Renewable and Sustainable Energy Reviews 80 (2017) 1227–1238

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Particulate matter formation and its control methodologies for diesel engine: A comprehensive review

S. Mohankumar[a,*], P. Senthilkumar[b]

[a] Department of Automobile Engineering,Banari Amman Institute of Technology, Sathyamanglam, Erode 630401, India
[b] Madras Institute of Technology, Department of Automobile Engineering, Chennai-44, India

ARTICLE INFO

Keywords:
Biodiesel
Water emulsified fuel
Particulate matter
Diesel particulate filter

ABSTRACT

The diesel engine is being widely used in day to day life in both mobile and stationary applications. The main drawback is the release of harmful gasses like HC, CO, NO_x and particulate matter into the atmosphere. This affects both human beings and environment to a great extent and should be controlled effectively. This paper reviews the works on the control of diesel particulate matter in both pre-combustion and post-combustion techniques employed in the past few decades. The initial part of this review will discuss particulate matter composition and its structure. Then the various physical processes involved in the formation of particulate matter are discussed. Effects of fuel composition and its structure on soot formation are reported. Hazardous effects of particulate matter on both human beings and the environment are reviewed. Use of biodiesel water emulsified fuel as a fuel to control soot formation is highlighted. This review also highlights control of particulate matter by varying injection parameters like injection pressure, injection timing and auxiliary air injection. Multiple fuel injections within the same cycle to control NOx and particulate matter are also discussed. The conventional control technique of particulate matter by using Diesel particulate filter and its types are also compared with the new technologies. Various regeneration concepts to burn the collected soot are also highlighted. The major part of this review focuses on pre-combustion techniques to control particulate matter. This review paper, it is hoped, will be very useful for the researchers working on the control of diesel particulate matter.

1. Introduction

The diesel engine is an efficient power source. It is widely used in ground transportation and commercial applications. In spite of its popularity, diesel engines have the major drawbacks of high NOx and particulate emissions; this continues to be a matter of great concern and has to be paid serious attention. Extensive research has been carried out in recent years to control these emissions. Many pre-combustion and post-combustion technologies are implemented to control these emissions. This paper reviews the various control measures available for particulate matter emission in both pre-combustion and post-combustion stages. In pre-combustion several experiments conducted so far have concluded that it is possible to eliminate particulate matter formation within the cylinder chamber during early stages of combustion. This is accomplished by using contemporary injectors with oxygenated fuels or through the use of very small orifices. High injection pressure systems like common rail direct ignition (CRDI) system is used to control soot emission and improve fuel economy. Multiple injections within the single cycle are also a leading technology used to reduce NOx and particulate matter emission simultaneously. Variation of several injection parameters can be made possible with the help of electronic fuel injection technology.

As stated earlier, the initial part of this review deals with particulate matter and its composition. The various substances present in the particulate matter and their methods of separation are studied. The various physical processes involved in the soot formation are explained elaborately. Hazardous effects related to the particulate matter on both human beings and environmental issues are investigated. The second part of this review studies the effect of fuel structure and fuel composition on soot formation. The third part of this review concentrates on the use of oxygenated fuels and other fuel modifications to control particulate emission. The influence of injection parameters on PM emission is also highlighted in this section. The final part highlights the various post-combustion technologies like diesel particulate filter, diesel oxidation catalyst, and catalyzed diesel particulate filter to control DPM. This review discusses and summarizes the developments carried out in the last decade to control particulate matter in compression ignition engines providing a more current and relevant

* Corresponding author.
E-mail address: smkmts@gmail.com (S. Mohankumar).

http://dx.doi.org/10.1016/j.rser.2017.05.133
Received 14 June 2016; Received in revised form 11 May 2017; Accepted 19 May 2017
1364-0321/

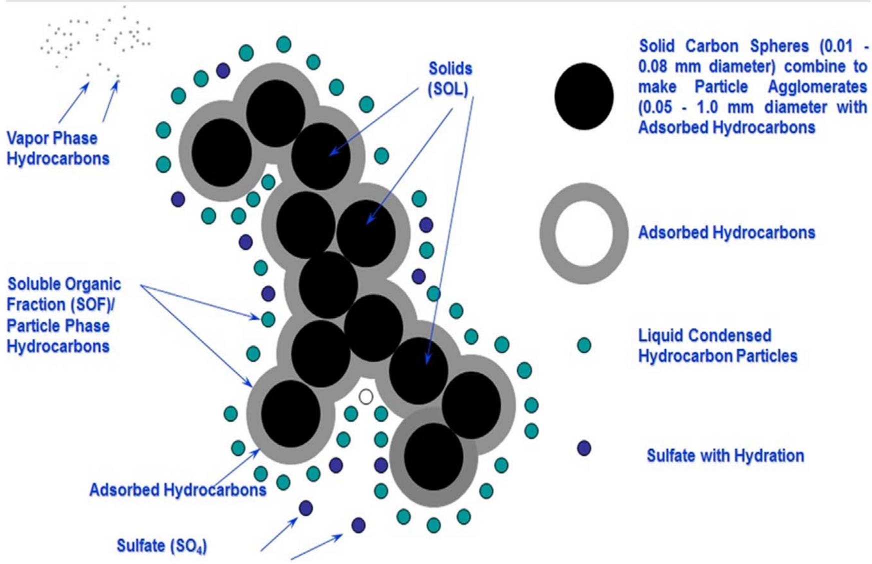

Fig. 1. Schematic representation of Particulate Matter.

view.

2. Particulate matter

2.1. Particulate matter composition

Particulate matter is the combination of soot and other liquid, solid phase materials. Particulate matter can be separated into a soluble and insoluble organic fraction. Soot formation usually takes place in fuel rich regions at elevated temperature without sufficient oxygen concentration. Liquid phase materials and hydrocarbons are absorbed on the surface of soot, depending on engine operating conditions and is shown in Fig. 1. Nearly 50% of PM is composed of soot. Soluble fraction present in particulates mainly consists of aldehydes, alkanes, alkenes, aliphatic hydrocarbons, PAH's and its derivatives. Various other constituents like lubricating oil, partially oxidized fuel and oil also contribute to a soluble organic fraction in the particulate matter [1].

Most of the particulate formed is in a size range from 7.5 to 1.0 µm [2]. This size factor is considered as an important factor in health aspects. Tiny particles are likely to be inhaled by human beings easily. They also get trapped in the bronchial passages and alveoli of the lungs. About 90% of the particulates emitted from the engine are in size range (< 50 nm). Most of the particulate mass lies in the accumulation mode range that is 50 nm < D < 1000 nm [3]. Soot formation usually takes place in the diesel engine at a temperature between about 1000 and 2800 K, at a pressure of 50–100 atm. The soluble organic fraction can be extracted from the particulate matter samples by adopting soxhlet and sonification methods. Since the particulates are mixtures of polar and non-polar components, full extraction requires different solvents. Methylene chloride, dichloromethane, and benzene-alcohol mixture are the most commonly used extractants to remove soluble organic fraction and soot.

2.2. Physical process of soot formation

Conversion of liquid phase hydrocarbons to soot and finally to gas phase happens in six steps, namely pyrolysis, nucleation, surface growth, coalescence, agglomeration, and oxidation. The overall process is shown in Fig. 2 schematically. The physical process of soot formation depends on various conditions like pressure, temperature, injection parameters and fuel structure. Soot formation and oxidation rate depend mainly on temperature and pressure of reaction [4].

2.3. Pyrolysis

Pyrolysis is the process in which organic compounds such as fuels undergo a change in the molecular structure at high temperature without sufficient oxygen concentration. These reactions are mainly dependent on temperature and concentration and are generally endothermic [5]. Fuel pyrolysis paves the way to the formation of peculiar species generally mentioned as precursors or building blocks for soot. Depending upon the type of flames produced pyrolysis and oxidation rate vary. Premixed flames produce less soot since it contains more oxygen content, whereas in diffusion flame soot formation rate increases due to less oxygen content. Oxidation rate increases when the temperature increases. This scenario clearly concludes that soot formation mainly depends upon the temperature and oxygen concentration. Some previous works have suggested that the presence of O, O_2, and OH radicals stimulate pyrolysis. This process occurs since free radical mechanism takes place in many of the reactions [5]. Unsaturated hydrocarbons, polyacetylenes, and polycyclic aromatic hydrocarbons (PAH's) are typical pyrolysis products. Among all the products formed acetylene plays a major role in pyrolysis reactions Acetylene can be easily oxidized to inert products if enough O and OH radicals are present in fuel [5]. Molecule size plays a major role; the radical pool size gets increased for larger molecules [6]. A study carried out by Haynes et al. [7] concluded that C_2H_2, C_2H_4, CH_4, C_3H_6, and C_6H_6 Considered as major products produced during pyrolysis in laminar diffusion flames.

2.4. Nucleation

Nucleation is the process in which particles are formed from gas phase reactants. As for the sizes of the nuclei formed in luminous flame, they initially have a diameter in the range of 1.5–2 nm [8]. Smith et al. had concluded from various previous studies that the initial number of soot nuclei in a diesel cylinder amounted to 250 nuclei per cubic micrometer (at a pressure of 6.5 MPa) [8]. In this process by radical addition of small size hydrocarbons, they combine to form large size aromatic molecules by particle inception process. This process usually takes place at temperatures in the range of 1300–1600 K. Particle nuclei formed has less contribution towards total soot mass, but it has a greater influence on the mass added later since they provide active sites for surface growth. Premixed and diffusion flame nucleation is restricted near the primary reaction zone in which temperature and ion concentration are higher. In one previous study concluded that soot