

Instantaneous Flow Rate Testing with Simultaneous Spray Visualization of an SCR Urea Injector at Elevated Fluid Temperatures

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ABSTRACT

Selective Catalytic Reduction (SCR) diesel exhaust aftertreatment systems are virtually indispensable to meet NO_x emissions limits worldwide. These systems generate the NH_3 reductant by injecting aqueous urea solution (AUS-32/AdBlue®/DEF) into the exhaust for the SCR NO_x reduction reactions.

Understanding the AUS-32 injector spray performance is critical to proper optimization of the SCR system. Specifically, better knowledge is required of urea sprays under operating conditions including those where fluid temperatures exceed the atmospheric fluid boiling point.

Results were previously presented from imaging of an AUS-32 injector spray which showed substantial structural differences in the spray between room temperature fluid conditions, and conditions where the fluid temperature approached and exceeded 104°C and "flash boiling" of the fluid was initiated. Subsequent testing was conducted using a novel instantaneous flow meter (dINJ) which gave further insight into injector flow behavior under flash boiling conditions.

The current work presents results obtained with the dINJ flow meter which for the first time are combined with simultaneous high speed video imaging to give a unique ability to analyze the injector flow and spray behavior. A description of the dINJ flow meter is provided. Testing was conducted at liquid spray and flash boiling operating points using a prototype design actively heated injector. A detailed analysis is presented of the injector flow and spray characteristics during the opening and closing transients, and some conclusions are drawn confirming previous observations of fluid evacuation from the sac volume after injector closing.

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INTRODUCTION

Nitrogen oxides (NO_x) emissions reduction legislation worldwide has led to the introduction of new exhaust aftertreatment systems, particularly for lean-burn technologies such as compression-ignition (diesel) engines. Innovative exhaust aftertreatment technologies have been industrialized that treat NO_x under the high-oxygen exhaust gas stream conditions typical of lean-burn engines.

One of these technologies comprises a catalyst that facilitates the reactions of ammonia (NH_3) with the exhaust NO_x to produce nitrogen (N_2) and water (H_2O). This technology is referred to as Selective Catalytic Reduction (SCR). Many original equipment manufacturers of passenger cars implement this type of system on their diesel powertrains today. A good example of various innovations

that have been implemented for SCR - close-coupled injection, SCR on Diesel Particulate Filters (DPF), and others - was described in reference [1] ¹.

Ammonia is difficult to handle in its pure form in the automotive environment, therefore it is customary with these systems to use a liquid aqueous urea solution, typically at a 32% concentration of urea ($\text{CO}(\text{NH}_2)_2$). The solution is referred to as AUS-32, and is also known under its commercial name of AdBlue® in Europe, and DEF - Diesel Exhaust Fluid - in the USA.

The urea solution is injected into the exhaust and transformed to NH_3 for the SCR reactions over the SCR catalyst. The preferred transformation of urea is through thermolysis to ammonia directly, and through hydrolysis of iso-cyanic acid (HNCO) to ammonia as an intermediary step [2, 3]:

1. Numbers in brackets refer to references listed at the end of this paper.

- Thermolysis: $\text{CO}(\text{NH}_2)_2 \rightarrow \text{NH}_3 + \text{HNCO}$
- Hydrolysis: $\text{HNCO} + \text{H}_2\text{O} \rightarrow \text{NH}_3 + \text{CO}_2$

The spray preparation of the injected urea solution is thought to have a significant influence on the evolution of these urea decomposition processes in the exhaust stream. Until recent years, there has been only limited information about spray quality as the AUS-32 fluid temperature in the injector increased to typical hot levels in exhaust-mount urea injection applications.

As a first step to this improved understanding, high speed video images were taken at the injector tip at different fluid temperatures. These images revealed significant changes in spray structure and also fluid delivery as temperatures approached the atmospheric boiling point of AUS-32 (104°C) [4, 5]:

- The main spray structure exhibited a higher vapor fraction as the temperature increased to and surpassed the atmospheric boiling point of the fluid - this included an expansion of the spray cone angle;
- At elevated temperatures, a non-negligible amount of spray and flow activity occurred after injector closing.

In an effort to clarify the behavior of the spray and the evolution of the spray structure when injecting into a hot environment, as opposed to a room temperature environment, backlighting spray measurements were performed using a hot air flow bench, and using a prototype injector that permitted active heating of the fluid inside the injection unit [6]. An example of the spray structure evolution from a liquid spray to a flash boiling condition at an exhaust temperature of 490°C is shown in [figure 1](#).

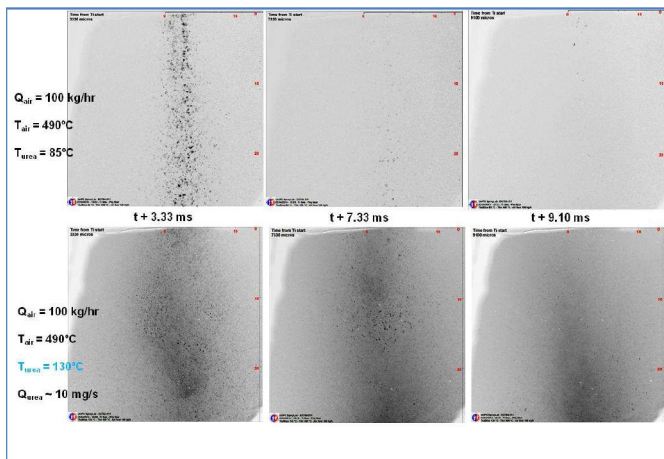


Figure 1. Liquid spray (top) vs flash boiling (bottom), $T_{\text{exh}} = 490^\circ\text{C}$ (Backlight composite imaging - [6])

This testing confirmed the observations made at lower ambient air temperatures, including the post-closing spray activity at high temperature. This was subsequently attributed to the evacuation of the injector “sac volume” - the volume between the injector sealing band and the orifice disk exit - [figure 2](#).

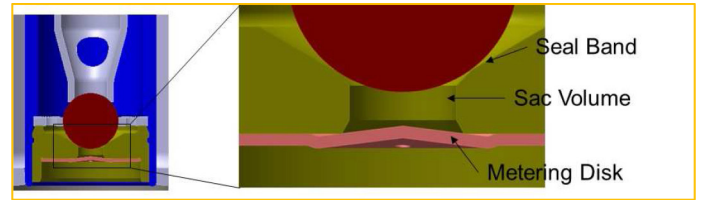


Figure 2. Description of injector “sac volume”

In addition to spray diagnostics, it is important to understand the evolution of the injector flow behavior at the elevated temperatures under consideration. Traditional instantaneous flow rate (or “shot-to-shot”) measurement devices are typically based on the so-called Zeuch method, which was developed into commercial measurement equipment in the 1980s by Ono Sokki for diesel injection systems [7] - see [figure 3](#).

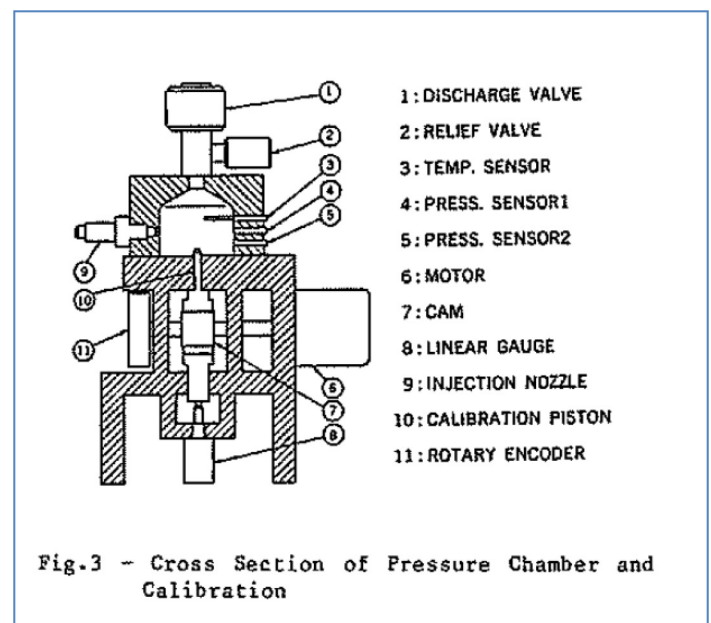


Figure 3. Schematic of Ono Sokki instantaneous flow rate meter based on Zeuch measurement method [7]

The measurement principle is based on injection of the fluid into a closed vessel and monitoring the pressure rate increase, which is proportional to the instantaneous volumetric flow rate as given by the following relation:

$$\frac{dV}{dt} = \frac{V}{K} \frac{dP}{dt}$$

where

V = vessel volume

P = vessel pressure

K = bulk modulus of the fluid.

This approach worked quite well with high pressures typical of diesel applications, and also with gasoline direct injection applications where the pressure increase in the vessel during the injection event was negligible with respect to the system supply pressure. However with low pressure applications typical of port injection or exhaust aftertreatment injection systems, the decrease in delta pressure became significant and reduced the representativity of the flow measurement.

An additional drawback with the Ono Sokki device (and other similar devices working on the same principle) was that injection into a closed liquid volume was also not representative of the real world where injection is into a gaseous medium. These devices were also unable to provide reliable flow information in the case of flash boiling sprays, where the dual phase nature of the spray rendered a determination of the bulk modulus of the fluid in the injection volume difficult or even impossible. A final disadvantage to these devices is the inability to perform simultaneous flow measurements and spray diagnostics.

The University of Perugia has developed a device that, while still relying on the Zeuch principle, performs the analysis on a fluid volume on the supply side of the injector. This approach recovers the representativity of a spray injecting into a gaseous environment, and also provides the opportunity to perform simultaneous flow and spray diagnostics.

Measurements were made with the University of Perugia measurement device, hereafter referred to as “dINJ”, including validation of the dINJ in comparison with the traditional Zeuch principle flow meters. That testing culminated in measurements under flash boiling conditions with injection of AUS-32 - these are summarized in figure 4 [8].

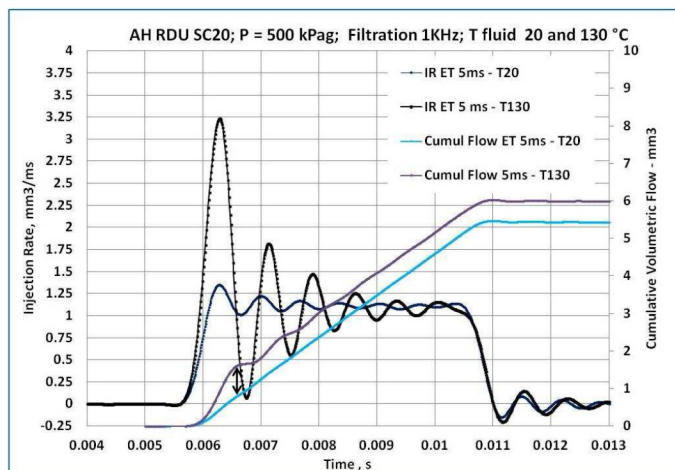


Figure 4. dINJ measurements of injection under liquid and flash-boiling conditions [8]

The measurements permitted a clearer understanding of the instantaneous flow behavior under flash boiling conditions. In particular, further insights were obtained to explain a generally observed increase in the mass flow per injection pulse at the flash boiling condition, however the precise details concerning this increase still remained hypothetical.

As mentioned, a unique advantage to the dINJ device is the ability to conduct simultaneous diagnostics of injector flow and spray behavior - this paper presents the results of those continued investigations. One objective of these investigations was to illuminate further the flow evolution leading to the flash boiling flow increase, and to study the effects of the oscillatory pressure behavior on the spray.

A description of the test setup and procedures is followed by a presentation of the simultaneous imaging and instantaneous flow measurement results. A discussion follows examining in more detail the injector opening and closing transients. The paper closes with a summary of the conclusions that can be drawn from the present testing campaign.

TEST BED AND PROCEDURES

The dINJ instantaneous flow meter is shown schematically in figure 5.

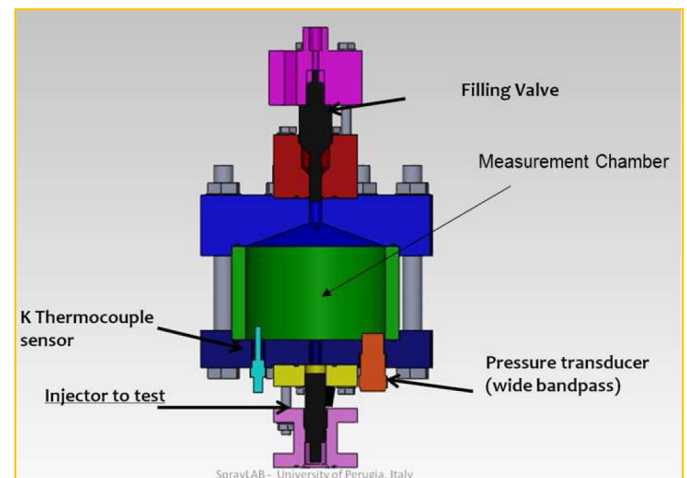


Figure 5. Schematic of dINJ instantaneous flow rate meter

The principle of operation consists of stabilizing the fluid volume in the upstream chamber (green) and then activating the test unit for the desired injection pulsewidth. The fluid temperature in the vessel is monitored, and the fluid pressure evolution is acquired with a pressure transducer. Once the test injection is complete, a separate filling valve is actuated to refill and restabilize the pressure in the fluid chamber before the next test cycle.

A typical pressure signal and derived volumetric flow rate is shown in figure 6 for one complete cycle.

The raw injection rate signal is subject to some oscillation/noise after the opening and closing transients - this is due to a number of factors related to the vessel geometry, relative location of the test injector and filling valve, and noise on the pressure derivative signal. In order to mitigate the effects of this noise, an 8th order Bessel low pass filter is applied with a cutoff frequency typically in the range of 1 - 2 kHz.