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Numerical analysis of deposit effect on nozzle flow and spray characteristics of GDI injectors

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HIGHLIGHTS

- High resolution X-ray scan was performed for the coked injector tip.
- Nozzle deposits can lead to extra cavitation inception points.
- Nozzle deposits can restrict the air/fuel interaction inside the counterbore.
- Coupled nozzle and spray simulations well captured the effect of deposits.

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ABSTRACT

Injector deposit is a common phenomenon for gasoline direct ignition (GDI) engines that greatly affects the spray behavior and consequently the combustion performance and emissions. In this study, the effect of deposit on both the in-nozzle flow dynamics and downstream spray behaviors was numerically investigated. High-resolution X-ray microtomographic scans were performed first to obtain nozzle and deposit morphologies and topology. In-nozzle simulation was then carried out in the Euler-Euler framework with cavitation taken into account by a homogeneous relaxation model (HRM). Finally, the effect of deposit on spray behaviors was evaluated in the Euler-Lagrangian framework, coupled with the in-nozzle simulation results. Results of the nozzle flow simulations highlight that the rough surface of the deposits leads to additional cavitation inception and restricts the flow area, causing mass flow rate losses. Deposits inside the counterbore act as an extension to the inner orifice and constrain the air recirculation. Turbulent levels at the exit of the counterbore are lower for the coked injector due to the reduced air/fuel interaction. Spray simulations have shown that deposits would lead to longer spray penetration, a smaller spray cone angle and larger droplets diameters. Simulation results agree reasonably well with the available experimental data.

1. Introduction

Injector coking otherwise known as the injector deposit is a serious issue for GDI engines and it has been observed to have negative effects on the engine performance and emissions [1]. Compared to traditional port fuel injection (PFI) engines, GDI engines are more susceptible to injector coking since their injectors are directly exposed to harsh in-cylinder conditions. Even in the earliest publications about GDI systems the risks of deposit formation on injectors were discussed [2,3].

For the traditional PFI engines, low-level fuel rate loss and spray pattern distortion caused by injector coking could be compensated by the engine control system, as they commonly operate under a homogeneous-charge combustion mode and their air/fuel mixture process is completed in the intake port [3].

With GDI engines, spray characteristics are more critical to retain a good and stable engine performance. This is especially true when GDI engines are running at the stratified-charge combustion mode, where the formation of the desired air/fuel mixture relies heavily on the carefully designed spray pattern and its interaction

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with the intake charge flow [4]. A relatively small amount of deposit accumulation on the injector can however restrict the fuel flow rate, distort such spray patterns and affect the combustion inside the cylinder. This may lead to lower fuel economy, higher emissions or even vehicle drivability problems such as misfire [1,5,6]. Thus, the injector coking effect is a significant concern for GDI applications and needs great attention.

The effect of injector deposit on spray characteristic and engine performance has been widely reported [7–12]. Song et al. studied the effect of deposit on multi-hole GDI injectors' spray behavior with a coked injector having been used in a vehicle for 58,000 km and they claimed that the deposit would increase the spray cone angle and reduce spray penetration [7]. Lindgren et al. studied the effect of deposit on swirl injectors with spray visualization technologies and found that the fouled injector produced denser and faster pre-jet compared to that of the clean injector [8]. Joedicke et al. conducted an accelerated deposit formation test using a fuel with additives that could accelerate the deposit formation [9]. After 55 h of a dirty-up test, 23.5% fuel rate loss was observed accompanied with 20%, 93% increase of HC, CO emissions and 2.45% increase of fuel consumption. In the work of Sandquist et al., after running for 60 h with a customized engine cycle, an 8.5% fuel rate reduction was observed together with 10% higher HC emissions under the work load of 5.5–8.5 bar IMEP compared with a clean injector [10]. Wang et al. used two coked and one clean multi-hole injector in a single cylinder spray guided DISI research engine to study the effect of injector coking on engine emissions [11]. The injector was fouled after running continuously for 54 h with 3.5–8.5 bar IMEP and 1500 rpm engine speed. It was found that the coked injector consistently produced higher emissions and the maximum difference was observed at the highest engine load of 8.5 bar IMEP, where the fouled injector produced 58% higher PN emissions and 300% higher PM emissions. Wang et al. conducted numerical studies of the effect of deposit on the in-cylinder air/fuel mixing process and found that the deposit would lead to severe fuel impingement on the piston and cylinder wall due to longer spray penetration and poorer spray dispersion [12]. Due to a lack of accurate deposit morphologies inside the injector, the spray simulations were conducted on the basis of calibration in their study.

Many studies have applied the Scanning Electron Microscopy (SEM) to investigate the GDI injector deposits [7,13–16]. Most of these studies focused on the deposit outside the injector tip, which had little effect on the spray behaviors. Among the few who studied the inner-nozzle deposit, Dearn et al. used the Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS) to study deposit formation inside a multi-hole GDI injector [13]. They showed that extensive deposits were formed in both internal and external injector holes and the external hole deposits were radially distributed and collected in the shoulder. Song et al. used the SEM technique to visualize the internal injector deposits and tried to link the deposit position with its effect on the spray behaviors [7]. However, due to the limitations with the SEM technique, the injectors have to be cut in order to give a view to the inner-nozzle structures. Detailed 3-D deposits morphologies were still not available.

In a recent work conducted by Xu et al., a compensative review of injector deposit was conducted [17]. The authors concluded that while extensive work had been done, the effect of GDI injector deposit was still not fully understood. It is also pointed out that CFD modeling can provide significant help in understanding the injector coking effect, but little work has been carried out so far because information about the 3-D structure and morphology of the deposits inside the nozzle was generally not available [17].

Based on the literature study, it can be concluded that a complete understanding of the GDI injector deposits is important, but detailed investigations of its effect on the spray behaviors are very limited and simulation work is barely seen. It is not clear how the deposits interact with the inner-nozzle fuel flow and alert the downstream spray. This paper is one of the first studies carrying out numerical studies of the injector deposit effect on the in-nozzle flow and spray behaviors. Simulations were carried out with commercial CFD software, CONVERGE [18]. High resolution synchrotron coherent X-ray microtomographic imaging was conducted first to obtain the detailed nozzle and deposit morphologies. The 3D reconstruction of the data was completed with Avizo 9.0.1 software, which allowed distinction between phases and also generation of high-spatial resolution models for both deposited injectors and the metal surface on which they were deposited. Two-phase inner nozzle flow simulations, taking into consideration cavitation effects, were then carried out to study the deposits impact on the nozzle flow behavior. Finally, coupled with the information provided by the in-nozzle simulation, spray calculations were carried out to study the effect of deposit on the spray characteristics. The results can provide practical guidance for the GDI injector design with better deposit resistance.

2. X-ray scan and deposit configuration

2.1. X-ray scan setup

In this study, tomographic scans with high spatial-resolution were conducted at the imaging beam line ID19 [19] of the European Synchrotron Radiation Facility (ESRF, Grenoble, France). In order to ensure a sufficiently high photon flux density in the hard X-ray regime, ID19 was operated in pink beam mode with the beamline's wiggler insertion device as the source (gap: 26 mm): 5.6 mm Al and 0.5 mm W attenuators in combination with a 1.4 mm diamond window suppressed the softer parts of the spectrum [20–22]. The effective spectrum seen by the detector has a mean energy around 90 keV. Additionally, 64 so-called compound refractive lenses made from Be were used to collimate the photons on the field-of-view of the detector. A mirror placed between the scintillator and the lenses allowed for a right-angle design, which kept the dose-sensitive components (lenses, electronics) out of the intense hard X-ray beam. The effective pixel size of the detector is 0.54 μm. A propagation distance between sample and detector of 110 mm was set in order to improve the contrast by propagation-based inline phase contrast. Then 9216 projection images were acquired over a 360 degree rotation, with the axis of rotation being shifted slightly off the center of the field-of-view. This approach allows stitching of projected images, which are taken at a 180 degree angular distance, in order to form a 180 degree tomographic scan with a lateral extended field-of-view (effectively, the new field of view is 3113 pixels wide). For post-processing, a 2×2 binning was applied.

Data were subject to mild sharpening and denoise processing and then selective phase segmentation using Avizo 9.0.1. The segmented 3D volumes were then converted from label fields to high-resolution surfaces. These surfaces were converted in .stl format for input into CFD simulation. Simplification was performed by reducing the full resolution surfaces to 5,000,000 triangles with appropriate smoothing, due to the complexity of the deposited surfaces; since this mitigated the issue of incomplete surface meshes for regions with complex topography and provided files of a data size that were useable for workstation computing.

2.2. Deposit configuration

Clean and coked GDI multi-hole injectors were used in this study. The coked injector exhibit deposit formation and morphol-