Simultaneous Visualization of Nozzle Cavitating flow and Erosion Damage for Modeling of Erosion Risk Prediction

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Abstract

In this study, the visualization of cavitating flow and erosion damage simultaneously inside a rectangular optical nozzle was carried out. The patterns of cavitating flow were visualized using high-speed camera and the erosion features on the aluminum foil attached on one inner wall of this nozzle were observed by scanning electron microscope(SEM). A cavitation erosion risk prediction model was introduced to predict the cavitation erosion aggressiveness and the positions of erosion damage. Moreover, the numerical results were validated against the experimental data in terms of the comparison of cavitation distribution and erosion areas.

Keywords: nozzle, visualization, cavitation, erosion risk, diesel

Introduction

Although current increasing fuel injection pressure improves the spray mixture quality and combustion performance and emission characteristics of internal combustion engines, it simultaneously enhances unsteady characteristics of nozzle cavitating flow for multi-injection process and also incurs strong transient movement of needle-valve. Furthermore, the instantaneous process of cavitation bubbles collapse leads to the fatigue damage of metallic surface because of the co-operative effects between shock waves and high-speed liquid jet. This undesirable behavior may result in erosion damage at the wall surface and further deteriorate spray characteristics. More seriously, the injector is susceptible to abrasion wear and fracture failure[1-3]. Dular et al.[4-5] adopted synchronous measuring device of venturi tube to carry out transient cavitating flow and erosion examination with water. Gavaises et al.[6-7] qualitatively analyzed the relationship between cavitation and erosion damage in the injector nozzles in terms of the internal cavitation distribution in a transparent nozzle and the location of erosion damage in an actual metal nozzle. Dular et al.[8-9] and Peters et al.[10] developed a new cavitation erosion model to predict erosionsensitive areas and erosion potential in the incubation period, through forecasting the formation situation of local microjets near surfaces. The regions where the local pressure exceeds a threshold pressure were regarded as the erosion areas in Li et al.'s work[11]. Gavaises et al.[12] and Koukouvinis et al.[13] conducted several studies of cavitation erosion prediction in Diesel injectors by LES model and locations of the pressure peak resulted from cavitation bubbles collapsing were also considered as prediction areas of erosion damage. In fact, high pressure peak indicates the fast mass transfer between the liquid phase and vapor phase during cavitation process. Moreover, the condensation source term of the cavitation model proposed by Zwart et al.[14] can be associated with the shock waves and microjet, and it can be therefore directly characterized the cavitation erosion risk on a nozzle hole surface[15].

The objective of present work is to investigate the relationship between cavitating flow and erosion damage inside an injector nozzle and build a cavitation erosion prediction model based on visual experimental data of cavitating flow and cavitation erosion. For this purpose, an experimental facility for simultaneous capture of cavitating flow and erosion damage in a simplified structure nozzle was set up. The visualization of nozzle cavitating flow under different fuel injection pressures was performed and also the morphology of cavitation erosion damage captured by SEM after different injection periods was analyzed. These experimental data can be provided for the verification of cavitation erosion model.

2.Experimental equipment and methodology

Fig. 1 displays schematics of cavitating flow capturing and erosion damage measuring apparatus. Fuel was discharged from a rectangular transparent nozzle into the fuel tank which was in the open air by a high pressure

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pump, so the back pressure was fixed at 0.1MPa. The transparent nozzle was made of acrylic materials for its similar index of refraction with commercial diesel. In order to capture the cavitation distribution inside the hole, this nozzle was located between a high-speed camera and a light source providing background lighting. The physical drawing and geometric size diagram of the nozzle, as shown in Fig. 2, were designed to clearly capture the cavity structure and carry out the cavitation erosion test. A piece of aluminum foil with a layer thickness of 0.06mm, which is sensitive to the erosion damage, was attached to the bottom side of the nozzle. Thus using high-speed digital camera can shoot pictures of cavitation flow and cavitation distribution area from the front and above view in the nozzle hole. Cavitation bubbles collapsed on the surface of aluminum foil after a certain time and it implied that cavitation erosion had occurred. The surface morphology of aluminum foil before and after the occurrence of cavitation erosion may be observed by employing scanning electronic microscopy technology (SEM).

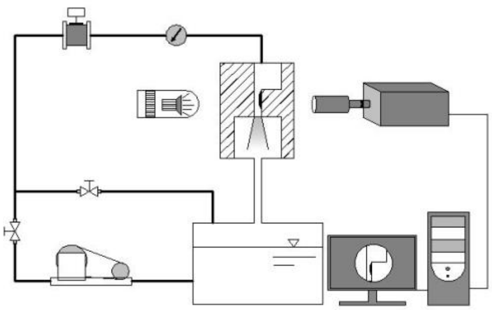


Fig. 1. Schematics of fuel supplying and cavitationvisualization system

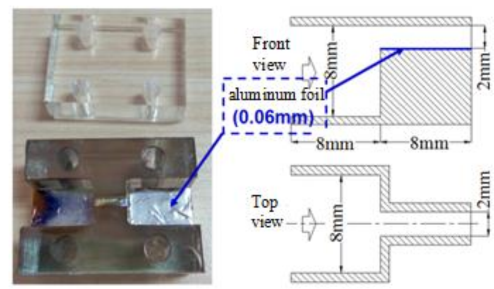
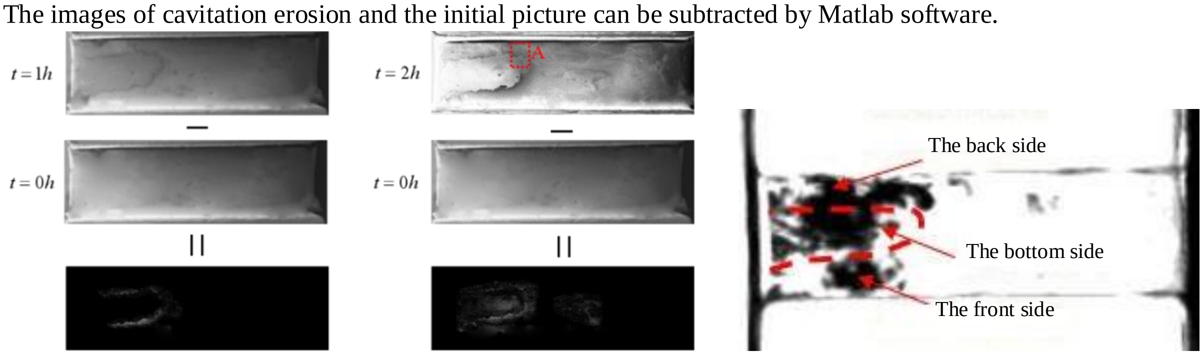


Fig. 2. Nozzle physical drawing and geometric dimension diagram

3.Experimental results

Fig.3 displays images of cavitation erosion on the surface of aluminum foil at P_{in}=0.5MPa. Fig.3(a) and Fig. 3(b) show the surface morphology of aluminum foil after cavitation erosion lasting 1 hour and 2 hours, respectively. The images of cavitation erosion and the initial picture can be subtracted by Matlab software.



(a) Cavitation erosion lasting 1 h (b) Cavitation erosion lasting 2 h (c) Cavitation region shot in the top viewport

Fig. 3. The relationship between cavitation and cavitation erosion on the surface of aluminum foil

It can be found from diagrams that cavitation erosion area increases gradually with the duration of cavitating flow. The mechanism of cavitation erosion can be explored in combination with Fig. 3(c), which demonstrates the cavitation distribution region taken in the top viewport. In Fig. 3(c), the cavitation area inside the nozzle is divided into three different regions, corresponding to the cavity area adhering to the surfaces of the front, back and bottom. From the relationship between cavitation and damage region on the aluminum foil under the same jet pressure, the most serious erosion occurs at the interface between cavitation region and liquid region, as shown in Fig. 3(a). As fuel injection sustains for 2 h, cavitation erosion aggravates from the boundary to the internal cavitation region, because the cavity undergoes phase transformation from vapor phase to liquid phase as known as bubbles collapsing at the interface. The phenomenon that severer shock waves or microjet attacks the wall may appear at these positions, resulting in erosion damage. Fig.4 is obtained by scanning electron microscope from the area A in Fig.3. The border between non-cavitation erosion region and cavitation erosion zone of a enormous amount of pits is fairly distinct.

Fig.5 provides images of cavitation and erosion damage under different jet pressures. The cavitation extends towards the outlet of nozzle and collapses in the downstream with increase of injection pressure, and so does cavitation erosion damage. The cavitation damage always occurs mainly at the interface between cavitation zone and liquid phase. Accordingly erosion on the surface of aluminum foil may be due to the collapse of cavitation bubbles in cavity zone.

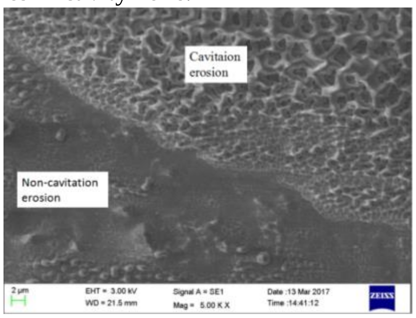
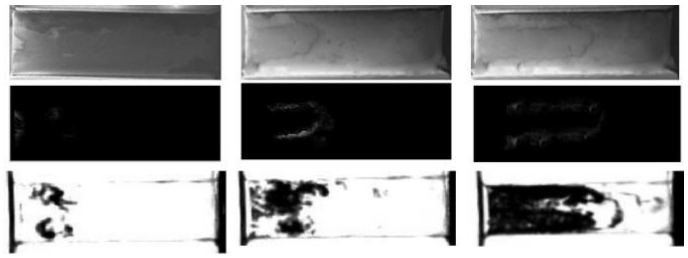


Fig. 4. Comparison of cavitation erosion and non-cavitation erosion on zone A of aluminum foil by SEM



P_1=0.4MPa   *P1=0.5MPa*   *P1=0.6MPa*

Fig. 5. Cavitation and cavitation erosion on the surface of aluminum foil under different injection pressures

4. Numerical anslysis

It is current extensively accepted that cavitation damage phenomenon on the nozzle surface of fuel injector is mainly attributed to repeated and unceasing wallop on the surface due to co-operative effects between microjet and shock wave which are caused by cavitation bubbles collapse during the instantaneous crushing process. In other words, cavitation erosion is directly correlated to collapse process of cavitation bubbles (the condensation phase transition from vapour to liquid). In this section, depending on this theoretic and cavitation model for two-phase flows in diesel injectors, the erosion risk prediction model is established and cavitation damage simulation is carried out against the erosion test mentioned above. The reliability of the cavitation erosion risk prediction model is verified against the test data.

4.1 Cavitation model and erosion risk prediction model

Computation fluid dynamic software Fluent is used in numerical simulations presented in this section. A RNG $k-\varepsilon$ turbulence model is utilized to reproduce the turbulence characteristics on the cavitating flow. The VOF method coupled with ZGB model based on Rayleigh-Plesset equation was performed for the simulation of cavitation multiphase flow inside the nozzle.The ZGB cavitation model assumes that all the initial bubbles in the fluid have the same size and the value is fixed to 10^{-6}m. The total mass transfer rate between liquid and vapor is estimated by the mass variation of a single bubble and bubble density *n*. The following formulacan be used to calculate the interphase mass change rate due to evaporation or condensation process.

$$R_e = F_{vap}\frac{3\alpha_{nuc}(1-\alpha_v)\rho_v}{R_B}\sqrt{\frac{2(P_v-P)}{3\rho_l}}, P < P_V \quad (1)$$

$$R_c = F_{cond}\frac{3\alpha_v\rho_v}{R_B}\sqrt{\frac{2(P-P_v)}{3\rho_l}}, P_v < P \quad (2)$$

Where F_{vap} and F_{cond} are two empirical correction coefficients corresponding to the evaporation and condensation phase transition processes.α_{nuc} is the nucleation site volume fraction and R_B is the cavitation radius. P_l and P_v are the flow field pressure and the vaporization pressure, respectively. ρ_l andρ_v are density of the fluid and vapor. According to the reference[9], vapor mass condensed rate in unit time can be related to an increment of the shock wave or pressure liquid hammer intensity generated by bubble collapse. In other words, the erosion risk on the nozzle surface of diesel engine should be directly proportional to mass transfer rate R_c during the condensation phase process. Therefore, the following formulation is introduced by using the Fluent UDF and a non-dimensional relative cavitation risk rate R_{rose} is applied to predict the erosion sensitive areas as well as the potential intensity of erosion impacts during the incubation period.

$$R_{CS} = F_{ero}\alpha\sqrt{\rho_v(P_w-P_v)}, P_w > P_v \quad (3)$$

$$F_{ero} = \frac{\eta}{R_B}\sqrt{\frac{\rho_v}{\rho_l}} \tag{4}$$

$$R_{rose} = \frac{R_{CS_{local}}}{R_{CS_{max}}} \tag{5}$$

Where F_{ero} is one coefficient in surface erosion risk prediction model, and η is empirical coefficient. P_w is the local pressure of liquid near the wall. The higher total vapor mass condensed is in the cell layer adjacent to the nozzle orifice wall, the more probably the erosion damage occurs. Accordingly, a dimensionless number, the relative risk of surface erosion (R_{rose}), is defined to qualitatively predict the potential risk of erosion damage at various locations on the inner wall surface of the nozzle. $R_{CS_{local}}$ is the local condensation rate and $R_{CS_{max}}$ is the maximum of candensation rate.

4.2 Comparison with experiment

The ZGB cavitation model and the corresponding erosion risk prediction model are conducted to simulate the cavitating flow and erosion damage under the injection pressure 0.5MPa in the same experimental nozzle as shown in Fig. 2. Fig.6 shows the physical model and computational domain, which are chosen for numerical simulation of internal cavitation and erosion damage in this particular nozzle. The cavitation distribution along the direction of top view of Fig. 2 in the nozzle under injection pressure 0.5 MPa obtained by experiment and numerical simulation shows a wonderful consistency as presented in Fig.7. Fig.8 exhibits the simulation result calculated by the erosion risk prediction model which is established on the basis of cavitation model and also gives the comparison of experimental results as mentioned in the previous section. It can also be discovered from the diagram that the prediction of cavitation erosion is in a wonderful coincidence with the experimental results. The cavitation erosion area occurs on the surface of aluminum foil, which is attached to bottom of the nozzle.And the simulation results demonstrate that substantial bubbles collapse in the same region, where lots of cavitation vapor phase is converted into liquid phase. In the simulation diagram, the red region indicates the highest dimensionless condensation rate(R_c), and also represents the area with high cavitation erosion risk. The outline of the zone with high condensation rate is very similar to the distribution of erosion damaged region on the aluminum foil utilized in the experiment. Therefore, it is reliable to select condensation rate or mass transfer between vapor and liquid as the prediction index of potential erosion damage risk.

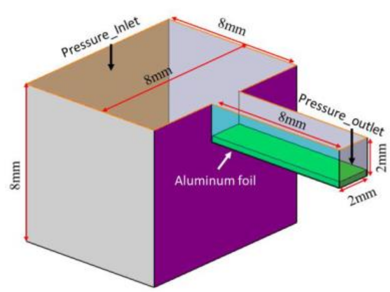


Fig. 6. Schematic diagram of the transparent nozzle withAluminum-foil on the bottom side

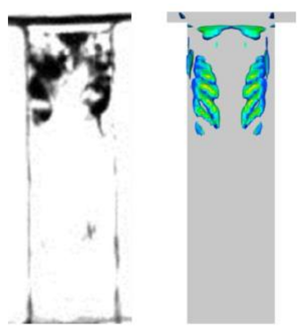


Fig. 7. Experimental cavitation picture (L) andiso-surfaces of vapor volume fraction of 0.9(R) underpressure drop of 0.50MPa

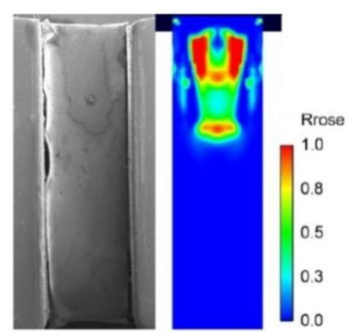


Fig.8.SEM scanning results of surface with erosion damage (L) and *Rrose*distribution on the bottom wall (R).

5. Conclusions

In this study, a coupled experimental and numerical study was carried out to make a investigation on the internal cavitating flow and erosion risk inside the diesel injector nozzles. An innovative approach of adhering the aluminum foil, which was adopted as a carrier for erosion damage on the inner wall of the nozzle was proposed to descry the cavitation erosion in the injector. The surface morphology of the erosion position over aluminum foil was observed by scanning electron microscope(SEM). In addition, a new cavitation erosion risk prediction model derived from ZGB cavitation model was proposed to predict the areas of erosion and assess the erosion potentialin these areas. Further on, a dimensionless coefficientR_{rose} was introduced to enable a qualitative prediction of damage. In comparison with experimental results, it could be concluded that the erosion risk prediction model was verified to find out the sensitive areas of erosion and the distinguish the risk probability of erosion among these areas.

Acknowledgments

This research was supported by the National Natural ScienceFoundation of China (No. 51776088, No. 51276084), a ProjectFunded by the Priority Academic Program Development ofJiangsu High Education Institutions, Six Talent Peaks Project ofJiangsu Province (2013-JNHB-017) and Natural ScienceFoundation of Jiangsu Province (BK20161349).

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