Applications of synchrotron X-ray micro-tomography on non-destructive 3D studies of diesel nozzle internal micro-structure

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Abstract: In diesel engines, the fuel spray breakup and atomization process have tremendous dependence on the nozzle internal geometries, then the performance, fuel consumption and emission of the engines will be affected. Based on the synchrotron X-ray micro-tomography, the three-dimensional models of the diesel nozzles were established. Then the internal geometries of the nozzle orifices, such as the diameter, the length and the inlet chamfer radius of the orifice, can be measured, making it possible to analyze the impact of different nozzle orifice processing methods. Meanwhile, the nozzle digital models were successfully applied to simulate the internal flow of high pressure fuel inside the nozzle; the effects of nozzle geometries on internal flow characteristics have been analyzed. The results show that these works are significant to the promoting of diesel nozzle processing technologies, and the revealing of high pressure fuel spray breakup mechanism.

1. Introduction

The performance, efficiency and pollutant emissions of diesel engines have tremendous dependence on the quality of fuel sprays [1,2]. Modern diesel engines employ fuel injectors with micro-orifices (typically less than 200-μm in diameter) to prepare fuel sprays and to acquire optimized liquid fuel breakup and atomization under very high injection pressure ranging from 150 to 250-MPa. At such high-injection pressures, the flow inside the nozzle is extremely sensitive to the fine internal geometries [3-5], such as the diameter, the length and the inlet chamfer radius of the orifice. When increasing the injection pressure, diesel nozzle geometry, even on μm length scale, is considered to be a key issue for the improving of fuel spray and atomization to meet the new stringent regulation [6,7].

However, as the access to the internal structure is very limited in these micro nozzle orifices, the researchers all over the world have proposed quite a few methods to obtain the internal structures of diesel nozzles, including optical diagnostic methods [8], sectioning methods [9,10], micro probe measuring methods [11,12], silicone molding method [13], commercial X-ray method [14], and synchrotron X-ray micro-tomography method [15]. However, these methods are either destructive or inaccurate and inconvenient, except for the synchrotron X-ray micro-tomography method.

By using synchrotron X-ray provided the Shanghai Synchrotron Radiation Facility (SSRF), three-dimensional models of the diesel nozzles were established. Then the characteristics of different orifice processing methods are compared based on the internal geometries acquired by measuring the 3D models. In addition, the real internal fuel flow inside the nozzle orifice has been simulated based on the corresponding internal structures.

2. Experimental Setup

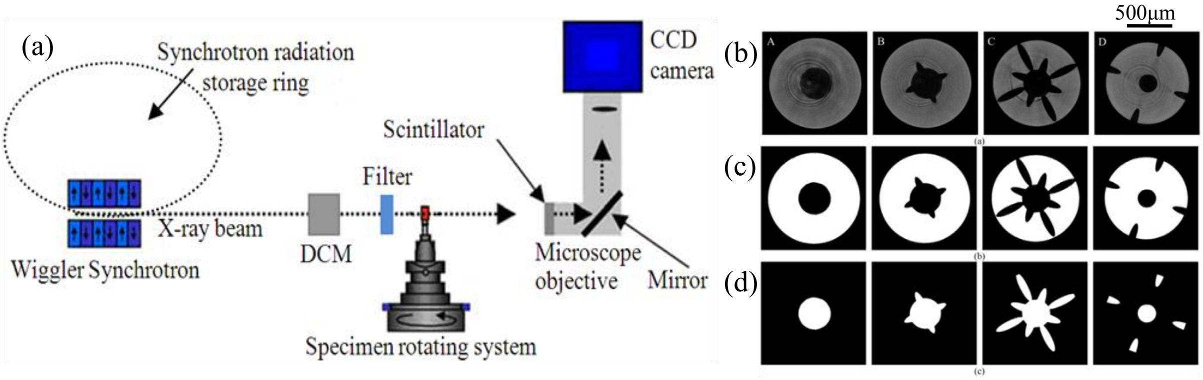

Figure 1. (a) A sketch of the synchrotron X-ray micro tomography setup at the beam line BL13W1 of the SSRF, (b) original slices, (c) binary slices, (d) binary orifice slices

In this study, the internal structures of diesel nozzles were revealed on the X-ray Imaging and Biomedical Applications Beam Line (BL13W1) of the SSRF. The detailed features of this beam line have been described by Li [16]. The experimental setup is sketched in figure 1a.

The diesel nozzle is held on the specimen rotating platform. The synchrotron X-ray penetrates its tip and irradiates the scintillator to form absorption images in a charge-coupled device (CCD) camera. The pixel size of the camera is 7.4μm×7.4μm corresponding to an actual spatial resolution of 3.7μm×3.7μm with a 2x objective lens. The X-ray photon energy of this beam line was tuned to 50 keV and the exposure time was set to 8s. During the computed tomography (CT) scanning process, the specimen rotates 180° to obtain sufficient absorption images to generate slices. In accordance with the nozzle tip size and spatial resolution, a total of 720 absorption images were captured, and the slices were then reconstructed. Fig. 1b shows one original slice. Using customized digital image processing method, the original slices were converted to binary slices and corresponding orifice slices to enhance the signal to noise ratio [15] (figures 1c and 1d). By stacking these reversed slices, the 3D digital models of the diesel nozzle were constructed directly, which can be used to illustrate the detailed internal surfaces and structures of the orifices and to measure their geometrical dimensions directly.

3. Results and Discussions

3.1. Orifice internal parameters measurement and orifice processing methods comparison

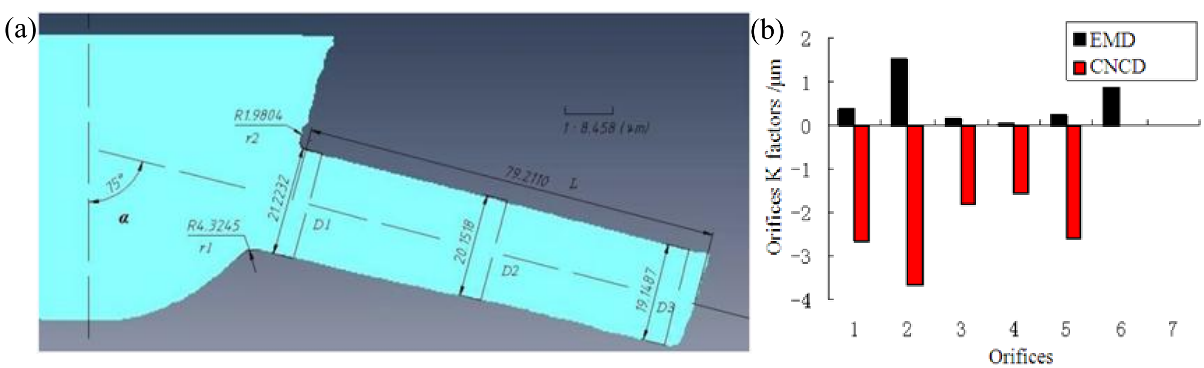

Figure 2. (a) shows the measurement of internal structure parameters, (b) is the nozzle orifice *K* factors comparison of different orifice processing methods

By cutting the 3D digital models, the internal geometry parameters, the orifice cone angle α, the orifice length L, the inlet diameter $D1$, the middle diameter $D2$, the outlet diameter $D3$, the top and bottom chamfer radii $r1$ and $r2$ can be measured, as shown in figure 2a.

Based on these parameters, the most popular orifice processing methods, computerized numerical control drilling (CNCD) and electrical discharge machining (EDM) drilling were compared and analyzed. One important parameter, K factor ($K=(D1-D3)/10$) are compared in figure 2b, the results show the K factors of the CNCD nozzle are all negative, however that of the EDM nozzle are all positive, which is good for the enhancement of the flow coefficient and the life of the nozzle.

Meanwhile, the effect of different hydro erosive grinding (HEG) time can also be researched, as shown in figure 3. By cutting the orifice from different angle (figure 3a), the parameters at different sections can be obtained. The comparison of the chamfer radii under different HEG time in figure 3b indicates that, longer HEG time can obviously smooth the orifice inlet.

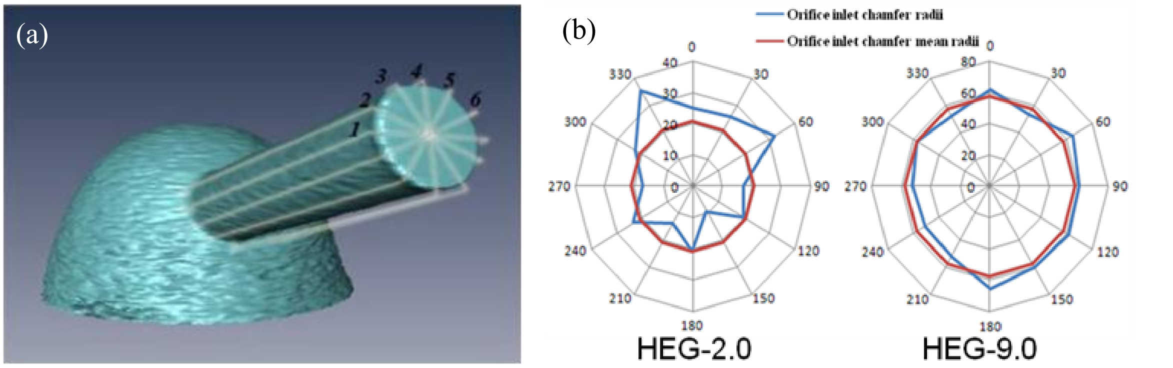

Figure 3. (a) shows different measurement sections along the orifice, (b) shows the inlet chamfer radii comparison under different hydro erosive grinding time

3.2. Fuel internal flow simulation based on orifice 3D digital models

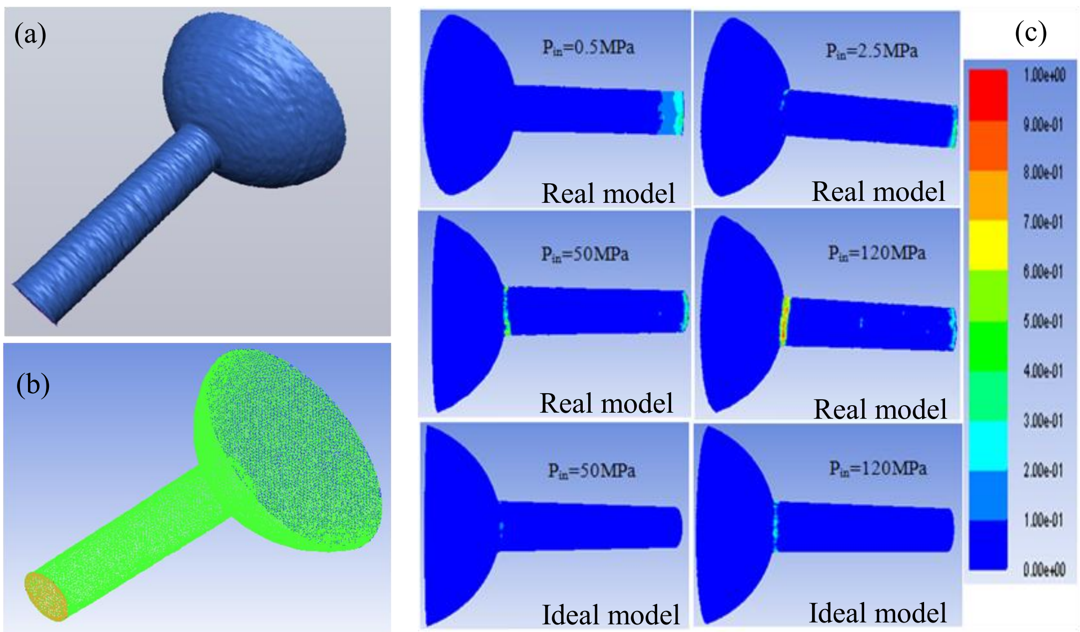

Figure 4. (a) is the real 3D digital model of a diesel nozzle, (b) shows the obtained computation gird according to (a), (c) shows the simulation results based on real model and the ideal model

The simulation of the high pressure fuel flows can acquire higher accuracy based on the orifice real 3D digital models reconstructed by the synchrotron X-ray micro-tomography, compared to the previous simulations base on the ideal 3D digital models generated directly in CAD software. The results and comparisons in figure 4 shows that, the inner flow characteristics are quite different in real and ideal models, especially the cavitation near the inlet area, which means that real model simulation can reveal the inner flows more closely to the real flow.

4. Conclusion

By using high energy X-ray micro CT technique, the internal geometries and the parameter dimensions can be observed and measured easily and accurately.

Through the analysis of nozzle inner geometry parameters, the nozzle orifice processing methods can be compared, which is significant to the quality control of diesel nozzle manufacture.

Simulation of orifice inner flow was operated successfully based on the real 3D models acquired in this study, and it represented huge difference compared to the ideal models under the same conditions.

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