Environmental and Health Risk Associated with Air pollution Emitted by Public Transportation, and a New Methodology for Reducing the Risk

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Abstract

Tiny smoke particles that are typically emitted today from a variety of vehicles are of major public concern, as they are known to cause major health and environmental problems. It is well recognized that those tiny particles are directly linked with lung cancer, and have harmful effect on the environment. As they are smaller than other types of particles (sub-micron size) it is more difficult to filter them and their residence time in the air, and hence exposure time, is much longer. It seems that at this stage, the worldwide extensive efforts to reduce their emission depend to a large extent on our scientific understanding of their formation and their dynamics before they are emitted. These involve a wide range of coupled phenomena related to combustion, fluid dynamics and chemistry which are taking place in the engine and in the exhaust system. Well-controlled oscillations of the flow-field in the exhaust system may cause the phenomenon of particle-grouping and eventually to coagulation/aggregation. The knowledge of how to control the characteristics of the underlying flow may lead to a desirable behavior and, in the case of sub-micron and nano-metric smoke-particles it may lead to extensive particles' coagulation resulting in a dramatic decrease in their number and hence reduction in health/environmental risks.

Hence, increase of smoke particles size by aggregation as they are in motion in the exhaust system will reduces their number, increase their size and enable us to capture them by conventional filters. Even if some of them are emitted, they impose lower risk. This target is the basis of the new methodology which we will elucidate, that is based on a mathematical model and lab experiments. The experiments show that the new design of exhaust systems leads to the desirable shift in the size distribution, and also show its potential for reducing the environmental problems associated with emission from transportation.

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1. Introduction

Air pollution from transportation is a major source of public concern. Special interest should be given to the dynamics of the sub-micron and nano-metric smoke particles which are emitted (Keith and Derrick, 1960; Sher, 1998). Exposure to these particles is associated with respiratory system diseases such as lung cancer (Pope III et al., 2002), asthma in adults (von Klot et al., 2002), in children and babies (Heinrich and Slama, 2007; Gent et al., 2009), bronchitis symptoms in children (WHO guidelines, 2000), chronic obstructive pulmonary disease (Young et al., 2009), and also cardiovascular disease (Dominici et al., 2006). In vivo experiments show that exposure to cigarette smoke can cause oxidative damage (Morrow et al., 1995) in addition to increased mortality observed in mice exposed to diesel engine smoke (Sagai et al., 1993). Nanoparticles can also penetrate the cardiovascular system, and they have been associated with vascular inflammation, blood cell coagulation irregularities, atherosclerosis and thrombosis (Simeonova, 2009; Nemmar et al., 2002; Heyder, 1986).

The smaller the particles the deeper they penetrate and deposit in the respiratory system (Davies, 1949; Glover et al., 2008) and in addition, the exposure time to those small particles increases. For example the residence time for 0.1\(\mu\)m particle is at least 100 times longer than for 1\(\mu\)m particle, and therefore the exposure time to these small particles is an important factor. Hence, a manipulation on particle size distribution is required, and is possible by employing a "grouping technique" which is describe now.

Recent work by Katoshevski and co-workers (2005, 2006 and 2008) and Sazhin et al. (2008) has been devoted to the phenomenon of clustering or "grouping" of particles (and droplets) in an oscillating flow field, see Fig. 1. From their theoretical and numerical analysis (backed up qualitatively by some experimental observations) it appears that there is a tendency of particles travelling in oscillating flow fields to form groups that is exhibited by regions of increased particle concentration separated from regions of reduced particle concentration. This phenomenon of preferential concentration was discussed by Rouson and Eaton (2001) in fully developed turbulent channel flow. Using a direct numerical simulation they showed that particles with Stokes numbers of order one based on the Kolmogorov scale were preferentially concentrated into longitudinal strips extending across the channel whereas larger particles remained randomly distributed (see more details on the Stokes number and Kolmogorov scale in Rouson and Eaton, 2001).

![Figure 1. Schematic presentation of grouping of particles in an oscillating flow field. The values of flow velocity are indicated by the sizes of the arrows. As particles travel downstream grouping take place, and this leads to particle coagulation. In the case of smoke-particles which are emitted from public transportation vehicles which are diesel-based, there is a high probability for coagulation to occur if the particles are gathered, that is, if grouping is manipulated/controlled.](image-url)
A recent experimental study by Katoshevski et al., (2010) has shown that it is possible to promote grouping/clustering and coagulation of smoke particles as they are in motion in an exhaust pipe of a Diesel engine, when employing a downstream velocity variation by a special pipe geometry. This controlled grouping leads to the coagulation of the particles and to the desirable shift in their size distribution. This is reflected in Fig. 2 where we show typical measurement results comparing the novel exhaust system with a regular one.

![Figure 2](image)

Figure 2. Recent measurement results of smoke-particle size distributions in two exhaust pipes which are connected in parallel to a Diesel engine, expressed in mass fraction difference. One of the pipes is regular, while the other one is novel. The difference in mass fraction between the two size distributions shows a decrease (negative values) in the amount of smaller particles at the expense of an increase (positive values) in the amount of the larger ones due to grouping and coagulation. This shift reduces the risk of the smaller smoke particles.

In the course of this paper we will briefly show the mathematical basis of the novel approach followed by calculation and experimental results, and concluding remarks.

2. The mathematical model, and results of calculations and measurements.

The model is detailed in Katoshevski et al., (2005, 2006, 2008, and 2010), while here we describe it in brief. The flow is characterized by standing wave form

$$U = U_a - U_b \cos(kx) \left[\sin(\omega t) + C\right]$$

(1)

where $U_a$ is the averaged velocity, $C$ is a constant, $U_b$ is the amplitude, $\omega$ is the angular velocity of the wave ($\omega = \frac{2\pi}{T}$ where $T$ is the wave period) and $k$ is the wave number ($k = \frac{2\pi}{L}$ where $L$ is the wave length). The constant $C$ is introduced in order to achieve the maximal and minimal velocity values at the areas of biggest and smallest diameter, correspondingly, and $C>1$ to fulfil that condition.

The equation of particle motion in dimensional form is:

$$\ddot{x} = \frac{1}{\tau_p} (U - \dot{x})$$

(2)
where $x$ is the particle location and 
\[ \tau_p = \frac{1}{18} \frac{\rho_p D_p^2}{\mu}, \]
\( \rho_p \) is the particle density, \( D_p \) is the particle diameter, and \( \mu \) is the viscosity of the host gas.

Substituting the velocity field (Eq. 1) into the particle equation of motion (Eq. 2) leads to the following,

\[ \ddot{x} + \frac{1}{\tau_p} \dot{x} + \frac{U_b}{\tau_p} \cos(\omega t) \left[ \sin(\omega t) + C \right] = \frac{U_a}{\tau_p} \]  

(3)

This equation allows us to calculate the trajectories of the particles and assess their grouping tendency. More details on the mathematical analysis are presented in the studies by Katoshevski et al., (2005, 2006, 2008, and 2010). The particles that are exposed to the above flow-field which admits oscillations and downstream velocity variations may tend to group and to coagulate as a function of the flow and particle characteristics. The calculations may show grouping, such as presented in Fig. 3. The figure shows examples of trajectories, for several particles which are initially (at Time=0) evenly spread along a line. With time two groups are formed. It is important to note that the above mentioned studies have shown that qualitatively similar behaviour is expected when the flow has a moving wave characteristics rather than a standing wave.

The grouping behavior which is described in the calculation shown in Fig. 3 is classified as "stable grouping" which is one of the three grouping-modes identified by using this approach. These modes include: 1) Stable grouping, II) Weak Grouping, and III) Non-Grouping. Hence, the first mode of behaviour, "Mode I" is characterized by the formation of particle groups and a subsequently stable conjoint motion. This mode is denoted here as stable grouping. "Mode II" stands for weak grouping, in which temporarily joined particles shift from one group to the other or groups break up. In contrast "Mode III" defines a clear non-grouping situation where there is very little tendency, if any, to aggregate. As grouping is associated with conditions, such as the host-flow velocity, the frequency of the oscillations as well as particle size, we may say that in certain range of conditions we expect to observe one of these modes. In most realistic cases, such as the cases, the two first modes will be observed.

Figure 3. An example for particle trajectory calculation, showing the formation of two groups. Each particle has a different initial position (at t=0). In case where coagulation takes place, as in Diesel engines, the groups form larger particles, which are less harmful for the health and the environment. The desire is to control grouping by flow manipulation according to the mathematical model.
The mathematical analysis reveals regimes in terms of the operating conditions, in which stable grouping is expected (Katoshevski, 2006). We take advantage of that and use it to the design a special exhaust pipe for Diesel engines which promote grouping. This grouping causes coagulation and reduce the number of the smaller smoke particles which are the most dangerous ones, both to the health and to the environment. Also, as is well known, the larger particles impose less health risk. The special exhaust pipe was compared in the lab to the regular one, and recent results where already presented in Fig. 2. The same results can be represented in terms of the change in percentage of the amount of particles rather than in terms of mass fraction, and this representation is striking as shown in Table 1. These measurements and way of representation are new. A dramatic decrease in the smaller and most harmful particles is observed. Similar results were recently obtained for a variety of engine operating conditions, that is, several RPMs and different engine loads.

Table 1. Particle mass-fraction changes in percentage, in terms of particle diameter for both pipes. This corresponds to the measurement of particle size-distributions, shown in Fig. 2. A reduction in the amount of the smaller particles and hence in the air pollution risk from Diesel-based transportation is clear when applying this new method.

| Dp [μ]     | Changes in % |
|------------|--------------|
| 0.3 -0.39  | -43.23       |
| 0.4 -0.49  | -41.25       |
| 0.5 -0.64  | -38.55       |
| 0.65 -0.79 | -39.35       |
| 0.8 -0.99  | 3.24         |
| 1.0 -1.59  | 49.45        |
| 1.6 -1.99  | 100.98       |
| 2          | 181.68       |

3. Concluding Remarks

The sub-micron smoke-particles which are emitted from vehicles and especially from Diesel-based ones impose a great risk to the health and the environment. As the particles are larger they are less harmful. The new concept which is presented here, and that is based on both a mathematical model as well as experiments leads to a shift in the size distribution by particle grouping and coagulation. Hence, the mathematical model can serve as a tool for designing a desirable exhaust system. Designing the novel exhaust-system for Diesel cars, trucks and public transportation may certainly lead to a dramatic reduce of the risk for the health and the environment, associated with smoke-particles emitted by transportation.

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