ACOUSTIC AND TURBULENT AGGLOMERATION OF SODIUM AEROSOLS

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ABSTRACT

Tests of turbulent and acoustic agglomeration of captive sodium fire aerosols at concentrations of 0.1 to 20 gm/m³ were conducted in 90 m³ and 0.65 m³ vessels to evaluate these mechanisms for direct application air cleaning systems. Aerosol mass concentration decay with time was monitored by sequential filter samples. Turbulence was generated mechanically with a 51 cm diameter centrifugal fan impeller and a reverberant acoustic field was created with an electronic siren. The effectiveness of each method over a range of particle concentrations and power densities was evaluated by an agglomeration index, a measurement of particle growth based on sedimentation characteristics. Both turbulent and acoustic treatment markedly enhanced sedimentation rate compared to undisturbed settling. The effectiveness of both methods increased with increasing aerosol mass concentration and increasing power input per unit volume of aerosol. The agglomeration index reached 20 for turbulent agglomeration at an aerosol mass concentration of 3 gm/m³ and 7 for acoustic agglomeration at 14 gm/m³ when using an acoustic intensity of 145 dB. Turbulent agglomeration was more effective than acoustic agglomeration for the same mass concentration and power density conditions.

INTRODUCTION

A study is being conducted in the Harvard Air Cleaning Laboratory to examine the feasibility of using direct application air cleaning as a treatment method for high concentrations of sodium fire aerosol that would likely fill a reactor containment vessel following a release inside a liquid metal fast breeder reactor. Most particulate air cleaning systems are dynamic,

flow-through devices where particulate matter is continuously removed from a stream of dust laden gas as it passes through the device. A less common, approach can be applied when the dust laden gas is confined within a vessel. This approach treats the entire gas volume simultaneously, as a batch process, to reduce airborne particulate concentrations as rapidly as possible.

Leakage from the containment vessel is expected to be small, (no more than 0.1% of the containment volume per day). Because it is continuous, significant public health benefits to the surrounding community would accrue from a rapid reduction in airborne particulate concentration within the containment vessel. To reach the design goal, reducing by a factor of 10 the two-hour integrated concentration, it is necessary to reduce the airborne concentration within a matter of minutes by 50% or more. Although rapid clean up can be accomplished by a conventional air cleaning loop, such a system would have to be very large and expensive to treat a containment volume of 7×10^4 m³ in a few minutes. A direct application air cleaning approach, on the other hand, has considerable potential for this situation because it treats the entire containment volume simultaneously without the necessity of having to pass large volumes of gas through air cleaning devices..

Three approaches have been evaluated experimentally: scavenging by inert powder injection, enhancement of coagulation by mechanically generated turbulence, and enhancement of coagulation by high intensity sound. The latter two methods are similar and are the subject of this report. Inert powder injections have been described in Reference 3. Both turbulence and high intensity sound enhanced coagulation by applying energy to the gas, throughout its volume, to create relative motion between particles.

Because of the complex geometry of a containment vessel, including its machinery, the use of a tuned sonic coagulation system was not considered feasible and consequently no attempt was made to evaluate such a system. Instead, random traveling waves in a reverberant enclosure were used. Mechanically generated turbulence was produced with a centrifugal blower wheel. The experiments provided some insight into coagulation mechanisms and the effectiveness of two different methods operating under similar conditions. Effectiveness was evaluated by monitoring the change in aerosol mass concentration as a function of treatment time in 0.65 and 90 m³ chambers. Results show the effect of initial mass concentration and applied power density on coagulation rate.

EXPERIMENTAL PROCEDURES

1. Aerosol Generation for Turbulent Agglomeration Tests

Turbulent agglomeration tests were conducted in a 90 m³ sealed chamber, 4 meters in height. Sodium aerosol was generated by burning the metal in an electrically heated steel pot. The sodium pool, 260 cm² in area, produced a dense white aerosol that filled the chamber within 10 minutes after initiation of a fire. A one pound sodium pool fire would burn for 20-30 minutes. Decay in mass concentration with time was obtained with open-faced MSA 1106B high efficiency filter samples taken near mid-chamber height. Ten to 15 samples were taken over a 3 to 6 hour period at 18.4 lpm for 0.5 to 3 minutes. Less than 1% of the aerosol was removed by sampling.

Undisturbed mass concentration decay tests were conducted in the 90 m³ chamber to serve as a baseline against which to measure the effectiveness of turbulent enhancement. The results shown in Figure 1 were obtained from eight baseline tests following the burning of 1 lb. sodium. Initial chamber relative humidity ranged from 14 to 22%. Analysis of the unhindered settling data showed that this aerosol has the decay characteristics equivalent to that for 4 μ m monodisperse particle under stirred settling. The actual mass median diameter (MMD) and geometric standard deviation (GSD) of the aerosol cloud was determined with the aid of eight-stage Andersen impactors and an aerosol centrifuge [1]. The size distributions, 20 minutes after initiation of a 1 lb. sodium fire for all of the generated aerosols were found to be nearly the same with a MMD of 2.1 μ m and a GSD of 1.8. Measurements taken at later times indicated an equilibrium between sedimentation and growth with MMD stabilizing at about 3 μ m.

Measurements were made of particle density and dynamic shape factor from the aerodynamic equivalent diameters determined by aerosol centrifuge and geometric parameters measured in the scanning electron microscopy [2]. Untreated aerosols aged from 34 to 376 minutes gave an average particle density of 0.66 gm/cm³ and average dynamic shape factor of 1.2 [2].

Quantitative chemical analysis indicated that the aerosol particles were porous sodium carbonate with some water of hydration [3]. During the undisturbed settling tests, aerosol deposition per unit area of chamber wall was 0.10 to 0.01 of the amount that settled on the floor.

FIGURE 1

BASELINE CONCENTRATION DECAY PROFILE FOR 1.0 LB.
SODIUM FIRES IN 90 M³ AIR-FILLED CHAMBER

2. Turbulent Agglomeration Tests

A 7.5 HP, 3,000 cfm centrifugal blower (New York Blower Co., type GI, size 20) was placed in the center of the 90 m³ chamber to induce turbulence. The blower was started shortly after peak aerosol concentration was reached. The time decay history of five such tests with peak aerosol concentration was reached. The time decay history of five such tests with peak aerosol concentration near 2 gm/m³ is presented in Figure 2.

The blower was run with and without the scroll casing in place to distinguish the effect of centrifugal deposition from the effect of turbulence enhanced agglomeration and sedimentation. Operation with the scroll casing off takes away a major surface for deposition, though some cleaning credit must still be taken because of particle impaction on the fan blades. Removing the casing did not greatly change the decay profile from casing-on performance, as can be seen in Figure 2. The primary aerosol decay mechanism was, therefore, by enhanced agglomeration and sedimentation onto the chamber floor. Analysis of samples of wall, floor, and blade deposits indicated that aerosol deposition occurs, roughly, 28% on walls, 65% on floor, and 7% on the fan blades.

Substantially faster decay rates were obtained with turbulent agglomeration when the peak aerosol mass concentration in the chamber was above 2 gm/m³. One such test is shown in Figure 3.

By using different pulley combinations on the blower, it was possible to generate different levels of turbulence in the chamber. Power densities, determined from measurements of fan speed and electricity consumption, are discussed in a later section. Assuming an electrical to mechanical energy conversion efficiency of 0.80 power densities in the range of 20-70 watts per cubic meter of chamber volume were utilized.

3. Acoustic Agglomeration Tests

Efforts to determine the effect of acoustic agglomeration on sodium combustion aerosols began with the search for a suitable and convenient source of high intensity sound. The first sound generating devices employed in this research were pulse jet engines [4]. A special pulse jet engine constructed by Ontario Research Foundation (Canada) was unable to provide a sound field of sufficient intensity for acoustic agglomeration experiments in the 90 m³ chamber. These tests were described in Reference 3.

FIGURE 2

TURBULENT AGGLOMERATION AEROSOL CLEARANCE TESTS

FIGURE 3

TURBULENT AGGLOMERATION FOR AEROSOL
CONCENTRATION OF 12 GM/M³

For later tests, a Federal CJ-24 electronic siren (a type employed in emergency vehicles) was used to generate intense sound fields in a steel chamber having a volume of 0.65 m^3 and an average internal height of 75 cm (Figure 4). A smaller chamber was needed because the acoustic power radiated by a single CJ-24 siren will not produce adequate sound levels throughout a 90 m^3 chamber. The CJ-24 "siren" is not a gas-dynamic rotating siren, by the usual definition, but is a very powerful loud speaker powered by a PA-20A amplifier and signal generator. When 60 watts of electrical power were used to energize this siren, sound pressure levels of 145 dB were measured at the sampling port shown in Figure 4. The frequency spectrum was broad band with a peak in the 600 to 1,200 Hz range. Variations in intensity did not exceed 3 dB throughout the 0.65 m^3 chamber. The siren was used in the "yelp" signal mode, a complex wave form in the audible range which has a superimposed oscillation of approximately 5 Hz. The acoustic power of the siren was calculated from data supplied by the manufacturer. The acoustic power output of the siren for lower sound pressure levels was calculated by assuming a reverberant field in the chamber with constant wall losses. Acoustic tests were performed at 145 dB, 132 dB, and 125 dB, spanning a power density range from 10 watt/m^3 to 0.1 watt/m^3 . Sound pressure levels were measured with a General Radio octave band analyzer in the flat response mode.

In a typical test, between 50 and 100 gm of sodium metal was heated rapidly to burning temperature in a steel pot and allowed to burn for 10 minutes filling the sealed chamber with a dense sodium aerosol. Open-faced glass fiber filter samples were obtained at mid-chamber height to determine the mass concentration over time for unperturbed and siren-on conditions. Each filter sample was restricted to 9.2 liters (1.4% of the chamber volume) to minimize depletion of the aerosol by sampling. Up to 11 samples were taken giving a maximum concentration decrease due to sampling of 14%. Because unperturbed and siren-on tests were sampled at roughly the same time intervals, changes in concentration due to sampling were identical for each.

Figure 5 shows mass concentration decay results for unperturbed sedimentation in the small chamber and sedimentation enhanced by acoustic agglomeration. The curves for the three sonic tests indicate moderate enhancement of sedimentation.

RESULTS

Data for undisturbed settling and turbulent agglomeration tests in the 90 m^3 chamber are summarized in Table 1. The basic parameters which were extracted from the concentration decay graphs for each test are initial aerosol mass concentration

FIGURE 4

0.65 M³ CHAMBER FOR ACOUSTIC AGGLOMERATION EXPERIMENTS

FIGURE 5

ACOUSTIC AGGLOMERATION AND UNDISTURBED SETTLING
IN A 0.65 M³ CHAMBER

TABLE 1 - SUMMARY OF UNDISTURBED SETTLING AND TURBULENT AGGLOMERATION TESTS IN 90 M³ VESSEL

Initial Aerosol Mass Conc'n (gm/m ³)	Time for $C/C_0=e^{-1}$ (min.)	Mass Fraction Removed in 5 min.	Mono- disperse Equivalent Size (μ m)	Agglomer- ation Index I_A	Power Density watts/m ³
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Undisturbed Settling Tests

6.5	47	0.10	9.2	4.4	0
3.8	105	0.047	6.2	3.0	0
2.4	162	0.031	5.0	2.4	0
1.6	175	0.028	4.8	2.3	0
1.1	290	0.017	3.7	1.8	0
0.084	592	0.008	2.6	1.2	0

Turbulent Agglomeration Tests

3.4	3.4	0.76	33.8	16.1	27
3.1	2.1	0.91	43.7	20.8	27
2.0	7.5	0.49	23.1	11.0	21
2.0	2.3	0.89	41.7	19.9	27
1.9	3.8	0.74	32.5	15.5	71
1.7	16	0.27	15.8	7.5	18
1.6	15	0.29	16.3	7.8	18
1.3	12.5	0.33	17.9	8.5	27
1.2	25	0.18	12.7	6.0	18
0.94	13	0.32	17.6	8.4	18
0.85	25.5	0.18	12.5	6.0	27

(C_0) and time (t_e) for the mass concentration to reach (C_0/e). For undisturbed settling, the initial mass concentration was considered to be the peak concentration reached. For the turbulence tests, initial concentration was defined as the measured concentration at the time turbulence was initiated, usually within a few minutes of peak chamber concentration. Data from undisturbed settling and acoustic agglomeration tests in the 0.65 m³ chamber are similarly presented in Table 2 and defined in like manner.

Most mass concentration decay profiles gave straight lines when plotted semi-logarithmically, indicating exponential decay functions. Stirred settling conditions occur in the chambers due to thermal convective motion and energy from the agglomeration mechanisms themselves. It is well known that stirred settling of monodisperse aerosols produces exponential mass concentration decay. Even though the sodium aerosol is not monodisperse, it is extremely useful to approximate aerosol settling characteristics by the exponential decay of a monodisperse aerosol with $1/e$ decay time, t_e , measured directly from the concentration data. The mass fraction removed, $f(t)$, in any standard time interval (e.g., 5 minutes, as in Tables 1 and 2) is readily determined from the relation,

$$f(t) = 1 - e^{-t/t_e} \quad (1)$$

More significantly, the particle diameter of an "aerodynamically equivalent monodisperse aerosol" with the same settling characteristics, d_* , can be derived from the decay profiles. We have, for a stirred settling monodisperse aerosol of diameter, d_* , in a chamber of height, h ,

$$C(t)/C_0 = \exp\left(\frac{\rho d_*^2 g t}{18 \eta h \chi}\right) \quad (2)$$

where g = gravitation acceleration
 η = gas viscosity
 ρ = particle density
 χ = aerodynamic shape factor

Equating the bracketed quantity in Equation 2 with t/t_e gives d_* as,

$$d_* = \left(\frac{18 \eta h \chi}{\rho g t_e}\right)^{1/2} \quad (3)$$

TABLE 2 - SUMMARY OF UNDISTURBED SETTLING AND ACOUSTIC AGGLOMERATION TESTS IN 0.65 M³ VESSEL

Initial Aerosol Mass Conc'n (gm/m ³)	Time for $C/C_0=e^{-1}$ (min.)	Mass Fraction Removed in 5 min.	Mono- disperse Equivalent Size (μ m)	Agglomer- ation Index I_A	Power Density watts/m ³
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Undisturbed Settling Tests

21.5	13	0.32	7.6	3.6	0
16.5	11	0.37	8.3	4.0	0
8.2	20	0.22	6.1	2.9	0
6.8	23	0.20	5.7	2.7	0

Acoustic Agglomeration Tests

14.2	3.3	0.78	15.1	7.2	9.1
10.5	4.9	0.64	12.4	5.9	9.1
9.0	5.3	0.61	11.9	5.7	9.1
7.6	7.0	0.51	10.4	5.0	0.46
4.2	28.5	0.16	5.1	2.4	0.091

Values for d_* computed for each test are given in Tables 1 and 2.

A useful parameter for characterizing both undisturbed and enhanced agglomeration tests is the "agglomeration index", I_A , defined here as the ratio of d_* to the initial aerosol MMD. Eight-stage Andersen impactor data indicate that within the first 20 minutes after initiation of a sodium pool fire, the MMD of the aerosol is about 2.1 μm . Using this reference MMD to form the agglomeration index, we have plotted I_A versus initial mass concentration for undisturbed settling tests and for turbulent and acoustic agglomeration tests as shown in Figures 6 and 7. No distinction is made in these figures between tests at different power densities. Because of the limited range of our power densities, strong statements about their relation to I_A are not justified.

Figures 6 and 7 also present trend lines fitted to the data. In each case, the trend line is constrained to pass through $I_A = 1.0$ at zero mass concentration, a constraint which has an obvious and strong physical interpretation. As expected from basic coagulation theory [5] each of the four trend lines shows increasing agglomeration indices with increasing mass concentration. Enhanced agglomeration rate leads naturally to an increased average particle size due to agglomeration in a given time period. By adding turbulent or acoustic energy to the aerosol, relative motion between particles is enhanced and agglomeration speeded up. For the range of power densities used, turbulence yields a higher agglomeration index than acoustic for the same initial mass concentration.

For the turbulence experiments and the acoustic tests, the following results of multiple regressions of agglomeration index with respect to initial mass concentration and power density were obtained. The point $I_A = 1$ at $C_0 = 0$ was included in each case:

$$I_A = 0.302 + 4.85 C_0 + 0.093 P \quad \text{turbulent agglomeration}$$

$$I_A = 1.05 + 0.441 C_0 + 0.029 P \quad \text{acoustic agglomeration}$$

where C_0 = initial mass concentration in gm/m^3
 P = power density in watts/m^3

Significance tests of the regression equation coefficients showed that both concentration coefficients were significant ($P < 0.02$) and both power density coefficients were not significant. It is apparent that turbulent agglomeration is more effective than acoustic agglomeration for a given initial mass concentration and that turbulent agglomeration is enhanced to a greater extent

FIGURE 6

AGGLOMERATION INDEX AS A FUNCTION OF MASS CONCENTRATION
FOR TURBULENT AGGLOMERATION AND UNDISTURBED SETTLING TESTS
IN A 90 M³ VESSEL

FIGURE 7

AGGLOMERATION INDEX AS A FUNCTION OF MASS CONCENTRATION FOR TURBULENT AGGLOMERATION AND UNDISTURBED SETTLING TESTS IN 0.65 M³ VESSEL

for a fixed fractional increase in initial mass concentration than is acoustic agglomeration.

DISCUSSION AND CONCLUSION

The range of agglomeration indices found in our acoustic experiments is consistent with analogous measurements made by other researchers. Although no previous work compares directly with our research because sound sources were usually employed only for brief periods (seconds) on flowing rather than fixed volume systems, Scott [4] and Volk and Moroz [5], obtained agglomeration indices from 3 to 9 for sound pressure levels from 120 dB to 165 dB. Their mass concentrations were in the range 0.5 to 2.5 gm/m³ and sound was continued from 2.5 to 40 seconds.

By using the concept of "scale of turbulence" noted by Fuchs [6], it is possible to gain some insight into why turbulent agglomeration does not show significant increases in effectiveness for significant increases in power density. The internal scale of turbulence, λ_0 , used by Levich and referred to by Fuchs, is defined for a turbulent medium by,

$$\lambda_0 = \left(\frac{v^3}{\epsilon}\right)^{1/4} \quad (4)$$

where v is the kinematic viscosity of the medium and ϵ is the power density per unit mass of the medium. For the range of power densities employed here the scale of turbulence, λ_0 , ranges from 90 μ m to 120 μ m; a range unlikely to be associated with large changes in agglomeration index.

Turbulent motion and high intensity reverberant acoustic fields induce rapid agglomeration of sodium aerosols. The higher the initial aerosol mass concentration, the more effective are these agglomeration mechanisms which produce enhanced sedimentation. For 'undisturbed' settling, sedimentation is similarly enhanced by increasing initial mass concentration. For the same energy expenditure turbulence appears to be a more effective agglomerating mechanism than acoustic energy at a fixed mass concentration. Increasing the applied power density of turbulence or sound produces smaller increases in agglomeration index than does a similar fractional increase in initial mass concentration. Both mechanisms show promise for direct application air cleaning systems. Because of the relative ease of generating turbulence versus generating a large-scale high intensity sound field, turbulent agglomeration may be preferred.

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