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A computational investigation on the influence of the use of elliptical orifices on the inner nozzle flow and cavitation development in diesel injector nozzles

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ABSTRACT

In this paper a computational study was carried out in order to investigate the influence of the use of elliptical orifices on the inner nozzle flow and cavitation development. With this aim, a large number of injection conditions have been simulated and analysed for 5 different nozzles: four nozzles with different elliptical orifices and one standard nozzle with circular orifices. The four elliptical nozzles differ from each other in the orientation of the major axis (vertical or horizontal) and in the eccentricity value, but keeping the same outlet section in all cases. The comparison has been made in terms of mass flow, momentum flux and other important non-dimensional parameters which help to describe the behaviour of the inner nozzle flow: discharge coefficient (C_d), area coefficient (C_a) and velocity coefficient (C_v). The simulations have been done with a code able to simulate the flow under either cavitating or non-cavitating conditions. This code has been previously validated using experimental measurements over the standard nozzle with circular orifices. The main results of the investigation have shown how the different geometries modify the critical cavitation conditions as well as the discharge coefficient and the effective velocity. In particular, elliptical geometries with vertically oriented major axis are less prone to cavitate and have a lower discharge coefficient, whereas elliptical geometries with horizontally oriented major axis are more prone to cavitate and show a higher discharge coefficient.

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1. Introduction

With further demands in the future to reduce the emission levels for diesel engines, after treatment devices like particulate traps and selective catalytic reduction seem inevitable. Even though those devices will be necessary, it is important to keep the raw emissions low in order to minimize the cost and the complexity of the devices. The main emissions of diesel engines are particulates and nitrogen oxides. The characteristics of the diesel engine tend to trade off these emissions, so that one emission is increased when the other one is reduced. Finding a technical solution that reduces both kind of emissions (or at least reduces one while the second remains unchanged over most of the engine operating range) is of great interest. One of the most important processes controlling the combustion efficiency and therefore the emissions formation is the air–fuel mixing process. It is well known that the time for the combustion kinetics is fast compared to the time of mixing [1]. The mixing process is therefore controlling the combustion. Once the fuel is injected into the combustion chamber, the fuel mixes with air and vaporizes. The air–fuel mixing process depends on spray characteristics, which in turn depend on the injection pressure and the dimensions and geometry of the nozzle orifice among other factors [2–6].

Some investigations in the literature have shown that air entrainment of jets injected into gas is considerably increased if elliptic orifices are used instead of circular orifices [7,8]. In other studies where liquid fuel was injected into gas trough elliptical nozzles researchers have shown that the spray cone angle in the minor axis plane is higher than the spray cone angle in the major axis plane, indicating that air entrainment is enhanced [9]. The same behaviour has been shown in more recent research; for example in Lee et al. [10] who compared an elliptical geometry nozzle hole with a conventional cylindrical one. From the main results of their study, it was shown that the spray tip penetration became shorter and the spray cone angle became wider with the elliptical geometry due to the fast break up of the fuel liquid column. Hong et al. [11] also studied the effect of elliptical nozzles on the spray characteristics and they observed a larger spray angle in the elliptical nozzle than in the circular nozzles.

Since improved air entrainment could have positive effects on the emissions of NOx and particulates, Matsson et al. [12] performed an investigation on the influence of non-circular orifice geometries. The tests were made using a passenger car diesel

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Nomenclature

A	area
A_{eff}	outlet effective area
A_o	outlet area
a	major axis of the ellipse
b	minor axis of the ellipse
C_a	area coefficient, $C_a = \frac{A_{eff}}{A_o}$
C_d	discharge coefficient, $C_d = \frac{\dot{m}_f}{\rho_l A_o u_{th}} = \frac{\dot{m}_f}{A_o\sqrt{2\rho_l \Delta P}} = C_v C_a$
C_v	velocity coefficient, $C_v = \frac{u_{eff}}{u_{th}}$
c	speed of sound
D_{eff}	effective diameter
D_H	Hydraulic diameter
D_i	diameter at the orifice inlet
D_o	diameter at the orifice outlet
e	eccentricity
K	cavitation number
k	turbulent kinetic energy
k-factor	orifice conicity factor
L	orifice length
$\dot{M}_f$	momentum flux
$\dot{m}_f$	mass flow
P	orifice wetted perimeter
p	pressure
P_b	discharge back pressure
P_i	injection pressure
p_{sat}	vaporisation pressure
r	rounding radius at the inlet orifice
t	time
u	velocity
$\bar{u}$	averaged velocity
u_{eff}	effective velocity, $u_{eff} = \frac{\dot{M}_f}{\dot{m}_f}$
u_{th}	theoretical velocity, $u_{th} = \sqrt{\frac{2(P_i - P_b)}{\rho}}$

Greek symbols

ΔP	pressure drop, $\Delta P = P_i - P_b$
Ψ	fluid compressibility
Ψ_l	liquid compressibility
Ψ_v	vapour compressibility
γ	vapour mass fraction
μ	fluid viscosity
μ_l	liquid viscosity
μ_v	vapour viscosity
ρ	fluid density
ρ_l	liquid density
ρ_{lsat}	liquid density at saturation
ρl°	liquid density at a given temperature condition
ρ_{vsat}	vapour density at saturation
ρ_v	vapour density

engine and a single cylinder engine with optical access. The results showed a reduction in NOx for the nozzle with elliptical orifices in comparison with the reference circular nozzle. Nevertheless, the use of elliptical nozzles did not affect on soot particulates.

Although there are a lot of referenced works in the literature, most of them, with exception of Hong et al. [11], aim at analysing the influence of the use of elliptical nozzles on the spray and combustion process, but treating the nozzle itself as a black box, thus without investigating which are the changes in the flow pattern inside the nozzle that promote the improvement of the air–fuel mixing process through the increment of the spray cone angle. Only Hong et al. [11] have tried to link the internal nozzle flow characteristics in terms of cavitation appearance and intensity to the shape of the spray when comparing circular and elliptical nozzle holes. With this aim, they used non-conventional transparent acrylic symmetric models for visualization purposes. The cross-sectional areas of circular and elliptical nozzles were the same and based on a 3 mm diameter circular nozzle, therefore quite far from being representative values for standard nozzle hole diameters in Diesel injectors (0.1–0.2 mm). The authors reported a lower discharge coefficient for the elliptical nozzles and a lower discharge coefficient than that of the circular nozzle at the same Reynolds number.

The aim of the present paper has been to evaluate the potential of using non-conventional elliptical nozzle holes by means of CFD (computational fluid dynamics) calculations, comparing the results of four different elliptical nozzles with a base standard circular nozzle hole. The comparison has been made in terms of mass flow, momentum flux and other important non-dimensional parameters which are important features describing the behaviour of the inner nozzle flow: discharge coefficient (C_d), area coefficient (C_a) and velocity coefficient (C_v). Furthermore, the fact that non-convergent holes are used makes the nozzles prone to cavitate [13]. Thus, critical conditions for cavitation inception, its development and morphology have also been studied and analysed.

The final objective is to identify a connection between the different expected flow pattern in elliptical nozzles and the different spray cone angle behaviour confirmed in the experiments referenced above. If we consider two different nozzles, the former with elliptical orifices and the latter with circular orifices, since the elliptical orifice has a bigger perimeter for the same cross-sectional area, atomization due to air–fuel interaction is supposed to be enhanced, which is in agreement with the experimental results. Nevertheless, there should also be other reasons as far as flow characteristics are concerned: differences in flow regime, cavitation inception and development, effective injection velocity, etc. The present paper will be focused on this kind of differences.

For that purpose, a Homogeneous Equilibrium Model able to model the cavitation phenomenon was used. The code is implemented in the version 1.5 of OpenFOAM^R [14]. This code has been extensively validated with mass flow measurements, momentum flux measurements and injection velocity at the nozzle exit. The validation was done over one of the nozzles used in the present investigation: the standard nozzle with circular orifices. The results obtained from simulations and their comparison with the experimental data showed that the model is able to predict the behaviour of the fluid in both cavitating and non-cavitating conditions with high level of confidence.

As far as the structure of the paper is concerned, it has been divided in 6 sections. First of all, in Section 2, a description of the CFD approach is made, where the equations governing the model and how they are solved are explained in detail. Following, the geometry characteristics of the five nozzles, the injection conditions (injection pressure and backpressure) and fluid properties used for the simulations are described in Section 3 where a validation of the cavitation model is also shown. In Section 4, results of mass flow, momentum flux and flow coefficients are presented and analysed for all the nozzles. A special attention is paid to cavitation inception conditions and morphology in the different nozzles tested. The influence of cavitation on the flow parameters is widely analysed and discussed in this section. Due to the high volume of results and comparisons, a synthesis is presented in Section 5, mainly focusing on the mixing process. Finally, the main conclusions of the investigation are drawn in Section 6.

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