

Particle Number Reduction in Automotive Exhausts Using Acoustic Metamaterials

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ABSTRACT

Air pollution caused by exhaust particulate matter (PM) from vehicular traffic is a major health issue. Increasingly strict regulations of vehicle emission have been introduced and efforts have been put on both the suppression of particulate formation inside the engine cylinders and the development of after-treatment technologies such as filters. With modern direct injected engines that produce a large number of really small sub-micron particles, the focus has increased even further and now also includes a number count.

The problem of calculating particle trajectories in flow ducts like vehicle exhaust systems is challenging but important to further improve the technology. The interaction between particles and oscillating flows may lead to the formation of particle groups (regions where the particle concentration is increased), yielding a possibility of realizing particle agglomeration. The oscillating flow may simply be hydrodynamic or as assumed here: the flow oscillations are created by sound propagation rather than hydrodynamic approaches. An analysis is presented which gives the relationship between the speed of sound, the mean flow velocity and the amplitude of the acoustic particle velocity for particle agglomeration to be feasible. It is shown that it can be achieved if the convective speed of sound is reduced to the same order as the mean flow velocity. It is therefore suggested to use the so-called acoustic metamaterials, which can help control, direct and manipulate sound waves. At this stage a phenomenological 1D model is used for the analysis, which allows the authors to build an understanding of the effect of the sound waves and flow oscillations on particle motion and paves the way for further analysis on particle agglomeration.

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INTRODUCTION

Complete and incomplete combustion of fuel in internal combustion engines (ICE) may result in the formation of complex mixtures of gaseous (gas-phase hydrocarbons, CO, CO₂, NO, NO₂, SO₂) and particulate exhaust (carbonaceous matter, sulfate and trace elements), which can lead to health conditions such as asthma and lung cancer. Especially, for submicron particles, which constitute the vast majority of both the number and mass of diesel engine exhaust particulate matters (PM), they prove to have a longer residence time in air and higher penetration ability into the human respiratory system, indicating a larger risk to both the environment and human health [1, 2].

Current exhaust PM control techniques include both the suppression of particulate formation inside engine cylinders and the development of after-treatment devices, such as particulate filters (DPF and GPF). To keep the pressure loss penalty over the device as small as possible these filters are most often of deep bed filtration type where the mean pore size of filter media (typically micrometers) is bigger than the

mean diameter of collected particles (typically nanometers), and the particles are deposited on the media through a combination of diffusional and inertial deposition. In practice, when the filter get saturated, there is also a contribution from surface-type filtration, where the pore diameter is generally smaller than the particle diameter, and the particles are deposited through sieving [3, 4].

This paper provides a new PM after-treatment concept, particle grouping/agglomeration, which can shift the size distribution of exhaust PM. Particle grouping/agglomeration refers to the formation of particle groups where the particle number and mass concentrations are clearly higher than in other regions. The grouping phenomenon can be related to non-zero relaxation time of particles in an oscillating flow field. When the flow velocity behaves as either a propagating or a standing wave, particles may experience acceleration or deceleration, depending on their relative position in the wave, which can lead to the separation or agglomeration of particles. Eventually, stable regions where particles can be accumulated will form [5].

Based on the research of Katoshevski and coworkers, particle trajectories will converge under the condition that the ratio of the relative velocity between the steady flow and flow phase and the amplitude of the flow oscillation velocity is no larger than 1 for moving wave scenarios and 0.5 for the standing wave ones [6].

Following the 1D hydrodynamic model suggested by Katoshevski, but assuming the flow oscillations are created due to sound propagation, rather than geometry changes of the exhaust pipe or other mechanisms, an analysis is presented in this paper which gives the relationship between speed of sound, the mean flow velocity and the amplitude of acoustic particle velocity for particle agglomeration to be feasible. Unlike some other work in which particles agglomerate due to the interaction between acoustic radiation forces, fluid drag, buoyancy and gravity forces within an horizontal ultrasonic standing wave field [7], particles in our model are subject only to viscous drag force generated due to the relative motion between the flow and the particles [8], and the flow oscillations are caused by the noise emitted from rotational machines, such as ICE, instead of external sound sources.

One among other primary conditions for particle agglomeration to be achievable in this acoustic model is that the convective speed of sound should be of the same order as the mean flow velocity, which means, in the case of vehicle exhaust systems where the Mach number of the exhaust flow is no larger than 0.3, the sound speed should be much slower than that in normal cases (around 340 m/s at room temperature). To address such issue, the so-called acoustic metamaterials [9, 10, 11, 12] are resorted to, with a thorough analysis conducted upon the extraction of effective properties from metamaterial models.

Basic equations and approximations of the hydrodynamic model put forward by Katoshevski are presented in Section 2, following which an acoustic analogue is proposed in Section 3. The focus of Section 4 is on how to achieve the ‘slow sound speed’ with the application of acoustic metamaterials, with a specially designed periodic acoustic structure presented for initial analysis (the structure may have questionable applicability in practical use but is used to illustrate the concept). In Section 5, based on the analysis in the previous two sections, particle trajectories inside the metamaterial model are investigated using numerical approaches. The main results of the paper and plan for future work are summarized in Section 6.

HYDRODYNAMIC MODEL FOR PARTICLE AGGLOMERATION

Katoshevski et al. [13] studied and mathematically demonstrated the process of particle grouping in a 1D oscillating flow. The essence of their model is that particles from different initial positions can converge or diverge under successive acceleration and deceleration, thus leading to agglomeration at some certain locations. A schematic diagram of the grouping phenomenon in an oscillating flow is shown in Figure 1. The length of the arrows represents the values of flow velocity.

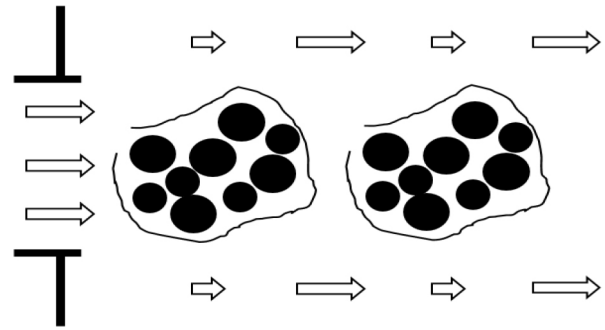


Figure 1. A schematic diagram of particle agglomeration in a 1D oscillating flow.

Consider particle motion in a 1D periodic flow described by the following equation:

$$v_f(t, x) = V_a - V_b \sin(kx - \omega t) \quad (1)$$

in which $v_f(t, x)$ is the dimensional flow velocity at time t and position x , V_a the dimensional mean flow velocity, V_b the dimensional amplitude of oscillation velocity, k the wave number and ω the angular frequency. The dimensional flow phase velocity can be expressed as $V_\omega = \omega/k$.

Normalizing the velocities by V_ω , distance by k^{-1} and time by ω^{-1} will lead to the following motion equation in the Stokes limit:

$$\frac{du_p}{d\tau} = F_d = \frac{1}{St} (u_f - u_p) \quad (2)$$

where F_d is the viscous drag force, which is a function of the relative motion between the particles and the flow, $St = \rho_p \omega D_p^2 / 18\mu$ the Stokes number (ρ_p is the particle density, D_p the particle diameter, μ the dynamic viscosity of the fluid), τ the dimensionless time and u_f and u_p the dimensionless fluid and particle velocity, respectively ($u_f = v_f / V_\omega$, $u_p = v_p / V_\omega$, v_p is the dimensional particle velocity). The condition of small St is required. Usually, for sufficiently small particles or low frequencies, the condition $St \ll 1$ can be easily satisfied. Also, the particle Reynolds number Re_d should be no larger than 2, otherwise a different expression for the Stokes number should be used instead.

Transfer the particles into a frame of reference moving at the flow phase velocity V_ω so that the dimensionless particle velocity in the new frame of reference becomes $U_p = \Delta v / V_\omega = (v_p - V_\omega) / V_\omega = u_p - 1$, and the dimensionless particle position becomes $X = (x - V_\omega t) / k^{-1} = kx - \omega t$. In this way, Eq. (2) can be rearranged as:

$$\frac{dU_p}{d\tau} = \frac{1}{St} (U_a - 1 - U_p - U_b \sin X) \quad (3)$$

It is fairly straightforward to categorize the patterns Eq. (3) describes as:

1. If $U_a - 1 - U_p > U_b$, then the condition $\frac{dU_p}{d\tau} > 0$ is always satisfied and the particles are expected to accelerate for all times and locations.

2. If $U_a - 1 - U_p < -U_b$, then the condition $\frac{dU_p}{d\tau} < 0$ is always satisfied and the particles are expected to decelerate for all times and locations.
3. If $U_a - 1 - U_p = \pm U_b$, then $\frac{dU_p}{d\tau} > 0$ or $\frac{dU_p}{d\tau} < 0$ except when $X = \pm\pi/2$, where n is an integer, and the particles are expected to accelerate or decelerate for all times and locations, indicating similar physics in the previous two cases.
4. If $-U_b < (U_a - 1 - U_p) < U_b$, then $\frac{dU_p}{d\tau} > 0$ when $U_b \sin X < (U_a - 1 - U_p) < U_b$ and $\frac{dU_p}{d\tau} < 0$ when $-U_b < (U_a - 1 - U_p) < U_b \sin X$. In this scenario, the particles will experience successive acceleration and deceleration, providing the possibility for particles with different initial locations or velocities to be 'trapped' in the vicinity of the equilibrium points:

$$X = X_0 = \sin^{-1}[(U_a - 1 - U_p)/U_b] + 2\pi n \quad (4)$$

when their acceleration goes to zero.

In the limiting case in which $U_p = 0$, Eq. (4) can be simplified as the following expression:

$$\sin X_0 = \beta \equiv (U_a - 1)/U_b = (V_a - V_w)/V_b \quad (5)$$

If Eq. (5) has a solution, then particles with different initial velocities and locations can be expected to reach the position X_0 . Therefore, the necessary condition for particle grouping can be presented as $|\beta| \leq 1$ [6].

It is also found by Katoshevski that if we introduce a new dimensionless time $\tau' = \tau \sqrt{U_b St}$, then Eq. (3) can be rearranged as

$$X'' + \alpha X' + \sin X = \beta \quad (6)$$

where $X'' = \frac{d^2 X}{d\tau'^2}$, $X' = \frac{dX}{d\tau'}$ and $\alpha = 1/\sqrt{St U_b} \propto 1/D_p$ which indicates the inertia of the particles. Only when α is larger than a certain threshold particle grouping occurs [5].

A numerical solution to Eq. (3) using the Runge-Kutta method is illustrated in Figure 2. The analysis was performed upon particles with diameters of 2 μm and density of 600 kg/m^3 entrained by an oscillating flow with a phase velocity of 50 m/s (the angular frequency and the wave number are $\omega = 10^5 \text{ rad/s}$ and $k = 2000 \text{ rad/m}$, respectively). In Figure 2 (a), $V_a = 60 \text{ m/s}$ and $V_b = 20 \text{ m/s}$, making $\beta = 0.5$. In Figure 2 (b), $V_a = 80 \text{ m/s}$ and $V_b = 20 \text{ m/s}$, making $\beta = 1.5$. The dynamic viscosity of the fluid is $\mu = 3.3 \times 10^{-5} \text{ Ns/m}^2$. The particle diameter of 2 μm can be seen as an upper limiting case. In practice all particles are substantially smaller than this ($< 100 \text{ nm}$), and will be increasingly more straightforward to control with this technology as α increases.

Six particles are entrained simultaneously over the range of x from 0 to 3.14 mm (one wavelength) in such a way that the initial distance between each adjacent two is equal to 1/5 of the wavelength. The

initial velocity of the particles are taken the same as the flow velocity at $t=0$. Different patterns of particle motion can be found in the two plots. In Figure 2 (a), after no more than 0.15 ms, two particle groups formed with a distance of around one wavelength in between, and the particle velocity becomes equal to the flow phase velocity. In Figure 2(b), on the other hand, no clear pattern of agglomeration can be found. The numerical results indicate that the analysis of the grouping condition is correct.

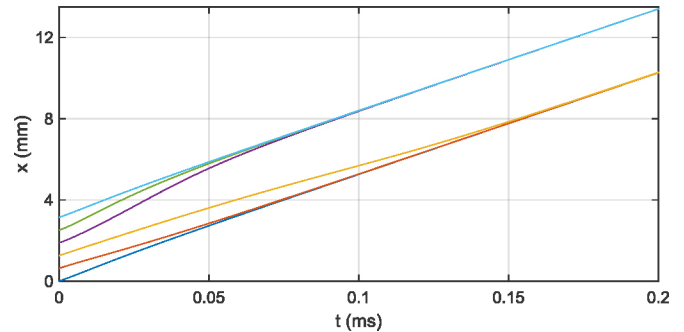


Figure 2 (a). The numerical result of distance versus time for six particles in an oscillating flow.

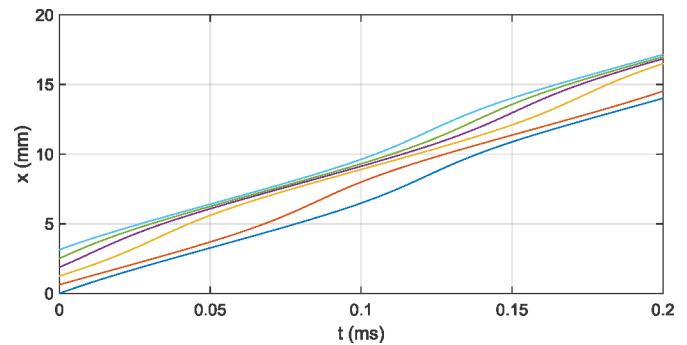


Figure 2 (b). The numerical result of distance versus time for six particles in an oscillating flow with $\beta=1.5$.

Figure 3 illustrates the regimes of grouping and non-grouping determined via both α and β . Grouping is more likely to happen for larger α , i.e. smaller particles, indicating that the grouping mechanism given in this paper works better for fine or even ultra-fine particles. In the following simulations, the particle size will therefore be kept at 2 μm to keep a "worst case scenario"-test.

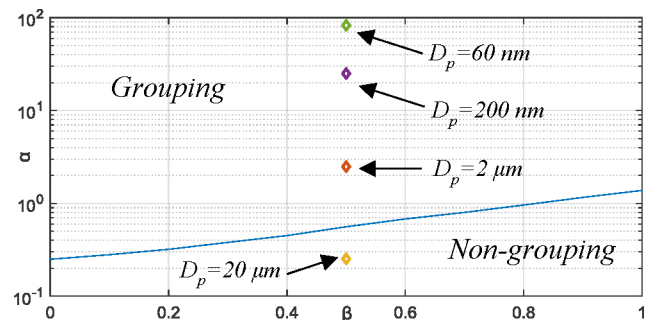


Figure 3. Regimes of grouping and non-grouping for different values of α and β .