BILINGUAL PUBLISHING CO.
Pioneer of Global Academics Since 1984

**Journal of Atmospheric Science Research**
https://ojs.bilpublishing.com/index.php/jasr

ARTICLE

# On the Impact of Bell Sound on Ambient Particulates

**Konstantinos Kourtidis**[*] **Ageliki Andrikopoulou**

Department of Environmental Engineering, Democritus University of Thrace, Xanthi, 67100, Greece

ARTICLE INFO

*Article history*
Received: 04 October 2022
Revised: 05 November 2022
Accepted: 07 November 2022
Published Online: 14 November 2022

*Keywords*:
Sound
Aerosols
Particulate matter
Sound pressure level

ABSTRACT

Here the authors examine whether bell sounds can have an impact on ambient aerosol levels and size distribution under atmospheric conditions. The authors present calculation results for acoustic the coagulation by church bell sounds for a range of ambient aerosol types. The results show that for orthokinetic sonic agglomeration, while the frequency spectrum of church bells is ideal for causing coagulation of ambient aerosols, the sound pressure level (SPL) becomes too low for an effect. However, in very polluted conditions, at extremely short distances from the bell dust aerosols can readily undergo sonic coagulation.

## 1. Introduction

People have tried to influence atmospheric properties with sound for a long time. In the French wine-growing regions, church-bells were traditionally rung in the case of incoming storms to suppress hail. In 1575 Pope Urban VIII authorized a prayer for consecrating church bells that called for "driving away the harmful storms, hail and strong winds" [1]. Church-bell ringing was, near the turn of the 19th century, replaced by firing upward rockets or cannons. Numerous loud sound-producing devices have been deployed in Europe at around that time [2]. In the last two decades, hail canons have been employed in California vineyards, parking lots for newly manufactured cars in the NISSAN Motor Corporation factory in Canton, United States of America (U.S.A.), the Volkswagen plant in Puebla, Mexico, and elsewhere. There is no evidence for the effectiveness or ineffectiveness of these devices. A recent review [3] summarized a variety of measurements, concluding against the use of cannons or explosive rockets. Both church bells as well as sonic hail canons, use sound to potentially impact the hail generation process.

---

*Corresponding Author:
Konstantinos Kourtidis,
Department of Environmental Engineering, Democritus University of Thrace, Xanthi, 67100, Greece;
*Email: kourtidi@env.duth.gr*

DOI: https://doi.org/10.30564/jasr.v5i4.5121

Particle agglomeration, the increase in the size of particles, contributes to cloud formation and aerosol sedimentation. Sound is known to cause agglomeration at high SPLs, termed acoustic agglomeration or acoustic coagulation, due to particle resonance and the resulting relative motion of particles, and hence could potentially impact atmospheric particles. Acoustic agglomeration in air pollution control devices has been studied for some decades now and is an effective method for removing fine particles from industrial exhausts by coagulating them into coarser particles [4-7].

The main identified mechanisms for agglomeration are orthokinetic collision and hydrodynamic collision, the latter through mutual scattering interaction, mutual radiation pressure interaction and acoustic wake influence. Orthokinetic collision is the main mechanism of sonic agglomeration for polydisperse particles at low frequencies and medium particle size ratios. The orthokinetic mechanism refers to collisions between differently sized particles located within a distance that is approximately equal to the displacement amplitude of the acoustic field and with their relative motion substantially parallel to the direction of vibration [8]. It is based on the different resonance rate η of the particles due to their different sizes $d_1$, $d_2$ (different amplitudes for different sizes resulting in increased collisions) and is not very effective for particles much smaller than 1 μm. The orthokinetic model does not explain the observation of interactions between particles initially separated at distances much larger than the acoustic displacements and the agglomeration of particles of similar sizes [9,10]. In these cases, the main mechanism is a hydrodynamic collision (less drag on the trailing particle). Hydrodynamic interaction refers to collisions caused by the viscous interaction between particles and their surrounding medium (air in our case), and can occur for particles that are separated at distances much larger than their acoustic displacement amplitudes. In general, two approaches to account for hydrodynamic forces have been proposed—mutual radiation pressure interaction and the acoustic wake effect. The mutual radiation pressure interaction is based on the Bernoulli principle and is possible only for interparticle distances $< 5(d_1+d_2)$ whereas for interparticle distances $> 10(d_1+d_2)$ it is negligible. It results in the more relative motion of two particles when $d_1/d_2=1/3$ and no relative motion when $d_1/d_2 = 1$ (i.e. monodisperse particles), hence other mechanisms have to bring first the particles near each other. The mutual scattering interaction is due to the reflection of the sound wave on a particle and the resulting interaction between nearby particles. The acoustic wake effect is the main mechanism of sonic agglomeration for monodisperse particles < 1 μm at high sound frequencies, increasing with increasing particle size. It is not of significant influence when the orthokinetic collision prevails. It is based on the asymmetry of the airflow field around a moving particle at the mean and high Reynolds numbers. Particles are excited by the sonic field and move, air wake is created, the pressure drops behind the particle (wake area), and causes particle attraction in the wake area (perpendicular to flow field) and particle repulsion (in line to flow field), and temporary pseudo-agglomerates form.

Factors influencing acoustic agglomeration are the sound frequency, the sound pressure level, and the particle sizes. For orthokinetic collision, sound frequencies around 50 Hz ~ 500 Hz are more effective, while for the acoustic wake effect the effect increases with frequency, being more effective at frequencies above 800 Hz. For both types of agglomeration, the interparticle distance that in the event of a collision leads to agglomeration increases exponentially with SPL. The acoustic wake effect increases with particle size, while for orthokinetic collision the effect is more pronounced for sizes around 2 μm (depending on the frequency and relative particle sizes).

So, it is not a trivial problem and it is interesting to explore whether bell sounds can have an effect on the size distribution of atmospheric aerosols under ambient conditions. The present paper addresses the problem and also contribution toward a better understanding of the influence of ambient sounds on atmospheric aerosols. We present here calculations for acoustic orthokinetic agglomeration for different types of atmospheric particles by bell sounds. The reasons for the use of bell sounds in this work as agglomeration excitation input are many: Bell sounds are ubiquitous in many parts of the world [11-13], are quite loud, and can be heard at large distances. Additionally, they have a multitude of peak frequencies over a wide range of the audible spectrum, making the study interesting and more promising. When a bell is struck its sound has a number of simultaneously produced single frequency components generated by the excitation of normal modes of the particular bell. It has been shown [14,15] that the frequency spectra of bell-like sounds can be approximately described by a law of the form $f_{m.n} = c(m + bn)^p$ where m and n are non-negative integers while b, c and p are constants such that $1 \leq b \leq 2$ and $1.4 \leq p \leq 2.4$. Finally, using bell sound as the agglomeration excitation input, some insight might be attained on earlier notions that bell sounds might influence atmospheric properties.

## 2. Materials and Methods

### 2.1 Bell Sound Measurements

The bell sound measurements (Figure 1) were made in Xanthi at distances 40 m, 80 m and 170 m from the bell of St. Prodromos church with a Casella CEL 490 sound level meter combined with a Casella CEL 920 frequency analyzer. The particular church bell provides the advantage of being in the old part of the city which is under historical conservation status and hence traffic and other anthropogenic sounds are very limited.

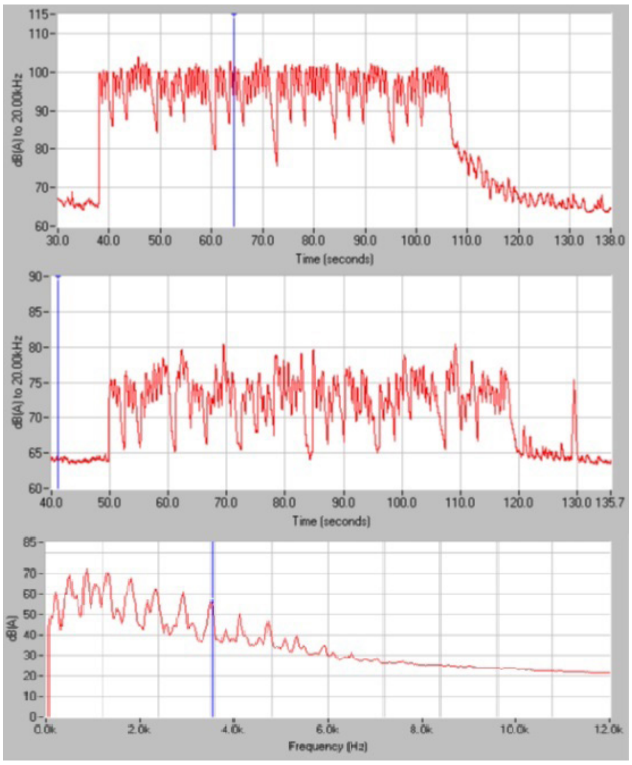

**Figure 1.** SPL at 40 m (top) and 170 m (middle) from the bell, and frequency spectrum up to 12 kHz (bottom) of the bell of St. Prodromos Church. Note the different y-axis scales of the panels.

### 2.2 Calculations of Acoustic Agglomeration

As Rayleigh showed in 1879 [16], the fundamental vibration frequency of a droplet of radius $r_0$ is $\omega_0 = (2\sigma/\pi^2\rho r_0^3)^{1/2}$, where σ is the surface tension and ρ is the density of the fluid. The resonance of particles in a sonic field can be characterized by the resonance rate $\eta = U_p/U_o = 1/[\mathrm{sqr}(1+(\omega\tau_p)^2)]$ [17-20] with η being the resonance rate with values from 0 (no resonance) to 1 (complete resonance) and ω the radial velocity of the sound wave, $\omega=2\pi f$. $U_p$ and $U_o$ are representations of the particle and fluid velocity, respectively, and $\tau_p$ is the relaxation time of the particle, i.e. the time the particle needs to react to an external influence, in our case the sonic field, $\tau_p = 2\rho\omega r^2/9\mu$, μ being the dynamic viscosity of the fluid.

Effective agglomeration length, $L_{eff}$, is the maximum interparticle distance that in the event of a collision leads to agglomeration. $L_{eff} = \varepsilon \cdot L$, where ε is the collision efficiency $0<\varepsilon<1$ and L is the maximum interparticle distance that can cause a collision.

For the calculation of the orthokinetic effective agglomeration length $L_{eff} = \varepsilon \cdot L$ we used first $U_g = [10\verb|^|(SPL-94)/20]/(c_0\rho_0)$ which gives the range of oscillation speed of the excited medium [21], with $c_0$ the speed of sound in air. Then, we calculate the relative resonance between the two particles $\eta_{12} = \omega(\tau_1-\tau_2)/\mathrm{sqr}[1+(\omega\tau_1)^2(\omega\tau_2)^2]$, where $\tau_1$, $\tau_2$ are the relaxation times of the two particles. The collision efficiency ε can then be calculated from $\varepsilon = [St/(St+A)]^B$ with A = 0.65, B = 3.7 constants [22], and St the Stokes number $St = \rho_p\eta_{12}U_g d_2^2/18\mu d_1$, and the maximum separation distance between two oscillating particles of different size L can be calculated from $L = |x_{p2}-x_{p1}| = \eta_{12}U_g/\omega$, with $x_{p2}$, $x_{p1}$ being the displacement range of the small and large particle, respectively.

## 3. Results and Discussion

At distances 40 m, 80 m and 170 m from the bell, the respective mean SPL was 90, 82 and 74 db[A]). Higher SPLs are observed in the range of 20 Hz to 2 kHz (Figure 1), while the range of the bell frequency extends beyond 12 kHz.

We performed a range of calculations to study the impact of bell sound on aerosol agglomeration under ambient conditions [23]. For the concentrations and size ranges of particulate matter, we used data reported for Athens [24]. For Athens, the dominant range for number concentrations is 0.11 μm ~ 0.28 μm and > 10 μm for volume concentrations. So, for the large particles we use $d_1$ = 10 μm and for the small particles $d_2$ = 0.11 μm or $d_2$ = 0.28 μm. The number of concentrations has been set at $2 \times 10^6$ particles/lt. For the mass density of particles we use 1000 kg/m$^3$ (density of water, representing liquid particles) and 2500 kg/m$^3$ (mean density of limestones, representing dust particles). For resonance rate calculations with constant particle diameter we use sound frequencies ∈ [20 Hz ~ 20 kHz], range of aerodynamic diameters between 0.01 μm ~ 40 μm, potential air viscosity μ = 18.27 μPa s and air density $\rho_g$ = 1.2 kg/m$^3$.

The resonance rate results (Figure 2) show that lower frequencies are more effective at inducing resonance than higher ones. They also show that the lighter liquid particles have higher resonance rates than the heavier dust ones at any given frequency in the range of 20 Hz ~ 20 kHz. We observe complete resonance up to the very high sound frequencies for very fine particles with aerodynamic diameters of 1 μm or less. For very low f = 50 Hz, liquid particles up to 28 μm and dust particles up to 18 μm have resonance rates > 0.8. At 150 Hz, liquid particles up to 16 μm and dust particles up to 10 μm have resonance rates > 0.8, while at 500 Hz, liquid particles up to 10 μm and dust particles up to 5.6 μm, respectively, have resonance rates > 0.8. Hence, the frequency spectrum of a bell, especially it's lower part, can induce resonance to a variety of particle sizes and may have the potential to cause agglomeration if the SPL is high enough.

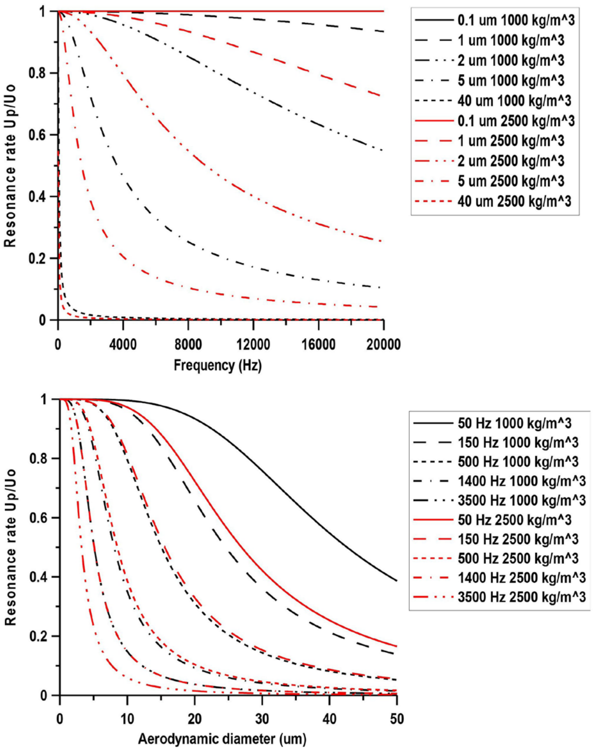

**Figure 2.** Upper panel: Resonance rate as a function of sound frequency and particle diameter for particle mass densities of 1000 kg/m$^3$ (black lines) and 2500 kg/m$^3$ (red lines). Lower panel: Calculations of resonance rate with constant sound frequency for particle mass densities of 1000 kg/m$^3$ and 2500 kg/m$^3$.

Now we calculate the effective agglomeration length for a large particle $d_1$ = 10 μm and a smaller one $d_2$ = 0.28 or $d_2$ = 0.11 for the SPLs at the different frequencies observed 40 m from the bell (Figure 1). The effective agglomeration length results show that $L_{eff}$ is between $10^{-15}$ μm and $10^{-28}$ μm for f < 6000 Hz and even smaller for higher frequencies (Table 1). For particle number concentrations near 2 × $10^6$ particles/lt, the interparticle distance at rest is 800 μm, hence, particle agglomeration in the atmosphere of Xanthi under the bell influence does not seem possible under these conditions, as the interparticle distance is orders of magnitude larger than $L_{eff}$.

Now we study two cases at high SPL = 160 dB. We use again ρ= 1000 kg/m$^3$ for liquid particles or 2500 kg/m$^3$ for dust particles, and f ∈ [250 Hz ~ 9200 Hz]. Case 1 (Figure 3, upper panel): For particles with diameters $d_1$ = 10 μm, $d_2$ = 0.28 μm, $L_{eff}$ is in the range 0.07 μm ~ 14.7 μm, which is much smaller than the inter-particle distance of 800 μm at 2×$10^6$ particles/lt. If $N_{aerosol}$ = $10^9$ particles/lt, i.e. very polluted conditions, the inter-particle distance becomes 100 μm, which is again larger than $L_{eff}$ even at low frequencies.

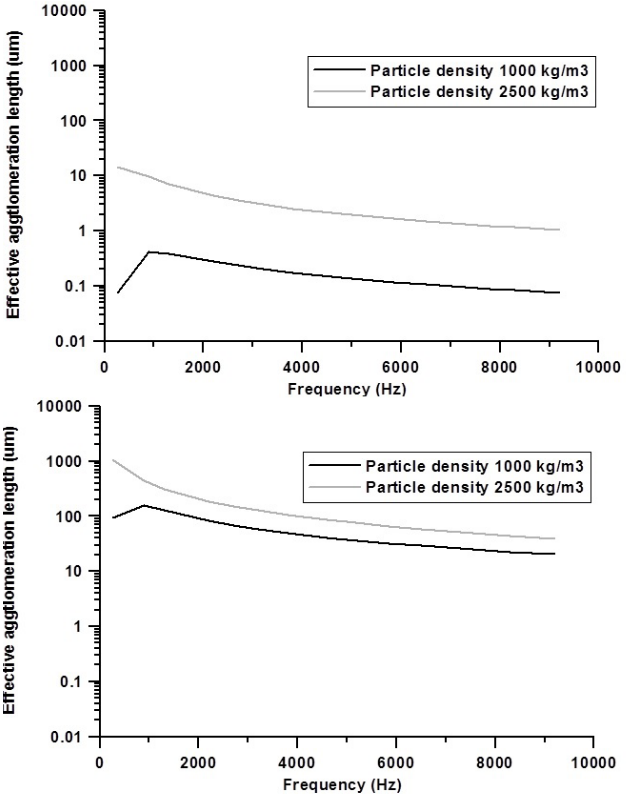

**Figure 3.** Calculation of the effective agglomeration length versus frequency for Case 1 (upper panel) and Case 2 (lower panel) for particle mass densities of 1000 kg/m$^3$ and 2500 kg/m$^3$. See text for explanation of Case 1 and Case 2 conditions.

Case 2 (Figure 3, lower panel): For particles with diameters $d_1$ = 10 μm, $d_2$ = 1 μm, $L_{eff}$ is in the range 20 μm ~ 1076 μm. For dust particles and frequencies < 4000 Hz (which is the range of maximum SPL of the bell), $L_{eff}$ is above the inter-particle distance of 800 μm (2×$10^6$ particles/lt) at frequencies < 500 Hz. At very polluted conditions ($10^9$ particles/lt), where the interparticle distance becomes 100 μm, $L_{eff}$ for dust particles is larger than the interparticle distance for all frequencies < 4000 Hz and $L_{eff}$ for liquid water particles is larger than the interparticle distance for frequencies in the range 500 Hz ~ 1500 Hz. Hence, at very close distances near the bell (a few centimeters), where SPL can be near 160 dB, agglomeration of particles becomes possible.

**Table 1.** Effective agglomeration length ($L_{eff}$, in μm) calculations[1]. Particle density is denoted by $\rho$.

| | $d_2$=0.28 | | $d_2$=0.11 μm | |
|---|---|---|---|---|
| | $\rho$=2500 kg/$m^3$ | $\rho$=1000 kg/$m^3$ | $\rho$=2500 kg/$m^3$ | $\rho$=1000 kg/$m^3$ |
| Min value | $2.6 \times 10^{-28}$ | $8.7 \times 10^{-30}$ | $2.6 \times 10^{-31}$ | $8.6 \times 10^{-33}$ |
| Max value | $2.2 \times 10^{-17}$ | $1.1 \times 10^{-19}$ | $2.2 \times 10^{-20}$ | $1.1 \times 10^{-22}$ |

[1] Potential air viscosity $\mu=18.27 \times 10^{-6}$ Pa s, air density 1.2 kg/$m^3$, sound velocity 344 m/s @20 °C, particle size $d_1$ = 10 μm, $d_2$ = 0.11 μm or 0.28 μm.

The results show under some circumstances noise can influence aerosol pollution, through the coagulation of particles, which will increase their size. This will have two consequences on aerosol pollution: First, lower concentrations of small particles, which is of interest as smaller particles are of more concern to health. Second, as particles grow larger due to agglomeration, they might be removed gravitational more quickly from the atmosphere. Clearly, more research is needed in this direction to clarify the matter. In future work we plan to access the agglomeration potential for a wider range of particle sizes. Also, there are still open questions that could be addressed in the future: 1) Are there other atmospheric conditions regarding SPL, sound frequency spectrum and aerosol characteristics that can cause agglomeration under atmospheric conditions? Thunder is an interesting candidate, as SPL can be very high [25], and, additionally, has frequency spectra with peaks around 50 Hz ~ 100 Hz [26], where orthokinetic agglomeration can be very effective. 2) Can other mechanisms of sound impact on particulates cause measurable modulations of aerosol size distributions under ambient conditions? It is known that liquid droplets can undergo deformation and breakup if exposed to a gas stream of sufficient velocity [27,28]. Especially for thunder, which is loud and occurs in cloud environments where large numbers of droplets are present, this might be an interesting and important mechanism.

## 4. Conclusions

The aerosol characteristics (size distribution, number density) in the atmosphere of Xanthi, as in most small towns in Europe, are not ideal for acoustic agglomeration under church bell sound. Church bell spectra have ideal frequencies to cause acoustic agglomeration but the SPL of the bell at distances larger than a few cm from the bell is prohibitive for acoustic agglomeration. At very close distances however, SPL can be large enough for acoustic agglomeration, especially under very polluted conditions. In this case, dust particles agglomerate more readily than liquid particles.

## Author Contributions

Konstantinos Kourtidis performed the theoretical work, the bell sound measurements, and wrote the manuscript. Ageliki Andrikopoulou performed the calculations.

## Conflict of Interest

No conflict of interest.

## Funding

This research received no external funding.

## References

[1] Oddie, B.C.V., 1965. The hail cannon, an early attempt at weather control. Weather. 20, 154-156.

[2] Changnon, S.A. Jr., Ivens, J.L., 1981. History repeated: The forgotten hail cannons of Europe. Bulletin of the American Meteorological Society. 62(3), 368-375.

[3] Wieringa, J., Holleman, I., 2006. If cannons cannot fight hail, what else? Meteorologische Zeitschrift. 15(6), 659-669.
DOI: https://doi.org/10.1127/0941-2948/2006/0147

[4] Scott, D.S., 1975. A new approach to the acoustic conditioning of industrial aerosol emissions. Journal of Sound and Vibration. 43(4), 607-619.

[5] Hoffmann, T.L., Koopmann, G.H., 1996. Visualization of acoustic particle interaction and agglomeration: Theory and experiments. The Journal of the Acoustical Society of America. 99, 2130.
DOI: https://doi.org/10.1121/1.415400

[6] Gallego-Juárez, J.A., De Sarabia, E., RodrÍguez-Corral, G., et al., 1999. Application of acoustic agglomeration to reduce fine particle emissions from coal combustion plants. Environmental Science & Technology. 33(21), 3843-3849.
DOI: https://doi.org/10.1021/es990002n

[7] Ng, B.F., Xiong, J.W., Wan, M.P., 2017. Application of acoustic agglomeration to enhance air filtration efficiency in air-conditioning and mechanical ventilation (ACMV) systems. Plos one. 12(6), e0178851.
DOI: https://doi.org/10.1371/journal.pone.0178851

[8] Riera, E., González, I., Rodríguez-Corral, G., et al., 2015. Ultrasonic agglomeration and preconditioning of aerosol particles for environmental and other applications. Gallego-Juárez, J.A., Graff, K.F. (Eds.),

Power Ultrasonics; Woodhead Publishing. pp. 1023.
DOI: https://doi.org/10.1016/B978-1-78242-028-6.00034-X

[9] de Sarabia, E., Gallego-Juárez, J.A., Rodríguez-Corral, G., et al., 2000. Application of high-power ultrasound to enhance fluid/solid particle separation processes. Ultrasonics. 38, 642-646.
DOI: https://doi.org/10.1016/S0041-624X(99)00129-8

[10] González, I., Gallego-Juárez, J.A., Riera, E., 2003. The influence of entrainment on acoustically induced interactions between aerosol particles—an experimental study. Journal of Aerosol Science. 34, 1611-1631.
DOI: https://doi.org/10.1016/S0021-8502(03)00190-3

[11] Kim, S.H., Lee, C.W., Lee, J.M., 2005. Beat characteristics and beat maps of the King Seong-deok Divine Bell. Journal of Sound and Vibration. 281, 21-44.

[12] Samolov, A., 2010. Analysis of just noticeable difference in spectrum of church bell sound. Telfor Journal. 2(2), 82-85.

[13] Zhang, D., Kong, K., Zhang, M., et al., 2020. Courtyard sound field characteristics by bell sounds in Han Chinese buddhist temples. Applied Sciences. 10, 1279.
DOI: https://doi.org/10.3390/app10041279

[14] Perrin, R., Charnley, T., Banu H., et al., 1985. Chladni's law and the modern English church bell. Journal of Sound and Vibration. 102, 11-19.

[15] Swallowe, G.M., Charnley T., Perrin, R., 1993. New musical scales. The Journal of the Acoustical Society of America. 94, 1166-1167.

[16] Rayleigh, J.W.S., 1879. On the capillary phenomena of jets. Proceedings of the Royal Society of London. 29, 71-97.

[17] Brandt, O., Freund, H., Hiedemann, E., 1937. Suspended matter in a sound field. Zeitschrift fuer Physik. 104, 511-533.

[18] Temkin, S., Leung, C.M., 1976. On the velocity of a rigid sphere in a sound wave. Journal of Sound and Vibration. 49(1), 75-92.

[19] Hoffmann, T.L., Koopmann, G.H., 1997. Visualization of acoustic particle interaction and agglomeration: Theory evaluation. The Journal of the Acoustical Society of America. 101, 3421.
DOI: https://doi.org/10.1121/1.418352

[20] González, I., Hofmann, T.L., Gallego-Juarez, J., 2000. Precise measurements of particle entrainment in a standing-wave acoustic field between 20 and 3500 Hz. Journal of Aerosol Science. 31, 1461-1468.

[21] Noorpoor, A.R., Sadighzadeh, A., Habibnejad, H., 2012. Experimental study on diesel exhaust particles agglomeration using acoustic waves. International Journal of Automotive Engineering. 2(4), 252-260.

[22] Loeffler, F., 1988. Staubabscheiden; George Thieme Verlag: Stuttgart-New York.
DOI: https://doi.org/10.1002/star.19890410313

[23] Andrikopoulou, A., 2013. A study of the influence of sound level pressure variations on the levels and size disributions of atmospheriuc aerosols. M.Sc. Thesis, Department of Environmental Engineering, Demokritus University of Thrace.

[24] Flocas, H., Asimakopoulos, V.D., Helmis, C.G., 2006. An experimental study of aerosol distribution over a Mediterranean area. Science of the Total Environment. 367, 872-887.

[25] Few, A.A., Dessler, A.J., Latham, D.J., et al., 1967. A dominant 200-hertz peak in the acoustic apectrum of thunder. Journal of Geophysical Research. 72(24), 6149-6154.

[26] Bodhika, J.A.P., Fernando, M., Cooray, V., 2014. A preliminary study on characteristics of thunder, pulses of lightning. 2014 International Conference on Lightning Protection (ICLP), Shanghai, China. pp. 260-264.

[27] Wierzba, A., 1990. Deformation and breakup of liquid drops in a gas stream at nearly critical Weber numbers. Experiments in Fluids. 9, 59-64.
DOI: https://doi.org/10.1007/BF00575336

[28] Guildenbecher, D.R., López-Rivera, C., Sojka, P.E., 2011. Droplet deformation and breakup. Ashgriz N. (eds) Handbook of atomization and sprays. Springer, Boston, MA.
DOI: https://doi.org/10.1007/978-1-4419-7264-4_6