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EVALUATION OF SONICS FOR FINE PARTICLE CONTROL

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EVALUATION OF SONICS FOR FINE PARTICLE CONTROL

by

R. Hegarty and L.J. Shannon

Midwest Research Institute
425 Volker Boulevard
Kansas City, Missouri 64110

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Industrial Environmental Research Laboratory
Office of Energy, Minerals, and Industry
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SUMMARY

The aim of this investigation was to analyze and evaluate sonic agglomeration as an approach to improving our ability to control fine particulate pollutants (i.e., particles in the 0.1 to 3.0 μm diameter range) emitted from stationary sources.

Acoustic fields have frequently been cited as an effective means to rapidly agglomerate particles and droplets to a sufficient size whereby they can be readily and efficiently collected in a conventional control device. Particle agglomeration in an acoustic field occurs by a complex process which is not well understood. Existing theories provide a reasonably detailed description of the mechanisms assumed to occur in the agglomeration process, but the equations describing the postulated mechanisms have not and perhaps cannot be integrated into a single tractable mathematical expression. A simpler approach using a modified form of Smoluchowski's equation for thermal agglomeration has been advanced by several investigators. The equation describing the agglomeration process based on this approach is

$$n = n_o e^{-K_a t}$$

where K_a is the acoustic agglomeration coefficient and t is the residence time. The acoustic agglomeration coefficient can be related to several parameters that influence the postulated mechanisms underlying the agglomeration process.

Mednikov[1/] has developed the most complete model for acoustic agglomeration. His model subdivides the aerosol into its small particle concentration n_2 and its large particle concentration n_1 (assumed to be constant with time). Mednikov's model leads to the result that the

acoustic agglomeration coefficient is proportional to the quantity $\left[n_1 \overline{r_1^2} J^{1/2}\right]$ where r_1 is the radius of the large particles and J is the sound intensity. Combining Mednikov's model with the relationship obtained from the modified Smoluchowski equation results in the prediction that acoustic agglomeration rates are dependent upon the quantity $\left[n_1 \overline{r_1^2} j^{1/2} t_{res}\right]$.

Experimental studies at laboratory, pilot-scale and full-scale level provide data which confirm most of the parametric dependencies predicted by the above theoretical approach. In addition, the experimental work has shown that:

- Sound intensities of 150 to 160 db (0.1 to 1.0 w/cm^2) are required for industrial applications.
- Residence times of 5 to 10 sec are tenable for industrial applications.
- Sonic agglomeration rate is strongly affected by the concentration by weight of particles and efficiency of agglomeration decreases rapidly at concentrations below 2 to 5 g/m^3 (1 to 2 grains/ft^3).
- Highly polydisperse aerosols are easier to agglomerate than a low polydisperse aerosol (i.e., if particles are all of nearly same size, acoustic agglomeration is not effective.
- Injection of atomized water into low concentration aerosols seems to improve sonic agglomeration.
- Physical properties of aerosol particles have comparatively little effect on acoustic agglomeration.
- Viscosity, temperature, and pressure of gases are generally about the same in most aerosols and these factors are not important as a rule.
- Agglomerates formed in sonic fields often do not have a high degree of stability and they may be broken up in the collection device, especially in cyclones.
- Explosive aerosols can be safely agglomerated by acoustic fields.

The utilization of sonic agglomeration for industrial gas cleaning requires the coupling of an agglomeration chamber to a particulate collection system. Cyclones, electrostatic precipitators, and fabric filters have been used or proposed as the collection system with cyclone systems being the prevalent system in previous applications. For a sonic agglomerator to be of significant help in the collection of fine particles, the ratio of the final to initial mean particle radius or diameter must be in the range of 5 to 20. The lower end of the range would correspond to the use of a high efficiency system as the collector (i.e., electrostatic precipitator, fabric filter, venturi scrubber) while the upper side would reflect the use of a low efficiency system as the collector (i.e., cyclone, spray scrubber). To achieve a growth ratio of 5 to 20 in equipment of reasonable length and diameter, sound intensities of 160 db (1.0 w/cm^2) or greater will be necessary. Specific energy consumptions of the order of 10 to 20 hp/1,000 cfm appear to be necessary as a direct result.

Because of the high energy requirements, the application of sonic agglomeration to industrial gas cleaning problems involving predominantly fine particles does not appear promising.

INTRODUCTION

Numerous investigations have shown that aerosol particles behave in a substantially different manner in an acoustic field than in an unperturbed medium or in a turbulent stream. Soon after an aerosol is exposed to a suitable acoustic field, particulate agglomeration is noted and particulate formations are seen moving about in a complex manner. Successful agglomeration of particulates by acoustic fields in laboratory experiments has led to the development of sonic agglomerators for use in industrial gas cleaning applications. However, sonic agglomerators have not enjoyed a widespread utilization, especially in the United States.

Sonic agglomeration occurs by a complex process which is not well understood and existing theory provides only nominal guidelines for the design of commercial systems. The present study was undertaken to review (1) the current state of knowledge of sonic agglomeration on both the theoretical and experimental level, (2) previous industrial experience with sonic agglomeration, and (3) recent advances in hardware for sonic agglomerators. The results of this review were then to be used to assess the utility of sonic agglomeration as a means of enhancing the collection of fine particulate pollutants.

The following sections of this report present the results of the literature search conducted as part of the task, a discussion of the theoretical aspects of sonic agglomeration, an overview of the results of laboratory- and industrial-scale applications of sonic agglomeration, a comparative analysis of performance, energy requirements, etc., between sonic agglomerators and other control systems, and conclusions and recommendations.

LITERATURE SEARCH

An extensive literature search was conducted as the initial stage in the task. Various scientific abstracts (e.g., Chemical Abstracts, Engineering Abstracts, Air Pollution Abstracts) and selected technical journals were searched for relevant publications. Patent literature was also scanned. Approximately 500 references dealing with the general subject of aerosol interaction with acoustic fields were identified. The literature search clearly indicated that detailed work on sonic agglomeration is predominantly of foreign origin. In addition to the reference list delineating the specific papers cited in the text, a supplementary reading list is presented in Appendix A.

THEORETICAL ASPECTS OF SONIC AGGLOMERATION

Several different effects have been postulated as being responsible for particle agglomeration resulting from acoustic fields including (1) hydrodynamic forces between the particles and (2) additional collisions due to the different vibrational amplitudes of different sized particles. Although no comprehesnive theory is available, Mednikov[1] has presented the most thorough discussion of sonic agglomeration. Mednikov's general approach will be used as the basis for our discussion of the theoretical aspects of sonic agglomeration.

Acoustic coagulation (i.e., sonic agglomeration) involves the response of aerosol particles suspended in a gaseous medium to forces arising from an impressed sound field. In general we are concerned with particles above 0.1 μm in diameter. Below 0.1 μm, Brownian agglomeration is a more rapid and efficient means of particle agglomeration. The speed with which aerosol particles react to forces is obviously important. The rate at which the equilibrium state of a particle-medium system is restored, as well as the sensitivity of the particle to changes in the forces acting on it, is determined by a parameter called the relaxation time τ of the particle, given by

$$\tau = \frac{2}{9} \frac{\rho_p}{\eta} r^2 \qquad (1)$$

where ρ_p is the density of the (assumed spherical) particle, η is the dynamic viscosity of the medium, and r is the radius of the particle. The smaller the relaxation time of the particle, the more rapidly the particle takes on a new velocity relative to the medium. Normally, the relaxation time is very small for aerosols undergoing coagulation. For example, a particle with $r = 0.1$ μm has a relaxation time $\tau \approx 10^{-7}$ sec, while a particle of radius $r = 10$ μm has a relaxation time $\tau \approx 10^{-3}$ sec.

From the above, it can be seen that if the particles suspended in a vibrating gas are quite small, they are carried along with the motion, while if the particles are quite large, they will remain virtually stationary in the vibrating medium. One measure of the degree to which any specific particle is carried along with the motion of the medium is the ratio of the amplitude of displacement (or velocity) of the particle undergoing vibration to that of the vibrating medium. This ratio, called the degree (or coefficient) of entrainment of the particle, is given by Mednikov[1] as

$$\mu_p = \frac{1}{(1 + \omega^2\tau^2)^{1/2}} \tag{2}$$

where ω is the angular velocity equal to $2\pi f$ and f is the frequency. The values of μ_p will range between zero and one. For very large particles, $\mu_p \approx 0$ as the relaxation time τ becomes very large, while for very small particles, $\mu_p \approx 1$ and the aerosol particles will follow the vibration of the medium. Another parameter that is useful is the flow-around factor μ_g, given by:

$$\mu_g = \omega\tau\mu_p = \frac{\omega\tau}{(1 + \omega^2\tau^2)^{1/2}} \quad . \tag{3}$$

Note that the entrainment factor μ_p and the flow-around factor μ_g obey the following relation:

$$\mu_p^2 + \mu_g^2 = 1 \quad . \tag{4}$$

Employing the concepts of relaxation time and entrainment factor (or flow-around factor), we can begin a discussion of the way in which acoustic coagulation of aerosols is envisioned to work. Agglomeration of particles requires collisions between the particles. According to many investigators, it appears that the so-called orthokinetic interaction between aerosol particles is the primary mechanisms accounting for particle collisions and subsequent coagulation in acoustic fields. Basically, orthokinetic interaction occurs between two particles of different dimensions (or densities) which are moving at different velocities. Because of their relative motion, they will, in the course of this motion, approach or separate from each other. This interaction occurs during vibratory, drift and pulsational motion of the particles. However, the orthokinetic interaction which occurs when the particles are executing vibratory motion is by far the most important in acoustic coagulation.

Many authors postulate that orthokinetic collision between two vibratory particles becomes possible when the smaller particle gets into the "aggregation volume" of the larger particles (see Figure 1). This volume is generally considered to consist of a cylinder with a radius equal to the sum of the radii of the two particles.

$$r_a = r_1 + r_2 \quad , \tag{5}$$

and an altitude equal to twice the difference between the amplitude of the displacements that the particles undergo during vibration.

$$h_a = 2\ (A_{p_2} - A_{p_1}) \quad . \tag{6}$$

If A_g is the amplitude of the displacement of the gaseous medium, then we can employ the concept of the particle entrainment factor and write:

$$A_{p_2} = \mu_{p_2} A_g, \; A_{p_1} = \mu_{p_1} A_g \tag{7}$$

and thus

$$h_a = 2\ (\mu_{p_2} - \mu_{p_1})\ A_g \quad . \tag{8}$$

To complete the picture, the aggregation volume would have hemispheres at the ends. According to Mednikov, however, this picture of the aggregation volume needs modification. First, it neglects the phase differences between the vibrations of the interacting particles, and second, it ignores flow in the medium around the particles, which results in the particles being deflected somewhat to the side as they approach each other.

To satisfy the first objection, Mednikov proposes that the altitude of the aggregation volume be written as:

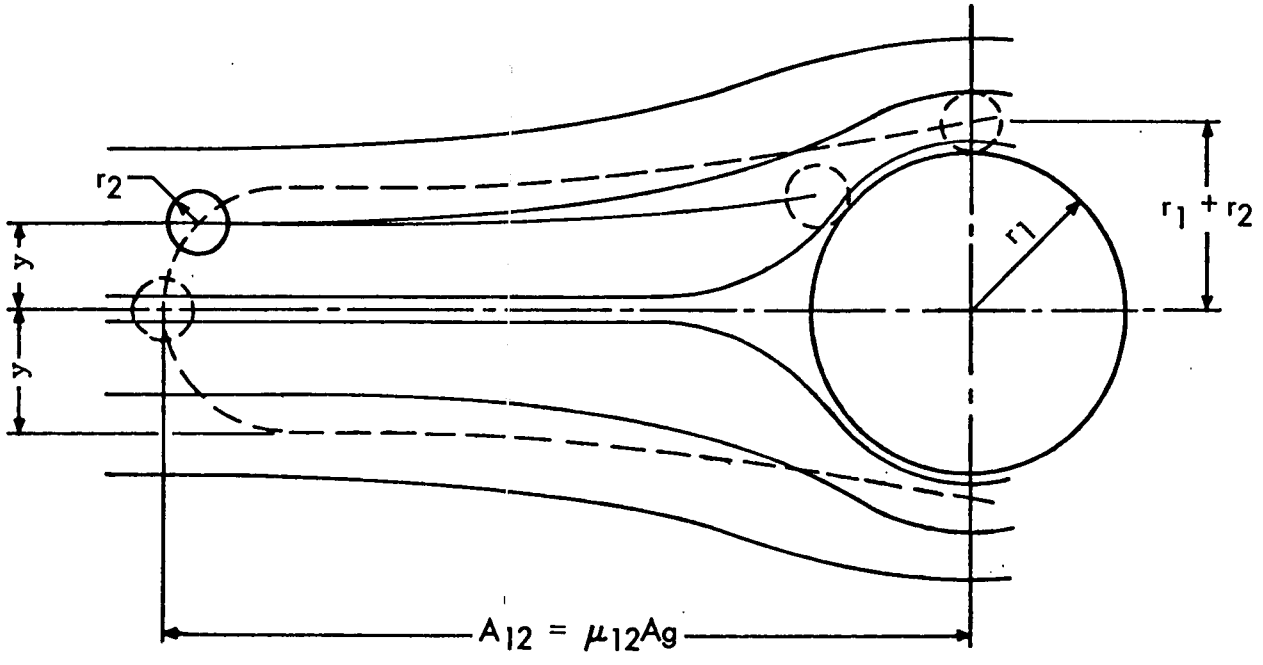

Figure 1. Orthokinetic collision of aerosol particles. The "aggregation" volume for a single approach of particles is shown by the dotted line.

$$h_a = 2\ \mu_{12}\ A_g \tag{9}$$

where

$$\mu_{12} = \left\{\mu_{p_1}^2 + \mu_{p_2}^2 - 2\ \mu_{p_1}\mu_{p_2}\left(\mu_{p_1}\mu_{p_2} + \mu_{g_1}\mu_{g_1}\right)\right\}^{1/2} \tag{10}$$

is the degree of relative motion of the particles. Examination of Eqs. (2), (3) and (10) indicates that there is an optimum frequency of sound at which μ_{12} will be a maximum. If the derivative of Eq. (10) is taken with respect to ω and set equal to zero, the following equation for the optimum frequency is obtained

$$\omega_{opt} = \frac{1}{r_{2rr}\tau_1} = \frac{9\eta}{2\ \rho_p r_1 r_2} \tag{11}$$

or

$$f_{opt} = \frac{9}{4\pi}\frac{\eta}{\rho_p r_1 r_2} \tag{12}$$

where $r_{2rr} = \dfrac{r_2}{r_1}$ is the reduced radius of the smaller particle.

Brandt, Freund, and Hiedemann[14] have developed a similar relationship for single particles by neglecting the buoyancy effect of the gas on the particle and assuming that Stokes' law can be applied to the relative motion of the particle through the gas. The ratio of the amplitude of particle vibration to the amplitude of vibration of the gas was found to be

$$\frac{A_p}{A_g} = \frac{1}{\left\{\left[\dfrac{\pi d^2 f \rho_p}{9\eta C}\right]^2 + 1\right\}^{1/2}} \tag{13}$$

where d = particle diameter

C = Cunningham correction factor.

For constant particle density and gas viscosity, Eq. (13) simplifies to

$$\frac{A_p}{A_g} = \frac{1}{\left[kd^4 f^2 + 1\right]^{1/2}} \tag{14}$$

For particles of unit density vibrating in air, the relative amplitude has been plotted (Figure 2) for frequencies varying from 1 to 100 kc/sec. For the highest frequencies (50 and 100 kc/sec) the curves can only be taken as approximations, as the assumptions regarding the Stokes' law region no longer hold.

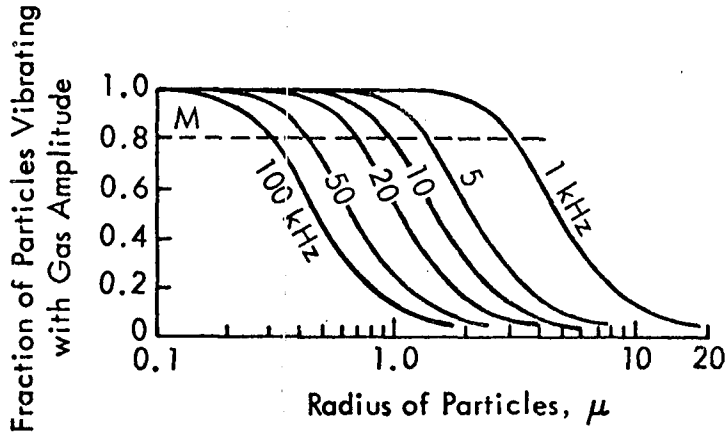

Figure 2. Fraction of particles of unit density of various radii vibrating with gas at sound intensities between 1 and 100 kc/sec amplitude. The broken line at 0.8 (80%) indicates the size above which nearly all particles are considered to vibrate with the gas.[14]

Figure 2 shows how, until a certain particle size, the aerosol particles swing along with the vibrations in the gas. This size can be called the critical particle size for the particular frequency, while a critical frequency for a particular particle size can be similarly calculated. The critical particle size is indicated by the point where the curves enter the steep gradient after their initial shallow decrease, which occurs at approximately the 80% value of A_p/A_g shown by the broken line in Figure 2. Substituting 0.8 for A_p/A_g in Eqs. (13) or (14) gives the critical particle diameter d_c

$$\left[\frac{d_c^2 \rho_p f}{C\eta}\right] \approx 2.2 \qquad (15)$$

or

$$d_c^2 f \approx 4 \times 10^{-4} \text{ cm}^2/\text{sec} \qquad (16)$$

Equations (15) and (16) indicate that as a first approximation, a unique relation exists between the critical particle size and the frequency of vibration of the gas, which for particles less than 7 μm occurs at frequencies greater than 1 kc/sec and extends into the ultrasonic region. These equations enable the critical frequency or particle sizes to be readily calculated. Frequencies of tens to hundreds of kilocycles are indicated for fine particles. However, frequencies this high attenuate so rapidly with distance from the sound source in gases that the aerosol flowing through the chamber will encounter no acoustic field for the greater part of the time. Thus, lower frequencies would have to be used in any actual application.

The second objection to the simplified picture of the aggregation volume concerns the trajectory of the smaller particle as it approaches the larger particle. If the smaller particle were so small that it was of size comparable to the gas molecules, it would follow the motion of the gas along its original line of flow and the possibility of its being captured by the larger particle is equal to zero, since all the flow lines go around the larger particle without intersecting it. However, actual aerosol particles have inertia, so that the smaller particle is deflected from its original flow line. In this case, the aggregation volume is of the form shown by the dotted line in Figure 1. Mednikov defines the capture coefficient of particles, ε , by the following relation:

$$\varepsilon = \left(\frac{y}{r_1}\right)^2 = y^2_{rr} \tag{17}$$

where y is as given in Figure 1.

In effect, ε is the reduced radius of the aggregation volume. Mednikov derives estimates for the minimum and maximum values of this reduced radius:

$$\varepsilon_{min} = \frac{r_{2rr} + 1.5}{r_{2rr} + 1} r^2_{2rr} \tag{18}$$

and

$$\epsilon_{max} \cong \left(\sqrt{\epsilon_L} + r_{2rr}\right)^2 \qquad (19)$$

where $$\epsilon_L = \left(1 + \frac{0.75 \log 2\ k}{k - k_{cr}}\right)^{-2}$$

$$k = \frac{U_{21}\tau_2}{r_1}$$

$$k_{cr} = 1.49 \sqrt{\frac{16 - 3\ R_e}{24 + 12\ R_e}}$$

and U_{21} and τ_2 are the relative velocity and relation time of the small particle, and R_e is the Reynolds number for the flow. Thus, the aggregation volume turns out to be considerably less than the volume of a cylinder of radius $r_1 + r_2$.

Although this concept of a large particle sweeping its aggregation volume clear of smaller particles by colliding and coagulating with them is the ultimate means by which sonic agglomeration works, it alone cannot explain the extent to which acoustic coagulation has been observed to occur. For once the aggregation volume has been cleared of small particles (during one period of vibration), no more collisions or coagulation would be possible. Thus, there must be one or more mechanisms which account for particles refilling the aggregation volume and allowing coagulation to continue. In actuality, two primary and two secondary mechanism for refilling the aggregation volume have been suggested.

The first primary mechanism accounting for the refilling of the aggregation volume is called the parakinetic interaction between aerosol particles. This type of interaction is a result of the distortion of the fields of flow around the particles during relative motion, and is due to the difference in dimensions or densities. Mednikov shows that the flow lines around aerosol particles in a sonic field are asymmetric in the direction of flow (see Figure 3), so that a particle moving toward another one during one-half cycle of vibration will follow a different flow line than it will as it moves away during the other half of vibration. Figure 4 shows what would happen to a gaseous particle vibrating near an aerosol

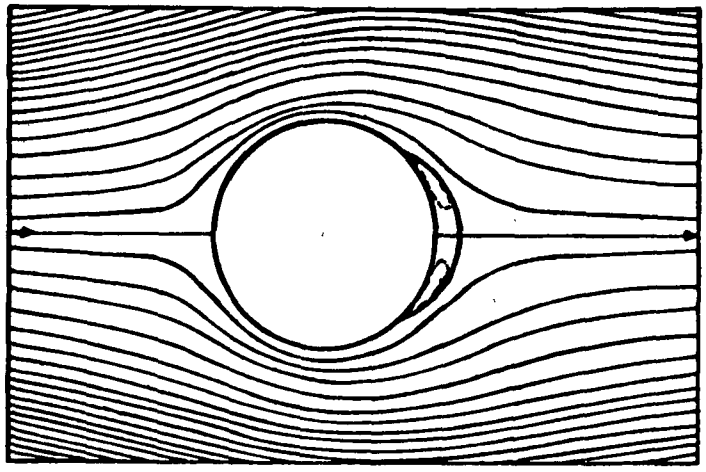

Figure 3. Flow lines around a streamlined spherical particle for $R_e = 1$.

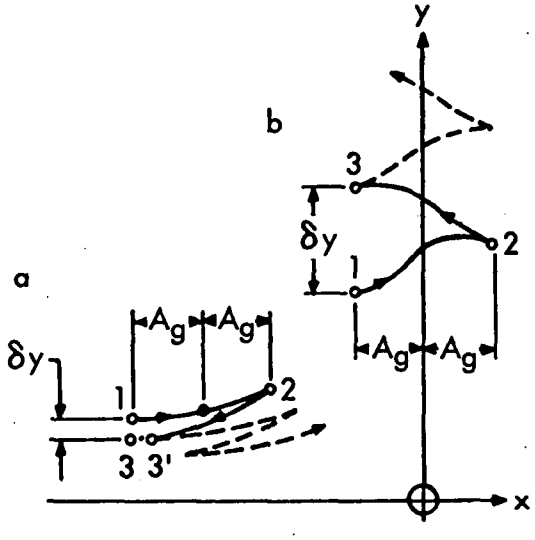

Figure 4. Hysteresis in the flow around an aerosol particle; (a) near the center line, (b) far from the center line.

particle. In (a), a particle of the medium is vibrating close to the center line of the aerosol particle (x-axis) and far to the left of the y-axis. During one-half cycle of the vibrations, the particle moves from Point 1 to Point 2 along one flow line. When the motion reverses itself, however, the particle moves from Point 2 to Point 3 along another flow line and thus returns to a position closer to the center line. In like manner, a particle far from the center line and near the y-axis will also move along two different flow lines during one complete cycle, but in this case, it will find itself further from the center line. An aerosol particle would behave similarly when vibrating near a larger particle, except that its inertia would cause it to deflect slightly from the original flow lines. Mednikov has termed this tendency of a aerosol particle to move toward the center line "self-centering" while the opposite tendency is called "self-decentering."[1/] Figure 5 shows the effect of inertia on these tendencies. Indications are that the parakinetic interaction between aerosol particles is extremely large. As a result of the self-centering phenomenon, orthokinetic collision is not limited to vibrating particles initially in the aggregation volume, but is also possible for particles that are far outside. In fact, according to Mednikov, the parakinetic effect is the primary interactional effect out to a distance of 40 to 60 particle radii from the coagulation center (i.e., aggregation volume).

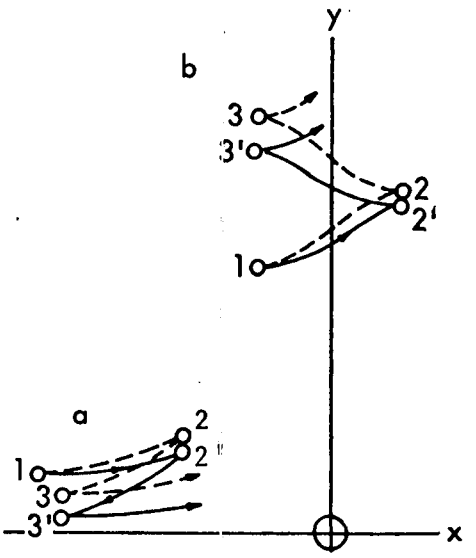

Figure 5. Diagram showing how self-centering (a) and (b) of aerosol particles occurs in a sonic field.

The second primary mechanism accounting for particles entering the aggregation volume is the so-called attractional interaction between aerosol particles. This interaction, like the parakinetic interaction, results from the mutual distortion of the fields of flow around the particles, but in this case, the interaction is due not to the asymmetry of the flow lines but to the asymmetry of the velocity fields around the particles. Mednikov shows that attraction occurs only for particles of different sizes, a fact not realized for many years. The reason for this attraction is that, as two particles vibrate, the particle trailing during one-half cycle enters a "dead" zone behind the leading particle. In this dead zone, the medium is moving more slowly than it is in front of the leading particle. Thus, the trailing particle has a greater relative speed with respect to the medium than does the leading particle, and the two particles approach. During the second-half cycle, the two particles exchange roles, and again they approach each other because of the asymmetry of the velocity fields.

It is noted by Mednikov that the attractional approach rate of aerosol particles is strongly dependent on the frequency. For each size particle, there is an optimum frequency at which the attractional approach rate of the particles is a maximum. The optimum frequency decreases as the particle size increases, a trend also noticed in the orthokinetic interaction mechanism. Both the parakinetic and attractional interactions can easily account for the rapid refilling of the aggregation volume and continued coagulation observed in a sonic field. As was already mentioned, the parakinetic effect is capable of bringing particles into the aggregation zone from as far away as 40 to 60 particle radii from the coagulation center. Significant attractional interaction effects seem to occur at almost twice this distance (i.e., 100 to 120 radii).

However, eventual collision and coagulation is not restricted to particles within the extended region of parakinetic and attractional interaction. Two secondary mechanisms can be isolated which can account for particles coming close to a large particle (coagulation center) so that the primary mechanisms can take over. The first such mechanism is that of particle drift. Aerosol particles can experience drift in an acoustic field due to a number of causes. Particles are found to drift due to the action of the acoustic wind, which is a translational acoustic streaming in the medium. The drift velocity of a particle due to this acoustic wind is usually greater than the drift velocity due to any other cause and is found to be proportional to J/η where J is the sound intensity, defined as the flux of acoustic energy passing through 1 cm^2 of the sound wave front per second. The most commonly used unit of sound intensity is

watts per square centimeter. Another definition which will be useful is that of the sound level L, expressed in decibels (db). The sound level is related to the sound intensity by the equation $L = 10 \log_{10} J/J_o$, where $J_o = 10^{-16}$ w/cm^2. Although it is not certain, a commonly accepted opinion is that the acoustic wind is a result of the radiation pressure gradient set up by absorption of the sound waves in the medium.

Four other causes of particle drift in an acoustic field can be identified. Particle drift might be due to the difference in phase of the vibrations of the particles in the medium. This drift is somewhat retarded by the periodic viscosity changes in the medium, and is the predominant type of drift in an undistorted traveling wave and does not exist in a standing wave field. The maximum value of this drift velocity is about 0.5 cm/sec. Particle drift due to wave form distortion is the predominant type of drift in a distorted traveling wave or a distorted standing wave with large particles ($r > 5$ μm). The drift velocity can reach quite high values, on the order of 10 cm/sec or more, if the amount of distortion and the asymmetry are quite large. Particle drift due to acoustic radiation pressure is significant only for large particles in an undistorted standing wave. For very large particles and high frequencies, the velocity can reach very high values, such as 10 to 40 cm/sec. The last cause of particle drift is the asymmetry in the vibrations of the medium in a standing wave field with small sized particles. This drift velocity might reach a value of 0.5 cm/sec. The drift velocity of aerosol particles is strongly dependent on the particle size and the frequency. In addition, the drift velocity of a particle due to any of these causes is proportional to the sound intensity J.

The other secondary mechanism by which aerosol particles might approach a coagulation center results from the interaction of particles with the pulsations of the vibrating medium. With the concentration gradient set up by the clearing of the aggregation volume after each cycle of vibration, distant particles might approach the coagulation center in a purely diffusional way. In addition, particles of different sizes will have different velocities due to the turbulence of the medium.

The overall mechanism which has been postulated for sonic agglomeration can be summarized with the aid of Figure 6. The basic mechanisms accounting for acoustic coagulation, as described in the preceding paragraphs, are depicted in Figure 6. The actual particle collisions and resulting coagulation take place in the aggregation volume, where the orthokinetic interaction mechanism is dominant. In this volume, the aerosol particles take part in the vibrations of the medium to differing degrees, and the resulting collisions account for the coagulation noticed in aerosols undergoing sonic treatment. It should be noted that the actual size of the

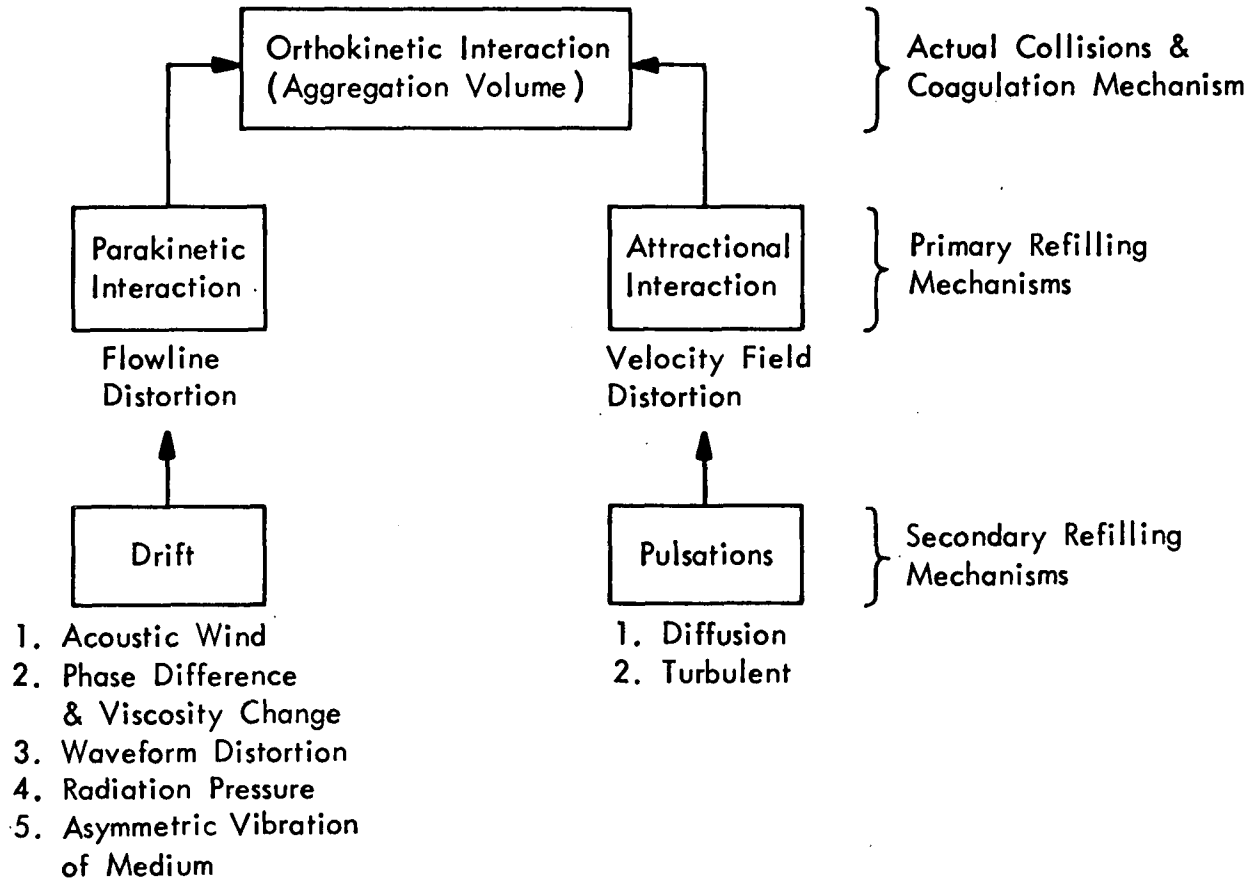

Figure 6. Diagram of overall mechanism postulated for sonic agglomeration.

aggregation volume is a function of the relative sizes of the interacting particles, and thus two small particles of different sizes approaching the same large particle (coagulation center) would experience different aggregation volumes.

St. Clair[2] objected to orthokinetic interaction as the main coagulation mechanism because he could see no way for additional particles to refill the aggregation volume once it had been swept clean by the large particle. Mednikov and others refute this objection, however, through the use of the two primary mechanisms of parakinetic interaction and attractional interaction. In the parakinetic interaction, once a small particle approaches to within about 50 particle radii of the coagulation center, the distortion of the flow lines around the interacting particles causes the small particle to enter the aggregation volume. Likewise, in the attractional interaction, the distortion of the velocity fields around the particles will draw a particle into the aggregation volume after it has approached to within 100 particle radii of the coagulation center. Thus, these two primary mechanisms account for the refilling of the aggregation volume once the particles approach to within a certain distance of the coagulation center.

There are also two secondary mechanisms which can account for particles coming close enough to the aggregation volume for the primary mechanisms to take over. Particle drift can be caused by a number of factors, the most important of which is the acoustic wind. The turbulence of the medium is also important as the particles take part in turbulent pulsations. Thus, particles very far from a coagulation center can eventually enter the aggregation volume and be coagulated. It has been tacitly assumed in the discussion of these mechanisms that the flow velocity is relatively low. For very high velocities. inertial effects would greatly complicate matters and the above mechanisms would have to be modified.

Equations describing the postulated processes involved in sonic agglomeration have not and perhaps cannot be integrated into a single tractable mathematical expression. A simpler approach using a modified form of Smoluchowski's equation for thermal agglomeration has been advanced by several authors including Mednikov. According to Smoluchowski the normal coagulation rate of an aerosol will obey the following relation:

$$\frac{dn}{dt} = -Kn^2 \qquad (20)$$

where n is the particle count concentration, K is the coagulation constant, and t is the time. Considering the orthokinetic interaction process as the main collision and coagulation mechanism, it seems reasonable to say, first, that the number of large particles, $n_1 = n_{10}$, remains a constant, and second, that the number of small particles, n_2, is much larger than n_1 ($n_2 \gg n_1$). In this case, Eq. (20) becomes:

$$\frac{dn}{dt} = -K_a n_2 \quad . \tag{21}$$

If the particle count concentration (essentially n_2 as a result of preceding assumption) at $t = 0$ is n_o, the solution of Eq. (21) is:

$$n = n_o e^{-K_a t} \quad . \tag{22}$$

If the assumption is made that the primary and secondary filling mechanisms can keep the aggregation volume filled with small particles in such a way that the rate of coagulation is dependent on the speed of the orthokinetic interactions, then one might say that a state of reaction control had been achieved. If this is the case, the acoustic coagulation constant K_a must be proportional to the number of large particles n_{10}:

$$K_a = K_{a_1} n_{10} \quad . \tag{23}$$

Likewise, the coagulation constant should also be proportional to the volume of the aggregation zone. If the aggregation volume is taken to be a cylinder with radius ϵ, as given by Eq. (17), and altitude h_a, given by Eq. (9), then K_{a_1} can be written as:

$$K_{a_1} = \beta \epsilon \pi r_1^2 h_a = \beta \epsilon \pi r_1^2 \, (2 \, \mu_{12} \, A_g) \tag{24}$$

where β is a filling factor which must be determined experimentally. The acoustic coagulation constant K_a can now be written:

$$K_a = 2\pi\beta n_{10} \epsilon r_1^2 \mu_{12} A_g \tag{25}$$

A_g is the amplitude of the displacement of the medium (i.e., gas molecules) and can be related to the sound intensity J by the following equation:

$$A_g = \frac{1}{\omega} \sqrt{\frac{2J}{\rho_g C_g}} \tag{26}$$

where ρ_g and C_g are the density of the medium and the speed of sound in the medium, respectively. Considering Eqs. (25) and (26), it can be seen that:

$$K_a \sim J^{1/2} \tag{27}$$

Inspection of Eqs. (22), (25), (26), and (27) shows that sonic agglomeration will be strongly influenced by frequency, particle size distributions, sound intensity, particle number density, and exposure time. Specifically, the acoustic agglomeration rate will be improved by increasing the quantity $\left[n_1 \overline{r_1^2} J^{1/2} t_{res}\right]$. Experimental evidence exists which confirms most of the parametric dependencies predicted by the above-mentioned equations. The results of laboratory and field studies of sonic agglomeration are discussed in the next section.

LABORATORY, PILOT-SCALE AND FULL SCALE STUDIES OF SONIC AGGLOMERATION

Both laboratory and field studies of sonic agglomeration have shown that aerosols can be agglomerated in acoustic fields under appropriate conditions. An overview of the results of work in both areas is presented next.

LABORATORY OR SMALL-SCALE STUDIES OF SONIC AGGLOMERATION

Some experimental evidence exists which directly supports the microscopic coagulation mechanisms which have been discussed. For instance, Schlichting[3] provided pictures confirming the parakinetic interaction between aerosol particles. Gorbachev and Severnii[4,5] studied the elementary interaction between two water droplets suspended on glass threads and proved that an attractional interaction mechanism was occurring between the particles. Most experimental studies, however, cannot provide direct evidence of microscopic mechanisms, but rather do demonstrate parametric dependencies.

Nearly all experimental data available show excellent agreement with Eq. (22) (i.e., $n = n_o e^{-K_a t}$). One such verification was made by Brandt[6] in experiments on the acoustic coagulation of a paraffin oil fog. Some of his results are shown in Figure 7. The radii of fog droplets used by Brandt were in the range 0.2 to 1.9 μm and the concentration was 15 to 20 g/m^3. The curves given in Figure 7 yield the following values for the coagulation coefficient.

$$J = 0.0067 \text{ w/cm}^2, \; K_a = 0.43$$

$$J = 0.06 \text{ w/cm}^2, \; K_a = 0.92$$

$$J = 0.11 \text{ w/cm}^2, \; K_a = 1.28$$

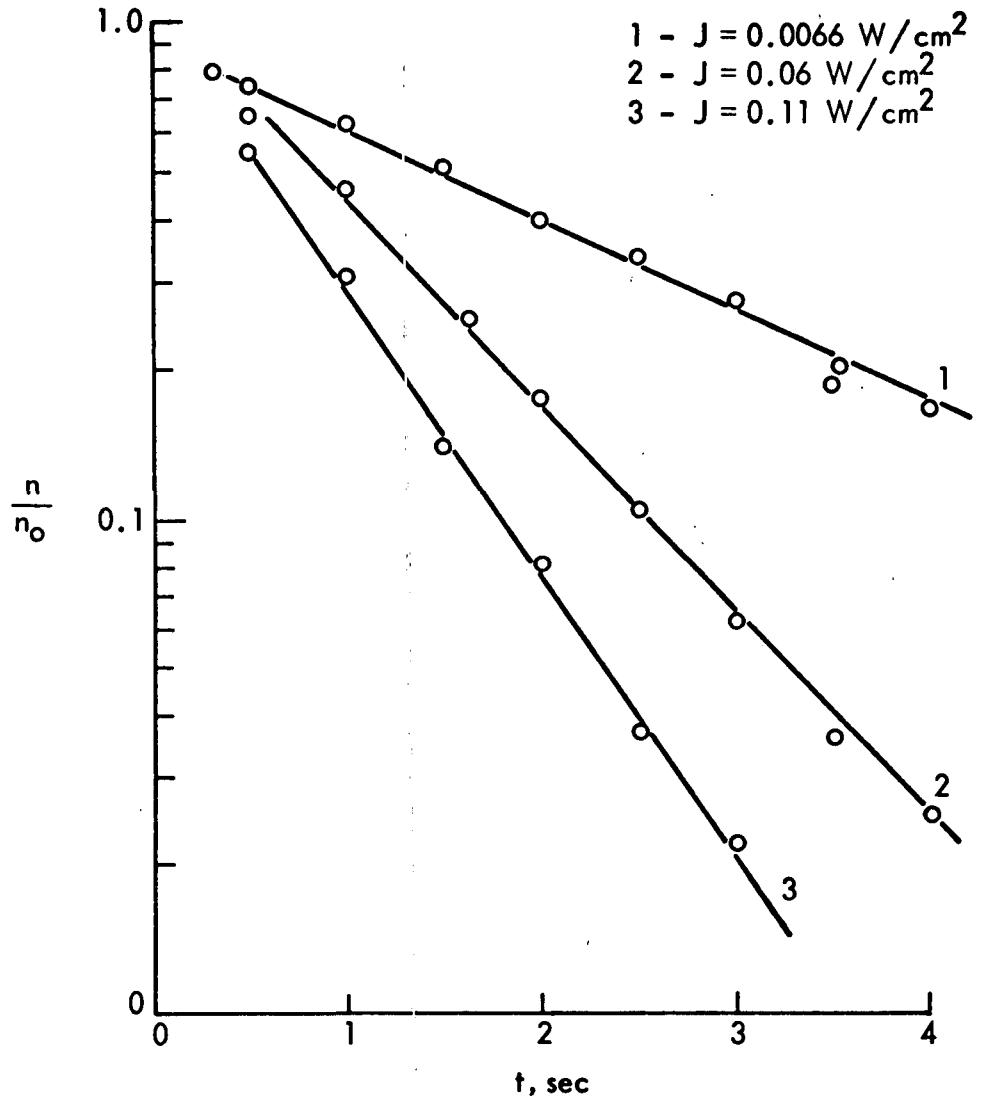

Figure 7. Acoustic coagulation rate of a paraffin fog as a function of sound intesity (f = 10 kc/sec).

Experiments by Brandt and Freund[8] and Neumann and Norton[9] show that the coagulation coefficient is a function of the square root of sound intensity as predicted by Eq. (27) (see Figures 8 and 9).* It has also been noted, that sound absorption in a medium increases as the intensity increases so that, from an economic standpoint, it is not recommended that very high sound intensities be used in industrial aerosol coagulation. Most often, the sound intensity used is of the order of 0.1 w/cm^2 to 1 w/cm^2.

It has been shown experimentally that the frequency of the sound used has a very substantial effect on the acoustic coagulation process. In fact, numerous experiments have shown that each aerosol has an optimum frequency at which acoustic coagulation proceeds in the most efficient manner. The optimum frequency is not a function of either sound intensity or the treatment time (see Figure 10), but is a function solely of the properties of the aerosol as predicted by Eq. (12).

Experiments also have shown that the efficiency of the sonic agglomeration process decreases rapidly at mass concentrations below 2 to 5 g/m^3. On the other hand, very high concentrations (> 100 g/m^3) are also undesirable since there is an exceedingly large decrease in sound intensity with distance from the sound source at such high concentrations, and this reduces the coagulation rate in the aerosol.

Experiments have also shown that an increase in the viscosity, temperature, or pressure of the gas all have a negative effect on the coagulation rate in the aerosol. It should be noted, however, that a high temperature does not prevent the process from occurring; it merely slows it down. This was supported by Stokes[12] who noted that the cooling and dehumidification (which reduces the viscosity) of the aerosol aided agglomeration. Boucher[13] made a claim that increased viscosity enhances agglomeration, but this is not supported by experimental evidence.

The addition of atomized water to a low concentration aerosol is generally found to increase the efficiency of agglomeration. Figure 11 presents the results of addition of water to a gas black aerosol. The addition of water apparently increases the efficiency of agglomeration and subsequent collection of particles in the cyclone collector.[16] There is some question as to whether the water drops promote agglomeration, act more as a scrubbing media, or both. If the water drops promote agglomeration, they would do so by increasing the number of coagulation centers.

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* In Figures 8 and 9, the index of agglomeration, I , is the ratio of the final to the initial mean particle diameter.

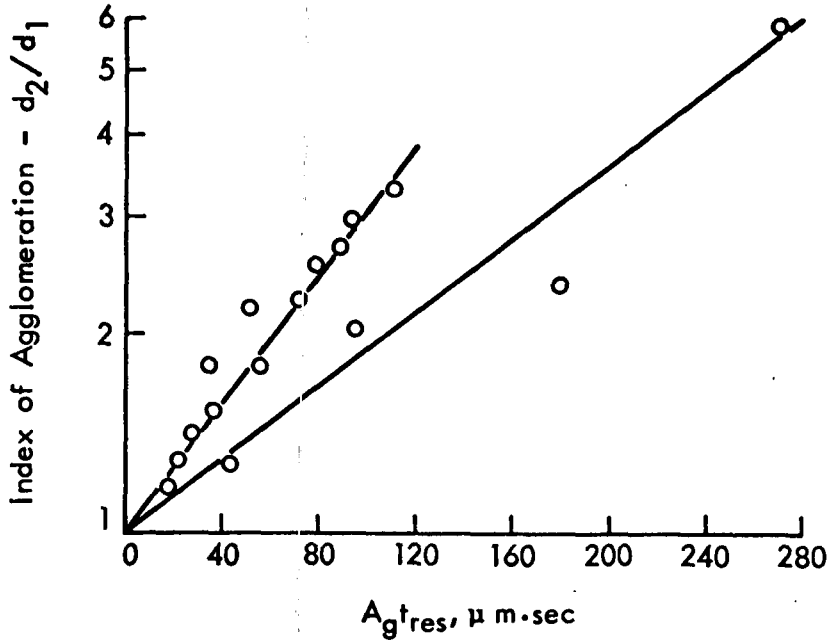

Figure 8. Degree of agglomeration of tobacco coke particles as a function of the product $A_g t_{res}$ (f = 10 kc/sec).

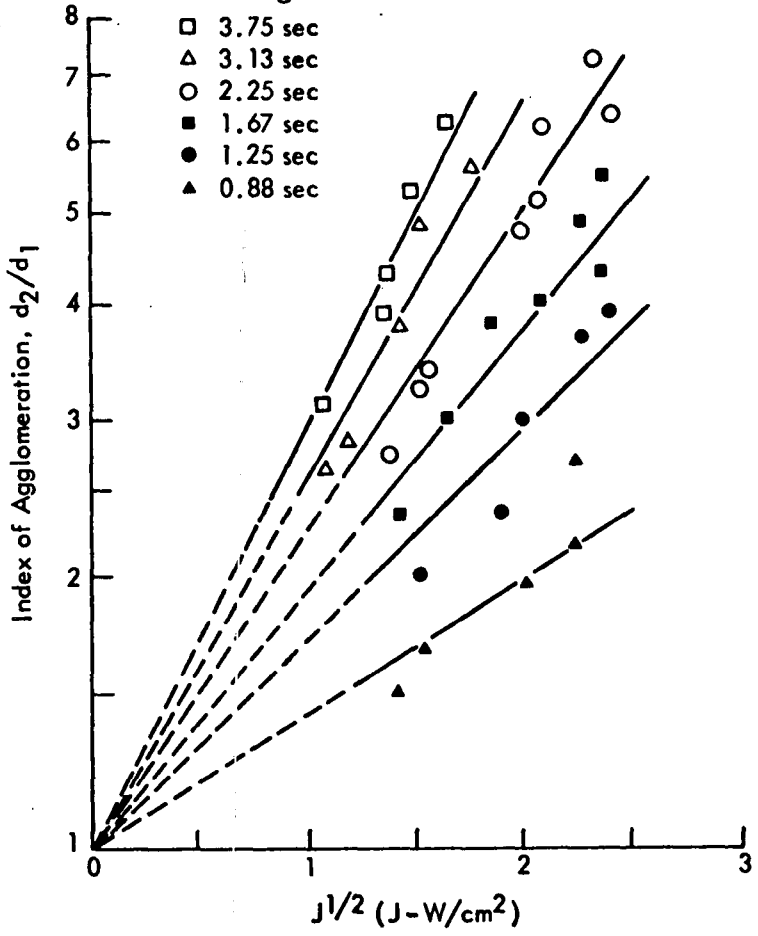

Figure 9. Degree of agglomeration of titanium tetrachloride particles as a function of the quantity $J^{1/2}$ (f = 1.6 kc/sec).

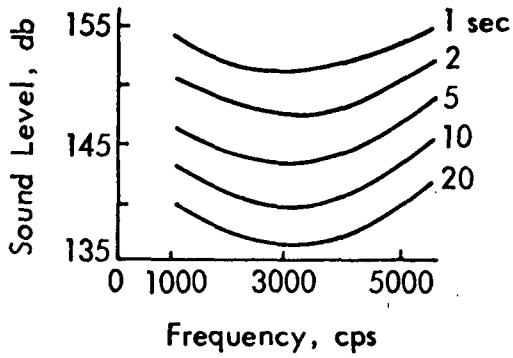

Figure 10. Sound level required for 50% agglomeration of a water fog for different times and frequencies.

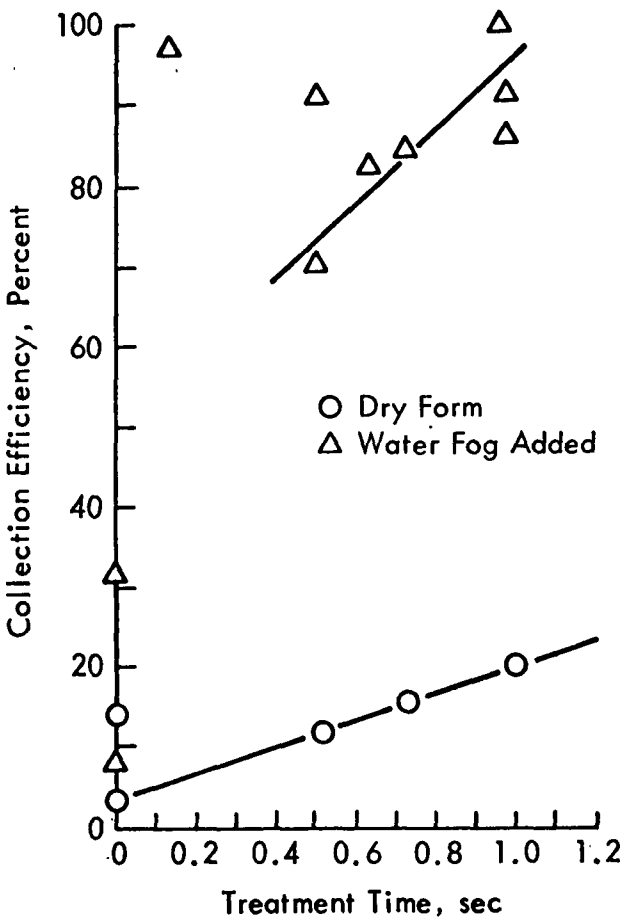

Figure 11. Acoustic coagulation efficiency of gas black (p_c = 0.35 atm, f = 2.1 kc/sec) as affected by adding a water fog.

Reference 17 discusses the results of a series of tests to determine the performance of a sonic agglomerator-cyclone collector system currently being developed by the Braxton Corporation. Since the agglomeration rate should be enhanced by both a higher concentration and wider size range of the inlet particulate, the Braxton system is designed to allow the admission of steam and/or water droplets. The collector efficiencies of the Braxton device using suspended cupola dust and different combinations of sound, steam and water ranged from 81 to 97%. These efficiencies are based on using a cyclone after the sonic agglomerator equal in collection efficiency to the cyclone used for sampling during these tests.

The correlation coefficients for the small particle reduction for all test runs with sound, water and steam individually and neglecting other operating parameters were 0.68, 0.65, and 0.06, respectively. The coefficients for sound and water were statistically significant while that for steam was not. A multiple regression analysis of those tests using cupola dust showed that the use of steam is not significant, but that the use of water sprays and the sonic generator are highly significant in reducing the mass of fine particles. The regression analysis also showed that the sonic generator has less influence on fine particle reduction than does water sprays when using resuspended cupola dust. A possible scrubbing action by the water droplets is indicated.

FIELD STUDIES OF SONIC AGGLOMERATION

Sonic agglomeration chambers in conjunction with cyclone collectors or other control devices have been used in industrial gas cleaning applications on a random basis for many years, especially in Europe and Russia. Table I presents a summary of some applications. The applications in Table 1 date to the 1950 to 1960 time period.

The test data from industrial systems show essentially the same parametric dependencies as noted in laboratory work. The exponential nature of the process (i.e., $n = n_o e^{-K_a t}$) is confirmed as well as the existence of optimum frequencies. Table 2 presents a compilation of data on optimum frequencies required for acoustic agglomeration of different aerosols. The data in Table 2 show that the optimum frequency varies inversely with particle size in agreement with the theoretical prediction given in Eq. (12). Performance variations with changes in inlet grain loadings, particle size, and water addition are shown in Table 1 and Figures 12 and 13.

Analyses of industrial applications indicate that the sound generators usually operate in the 1 to 4 kc/sec range and sound intensities in excess of 130 db are necessary (130 db = 10^{-3} w/cm^2).* Contact times of about 4 sec have generally been used in industrial systems.

* Intensities of 150 to 160 db are common.

Table 1. SUMMARY OF INDUSTRIAL TESTS WITH SONIC AGGLOMERATORS

	Aerosol and Gas Stream Properties				Agglomeration Chamber					Collector System		
Aerosol Type	Particle Radius r (μm)	Concentration by Weight (g/m^3)	Temperature (t, °C)	Volume Treated (Q, m^3/hr)	Type and Dimensions (D_c x H_c, m)	Type of Siren	Frequency f (kc/sec)	Intensity, J (w/cm^2)	Length of Sonic Treatment t_o (sec)	Type	Percentage Removed Without Sound η_h (%)	Percentage Removed With Sound η_{si} (%)
Gas furnace black	0.03-0.07	1.2-12.6	40	1,700-2,000	Experimental direct flow 1.1 dia. x 6.6	Dynamic, radial	4	0.5-1.0	4.5	Two cyclones 1.3 in dia. (in series)	40	83-90
Gas furnace black	0.03-0.07	1.2-2.1	40	1,700-2,000	The same, with water addition	The same	2-4	0.5-1.0	1.2	The same	8-32	99
Aggregated gas black	0.5-15	0.5-2.5	-	600	Experimental reverse flow with water 0.5 dia.	Dynamic, axial	3	0.1	10	One or four cyclones (in parallel)	68-72	95
Atomized carbon black	0.1-0.2	26	82	45	Experimental, rising stream 0.29 dia. x 1.9	Static with pump-off	4.6	1.0	7	Two cyclones and a glass cloth filter (in series)	(30)[a]	99.98 (97)[a]
Hard coal black	0.5-1.0	0.5-2.4	80-90	90-100	Experimental, reverse, flow, 0.2 dia. x 2.5	Dynamic, axial	3.6	0.10-0.14	3-4	Cyclone 0.15 m dia.	68-74 (81)[b]	87 (97)[b]
Sulfuric acid fog	0.5-5.0	5-40	180	1,700	The same, 0.6 dia. x 6	The same	2.15	0.1	3	Multicyclones (in parallel)	84	99.6-99.9
Natural sulfuric acid fog	0.25-2.5	1	50	40,000	Industrial, composite flow, 2.4 dia. x 10.5 (2 sets)	Dynamic, radial	2.25	0.1	4	Two cyclones (in parallel)	-	90
Dilute sulfuric acid fog	2.5-50, predominant 7.5	0.5-1.2	20	1,800	Experimental, reverse flow, 0.64 dia x 11	Dynamic, axial	1-2	0.1	7	Four cyclones (in parallel)	69-72	78-82

Table 1. (Concluded)

Aerosol Type	Aerosol and Gas Strem Properties				Agglomeration Chamber					Collector System		
	Particle Radius r (μm)	Concentration by Weight (g/m^3)	Temperature (t, °C)	Volume Treated (Q, m^3/hr)	Type and Dimensions (D_c x H_c, m)	Type of Siren	Frequency f (kc/sec)	Intensity, J (w/cm^2)	Length of Sonic Treatment t_o (sec)	Type	Percentage Removed Without sound η_n (%)	Percentage Removed With Sound η_{si} (%)
Zinc oxide sublimate from roasting zinc ore	0.5-5.0, predominant 2.5	1-2	40-100	1,600	Experimental, reverse flow, 0.75 dia. x 10	Dynamic, axial	3-3.5	0.1	10	Cyclone	84-87	94-98
Zinc oxide sublimate from copper smelting	0.5-4.0	0.5-20	50-350	1,300-2,160	The same, 1.0 dia. x 9	Dynamic, radial	3-9	0.13	10	Cyclone 1.35 m dia.	70	90-95
Zinc oxide sublimate from brass melting	0.4-0.6	10	400	7,000	The same, 0.7 dia. x 10	Dynamic, axial	0.7	0.6	2.5	Cyclone 0.15-0.3 m dia. and filters (in series)	-	99.8
Coke gas (tar)	0.5-5.0, predominant 2.5	30-70	40-60	1,300-2,100	The same, 0.5-0.64 dia. x 9	The same	4	0.1	5-8.5	Two cyclones (in parallel)	88	99-99.8
Cracking gas (condensate)	0.5-5.0	5-70	35	1,200	The same, 0.5 dia. x 9	The same	4	0.1	5	The same	76-82	97.5-99.3
Cracking gas (condensate)	0.5-5.0, predominant 3.0-3.5	6-15	40	12,000	Industrial, reverse flow, 1.6 dia. x 11 (2 sets)	The same	3.5	0.1	6	Two Pelouze tar extractors (in parallel)	73	95
Open-hearth furnace smoke	2.5 (55%)	2	150	5,000	Experimetnal, reverse flow with water addition	Dynamic	2.2	-	-	Wet type W rotoclone	45	90.7
Carbide furnace smoke	0.5-15, predominant 0.5	0.25-2.8	120	500	Experimental, reverse flow	Static	7-10	-	4-6	Multicyclones (in parellel)	11	94
Carbide furnace smoke	The same	0.25-2.8	120	500	The same, with water addition (5 g/m^3)	Static	10.5	-	4-6	The same	-	86

a/ Result without cloth filter, in parentheses.
b/ Result from water addition, in parentheses.

Table 2. OPTIMUM FREQUENCIES FOR SONIC AGGLOMERATION,[1/] INDUSTRIAL TESTS

Aerosol	Particle Radius[a/] r (μm)	Optimum Frequency f_{opt} (kc/sec)
Furnace gas black	0.03-0.07	3.5-4.0
Aggregated carbon black	0.5-15.0	3.0
Zinc oxide sublimate	0.5-5.0 / 2.5	3.0-3.5
Coke gas fog	0.5-5.0 / 2.5	3.5-4.0
Cracking gas fog	0.5-5.0 / 3.0	3.5-4.0
Dilute sulfuric acid	2.5-50	1.0-2.0

a/ The numerator gives the maximum radii, while the denominator gives the predominant radius.

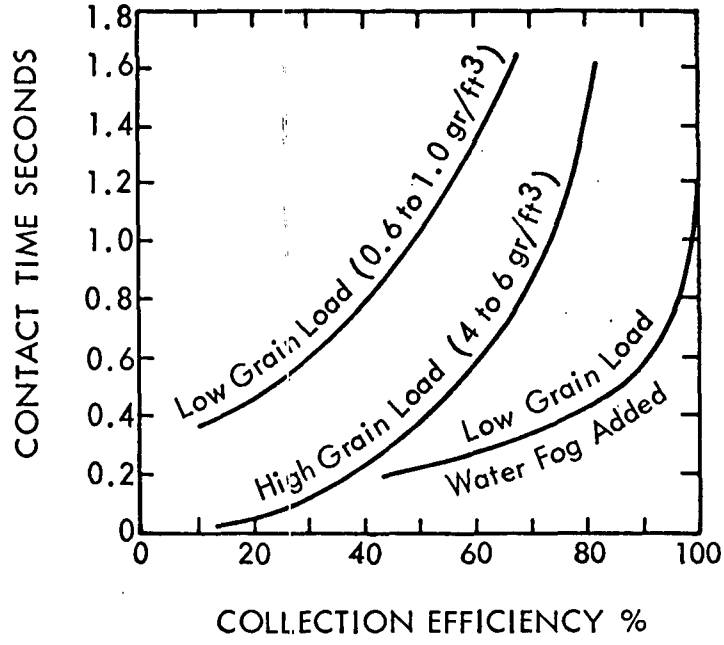

Figure 12. Collection efficiency of 93.5-95.0 scale furnace black as a function of time and exposure (cyclone collector).[10]

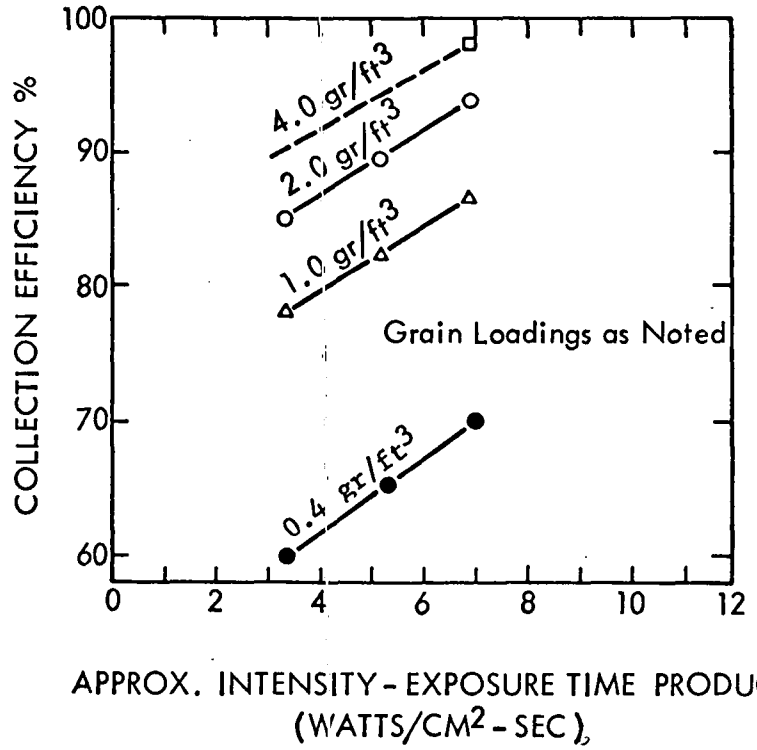

Figure 13. Performance of sonic carbon black collection system (three cyclones in series).[10]

SUMMARY OF LABORATORY, PILOT-SCALE AND FULL-SCALE DATA

Testing of sonic agglomerators at the laboratory, pilot-scale and full-scale plant level have resulted in the following observations:

1. Frequency has a strong effect on sonic agglomeration and an optimum frequency exists for various particle sizes.

2. Optimum frequency increases with decreasing particle size.

3. Sound intensity has a significant effect on sonic agglomeration and the particle growth rate varies with the square root of the sound intensity.

4. Sound intensities of 150 to 160 db have been used in previous industrial applications.

5. Sonic agglomeration rate is strongly affected by the concentration by weight of particles and efficiency of agglomeration decreases rapidly at concentrations below 2 to 5 g/m^3 (1 to 2 $grains/ft^3$).

6. Polydisperse aerosols are easier to agglomerate than relatively monodisperse aerosols (i.e., if particles are all of nearly same size, acoustic agglomeration is not effective).

7. Injection of atomized water into low concentration aerosols seems to improve sonic agglomeration. Improvement from water injection is due primarily to the fact that additional coagulation centers are available.

8. Reduction of turbulence in the agglomeration chamber generally results in a decrease in the agglomeration rate.

9. Physical properties of aerosol particles have comparatively little effect on acoustic agglomeration.

10. Viscosity, temperature, and pressure of the gas are generally not important.

11. Agglomerates formed in sonic fields often do not have a high degree of stability and they may be broken up in the collection device, especially in cyclones.

COMPARATIVE ANALYSIS OF SONIC AGGLOMERATORS AND CONVENTIONAL CONTROL SYSTEMS

The utilization of sonic agglomeration for industrial gas cleaning requires the coupling of an agglomeration chamber to a particulate collection system. Cyclones, electrostatic precipitators, and fabric filters have been used or proposed as the collection system with cyclone systems being the prevalent system in the past. For a sonic agglomeration system to be competitive with a conventional control device, it must offer improved collection efficiency at reasonable cost or reduced cost for the same degree of efficiency. Analysis of the performance and energy requirements of sonic systems is clearly in order, and since our interest is mainly in the collection of fine particles, our comparative analysis will be confined to that size range.

Increasing the size of submicron particles by sonic agglomeration to a size where they can be readily collected by inertial methods requires a relatively long treatment time, a considerable expenditure of energy or both. If the acoustic coagulation coefficient is known, the time required to achieve a given increase in particle size can be estimated from Eq. (28) which is a rearrangement of Eq. (22).

$$t_o = \frac{3}{K_a} \ln \left[\left(\frac{\rho_p}{\rho_{p_o}} \right)^{1/3} \frac{r}{r_o} \right] \tag{28}$$

Recalling that K_a is proportional to $J^{1/2}$, Eq. (28) can be written as

$$t_o \, J^{1/2} \cong 3 \ln \left[\left(\frac{\rho_p}{\rho_{p_o}} \right)^{1/3} \frac{r}{r_o} \right] \tag{29}$$

If it is assumed that the density of the agglomerate is the same as the original particulate, Eq. (29) becomes

$$t_o J^{1/2} \approx 3 \ln \left[\frac{r}{r_o} \right] \quad . \qquad (30)$$

Figure 14 presents a graphical depiction of Eq. (30) while Figure 15 presents the experimental data of Neumann and Norton[9] in a slightly different form than Figure 9.

For a sonic agglomerator to be of significant help in the collection of fine particles,* the ratio of the final to initial mean particle radius or diameter must be in the range of 5 to 20. The lower end of the range would correspond to the use of a high efficiency system as the collector (i.e., ESP, fabric filter, venturi) while the upper range would reflect the use of a low efficiency system as the collector (i.e., cyclone, spray scrubber). To achieve a growth ratio of 5 to 20, Eq. (30) predicts that the product of $t_o J^{1/2}$ would range from 5 to 9. Assuming the experimental data in Figure 15 can be used for illustrative purposes, growth ratios of 5 to 20 would require that the product of $t_o J$ vary from 6 to 20 in real systems.

At first glance one might assume that either t_o or J could be varied to achieve the desired product of t_o and J . However, sound absorption in the medium increases rapidly as the sound intensity increases and it is not economical to use very high sound intensities. As noted previously sound intensities of 150 to 160 db (0.1 to 1.0 w/cm^2) were common in previous applications. With the preceding values of J , the exposure time would have to be in the range of 6 to 200 sec. Exposure times up to 10 sec have been used, but clearly the 200 sec is not feasible. It is clear that sound intensities of 1.0 w/cm^2 or greater will be needed if fine particles are to be agglomerated in residence times suitable for industrial applications.

The preceding discussion regarding Eq. (30) and Figure 14 did not consider the efficiencies of the sound source system and other equipment. When one makes allowances for system inefficiencies, the energy or exposure time requirements are more severe as indicated by actual data in Figure 15. Equation 31, developed by Mednikov relates the specific energy required to agglomerate an aerosol to the efficiencies of various components of a sonic agglomerator.

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* For the purposes of this discussion, fine particles will be defined as those in the size range of 0.1 to 3 μm in diameter.

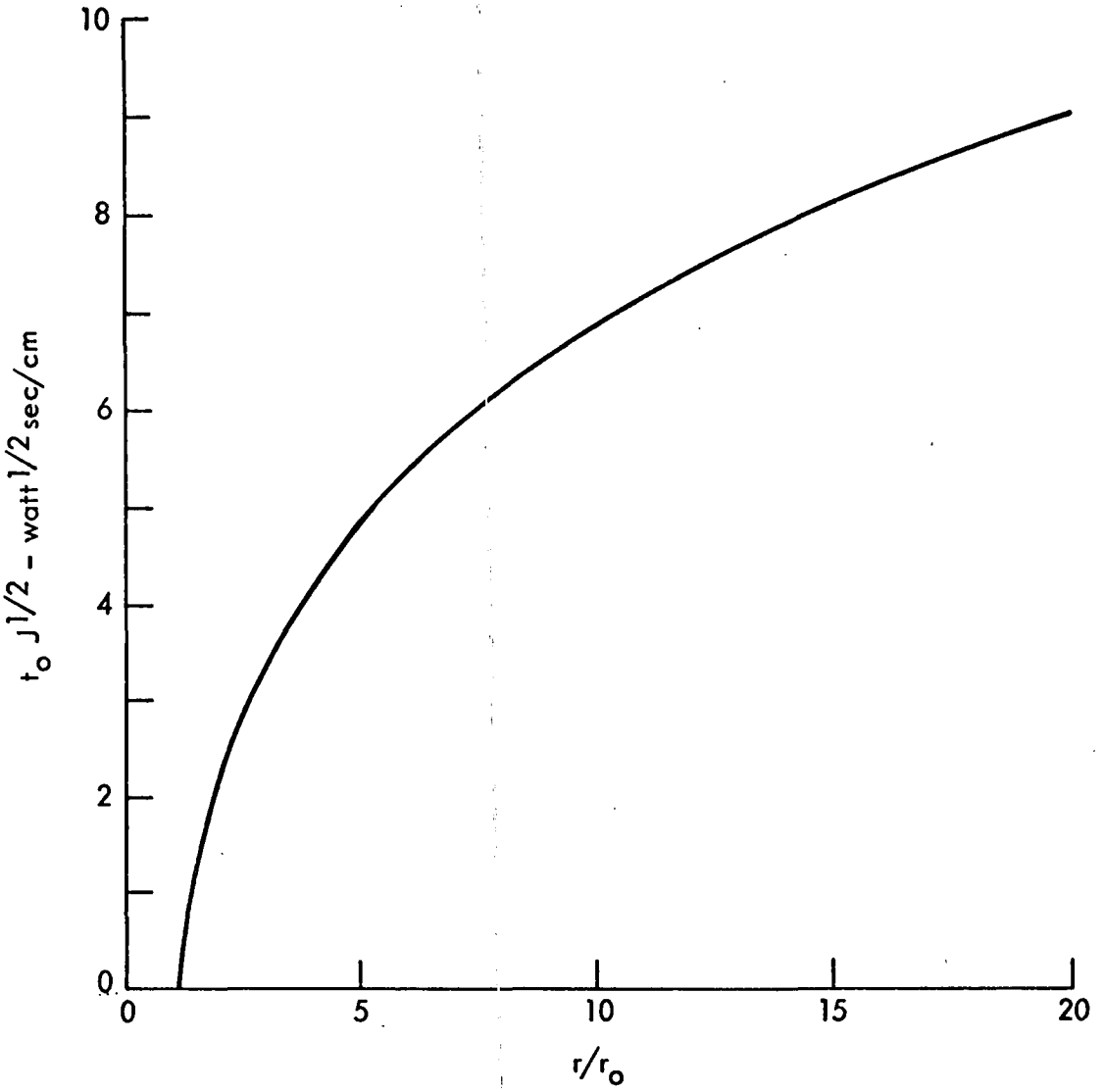

Figure 14. Predicted sound intensities as a function of agglomeration index.

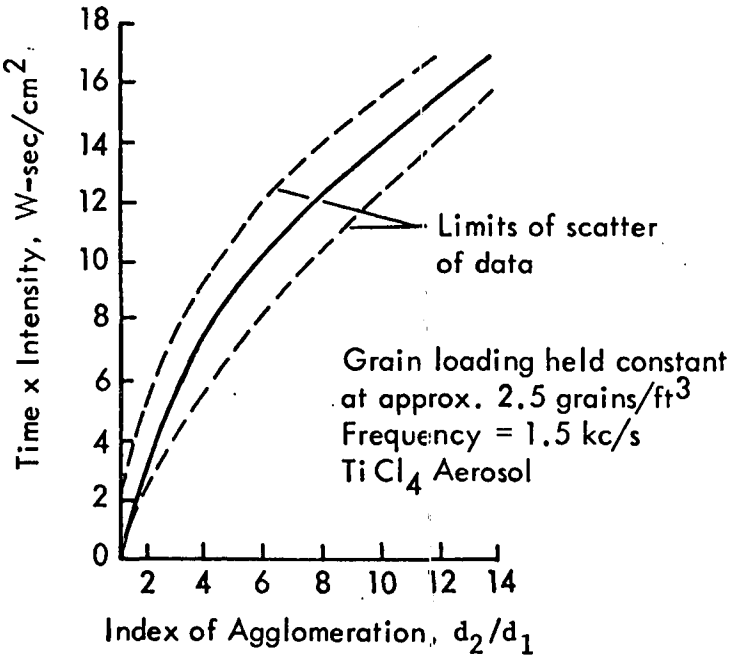

Figure 15. Correlation of data on agglomeration and sound intensity.[9]

$$E = \frac{J\ t_o}{(0.36)\ \epsilon_s \epsilon_c \epsilon_{uf}\ H_o} \qquad (31)$$

where E = specific energy, kw-hr/1,000 m^3

J = sound intensity, w/cm^2

t_o = exposure time, sec

H_o = height of agglomeration chamber, m

ϵ_s = acoustic efficiency of sound source

ϵ_c = overall efficiency of compressor during sound source

ϵ_{uf} = utilization factor of agglomeration chamber (i.e., factor to account for losses in chamber)

The acoustic efficiency of the sound source (ϵ_s) and the compressor efficiency (ϵ_c) can be estimated for various types of equipment, but ϵ_{uf} must be determined by experiment for a given chamber.

Equation 31 can be used to estimate specific energy requirements if assumptions are made regarding the various efficiency terms and the dimensions of the acoustic chamber. Example calculations are presented in Table 3 and are based on the following assumptions:

a. J = 150, 160, 165, and 170 db

b. gas flow 1,000 m^3/min (35,300 cfm)

c. d_2/d_1 = 2, 5, 10, 15, 20

d. $\epsilon_c = 0.65$, $\epsilon_s = 0.5$, $\epsilon_{uf} = 0.7$*

e. cylindrical chamber with diameters of 2 and 4 m.

Several observations on the data in Table 3 are in order. First, the specific energy requirements are dependent only upon sound intensity and chamber height (actually chamber volume). Second, at the low level of sound intensity (i.e., 150 db) very long chambers are required to achieve

* Data on these efficiences are not generally available. Mednikov cites a value of $\epsilon_c = 0.65$, and Ref. 15 mentions that dynamic sirens of recent design have efficiences (i.e., ϵ_s) of about 50%. The value of $\epsilon_{uf} = 0.7$ is an arbitrary assumption.

Table 3. ESTIMATED SPECIFIC ENERGY REQUIREMENTS FOR EXAMPLE SONIC AGGLOMERATOR

J								$E = \frac{J\ t_o}{(0.36)\ \epsilon_s \epsilon_c \epsilon_{uf}\ H}$	
db	w/cm^2	d_2/d_1	$J^{1/2}\ t_o$	t_o (sec)	D (m)	H (m)	(0.36) $\epsilon_s \epsilon_c \epsilon_{uf}$ H	kw-hr/1,000 m^3	hp/1,000 cfm
150	0.1	2	2	6.6	2	35	2.9	0.23	0.5
					4	9	0.74	0.89	2.1
		5	5	15	2	80	6.6	0.23	0.5
					4	20	1.7	0.89	2.1
		10	7	21.6	2	115	9.4	0.23	0.5
					4	29	2.4	0.89	2.1
		15	8	25.3	2	134	10.4	0.23	0.5
					4	34	2.8	0.89	2.1
		20	9	28.1	2	149	12.3	0.23	0.5
					4	37	3.0	0.89	2.1
160	1.0	2	2	2	2	11	0.90	2.3	5.2
					4	2.8	0.23	9.1	21
		5	5	5	2	25.5	2.1	2.3	5.2
					4	6.4	0.52	9.1	21
		10	7	7	2	36.6	3.0	2.3	5.2
					4	9.2	0.75	9.1	21
		15	8	8	2	43.9	3.6	2.3	5.2
					4	10.7	0.88	9.1	21
		20	9	9	2	47.8	3.9	2.3	5.2
					4	12	0.98	9.1	21
165	3.2	2	2	1.2	2	6.4	0.53	7.2	16.4
					4	1.6	0.13	29.5	67.2
		5	5	2.7	2	14.3	1.2	7.2	16.4
					4	3.6	0.3	29.5	67.2
		10	7	3.9	2	20.7	1.7	7.2	16.4
					4	5.2	0.4	29.5	67.2
		15	8	4.5	2	24	2.0	7.2	16.4
					4	6	0.5	29.5	67.2
		20	9	5.0	2	26	2.1	7.2	16.4
					4	6.6	0.54	29.5	67.2
170	10	2	2	0.7	2	35	0.28	25	57
					4	0.9	0.07	94.6	215
		5	5	1.5	2	8	0.66	25	57
					4	2	0.16	94.6	215
		10	7	2.2	2	11.7	1.0	25	57
					4	2.9	0.24	94.6	215
		15	8	2.5	2	13.3	1.1	25	57
					4	3.3	0.27	94.6	215
		20	9	2.8	2	14.9	1.2	25	57
					4	3.8	0.3	94.6	215

necessary particle growth. In fact, at all ratios of d_2/d_1 exceeding 2, the length of the chamber is more than 60 ft. Third, more acceptable chamber lengths can be achieved at higher sound intensities, but the specific energy requirements increase rapidly with sound intensities. With regard to the last point, the data in Table 3 suggest that sound intensities of 160 db or greater will be necessary to grow fine particles to an acceptable size in realistic equipment sizes. At the high growth ratios (i.e., $d_2/d_1 > 5$), a 4-m diameter chamber would be necessary to maintain a reasonable chamber length. Specific energy values of approximately 5 hp/1,000 cfm are required for moderate growth ratios ($d_2/d_1 < 5$) in a 2-m diameter column of reasonable length, while energy values in excess of 20 hp/1,000 cfm are needed for high growth ratios ($d_2/d_1 > 5$) in a 4-m diameter chamber of reasonable length.

Apart from increasing the cost of equipment, very long chambers are undesirable from the standpoint of increasing acoustic losses in the chamber. The longer the sound chamber the greater the attenuation of sound in the chamber. This means that the acoustic coagulation coefficient decreases as the chamber is made longer. As noted previously sound absorption by the gas phase also increases as sound intensity increases. The key conclusion emerging from the example calculations and the influence of chamber length and sound intensity on efficiency is that chamber diameters of 4 m or larger and sound intensities of 160 db or greater are likely to be needed to growth fine particles to the requisite size levels for relatively easy collection. Quite large energy consumptions (i.e., of the order of 20 hp/1,000 cfm) appear to be necessary as a direct result.

By way of comparison with the estimated values of energy consumption, Mednikov reports specific energy consumptions on actual industrial systems of 0.65 to 20 kw-hr/1,000 m^3 of gas (1.5 to 46 hp/1,000 cfm). However, it must be noted that the reported values for industrial applications are in some cases for aerosols that did not contain a high percentage of fine particles. Mednikov states that minimum total energy requirements of 4 to 10 hp/1,000 cfm should be achievable with optimum design.[1/] The minimum values quoted by Mednikov are for a "typical" industrial aerosol and presumably represent the energy needed to grow the particles to a sufficient size to be removed by inertial devices. For an aerosol stream containing a high percentage of fine particles, it seems reasonable to assume that the upper figure of 10 hp/1,000 cfm represents the likely minimum energy requirement even if an ESP or fabric filter is used as the collector rather than an inertial device.

Measures which might be taken to improve the efficiency of the sonic agglomerator and decrease the energy usage include:

1. Addition of water drops to increase number of agglomeration centers;

2. Treating aerosol with a number of frequencies; and

3. Optimizing chamber designs.

However, even if the above steps are taken and are successful, energy consumption is still likely to be moderately high. For example, specific energies calculated from Eq. (31) assuming that $\epsilon_s = \epsilon_c = \epsilon_{uf} = 1.0$ are 1.2 and 4.7 hp/1,000 cfm for chamber diameters of 2 and 4 m and a sound intensity of 160 db. At 165 db the corresponding numbers are 4 and 15 hp/1,000 cfm.

Since the extent to which fine particles are removed from a gas stream depends both on the amount of growth in the agglomerator and the efficiency with which particles are collected by the control device coupled to the agglomerator, the total energy required is the sum of that for the agglomerator and the control system. Typical energy usages for conventional control systems are:

1. Cyclones--0.5 to 5 hp/1,000 cfm

2. Fabric filters--2 to 3 hp/1,000 cfm

3. Electrostatic precipitator--1 to 1.5 hp/1,000 cfm

4. Venturi scrubber--10 to 20 hp/1,000 cfm

Even under ideal conditions, a sonic agglomerator would add an energy burden equivalent to that of the collection device that must be coupled to it. In order to reduce energy consumption in the agglomeration chamber (i.e., reduce the requisite growth ratio d_2/d_1), high efficiency collectors such as an ESP, fabric filter, or venturi scrubber should be used. It seems likely that the high efficiency control devices alone might do nearly as good of a cleaning job as would a combination sonic agglomerator-high efficiency collector. The utility of a sonic agglomerator as an aid to controlling fine particulates seems doubtful at best.

CONCLUSIONS

The application of sonic agglomeration to industrial gas cleaning problems involving fine particles does not appear promising. The energy requirements of current sonic agglomerators coupled to an inertial separator are very high, of the order of 10 to 20 hp/1,000 cfm, if a gas stream containing predominantly fine particulates is to be controlled. Replacement of an inertial collector by a high efficiency ESP, fabric filter, or venturi scrubber might reduce the energy requirements to 5 to 10 hp/1,000 cfm. However, if it is necessary to use a high-efficiency collector, the utility of a sonic agglomerator is suspect unless considerations other than energy consumption are important (i.e., a need exists to control a highly toxic stream composed of fine particles).

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APPENDIX A.

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16. ABSTRACT The report gives results of an evaluation of the potential of sonic agglomeration as a means of improving capabilities for controlling fine particle emissions. Available theoretical and experimental information indicates that sonic agglomerators can increase the mean particle size of aerosols; however, the energy requirements are quite high when the gas stream contains predominantly fine particulates. Even under ideal conditions, energy consumption would range from 1 to 15 hp/1000 cfm. These ideal energy levels are not very competitive with other devices capable of removing fine particulates, especially when a high efficiency control system is required as a collector in order to minimize energy consumption in the sonic agglomerator.

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