Flashing injection of CO_2-dissolved mixture

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An experimental study on flashing injection of gasoline-dissolved CO_2 mixtures through specially designed injectors was performed. The injectors used comprised an expansion chamber in order to promote the CO_2 flashing. Malvern Mastersizer-X was used to measure the spray characteristics. High-speed digital video camera was employed to visually register the expansion chamber flow patterns.
The geometry of the expansion chamber was optimized to produce minimum SMD. The high-speed camera photographs, have revealed the different flow regimes inside the expansion chamber under different operation conditions, and thus provided a solid ground to explain the relationship between the optimal chamber dimensions, the operation conditions, and the observed characteristics of the spray.

1. Introduction

In order to limit unburned hydrocarbons emissions in IC engines to an acceptable level, the injected fuel must vaporizes before the spark is introduced. Moreover, the complete evaporation of the fuel can make the ignition process more robust [1]. Previous studies showed that fuel droplet of SMD<25μm is an essential requirement for gasoline direct injection engines. The most common technique for gasoline direct injection combustion systems involves an elevated fuel pressure in combination with a swirl nozzle. The required fuel injection pressure for achieving SMD of 15 to 25μm is typically between 5 and 13MPa [2].
Recently, a unique technique for achieving the desired fuel spray characteristics has been proposed. It involves atomization of fuel containing dissolved gas and is based on the flash boiling phenomena. Because it enhances atomization and increases initial spray angle for rapid fuel-air mixing along with reduction of spray penetration [3], the flash boiling fuel atomization has a promising potential application to direct injection engines. A number of studies have been performed on atomization and combustion of diesel fuel containing dissolved CO_2 [4, 5, 6]. It was found that the characteristics of the spray for the liquefied CO_2 mixed fuel are better than those of a pure diesel fuel spray. This has been attributed to the flash boiling process. The effect is promoted as the ambient pressure decreases and the mole fraction of the CO2 increases [4]. Zhen et al. [5] studied the flow pattern of diesel fuel containing dissolved CO2 in a hole-type injector with different aspect (L/D) ratios. They found that cavitations phenomena at the sharp edges of the orifice affect the atomization performance of a given injector by changing the inside orifice flow pattern. They also concluded that increasing the nozzle L/D ratio improves the spray quality of the fuel-CO_2 mixture [6].

Zeigerson-Katz and Sher [7, 8, 9], and Solomon et al. [10, 11], studied the effect of installing an expansion chamber downstream the discharge orifice, for liquid containing dissolved gas. They have observed a positive effect of the expansion chamber on the SMD of the final spray. Geometrical parameters of the chamber were optimized with respect to their maximum effect on the atomization of the mixture. Sher and Bar [14] studied theoretically the role of the expansion chamber in the flashing process. They suggested a physical-grounded explanation to the existence of an optimal volume and inlet to discharge orifice diameter ratio (Di/De) with respect of their maximum effect on the atomization of a binary mixture. The effect of the pressure of the expansion chamber for the fuel-CO_2 mixture atomization for means swirl atomizers is reported elsewhere [12, 15].

2. Experimental set-up and procedure

The experimental set-up is shown schematically in fig. 1. The pressure control unit maintains a constant supply flow of the mixture in test under steady-state conditions. The unit comprises of a Rosemount pressure transducer that is calibrated for pressures of 0–10MPa over the entire voltage output, controlling unit, and pneumatic Samson needle valve. An axial velocity in the order of 1m/s at the measuring location was obtained. The injector geometry and its dimensions used in the present study are presented in fig. 2. The expansion chamber was made of Perspex to allow visual observation and recording of the flow pattern. A high-speed video camera, of up to 8,000 frames/s was used.

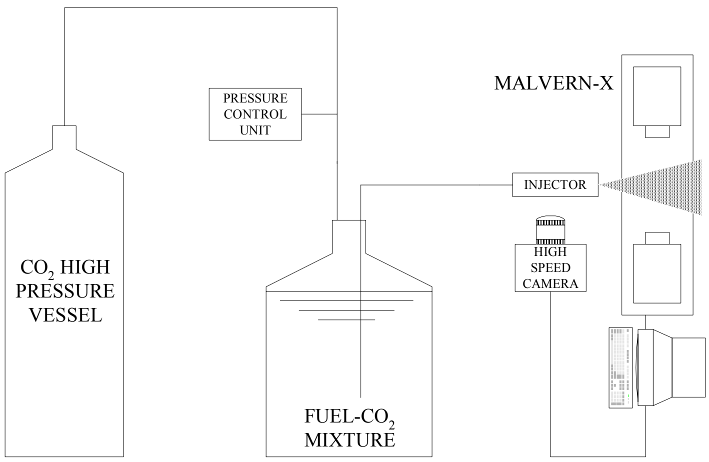
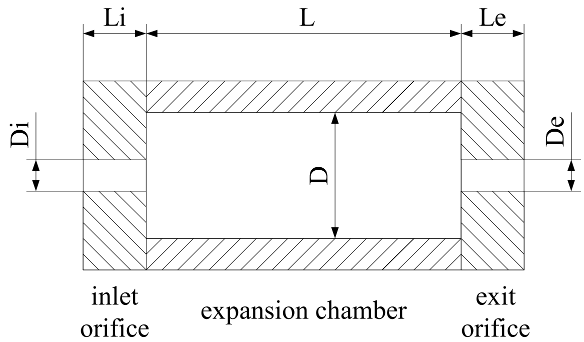


Fig. 1. Experimental set-up

In each experimental set a desirable amount of CO_2 was dissolved in the fuel and allowed to reach equilibrium overnight. Based on some prior calibrated solubility experiments [12], the final equilibrium pressure determined the exact volumetric CO_2 to fuel ratio. The mixture was driven by CO_2 gas (from the high pressure vessel) through the injector to the atmosphere. A Malvern Mastersizer-X was used to measure the spray quality, and a high-speed video camera was used to record the flow pattern inside the expansion chamber. The pressure inside the expansion chamber was measured by using an ATEX 2640 pressure traducer.



L = 5, 7.5, 10, 12.5, 15, 17.5, 20, 22.5, 25, 30, 40, 50 mm
D = 10 mm
Li = Le = 0.8 mm
Di = 0.2mm
De = 0.2, 0.3, 0.4, 0.5 mm

Fig. 2. Injector geometry

The experiments were carried out in the range of injection pressures from 0.8 to 1.3MPa. No spray was observed below 0.8MPa. Above 1.3MPa the high optical density of the spray imposed a technical limit. For this pressure range, for all the injector-pressure combinations, the obscurations didn't exceed 37%. Spray measurements were carried out at a distance, S, of 100 and 150mm downstream the discharge orifice.

2. Results and discussion

The goal of the present study is to investigate the influence of the geometric parameters of the injector and injection pressure on the spray parameters of fuel-CO_2 dissolved mixtures. SMD and D90 were chosen to characterize the spray quality. The D90 was chosen due to the major effect of large droplets on the emission of unburned hydrocarbons. The repeatability of the results was found to be within ±15%.

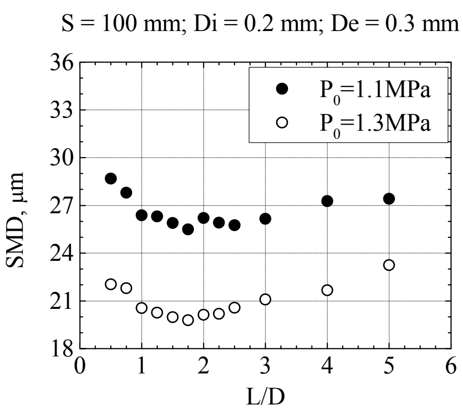


Fig. 3. SMD at S=100mm

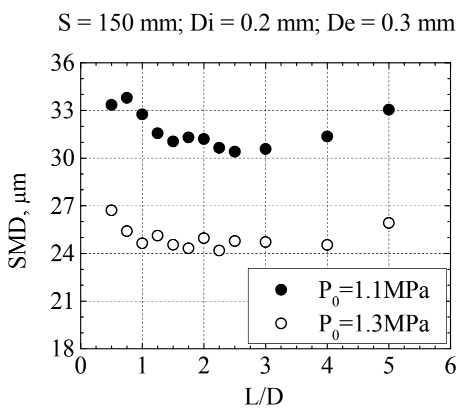


Fig. 4. SMD at S=150mm

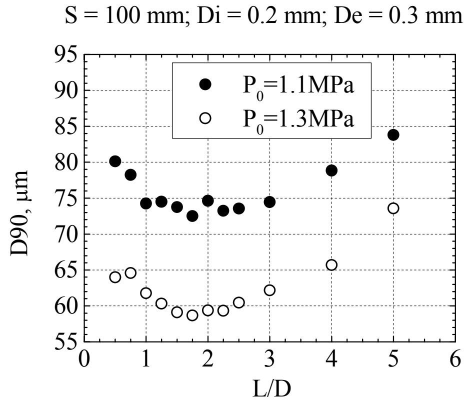


Figure 5. D_{90} at S=100mm

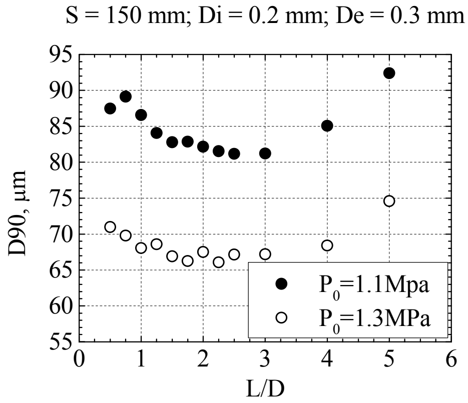


Figure 6. D_{90} at S=150mm

Figures 3 and 4 show how the injection pressure and the measurement distance affect the SMD vs. the expansion chamber aspect ratio (L/D). The effect on the D90 is shown in figs. 5 and 6. Injection pressures of 1.1MPa and 1.3MPa correspond to CO_2 mass fraction of 5.5% and 7%, correspondingly. Following the recommendations of [6, 7 and 8] for optimal performances, the orifices' diameters of the injector, De and Di, were selected such as De/Di=1.5.

For all cases, a higher injection pressure results in a lower SMD for the following two main reasons: a) the CO_2 content is higher, thus higher vapor pressure (more nuclei per unit volume are generated and faster bubble growth rate is expected), and b) the discharge velocity is higher and thus higher shear stresses are anticipated. Figures 3 and 4 demonstrate the effect of the downstream measuring distance. When the distance increases, higher SMD is recorded; this is due to the faster evaporation rate of the smaller droplets (their surface area to volume ratio is higher).

The effect of the aspect ratio of the expansion chamber (L/D) is well demonstrated in fig. 5 (P_0=1.1MPa and S=100mm); when this ratio is optimized from 0.5 to 1.75, D90 is reduced from 80 to 73μm. This is an important improvement since according to the D2 law, when a droplet of an initial diameter of 73 will completely evaporate, the droplet of 80μm will still have a diameter of 34μm. When the aspect ratio is optimized, lower HC emission is therefore expected.

Figures 3-6 clearly show an optimal value for the L/D ratio. This ratio corresponds to an optimal residence time that is required to achieve the desired optimal void fraction at the discharge orifice [14]. A shorter residence time results in a lower void fraction and a higher SMD is expected. A longer residence time may lead to an extensive bubbles coalescence, phase separation, and thus stratified flow at the exit. Under these conditions, unstable process has been observed. The strong scattering of the results, as shown in fig. 7, supports the noticed instability.

Figure 8 presents the effect of the expansion chamber length on the flow pattern inside the chamber (here P_0=1.1MPa, Di =0.2mm, and De =0.3mm). The flow direction is from left to right. Slow-motion playbacks revealed that steady toroidal vortex is developed (common for a wide range of chamber geometries), such as strong backflow occurs along the walls. At the center of the photographs of 5 and 10mm long chambers, a non-homogeneous region appears at the center of the chamber.

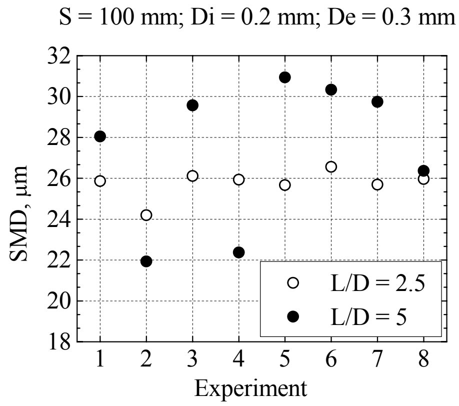


Fig. 7. Atomisation instability

Slow video playback showed that these regions are large-size gas bubbles (the pixel density of the video recording allowed us to register only bubbles bigger than 150µm). These bubbles develop in the center of the toroidal vortex and after reaching some appreciable size are expelled toward the walls of the chamber. This process results in non-uniformities of the resulting spray. Further increase of the chamber length to 30mm (close to the optimal length for minimal SMD) appears to elongate the toroidal vortex shape, to decrease the rotation speed and to eliminate the non-uniformities regions. A smilingly homogeneous bubbly pattern prevails in the entire chamber volume. For the 50mm chamber length, a similar flow pattern appears up to midway, and then the two phases seem to separate one from the other. The large bubbles are subjected to buoyancy forces and appear to accumulate at the upper chamber wall. In this case, unstable flow has been observed.

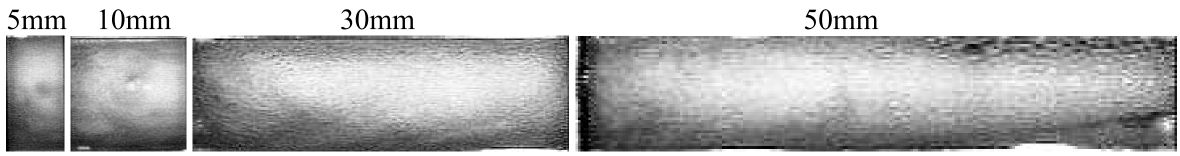


Fig. 8. Flow pattern photographs for four different chamber lengths (L).

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