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Simulations on the cavitating flow and corresponding risk of erosion in diesel injector nozzles with double array holes

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ABSTRACT

Simulations research has been conducted to make a further study about the influences of nozzle K_{factor} and needle lifts on the cavitation flow and erosion risk inside the diesel nozzle with double array of holes. The relative risk of surface erosion (Rr_s) was utilized as an index to evaluate the risk of cavitation erosion on the nozzle hole-surface. The simulation results illustrate that the intensity of cavitation on the hole-surface decreases significantly with K_{factor} declining, and the cavitation draws back to the orifice entrance where it initially originates from. The invert conical hole suffering high risk of erosion damage and the positions with highest risk of erosion appear on the supine surface and the entrance of inlet orifice. Besides the needle lifts also have impacts on the cavitation and risk of surface erosion but little influence on mass flow rate. Cavitation can be found around the closing surface on the sac and the supine surface of nozzle holes under low needle lifts. With the needle lift rising, the bubble clouds are depressed efficiently and shrink together towards the inlet orifice corner of the hole, but the risk of erosion for the nozzles is increasing. And L-hole surface is more likely to be damaged due to cavitation erosion for the vapor phase condensates quickly and centrally.

1. Introduction

In order to control combustion and pollutant formation, direct injection techniques and high injection pressure are implemented extensively to achieve efficient mixture between fuel and air in the combustion chamber [1]. There is a clear tendency of adopting common-rail injection system to meet the future legislation of combustion emissions from diesel engine [2–4]. As an important part of the fuel injection system, injector nozzles play an important role in the optimization of fuel atomization and spray [5–7].

The fluid flows with a high velocity inside of the nozzle before it is injected into the combustion chamber, for the common rail injection system can supply so high injection pressure as to 250 MPa even 300 MPa. And the static pressure near the entrance of the nozzle-hole drops significantly even lower than the saturation pressure of diesel because the fluid accelerates strongly as it is squeezed through the nozzle hole resulting in rollercoasters in the velocity and pressure field. And the liquid fuel is transferred to vapor near nozzle hole-entrance for the low pressure existed there. According to Ref. [8], after the cavitation region extends to the hole-exit, many bubbles collapse near the nozzle which can contribute to the atomization and spray of fuel jet. However, the collapse of cavitation bubbles inside of the mechanical equipment also has serious adverse consequences including erosion, machinery vibrations and noise which have become an open scientific object not only in some hydraulic machinery [9] such as pump, propulsion system of ship but also the fuel injection system in which the cavitation erosion damage may result in the degradation of injector performance [10]. More importantly, even the cavitation erosion damage to the nozzle-hole internal surface is not severe enough as it still being kept in usage in the diesel engine; these weak damages still influence the internal flow and then spray atomization process, for they induce hole-to-hole variations of flow rate and the precise control of injected fuel mass. Therefore, great efforts have been made to research mechanisms of cavitation and erosion to find methods of avoiding or decreasing their negative effects.

For the erosion is induced by the cavitation, many scholars try to control and decrease the intensity of cavitation by modifying the nozzle geometry and dynamic boundary conditions which are regarded as two important factors impacting the cavitation formation and bubble collapse causing serious erosion damage on the wall surface. And nozzle geometries have been widely investigated

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because of their tiny flow area and significant influences on the flow coefficient and the cavitation formation [11]. According to the previous investigations, the orifice entrance corner plays an important role in decreasing the intensity of cavitation by depressing the pressure drop and achieving a smooth change in flow direction. Shervani-Tabar [12] and Lee [13] simulated and find that increasing R/D, the ratio of inlet orifice's curvature radius to orifice's diameter, leads to the reduction of the bubble collapse. Pressure loss goes up between the nozzle-hole entrance and outlet as L/D rising. Molina et al. [14] reported that elliptical geometries with vertically oriented major axis are less prone to cavitate.

Besides the orifice conicity K_{factor} is another key geometrical parameter influencing the nozzle cavitating flow [15]. Winklhofer et al. [16] performed a famous experimental study on three quasi-2D throttle including both the conical and cylindrical nozzle. The experimental data shows that strong throttle contraction shifts the pressure recovery zone closer to the throttle entrance, and the cavitation is depressed with the outlet width decreasing. F. Brusiani [17] reproduced the cavitation flow inside of the nozzles using two different cavitation model including homogeneous relaxation model [18] and Singhal's cavitation model [19]. Som et al. [5] have conducted a simulation on the cavitation and turbulence generated inside the hydro ground and conical nozzles and pointed out that conicity and hydro grinding significantly reduce cavitation and turbulence levels. Benajes et al. [20] observed that compared to a cylindrical orifice, a conical orifice reduces cavitation and increases flow efficiency and exit velocity. Salvadora et al. [21] made numerical simulations on the internal flow and cavitation phenomenon in 3 nozzles with different convergence-divergence levels and found that low convergence-divergence level can depress the cavitation phenomenon. Brusiania et al. [22] compared the fluid dynamic performances of cylindrical nozzle and conical nozzle and concluded that conical holes reduce the mass flow rate and enhance the flow uniformity for the significant reduction of turbulence level.

Except for the nozzle geometries, dynamic boundary factor such as needle lift has also been widely investigated. Masuda et al. [23] have made simulations to research the influence of needle valve movement on the cavitating flow inside the valve covered orifice nozzle using an Eulerian three-fluid model coupled with a cavitation model. Soriano et al. [24] reported a similar unsteady computational study on nozzle internal flow and fuel primary breakup taking the injector nozzle needle movement into account. To invest the cavitation evolution inside the real size nozzle, He et al. [25] replaced the tip of a real size nozzle with a transparent one. They reported that the appearance of string cavitation has a close relationship with needle lift with the injection pressure up to 110 MPa. A similar methodology can also been found in the works of Badock et al. [26]. Desantes et al. [27] conducted a Large eddy simulation to research the evolution of the internal flow and turbulence development under six different needle lifts. And they found that the cavitation bubbles flow along the upper surface of the orifice under high needle lifts but cavitation appears at the needle seat and the bottom surface of the hole for low needle lifts conditions. These numerical and experimental studies reveal the formation of cavitation can be impacted greatly by the needle position due to its influence on the velocity and pressure field. But none of them associate the cavitation erosion with the needle lift directly.

Those investigations above provide a deep understanding of effects of inlet orifice curvature radii, nozzle-hole conicity and needle lifts on the internal cavitating flow characteristics and supply many valuable methodologies of controlling the cavitation in injector nozzles. However, there is another fact that the cavitation depression implies that all of the bubbles generated collapse inside the nozzle which may result in a serious erosion damages on the wall surface. Actually, this relationship between cavitation development and erosion damage is very complex and has not been learned well, because seldom studies have been conducted although the scientific object has attracted more and more attention recently [28].

For instance, the X-ray CT scans of the real diesel injector after 1000 h of continuous working showed that the orifice and needles are susceptible to cavitation erosion [10]. Bergeles et al. [29] proposed an erosion aggressiveness index (EAI) to identify the surface areas prone to erosion due to bubble collapse. The erosion prediction was based on the total derivative of pressure at the position where the bubbles collapse. And the cavitation induced erosion on the needle surface was captured successfully in their simulations. Edelbauer et al. [30] estimated the cavitation erosion by mass transfer term within a critical distance from the wall. Impacts of bubbles collapse was connected to the negative mass transfer rate. But they just presented the instantaneous and mean depth of penetration rate in a rectangular micro-scale throttle without considering the influence of nozzle geometry on cavitation and corresponding erosion.

Pressure peaks due to vapor collapse was correlated with erosion development in industrial injectors in Koukouvinis's Large Eddy Simulations [10] along with a two phase homogenous mixture model. In fact, high pressure generated indicates a fast mass transfer between the vapor and liquid phase. But the refined meshes and time cost required in LES simulation is a big challenge in industrial usage. Brusiani's works [31] provide a new evaluation of the cavitation erosion risk. They associated the erosion risk with condensation rate source term proposed by Zwart cavitation model. It was reported that the erosion risk rises as the throat narrowing, though the cavitation tendency shows a significant reduction. But this evaluation methodology of erosion risk needs verifying by experiment, and it will be more meaningful if this verified erosion model could be applied to predict the erosion damage inside the real size injector nozzle and finally realize the optimization of injector nozzle geometry coupled with the analysis of flow rate characteristics.

In this paper, an new erosion risk prediction model was setup base on the mass transfer rate between different phases, and the model was utilized to investigate the erosion risk in nozzles with double array of holes after being verified by erosion experiment in a throat nozzle. The internal flow characteristics and the erosion risk inside the nozzle with different K_{factor} have been analyzed simultaneously under different needle lifts. And the paper is organized as follows: the transport equations and description of the cavitation model and erosion risk prediction model are provided first, followed by the validations of ZGB cavitation model and erosion risk evaluation methodology in simplified nozzles. Then the effects of nozzle K_{factor} and needle lifts on the cavitation and risk of surface erosion are researched and analyzed. Finally, some important conclusions are derived as guides for the injector nozzles' design and manufacture.

2. Mathematical modeling of turbulence, cavitation and erosion risk prediction

In this section, a brief description of the mathematical models including turbulence and cavitation model will be presented. Inside the diesel nozzle, turbulence significantly increases the rate of mixing of momentum, and here *RNG* $k-\varepsilon$ model [32] was utilized to catch the turbulence flow characteristics. As a modification of the stand $k-\varepsilon$ turbulence model [33], additional terms and functions have been added to the transport equation for k and ε equations to improve the accuracy for rapidly strained flows and swirling flows. It provides an analytically derived differential for-