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Full Length Article

Application of electrostatic force for the atomization improvement of urea-water sprays in diesel SCR systems

Raditya Hendra Pratama[a], Seoksu Moon[b,*], Hyun-Ha Kim[c], Mitsuharu Oguma[a]

[a] Research Institute for Energy Conservation, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba East, 1-2-1 Namiki, Tsukuba, Ibaraki 305-8564, Japan

[b] Department of Mechanical Engineering, Inha University, 100 Inha-ro, Michuhol-gu, Incheon, South Korea

[c] Environmental Management Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba West, 16-1 Onogawa, Tsukuba, Ibaraki 305-8569, Japan

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ABSTRACT

Urea-based selective-catalytic-reduction (SCR) system is one of the techniques applied to reduce NO_x emission in diesel engines. Due to the application of low injection pressure to prevent the wall-wetting of the urea-water solution to the exhaust pipe, the spray atomization, which is important to increase the NO_x conversion efficiency, is still unsatisfactory. In this study, we pay attention to the electrostatic force as a source to improve the spray atomization of the urea-water solution. An electric voltage up to 7 kV was charged to a single-hole nozzle injector and various injection pressures up to 7 MPa were applied to investigate how the effect of electric charge on spray atomization appears differently in different flow regimes. High-speed visualization was conducted to observe the macroscopic spray structure. The microscopic spray characteristics were analyzed by a laser diffraction technique. The results showed that the electrostatic force effect, which results in finer droplet size and wider spray coverage area, is obtained especially at higher applied voltage in two different manners depending on the injection pressure, i.e. electrostatic induced jet breakup as a dominant effect at low injection pressures and electrostatic repulsion force-induced spray expansion as a dominant effect at high injection pressures.

1. Introduction

The environmental problems caused by exhaust emissions of engines fueled with conventional fossil fuels have become one important issue since it affects the human body and environment. One of the pollutants which has a serious impact on the health and environment is the nitrogen oxides (NO_x) emission. This leads many countries to have strict regulation on the NO_x emission. One example showing the matter has taken into serious action is that the exhaust gas emission regulation in Japan has forced heavy-duty diesel engine vehicles to keep their emission below the limit, whose value has been reduced for more than 90% in 20 years [1].

In order to meet the strict regulation of NO_x emission, a lot of efforts have been paid to develop NO_x reduction techniques, one of which is the urea-SCR system. However, there are still a lot of improvements need to be achieved in order to obtain higher NO_x conversion efficiency. The review of diesel emission control by Johnson raised several challenges for the urea-SCR system development such as the complexity of urea-water solution storage and delivery systems, the difficulty to ensure complete evaporation of the urea-water solution, and controlling the urea-water solution injection rate to maximize NO_x reduction [2]. Another challenge is the deposition of urea and/or urea decomposition products in the urea-SCR system, which is strongly affected by exhaust gas temperature and injection rate [3]. Another issue is spray wall impingement in the urea-SCR system caused by the insufficient spray atomization and evaporation which then leads to the aforementioned deposition of urea and lower efficiency of NO_x conversion. The injection pressure of urea-water solution in the urea-SCR system has been kept lower than 1 MPa [4–7] to avoid the wall-impingement by suppressing the spray penetration but it has deteriorated the spray atomization and evaporation. An experiment by using a 3-hole commercial injector was conducted to understand the effect of wall impingement of urea-water sprays by the spray cooling effect on the exhaust channel wall, as well as to characterize the injected and impinged urea-water

Abbreviations: ASOI, After start of injection signal; DC, Direct current; EHD, Electrohydrodynamic; GDI, Gasoline Direct Injection; LDSA, Laser Diffraction Spray Analysis; SCR, Selective catalytic reduction; SMD, Sauter mean diameter

* Corresponding author.
E-mail address: ss.moon@inha.ac.kr (S. Moon).

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droplets [8,9]. Another similar experimental setup by using a 6-hole commercial injector was done to evaluate the spray atomization characteristics by varying exhaust gas crossflow condition [10]. The experiments [8,10] were also conducted with visualization of the spray by using shadow imaging and Mie-scattering techniques. There are several studies discussing spray modeling in the urea-SCR system, among others, were done by Birkhold et al. to evaluate different configurations during the development process of Urea-SCR system [11,12], and by Jeong et al. to get an optimum design of urea injector for reducing ammonia slip (abundant unreacted ammonia in the gas stream after catalyst) [13]. Studies to improve the decomposition of urea to ammonia were done by using a wire-mesh thermolysis filter [14], thermolysis and hydrolysis [15], and air-assisted injector [16]. From these previous studies, we understand that enhancement of urea-SCR performance is depending on the distribution quality of urea-water sprays in the SCR system as well as the decomposition process to get the ammonia which then reacts with the NO_x. Therefore, spray atomization of the urea-water solution in the urea-SCR system is critical to maximizing the NO_x reduction.

There are several ways to improve liquid atomization, one of which is by applying an electric charge to the liquid before it is injected or sprayed which is well known as electrohydrodynamic (EHD) spraying or electrostatic spraying. An early study of electrostatic spraying was done by Vonnegut and Neubauer in the early 1950 s by simply using a microcapillary tube and charging several thousand volts to a liquid, in this case, is water, to show a novel technique of production of monodisperse liquid droplets [17]. The electrostatic spraying has attracted other researchers to work on the topic that experiments were conducted to understand effects of several parameters on the injected spray, i.e. applied voltage [18,19,28–34,20–27], flow rate [19,20,25–28,33,35–37], capillary diameter [19,25], capillary shape [20], and some liquid properties, such as electrical conductivity [19,25,35], permittivity [35,37,38], surface tension [25,35,37,38], and viscosity [25,35,37,38]. These parameters are well-known as the basic parameters governing the electrostatic atomization and the liquid atomization itself. Thus, understanding these parameters is important when applying the electrostatic spray in a specific system. There are some common liquids used in the experiment of electrostatic spray and some of them are used to investigate the effect of liquid properties. As reported in previous studies, some liquids were used in the experiments, such as water [17,20,24,27,28,31,38], ethanol [21,27,28,33,34,39], ethylene glycol [22,27,36], heptane [25,40], butanol [28,37], glycerol [38], isopropanol [28], hexadecane [19], propanol [28], kerosene [30], and some liquid mixtures [19,24,26,29,32,35,38]. These liquids present important information about the effect of liquid properties, i.e. density, viscosity, surface tension, electrical conductivity, and relative permittivity, on electrostatic atomization.

There has been no research discussing the improvement of the urea-water spray atomization by applying electrostatic force despite a lot of studies have discussed the fundamental of electrostatic spray phenomenon and its mechanism. This leads us to study the application of electrostatic force-assisted spray atomization in the urea-SCR system. In the electrostatic spray study, the typical range of electrical conductivity of the liquid is $10^{-9} - 10^{-1}$ S/m, where 10^{-9} S/m and 10^{-1} S/m are regarded as the low limit and the high limit [20]. As shown in Fig. 1, the urea-water solution has high electrical conductivity compared to liquid fuels and water applied in the previous studies [28,41]. Even though injecting urea-water solution by a high-pressure injector can also atomize it into a smaller droplet, improvement in atomization at lower injection-pressure is required to avoid wall impingement since urea-SCR system channel has relatively narrow space.

In this study, electrostatic force-assisted atomization of the urea-water solution was studied using a modified Denso gasoline direct injection (GDI) injector at different pressures, which can be used for diesel NO_x removal. The experiment was conducted by visualizing the phenomenon by a high-speed camera with the Mie-scattering technique. Time-resolved high-speed camera imaging combined with the Mie-scattering technique was applied to track the spray pattern of urea-water solution for an entire cycle of the single injection event. Droplet size and distribution measurements were also conducted by a laser diffraction technique. The effect of injection pressure is also investigated to understand the dominant factor which affects the atomization of urea-water in the presence of electrostatic force. This study is an early stage study to understand the electrostatic spray phenomenon for real large-scale application, i.e. urea-SCR system application.

2. Experimental setup

The experimental apparatus and schematic diagram of the setup are summarized in Fig. 2. The high-speed imaging combined with the Mie-scattering technique was used to visualize the spray pattern with a high time-resolution. The experiment was conducted by applying high voltage direct current (DC) to a nozzle and injecting the liquid by using a pump (LC-20AP, Shimadzu). The electric current was measured during the injection with applied voltage. The liquid used in the experiment was AdBlue (urea-water solution), which is composed of 32.5% of urea and 67.5% of water. The liquid was pumped from the tank to the injector then injected into the ambient air. The injector used in the experiment was Denso single-hole-modified gasoline injector with 0.1 mm in hole diameter. The modification in the nozzle part was made by adding an elongation part to apply the high voltage DC to it. Unlike the other common experiments of electrostatic spray, in this experiment, the liquid was not continuously pumped but was injected with a specific frequency and injection period. A delay generator was used to synchronize the injection and the timing of Laser Diffraction Spray Analysis (LDSA; MicrotracBEL – LDSA-1400A) measurement as well as high-speed visualization. A pulsed high voltage DC power supply was used in the experiment. The pulse power supply was used since a continuously applied voltage to the nozzle causes a spark in the interval between injections when the liquid is not flowing, which is avoided for a safety reason. Thus, the voltage-on time was controlled by a delay generator (Stanford Research System Inc., DG645) to synchronize it with the time of liquid injection. The positive polarity of voltage charge was used throughout the study due to its better stability in stable atomization than the negative one [42].

The high-speed visualization with the Mie-scattering technique was conducted to observe the whole phenomenon during an injection event. The high-speed camera was set with 10,000 fps in frame rate and 100 μs in shutter-speed to capture a micro-scale spray since the shorter shutter-speed cannot capture the micro-scale spray which has low scattering light intensity. A light source was positioned in front of the spray to directly illuminate the spray from the camera side to get a strong scattering light. The schematic picture of the experimental setup of the high-speed visualization with the Mie scattering technique is shown in Fig. 2. Detail information of the high-speed imaging setting is written in Table 1.

For LDSA measurement, a laser beam with approximately 11 mm in diameter was transmitted into the spray. The diffracted lights from the spray were captured by the detector in the light-receiver device and then processed by the device to get the information of spray droplet distribution and Sauter mean diameter (SMD). Before the start of measurement, the detector was adjusted to the center of the laser light to get a correct calculation of droplet distribution and size. The spray measurement was conducted at 30 mm downstream from the nozzle exit and center of the liquid jet, therefore laser beam positioning was carefully conducted before the measurement. The measurement was done by 20 times sampling for each case and the results presented in this study is the average value of the samples.

In this experiment, the injection pressures were varied from 1 MPa to 7 MPa. These pressures were set to investigate how the electrostatic force effect appears differently based on the flow breakup regimes defined in traditional studies [43], which details will be discussed in the