

Effect of Injection Parameters on Spray Characteristics of Urea-SCR System

Xian Shi, Jun Deng, Zhijun Wu and Liguang Li
Tongji University

ABSTRACT

Urea-SCR system is one of the after-treatment methods for diesel engines, which could effectively reduce the NO_x emissions and enable diesel engines to meet increasingly stringent emission legislations. Within the urea-SCR system, characteristics of urea-solution spray, especially the distribution uniformity of spray droplets as well as gaseous NH_3 within the exhaust pipe, play an important role in the efficiency of catalytic reduction.

In this paper, an SCR spray visualization test bench was set up. Urea-solution from a non-air-assist injector is injected into the steady stream of simulated exhaust gas flow. The transient characteristics of spray are recorded by high-speed photography. Specific spray characteristics in the original photographs, i.e. mixing distance and degree of uniformity are extracted. The influence of injection pressure and injection angle on spray characteristics are tested in different sets of experiments. Wall impingement on the inner surface of the pipe is also captured in several experiments and discussed.

The experimental results reveal that: within a reasonable injection pressure range, the spray develops without impinging on the pipe wall. When the injection pressure becomes lower, the urea-solution droplet distribution shows better axial concentration uniformity. The mixing distance decreases as injection pressure decreases. Meanwhile, compared to the forward, i.e. downstream, direction of injection angel, reversing injection angle helps the spray atomize better with higher homogeneity. Injection parallel to the radial direction acquires the shortest mixing distance.

CITATION: Shi, X., Deng, J., Wu, Z. and Li, L., "Effect of Injection Parameters on Spray Characteristics of Urea-SCR System," *SAE Int. J. Engines* 6(2):2013, doi:10.4271/2013-01-1067.

INTRODUCTION

The selective catalytic reduction (SCR) based on urea-water-solution is an effective technique to reduce nitrogen oxides (NO_x) emitted from diesel engines. Urea-water-solution (UWS, containing 32.5 wt% urea; brand name: AdBlue) is sprayed into the hot exhaust stream and subsequently the reducing agent (ammonia, NH_3) is generated by evaporation of water, thermolysis of urea and hydrolysis of isocyanic acid (HNCO) [1].

In actual exhaust configurations, impingement of droplets on the catalyst and the walls cannot be avoided due to the slow evaporation and thermolysis, as well as the inertia of the droplets [2]. Besides, owing to oscillated exhaust gas flow caused by multi-cylinders and specific injection parameters, droplets may not be able to spatially distribute equally which results in extra spray impingement. Especially in passenger car applications where dosing systems with non-air-assisted atomizer have to be applied in combination with small tube diameters, droplets are not formed uniformly from the spray which decreases the evaporation efficiency as well as its

mixing rate with exhaust gas. Deposition of droplets and wall film formation can occur if the surface temperature decreases below a critical temperature. Evaporation from the wall film leads to further cooling and an increasing risk of formation of melamine complexes [1]. If the reducing agent could be fast broken up or evaporated, and equally mixed with exhaust gas flow right after injection, it would help improve the conversion ratio of NO_x , as well as reduce wall impingement.

Many studies on urea-SCR system have been conducted in the past and most of them focused on theoretical simulation and analysis: Birkhold et al. [2] theoretically investigated the evaporation of water from a single droplet of urea water solution by a Rapid Mixing Model and a Diffusion Limit Model. The results show that the decrease in vapor pressure due to increasing concentration of urea in the droplet results in a continuous increase of the droplet temperature and a slower evaporation ratio compared to pure water. Van Helden et al. [3] used water instead of UWS in a CFD study and estimated the concentration of the reducing agent from the water vapor concentration. Wurzenberger and Wanker [4]

Table 1. Experimental Conditions of Spray Visualization

Ambient Gas Mass Flow (m^3/h)	170			
Ambient Gas Temperature (K)	473			
Illumination Source	Afeng PTW-2000 Halogen Lamp (2 kW)			
Simulated Exhaust Pipe Diameter (mm)	127			
Injector Type	Tenneco Elim-NOXGen 1.0 (Non-air-assisted, single hole, continuous injection available)			
Nozzle Hole Diameter (mm)	0.3			
Injection Pressure (bar)	4.0	6.0	8.0	
Injection Angle (°)*	45	60	90	-45
Injection Quantity (g/s)	1.258			
Frame Rate (fps)	25000 (available from 6688 to 500000)			
Resolution (pixel)	800 × 600			

*Definition of "Injection Angle" refers to Fig.5

modeled the thermal decomposition as a homogeneous gas phase reaction, which followed the evaporation of UWS to water vapor and gaseous urea. Strots et al. [6] introduced the experimental idea of weighing the solid matter from the urea spray. Based on the relationship between weight and other parameters such as injection speed and exhaust gas temperature, relative optimization of urea-SCR system is proposed. There are still many other papers and studies focusing on SCR system. However, almost all papers in this field tend to exploit numerical or analytical models for interpretation of typical phenomenon. According to our knowledge, few studies have been published on the experimental relationship between droplets distribution and injection parameters.

In this study, an experimental test bench of urea-SCR system has been set up, in which injection pressure and injection angle could be altered. Therefore, the effect of different injection parameters can be studied and the spray droplet formation within each set is captured by the high-speed camera. In order to evaluate the droplet distribution based on spray images, two characteristics, i.e. mixing distance and degree of uniformity, were defined and clarified in the image-processing program. Spray image processing and comparison between different experiments reveals that a correlation between droplet distribution and injection parameters is found. As spray characteristics are influenced by injection mechanism of the whole system, this research could provide valuable insight not only for a better understanding of interaction between spray and gas flow, but also for the design and manufacture of urea-SCR system.

EXPERIMENTAL SETUP

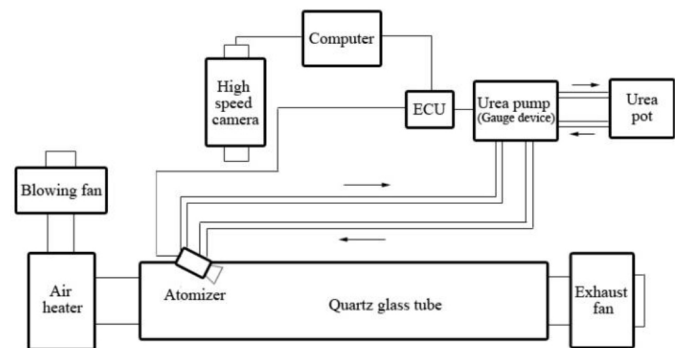


Figure 1. Schematic Diagram of Visualized Urea-SCR System

The experimental test bench as shown in Fig. 1 is a simplified model of urea-SCR system applied in commercial vehicles and provided by Tenneco China. For the purpose of simulating the real exhaust atmosphere of applied vehicle, temperature-controlled air flow device, including air boiler, variable-speed fan and thermo-couple sensor, is exploited to substitute the exhaust gas. To facilitate visualization a transparent quartz glass tube is adopted instead of stainless steel pipe used in real exhaust system. Within the injection mechanism, a non-air-assisted injector (Tenneco Elim-NOXGen 1.0) is installed on one end of the glass pipe which could alter its injection angle by mechanical devices and injection pressure by ECU input.

All the experiments are conducted under continuous injection. The nozzle diameter is 0.3 mm and average injection quantity of urea-solution is 1.258 g/s. In this experiment, the diameter of the quartz glass tube (simulated exhaust pipe) is 127 mm while ambient gas temperature

remains 473 K. Besides, the air mass flow stabilizes at $170 \text{ m}^3/\text{h}$ controlled by air flow sensor.

After the start of injection, a high-speed camera placed vertical to the axis of tube records the formation of spray at 25000 *fps* so that droplets of the spray could be captured by the photographing images. The evolution of the spray is constructed from a series of images. In order to obtain images with sufficient brightness, a 2 kW halogen lamp is placed as the illumination source.

Fig.2 is the user-interface of a self-coded image processing program and the flow diagram of the program. The method of image processing is based on basic gray-value image analysis, in which spray or droplet objects are represented by a group of pixels. Variance computation and Fast Fourier Transformation are exploited to evaluate the pixel distribution, which reflects the spray droplet formation. The accuracy of such algorithms depends on the revolution of images, which refers to 800×600 in this situation.

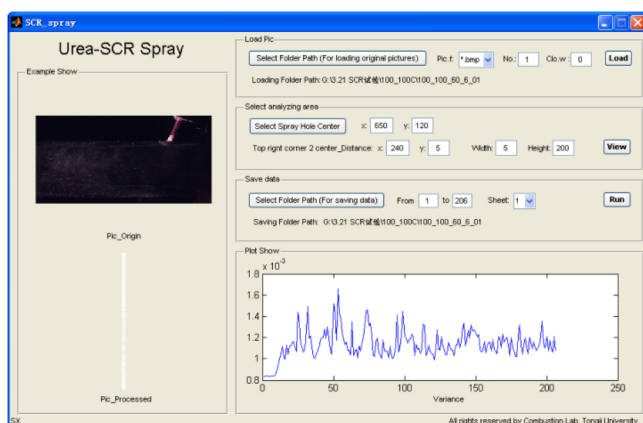


Figure 2. Interface of Urea-SCR Spray Image Processing Program & Flow Diagram of Program

SPRAY DROPLET FORMATION

In this section, one single droplet will be kinetically analyzed to achieve a comprehensive understanding of spray development and droplet's distribution. When the urea solution is pumped from the urea storage tank and injected by the atomizer, the liquid is shattered into small droplets due to the high injection pressure and fluid motion through the nozzle hole. After one droplet is formed, it remains a forward

movement under a certain speed, which could be resolved into three components along three different orthogonal axes (Fig. 3). The speed of droplet is affected by the force derived from gas flow and its collision with other droplets or particles.

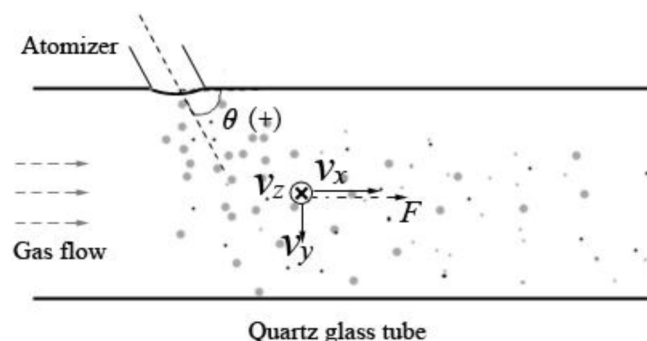


Figure 3. Velocity and Force Resolution of Single Droplet

According to Fig.3, the force F generally goes downstream along with the direction of gas flow. Under the continuous influence of F , v_x becomes larger and is going to reach a steady-state value when the gas flow stabilizes, i.e. the force F vanishes. In the meantime, as gas cavitation or vortex may exist around the nozzle of atomizer, the irregular flow motion casts a negative effect on v_z and v_y . In other words, as the spray continue to develop, v_z and v_y are vanishing and finally can be ignored compared to v_x in a developed mixing flow. At the start of injection, injection pressure accelerates droplets to a high initial speed of v_y while v_z is almost zero. Therefore, a single droplet is likely to move farther in the direction of axis Y than Z after it comes to steady state.

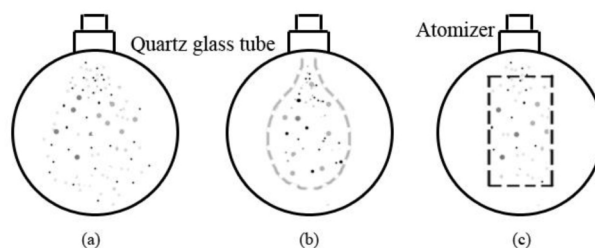


Figure 4. Droplets Distribution in the Radial Cross Section

According to single droplet analysis, it is reasonable to conclude that the droplet distribution area on the radial cross section generally has larger height and smaller width. Fig.4 shows the distribution of droplets in the radial cross section of quartz glass tube. With many gray or black little spots scattering in the radial cross section, Fig.4(a) represents the extrapolated distribution of urea droplets, while (b) is an ideal condition according to normal distribution model. Fig.4(c) is