be recirculated or sent to waste. The final stage was an unsprayed, 2" thick mist eliminator cell to remove entrained water droplets.

Sodium aerosols were generated in a 90 m^3 chamber. Elemental sodium was burned continuously in a heated steel pot to produce an aerosol of controlled concentration. A feed chute, 5 cm in diameter and 1.2 meters long and slanted 45 degrees from outside of the chamber to the sodium burning pot, was used to add small increments of sodium metal periodically throughout the course of each run. The rate of sodium addition was determined by monitoring the aerosol mass concentration in the chamber at ten minute intervals. In this manner, sodium fires were sustained for several hours and the sodium aerosol concentration maintained at $1 \pm 0.2 \text{ gm}/\text{m}^3$ by the addition of 35 to 50 g/min to the pool fire. For aerosol concentrations greater than $1.0 \text{ g}/\text{m}^3$, sodium was added at the rate of 85 to 110 g/min and $1600 \text{ cm}^3/\text{sec}$ of compressed air was directed onto the surface of the burning sodium pool to increase the burning rate by providing additional oxygen and turbulent mixing. Thermocouples were used to monitor the temperature of the sodium in the burning pot. Initially the burning pot was heated electrically, but rapid heater element failures led to the later use of a gas burner.

Sodium aerosol was withdrawn from the 90 m^3 aerosol chamber through a 25 cm diameter port that led to the prehumidification section upstream of the scrubber unit. Ports in the opposite chamber wall provided make up air. Other ports, located at mid-chamber height, were used to sample the chamber aerosol concentration. Chamber aerosol mass concentrations agreed with concentrations measured upstream of the scrubber unit, indicating negligible loss in the ductwork leading from the aerosol chamber to the scrubber unit.

Simultaneous isokinetic samples of the sodium aerosol concentration were collected up and downstream of the scrubber unit on all-glass absolute filter paper (MSA* 1106-B). After sampling was completed, and before the scrubber system was set to the next operating condition, the spray water rate to the cells was increased to about $0.5 \text{ cm}^3/\text{sec}/\text{cm}^2$ to clean the packing until the pressure drop across the filter had stabilized.

The deposit on sample filters was dissolved in 100 ml of deionized distilled water and the solution analyzed for sodium content by atomic absorption spectrophotometry. Because the all-glass filter paper contains some leachable sodium, measurements were corrected for filter blank which was less than a 0.5%

*Mine Safety Appliances, Pittsburg, PA

correction. By careful dilution to the most sensitive range of the atomic absorption spectrophotometer*, the sodium concentration was measured to an accuracy to $\pm 0.03 \mu\text{g/ml}$. From dilution calculations and the precision of the analysis the accuracy of the total sodium collection efficiency measurements was determined to within $\pm 6\%$.

Eight stage Anderson 2000** cascade impactors were used at 28.3 lpm to determine the particle size distribution of the sodium aerosol upstream and downstream of the scrubber and the fractional efficiency for each cell packing. The cascade impactor measurements provided nine particle size ranges from 0.4 to 9.0 μm .

Results and Discussion

Pressure drop across two wet cells in series was measured at two water spray rates (0.210 and 0.387 $\text{cm}^3/\text{sec}/\text{cm}^2$) and at two face velocities (185 and 289 cm/sec). Pressure drop across the wet cells increased with increasing water rate, increasing face velocity, and, for some packing materials, with time of operation. Figure 2 presents pressure drop data at a face velocity of 185 cm/sec for each of the wetted cell packing materials as a function of exposure duration. The pressure drop of the fine and coarse B-GON pads increased more rapidly at the lower water spray rate than at the higher spray rate, but there was very little change in pressure drop at either water spray rate for the Berl saddles and stainless steel fiber packings.

In Figure 3, pressure drop across two wet cells as a function of scrubbing time is shown for the higher face velocity of 289 cm/sec. Again, the B-GON pads showed a greater pressure drop increase with time at the lower water spray rate, whereas Berl saddles and stainless steel fibers leveled off at a constant pressure drop after a small initial build up. Measurements of the pressure drop across individual cells indicated that an increase in pressure drop with time was a result solely of the increased resistance of the first cell.

Results of efficiency measurements for six packing materials are summarized in Table II in terms of the three dichotomous system variables: face velocity, water rate, and humidification. Except for one outlier, the efficiencies ranged from 59 to 92% with a maximum range for any packing material of 20%. Because of the narrow range and the high variability of the results, no clear patterns emerge. This fact was confirmed by the factorial analysis which failed to show significance for any of the system variables or interactions. The most important, though non-significant, effect came from face velocity, followed by water rate, and then, by humidification. The results for the stainless steel fibers, based on the largest number of measurements, showed consistent but modest increases in efficiency with face velocity and humidification. It is noteworthy that prehumidification had a weak and inconsistent effect on efficiency. Apparently, these hygroscopic particles grow so rapidly that they reach full growth in the region of the cell spray water and prehumidification is unnecessary. The curly glass fibers deteriorated noticeably after 90 minutes of exposure to the strong caustic scrubbing solution whereas other materials showed no visible

*Perkin-Elmer Model 360

**Anderson 200, Atlanta, GA

change after 8 hours of exposure.

A typical particle size distribution of the sodium fire aerosol upstream of the scrubber system is shown in Figure 4. All upstream size distributions showed a good fit to the log normal size distribution. Table III presents size distributions for several scrubber runs. The average Mass Median Diameter (MMD) was $1.50\text{ }\mu\text{m}$ with an average Geometric Standard Deviation (GSD) of 2.01. These particle size distributions are in reasonable agreement with data reported by Viles et al.³ (ie., MMD = 1.26 to $1.74\text{ }\mu\text{m}$ and GSD = $2.65 - 3.36$ in a nitrogen atmosphere) and Lauben et al.⁴ (MMD = $1.4\text{ }\mu\text{m}$ and GSD = 1.95).

Collection efficiency as a function of particle size was determined using up and downstream Anderson impactor sampling. Table IV presents the efficiency for 9 particle size ranges for each of the cell packing materials tested. In general, collection efficiency was near 100% for particle sizes larger than 2 or $3\text{ }\mu\text{m}$. As shown in Figure 5, the lowest collection efficiency was found in the $0.40\text{ }\mu\text{m}$ to $1.1\text{ }\mu\text{m}$ particle size range. The increased efficiency for particles less than $0.5\text{ }\mu\text{m}$ shown in Figure 5 is not a result of diffusion of particles to collector surfaces. Although this mechanism becomes more effective as particle size decreases, it is comparatively weak for submicrometer particles. As shown in Table V, the predicted system efficiencies due to diffusion and impaction continue to decline as particle size decreases in the submicrometer range.

The apparent increase in collection efficiency for particles less than $0.40\text{ }\mu\text{m}$ is thought to result from depletion of particle mass in this size range as a result of particle growth in the humid atmosphere rather than from collection. Growth by water adsorption occurs for all sizes of particles passing through the scrubber and shifts the size spectrum upward with a net reduction in the numbers of particles in the smallest sizes. This means that the smallest particles are depleted by growth to larger sizes and the larger particles are depleted by inertial removal, leaving an intermediate size of maximum penetration. The size of maximum penetration depends on the inertial removal characteristics of the scrubber, the particle size distribution, and the particle size growth that occurs in the scrubber. For this particular system, i.e., a sodium pool fire in a normal atmosphere and a wet cell scrubber operated as described above, the apparent particle size for maximum penetration occurred between 0.5 and $1.0\text{ }\mu\text{m}$.

Conclusions

Based on the results presented here, it may be concluded that it is feasible to use a wet cell scrubber upstream of a HEPA filter to reduce the loading of sodium combustion aerosol reaching the HEPA filter by a factor of ten or more (depending on scrubber size) for a period of many hours. A satisfactory design requires at least three cells in series, a face velocity of $200-300\text{ cm/sec}$, and a water rate of $400\text{ cm}^3/\text{sec}/\text{cm}^2$.

The most satisfactory single packing material studied was $50\text{ }\mu\text{m}$ diameter stainless steel fibers at a face velocity of 289 cm/sec . This material gave the lowest pressure drop and showed little tendency to clog when operated at a water rate of $0.387\text{ cm}^3/\text{sec}/\text{cm}^2$. At this operating condition, typical sodium fire aerosols were removed by two 10 cm deep beds in series at efficiencies in the 80-90% range. Although the fine B-GON pads have higher efficiencies than the stainless steel fibers, they were unsatisfactory because the flow resistance of the B-GON pads increased with time for all operating conditions as a result of

incomplete wetting.

Combinations of packing materials may provide better performance than the use of a single material. Because the cell packings that gave the highest efficiencies tended to clog with time, they should be preceded by non-clogging, though lower efficiency, cells in a manner similar to a graded fiber diameter deep bed filter, i.e., the upstream cells would reduce the loading on the high efficiency cell so that the latter would never clog or would clog at an acceptably slower rate. Such a system might consist of a Neva-clog screen or $\frac{1}{4}$ " Berl saddles for the first cell (which would remove about 60% of the particulate mass but would not clog under any realistic conditions), a second cell of 50 μm stainless steel fibers which would capture an additional 25 to 30%, and a final cell of 35 μm stainless steel fibers which would ensure an overall efficiency in excess of 90%. Such a system would operate for 7 to 10 hours at a face velocity of 185 cm/sec and an inlet concentration of 1 gm/m³ before it increased in resistance by one inch of water.

The curly glass fibers displayed inadequate chemical resistance to sodium fire aerosol after 90 minutes exposure, but other materials showed no visible change after 8 hours of exposure.

It was found that there is little advantage to using a prehumidification stage. This space could be used more profitably by installing a low resistance, non-clogging stage to reduce the possibility of clogging of subsequent stages.

Packing materials that were non-clogging at an aerosol concentration of 1 gm/m³ were also non-clogging at 5 gm/m³.

Because cells clog rapidly without continuous application of water, the water system must be designed to preclude even momentary interruptions of water and the water spray must be initiated prior to aerosol flow.

Although the use of a high water rate, 0.387 cm³/sec/cm², had little effect on system efficiency, it prevented or reduced the rate of clogging.

The combined effect of particle growth by humidification and particle capture in the scrubber resulted in a most penetrating particle size. For the conditions evaluated, this size was between 0.5 and 1.0 μm .

Acknowledgement

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Table I. Characteristics of cell packings.

<u>Cell packing</u>	<u>Fiber Size</u>	<u>Packing Density</u>	<u>Porosity</u>
curly glass fibers	35 μm	16 kg/m^3	.99
stainless steel fibers	50 μm	30 kg/m^3	.99
coarse B-GON* pads	410 μm	26 kg/m^3	.96
fine B-GON* pads	208 μm	31 kg/m^3	.96
ceramic Berl saddles	1/4" nominal	678 kg/m^3	.72

*Monofilament polypropylene fibers manufactured by Kimre Inc., Perrine, Florida 33157.

Table II. Sodium removal efficiencies in percent for 7 cell packing materials.

Cell Packing	185 cm/sec Face Velocity				289 cm/sec Face Velocity			
	Water Rate				Water Rate			
	0.210 cm ³ /sec/cm ²		0.387 cm ³ /sec/cm ²		0.210 cm ³ /sec/cm ²		0.387 cm ³ /sec/cm ²	
	Humidification		Humidification		Humidification		Humidification	
	No	Yes	No	Yes	No	Yes	No	Yes
Curly Glass Fibers	*86 (3)	*89 (17)	—	89 ** (10)	—	—	—	—
Neva Clog Screen	—	—	57 (4)	70 (5)	—	—	51 (4)	65 (6)
Neva Clog Screen and Curly Glass Fibers	—	—	—	90 ** (35)	—	—	—	—
Coarse B-GON Pads	61 (1)	63 (1)	59 (1)	70 (1)	60 (1)	66 (1)	68 (1)	73 (1)
Fine B-GON Pads	89 (1)	88 (1)	89 (1)	82 (1)	92 (1)	87 (1)	88 (1)	89 (1)
Stainless Steel Fibers	70 (3)	75 (4)	70 (3)	81 (5)	81 (3)	83 (3)	81 (3)	80 (7)
Porcelain Berl Saddles	62 (1)	49 (1)	81 (1)	68 (1)	63 (1)	68 (1)	72 (1)	61 (1)

number of observations shown in parentheses

*Water rate was 0.210-0.284 cm³/sec/cm²

**Water rate was 0.318-0.340 cm³/sec/cm²

Table III. Aerosol particle size characteristics.

Scrubber Run #	Chamber Aerosol Concentration (g/m ³)	Mass Median Diameter (μm)	Geometric Standard Deviation
19	0.75	1.58	2.03
20	0.96	1.63	1.90
21	0.85	1.57	2.01
22	0.88	1.50	2.37
23	1.05	1.58	2.10
25	0.82	1.70	2.12
26	1.02	1.33	1.95
27	0.88	1.38	2.14
28	4.75	1.48	1.84
29	4.75	1.41	1.56
30	0.96	1.37	2.09
Average of 11 measurements		1.50	2.01

Table IV. Fractional efficiency of 5 packing materials

Cell Packing Material	Face Velocity cm/sec	Aerosol Particle Size Range, μm								
		<.4	0.4-0.7	.7-1.1	1.1-2.1	2.1-3.3	3.3-4.7	4.7-5.8	5.8-9.0	>9.0
Neva	185	48	28	29	51	94	94	77	74	64
Clog										
Screen**	289	67	58	49	67	67	100	67	83	95
Coarse	185	68	51	22	43	55	98	100	89	75
B-GON										
Fine	289	94	69	66	96	99	98	100	100	81
B-GON										
Stainless	185	62	22	*	*	96	96	100	100	100
Steel										
	289	71	39	42	85	100	100	100	100	100
Berl	185	95	57	*	*	95	100	100	100	100
Saddles										

*Unreliable datum.

**Evaluated without mist eliminator stage.

Table V. Calculated* scrubber efficiency due to diffusion and impaction for cells each packed with 10 cm of 50 μm diameter fibers.

<u>Particle Size, μm</u>	<u>Eff. due to diffusion</u>	<u>Eff. due to impaction</u>	<u>Total eff.**</u>
0.25	2.0%	0.05%	2.0%
0.55	1.1	4.5	5.5
0.9	0.8	34.7	35.4
1.6	0.6	98.6	98.6

* Efficiencies calculated using the methods described in reference (5).

** Assumes single fiber efficiencies for diffusion and impaction are additive.

FIGURE 2. LOADING CHARACTERISTICS OF SIX PACKING MATERIALS AT 185 cm/sec

FIGURE 3. LOADING CHARACTERISTICS OF FIVE PACKING MATERIALS AT 289 cm/sec

FIGURE 4. SODIUM FIRE AEROSOL INLET PARTICLE SIZE DISTRIBUTION

Figure 5
Fractional Efficiency

FIGURE 5. FRACTIONAL EFFICIENCY