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Numerical study of the internal flow and initial mixing of diesel injector nozzles with V-type intersecting holes

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HIGHLIGHTS

- The diesel injector nozzle with V-type intersecting hole was designed.
- Internal flow and near-field mixing for these nozzles were numerically examined.
- Intersecting hole eliminates cavitation, leading to higher discharge coefficient.
- Impact effect of intersecting hole yields a fan-shaped jet, enhancing initial mixing.

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ABSTRACT

A V-type intersecting hole nozzle, in which each hole is formed by the coalescence of a pair of sub-holes, has been developed to improve fuel-air mixing for diesel engines. In this paper, a numerical study has been conducted to examine the effects of the V-type intersecting hole structure on the internal flow of a nozzle and the initial stage of the fuel-air mixing processes. With this aim, a multi-phase flow calculation has been implemented on seven V-type intersecting hole nozzles with impact angles ranging from 20° to 50° and a referenced cylindrical hole nozzle under injection pressures varying from 60 MPa to 240 MPa. The comparison was made in terms of mass flow, momentum flux, effective velocity, discharge coefficient, area coefficient and velocity coefficient. The three-fluid model, which was validated using X-ray experimental data of an Engine Combustion Network (ECN) Spray A injector, was employed to calculate the associated multi-phase flow. The main results show that use of a V-type intersecting hole in a nozzle eliminates cavitation, leading to higher mass flow and momentum flux. Correspondingly, for these V-type intersecting hole nozzles, the discharge coefficients are insensitive to injection pressure, but decrease with an increasing impact angle, and are 20–30% higher than those of the cylindrical hole nozzle. These higher discharge coefficients mainly result from very high area coefficients that are approximately 0.98 at all injection pressure conditions because of the non-cavitating nature of the in-nozzle flow. Moreover, the impact effect of a V-type intersecting hole results in a fan-shaped jet with a very large spreading angle (25–40°) at the dispersion plane and a relatively narrower angle (approximately 12°) at the impact plane. The jet spreading angles at both planes are wider than that of the cylindrical hole nozzle (approximately 7°), indicating a noticeable improvement in the initial fuel-air mixing. Additionally, an increase in the impact angle of a V-type intersecting hole nozzle promotes initial mixing in terms of yielding a wider jet spreading angle, in spite of a slightly lower effective velocity.

1. Introduction

With the challenge presented by legislated limitations in both fuel consumption and pollutant emissions for diesel engines, common rail system with high injection pressure has been extensively developed and implemented to improve fuel-air mixing, thereby controlling combustion and pollutant formation processes [1]. This

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Nomenclature

A_{eff}	effective area of nozzle orifice
A_o	area of orifice outlet
C_a	area coefficient
C_d	discharge coefficient
C_v	velocity coefficient
d_H	hydraulic diameter
d_s	diameter of sub-hole
k, l	phase indicator
g	acceleration of gravity
L_U	length of the upper sub-hole
L_L	length of the lower sub-hole
M_{kl}	interfacial momentum exchange rate
$\dot{M}_f$	momentum flux of a nozzle hole
$\dot{m}_f$	mass flow of a nozzle hole
p	pressure
P_o	perimeter of orifice outlet
Δp_o	difference between injection and back pressure
R	diameter of the vapor bubble
t	time
T_k^t	Reynold stress of phase k
V_k	velocity of phase k
V_{kl}	interfacial velocity
u_{eff}	effective velocity of a nozzle hole
α_k	volume fraction of phase k
α	jet spreading angle at the impact plane
β	jet spreading angle at the dispersion plane
γ	impact angle of a V-type intersecting hole nozzle
ρ_k	density of phase k
ρ_l	density of liquid phase
Γ_{kl}	interfacial mass exchange rate
Γ	mass exchange rate of a single bubble
τ_k	shear stress of phase k

has necessitated developing a further understanding of the complicated flow behaviors both inside and outside the injector nozzle, including the cavitation and atomization phenomena [2,3]. The initial stage of fuel-air mixing in the near-field of a spray, known as primary atomization, rather than second atomization, which mainly appears in the far-field, has been identified as the dominant process of atomization [4,5].

It is well known that the fuel-air mixing process is largely determined by spray characteristics; these characteristics are strongly affected by the injection pressure and geometrical structure of the nozzle orifice among other factors [6–9]. Particularly, the influences of the nozzle geometry are so complicated that sometimes, a subtle geometrical change inside the nozzle can result in large variations in internal flow behaviors and thereby in spray evolution [10]. This phenomenon implies that there are most likely some potential options for improving the spray characteristics through appropriate nozzle geometry design in addition to increasing injection pressure and reducing the orifice diameter, which have been the primary options used [11,12].

There have been a number of efforts performed on examining diesel injector nozzle geometry other than the generally used cylindrical, unrounded inlet hole nozzle [13–15]. A topic that has received extensive focus is tapered hole nozzles, which have been found to have several advantages over ordinary nozzles under several conditions [8,14–16]. Moreover, the use of a rounding radius at the orifice entrance is of great interest [17]. Additionally, the use of a group-hole in nozzles has been reported to improve air entrainment and combustion [18,19]. Another interesting method is the use of elliptical holes for nozzle, which has been reported to enhance fuel atomization and mixing [20,21], and this enhancement has been interpreted from the view of internal flow dynamics in a recent numerical study [22]. It is noted that a considerable approach to nozzle flow has largely been through numerical simulation with Computational Fluid Dynamics (CFD), given the challenges in experimental measurements of the flow inside a real nozzle [10,11]. Briefly, the idea of improving spray characteristics via a specially designed nozzle geometry has achieved several encouraging results.

Similarly, based on the aforementioned idea, Long et al. [23] proposed the design of an intersecting hole nozzle in which each hole is formed by the coalescence of a pair of sub-holes. The only difference between an intersecting hole nozzle and a standard commercial nozzle is in the internal geometry of the holes; this difference is geometrically demonstrated in Fig. 1. As is shown, the axes of the pair of sub-holes in the intersecting hole nozzle, line AO and BO, intersect at the surface of the nozzle tip (point O), resulting in a V-type hole structure. Therefore, this type of nozzle is denoted as a V-type intersecting hole nozzle. The angle AOB, i.e., angle γ in Fig. 1, is denoted as the impact angle of the intersecting hole. Line XO (x axis), the central line of angle AOB, is defined as the axis of the intersecting hole.

V-type intersecting hole nozzles have been tentatively applied in a diesel engine [24], achieving an evident reduction in fuel consumption. Furthermore, the characteristics of spray emerging from V-type intersecting hole nozzles with two impact angles have been experimentally investigated by Leng et al. [25] and Dong et al. [26], reporting that the sprays are fan-shaped, i.e., the sprays show distinctly different spreading angles at different directions and have higher air entrainment rate than spray emerging from a cylindrical hole nozzle with the same exit flow area. These studies preliminarily show that V-type intersecting hole nozzles have the potential to improve fuel-air mixing and deserve further investigation. With the aim of characterizing the internal flow behaviors, Leng et al. [27] conducted a CFD calculation on two intersecting hole nozzles, finding that the intersecting hole nozzle can suppress cavitation and produce a much higher discharge coefficient. However, these studies mainly focus on the differences among a conventional cylindrical orifice nozzle and intersecting hole nozzles with a limited range of impact angles (approximately 20–30 degrees). The flow and spray dynamics of V-type intersecting hole nozzles with an extensive range of impact angles have not been studied. Additionally, the mechanism behind the morphology of the spray, i.e., the fan-shaped spray, emerging from V-type intersecting hole nozzles has not been well understood.

The purpose of the current study was to examine the influences of the V-type intersecting hole structure on the internal flow and initial mixing dynamics of diesel injector nozzles by means of CFD calculations, comparing the results of V-type intersecting hole nozzles with different impact angles, to unravel the mechanism of the formation of a fan-shaped spray and the effects of the impact angle for V-type intersecting hole nozzles. The comparison was made in terms of the mass flow, momentum flux, effective velocity, and several important non-dimensional parameters that characterize the internal flow dynamics, including the discharge coefficient