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Review article

A literature research about particle emissions from engines with direct gasoline injection and the potential to reduce these emissions

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ABSTRACT

With the growing proliferation of direct injection, particulate emissions from gasoline engines have become a focus of exhaust emission legislation and research. A key focus is on considering the health effects of particles and their accumulated components, such as polycyclic aromatic hydrocarbons (PAH). In addition to the formation mechanisms and measurement methods, which are based on investigating diesel engine emissions, the morphological and chemical properties are also being examined. The measurement technique and investigation to reduce particulate emissions of diesel engines are advanced. The compliance of these researches to gasoline engines is arguable.

Latest gasoline combustion concepts already ensure a very low particulate emission level. Especially fuel design holds a big potential for further improvements.

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Contents

1. Introduction

The ideal chemical reaction of fuel in the combustion chamber produces carbon dioxide and water. However, as a result of the transient combustion processes, the following additional combustion products are also created: unburned hydrocarbons (HC), carbon monoxide (CO), soot, atmospheric nitrogen oxides (NO_x),

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polycyclic aromatic hydrocarbons (PAH), and if the fuel contains sulphur or heavy metals, their oxides [1].

1.1. Combustion concept

With regard to the combustion process, a distinction is made between diesel, gasoline and gas engines. Diesel and gasoline engines are combustion engines with significant differences.

Diesel engines work with an internal mixture formation with high injection pressure >2000 bars and are usually charged. It has been known for many years that diesel engines with internal mixture formation cause particulate emissions.

Gasoline engines are operated with internal or external mixture formation and either naturally aspirated or charged. To improve performance and fuel consumption direct injection with up to 200 bars has been established. Due to the internal mixture formation and the partially diffusive combustion, the direct injection gasoline engine (DI gasoline engine) also emits particles. The particle number emissions are 80% lower than for a diesel engine without a Diesel Particulate Filter (DPF).

Like gasoline engines, gas engines also work with internal and external mixture formation; depending on the basic engine, ignition is via spark ignition or self-ignition [2,3].

1.2. Legislation

As a result of the legislation adopted by the EU, the permissible particulate matter mass for diesel engines have been reduced from 0.14 g/km (EU1) to 0.005 g/km (EU6). There has been a particulate matter mass limit for all gasoline engines since EU5 which is 0.005 g/km. When the limit for the particle number emissions for diesel engines was introduced, it was defined at 6.0×10^{11} #/km. For DI gasoline engines, the EU6-limit is now 6.0×10^{12} #/km and will presumably be tightened to 6.0×10^{11} #/km [4].

Scientific studies on particulate emissions (particulate mass and -number) for DI gasoline engines and their reduction have been undertaken with the breakthrough of this technology and the expected EU6-limits.

To obtain an initial overview of the current literature, results for particulate emissions from DI gasoline engines have been summarised and compared [5].

The research for this was based on publications from database analysis, technical books, dissertations, SAE papers, as well as contributions to periodicals and conferences.

2. Scientific studies and findings

2.1. Introduction to the DI gasoline engine

Many studies aim at investigating the formation of particles, their mass and number refer to diesel engines [6]. The development of the DI gasoline engine was driven by the increased demand for vehicles with lower fuel consumption. In comparison to the gasoline engine with port-fuel injection (PFI), the DI gasoline engine demonstrates fuel consumption benefits of approx. 5–10% [7], meaning that it emits less CO_2 and reaches a higher specific output, especially in the lower engine speed range [8]. However, under standard conditions, more particles are emitted as a result of the incomplete combustion [8,9]. From an analytical perspective, under standard conditions these particles are treated in the same way as diesel particles [10] but there are differences in concentration, size, morphology and chemical composition [11,12].

2.2. Health background

Previous studies on the health aspects of particulate emissions are based on the emissions from diesel engines [13–15] and have limited significance when it comes to gasoline engine particulate emissions. However, since 2012, diesel particles have been classified as carcinogenic [16]. The statement made by the European Research Group on Environment and Health in the Transport Sector (EUGT) doubts whether the underlying studies are up-to-date [13]. This highlights the importance of studies to be conducted on modern engines.

There are critical aspects that should be included in the health considerations: the half-life in the lung, the toxicity [10,17], the penetration depth [15] and secretion of the nanoparticles into the respiratory system [18]. The studies of Seaton et al. show that the alveolar particles ($PM_{2.5}$) are more dangerous to the human respiratory system than larger particles (PM_{10}) due to their deeper penetration depth [19]. The nanoparticles reach the alveoli, where the self-cleaning process by macrophages fails [20]. Further studies show that the particle surface and the chemical properties are more relevant than the mass [21]. In particular, those "substances, such as hydrocarbons [...], fuels and lubricants [...] and sulphates [...] accumulated" on the particles create a health risk [8]. With regard to the particles, the "aerodynamic and/or thermodynamic properties [decide] on how and where they are deposited in the respiratory tract [...], while the physical–chemical and biological properties of the particles determine their interactions with the cells" [22]. According to Filser et al. [23], the most important substances for the human health found in the exhaust gas from diesel engines include PAH and nitrated polycyclic aromatic hydrocarbons (nitro-PAH). The lead compound Benzo(a)pyren (BaP) is used as an indicator for PAHs [24].

There are many studies that examine the health aspects of diesel engines, and equally numerous investigations in relation to the particulate emissions.

2.3. Particle formation mechanisms

Particles "occur [...] during the combustion of fuel in the combustion chamber [and] [...] through nucleation of supersaturated vapours in the exhaust gas after-treatment system" [25].

The formation process in the combustion chamber is described by six processes: pyrolysis, nucleation, surface growth, coalescence, agglomeration and oxidation [26,27]. There are various hypotheses for these processes. These include the propargyl radical hypothesis (according to Glovitvhev) [28], the polycycle hypothesis (according to Bockhorn) [29], the radical hypothesis (according to Siegmann) [10], the elementary carbon hypothesis [30], the largely accepted acetylene hypothesis [10,28,26,31] and a formation because of sticking of polycyclic aromatic hydrocarbons (PAH) [32]. These theories are based on studies of diesel engines and, due to the similar particle number and morphology [33] of gasoline and diesel engines under increasing load and fuel enrichment, are transferred to the DI gasoline engine [10].

During thermal pyrolysis, the higher molecular hydrocarbons decompose into small unsaturated hydrocarbons, such as acetylene and butadiene [34]. This reaction is a dehydration with a high activation energy. The oxidative pyrolysis, in which the decomposition reactions take place using oxygen and hydroxide, happens at approximately 1900–2300 K and under lack of oxygen [28]. With regard to particle formation, new particles are created. During this polymerisation the primary particles (5–30 nm) grow into spheres. After temperature peaks have faded out, the nucleation particles coagulate into bunches of particles (70–100 nm). This phase of the nucleation can be heterogeneous or homogeneous [25]. Surface growth and spatial growth through PAH [35] as well as further coagulation increase the particle volume [25]. Particles age and become more viscous, meaning that they no longer coagulate but stick together [28].

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