A Methodology for the hydraulic characterization of a Urea-Water Solution injector by means of Spray Momentum Measurement

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Abstract
Selective Catalytic Reduction (SCR) is a technology that allows the internal combustion engines to comply with the stringent regulations set for exhaust gases, specifically Nitrous Oxides (NOx) emissions. For a proper operation of the SCR, a urea-water solution (UWS) injector must dose an adequate amount of liquid into the exhaust pipe in order to avoid deposit formation and to guarantee the SCR system efficiency. This task requires the knowledge of the performance of the injector. Then, the goal of this work is to study the hydraulic performance of an UWS injector, by means of measuring the spray momentum flux in order to understand the influence of different variables as injection pressure and cooling temperature on the flow characteristics. The tested injector was cooled at two different temperatures, 25 and 80 ℃, and the injection pressure of the UWS was set at 4,6 and 8 bar for each measured temperature during the tests. The measurements were carried out using an experimental facility developed at CMT-Motores Térmicos for the determination of the UWS Spray Momentum flux, where a piezoelectric pressure sensor was located near the nozzle exit of the injector, which measures the impact force of the spray. Additionally, the proposed methodology allowed to determine the injected mass flow, capturing the transient events of the injection, such as the opening and closing stages. Moreover, mass flow rate measurements of the injector were performed under the same operating conditions, determining the influence of the injection pressure and the cooling temperature. Regarding the pressure, the tendency was as expected, the higher the injection pressure the higher the flow rate. On the other hand, when the temperature was increased the mass flow was slightly reduced. Additionally, the proposed methodology allowed to determine the injected mass flow, capturing the transient events of the injection, such as the opening and closing stages.

Keywords
Urea spray, Spray momentum, Hydraulic characterization, Urea injection.

Introduction

With the intention of reducing pollutant emissions and complying with existing regulations, most vehicles with combustion engines have incorporated Selective Catalytic Reduction (SCR) systems in the after-treatment set [1, 2]. The SCR configuration in current systems (and in the near future) requires a proper delivery of the Urea-Water Solution (UWS) in order to have efficient NOx reduction reactions, demanding an accurate fluid dosing and ensuring a correct atomization and evaporation, in order to avoid wall impingement and deposit formation. Therefore, the UWS injection process needs to be well understood and characterized for suitable injector selection during the design and also for calibration process [3]. Until a few years ago the information regarding to UWS systems was very limited. However, recently, several authors have devoted their research topic to characterize these systems and they have realized the necessity of determining the amount of injected mass [4], since it provides direct information of the unit dosage and because it is an essential parameter for correct initialization of CFD modeling [5, 6].

This scenario obliges to determine experimentally the UWS mass flow rate or at least the injected mass per shot. The most used methodologies for the mass flow determination are the Bosch and the Zeuch method [4, 7]. In general, the measuring principle is based on injecting the fluid into a closed volume, and registering the pressure wave generated by a piezoelectric pressure sensor, which is proportional to the injection rate. Both systems are widely used for diesel and gasoline dosing applications, where injection pressures are quite high (specially in diesel can reach 250MPa). Additionally, the main characteristic of those devices is that the injection is performed into liquid.

However, the direct implementation of those methodologies to UWS is not so evident, since the UWS injection pressures are very little in comparison to diesel and gasoline direct injection systems; moreover, real UWS injection process is in exhaust gas conditions, very different to injecting into liquid, and at low values of discharge pressures close to atmospheric. In this sense, some other authors have implemented another methodology based on the momentum flux measurement [8, 9, 10] for the gasoline spray, injecting into gas and obtaining good results. The fact that this technique allows to measure the evolution of the injection in a gaseous medium makes it attractive for the application that concerns UWS systems.

Therefore, this paper focuses on the implementation of a methodology for determining the mass flow rate from the momentum flux measurements in a UWS injector. To accomplish this target, an experimental test rig was designed and calibrated at CMT-Motores Térmicos able to measure the momentum flux and to adjust the signal using as a reference the total injected mass measured with a calibrated scale. Afterwards, several experiments were conducted at typical injection pressures and injector cooling temperatures used in SCR systems, providing useful information of the instantaneous flow behaviour, especially during the opening and the closing stages of the injection.

The manuscript is divided into five sections. After the Introduction, the theoretical background section details the theory that supports the relationship between the two magnitudes: flow rate and momentum flux, and the hypothesis behind this study. The third section presents the experimental facility employed for measuring the momentum flux and total mass, as well as the calibration procedure of the test rig. The fourth section shows the results and the analysis, focusing on the steady phase of the injection and also on the opening and closing events. Finally, the conclusions obtained through the execution of this work are presented.

Theoretical Background

The real flux at the hole exit is determined by the velocity profile and the fluid density. The real shape of the velocity profile is experimentally hard to determine, nevertheless, it is possible to define an effective velocity and an effective area in a sense that these are representative of the flow. The definition of these parameters is based on the consideration of a simplified flow, which is characterized by an effective area, smaller than the geometrical area, and with an effective velocity and density (equal to the fluid density) uniform in all the section. Based on this assumption the momentum flux and the mass flow through the hole could be defined as Eq. 1 and Eq. 2 respectively:

$$\dot{M} = C_v^2 \cdot C_A \cdot \rho \cdot A_o \cdot U_{th}^2 \quad (1)$$

$$\dot{m} = C_v \cdot C_A \cdot \rho \cdot A_o \cdot U_{th} \quad (2)$$

Combining Eq 1 and Eq. 2 an expression for the injection rate as a function of the momentum flow is obtained as is stated in Eq. 3:

$$\dot{m} = \sqrt{C_A \cdot A_o \cdot \rho} \cdot \sqrt{\dot{M}} \quad (3)$$

Furthermore, if momentum flux can be determined experimentally it is possible to calculate the mass flow directly from Eq. 3 and the injected mass from:

$$m_{inj} = \int_0^t \dot{m} \cdot dt \quad (4)$$

By measuring the injected mass, it is possible to compare the calculated injected mass with the measured one (Eq. 5) in order to obtain an adjustment coefficient K that should take a value near one if all assumptions made are correct.

$$\int_0^t \dot{m} \cdot dt = K \cdot m_{exp} \quad (5)$$

Finally, combining equations 3, 4 and 5, the mass flow can be determined as:

$$\dot{m} = K \cdot \frac{m_{exp}}{\int_o^t \sqrt{\dot{M}} \cdot dt} \cdot \sqrt{\dot{M}} \quad (6)$$

Some hypothesis should be considered in order to apply the equations aforementioned: the spray should travel perpendicular to the target and all the nozzle holes are considered identical, with the same mass flow. For the first assumption, a set of images of the spray were taken in the nozzle near field, using the DBI technique. In this work the images were obtained at 4.6 mm from the nozzle exit, with a window size of 6.4 x 5.4 mm. The experimental setup is widely explained in the work by Payri *et al*[3]. The images obtained for the first few instants of the injection event are presented in Figure 1, there it can be seen that the 3 sprays are travelling very close to each other, almost collapsing in only one plume, which is in the injector axis, and should travel perpendicular to the force sensor target.

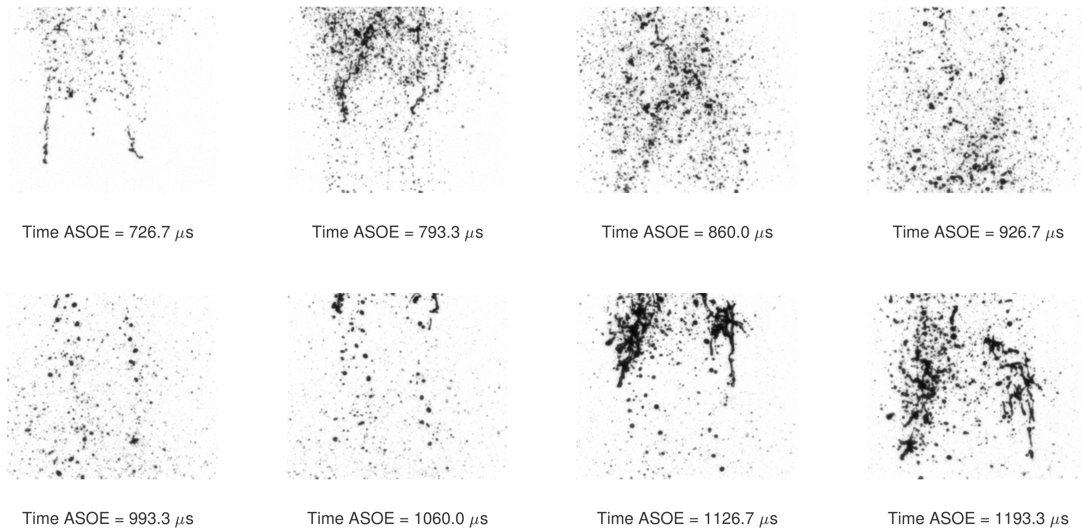

Figure 1. Beginning of the injection seen with the Diffused Back Illumination visualization technique.

Material and methods

To perform this study a commercial urea water solution injector was tested under different conditions of pressure and cooling temperature. A description of the tools and instruments used will be shown in the following paragraphs.

The injector used for this study is a dossing module from Bosch, which has 3 orifices with a diameter of 135 µm each, also the injector is water-cooled and it was operated at 2 different cooling temperatures and 3 injection pressures. A summary of the injector characteristics and test conditions is provided in table 1.

Table 1. Injector properties and test conditions.

Injector	Bosch
Holes	3
Diameter	135 µm
Injection Pressure	4-6-8 bar
Injector cooling temperature	25-80 °C
Energizing time	5 ms

With adequate experimental equipment it is possible to measure the impact force of the urea water solution spray on a surface and this is equivalent to the momentum flux of the spray. This force is measured with a calibrated piezoelectric pressure sensor and it is placed at a certain distance (between 2 and 11 mm) from the nozzle exit of the injector so the impingement area of the spray is smaller than the target of the sensor. The force measured by this sensor is equal to the momentum flux at the nozzle exit, having the previous considerations in mind and due to the conservation of momentum. The initial design of this experimental facility was done in [11] and was devoted primarily to study diesel injectors and later on it was adapted for GDI purposes as well.

To Perform the measurements of momentum flux, small modifications were made in the installation to visualize the UWS spray in order to set and align the piezoelectric sensor and the injector as can be seen in Figure 2. Once the injector is mounted, it is connected to a signal generator which allows the control of the pulse sent to the injector and its duration. To control the temperature of the injector a cooling/heating system was connected to the injector cooling inlet/outlet. For the pressure of the working fluid the injector was connected to a hydro-pneumatic pressurized system.

To obtain a good estimation of the experimental errors fifty repetitive measurements were carried out for the same test point (energizing time, injection pressure and injector cooling temperature). With proper calibration of the used equipment the standard deviation for the test is approximately 0.5%.

Additionally, with the purpose of obtaining the total injected mass quantity, a gravimetric scale was used. The quantity of the measured mass with the scale should correspond with the integral of the mass flow rate [7] therefore it will be used for adjusting the curve calculated with the momentum flux measurements.

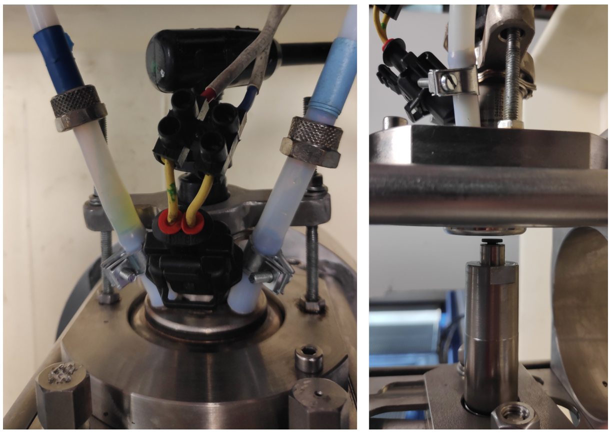

Figure 2. Piezoelectric sensor and injector aligned in the installation to measure momentum flux.

Results and discussion

Figure 3 shows a typical momentum flux signal, where the time corresponds to the time after the start of energizing (ASOE). The momentum flux signal presents some noise, therefore in order to work with the obtained data and to calculate the rate of injection as was explained in the theoretical background, a low pass filter is applied. An example of the filtered curve can be observed in Figure 3.

A fluctuation of the raw signal is observed during the opening transient of the injection event (between 0.6 and 1.0 ms ASOE). This high amplitude in the signal can be attributed to the first packages of the spray that are getting out of the nozzle hole. This phenomenon has been seen during the visualization measurements of the spray in the near nozzle region displayed in Figure 1, that were carried out in [3] (in that work the images were used for the spray droplet diameter and droplet velocity characterization). In those images it can be observed how in the first instants of the injection the droplet flow is not constant. The image taken at 726 µs registered the first droplets of the injection; subsequently, the three consecutive images (from 726 to 1060 µs) show a dense spray with higher droplet quantity, and, later on, in the next three images there is a sudden reduction on the droplet number (less dark shadows in the image), indicating that something is happening in the dynamic of the spray. Afterwards, in time frame 1126 µs, the droplet density recovers and the injection continues in the stabilized conditions. Those group of droplets can be treated as packages that are traveling in small bursts during the injection beginning, until the flow stabilizes.

The packages of fluid coming out of the nozzle in the initial moments of the injection event travel at different velocities, which promotes the coming spray to reach these initial packages of fluid. This generates an accumulation of mass in the front of the spray that is reflected in the momentum flux signal, capturing the momentum of the accumulated mass rather than the one of the spray [11, 12].

The oscillation in this initial stage of the momentum flux signal is also due to the initial burst of the injection event (Fig 1) where the density of the spray vary, showing stages where there is accumulated fluid and others were it is scarce. This oscillation has a short duration and afterwards the signal becomes steady showing small variation until the end of the injection event.

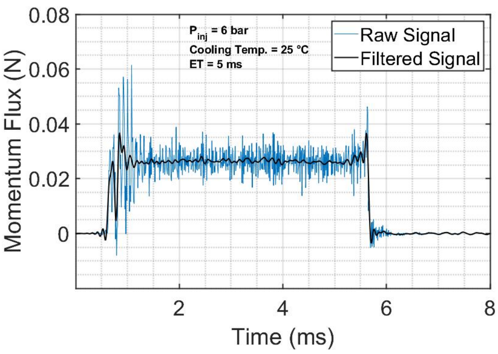

Figure 3. Raw signal form obtained from the piezoelectric sensor.

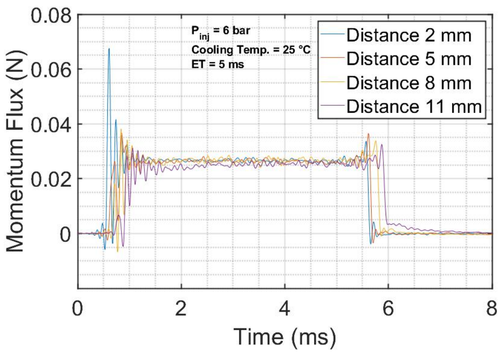

Figure 4. Momentum flux signal measured at different distances from the nozzle exit.

On the other hand, in order to measure all the sprays properly it is necessary to locate the sensor in an adequate position. To find the right position the signal is measured at different piezoelectric sensor locations, then the signal was measured at 2, 5 ,8 and 11 mm from the nozzle exit. Figure 4 shows the effect of the distance of the sensor to the nozzle exit over the momentum flux signal.

It can be observed how the momentum flux signal becomes slightly weaker as the location of the sensor moves further away from the nozzle exit, specially when the sensor is moved from 8 mm to 11 mm away from the nozzle, where the whole spray might not be hitting the target. Furthermore, while the sensor is closer to the nozzle exit the momentum flux signal starts and ends earlier due to the shorter distances that the spray has to travel. This should be considered in the signal processing in order to phase it with the start of injection in the hole exit. Considering the results shown in Figure 4, it was decided to perform the measurements with the piezoelectric sensor at a distance of 5 mm from the nozzle exit because the stabilized signal did not differ in a significant amount respect to the signal from 2 mm. From this point forward, all the presented results correspond to the measurements of the momentum flux with the sensor at 5 mm from the nozzle exit.

Effect of the injection pressure on the momentum flux of a UWS injector.

The measurements of the momentum flux were carried out for three different injection pressures and two cooling temperatures. In Figure 5 the momentum flux measure as a function of time (after the start of energizing, ASOE) is presented, where three curves representing the injection pressure of 4, 6 and 8 bar are plotted. The curves present a similar shape showing the three phases of the injection event: the opening of the injector, the needle fully opened and the closing of the injector.

During the opening phase of the injection event, the three curves presented in Figure 5 display a fluctuating behaviour (explained in the previous section). Additionally, it is observable in the figure how as the injection pressure is increased, the peak value of the fluctuation becomes higher. Regarding the stabilized phase of the injection event, between 1.5 and 5 ms ASOE, the momentum flux presents a steady behaviour, suggesting that the conditions upstream and downstream of the nozzle remain the same during this phase, specially the injection pressure in the feeding line and the needle movement inside the injector. This is in contrast to what is found in the literature for other kind of injectors as GDI or diesel [9, 13, 14] where usually there are fluctuations in the pressure line and needle lift that are evident in the momentum flux curves [11]. Lastly, instants before the end of the injection event, an increase in the momentum flux signal is registered and is similar for all the tested conditions. This behaviour might be attributed to the closing of the injector needle, pushing through the orifices the final stream of liquid as it returns to its seat, but further studies must be performed in order to confirm the cause of this behaviour.

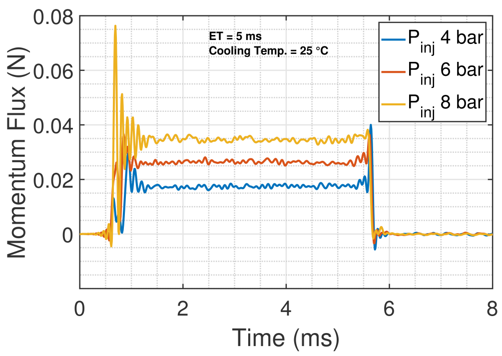

Figure 5. Comparison of the effect of injection pressure over the momentum flux signal.

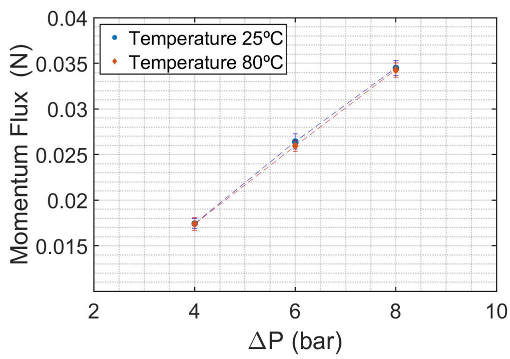

Figure 6. Average of the Stabilized Momentum Flux for each tested condition

An average of the momentum flux signal is calculated with the data obtained during the fully opened needle (the stable region) in order to compare the behaviour of the momentum flux for every tested condition. In Figure 6 the averaged momentum flux signal versus the pressure difference is presented, where the blue line in the plot represents the momentum flux for the 25 ℃ cooling fluid temperature, meanwhile the red line represents the curve for the 80 ℃. The momentum flux value increased linearly with the difference of pressure and the effect of the coolant liquid temperature over the acquired signal is negligible for the three tested injection pressures. Further measurements are planned to be done in order to evaluate the influence of the coolant fluid at higher temperatures closer to the flash boiling point of the UWS fluid.

Rate of injection determination

The experimental results obtained for momentum flux altogether with the equations presented in the theoretical background, were used for the determination of the instantaneous rate of injection. In Figure 7 two rate of injection curves are presented. The blue line represents the ROI curve calculated directly with Eq. 3 and the red curve represents the one obtained with the Eq. 6, that is corrected considering the experimental injected mass quantity.

Figure 8 illustrates the measured injected mass against the square root of the injection pressure. The injected mass values were used to correct the ROI signal calculated with Eq. 6 for each tested condition.

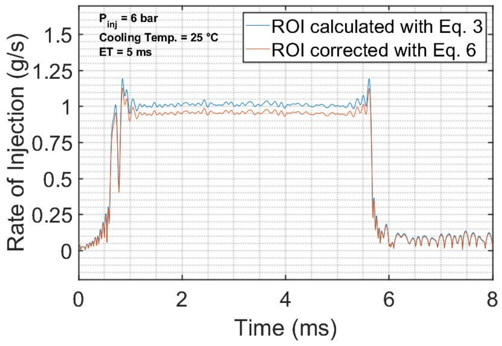

Figure 7. Comparison of the Rate of Injection (ROI) signals.

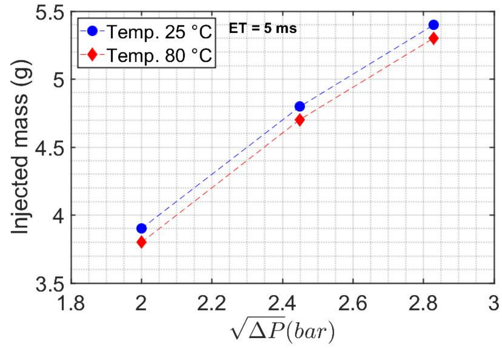

Figure 8. Experimental injected mass.

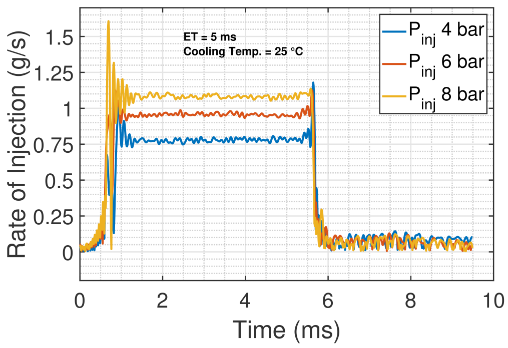

Figure 9. Comparison of the effect of injection pressure over the Rate of Injection.

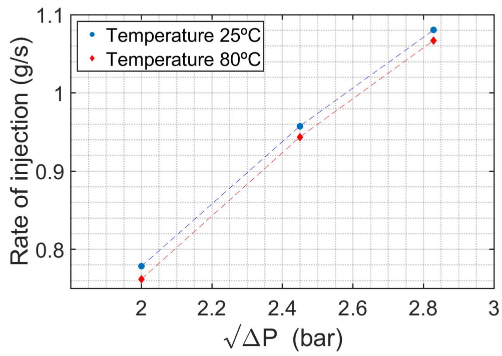

Figure 10. Average of the Stabilized Rate of injection for each tested condition.

Figure 9 presents the rate of injection as a function of time. The image displays three curves which represent the injection pressures of 4 ,6 and 8 bar at an injector cooling temperature of 25 ℃. The curves present the corrected rate of injection calculated with the data obtained with the measurements of the momentum flux and the injected mass using equation 6. It is observed that the ROI curve increases as the injection pressure is raised from 4 bar to 8 bar.

To compare the behaviour of all the tested conditions, an average of the mass flow is calculated in the phase where the injector is fully opened for every tested condition. Figure 10 presents the average of the ROI versus the square root of the injection pressure difference, where the two lines representing the temperatures of 25 ℃ (blue line) and 80 ℃(red line) increase linearly with the square root of the pressure difference. Additionally, the effect of the temperature of the cooling fluid can be appreciated, where the line corresponding to the mass flow of 80 ℃ is below the line of 25 ℃ due to the decrease in the density of the injected UWS. These observed behaviours of the rate of injection for a UWS injector are in concordance with the results available in the literature for fuel systems, such as diesel and GDI [15, 16].

The importance of these results relays on the method to obtain the ROI of an UWS injector through the measurements of the momentum flux of the spray, which is not feasible to obtain with traditional measurement techniques due to its operation conditions of low discharge pressure and gaseous environment. Also, the level of agreement between the equations that were formulated in previous sections and the experimental measured injected mass, where the difference between the two is well below 1%.

Finally, the type of information obtained with this methodology is useful for validating numerical models (or as inputs for CFD simulations), as well as for the design and calibration process.

Conclusions

In this research, the momentum flux signal of a Urea-Water Solution (UWS) injector was measured. The experiments were performed in an experimental facility developed at CMT-Motores Termicos for the determination of the

UWS spray momentum flux, where a piezoelectric sensor was located near the nozzle exit of the injector, which measures the impact force of the spray. Three different injection pressures and two injector cooling temperatures were tested.

The acquired momentum flux signals obtained after 50 repetitions were averaged and then filtered with a low pass filter in order to be able to analyse the data. The resulting curves presented the behaviour of a typical injection: a first phase where the opening of the injector occurs, a stable region where the needle of the injector is fully opened and the closing of the injector. The momentum flux measurements during the stable region of the injection event were averaged for all the tested conditions and then compared. The momentum flux increased with the pressure difference, meanwhile the temperature of the cooling fluid had a negligible effect in the tested range.

The results obtained from the momentum flux measurements were used to calculate a Rate of Injection (ROI) curve for each test point, then these curves were corrected using the measured injected mass. The obtained results are promising because the curves behave as those found in the literature for fuels systems, suggesting that this method is adequate for the hydraulic characterization of the UWS injector. The ROI linearly increases with the square root of the pressure difference and the cooling temperature of the fluid has a considerable effect decreasing the ROI as the temperature is raised.

Overall, the momentum flux measurement is a robust measuring technique that provides useful information about the injection event and the injector performance. The results obtained with this methodology can work as inputs for Computer Fluid Dynamics (CFD) or can be used to validate numerical models. Additionally, the measured momentum flux and the calculated ROI can be used for the Selective Catalytic Reduction (SCR) design and calibration process.

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Nomenclature

UWS	Urea Water Solution
SCR	Selective Catalytic Reduction
ROI	Rate of Injection
ASOE	After Start Of Energizing
CFD	Computer Fluid Dynamics
$\dot{M}$	Momentum Flux [N]
$\dot{m}$	Mass Flow [g/s]
C_v	Velocity Coefficient [-]
C_A	Area Coefficient [-]
ρ	Density [Kg/m^3]
P_{inj}	Injection Pressure [bar]

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