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Review article

Controlling nanoparticles emission with particle-grouping exhaust-pipe

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ABSTRACT

An experimental study is presented, which assesses the capability of a novel concept of particle-grouping technique in reducing the emission of nano-particles from transportation systems. This size-class of emitted particles is known to be both more harmful for the health than the larger particles and far more difficult to manipulate, yet, as described here, the grouping concept leads to their elimination to some extent, by promoting their coagulation with particles in their vicinity. This is achieved with a "grouping exhaust" system that is designed to form a specific oscillating flow according to a mathematical model for each engine, based on engine characteristics [FUEL, 2010, 89:2411-2416]. The system has shown previously to be efficient with respect to micron-sized particles while here the focus is on the nano-particles, showing its efficiency in reducing the number of those particles for both diesel as well as gasoline engines and at a wide range of operating conditions.

Contents

1. Introduction

The health effects, caused by exposure to particulate matter (PM) emitted from internal combustion engines, are well known and well-studied over the last 2 decades. Human epidemiological and medical studies have pointed out a clear connection between asthma, lung cancer and mortality, and particulate matter exposure [1]. Based on research made by the International Agency for Research on Cancer [2], the World Health Organization (WHO) classified Diesel engine exhaust particles as carcinogenic to humans (group 1). However, the health effects caused by exposure to particles are not uniquely related to Diesel but also to gasoline engines.

Of increasing concern are the health effects caused specifically by nano-size particle-emissions. These are particles less than 100 nm in size. They are mostly made of hydrocarbons and sulfates that are generated by nucleation in the combustion zone or in the afterburning phase where the emitted gases are diluted and cooled [3]. The nano-size particle weight is only 1–20% of the total particle mass while in number their percentage may be more than 90%. Due to their small size, their residence time in the air is much longer and so is the human exposure to these harmful particles.

In urban areas, the major contributor of nano-size particles to the atmosphere are internal combustion engines [4]. The nano-size particles emitted from vehicle exhausts might penetrate the

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respiratory system, diffuse to the blood stream, and then be conveyed to the brain. Those particles and their products can trigger oxidative stress, toxicity and inflammation in brain tissue [5].

Over the last years a number of attempts have been made to suppress the formation rate of particles inside the cylinder and to reduce the emitted particle mass with after-treatment devices. The DPF (Diesel Particulate Filters) is one of the most efficient after-treatment devices for micron scale particulate matter. The DPFs, especially the wall flow filters were proven to be very efficient in controlling and reducing micro-size particulate matter [6]. Using finer filters to capture the smaller particles, in particular in the nano-size, may lead to higher engine back pressure thus requires more complex by their structure to avoid backpressure and keep high performances thus they are expensive DPFs. For this reason, there is a strong desire for new technologies and new means to reduce the number of nano-size particles emitted from vehicles.

A promising method, Grouping, recently developed by Katoshevski and co-workers [7–11], induces clustering and coagulation of particles leading to a significant reduction in particle number and increasing particle size as illustrated in Fig. 1, thus allowing the use of simple effective DPFs. This approach is employed in the present study. The clustering is governed mainly by manipulating the characteristics of the flow velocity along the pipe by its geometry. The pipe geometry design was based on the method presented by Katoshevski et al. [11].

The trajectories of nano-size particles of up to the order of 20 nm are dominated by Brownian motion and cannot be easily manipulated by flow control. However, our calculations [10] have shown that the grouping effect is noticed from around the size of 50 nm and larger, hence it is expected that up to around 1000 nm a combined effect of grouping and Brownian motion will be noticeable. While coagulation occurs due to interaction forces between particles such as Van Der Walls, electrostatic and capillary forces [12], the combined effect is expected to increase the probability of coagulation especially when a nano-size particle is in the vicinity of a larger particle. Soot emission which is one of the major pollutants emitted from exhaust systems, is a good example of such nano and submicron size particles interaction. In this case due to its fractal-like shape and the sintering of the soot, its clusters contain thousands of nano-size spherules in a size range of 15–20 nm [13]. The grouping, followed by coagulation ends up with a dramatic decrease in particle number [11] which is also a stringent requirement of the new Euro-6 regulations.

These arguments and new regulations lead us to the current study which is an extended investigation of the grouping potential as presented in Ref. [11], in which a Diesel engine was coupled to an engine dynamometer, tested under steady engine speed and load conditions, and particles in the range of 0.35–2 μm were recorded. In the present study we have recorded nano and micro-size particles with sizes ranging between 10 nm and 2.4 μm as emitted from SI (Spark Ignition) and CI (Compression Ignition) engines. This time we not only focus on the nano scale but also examine the effect of transient conditions, and along a standard driving cycle with transient load and engine speed.

The mathematical representation of the grouping phenomenon has been presented in detailed in Refs. [10,11]. It was found that the grouping extent is dominated by two non-dimensional parameters α (that include the root of Stokes number and the dimensionless amplitude velocity), and β (the ratio between the dimensionless average velocity and the dimensionless amplitude velocity). The mean velocity of the gas flow, its amplitude, oscillation frequency, wave-length and Stokes number have thus been found the more important parameters that affect the grouping phenomenon.

2. Experimental setup

Four types of engines under different running conditions were tested: (1) A Ford transit 2L Diesel engine coupled to an engine dynamometer was examined under steady and transient conditions, (2) A heavy-duty MAN 10L vehicle installed with a Diesel engine was mounted on a chassis dynamometer under steady conditions, (3) A light-duty Peugeot 1.5L vehicle with a gasoline engine was investigated with a chassis dynamometer under steady-state conditions and (4) A light-duty Citroen 1.5L vehicle with a gasoline direct injection engine with a roller chassis dynamometer under a standard driving cycle. The basic data of each engine is presented in Table 1.

For each engine we have designed a specific particle-grouping exhaust-pipe according to its parameters. These include exhaust gas mass flow-rate, range of engine speed, the valves timing, and other relevant data. The parameters were introduced into the mathematical model [11], to optimize the pipe dimensions. The dimensionless parameter α (see above) was found to be the more influential parameter.

The present study is an extended study of the grouping potential as presented in Ref. [11], in which a Diesel engine was coupled to an engine dynamometer, tested under steady engine speed and load conditions, and particles in the range of 0.35–2 μm were recorded. In the present study, as already mentioned, we have

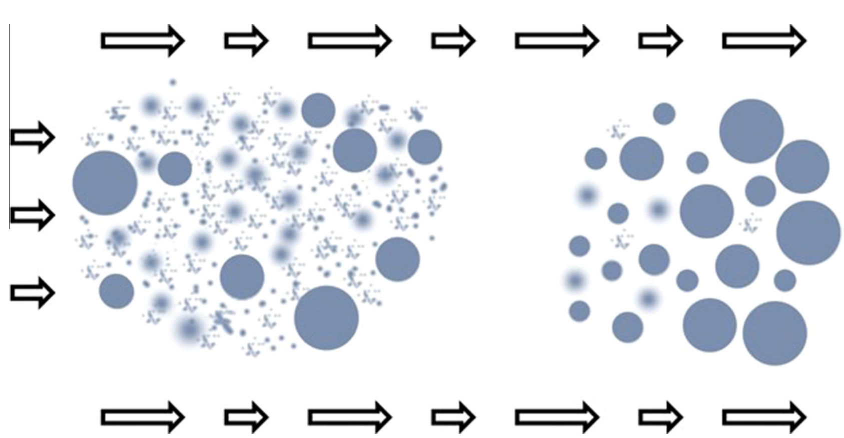

Fig. 1. Particles with various diameters in the presence of an oscillating flow with downstream variation causing clustering and coagulation.