A new approach for an induced coagulation of particulate matter through thermo-acoustic agglomeration

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ABSTRACT

To provide a good level of indoor air quality and thermal comfort, mechanically-based ventilation systems in high-rise buildings play a vital role in delivering adequate fresh air exchanges, because densely populated and insufficiently ventilated buildings can greatly affect human health. Generally, low-grade filters inside their mechanical ventilation ductworks have a minimum efficiency rating value (MERV) of less than 1–4 (ASHRAE Standard 52.2.-1999). However, they are not effective for capturing fine or ultrafine particles at a sub-micrometre scale. Instead, the use of high-efficiency particulate air (HEPA) filters is a common alternative to achieving a higher capturing efficiency, yet it may induce a greater pressure drop with strong reliance on HVAC fan power to overcome the resistance, resulting in additional significant power consumption. Acoustic agglomeration is known as an efficient pre-treatment technique for promoting the formation of particle clusters to enhance the capturing efficiency of low-grade filters in mechanical ventilation systems. However, a key limitation in implementing electromagnetic acoustic transducers is that, they fail to be sufficiently sensitive to generate swift and precise responses which can cause the variation of unsteady airflows inside ventilation ducts. In addition, piezoelectric- or electrostatic-based acoustic devices are typically very large in size, thereby limiting their applicability in commercial engineering solutions. For the first time, we propose to develop a smart acoustic agglomeration technique enabled by thermo-acoustic (TA) waves, which can be directly generated from carbon nanotube (CNT) thin-film materials, and also 2D materials (e.g., graphene and hexagonal boron nitride (*h*BN)). Advances in nanotechnology over the last decade have realized the thermophone concept, which was discovered a century ago, and fundamentally differs from the mechanism of conventional acoustic devices to produce sound by mechanical vibration. The operating mechanism of this technique can be described by providing an alternating current to CNT thin-film materials, causing the surrounding medium (air) to be heated periodically. Therefore, an oscillating temperature field can be induced in the medium, resulting in thermal expansion and contraction to generate acoustic waves. This innovative control technique can be scalable to deliver a flat-band frequency range as well as high-intensity sound pressure outputs. In this work, we demonstrate TA effect, in the form of a standing wave, which can be modulated by an adaptive system to promote the coagulation of suspended particles in air.

1. INTRODUCTION

1.1. Mechanical Ventilation

According to the United Nations in 2019, 55% of the world's population resides in urban areas, which is expected to increase to 68% by 2050. Therefore, densely populated cities that have limited land has constantly increased high-rise developments of residential and commercial buildings. The challenge is to construct safe, comfortable and efficient indoor environments that promote quality living [1]. Many filtering technologies have been identified which include, catalytic oxidation, mechanical filtration, ozone, plasma, sorption and ultraviolet-germicidal-irradiation (UVGI) [2]. Due to the limited space in the design of ventilation ducts, deploying mountable electrical precipitators and fibrous-packed air filters with high removal efficiencies in ventilation ducts have been a widespread practice by building management services.

In the literature, standards for the aforementioned ventilation methods and systems are still under development [3-5]. Relevant studies have reviewed air distribution methods that contribute to mitigating climate change and reduce carbon footprints [6, 7], while energy consumption dependence to air temperature in ventilation configurations and ventilation methods has been studied [8]. Developing personalized ventilation is a common theme [9]. The influence of sinusoidal air flow and distance on human responses has been studied [10].

Effective mechanical ventilation systems for air conditioning require a smarter and more effective technique to remove airborne aerosols and particulate matter [11]. However, the continued use of high-efficiency particulate air (HEPA) filters need to comply with NFPA-96 and ASHRAE-62 standards that enforce mandatory ventilation and fire protection policies, inevitably lead to expensive upgrades for extraction fans on high-rise buildings, and result in high energy consumption and maintenance costs. For example, MERV 11 or higher rated filters would severely restrict airflow and therefore, is considered not suitable for most HVAC systems due to airflow resistance. Experimental methods for filtering such as fibrous types, thrombe wall, biofiltering, electrostatic and cold plasma types have also been reviewed [12] along with air jets methods to remove particles as a viable alternative to mechanical methods [13].

Currently, HEPA filters rely on four filtration mechanisms: diffusion, interception, inertial impaction and electrostatic attraction. Most HEPA filters that rely on the first three mechanisms are composed on randomly arranged fiberglass materials. The performance is highly dependent on their diameter, filter thickness and face velocity. As the air space between the HEPA fibers are typically greater than 0.3 µm, they are designed to capture fine particles. The use of a pre-filters which function to condition the incoming air, made from granular activated carbon, or carbon cloths can reduce the dependence on the HEPA filter and extend their life-time. Emerging techniques such as thermo-acoustic (TA) agglomeration is currently emerging as a non-invasive acoustic aerosol manipulation technique, which is based on acoustic levitation or acoustophoresis.

1.2. Acoustical Particle Manipulation

Reports in the literature for simulating the manipulation of acoustical particles have been investigated by Fu et al., [14], and Lei et al., [15] on Rayleigh streaming flows in acoustic radiation forces. Prisbrey et al., [16] also provided numerical simulations for non-contact particle manipulation via ultrasound wave fields. Yuen et al., [17] simulated the removal of 6 µm particles without the need to specifically solve the Rayleigh integral and for the Gor'kov potential and conducted a study [18], for removing aerosols between 0.3 to 6 µm sizes using a 100W power transducer, which removed 12–20% at 90 L/min. Further, they explained that the removal efficiency is proportional to the duration that the aerosols exposed to the acoustic fields, while maintaining a negligible pressure drop, thus minimizing power consumption. The same researchers studied an acoustic streaming effect, which induces aerosol depositions through a hanging plate platform type ultrasonic transducer oscillating at 19 kHz vertically at 44W power. Aerosols that aggregate into 6 µm diameter particles, experience strong enough acoustic radiation forces that travel against drag and gravitational forces which indicate a low face velocity limit of 0.3 m/s is necessary for this device to work [19]. However, TA agglomeration through the emission of standing waves has recently been shown to induce better coagulation of particles, which affect the aerosol size distribution. Thus, this aggregates finer particles into coarser ones, allowing the capture these larger particles without relying on very fine HEPA filters.

To achieve TA agglomeration, a novel loudspeaker is required instead of conventional mechanical acoustic transducers. It requires novel flexible materials to such as low heat capacity per unit area. A significant breakthrough on loudspeakers by Xiao et al., [20] through use of carbon nanotubes which exhibited exemplary sound emitting properties, while single walled carbon nanotube films were reported thereafter [21]. TA chips with carbon nanotube thin yarn arrays have been reported by Wei et al. [22]. Many different materials have also been highlighted for loudspeakers [23]. Recently, a greater focus has turned to 2D materials such as graphene [24, 25], Ti_3C_2 has also been reported as highly effective materials as loudspeakers [26]. Newer designs of TA devices have identified broadband signal responses [27] and with gap separation of the loudspeaker material to the substrate [28] show that higher performance can be achieved.

In this work, we present the design of a TA agglomeration technique as simulated in COMSOL Metaphysics® software package. The model presented here is a scaled representation of ventilation ducts, and we examine how effective this technique can control aerosol particles to promote coagulation of suspended particles.

2. MEHODOLOGY

2.1 Thermo-acoustic Emitter

TA waves, which can be directly generated by 2D material based transducers, have been investigated through many existing publications as abovementioned. Unlike the usual pressure-velocity variation, TA waves that came from the thermophone concept [29] are created by a temperature-position displacement for generating sound. Based on this mechanism, standing waves can be generated by a graphene-based TA device as adopted in this work, which is intended to achieve produce sound pressure waves at resonance. As a 2D material, graphene exhibits low specific heat capacity and high thermal conductivity [30] and thus, it is attractive not only for mass semiconductor fabrication, but for scaling and miniaturization for appropriate fitting into ventilation ducting. The use of a TA thin-film which is suspended on a substrate, for our design has numerically shown to be highly effective for emitting acoustic waves [28]. Figure 1(a) illustrates a schematic diagram of the proposed device with graphene material suspended on a substrate. Figures 1(b) and 1(c) show the fabricated prototype of a graphene based TA device and an experimental setup in the in-house clean room, respectively. In addition to graphene, *h*BN material is another good candidate as this is the most stable crystalline form to have a layered structure similar to graphite. It shows remarkable chemical and thermal stabilities [31], e.g., it is stable to decomposition at temperature up to 1000 °C in air.

In this work, we propose to integrate a multiple graphene devices onto a printed circuit board (PCB) in a parallel array configuration, which operate simultaneously to function as a loudspeaker to emit a standing wave at resonance. Figure 2(a) shows the schematic diagram of a 2×2 array of TA devices, which are mounted onto a PCB and Figure 2(b) shows the TA loudspeaker inside a three section based ducting model induce the acoustic agglomeration and therefore, the coagulation of suspended particles is formed in the enclosed tube. In this work, we assume that the array of TA devices is one loudspeaker device in unity and modelling the computational fluid dynamics (CFD) is provided to examine the performance parameters and operation conditions, which are needed for inducing acoustic agglomeration.

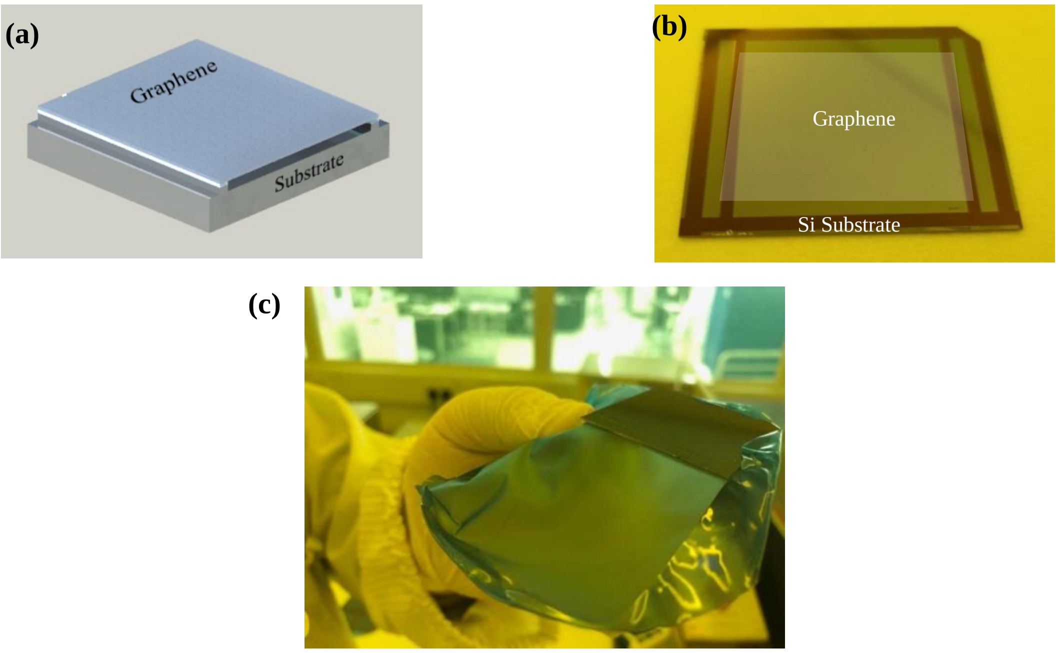


Figure 1: (a) A 3D schematic diagram of the proposed design with 2D graphene sheet suspended on a substrate; (b) a photo of the fabricated graphene-based TA device; and (c) a photo of fabrication work in the in-house cleanroom.

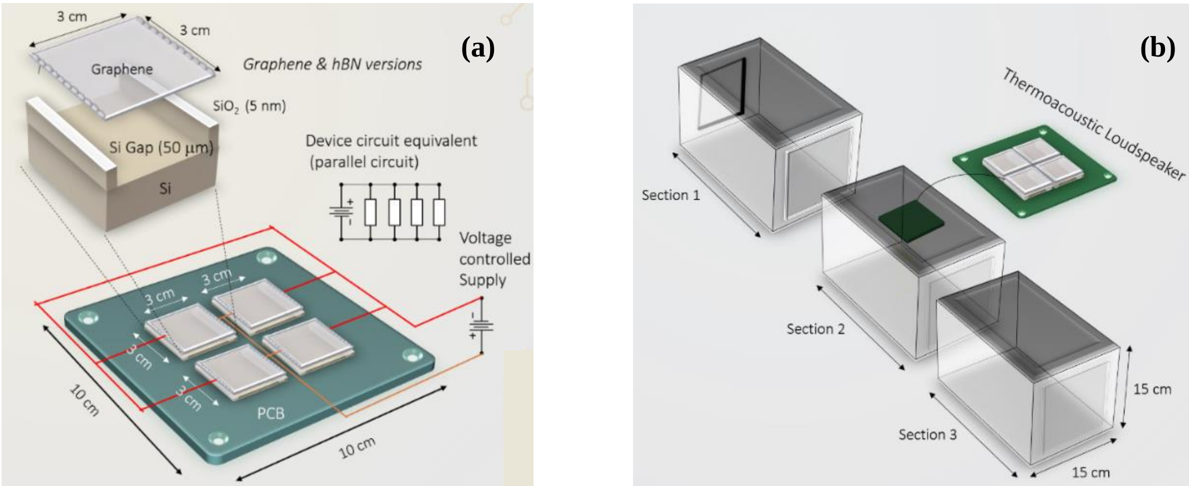
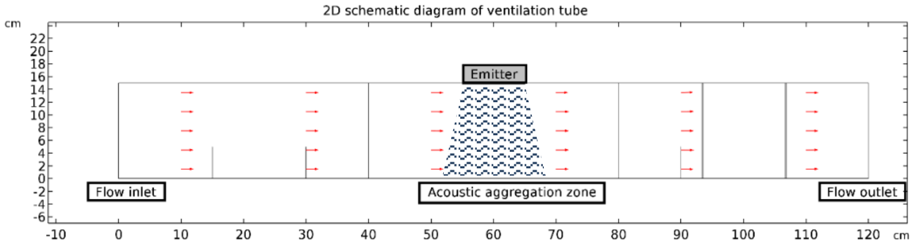


Figure 2: Schematic diagram of the proposed devices: (a) 2×2 acoustic agglomeration device array loudspeaker as mounted onto the PCB; and (b) the loudspeaker as integrated into a three section based ducting model tube.

2.2 Simulation parameters

In this work, we examined the acoustics and flow properties in a ventilation tube, by setting up a 2D representation of the expected behavior of TA agglomeration in a virtual environment using the COMSOL Metaphysics® software. Figure 3(a) shows a photo of typical ventilation ducting in commercial buildings, which then lead into the ducting and thus office or living quarters. Figure 2(b) illustrates a cross-sectional diagram of a typical ventilation system with the loudspeaker considered as an acoustic emitter, and thus the formation of standing waves emerges within an acoustic aggregation zone. The diagram illustrates the airflow direction originating from an inlet through to the outlet via an acoustic aggregation zone, which is designed to mitigate the aerosol particles.

(a) **(b)**

Figure 3: (a) Photo of typical ventilation ducting on a building (https://www.ecms-ltd.co.uk); and (b) a schematic diagram of ventilation ducting for simulation

Important parameters in the design that govern the initial conditions are considered in this work. These are: (i) the size of the tube; (ii) the operating frequency at resonance that can suspend the aerosol particles through standing waves; (iii) the minimum sound pressure level of standing waves to manipulate the aerosol particles; and (iv) the emission acoustic angular spread at which the waves occur need to found as it can determine the level of acoustic coverage in the tube. To achieve TA agglomeration, the analysis of a time-dependent particle trajectory and their minimum sound pressure levels required during operation allows us to examine the behavior on acoustic resonance and how it affects the aerosol particles as they pass through the tube.

To determine the standing wave characteristics such as the emitter resonant frequency, the cross-sectional height of the ventilation tube is typically between 10 to 20 cm, which is a small-scale size appropriate for modelling some of the smaller ducting area and interconnects in ventilation systems. A tube length of 120 cm is designed for this simulation, while the height of the tube is examined between 10, 15 and 20 cm, respectively. Equation (1) is used to obtain the resonant frequencies that generate standing waves in a closed tube, as given by:

$$f = \frac{c}{2L} m \qquad (m = 1, 2, 3 \dots) \tag{1}$$

where f is the frequency in Hz, c is 343 m/s, L is the height of the ventilation tube, and m is harmonic order. As there are an infinite number of harmonics for this system, we assume that it can achieve a whole number of half acoustic wavelengths $\lambda/2$. For example, in a 15cm tube, the fundamental resonance frequency is calculated as 1,143 Hz and the 9^{th} harmonic standing wave is therefore 10,287 Hz. We selected the 9^{th} harmonic frequency as it has previously been identified as it a frequency which can achieve acoustic agglomeration [32].

3. RESULTS & DISCUSSION

3.1 Simulation Data

Using the COMSOL Metaphysics® software package, we have simulated acoustic behavior in a 2D model representing the cross-sectional ventilation ducting with a length 120 cm as shown in Figures 4–6. Each of the figures discusses the different parameters investigated which, Figure 4 identifies the standing wave behavior based on different size ducting, while Figure 5 presents the different operating resonance frequencies, and Figure 6 shows the particle trajectories which the aerosol particles undergo during acoustic agglomeration.

In the model, the wall boundaries at the top and bottom are constructed of rigid surfaces and the inlets and outlets are empty voids with air flow at 0 m/s. In Figure 4, we investigated the effect on the tube size, whereby the cross-sectional height is varied from 10, 15 to 20 cm. We have selected the 15 cm height for the tube as similar to [32] and the emitter generates the standing wave at the middle as indicated by the 60 cm mark. The simulation shows that standing waves can be sustained under resonance at a minimum sound pressure level of 70 dB, which can be also maintained at the 9^{th}

harmonic frequency of 10287 Hz. As seen in the figure, the emitter generates an acoustic wave profile extents into the tube covering a triangular area according to an acoustic angular spread.

Using a linear extrapolation, acoustic angular spread is evaluated two sides of the acoustic field lines in Figure 4, as they converge at the top geometrically. The acoustic angular spread as depicted in these figures are determined as 56.1°, 55.1°, and 47.9°, respectively. Figure 5 shows the acoustic simulations in a 15 cm cross-sectional tube at three different resonance frequencies, i.e. 6858, 10287 and 20574 Hz, respectively. The acoustic angular spread as depicted in these figures are determined as 56.1°, 55.1°, and 47.9°, respectively. These results indicate that with increasing frequency, the angle of the emission spread decreases proportionally. We have selected 10 kHz as the higher frequencies can reduce the acoustic angular spread affect the emission distribution, as indicated by the curved plot in Figure 5(c). Operating with lower frequencies however, does not guarantee that a high sound pressure level can be sustained by the emitter [30]. Having the particles maintain their presence in a maximum amount of time within the acoustic agglomeration region is highly desired in maximizing this effect. Thus, in this 15 cm cross-sectional tube design, the fabrication of such devices can expect to achieve an acoustic spread of 55° with an operating frequency at around 10 kHz.

We investigate the acoustic agglomeration effect towards particulate matter (PM10) by inserting aerosol particles at a size of 10 µm and operating the emitter at 160 dB [33]. In the simulation, we insert particles at a concentration of 10,000 particles is released in the tube randomly. A generated airflow providing velocity to the particles is set at a rate of 0, 0.1, 0.3 and 0.5 m/s, which are plotted in Figure 6 respectively. The results from the simulations in these figures indicate that acoustic aggregation can occur and affect the particles by trapping them in the zone/region. It is observed that an acoustic spread of 55° is retained under the presence of airflow. Four different airflow rates were simulated, with the presence of PM10 particles. Simulated particle trajectory results in Figures 6(a) and 6(d) indicate the absence of acoustic agglomeration, which indicates the maximum and minimum flow rates, can be achieved through these operating parameters. Meanwhile, results in Figures 6(b) and 6(c) show the capture of PM10 particles within the acoustic aggregation zone, which shows that agglomeration effect, can be effective to control aerosol particles under a flow rate between 0.1 and 0.3 m/s.

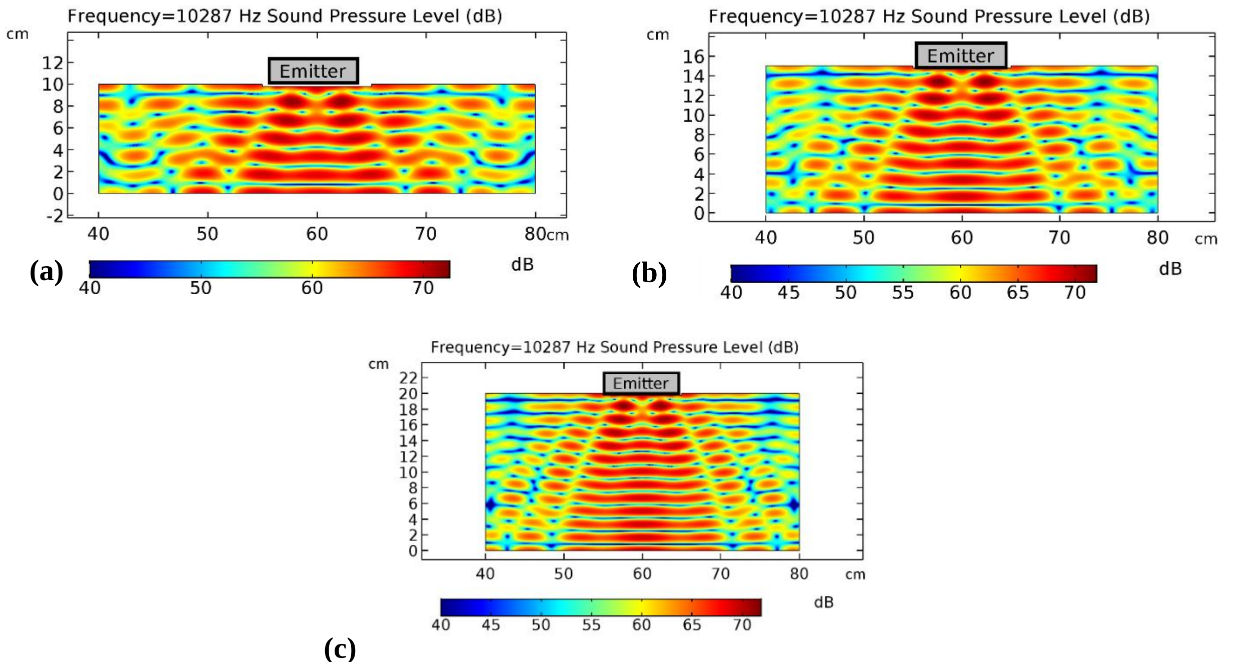


Figure 4: A 2D model simulation of a ventilation duct of different sizes were: (a) 10 cm, (b), 15 cm and (c) 20 cm. An acoustic loudspeaker emitter located at the top-center of the duct at 10287 Hz to demonstrate the formation of standing waves.

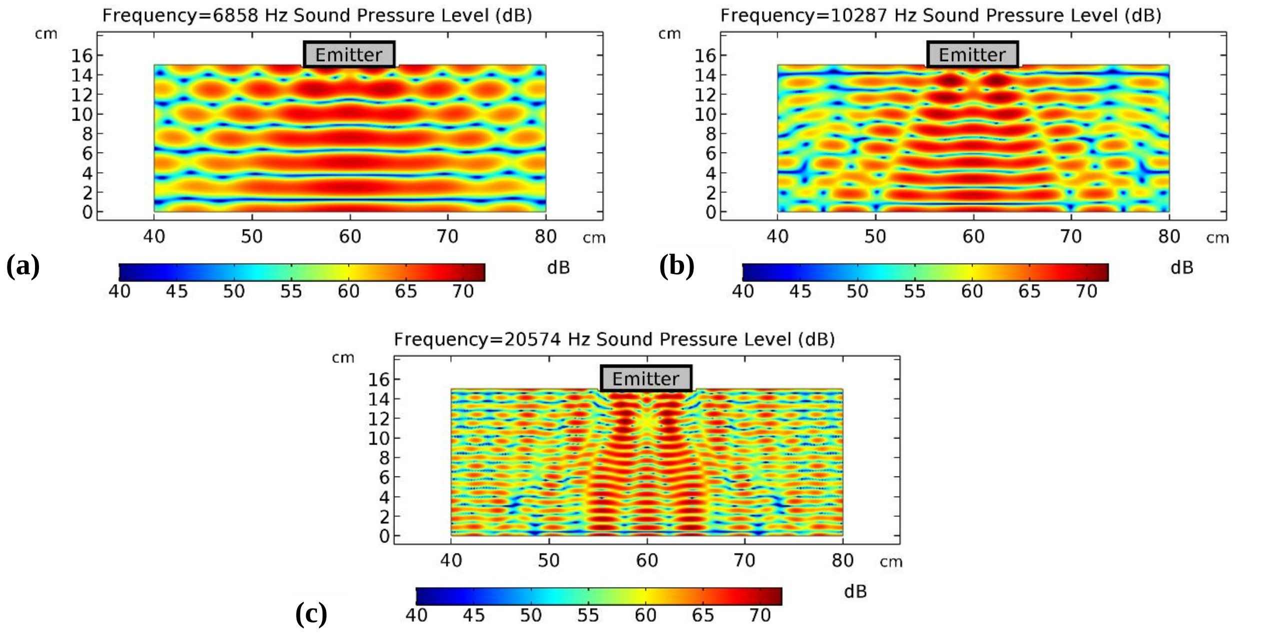


Figure 5: A 2D model simulation of a ventilation duct at 15cm size at different frequencies: (a) 6858 Hz, (b) 10287 Hz and (c) 20574 Hz to demonstrate their respective acoustic angular spread.

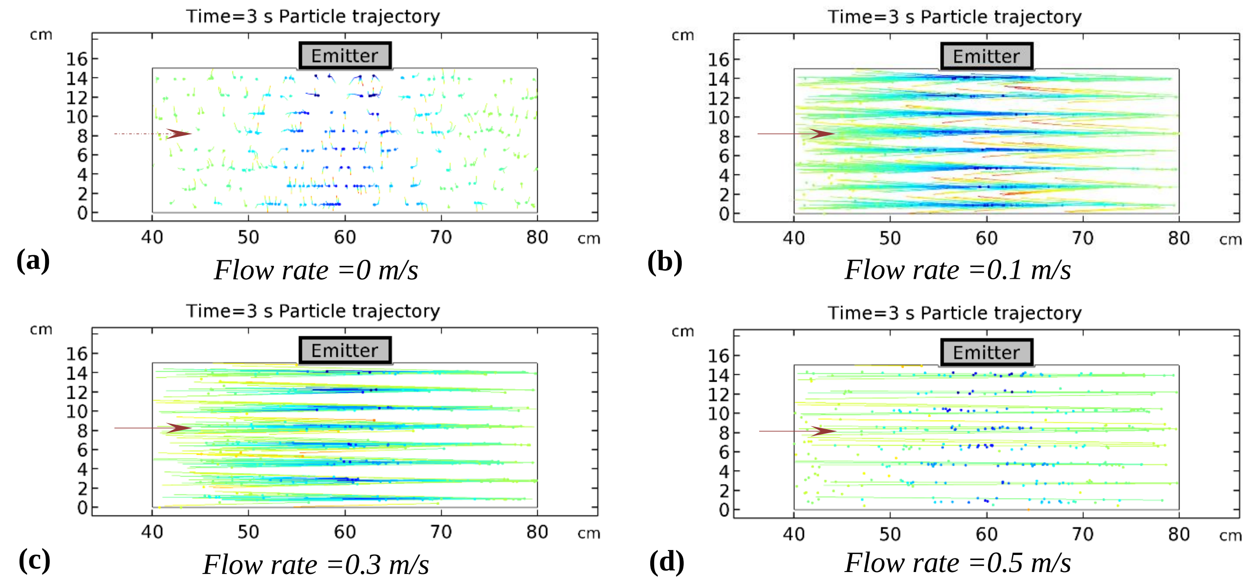


Figure 6: A 2D model showing the particle trajectory of PM10 sized matter as introduced into the tube at flow rates of (a) 0, (b) 0.1, (c) 0.3 and (d) 0.5 m/s, respectively. The arrow indicates the direction of the particles traveling across the tube and a snapshot of particles is captured at a time of 3 s.

4. CONCLUSIONS

In this work, we proposed a new TA agglomeration technique. The COMSOL metaphysics simulator was used to analyze its effects on the control of aerosol particles in a ventilation duct and promote the coagulation of these tiny particles into suspended clusters. We found that a minimum of 70 dB is required to generate standing waves, at 10 kHz frequencies and discussed their emission spread angles for different tube sizes. A cross-sectional design at 15 cm showed that it can support acoustic agglomeration at the flow rate of 0.1–0.3 m/s. The present CFD study sheds light on the design of a smart agglomeration technique, and it sheds insight into the acoustic-fluid interaction for better design analysis and improvements. Our future work will focus on the following two aspects to realize this technique:

(i) the fabrication of TA prototypes (i.e., emitter) is being conducted using graphene and *h*BN materials for in-house experiment; and

(ii) the use of very high sound pressure levels (e.g., 160 dB) for acoustic agglomeration must be replaced by an alternative design approach, e.g., using multi-agglomeration zones instead, because it is not feasible for using such high levels in practical applications.

5. ACKNOWLEDGEMENTS

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