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Combustion and Gasification Collection of Diesel Soot by Means of Microwave Heating

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Abstract: The experiment of integrated purification of diesel soot was made by means of microwave heating. The experiment includes combustion and gasification collection. The catalytic effect of ceramic carrier was used in the combustion process. In order to improve the purification efficiency of $PM_{2.5}$ particles, the surfactants were used in gasification collection. The model of computer control was set up so that the purification course could be controlled. The experimental principle was analyzed. Experiment result indicated that the diesel soot purifying efficiency is more than 90 %. The purification efficiency can be improved further by the optimization design of experimental device. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Diesel soot, $PM_{2.5}$ particle, Microwave heating, Combustion, gasification collection.

1. Introduction

$PM_{2.5}$ is suspended in the air, whose aerodynamic equivalent diameter is equal to or less than 2.5 µm particles. The haze weather is caused by PM particles and the decline of air quality is the results of natural factors and human activities. Combustion emissions account for over half of the fine particle ($PM_{2.5}$) air pollution and most of the primary particulate organic matter. Human exposure to combustion emissions including the associated airborne fine particles and mutagenic and carcinogenic constituents (e.g., polycyclic aromatic compounds (PAC), nitro-(PAC) have been studied in populations in Europe, America, Asia, and increasingly in third-world counties. Bioassay-directed fractionation studies of particulate organic air pollution have identified mutagenic and carcinogenic polycyclic aromatic hydrocarbons (PAH), nitrated PAH, nitro-lactones, and lower molecular weight compounds from cooking. A number of these components are significant sources of human exposure to mutagenic and carcinogenic chemicals that may also cause oxidative and DNA damage that can lead to reproductive and cardiovascular effects [1].

Source apportionment results showed that secondary components were the largest mass contributor of $PM_{2.5}$, accounting for 28 %; whereas soil-related sources were the largest contributor of $PM_{2.5-10}$, explaining about 49 % of the total mass during 2005-2007 in the juncture belt between urban and rural areas of Beijing [2]. The long-term monitoring data of elements in Beijing, ions, and black carbon showed that the major constituents of $PM_{2.5}$ were black carbon (BC) crustal elements, nitrates, ammonium salts, and sulfates. These five major components accounted for 20 %–80 % of the total $PM_{2.5}$. During this period, levels of Pb and S in PM remained rather high, as compared with the levels in other large cities in the world [3]. It is reported that the highest contributors to $PM_{2.5}$ were organic carbon (OC), nitrate, and sulfate in haze days in Guangzhou, OC/EC (elemental carbon) ratio is ranged from 2.8 to 6.2 with an average of 4.7 and the estimation on a minimum OC/EC ratio showed that secondary organic carbon accounted more than 36.6 % for the total organic carbon [4]. Researches showed that the EC came from automobile exhaust (about 50 %), coal combustion (about 15 %), cooking gas (about 10 %) and so on [5, 6]. SONG presented comparison of soot nano-structures of particulates produced from two different fuels (an ultra low sulfur diesel fuel and its B20 blend) on commercial direct injection diesel engine by means of high resolution electron microscopy imaging. This crystalline information such as the graphene layer size and orientation is used to interpret the quantitative reactivity difference measured in an idealized oxidation experiment [7]. SHI pointed that the comparative study was made on OC and EC emissions of diesel particulates between diesel and bio-diesel fuel in which the carbon composition of $PM_{2.5}$ emissions has little difference in percentage [8].

In order to adapt to the haze weather control requirements, the purification technology of diesel soot has received development. NEEFT explained that filters for collecting particulates from diesel exhaust gases would be examined in more detail and after treatment control systems for particulate removal would be reviewed. These could be divided into (i) non-catalytic filter based systems which used burners and electric heaters to burn the soot once it had been collected on the filter; (ii) catalytic filter-based systems which consisted of filters with a catalyst coating, or filters used in combination with catalytically active precursor compounds added to the diesel fuel; and (iii) catalytic non-filter-based systems in which gaseous hydro-carbons, carbon monoxide and part of the hydro-carbon fraction of the particulates were oxidized in the exhaust gases. Finally, recent trends in diesel particulate emission control would be discussed, indicating the growing importance of the catalytic solutions: the fast introduction of non-filter-based catalysts for diesel engines and the possible application of filters in combination with catalytically active precursor compounds added to diesel fuel [9]. ZHU proposed a novel approach of $PM_{2.5}$ removal through a temperature swing array of waste-gas and waste-water multi-phase cross-flow, employing fields of velocity, temperature and concentration generated in gas phase by heat and mass transfer crossing water columns to drive micron-particle moving towards gas-liquid interfaces.

The total collection efficiency was 91.4 % as the model predicted, while the measured efficiency was slightly over 80 %. It was proven, both by theory and practice, this approach of "waste-employed waste treatment" is highly cost-effective [10]. ZHAO reported that under the microwave power of 420 W, $Mn(NO_3)_2$ can help to improve the simultaneous desulphurization and denitration efficiency up to 95 % [11]. MA confirmed that microwave induced catalysis combined with activated carbon adsorption and reduction can effectively reduce nitric oxide to nitrogen, sulfur dioxide to sulfur in the flue gas [12]. LI revealed that diesel soot is a material well suited for incineration by microwave heating. A 50 % burn-off of diesel soot could be achieved at an incident power of about 900 W [13]. SU investigated and compared the micro-structure and oxidation behaviour of soot from the raw exhaust of a Euro IV test heavy duty diesel engine to that of spark discharge soot and hexa-benzocoronene (HBC, $C_{42}H_{18}$), and find a micro-structure-controlled reactivity toward oxidation of all three samples in 5 % O_2 in N_2. The spark discharge soot with its fine primary particles and fullerenoid structure has an onset temperature of 423 K for combustion, while the hexabenzocoronene with its well-ordered crystallites has a high onset temperature of 773 K [14]. CHONG in his study, soot samples were prepared by combusting toluene, n-hexane, and de-cane under controlled conditions, and their hydrophilic properties, morphology, microstructure, content of volatile organic compounds, and functional groups were characterized. The hydrophilicity of n-hexane and decane flame soot increased with decreasing fuel/oxygen ratio, while it almost did not change for toluene flame soot. Fuel/oxygen ratio had little effect on the morphology of aggregates and the graphite crystallite size. The primary particle size and the content of volatile organic compounds on soot decreased with decreasing fuel/oxygen ratio [15]. ZHANG based on enlargement of fine particles by heterogeneous condensation of water vapor, removal of $PM_{2.5}$ from combustion was investigated experimentally, and the results show that vapor heterogeneous condensation combined with normal inertial dust separator can effectively remove $PM_{2.5}$ of which the removal efficiency can reach more than 80 % and 60 % from coal and oil combustion respectively [16]. YANG pointed out that there exist prospects in simultaneously removing $PM_{2.5}$ with high efficiency in wet flue gas desulphurization by the following ways: improving the operating conditions of wet flue gas desulphurization, achieving supersaturation of humid flue gas, addition of wetting agent, application of the material with low surface energy as substrate of $PM_{2.5}$ condensation growth chamber [17]. MA by the use of a microwave device and active carbon, 96 % of the carbon monoxide and sulfur dioxide can be directly decomposed into environment-friendly nitrogen as well as valuable and recoverable elementary sulfur. An analysis is the microwave-induced catalytic reduction-based desulfuration and denitration mechanism, pointing out that the microwave reduces the activation energy of the above-cited removal reactions. This indicates that the microwave not only promotes the process of reactions with its thermal effect but also gives full play to its catalytic action [18].

Provisions of soot emission standard in china are that the control of decarburization and $PM_{2.5}$ is stricter during the 12th five-year plan (2011-2015) period. At present the purification control of diesel soot has become a focal point of research. To meet the new decarburization and $PM_{2.5}$ control equipments further, we carry out the experimental study of combustion and gasification collection of diesel soot by means of microwave heating. We hope it is helpful to expand the governance capacity of the atmospheric $PM_{2.5}$ pollution.

2. Experimental Principle

2.1. Combustion Purification

Diesel soot is a general term of exhaust fumes and smoke suspended in the air with different particle size. The carbon particle size is at 20-50 nm after combustion, with the density of 1.89 g/cm^3. In the expansion stroke, the carbon particles aggregate and absorb hydrocarbons on its surface into PM particles. PM particles are making up of solid carbon, organic carbon and sulfate. For the emission of Diesel Engine PM, the main ingredient is carbon 300 nm. When the exhaust temperature is at 500°C, PM is basically carbon microsphere aggregates, called soot. When the exhaust temperature is low, the soot will absorb and aggregate a lot of organic compounds, known as soluble organic fraction. PM particulate emission of diesel is complex chain or flocculent and particle size is between 20-1000 nm, which belongs to the long-term suspension of submicron particles in the air. The size of Diesel engine PM particle is less than 50 nm and is particularly vulnerable to inhale into the lungs and cause serious health hazards.

Microwave is an electromagnetic wave. The wavelength is 1 mm-1 m and frequency 300-300,000 MHz. When microwave is used for purifying diesel soot, the microwave energy is converted into internal energy of the molecules which take place a chemical reaction. The microwave technology has been more mature such as electrode less discharge, getting pure plasma and high density. The chemical reaction can be carried out in a thermal non-equilibrium state, and overcome the mutual restriction between thermo-dynamic and kinetic factors. Many magnetic sub-stances such as transition metals and their com-pounds, activated carbon have strong capability to absorb microwave, which is used as a catalyst to induce or participate in chemical reactions. The basic principle of microwave induced catalysis is of high intensity and short pulse microwave gathered to contain some "sensitizers" (such as the ferromagnetic metal) solid catalyst bed surface which allows the interaction between some surface points and micro-wave energy strongly. Microwave energy is converted into heat energy, so some surface points selectively is heated quickly to a high temperature (more than 1200°C), induced by high-energy electron radiation, ozone oxidation, ultraviolet photolysis and non equilibrium plasma and other reactions. It can form the active oxidizing substances so that the diesel soot takes place chemical reaction.

The emissions control for diesel engine includes the catalytic oxidation and filtration and these methods can make HC, CO reduce 50 %, PM particles decrease 50-70 %. The diesel particulate filter has high filter efficiency of carbon, up to 60 %. In emission of diesel soot, HC, CO, NO, SO etc. is polar molecules. The polar molecules can spin with high speed in the microwave heating. The more catalytic oxidation reaction occurs and PM is combusted to achieve further emission reduction effect.

2.2. Gasification Collection

The study on diesel soot of microwave heating has concentrated in the three way catalyst by purifying device. At present most of the research is still at the experimental stage such as the purification simulation of the harmful components in exhaust. It also does not consider the synergistic effect of gasification collection. The following carried out study on gasification collection of microwave heating by use of a surfactant liquid.

When diesel soot is burned by microwave heating, the residual PM is purified by gasification collection. The gasification collection requires two conditions. The first makes the gas-liquid two-phase perturb violent, full contact between PM particles and purifying liquid, the second is the particles should have hydrophilic. These are the two essential conditions of gasification purification. Based on the structure design of purification equipment, it should make full contact of gas-liquid two-phase have enough time and space. Selecting the purifying liquid, it should make less hydrophilic oily PM into hydrophilic dust. The surfactants should have wetting, dispersion and emulsification, the surface tension of water can be reduced making water easy spray condensation. Therefore the use of surfactant solution can reach to capture PM particle [19].

In the surfactant solution, microwave heating make the liquid molecules rotate speed and produce the heating effect and gasification. Formula is as follows.

$$\frac{\Delta T}{\Delta t} = \frac{2\pi f \varepsilon_0 \varepsilon_\tau^* |E|^2}{\rho C_p}, \quad (1)$$

where T is the temperature; t is the time; f is the microwave frequency; ε_0 is the vacuum dielectric constant; ε_τ^* is the imaginary part of the complex dielectric constant; E is the electric field intensity; ρ is the density; C_p is the heat capacity.

The formula (1) shows that the reaction can be controlled by the microwave frequency and duration. The control system should be established by use of sensor so that purification effect can get real time monitoring.

Running through the ceramic catalyst carrier, the microwave accelerates the motion of the liquid molecules and improves the capture effect on the PM particles of the diesel soot. Surfactant additives in the liquid improve the capture effect on PM particles further.

2.3 Purifying Control Process

The soot discharged can be detected and analyzed, as shown in Fig. 1. The portable gas detection technology is as the foundation, the diesel soot and the feature parameters are measured.

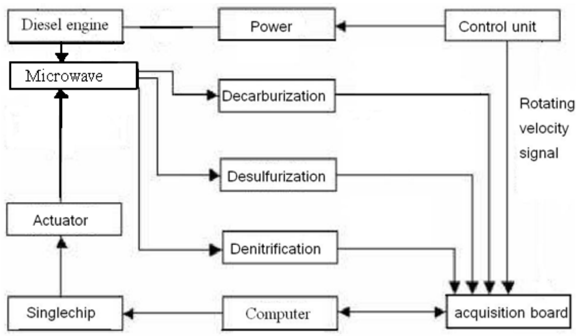

Fig. 1. Diesel engine exhausts gas detection system.

Its advantage is to simulate the real-time conditions, exhaust emissions data can quickly obtain on different status, different load, and different time. It improves the detection accuracy and reliability [20].

3. Experimental Research and Analysis

The experimental model of the soot exhaust channel is showed in Fig. 2. Because the microwave can penetrate the ceramic carrier which does not absorb the microwave energy, the combustion and gasification collection of the PM particles can be carried out simultaneously by the optimal design on the coupling fluid-solid ceramic carriers.

The Y-Al_2O_3 coating surface of the honeycomb ceramic carrier is coated again with a noble metal catalyst, which can effectively improve the micro-wave catalysis effect on diesel soot. After the soot is combusted, under microwave radiation, the aqueous solution containing surfactant takes places gasification purification on PM particles by microwave heating. The collection efficiency on PM particles doubled by adding 1 % surfactant in water. +NaOH solution, mud washing smoke agent, surfactant F68, non-ionic detergent and nekal solution can be used as purified liquid [19]. Gasification collection experiments show that the soot can be captured more than 70-85 % by adding 1 % surfactants in water, while only 20 % trapping efficiency with water.

The dual role both heating combustion and gasification purification effectively improve the purification efficiency on PM particles in the exhaust gas. Experiment result indicated that the purifying efficiency of diesel soot is more than 90 %. As the microwave power is increased, the removal efficiency of soot increased too.

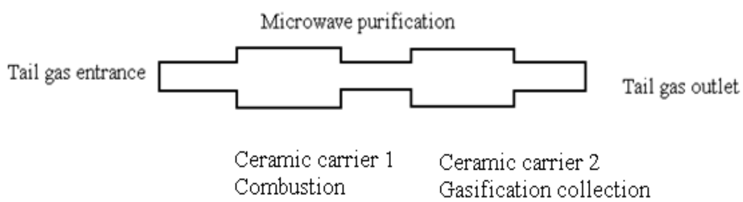

Fig. 2. Diesel engine exhaust channel.

4. Conclusion

At present, most of the clean devices of diesel soot are only installed with the simple ceramic carrier, which could not ensure the clean of $PM_{2.5}$ with higher efficiency. Hence, it is obligatory to amend the clean devices and improve their clean effect. The experimental model of a diesel engine exhaust emission is established, both the combustion and gasification purification process on $PM_{2.5}$ was tested by means of microwave heating, and the collection is effective.

Diesel soot is suited combustion purification due to its elemental carbon and organic carbon content. It can reduce 60 % of carbon emissions at the power of about 1000 W and with the power increasing, the purification efficiency increases. At the same time, setting gasification collection model, the emissions of PM particles can be reduced more than 90 % by microwave heating.

The results of this device still need to be tested in practice. The experiment is a preliminary. It also need to optimize the design of exhaust device according to the condition of diesel engine, and by control the output microwave power, to achieve efficient purification effect.

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