1. Introduction

In steel industry, many processes are accompanied by a formation of large amount of dust carried off from the furnaces together with exhaust gas. The size of dust particles and their content in the gas are known to be strongly dependent on the process conditions. Processes proceeding under higher temperatures (like BOF and EOF) generate very fine particles of submicron or micron sizes. If temperature is relatively low (for example, sintering process), much bigger particles are emitted during the process. It is commonly recognized that the fine particles are produced due to evaporation of materials under very high temperatures, while the big particles have their origin from a dynamic interaction between gas phase and liquid/solid material being processed. Another source of relatively big particles is a part of charged materials carried away by the exhaust gas.

Conventional steelmaking processes involve a number of operations such as injection of gaseous and solid materials into the furnaces where chemical reactions proceed. These processes emit a huge amount of dust particles of very different sizes. The examples of the processes are the converter process with minimum slag, converter process with raised scrap charge, and production of stainless steel by the smelting reduction method. Industrial implementation of these processes requires the development of new methods for the decrease in dust emission rate.

The present study focuses on the behavior of dust particles in a high temperature gas atmosphere exposed to powerful standing sound waves. Six resonance frequencies within the range of 0–1,000 Hz were chosen for the experiments because they provide high values of sound pressure in the working space. The particles (0.1–80 μm) were produced by evaporating a sample of Zn at temperature about 1,173 K under Ar atmosphere, cooling the Zn vapor and transferring the formed particles to a sonoprocessing chamber for sound exposure. The particle samples were taken at the upper place of the chamber, and the samples were analyzed for size distribution and number density in the gas phase.

Application of sound waves is found to result in enlargement of particles (acoustic agglomeration), and reduction of their number density and concentration in the gas. The experiments showed that the particle agglomeration is enhanced as the sound pressure amplitude increases, while the effect of sound frequency played a smaller role in the particle behavior. In the frequency range tested, the most evident agglomeration effect was obtained at frequencies of 210 and 991 Hz at which a 50% increase in particle size and 60% decrease of particle number density in exhaust gas can be achieved in comparison to the corresponding values without sound application. The experimental results are discussed on the basis of the orthokinetic mechanism in relation to the acoustically forced oscillation and collision between the differently sized particles.

KEY WORDS: powerful sound wave; sound frequency; sound pressure; high temperature exhaust gas; dust particles; acoustic agglomeration; particle number density; particle weight concentration.
gas as much as 50% as compared with no sound conditions. In a Hartmann generator, a compressed gas is passed through the generator nozzle to generate a powerful sound wave. Application of Hartmann generators is especially attractive to the processes in which gas is blown into the furnaces. In this case, sound waves can be generated simply by passing a part of the gas through a generator nozzle without any additional energy sources. In the experiments mentioned above, oxygen was served as a working gas of the Hartmann generators which were built in the tip of the converter lance in such a way that the generated sound waves propagated to the molten bath through the gas inside the converter.

Designing the sound generators and using them for removal of dust particles from off gas of high temperature processes requires a detailed and accurate knowledge on the behavior of the particles under various conditions of temperature, sound frequency, particle size, etc. Despite the availability of literature on relationships between particle size and sound wave characteristics mentioned above, application of the published results to high temperature conditions needs experimental verification because the most of the previous studies concerned with the effect of sound wave at room temperatures. In the present study, we investigate the behavior of dust particles in high temperature gas atmosphere exposed to powerful standing sound waves of frequency of 50–1000 Hz. The sound waves are generated by a powerful loudspeaker fixed at the top part of a vertically arranged experimental setup. In the experiments, zinc particles (0.1–80 μm), condensed from vapor in Ar carrier gas, are used as model particles in order to examine effects of sound pressure and frequency on the size of particles and their content in the exhaust gas. The obtained experimental results are discussed on the basis of the orthokinetic mechanism of the particle agglomeration.

2. Experimental

2.1. Set-up

Experiments were carried out by using a vertically arranged setup shown in Fig. 1. The set-up consisted of three parts: a high temperature unit, a sonoprocessing chamber and a sound generating unit. Three graphite tubes (I.D. 108 mm, total length 1.5 m) were mounted inside a stainless steel cylindrical shell (O.D. 150 mm). The lower part of the shell was installed inside a resistance furnace. The interior space of the lower graphite tube (hot zone) inside the furnace was heated up to 1173 K. Ar was used as a carrier gas to transfer Zn particles and/or Zn vapor from the hot zone to the sonoprocessing chamber. Ar gas was introduced into the high temperature zone through four inlet tubes fixed at the bottom lid. The flow rate of Ar gas was measured by a mass flow controller. A graphite crucible (I.D. 60 mm) was put on a vertically movable support.

A graphite perforated disk was placed between the lower and middle graphite tubes in order to separate the sonoprocessing chamber from the high temperature unit. The diameter and thickness of the disk were 120 and 5 mm, respectively. The diameter of each holes of the perforated disk was 2 mm. The holes were drilled at a distance of 10 mm from each other. The holes provide a free passage of Zn particles and Ar gas from the hot zone into the sonoprocessing chamber. The disk served also as a sound wave reflecting surface.

Temperature inside the sonoprocessing chamber was gradually decreased from 1173 K at the graphite disk to ~373 K at the upper part of the chamber. Four side tubes, A, B, C and D of the chamber were used for temperature measurement, gas outlet and dust sampling. The side tubes were equipped at the distances of 0.125, 0.25, 0.375 and 0.7 m from the perforated disk. The lower part of the shell was equipped with another horizontal side tube, E, for loading a Zn sample into the crucible.

The sound generating unit was fixed at the upper part of the stainless steel shell. The unit consisted of a converging stainless steel horn (height 0.9 m) and a powerful loudspeaker which operates in continuous mode at the maximum electrical input power of 250 W at the working frequencies from 20 to 1500 Hz. The horn together with the sonoprocessing chamber formed the working space of the present setup. A pressure transducer was inserted into the horn through a side tube attached to the horn wall, and thereby the sound pressure inside the sound generating unit was measured at a distance of 0.35 m from the loudspeaker. The distance between the loudspeaker and graphite perforated disk was 1.63 m.

2.2. Experimental Conditions

The experimental conditions are summarized in Table 1.

| Temperature at the crucible bottom, K | 1173 |
| Weight of zinc sample, kg | 0.01 |
| Experiment duration, min | 5 |
| Carrier gas | Argon |
| Frequency, Hz | 98, 210, 359, 439, 645, 991 |
| Speaker input electrical power, W | 0, 40, 70, 90, 130, 160, 190 |
| Sound pressure amplitude, Pa | 0–2500 |
| Flow rate of carrier gas, Nm³/s×10⁻⁷ | 4.77 |
| Dust sampling point | A |

Fig. 1. Experimental setup.
The experiments have been carried out at a fixed Ar gas flow rate under the conditions of resonance standing wave formed between the loudspeaker diaphragm and perforated disk. It is well known that application of sound wave on a resonance frequency results in a significant increase of sound pressure in the wave. The resonance frequencies were determined prior to the experiments by the following way. The loudspeaker was powered by AC voltage of a constant amplitude but variable frequency. The latter was varied from 50 to 1 000 Hz at 1 Hz interval by using a frequency synthesizer and a programmable GP-IB interface. The measurement data were stored by a programmable data acquisition processor and processed by a PC. As a result of this procedure, 5–6 peaks in sound pressure were found in the examined frequency range. Figure 2 shows a typical variation of sound pressure amplitude with frequency obtained at a voltage of 10 V. The resonant frequencies, at which the sound pressure amplitude exceeds 100 Pa, are indicated by the arrows in the figure. Under the given measurement conditions, the frequencies were 98, 210, 359, 459, 645 and 991 Hz. It should be noted that the resonance frequencies varied by 2–5 Hz from one measurement to another even being measured at the same conditions. This uncertainty in resonance frequency is supposed to be due to some fluctuations in temperature distribution within the sonoprocessing chamber.

Once a resonance frequency was determined, the sound pressure amplitude at the frequency can be controlled by supplying different electrical power to the loudspeaker. In the present experiments, the maximal value of sound pressure amplitude was 2 500 Pa.

2.3. Procedure

The furnace was heated up to 1 173 K under an atmosphere of Ar. After keeping the furnace temperature at the constant level over a time of about 30 min for thermal stabilization of the system, the Ar gas flow rate was set at $4.77 \times 10^{-5}$ Nm$^3$/s.

About 10 g of pure Zn was loaded into the crucible through the side tube E, and the crucible was moved up to the hot zone. An AC voltage signal of a predetermined amplitude was applied to the loudspeaker terminals to generate a standing sound wave in the preheated working space. In several seconds after the crucible being set at the hot zone, the Zn sample began to vaporize, and the Zn vapor was carried away from the crucible by Ar gas through the perforated disk to the lower part of the sonoprocessing chamber. The Zn vapor condensed into liquid droplets and/or solid particles owing to the temperature drop in accordance with the temperature gradient in the chamber. The liquid and solid particles were exposed to the sound wave during they rose up together with Ar carrier gas to the gas outlet. The time of sonoprocessing was 5 min.

To take the dust particle sample, a stainless steel sampling tube (I.D. 10 mm, O.D. 12 mm, length about 250 mm) was put into the sonoprocessing chamber through the side tube A. The sampling tube was connected to a water-filled bubbler. The particles trapped were washed away from the bubbler together with carrier gas stream. Thereby, the sampling with bubbler tended to give incorrect size distribution in large and small size ranges, although the medium size distribution could be well acceptable.

To estimate the sizes of relatively large and very small particles, we used an additional technique for sampling. The dust particles were trapped on a quartz plate (1×1 cm$^2$) fixed by a supporting rod at the side tubes A–D (Fig. 1) so that the plate was located at the center of the sonoprocessing chamber horizontally. The particles trapped on the plate, were analyzed by a SEM for size and shape.

3. Experimental Results

3.1. Determination of Sound Pressure Amplitude in the Working Space

As mentioned in the previous section, the sound pressure amplitude, $P_s$, was measured only at one location of the working space at a distance of 0.35 m from the loudspeaker. However, the amplitude of sound pressure is known to vary from its maximum value at the sound wave antinodes to minimum value at the wave nodes. In a standing wave, the nodes and antinodes are spaced at an interval of one forth of the wave length, $\lambda$, which is dependent on the sound velocity, $c$, and sound frequency, $f$ according to the relation $\lambda=c/f$. This means that the position of the maximum sound pressure is spaced at different distances from the measurement point depending on frequency and temperature, because the sound velocity is a temperature dependent value. Since the following discussion of the experimental results requires the knowledge of the maximum values of sound pressure in the working space, the distributions of temperature and sound pressure over the working space should be considered first.

The temperature distribution was obtained by a fitting of results of measurements performed at the levels of the sam-

![Figure 2](https://example.com/figure2.png)

Figure 2. Variation of sound pressure amplitude with frequency.
The sound pressure amplitude, as a result of the fitting procedure, the following relation between temperature, $T$, and distance from the perforated disk, $z$, was derived

$$T = 259.27 + 801.87e^{-0.538z} \quad (1)$$

To predict the sound pressure distribution, we solved the wave equation for various frequencies using the measured values of sound pressure as a boundary condition. It is known that, in the presence of temperature gradient, the wave equation can be given by the following second order differential equation

$$\frac{d^2 P_s}{dz^2} + \frac{1}{T} \frac{d T}{dz} \frac{d P_s}{dz} + \frac{\omega^2}{c^2} P_s = 0 \quad (2)$$

where $P_s$ is the sound pressure amplitude, $\bar{T}$ is the time-averaged temperature, $\omega$ is the angular frequency of the sound wave ($= 2\pi f$), $c$ is the sonic velocity which for an ideal gas can be expressed in terms of the universal gas constant, $R$, ratio of specific heats, $\gamma$, temperature, $T$, and molecular weight of gas, $M$, by Eq. (3).

$$c = \sqrt{\frac{\gamma RT}{M}} \quad (3)$$

The equation was integrated by using one of the standard subroutines for solving ordinary differential equations available with the Fortran PowerStation 4.0 Software. The boundary conditions imposed were as follows:

1) perforated disk: $z = 0$, $dP_s/dz = 0$

2) measurement point: $z = 1.28\, m$, $P_s = P_{s,exp}$

The first condition follows from the well known fact that location of rigid surface, reflecting a sound wave, is always coincident with a sound pressure antinode of the wave. The second condition equates the calculated and measured values of $P_s$ at the point of $z = 1.28$.

Figure 3 shows the calculated variations of sound pressure amplitude with distance from the perforated disk for all the resonance frequencies. For convenience of viewing, the results of Fig. 3 are presented by three pairs of curves with widely ranged sizes. A comparison between Figs. 4(a) and 4(b) illustrate representative SEM views of particles trapped on the quartz plate at the sampling points A and C, respectively. Obviously in the figures, the particles have spherical form with widely ranged sizes. A comparison between Figs. 4(a) and 4(b) reveals that the size of bigger particles increases from about 10 $\mu m$ at the point A to about 80 $\mu m$ at the point C.

### Table 2. Measured and predicted values of sound pressure amplitude, $P_s$

<table>
<thead>
<tr>
<th>No.</th>
<th>Frequency (Hz)</th>
<th>Measured $P_s$(Pa)</th>
<th>Predicted $P_s$(Pa)</th>
<th>Predicted SPL (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>98</td>
<td>953</td>
<td>1775</td>
<td>150</td>
</tr>
<tr>
<td>2</td>
<td>219</td>
<td>1306</td>
<td>2092</td>
<td>160</td>
</tr>
<tr>
<td>3</td>
<td>347</td>
<td>255</td>
<td>264</td>
<td>142</td>
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<td>4</td>
<td>449</td>
<td>217</td>
<td>325</td>
<td>144</td>
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<tr>
<td>5</td>
<td>645</td>
<td>205</td>
<td>310</td>
<td>144</td>
</tr>
<tr>
<td>6</td>
<td>992</td>
<td>290</td>
<td>292</td>
<td>143</td>
</tr>
</tbody>
</table>

3.2. Particle Characteristics and Gas Flow Conditions inside the Sonoprocessing Chamber

SEM analysis of particles shows that there is a significant difference in size of particles trapped at different locations inside the sonoprocessing chamber. Figures 4(a) and 4(b) illustrate representative SEM views of particles trapped on the quartz plate at the sampling points A and C, respectively, without sound application. Average temperatures in the chamber at the points A and C were 453 and 773 K, respectively.

In an attempt to explain the reasons for existence of such big particles in the sonoprocessing chamber, we estimated the size of the biggest particle under the present flow condition in the sonoprocessing chamber. It is well known that a particle, suspended in an upward gas flow, can rise up only when the vertical component of gas velocity, $V_v$, exceeds the particle terminal velocity, $V_t$. For a spherical particle of small Reynolds number, that is $Re < 0.1$, $V_t$ can be given by the following equation.

$$V_t = 0.5\left(\frac{18\mu g}{\pi R^2}\right)^{1/2}$$

$\mu$ is the viscosity of the gas, $g$ is the acceleration due to gravity, and $R$ is the radius of the particle.

The results of Fig. 3 and Table 2 reveal that the sound pressure amplitudes at the wave antinodes are larger than those at the measurement point. Obviously in Fig. 3, at frequencies of 98 and 210 Hz, the sound pressure is much larger than at the other frequencies.
Here, $r_p$ is the particle density, $d_p$ is the particle diameter, $m$ is the dynamic viscosity of gas, $g$ is the acceleration of gravity. In Eq. (5), $r_p$ and $m$ are dependent on temperature which varies over the sonoprocessing chamber. By making $V_T$ equal to the vertical component of gas velocity, $V$, one can calculate the diameter of biggest particle, $d_{p,M}$, which can be suspended by the upward-flowing gas stream at the given gas velocity. In the calculations, the dynamic viscosity and density of Ar, and the density of Zn were taken as the associated functions of temperature.\(^\text{17}\)

However, since high temperatures in the sonoprocessing chamber made it impossible to measure the gas velocity in the working space directly, we made an attempt to predict the velocity distribution from the results of numerical simulation by using the commercial CFD code PHOENICS (Version 3.4). The simulation was conducted on the basis of the standard k-ε turbulence model for a non-isothermal gas flow with allowance for buoyancy force due to the temperature dependence of gas density. In the calculations, the working space was divided into non-uniform grids of 70×20 computational cells in the axial, $z$, and radial, $r$, directions, respectively.

The boundary conditions were set according to the experimental conditions as following.

Gas inlet: $U=0, V=1.82\times10^{-2}\text{ m/s, } T=1\text{060 K}$
Side walls: $U=V=0, T=262.41+777.77\text{ e}^{-0.51}$
Top wall: Side walls: $U=V=0, T=303\text{ K}$

where $U$ and $V$ are the radial and axial velocities of gas, $T$ is the temperature, $P$ is the pressure. Subscript $a$ indicates the atmospheric pressure, that is 1.013×10\(^5\) Pa.

The vertical velocity of gas at the gas inlet corresponds to the superficial velocity calculated for the Ar gas flow rate of 4.76×10\(^{-3}\) Nm\(^3\)/s at $T=1\text{060 K}$. The temperature at the side and top walls was set according to measurement values.

Analysis of the calculated results reveals that the temperature gradient along the height of the working space gives rise to buoyancy forces that drive a vigorous convection inside the working space. Figure 5 presents the velocity vector field over the computational domain. For the sake of convenience, the figure is stretched by 5 times in the radial direction relative to the vertical direction. The inset in Fig. 5 displays the axis scales in the $z$ and $r$ directions, respectively. As seen in Fig. 5, in the working space, there are two big circulatory loops with the upward flow along the domain centerline and downward flow along the domain walls. Between the loops there is a stagnant zone at which gas velocity is so small that the corresponding vectors can not be seen in Fig. 5 at the given velocity scale. In the first loop at the center line, the vertical component of gas velocity is significantly increased with increasing the distance from the gas inlet. For example, at a distance of about 0.20 m above the gas inlet, the velocity is as large as about 0.25 m/s on the centerline. Once the gas flow reaches the level of sampling point A, it turns to the side wall and moves down along the wall to the perforated disk. Therefore, a considerable part of the Zn particles can be involved in the recirculatory motion before they leave the sonoprocessing chamber through the sampling tube A. This phenomenon should be favorable for enhancement of particle agglomeration because of longer residence time of particles in the chamber.

Substituting the numerically predicted values of the centerline velocity for $V$ in Eq. (5), we calculated the diameter...
of the biggest particle, \(d_{p,M}\). The result of the calculation is shown in Fig. 6 together with the maximum particle diameter obtained from the experiment. In the figure, the solid line represents the predicted dependence of \(d_{p,M}\) on the distance, \(z\), from the perforated disk. The experimental data are the results of SEM analysis of the particles trapped on the quartz plate for 5 minutes at the distances, \(z\), corresponding to the sampling points D, C and A. As seen in the figure, the numerically predicted values of \(d_{p,M}\) agree well with the experimental observations.

The size of smallest particles in the sonoprocessing chamber was estimated also from SEM images of particles trapped on the quartz plate. Figure 7 shows a typical SEM view of smaller particles adhered to the surface of larger one. Although the size of smaller particles is varied in a wide range, the size of smallest particles can be estimated as 0.1 \(\mu\)m in order.

3.3. Variation in Particle Size Distribution with Sound Frequency

Figure 8 presents cumulative frequency distributions, \(F\), for various sound frequencies, \(f\), at a constant input electrical power, \(R = 130\, W\), supplied to the loudspeaker. The corresponding values of measured and corrected sound pressure amplitude have already been presented in Table 2. Each of these curves was plotted by averaging the results of three measurements, at least.

As seen in the figure, under application of lower frequency sound waves, that is \(f=98\, Hz\), the particle distribution is similar to that without sound application. On the other hand, at frequencies of 210 and 991 Hz, the cumulative distribution curves are markedly shifted to the right, and the particle agglomeration effect is considerable under these conditions. The curves for \(f=359, 459\) and 645 Hz are intermediate between the curves of the first and second groups, and the effect of sound application on the particle agglomeration is moderate at these frequencies.

3.4. Variation in Concentration of Particles in Exhaust Gas with Sound Frequency

Figure 9 presents the relationship between sound frequency and the total number of particles, \(N\), trapped by the water bubbler during experiments performed at the same conditions as those of Fig. 8. The total number of the trapped particles is assumed to be proportional to the particle number density inside the sonoprocessing chamber at the level of sampling point. Therefore measurement of \(N\) can give additional information about the effect of sound wave on the particle agglomeration. For the convenience of comparison, \(N\) is divided by the total number of particle, \(N_0\) obtained in the absence of sound application. The results of Fig. 9 reveal that application of sound waves resulted in an appreciable reduction in the total particle number for all
frequencies tested in the present study. The reduction looks especially significant at frequencies of 98, 991 and 210 Hz, at which values of $N/N_0$ are equal to 0.24, 0.38 and 0.40, respectively. The considerable decrease in the total particle number at $f=210$ and 991 Hz is consistent to the results of the particle distribution presented in Fig. 8. The decrease in $N/N_0$ accompanied by the increase in $d_{i0}$ at these frequencies strongly suggests the phenomena of acoustically enhanced agglomeration of particles.

A SEM photograph presented in Fig. 10 gives an idea about the size and shape of particles formed under sound application at the frequency of 210 Hz. The particles were collected on the quartz plate at the sampling point A. Comparing Fig. 10 to Fig. 4(a) for particles trapped without sound application, one can confirm that the sound application results in the formation of particle agglomerate clusters of chain-like form.

It is of interest to compare the total weight of particles trapped by the bubbling technique in the experiments with and without sound application. The weight can be expressed as Eq. (4) in terms of particle number, $N$ and frequency distribution of particle size, $s$.

$$W = \frac{\pi}{6} N p_{Zn} \sum_{i=1}^{K} s_i d_i^3$$  \hspace{1cm} (6)

where $p_{Zn}$ is the Zn density. Index $i$ denotes the class of the sample size distribution. Although only a part of the particles can be trapped and analyzed by the method employed, it is reasonable to assume that the total weight of trapped particles, $W$, is proportional to the weight concentration of particles suspended in gas at the level of sampling point.

**Figure 11** is a plot of $W/W_0$ versus sound frequency at the same loudspeaker input power, $R_s=130$ W. The ratio of $W$ to $W_0$, where subscript 0 denotes no sound condition, indicates the variation in the weight of trapped particles relative to the values obtained without sound application. Bars represent the standard error of the mean. The significant decrease in the particle weight is observed at all the frequencies tested. Within the frequency range between 210 and 991 Hz, the decrease in $W$ is varied from 30 to 60 %, while $W/W_0$ seems to be not affected so much by frequency in this frequency range although a wide scatter of the data does not allow more detailed consideration regarding the effect of frequency on the weight of trapped particles. The decrease in $W/W_0$ with sound application can be attributed to the following. As shown above, the application of sound waves at the frequencies of 210–991 Hz results in the particle agglomeration. A part of agglomerated particles can drop down to lower parts of the sonoprocessing chamber because the terminal velocity of particles increases with their diameter.

However, the very low value of $N/N_0$ and $W/W_0$ at $f=98$ Hz shown in Figs. 9 and 11 can not be explained only by the particle enlargement because no agglomeration effect was found at this frequency. Possibly the decrease in particle number density at $f=98$ Hz is related to a strong convective flow produced by the loudspeaker when it operates at the low frequency. Because the flow is directed downward from the loudspeaker diaphragm, it can influence the path of particle motion inside the sonoprocessing chamber in such a way that the particles are not able to reach the upper levels of the chamber although additional measurements are needed to confirm this possibility.

### 3.5 Effect of Sound Pressure on the Particle Behavior

A series of experiments was carried out to examine the effect of sound pressure on the particle size and concentration. **Figure 12** shows particle size, $d_i (i=10\%, 50\%$ and $90\%)$ and relative number density of particles, $N/N_0$, plotted versus maximum amplitude of sound pressure in the working space at a fixed frequency of 210 Hz. In the figure, $d_{10\%}, d_{50\%}$ and $d_{90\%}$ are the characteristic diameters at which the cumulative frequencies, $F$ are equal to 10, 50 and 90 % respectively. Obviously in the figure, the characteristic diameters increase with the increase in sound pressure, while the particle total number decreases as sound pressure becomes higher.

**Figure 13** is a plot of the relative total weight of trapped particles versus sound pressure amplitude at $f=210$ Hz. The values of $W/W_0$ were determined in the same manner as those in Fig. 11. Despite the large scatter in the measurement results in Fig. 14, apparently, particle weight decreases with the increase in sound pressure. This phenomenon
indicates that the waves of higher sound pressure cause more intense agglomeration of particles.

Thus, the results of Figs. 11–13 reveal that the particle concentration in exhaust gas tends to decrease as the sound pressure increases, while the frequency has less pronounced effect on the particle concentration under the present experimental conditions. Except the frequency of 98 Hz, the obtained decrease of particle concentration with sound application can be attributed to the acoustically enhanced agglomeration of particles.

4. Discussion

4.1. Prediction of Particle Agglomeration Rate by the Orthokinetic Mechanism

According to the orthokinetic mechanism, when a particle is exposed to a sound wave, the oscillatory motion of gas in the sound wave forces the particle to oscillate with the same frequency. Because of a large difference in density between the gas and particle, displacement of particle, $a_p$, from its initial position differs from that of gas, $a$, in amplitude and phase according to Eqs. (7) and (8).

$$a = A \sin (\omega t)$$
$$a_p = A_p \sin \left( \frac{\omega t}{\sigma} \right)$$

where $A$ and $A_p$ are the amplitudes of gas and particle oscillations, $\omega$ is the angular frequency of the sound wave ($=2\pi f$), $f$ is the sound frequency, $\varphi$ is the phase shift between gas and particle oscillations. If the particle is enough small to obey the Stokes' law ($Re < 0.1$), the ratio, $\eta$, of $A_p$ to $A$ and $\varphi$ can be expressed by the following equations:

$$\eta = \frac{A_p}{A} = \frac{1}{\sqrt{1 + \omega^2 \tau^2}}$$

$$\tau = \frac{\rho_p d_p^2}{18 \mu_g}$$

$$\tan \varphi = \omega \tau$$

where $Re$ is Reynolds number for the particle motion ($=\rho_0 d_p \rho_g / \mu_g$); $\tau$ is the particle relaxation time; $d_p$ is the particle diameter; $\rho_g$ and $\rho_p$ are densities of gas and the particle respectively; $\mu_g$ is the gas dynamic viscosity. The ratio, $\eta$, is termed the "entrainment coefficient". Figure 14 presents $\eta$ as a function of particle diameter for the smallest and largest frequencies of the present experiments and for two temperatures which correspond to those of the lower and upper parts of the working space. It is notable in the figure that entrainment of particle by sound wave is enhanced at higher temperature.

At the low frequency in this figure (98 Hz), oscillation amplitude of particle is practically not different from that of the sound wave even for particles as big as 10 $\mu m$. On the other hand, at the high frequency of 991 Hz, $\eta$ is drastically decreased as particle size increases. Under this condition, the particles of different sizes are expected to oscillate with different amplitudes.

Since the real dust is a mixture of particles with various sizes, smaller particles can be oscillated vigorously by sound wave of a certain frequency, while larger particles can remain stationary under the same condition. This promotes collision and agglomeration of particles. Figure 7 presents some experimental evidence that particle agglomeration occurs by the orthokinetic mechanism. In the figure, the large agglomerate is probably formed as a result of acoustically driven collisions between a big particles of $d_p = 5 \mu m$ and small particles of $d_p = 0.1–0.5 \mu m$. 

![Fig. 12. Effect of sound pressure on characteristic diameters and number density of particles.](image1)

![Fig. 13. Effect of sound pressure on relative total weight of trapped particles.](image2)

![Fig. 14. Entrainment coefficient plotted against particle diameter.](image3)
The basic principles of the orthokinetic model has been reported in the literature (for example,18). The model is based on the above described concept of collision between small and large particles due to a relative motion induced by sound oscillations. Quantitatively, the collision is expressed by a parameter called “collision kernel”. Following Hoffmann,18 after some rearrangement, the collision kernel, \( \beta_n \), can be given as the following function of particle diameters, \( d_i \) and \( d_j \), particle entrainment coefficients, \( \eta_i \) and \( \eta_j \), and the acoustic velocity, \( U_a \).

\[
\beta_n = \frac{1}{4} (d_i + d_j) Y |\eta_i - \eta_j| \times U_a \quad \ldots \ldots (12)
\]

The physical meaning of \( \beta_n \) is the frequency of collision between two particles of different sizes when number densities of the both particles are unity. It should be noted that Eq. (12) has been derived under some simplifications because it does not account for the phase shift in oscillations of differently sized particles that obviously must exist as it follows from Eqs. (10) and (11). Another point to be made here is that the collision kernel is often termed as “agglomeration kernel” in the literature because each collision of particles is assumed to result in their agglomeration. In the present study, we do not distinguish the collision phenomenon from the agglomeration one too that suggests the same values of collision and agglomeration rates. Multiplying \( \beta_n \) by the number densities of \( i \)-th and \( j \)-th particles, \( n_i \) and \( n_j \), we obtain the rate of collision between particles of \( i \)-th and \( j \)-th sizes in unit volume. Then, one can easily derive the total collision frequency, \( Y_c \), for given \( d_i \) and \( n_i \) where indices \( i \) and \( j \) run from 1 to 4.

\[
Y_c = 0.5 \sum_{i=1}^{4} \sum_{j=1}^{4} \frac{1}{4} (d_i + d_j) Y |\eta_i - \eta_j| n_i n_j \quad \ldots \ldots (13)
\]

Factor 0.5 is needed in order to offset summing the collisions of each pair of particles twice. Thus, with regard to the above assumptions, \( Y_c \) presents the agglomeration rate between all particles included in the given particle population. Then, taking into account that the particle number density, \( n \), given as the product of particle size distribution, \( s \), and total number density of particles, \( n_v \), we can rewrite Eq. (13) as

\[
Y_c = 0.5 \sum_{i=1}^{M} \sum_{j=1}^{M} \frac{1}{4} (d_i + d_j) Y U_a |\eta_i - \eta_j| n_i n_j \quad \ldots \ldots (14)
\]

In this equation, the amplitude of acoustic velocity, \( U_a \), can be expressed through the measured values of sound pressure amplitude, \( P_s \), by the following relation.

\[
P_s = \rho c U_a \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (15)
\]

where \( c \) is the sonic velocity, \( \rho \) is the gas density.

4.2. Explanation on the Effects of Sound Waves on the Particle Behavior

The Eqs. (14) and (15) provide a useful information for explanations of the experimentally found influence of sound pressure and frequency on the particle behavior. According to these equations, the particle agglomeration rate is proportional to the amplitude acoustic velocity, \( U_a \), which is related to the sound pressure amplitude. It is well known from the theory of sound waves\(^{19}\) that sound pressure antinode, where the sound pressure amplitude reaches its local maximum, is always coincident with acoustic velocity node, where acoustic velocity amplitude reduces to zero, and vice versa.

In the case of the present experiments, according to the results of Fig. 3, the acoustic velocity amplitude should be increased from 0 at the perforated disk \( z=0 \) to its first maximum value at 1.02 m at \( f=98 \text{ Hz} \) and 0.57 m at \( f=210 \text{ Hz} \). In the case of \( f=98 \text{ Hz} \), the distance of 1.02 m locates higher than the sampling point A. This means that the zone, where the acoustic velocity amplitude can reach a larger value at \( f=98 \text{ Hz} \), is beyond the sampling position. This may be one of the reasons why no particle agglomeration enhancement was observed at this frequency in Fig. 8. On the other hand, at \( f=210 \text{ Hz} \), the zone of large acoustic velocity amplitude, \( U_a \), locates below the point A. This situation can lead to the apparently large effect of sound on the particle agglomeration at this frequency. As a result of particle agglomeration, a part of them falls to the bottom parts of the sonoprocessing chamber resulting in a significant reduction of particle weight concentration in exhaust gas which is the most essential result of the present study.

It is noted that the qualitative aspects of the present results of the sound pressure effect are in good agreement with those published in the literature. Tiwary and Reethof\(^{20}\) found that particles of initial diameter of 5 \( \mu \text{m} \) grew faster when exposed to acoustic fields of higher sound pressure levels. The sound frequency and pressure levels tested were 2000 Hz and 140–160 dB, respectively. In one of the earlier studies, Shaw et al.\(^{20}\) investigated the acoustical agglomeration of aerosols the size of which was ranged from 0.17 to 2 \( \mu \text{m} \). Their results revealed that the mass rate constant of aerosol removal from gas was drastically increased with the standing-wave nodal-point under the condition of sound intensity ranged from 135 to 155 dB at the frequencies of 640–1700 Hz.

In the present study, at frequencies of 359, 459 and 645 Hz, the effect of sound waves on the particle agglomeration looks not so strong. This could be explained by rather small values of \( U_a \), suggested from Fig. 3. However, the enhancement of particle agglomeration at \( f=991 \text{ Hz} \) as compared to that at \( f=645 \text{ Hz} \) suggests that the effect of frequency itself on the particle agglomeration rate may exist under the present experimental conditions. Although the effect of frequency has been briefly discussed for single particles in the section 4.1, additional comments should be made here. In the Eq. (14), the frequency effect is expressed in terms of the difference in the entrainment coefficients \( \eta_i \) and \( \eta_j \) which are dependent on frequency and particle diameter according to Eqs. (9) and (10). However, because the value of \( |\eta_i - \eta_j| \) for each couple of particles is multiplied by the collision diameter \( |d_i + d_j| \) and by fractions of \( i \)-th and \( j \)-th particles, \( s_i \) and \( s_j \) respectively, the effect of sound frequency is expected to be strongly dependent on the particle size and particle distribution both of which vary with location inside the sonoprocessing chamber and probably with time. A lack of the information about this variation makes more detailed analysis of the frequency effect difficult. Nevertheless, it is reasonable to expect for a given particle...
population that if the sound frequency is too low, all particles are oscillated with the same amplitude and no particle collision can occur. In this case, an increase of frequency can promote the particle agglomeration due to the fact that the difference in oscillation amplitudes of comparatively small and large particles should be increased with the frequency. However, if the frequency exceeds over a certain value, the oscillation amplitudes of the particles should be drastically decreased. Thus, there must exist the most effective frequency which is dependent on the particle population characteristics. Therefore, although this assumption needs to be carefully tested by additional experiments, it can be concluded that the sound frequency should be optimized with respect to particle size distribution in order to obtain a better effect of sound waves on the particle agglomeration.

5. Conclusions

A possibility for controlling the size and concentration of dust particles in high temperature exhaust gas by exposing them to resonance standing sound waves was investigated experimentally. Six resonance frequencies within the range of 0–1000 Hz were chosen for the experiments because they provide comparatively high values of sound pressure in the working space. The results of the study are summarized as follows.

(1) Due to the occurrence of resonance oscillations in the working space there was a strong dependence of the sound pressure amplitude on the sound frequency. The examined frequency range can be subdivided into three regions: lower frequencies, $f = 98$ and 210 Hz, at which sound pressure amplitudes are large, intermediate, $f = 359$–645 Hz, and higher frequencies, $f = 992$ Hz, both of which yield much smaller values of the sound pressure amplitudes.

(2) In the low frequency region, a significant enhancement of particle agglomeration was obtained at the frequency of 210 Hz. The enhanced agglomeration resulted in a considerable decrease of particle weight concentration supposedly due to falling the enlarged particles to the lower parts of the sonoprocessing chamber. For example, at this frequency a 50% increase in particle size, a 60% decrease in particle number density and about 40% decrease in particle weight concentration in exhaust gas was gained under a sound pressure level of 160 dB as compared to the corresponding values in the absence of sound application.

(3) At the intermediate frequencies, the effect of sound waves on the particle size and number density was much smaller as compared to that at 210 Hz because the reduction in sound pressure level to 142–144 dB. The further increase in frequency up to 992 Hz resulted again in a essential enhancement of particle agglomeration although the sound pressure level at this frequency was only 143 dB.

(4) The obtained experimental data can be well explained by the orthokinetic mechanism of particle agglomeration. According to the mechanism, firstly, particle collision rate in a sound wave varies directly as the amplitude of acoustic velocity, which in turn is proportional to the sound pressure amplitude. Secondly, the effect of frequency on the particle collision rate is rather complicated because it depends on the particle size distribution.

It must be emphasized that the above conclusions are mainly based on analysis of particles collected at one level inside the sonoprocessing chamber by the bubbling technique allowing the particles in the range of 1–20 $\mu$m to be analyzed. However, analysis of particles trapped by the quartz plate reveals that the particle size is varied in a wider range, from 0.1 to 80 $\mu$m. Furthermore, the particle size distribution can be changed from one level to another due to the temperature gradient inside the sonoprocessing chamber. Therefore, the temperature is expected to be one more important parameter for the particle agglomeration process. Experimental verification of the temperature effect will be the subject of our further investigations.

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REFERENCES

1) H. Sasamoto: CAMP-ISIJ, 10 (1997), No.1, 2.
4) K. A. Blinov, V. V. Yakovlev and S. V. Komarov: Proc. 6th Int. Iron and Steel Congress, ISIJ, Tokyo, (1990), No. 4, 65.
20) D. Shaw, J. Wegorzyn, S. Patel and M. T. Cheng: Journal de Physique, 40 (1979), C8-356.