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EVALUATION OF AN AUTOMOTIVE INJECTOR FOR DROPLETS GENERATION IN THE STUDY OF DISPERSED FLOW FILM BOILING IN LOCA CONDITIONS

Eduardo Dambros Telli
Carlos Roberto Altafini
Universidade de Caxias do Sul - R. Francisco Getúlio Vargas, 1130 - Petrópolis, Caxias do Sul – RS, Brazil
edtelli@ucs.br; craltafi@ucs.br

Giovani Dambros Telli
Universidade Federal do Rio Grande do Sul, Mechanical Engineering Graduate Program - Rua Sarmento Leite, 425- Centro Histórico, Porto Alegre – RS, Brazil
giovani.telli@ufrgs.br

Arthur V. S. Oliveira
Michel Gradeck
Université de Lorraine, CNRS, LEMTA, F-54000 Nancy, France
arthur.oliveira@univ-lorraine.fr ; michel.gradeck@univ-lorraine.fr

Abstract. *In order to improve an experimental workbench used to study the heat and mass transfer of a Pressurized Water Reactor (PWR) during a loss-of-coolant accident (LOCA) at sub-channel scale, has been emerged a demand for the replacement of a piezoelectric injector for another one capable to provide higher flow rate of injected water. These injected droplets are mixed with water vapor at high temperature, providing a dispersed steam-droplets flow that is injected in the test section. This work is an experimental characterization of a Marelli™ IWP220 electromagnetic automotive injector operating with demineralized water. The main purpose is to understand how the injector mass flow, droplet velocity and diameter vary according to adjustable parameters such as pressure injection and duty cycle. Scale weight apparatus was used to measure sprayed water mass through certain time to obtain mass flow rate and a Phase Doppler Anemometry (PDA) system to measure the droplets velocity by Doppler Effect and their diameter by phase difference. The results provided characteristic curves regarding these parameters, which in turn serve for evaluating and comparing injection capability to supply the desired droplet characteristics for dispersed flow film boiling studies. Droplet velocity rising with pressure, smaller droplets losing its kinetic energy to air friction and transient behavior of the electromagnetic injector were some noticeable effects in this work's results. The range of droplets diameters and liquid volume fraction values was found to be closer to LOCA conditions than with the piezoelectric injector. Moreover, the latter has no mass flow rate control besides pressure variation, also indicating that the former suits better for LOCA experimental studies.*

Keywords: *PWR Reactors, LOCA, PDA, automotive injection, droplet characteristics.*

1. INTRODUCTION

Nuclear energy is one of the latest non-renewable energy sources with practical achievement succeeded by human technology. Such promising advance requires efforts to develop studies, regarding mainly about the safety of nuclear facilities. A recent research from IAEA (2015) indicates that the most used nuclear reactor design is the Pressurized Water Reactor (PWR). This type of reactor uses high-pressure water as coolant, preventing it from evaporating when heated by the nuclear reaction and exchanging heat with a secondary system that carries the output energy through a steam turbine, which generates electricity.

One hypothetical accident considered in these reactors is the large-break loss-of-coolant accident (LOCA). When this accident takes place, the pressure drops and the temperature rises inside the reactor's core, inflating or even breaking the zirconium alloy tubes that are housing the uranium pellets. An emergence core cooling system is activated and the reflooding phase takes place, injecting water into the core. At this point, the fuel rods temperature is extremely high (above 1000 ºC) so the water rapidly evaporates, reaching the Leidenfrost regime. Yet some droplets still exist in liquid state, forming a dispersed two-phase flow that plays an important role to cool down parts of the fuel rods that are downstream of the water level.

There have been many efforts to study the thermohydraulic effects inside the core of PWR reactors under LOCA conditions. Several of practical experiences have been performed by many authors; such efforts reproduce through experimental benches the reflooding phase in a real reactor. In the studies of Lee et al. (1984), a model was developed in which the population and size of droplets in the biphasic region of the reflood phase was described. Two droplet generation mechanisms were witnessed: film fragmentation and hydrodynamic fragmentation. The evaporation rate was analyzed taking into account the convection and radiation heat transfers.

Lelong (2010) showed the interaction between water droplets and hot surfaces in a PWR during LOCA situation scale, obtaining important data to integrate into a mathematical model that aims to describe the studied flow. Moreover, Kim et al. (2017) made a reproduction of the reflood phase to understand the effect of the blocked zone length in the role of cooling, varying the reflooding rate. A 2x2 electrically heated rod assembly was used, simulating the same blockage ratio in different lengths. In addition to the thermal exchange phenomena, the behavior of the droplet diameter and velocity was also observed inside the blocked region.

From a compilation of these works – Lee et al. (1984), Lelong (2010) and Kim et al. (2017) – characteristics such as: droplet velocity, diameter, liquid volume fraction, vapor temperature and pressure, and also fuel rods temperature and emissivity can be extracted to better understand steam-droplets flow in the reflooding phase of a PWR under LOCA. For instance, the droplet diameter values lies between 50 and 1000 μm and the volumetric fraction ranges from 10^{-4} to 10^{-2} (volume of droplets divided by the volume of vapor); vapor temperature lies between its saturation temperature and 800 °C under a pressure of 3 bar; fuel rods can get from 300 to 1200 °C with a minimum emissivity of 0.5 and a maximum of 0.8.

In a study performed by Jin et al. (2018), reflood tests were made in a 7x7 representative rods arrangement to better understand the biphasic flow in transient state. The results suggest a low capability of heat exchange of the mixed flow in regions away from the quench front. On the other hand, in regions just downstream the cooling area, the flow was found to be almost in thermal equilibrium, indicating that the heat transfer in this area was very efficient. Besides that, it was discovered that the ratio of gas phase velocity between liquid phase velocity (slip ratio) is highly dependent of droplet diameter and reflooding time – the bigger the droplet and smaller the distance from the quench front, higher is the slip ratio.

Peña Carrillo (2018) had the purpose to characterize this dispersed steam-droplets flow representative of the reflooding phase at sub-channel scale. The author developed an experimental bench called COLIBRI, obtaining droplets characteristics such as diameter, volume fraction, velocity and temperature, as well as heat flow extracted by the two-phase flow. More details of this experimental bench can also be found in (Peña Carrillo et al., 2019) and Oliveira et al. (2020a). Although their experiment did not considered the flow redistribution effect, Oliveira et al. (2020c) used magnetic resonance velocimetry (MRV) to obtain three-component velocity fields of water flow within different test sections. The experimental results should enhance a mathematical model for describing the physical phenomena inside the PWR's core during a LOCA, such studies are described by Glantz et al. (2018) and Oliveira et al. (2020b). Nevertheless, the droplets in this study were smaller and the liquid volume fraction was very low compared to LOCA conditions.

In this regard, the present work focuses on evaluating the capacity of an automotive injector to supply water droplets and replace a piezoelectric droplet generator formerly used in the COLIBRI test bench. Mass flow rate and droplets characteristics, i.e. diameter and velocity, were measured at different pressures and duty cycles. A comparison is made of which injector is able to be more representative in generating droplets according to a LOCA situation.

2. METHODOLOGY AND EXPERIMENTAL PROCEDURE

There is interest in evaluating a Marelli™ electromagnetic automotive injector in order to substitute the currently used piezoelectric injector FMP TECHNOLOGY™, reference MTG-01-G. The latter has a fine intern membrane, which generates droplets with high precision diameters values that ranges from 50 to 200 µm and there is no mass flow rate control apart from controlling the injection pressure. The device to be evaluated is the automotive electromagnetic injector IWP220 by Magneti Marelli™, having a nominal relative pressure of 2.5 bar, therefore its range of use goes from 1 to 3 bar and a maximum volumetric flow rate of water obtained with this injector was 11 cm^3/s in a single spray.

Two experimental procedures took place: one to obtain the mass flow rate and another one regarding the droplet's characteristics using Phase Doppler Anemometry (PDA) technique, both at different pressures. For the first, the electromagnetic injector's duty cycle varied from 10 to 90% with a step of 10% for three levels of injection pressure – 1, 2 and 3 bar. An additional experiment was made to verify the temperature influence in mass flow rate results, varying temperature of the water through a thermal bath, three temperature values were adopted - 26, 50 and 75 °C - for a fixed pressure of 2 bar. As for the PDA measurements, the same three levels of pressure were adopted although the duty cycle had only three values: 20, 50 and 80%. The injector was connected to a 12 V source and a signal generator whose frequency was fixed at 45 Hz square wave, the test fluid was demineralized water supplied through a high-pressure tank of 6 bar, which could be regulated before reaching the injector. The assembly scheme for the experimental part of the study can be seen in Figure 1.

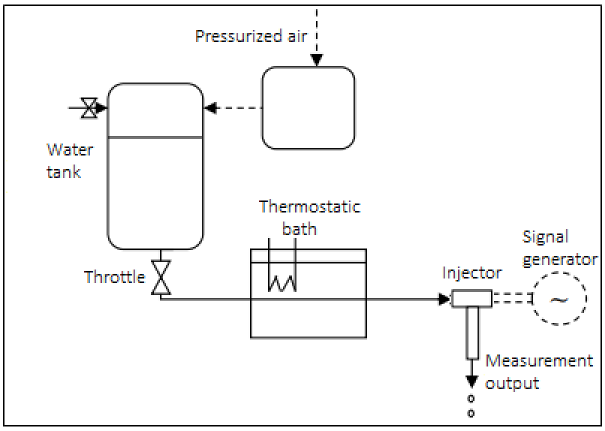

Figure 1. Simplified scheme of experimental procedure

To measure the injection mass flow rate, a recipient was used right after the injector, collecting the water in room temperature and pressure for about 30 seconds in each experiment. The collected mass was put in scale while the operation time was also measured with a manual timer, extracting finally the mass flow rate for each experience. In measurement output showed in Figure 1 is also contained the droplet's velocity and diameter measurements, made with Phase Doppler Anemometry (PDA) - technique, which uses two crossed lasers, forming an ellipsoidal measurement volume, in which the Doppler frequency effect is verified to measure droplet velocity and phase shift of two distinct laser detectors for diameter measurements, such technique is deeply described in Albrecht (2003). PDA system model used was Dantec 57X10 provided by DANTEC-DYNAMICS™ and includes enough components to vary some important parameters such as the size of the measurement volume - also translated as maximum detected droplet diameter: 2000 μm for this experiment, laser frequency through a Bragg cell, laser power and others geometric aspects of the assembly. After a calibration process of the whole system, signal is collected and processed by the BSA Flow Software. Using a three-dimensional system to position the lasers and the receptors with great precision, the injector's exit was located 3 centimeters above the measurement volume. The uncertainty of the droplets diameter measurement is 10%, while the velocity's is 5%.

All the data collected from these experiences was processed using MATLAB, translating PDA experiences into graphs that show correlations between velocity and diameter as well as the distribution of their values for the different operation conditions. As for the mass flow rate characterization, a mathematical model was developed that expresses the mass flow rate value as a function of the duty cycle and pressure, within the precision of 4%. To compare the values obtained in results to the ones found in literature, the calculation of the liquid volume fraction took place as shown in Eq. (1) and Eq. (2), suitable for experimental results. In these equations, $\dot{\mathrm{m}}$ (kg/h) stands for mass flow rate and ρ (kg/m³) for density, the subscript "D" makes reference to the word "Droplet", while the letter "V" to "Vapor". Although in the present work's tests there was no presence of water vapor; the values for vapor mass flow rate were adopted from the methodology used in the work of Peña Carillo (2018), which took place in the same workbench COLIBRI, being 2 kg/h the minimum and 8 kg/h the maximum vapor mass flow rate. As for the density values, 959 kg/m³ was used for the droplet density (1 bar and 100 ºC) and 0.493 kg/m³ for vapor density (1.3 bar and 300 ºC).

$$\alpha_{\max} = \left(\frac{\frac{\dot{\mathrm{m}}_{\mathrm{Dmax}}}{\rho_D}}{\frac{\dot{\mathrm{m}}_{\mathrm{Vmin}}}{\rho_{\mathrm{V}}} + \frac{\dot{m}_{D\max}}{\rho_D}} \right) \tag{1}$$

$$\alpha_{\min} = \left(\frac{\frac{\dot{\mathrm{m}}_{\mathrm{Dmin}}}{\rho_D}}{\frac{\dot{\mathrm{m}}_{\mathrm{Vmax}}}{\rho_{\mathrm{V}}} + \frac{\dot{m}_{D\min}}{\rho_D}} \right) \tag{2}$$

3. RESULTS AND DISCUSSION

At first, three volumetric flow rate (Q) linear relations has been found showed in Fig. 2 – one for each pressure level – as a function of the duty cycle (DC). By data regression, a model shown in Eq. (3) was found, which describes the volumetric flow rate relation with the experimental controlled parameters. Note that *P* stands for pressure in bar and *DC* for duty cycle in percentage. The error of this model has been verified to be lower than 4% inside this data array. The minimum mass flow rate found in kg/h was 2.43 and the maximum was 31.05, these values are used to calculate the liquid volume fraction [(Eq. (1) and Eq. (2)], which values are shown in Tab. 1.

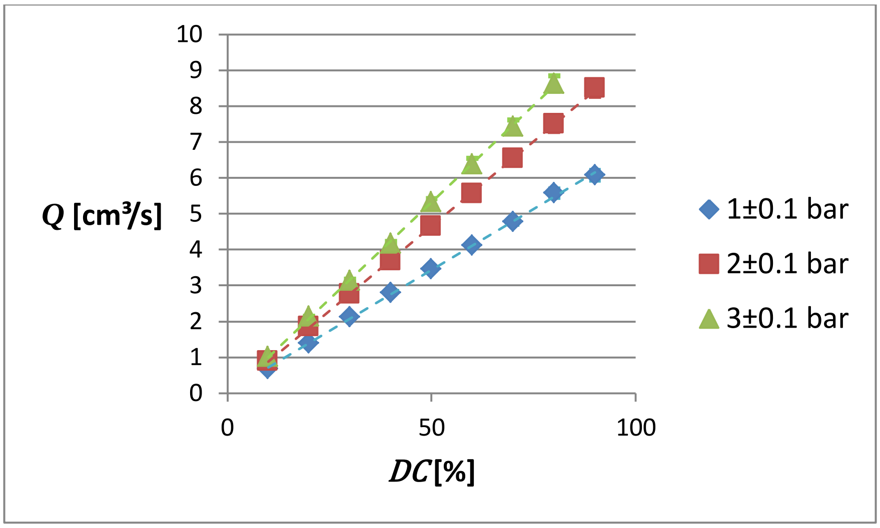

Figure 2. Measurements points for mass flow rate according to pressure and duty cycle

$$Q = \left[3.545 \ln P + 6.865\right]\left[0.01DC - 0.0031\right] \quad (3)$$

The distribution of droplet's diameters and velocity was plotted in graphs so it is possible to understand the droplets injection characteristics. Figure 3 and Figure 4 exhibit the behavior of the droplets diameter and velocity distributions, respectively, both with a fixed duty cycle of 50% and three levels of pressure. To check a correlation between diameter and velocity, a correlation graph was plotted and it is presented in Figure 5. Moreover, Figure 6 presents a global analysis of all PDA experiments within its associated error, being possible to check for correlations between parameters, both for droplet diameter and velocity.

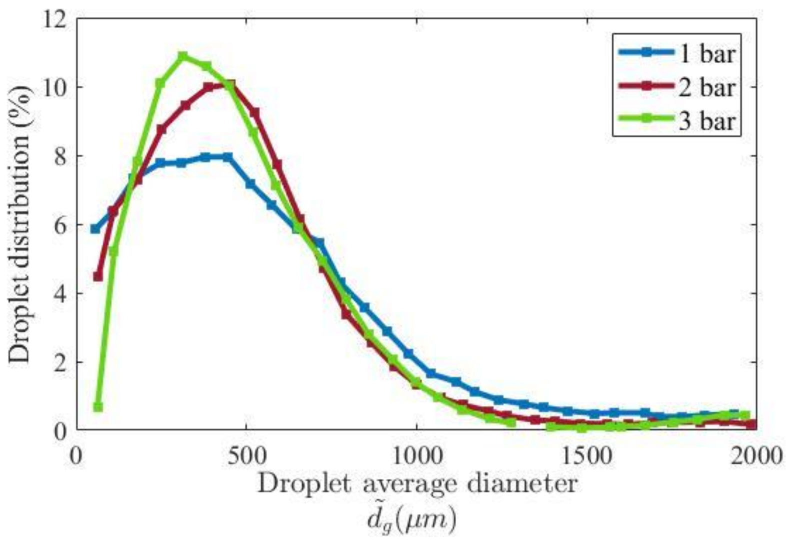

Figure 3. Distribution of the droplets average diameter for three levels of pressure with a duty cycle of 50%

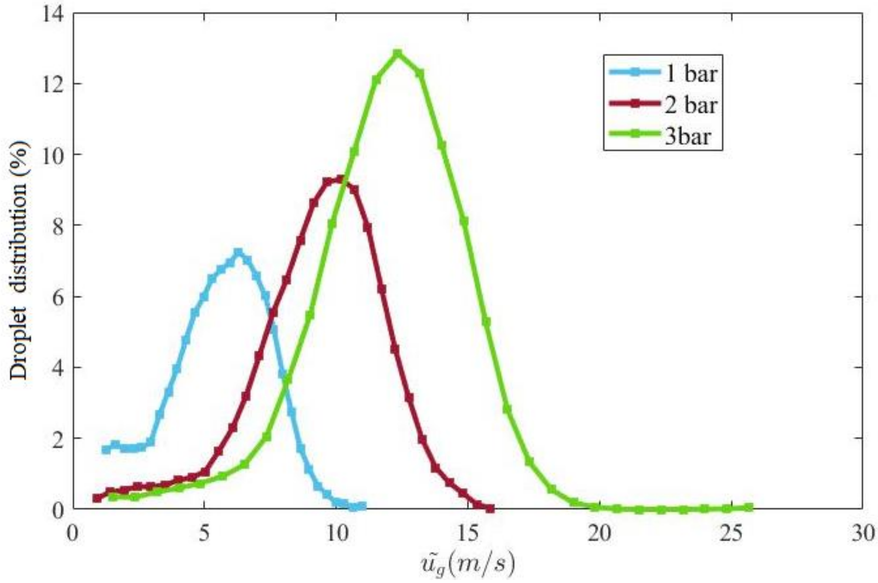

Figure 4. Distribution of the droplet's average velocity for three levels of pressure with a duty cycle of 50%

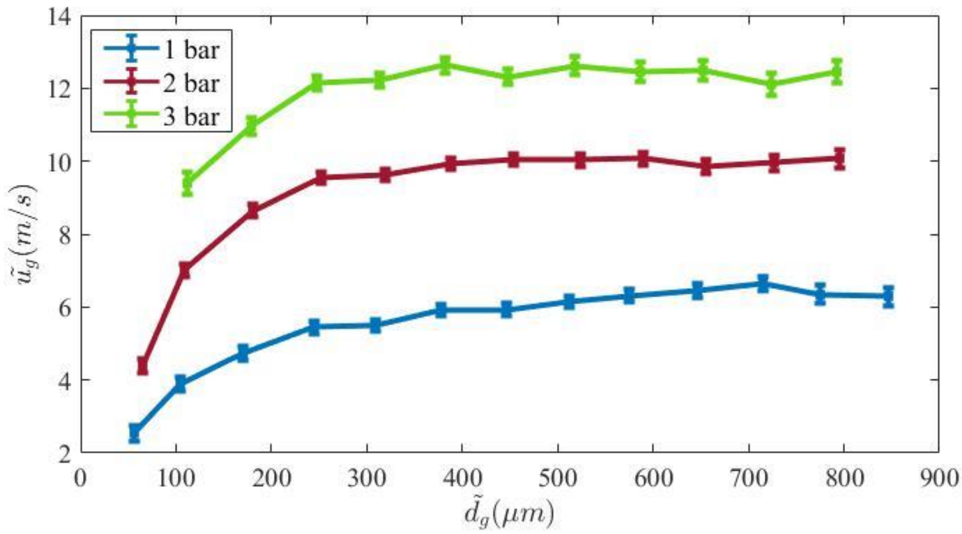

Figure 5. Velocity/Diameter correlation with three pressure levels and a fixed duty cycle of 50%

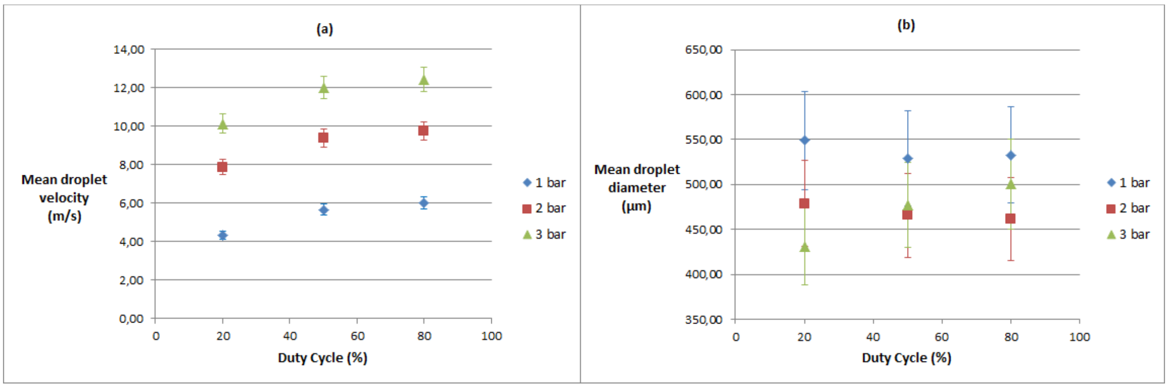

Figure 6. Droplet characteristics mean values for all PDA experiments.

In Figure 3, a slight pressure sensitivity can be noticed and so a steep rising curve until reaching the most counted diameter and then a steadly decreasing percentage for greater sizes. It is not possible to say that pressure has a strong correlation with mean droplet diameter since the error associated is significant if compared to the difference between these values, as it is possible to see in Figure 6. The shape found in distribution is a typical log-normal and is similar to the observed during COLIBRI experiments, as checked by Peña Carrillo et al. (2019). In Figure 4, it is clear how pressure plays an important role in increasing the droplets velocity, noting also percentage peaks, having a narrow array of velocity values. The average velocities (m/s) for 1, 2 and 3 bar corresponds, respectively, to: 5.67, 9.37 and 12.01, while the average diameter (μm) obtained were: 529.54, 465.65 and 477.36 – all these values for a 50% fixed duty cycle. Again, in Figure 6, this time regarding mean droplet velocity, besides the pressure influence, the duty cycle also plays a role in increasing the droplets velocity.

Figure 5 shows the correlation between the droplets diameter and velocity. It is clear once again that pressure has great influence, although for small droplets sizes this effect does not happen equally. Another phenomena takes place in the beginning of the graph and this is due to the small inertial forces of the small droplets that tend to follow the stream in which they are – in this case the steady room air – so the small droplets are rapidly decelerated because of the air resistance. Droplets larger than 250 μm are enoughly inertial so their velocity is nearly independent of their diameter.

The temperature influence in mass flow rate was verified to have insignificant effects in mass flow rate results, as the variance of results stayed under the experimental error percentage. Figure 7 presents the plot of a velocity distribution graph for a fixed pressure of 2 bar and three duty cycle curves. It is noticeable that there is a growing phenomenon of the mean droplet velocity for each DC level and that can be interpreted as a transient state of the electronic injector operation method, since its interior consists of a mechanical piece that closes and opens the valve every cycle. This effect can also be observed, although less clearly, in the diameter distribution graph in Figure 8, the higher is the duty cycle, less distributed are the droplet characteristic and the higher is the mean value.

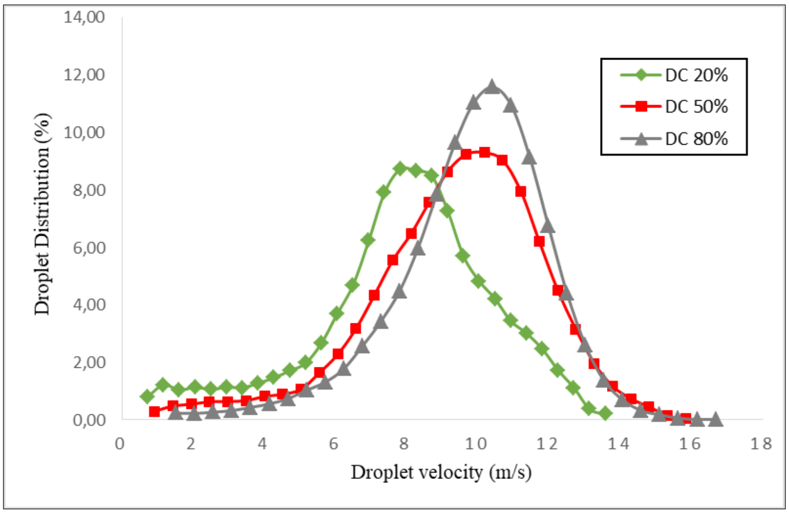

Figure 7. Droplet velocity distribution for three values of duty cycle and fixed pressure of 2 bar.

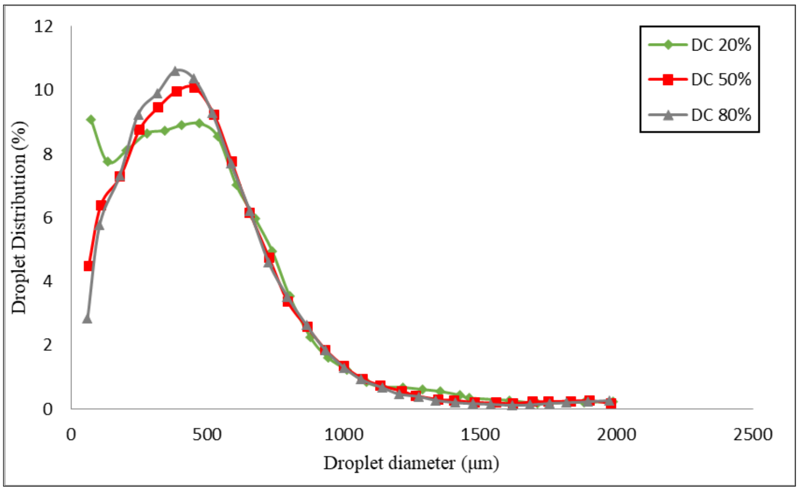

Figure 8. Droplet diameter distribution for three values of duty cycle and fixed pressure of 2 bar.

Finally, Table 1 shows the numeric range of the different parameters taken account in this study to compare the two injection methods. Notice that droplets velocity is not as comparable as the other two parameters in function of its strong correlation with the vapor velocity, which is different for each experiment. Yet it is clear that the automotive injector have greater similarity in these ranges of values than the piezoelectric injector, having a typical log-normal distribution curve with great range, while the piezoelectric injector presents much higher precision in droplet diameter values in a small range. Therefore, the injector tested can be more representative for experimental studies if the goal is to simulate droplets with a high diversity in its characteristics and have a better control of mass flow rate.

Table 1. Parameters comparison between different injection methods and LOCA conditions

Parameter	LOCA conditions	Piezoelectric injector	Automotive injector
Droplets diameter (μm)	50 - 1200	5 - 300	0 – 1300(1)
Droplets velocity (m/s)	5 - 14	15 - 20	3 – 18(2)
Liquid volume fraction (m³/m³)	$10^{-4} - 10^{-2}$	$10^{-4} - 2\times10^{-4}$	$6\times10^{-4} - 2\times10^{-3}$

(1) Distribution shown in Figure 3.
(2) Distribution shown in Figure 4.

4. CONCLUSION

The results of this work allowed the construction of a methodology for characterization of an automotive injector to be used in the experimental bench COLIBRI, having knowledge of the generated droplets characteristics, enlarging its operation conditions and potentially better reproducing LOCA conditions at sub-channel scale experiments. Some small-scale physical effects could be noticed during this work and contribute to understand how the reproduced flow behaves when droplet diameters tend to zero and the technical aspect of the electromagnetic injection of not being able to maintain a steady state of droplet characteristics while varying the duty cycle.

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