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Particulate matter emission characteristics of diesel engines with biodiesel or biodiesel blending: A review

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ABSTRACT

A pursuit of environment conservation as well as a fluctuated rise in diesel price has moved worldwide interests towards biodiesel, a kind of clean and renewable alternative fuel for the diesel engines. However, owing to heterogeneous mixing between the air and fuel, particle matter(PM) emissions have always been a main concern in the development of the diesel engines, especially in the face of continuously updated and progressively stringent PM emission regulation. Therefore, this paper sorts out and analyzes the studies published chiefly in scientific journals about particle matter emissions of the diesel engines used biodiesel or biodiesel/diesel blends as fuels compared with those from the traditional diesel fuels. The paper mainly includes the following sections. The first section deals with the fundamentals of particle matters from the biodiesel combustion including particle composition, physical and chemical properties. In the next, particle formation mechanism as well as PAH formation is introduced briefly. The effects of biodiesel property on particle emission are discussed in the third section. Then, the effects of operating parameters of the engines on PM emissions have been analyzed in the fourth section. After that, the influences of biodiesel blending on diesel particulate filter (DPF) and radiocarbon (^{14}C) analysis of biodiesel particles have been reviewed. At last, general conclusions are summarized and further research targets are proposed in this paper.

Contents

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1. Introduction

The earliest use of biodiesel can be traced back to the time Rudolph Diesel used biodiesel to fuel his early prototype diesel engine in 1900. After that, the use of biodiesel has waned because of some regulatory and political factors. However, the use of biodiesel rises again. This renewed interest is rooted from the points of its renewal origin, its decreased mutagenicity and its potential environmental benefits as compared with those of the conventional diesel [1–6]. But it is critical to the application of biodiesel that even the highly-refined oil is not suitable for the direct use in modern diesel engines unless the fuel properties are much more similar to diesel. Now biodiesel is commonly a kind of vegetable oil- or animal fat-based diesel fuel containing the long-chain fatty acid alkyl esters, and is produced typically through the chemical reaction of lipids and alcohol in the presence of the catalyst [7–9]. In the diesel engines, biodiesel can be used alone, or blended with diesel in any proportions. When using the blend of biodiesel and diesel as the vehicle alternative fuels, a blend of x% biodiesel and $(1-x)$% pure diesel on volumetric basis is conventionally called Bx. For example, B20 is a blend of 20% biodiesel and 80% pure diesel on volumetric basis.

Particle matter(PM) emissions produced from the diesel engines have been always the main concern to engine manufactures because they affect the performance of the engines and ambient environment. Particles are perhaps related to deposit formation in the combustion chamber, fouling of the exhaust gas recirculation (EGR) and increased wear when they are re-circulated to the engine with EGR [10]. However, the main concerns about particles are focused on the environmental perspectives: decreased visibility, adverse health effect and soiling of buildings. Because particles from the compression-ignition diesel engine are usually formed in a quite complex aerosol system, despite plenty of basic researches, neither the formation of PM in the compression-ignition diesel engine, nor its physical and chemical properties or effects on human health are completely understood now. Especially in the last decade, the increasing use of biomass derived fuels such as biodiesel adds another attention to the particle problem. Therefore, this paper aims to analyze and summary the recent studies on particle matter emissions from the diesel engines used biodiesel or biodiesel-diesel blend as fuel. Meanwhile, further research works are suggested in this paper.

2. Fundamental chemical and physical characteristics of particle matters

2.1. Chemical compositions

In EPA (Environmental Protection Agency) report, PM is defined as the particle-phase compounds emitted in the diesel engine [5]. The diesel particles typically consist of elemental carbon (EC), organic carbon (OC) and small amounts of sulfate, trace elements, nitrate, water, and unknown components [11]. In general, the chemical composition of PM plays a key role in its impacts on health and environment.

PM universally contains a large fraction of carbonaceous elements, which are also divided into EC and OC [12]. EC is the carbon that has undergone pyrolysis and contains only carbon atoms in pure form [11]. OC is the molecules containing C– and H– emitted from the diesel engine as the result of unburned fuel and lubricating oil [11], and it contains oxygen, sulfur, nitrogen, and small quantities of other elements. Both OC and EC contribute to the toxicity of PM and also contribute to regional haze and climate change. According to the reports on EC and OC in PM sample, the ratio of OC to EC is elevated for the biodiesel combustion, and this ratio increases with a rise of the biodiesel content in blend because the oxygenic property of biodiesel plays a great role in the soot generation and oxidation. However, the variation trend of OC and EC emission for biodiesel operation is inconsistent in recent literatures [13–16]. Chuepeng et al. [13] observed that the OC fraction for B30 operation was greater than that for ULSD operation regardless of the engine working condition. Williams et al. [14] found that the OC/EC ratio followed a trend of B100 > B20 > diesel, indicating that OC content became higher with a rise of biodiesel content. Chueng et al. [15] also reported that EC fraction in PM sample for SME biodiesel operation was lower than that for diesel operation in the light-duty vehicle; whereas OC fraction in PM sample for both biodiesel and diesel operation seemed similar during New European Driving Cycle. Song et al. [16] found that EC and OC for cottonseed oil operation at all driving modes decreased. Furthermore, EC emission increased with a rise of load at all speeds, and the lowest EC emissions appeared at the middle speed; whereas OC emission did not change as much as EC. The reason for such discrepancy among the OC and EC emissions of the various experiments is perhaps related with the operating condition, test method and fuel property.

At a relatively higher combustion temperature, fuel sulfur is converted to sulfur dioxide, then to sulfur trioxide, and finally to sulfuric acid in the presence of water [17]. Although little research is concerned about the sulfate emission for biodiesel operation, the existing knowledge indicates that the sulfate emission for biodiesel operation is higher than that of diesel. Shah et al. [18] proposed the oxygen enrichment in biodiesel contributed to the oxidization of the available traces of sulfur and SO_2 formation, and then SO_2 further took actively part in promoting the inorganic or heterogeneous nucleation. Therefore, relatively higher sulfate emission for biodiesel operation is regarded as an outcome of sulfate nano-particles generated during the nucleation process.

Although trace metal emissions are very low, they are detrimental to human health because of their toxic potential. The trace metal emissions come largely from the lubricating oil, fuel, additives and detergents. It was also accepted that higher metal content in fuel usually leads to higher metal content in the particle emissions. Now there are only a few literatures about the particulate-bound metals in biodiesel. Dwivedi et al. [19] found that the concentration of metals like Cr, Fe, Al, Zn, Mg increased while others like Pb, Cd, Na, Ni decreased when using B20 as the fuel. Cheung et al. [15] observed higher concentrations of Fe, Zn, Mg, but lower concentrations of Cr, Al, Pb, Cd, Na, Ni in particles from the SME biodiesel combustion when compared to that for diesel combustion. In the above studies, the particulate-bound trace metal emissions were chiefly attributed to the lubricating oil and fuel compositions as well as the engine wear. Betha et al. [20] observed that As, Co, Al, Mn were in higher concentrations for ULSD operation, while Cr, Cu, Fe, Ba, Zn, Mg, Ni, and K were in