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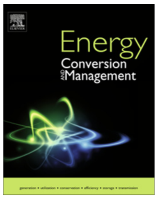

Linking instantaneous rate of injection to X-ray needle lift measurements for a direct-acting piezoelectric injector

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ABSTRACT

Internal combustion engines have been and still are key players in today's world. Ever increasing fuel consumption standards and the ongoing concerns about exhaust emissions have pushed the industry to research new concepts and develop new technologies that address these challenges. To this end, the diesel direct injection system has recently seen the introduction of direct-acting piezoelectric injectors, which provide engineers with direct control over the needle lift, and thus instantaneous rate of injection (ROI). Even though this type of injector has been studied previously, no direct link between the instantaneous needle lift and the resulting rate of injection has been quantified. This study presents an experimental analysis of the relationship between instantaneous partial needle lifts and the corresponding ROI. A prototype direct-acting injector was utilized to produce steady injections of different magnitude by partially lifting the needle. The ROI measurements were carried out at CMT-Motores Térmicos utilizing a standard injection rate discharge curve indicator based on the Bosch method (anechoic tube). The needle lift measurements were performed at the Advanced Photon Source at Argonne National Laboratory. The analysis seeks both to contribute to the current understanding of the influence that partial needle lifts have over the instantaneous ROI and to provide experimental data with parametric variations useful for numerical model validations. Results show a strong relationship between the steady partial needle lift and the ROI. The effect is non-linear, and also strongly dependent on the injection pressure. The steady lift value at which the needle ceases to influence the ROI increases with the injection pressure. Finally, a transient analysis is presented, showing that the needle velocity may considerably affect the instantaneous ROI, because of the volume displaced inside the nozzle. Results presented in this study show that at constant injection pressure and energizing time, this injector has the potential to control many aspects of the ROI and thus, the heat release rate. Also, data presented are useful for numerical model validations, which would provide detailed insight into the physical processes that drive these observations, and potentially, to the effects of these features on combustion performance.

1. Introduction

Internal combustion engines have played a significant part in shaping the world and people's way of life since their introduction over a century ago. Nevertheless, the ever increasing fuel consumption standards and the ongoing concerns about exhaust emissions have pushed the industry to research new concepts and develop new technologies that address these concerns and challenges.

A large part of this research and development process has been carried out on the fuel injection system because injection conditions play a determinant role in fuel spray formation, fuel/air mixing, and combustion performance [1,2]. The injection system hardware has seen several developments over the last two decades. Among these was the introduction of piezo-actuated injectors, which offer faster response and better control characteristics when compared to solenoid-actuated models [3,4]. These injectors are similar to each other in concept: the injector is remotely actuated and the needle is lifted through hydraulic pressure differentials. Therefore, from the control point of view, all these injectors behave in "binary" fashion: the fuel rate of injection

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(ROI) is mainly controlled by the injection pressure, and the total injected mass is a function of both injection pressure and energizing time (ET). To a certain extent, this limits combustion control, since the ET also determines heat release phasing and rates [5–7]. The recent introduction of direct-acting piezoelectric injectors [8] provides engineers with direct control over the needle lift—thus, over the instantaneous fuel flow—which opens a wide range of possibilities for controlling the injection event and combustion process [9–11].

Interest in understanding injector and spray behavior under partial needle lift conditions is not bound exclusively to direct-acting injectors, since conventional injectors also operate under these conditions in various situations (i.e., pilot injections and the start or end of injections). Chiavola and Palmieri [12] utilized a numerical computational fluid dynamics (CFD) model to study the effect of needle radial motion (needle wobble) on cavitation and flow patterns within a valve covered orifice nozzle, showing that the radial needle location (and speed) can greatly affect the hole-to-hole symmetry of the flow. Later, Som et al. [13] presented numerical results of the effects of needle lift over in-nozzle flow, showing that needle lift significantly affects the velocity fields through the needle seat, the nozzle sac, and the orifice. Ferrari and Mittica [14] presented a finite element model of a direct-acting piezoelectric injector that included electrical, mechanical, and hydraulic submodels, concluding that the injection pressure strongly affects the behavior of the direct-acting mechanism. Payri et al. [15–17] employed a prototype direct-acting injector to study the effect of steady partial needle lift on nozzle flow characteristics and macroscopic spray development. Their studies showed a strong relationship between fuel mass flow rates through the nozzle and estimated needle lift, also finding that needle lift and piezo actuator response are strongly affected by the injection pressure. Moreover, a strong correlation between the liquid length, vapor spray penetration rate, and needle lift was evidenced. Recently, Desantes et al. [18] employed a numerical CFD model to study the relationship between needle lift and ROI for a micro-sac multi-hole nozzle with cylindrical orifices. In their study, the authors show that the onset of the cavitation void occurs at the needle seat for low needle lift conditions, and moves downstream to the orifice when needle lift is high enough.

It is important to point out that actual needle lifts in the studies presented by Payri et al. [15–17] are unknown and were not directly controlled, so existing studies do not establish a direct link between needle lift values and spray formation response, for example, to validate CFD models.

Measuring instantaneous needle lift of diesel injectors under realistic operating conditions presents a considerable challenge. X-ray imaging is advantageous for this particular application, as the rays are able to penetrate the steel nozzle wall, eliminating the need for any modification of the injector. Synchrotron X-rays provide detailed measurements of the internal geometry of fuel injectors by exploiting the phase contrast that occurs when highly collimated X-rays are weakly diffracted by the phase boundaries at the nozzle walls [19]. Owing to the high flux of the synchrotron source, time-resolved measurements of the internal needle motion can be made with microscale precision using a high-speed camera [20]. These measurements have been coupled with observations of cavitation and gas ingestion inside the injector and changes in the external flow [21–23].

This paper presents an experimental analysis of the relationship between instantaneous partial needle lifts and ROI. A prototype direct-acting injector is utilized to produce steady injections of different magnitude by partially lifting the needle. Also, transient features such as ramp rates and injection rate shaping are explored. The ROI measurements were carried out at CMT-Motores Térmicos (CMT) utilizing a standard Injection Rate Discharge Curve Indicator (IRDCI) based in the Bosch method [24]. The needle lift measurements were performed at the Advanced Photon Source (APS) located at Argonne National Laboratory. The analysis pursues two different goals: first, to contribute to the understanding of the influence that partial needle lifts have over the instantaneous ROI; second, to provide extensive experimental data with parametric variations useful for numerical model validations, which could potentially be later employed to enhance the current understanding of partial needle lift and injection rate shaping over global combustion performance.

2. Materials and methods

2.1. Rate of injection measurements

The ROI measurements were carried out utilizing a commercial Injection Discharge Rate Curve Indicator (IRDCI) [24], which consists of injecting fuel into a fuel-filled long tube. The instantaneous ROI is proportional to the pressure signal measured by a piezoelectric pressure sensor [25]. For these experiments, a total of 50 injections were acquired at each test condition. Details of the full apparatus and technique can be found in the work of Payri et al. [25,26]. Injection pressure was measured at the common rail. Note that the final repetition-averaged ROI signal for a given test condition is scaled/corrected with the total injected mass, which is simultaneously measured by a precision electronic scale [25]. The fuel utilized for the ROI experiments was ISO 4113 calibration fluid. Details of the test conditions covered are presented in Table 1.

2.2. Phase-contrast imaging

X-ray measurements of needle displacement were performed at the 32-ID beamline of the Advanced Photon Source at Argonne National Laboratory [27]. The experiment setup is shown in Fig. 1, and the test conditions covered are presented in Table 2. A common-rail diesel injection system powered by an electrically driven mechanical pump delivered fuel to the injector. Injection pressure was measured at the common rail. The fuel was sprayed into a chamber pressurized with N_2. Kapton windows allowed the X-rays to pass through the chamber with minimum absorption. The experiments were conducted at room temperature. The fuel used was a commercial diesel surrogate with approximately 2% (by mass) cerium additive. The fuel had a density of 865.6 kg/m^3 and a viscosity of 3.22 cSt at 25 °C. For these experiments, a total of 21 injections were acquired for each test condition.

Table 1
Rate of injection experiments test plan.

Parameter	Test conditions					
Injection pressure [bar]	500	500	1500	1500	500	500
Back pressure [bar]	50; 11	50	50; 11	50	50	50
Control voltage [V]	135; 120; 105; 100; 95	90; 85	150; 132; 126	150; 118; 116; 114	85 → 120	95 → 120
Ramp rate [V/μs]	1	1	1	2	2	2
Injection shape	Square	Square	Square	Square	Boot	Boot