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Numerical investigation on transient flow and cavitation characteristic within nozzle during the oil drainage process for a high-pressure common-rail DI diesel engine

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ABSTRACT

In the present investigation, the transient developments of flow and cavitation within an injector's nozzle during the oil drainage process have been studied by numerical method for a high-pressure common-rail DI diesel engine, both the variation regulations of macro parameters (indicating flow characteristics and cavitation characteristics) and the distribution manners of important physical fields (indicating the cavitation evolution in the micro) have been obtained and analyzed. The obtained numerical results indicate that, during the oil drainage process, both mass flow rate and flow coefficient monotonously increase with declining variation rates, both averaged flow velocity and averaged turbulent kinetic energy also monotonously increase; however, to the curve of TKE-needle lift, there exist certain points give abrupt increase. The difference in TKE curve compared to averaged flow velocity is mainly attributed to the sudden variation of cavitation. Based upon the numerical results, the cavitation bubble will not be formed until the needle lift has been raised to a certain position due to the lower flow velocity and the lack of low (even negative) pressure zones. As needle rises, the primary bubbles are formed near the lower corner after nozzle's entrance; but as needle further rises, the positions at where bubbles are formed have been transferred to the upper corner and then being blow downwards orifice as the increase of flow velocity.

1. Introduction

Diesel engines, since 1892, are always playing utmost important roles in the field of propulsion, power, and energy for its highest thermal efficiency of any standard internal and/or external combustion engines [1–3]. For modern diesel engines, direct-injection (DI) has been regarded as a promising fuel supply method that makes diesel engine more environment-friend, more powerful, and smoother running [4–7] due to the brought improvements in raising fuel efficiency and reducing engine-out emissions [8,9], and high-pressure common-rail injection system has been selected as one optimal injection system since the capacities to satisfying more flexible and higher injection pressure [10,9,11]. To high-pressure common-rail injection system, cavitation behaviors existed within nozzle is one utmost important issue should to be solved [12–14]. As systematically investigated by Payri and his co-workers [15–18], cavitation has seriously effects on the injector's performance by influencing spray jet's penetration, Sauter mean diameter, the distribution of fuel, flow velocity, and the shear tension on flow's surface. Therefore, exploring the solution plans to the cavitation within nozzle is crucial to the design and the majoritarian of high-pressure common-rail injection system, and making fundamental investigations on flow and cavitation characteristics within nozzle are utmost significant even essential.

Heretofore, there rises a numerous literatures about investigations on flow and cavitation characteristics within nozzle in the past decades [19–23], and most of them focus on the cavitation issues in steady flows for exploring the influence mechanisms of cavitation at the maximum needle lift. Albeit approximately 90% of the flow during the whole injection is occupied at the maximum needle lift [24], the knowledge on cavitation characteristics obtained in steady flows hardly explore the detailed evolution of cavitation from the formation to the extinction within the nozzle during the whole injection process. Meanwhile, the actual injection process is transient process rather than steady process, and the hole to hole variation of the cavitation phenomena induced by the needle off axis movement also has great effects to the flow characteristics within nozzle [25,26], and hence the transient evolution of cavitation is very crucial to the actual performance of injectors; especially, the bubbles are

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always formed during the oil drainage process rather than at the maximum needle lift [27–35]. Therefore, making fundamental investigations on flow and cavitation characteristics in transient flow is necessary for an in-depth understanding on cavitation phenomenon within nozzle and has actual significance to the performances of high-pressure common-rail injection system.

Hitherto, some scholars have made valuable investigations on transient flow and cavitation characteristics within nozzle by experimental and/or numerical methods. Payri et al. [29] experimentally observed the evolution of transient cavitation within injector by laser technology and reported remarkable conclusions, but few information about the effects of needle movement on cavitation characteristics has been reported. Lee and Reitz [27] numerically studied the evolution of transient flow within nozzle during needle closing process, the results pointed out that raising close speed of needle (more than 0.7 m/s) will enhance the cavitation within the nozzle. Som et al. [30] numerically studied the distributions of vapor fraction and velocity magnitude within nozzle under different needle lifts, and the results indicated that cavitation patterns dramatically shift with the movement of needle lift. Jia et al. [31] numerically observed the evolution of transient cavitation within a conical-spray injector under the condition of 0.1 MPa ambient pressure with 100 MPa injection pressure, but a further quantitative investigation on transient cavitation characteristics at different needle lifts had not been reported. Salvador et al. [32] employed one-dimensional simulation to numerically study the effects of needle movement on the cavitation behaviors in a biodiesel flow; however, the relationship between needle movement and cavitation characteristics had not been reported. Salvador et al. [28], latter, numerically studied the internal flow and cavitation phenomenon in diesel injector nozzles under different needle lifts by three-dimensional simulations, and the results indicate that the influence mechanism of needle lift on cavitation phenomenon is different at different lifts. He et al. [33] numerically studied the evolution of transient cavitation within diesel injector under different injection pressures, and the results indicated that needle movement can induce a strong transient variation of cavitation flow within nozzle (especially when needle tends to be fully closed). From the aforementioned literatures, it can be clearly known that the general performance of nozzle is closed to the transient flow and cavitation characteristics which are directly dominated by dynamic characteristics of needle; however, the relevant investigations on transient cavitation are still scarcer than the cavitation characteristics at the maximum needle lift, and most of them focus on the variation of transient flow and cavitation induced by closing needle (oil off process) rather than opening needle (oil drainage process, which seriously influences the injection performance at the subsequent maximum needle lift). Therefore, in-depth and systematic investigations on transient cavitation characteristics within nozzles (especially during oil drainage process) are still necessary and needed in the future.

For providing more information on the understanding of transient cavitation characteristics within injector's nozzle for high-pressure common-rail injection system, the present investigation numerically studies the characteristics of transient cavitation flow within nozzle during oil drainage process and analyzes the influence mechanism of needle movement on the transient cavitation within nozzle.

2. Methodology

2.1. Numerical approach to the simulation

Heretofore, most investigations about transient cavitation characteristics were conducted by numerical simulation, dynamic meshing technologies have been widely employed since they can realize a clear observation on the evolution of cavitation within fluid domain, and smoothing method is the utmost common selection of mesh method among various dynamic meshing technologies. However, owing to nozzle's complex structure and narrow telescopic space (generally, for the injector employed by high-pressure common-rail injection system, the maximum lift of needle is lower than half one millimeter), the grid quality of the fluid domain (especially the domain of needle cone) generated by smoothing method hardly be assured, and consequently significances on the accuracy even the rationality of the calculated results. For overcoming the issues may brought by smoothing method, the present investigation employs Quasi-steady method rather than dynamic method to simulate the transient cavitation characteristics as what had been conducted in many works by previous scholars [34,35].

For the duration of transient flow within nozzle (fluid particle flows from the orifice's inlet to the outlet), the time cost can be considered as the time scale for transient variation of fluid field since the mentioned process is on behalf of one set update of the flow fluid insides the nozzle. For the investigated nozzle, the distance between the orifice's inlet and the outlet is 3.5 mm, the mean speed of the flow through the orifice is about 360 m/s; and thus the time scale of fluid field's single update is about 0.0097 ms. Fig. 1 shows the evolution curve of needle's movement speed for a single injection process. As can be seen, during the opening process of needle (i.e. oil drainage process), the maximal movement speed it can realized is 0.67 m/s; considering the maximal needle lift is 0.285 mm, the smallest time scale (namely, the shortest time cost on the full opening) is no less than 0.43 ms. Compared to 0.0097 ms the time cost by one update of fluid field, the variation frequency of the transient flow induced by needle's movement is too slow to be considered as constant; and thus taking quasi-steady method to the present investigation is reasonable.

2.2. Fluid domain and the general settings

For making in-depth understanding of the transient cavitation characteristics within nozzle, three-dimensional simulation calculations have been conducted on a commercial diesel injector applied in a high-pressure common-rail injection system. Since

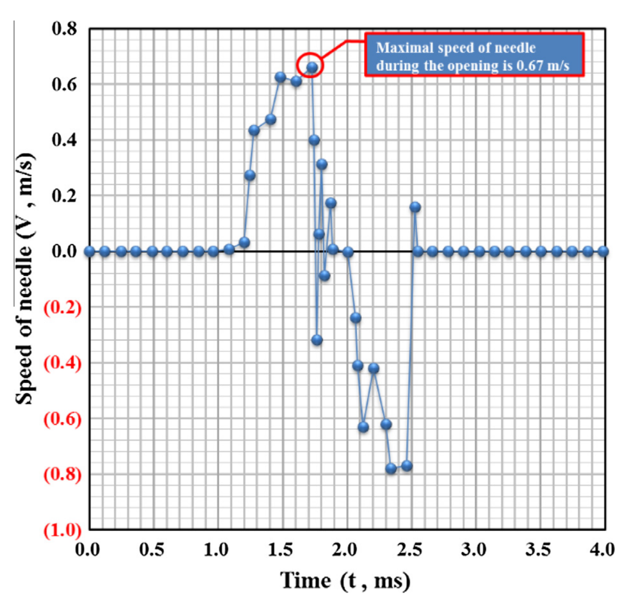

Fig. 1. Evolution curve of needle's movement speed for a single set.