Acoustic Agglomeration Process of Fine Particles in a Resonance Structure

Chen-hao SHI [1], Jian ZHANG [2], Yun ZHAO [3], Jie LIANG [1]

1 College of Environmental Science and Engineering, Hunan University, Changsha, 410082, China
2 School of Information Science and Engineering, Central South University, Changsha, 410083, China
3 School of Optoelectronic Science and Engineering, National Defense Science and Technology University，Changsha, 410073, China

Abstract: It was proved that the acoustic agglomeration technology has a good application prospect in the removal of fine particles. In this paper, a removal system of acoustic agglomeration is constructed by the acoustic resonance structure. With the finite element simulation model, the effect and condition of sound pressure level (SPL) increment of high intensity sound in the resonance structure are defined. In the experiment, the contrast of the sampling weight and particle size distribution changes of fine particles was compared under different operating conditions to examine the effect of acoustic agglomeration on the removal efficiency of fine particles. The results show the SPL increment of 10dB is obtained with SPL 145-165 dB when the working frequency is changed from 400 to 2000 Hz. Under the action of acoustic agglomeration, fine particles in the aerosol were significantly reduced, and the removal effect is markedly improved with the increase of SPL.

1. Introduction

In recent years, the fine particles, mainly PM2.5, have become the main pollutant of urban atmospheric in China 0. In the current air pollution control, it is urgently necessary to develop industrial scale fine particles emission reduction technology for the combustion energy system. The removal method based on the acoustic agglomeration principle has a good application prospect, due to its short working time, significant effect, easy to use, and high temperature, high pressure and corrosive prevention. However, the complex mechanism of acoustic agglomeration, lack of high-power and high intensity sound source and high energy consumption are the three major bottlenecks in the practical application of the acoustic agglomeration technology 0.

There have been many theoretical and experimental works on acoustic agglomeration0, but most of their experimental platform is bulit on imitative conventional dust removal devices combined with an acoustic agglomeration system. Furthermore, the results are not totally consistent because of the complex mechanisms and different experimental conditions. Zhou etc. 0used sound wave to work on conventional dust removal devices and found that the optimized sound frequency and SPL were 1.4 kHz and 142dB. Gallego0compared the effect of 10 kHz and 20 kHz sound wave on flue gas generated by a coal-fired fluidized bed and proved that 20 kHz sound source was better than 10 kHz for agglomeration.Wang Jie0compared high-frequency (1 kHz and 20 kHz) acoustic wave with low-frequency (0.5~3 kHz) acoustic wave and found that low-frequency acoustic wave did better than the high one working on coal fired flue gas. Although there was no common view on the optimized conditions because of the varied investigated operating conditions, overall the works proved the effect of sound wave.

However, few works have been done to indicate the positive effect of sound wave with the professional dust removal equipment based on strong sound system, which is exactly closely related to the actual industrial application.Conventional acoustic agglomeration tests are usually carried out in plane traveling wave or standing wave condition. The existing experimental results show that the acoustic agglomeration efficiency of the polydisperse aerosols for the industrial flue gas normally has the optimal agglomeration frequency, and the agglomeration efficiency is significantly enhanced with the increase of SPL. Therefore, replacing the constant section traveling wave/standing wave tube by the acoustic resonance cavity0, and as the acoustic resonance frequency is equal to the optimal frequency, the removal of fine particles under the condition of acoustic structure resonance can reduce the sound power consumption at the premise of keeping high reduction efficiency.

2. Experimental Platform

Figure 1 shows the test system of acoustic agglomeration of fine particles based on acoustic resonance structure. The system consists of a standing-wave tube, which is composed of thin tube and square tube in series, where the cross-section dimension of square thick tube is 0.3 m with its length 0.5 m, and the cross-section length of thin one (condensed tank) is 0.1 m with its initial length 1.5 m. The thin tube is connected with the piston (changing the variable position) to adjust the length of the tube, and then change the resonance frequency of the standing wave tub. The standing wave tube is driven by four electro-acoustic unit, which is connected with the thick tube. Electro-acoustic unit is composed of 150 W, 400-5000 Hz compression driver and conical horn. Inlet and outlet diameters of the horn are 0.05 m and 0.1 m respectively, and its length is 0.2 m (Dip angle is approximately 7 deg.). The frequency and intensity of sound wave are regulated by a signal generator and power amplifier. The amplitude of driving current of a single sound source is 3 A at full capacity.

Compared with commonly used constant section standing wave tube, the two-stage standing-wave tube with abrupt varying section can be used to improve the effect of acoustic agglomeration in the thin tube from two aspects: (1) one end of the thick tube is allowed to connect more compression drivers to provide higher input power. (2) The standing-wave tube with abrupt varying section is a kind of dissonant standing-wave tube, i.e., the high order resonance frequency is unequal to an integer multiple of the first order resonance frequency. Therefore, under the condition of the structural resonance and the high intensity acoustic field, the nonlinear distortion of the acoustic wave is lower, and sound saturation and shock wave will not occur generally.

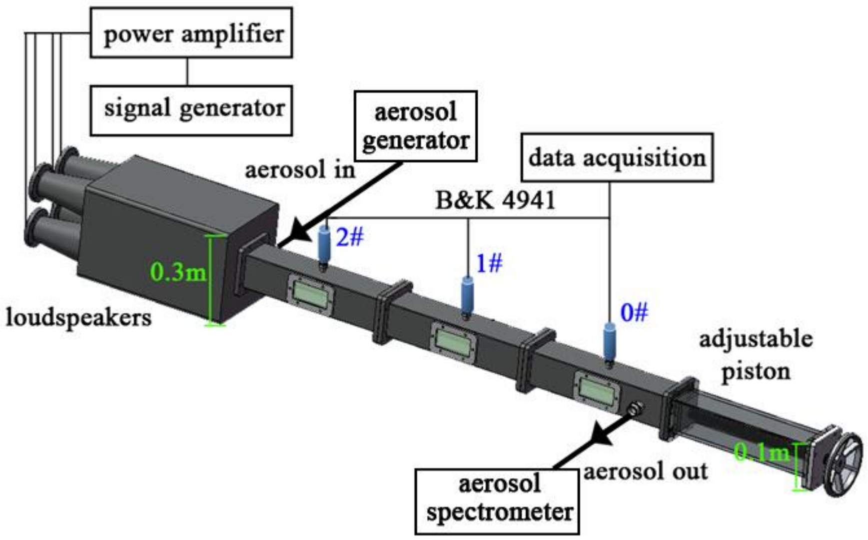


Figure 1. .Acoustic agglomeration system.

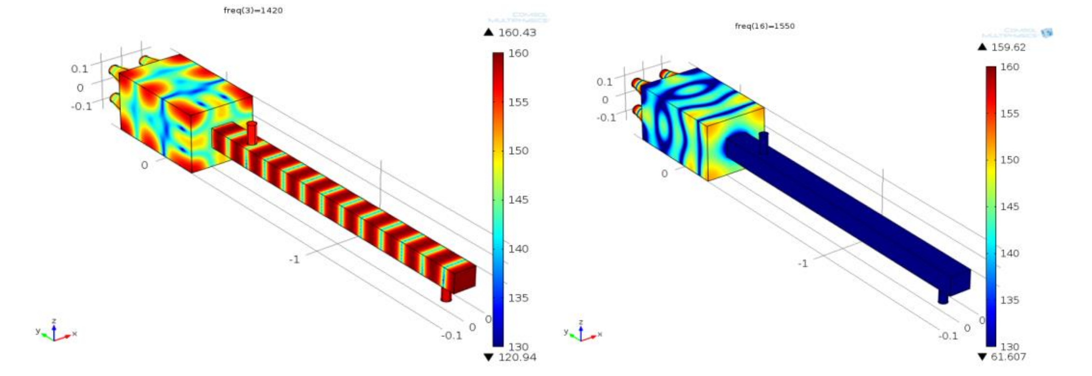
According to the waveguide theory, the cut-off frequency of acoustic agglomeration chamber with length of 0.1m is 1715 Hz, which can cover the effective frequency band (400-1500Hz) for acoustic agglomeration of fine particles. According to the law of quarter wavelength, the adjustable piston stroke is 0.5 m, which is more than half wavelength and in the adjustment range of the resonance frequency in the working frequency band.

The input gas to the agglomeration chamber is generated by the SAG-410 Topas aerosol generator, and the range of mass concentration is 0.012-13 g/m^3. When the gas is mixed with the compressed air, the range of gas volume flow is 7.2-18 m^3/h, and the range of corresponding action time by high intensity acoustic wave is 3-7 s. Three B&K 4941 high intensity acoustic microphones, 0#, 1# and 2#, are installed uniformly along the thin tube, which locate at point of the 0.5 m long tube, respectively. 0# is near the end of the adjustable piston, and the 2# is near the end of the sound source. The acoustic microphones are connected with the B&K 3050 data acquisition system to obtain the acoustic signals of measuring point. A particle size spectrometer is installed at the gas outlet of agglomeration chamber, which is used to measure the particle size distribution characteristic of the particles with and without the sound waves, and to complete the sampling of fine particles. The flue gas outlet is connected with a fine particulate sampling instrument, and the particle size of the sample is collected ranging from 2.5 to 10 μm by sampling membrane filter.

3. Strong Sound Field Characteristics

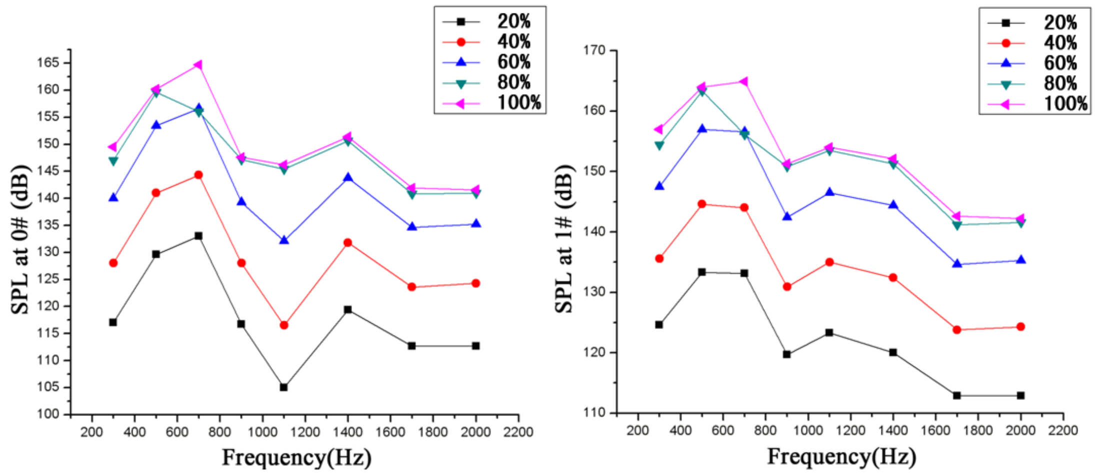
3.1. *The Time Domain Signal and Frequency Response*

Using the frequency domain acoustic module of Comsol Multiphysics, the acoustic field distribution in the experimental system is calculated. The results show that three high order resonance frequency of the system is 1570 Hz, 1510 Hz and 1420 Hz respectively. The SPL of agglomeration chamber is lowest when the frequency is 1550 Hz. When the structure resonance occurs, the SPL in the thin tube is above 10 db comparing with that in the thick tube. The internal acoustic field distribution at the frequency of 1420 Hz is shown in Figure 2.(a), it can be seen that there is a plane standing wave acoustic field in the agglomeration chamber, and the acoustic field distribution is very inhomogeneous in the thick tube, and sound intensity of thin tube (see Figure 2. (a)) is obviously higher than that of thick tube (see Figure 2. (b). A similar standing wave acoustic field is observed at the other two resonance frequencies.



（a）1420Hz （b）1550Hz

Figure 2. Acoustic field distribution under the resonance condition.



（a）0# （b）1#

Figure 3. The RMS SPL of every measuring points at different frequency and sound intensity.

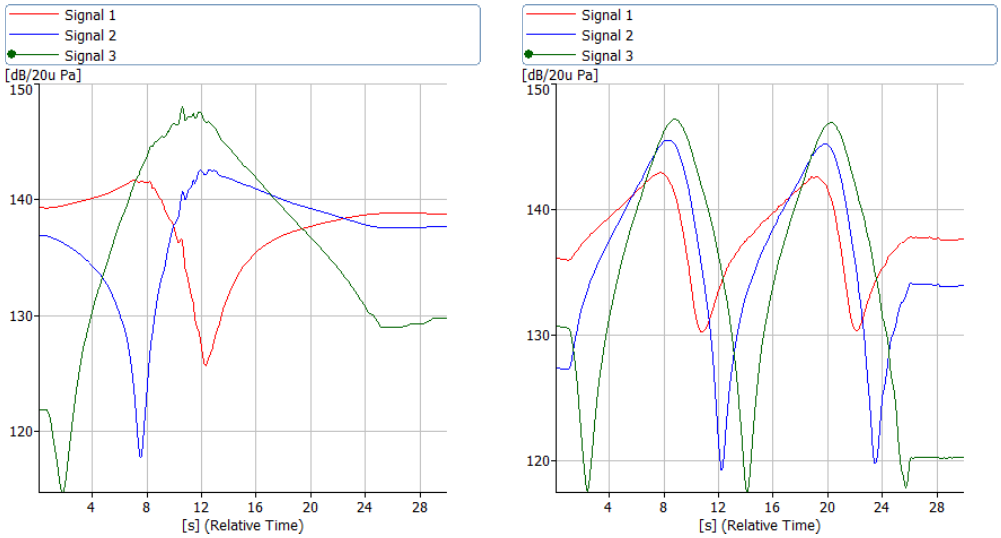
Figure 3 shows the RMS sound pressure level of 0# and 1# monitoring point close to the adjustable piston at different frequency and intensity of the sound source. It can be seen that under the effect of standing wave field, the SPL fluctuations within the working frequency band of compression driver increased significantly. The SPL is highest when the frequency is 700 Hz, and is increased by more than 10 dB compared with the results of single source driver, which indicates that phase congruency of different sound source is better. When the drive current of compression driver is changed from 20% to 80%, the frequency response curve shape and the increase amplitude of SPL basically exhibits no change. When the agglomeration effect is efficiently in the range of 400 - 1500 Hz, the loudest level is as high as 150-165 dB. Compared with the results of Figure 2, the peak value of sound pressure frequency response at fixed monitoring point could not reach the maximum sound pressure level of the

IOP Conf. Series: Earth and Environmental Science **78** (2017) 012001 doi:10.1088/1755-1315/78/1/012001

agglomeration cabin. At the same time, because the structural resonance frequency is not chosen as the measurement frequency, the measurement results of Figure 3 are lower than the actual intensity of the acoustic agglomeration process.

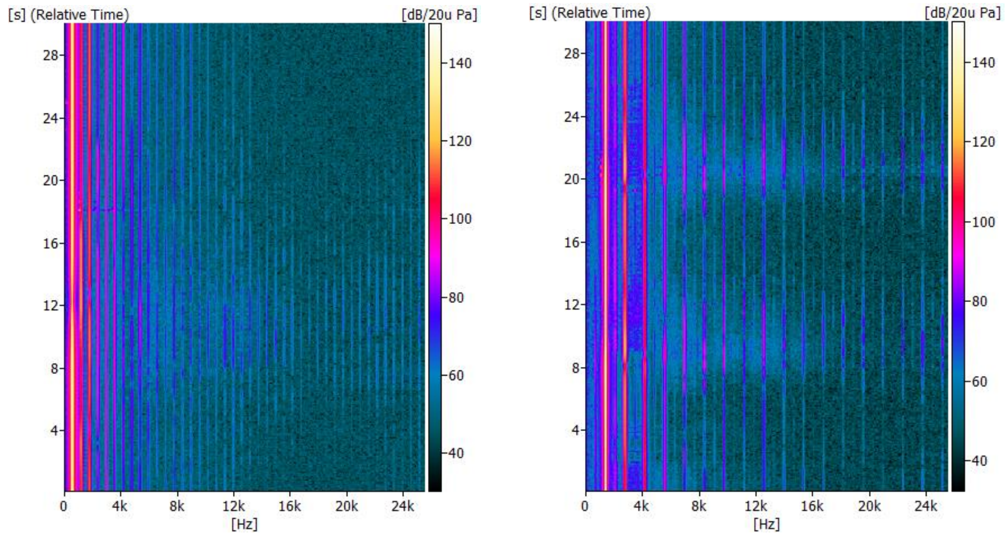
3.2. Resonance Frequency and Harmonic

Resonance frequency of the standing-wave tube with abrupt varying section is determined by the length and sectional area of thick tube and thin one, adjusting individually the length of agglomeration chamber can make the resonance frequency be consistent with the sensitive frequency of acoustic agglomeration. When the position of adjustable piston is changed, the resonance frequency of standing wave tube will change, and the relative position of the measuring point in the sound field also changes.



(a) 600Hz (b) 1400Hz

Figure 4. The RMS SPL of every measuring point when the adjustable piston position is changed and the driving current is 40%.



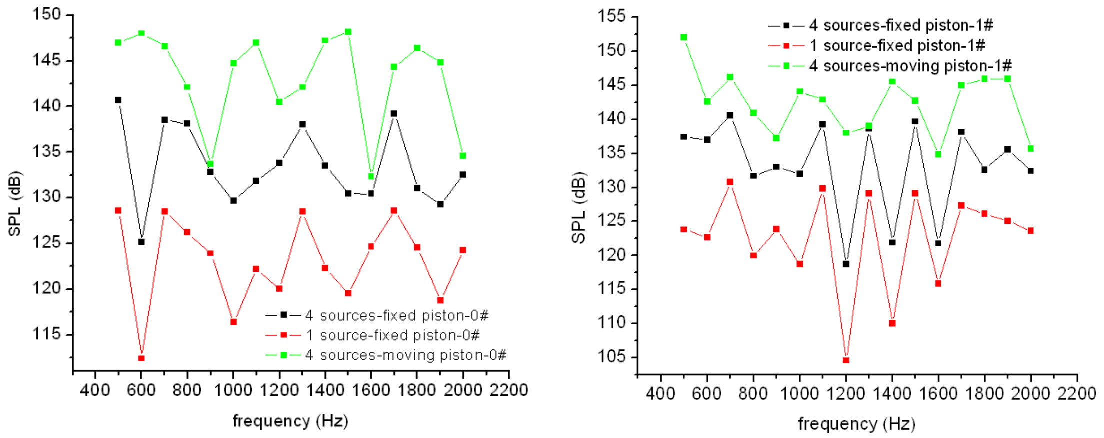
(a) 600Hz	(b) 1400Hz

Figure 5. The RMS SPL of measuring point 2 when the adjustable piston position is changed and the driving current is 40%.

Figure 4 shows the change of SPL of measuring point when the piston position is changed and the amplitude of driving current at full capacity is 1.2 A. When the frequency is 600 Hz, SPL of the measuring point in the curve reaches a maximum value, which is higher than the SPL measured at the initial position of piston. The data of measuring point 0# and 2# are basically the same, and the time moment of the maximum SPL of 0# and 2# is different with that of 1#. When the frequency is 1400 Hz, because the piston stroke is greater than the acoustic wavelength, the SPL periodically changes over time. The time moment of the maximum SPL at different points is different. Similarly, the maximum SPL is higher than that of the initial position of the piston.

Figure 5 shows the change of spectrum over time at 1#when piston position is changed and the amplitude of driving current at full capacity is 1.2 A. It can be seen that the main energy appears at the fundamental frequency, at the same time, there is an obvious high order harmonic, where harmonic component becomes more significant when the SPL is higher.

The maximum SPL of each test point driven by single sound source (fixed piston) or 4 sound sources (fixed and adjustable piston) are shown in Figure 6 It can be seen that the SPL driven by 4 sound sources is 10 dB more than that by the single source, and the phase congruency of different sound sources is better. Moving the piston to a proper position, the effect of resonance will occur from 4 acoustic sources, which improve the loudest SPL level. The intensity of the acoustic signal recorded under the fixed piston and fixed measured point condition is actually less than the intensity of the acoustic wave in the process of the acoustic agglomeration.



（a）0# （b）1#

Figure 6. The RMS SPL at fixed and mobile piston measuring point when the driving current is 40%.

4. Fine Particle Coagulation Results

The effect of acoustic agglomeration varies with the frequency and intensity of sound waves. Figure 7 shows the change of mass of PM2.5 in the flue gas under different frequency sound waves. The PM2.5 concentration in the initial distribution of flue gas is 49.64 mg/m^3, and the agglomeration effect of fine particles in the high intensity acoustic field is obvious. When the frequency is lower, the content of fine particles in the flue gas is higher, while that in the range of 1000 - 1300 Hz is the smallest. However, when the frequency is further increased, the content is increased. That is, for flue gas generated by coal-fired fly ash, the optimal frequency for sound agglomeration is in the range of 1000 - 1300 Hz.

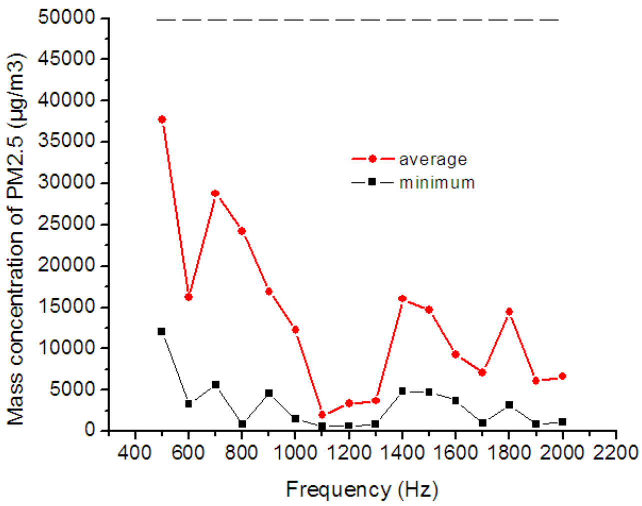


Figure 7. Variation of PM2.5 mass concentration in flue gas under different frequency sound waves.

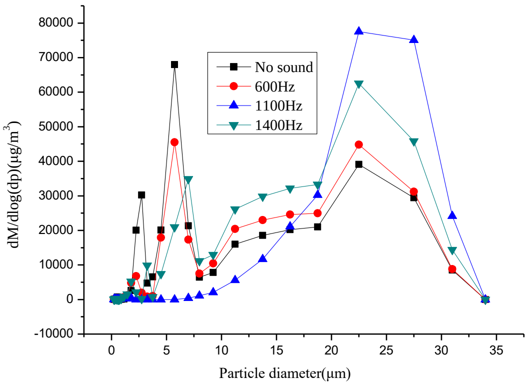


Figure8. Variation of particle size distribution (mass) of particles in flue gas by 600 Hz, 1100 Hz and 1400 Hz sound waves.

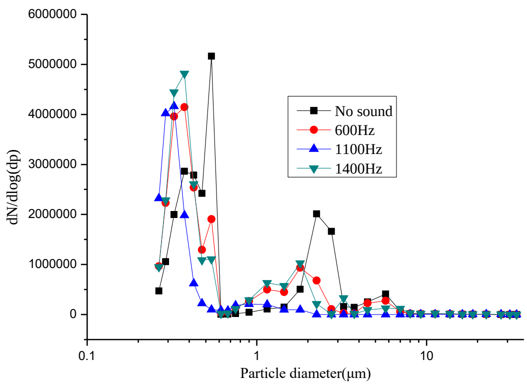


Figure9. Variation of particle size distribution (quantity) of particles in flue gas by 600 Hz, 1100 Hz and 1400 Hz sound waves.

Figure 8 and Figure 9 give the variation of the mass and the number of different size particles in the flue gas under the action of 600 Hz, 1100 Hz and 1400 Hz, respectively. It can be seen that there are a large number of fine particles in the initial distribution of flue gas, and the particle number distribution showed a typical bimodal structure. There are more numbers of particles with about 6 μm in size, and the most numbers of particles with about 0.5 μm and 2 μm in size. In the results of the initial gas particle mass distribution, the weight of the particles about 10 μm and 2 μm in size are larger, and the particle weight of 6 μm in size is the largest. At the optimal frequency of 1100 Hz sound waves, the mass of particles below 5 μm in size decreased significantly, and the mass of particles above 10 μm in size has a certain increase, which proves the effect of particles agglomeration is active. In the results of number distribution, the number of particles in the range of 0.5 to 2 μm in size decreases sharply, however, the number of particle 0.3 μm in size has a certain increase. In addition, under the actions of the sound waves at the frequency of 600 Hz and 1400 Hz, which are far away from the optimal frequency, the agglomeration effect of particles is significantly decreased.

5. Conclusion

In order to provide high efficiency and low energy consumption of removal system of fine particles based on the acoustic agglomeration technology, the acoustic resonance structure is designed based on the standing-wave tube with abrupt varying section, which replaces the conventional experimental system. The experimental tests and numerical computations are carried out to study the acoustic properties and the agglomeration process of fine particles. The following results were obtained:

- In the range of the sensitive frequency (1000 Hz - 2000 Hz) of acoustic agglomeration of the fine particles, there are multiple resonance frequencies in the standing-wave tube with abrupt varying section, and the SPL increment of 10 dB is obtained when structure resonance occurs. In the range of frequency from 500 Hz to 2000 Hz, the SPL in the agglomeration chamber can reach 145 to 165dB.
- The particle size distribution in the flue gas generated by the fly ash from the power plant is a typical bimodal structure. Under the action of high intensity sound waves within the measured frequency band, the mass of the particles below 5 μm in size is decreased significantly, and the mass of the particles above 10 μm in size has a certain increase. Especially at the sensitive frequency of 1100 - 1300 Hz, the mass aggregation of PM2.5 is decreased by more than 90%.
- The acoustic energy in the agglomeration chamber appears at the fundamental frequency, and the harmonic components are reduced by the resonance of the acoustic wave in the standing wave tube. Shock wave caused by the nonlinear effect is not found in the experimental results.

In the future, we shall connect our acoustic agglomeration system with the bag filters in the power plant to test the overall effect of removal of PM2.5 particles.

6. References

[1] Hoffmann T L. Environmental implications of acoustic aerosol agglomeration [J]. Ultrasonics,2000, 38(1–8):353-357.

[2] Du X, Kong Q, Ge W H, Zhang S J, Fu L X. Characterization of personal exposure concentration of fine particles for adults and children exposed to high ambient concentrations in Beijing, China. Journal of Environmental Sciences, 2010, 22(11): 1757–1764.

[3] Lin-jun Yang.Combustion source of fine particulate matter pollution control technology[M].Chemical industry press, 2011.32-67.(in Chinese)

[4] Zhou D, Luo Z, Jiang J, et al. Experimental study on improving the efficiency of dust removers by using acoustic agglomeration as pretreatment[J]. Powder Technology, 2016: 52-59.

[5] Yao gang, Zhao bing, xiang-lin Shen. Coal particulate matter waves together effect of experimental research and numerical analysis. Thermal power engineering, 2006,21(2):175-178.

[6] Fan F, Chen H, Yuan Z, et al. Convergence of Fine Particles under Standing-Wave Condition[C]// International Conference on Bioinformatics and Biomedical Engineering. IEEE, 2010:1-4.

[7] G.X.Zhang, J.Z.Liu, J.B. Wang etc, Theoretical study of acoustic wake effect in acoustic

agglomeration, Journal of Chemical Engineering of Chinese Universities, 2013,27(2):199-204.

[8] J.A. Gallego-Juarez, et al., Application of acoustic agglomeration to reduce fine particle emissions from coal combustion plants, Environmental Science & Technology,1999,33(21): 3843-3849.

[9] Wang J, Liu J, Zhang G, Zhou J, Cen K. Orthogonal design process optimization and single factor analysis for bimodal acoustic agglomeration. Powder Technol. 2011; 210(3):315-22.

[10] Liu J Z, Zhang G X, Zhou J H,Wang J, Zhao W D, Cen K F. Experimental study of acoustic agglomeration of coal-fired fly ash particles at low frequencies. Powder Technology, 2009, 193(1): 20–25.

[11] Jianzhong Liu, Jie Wang, Guangxue Zhang, Junhu Zhou, Kefa Cen. Frequency comparative study of coal-fired fly ash acoustic agglomeration. Journal of Environmental Sciences, 2011,23(11):1845–1851.

[12] Min qi, Peng feng.Mutation section standing wave tube and high pure standing-wave field experimental research. Journal of acoustics, 2010,35 (2): 185-191.

[13] Lawrenson C C, Lipkens B, Lucas T S, et al. Measurements of macrosonic standing waves in oscillating cavities[J]. Journal of the Acoustical Society of America, 1997, 102(5):623-636.

[14] Ilinskii Y A, Lipkens B, Lucas T S, et al. Nonlinear standing waves in an acoustical resonator[J]. Journal of the Acoustical Society of America, 1998, 104(5):2664-2674.

[15] Ilinskii Y A, Lipkens B, Zabolotskaya E A. Energy losses in an acoustical resonator.[J]. Journal of the Acoustical Society of America, 2001, 109(5 Pt 1):1859.