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Characterization and prediction of the discharge coefficient of non-cavitating diesel injection nozzles

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HIGHLIGHTS

- A new expression to characterize discharge coefficients has been developed.
- The method can be used with multi and single-hole nozzles under non-cavitating conditions.
- The deviation between experiments and predictions is lower than 1.52%.
- The asymptote of the discharge coefficient depends on the geometry of the nozzle inlet.
- The discharge coefficient seems to depend on a balance between $1/\sqrt{Re}$ and $1/Re$.

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ABSTRACT

An experimental and theoretical study about the characterization of the discharge coefficient of diesel injection nozzles under non-cavitating conditions is presented in this paper. A theoretical development based on the boundary layer equations has been performed to define the discharge coefficient of a convergent nozzle. The discharge coefficient has been experimentally obtained for a standard diesel fuel under a wide range of Reynolds numbers by two different techniques: mass flow rate measurements and permeability measurements. Five different nozzles have been used: two multi-hole nozzles that have been tested in the frame of this work, and three other single-hole nozzles, the data of which have been taken from previous studies. The experimental results show good agreement with the theoretical expressions, proving that it is possible to predict the discharge coefficient of a non-cavitating nozzle with the equations shown in this paper.

1. Introduction, justification and objective

The increasingly restrictive pollutant emissions regulations applicable to internal combustion engines cause a continuous investigation in different methods to reach clean, efficient and marketable engines. Several of the explored methods are focused on the injection system and injection strategy [1], since the way the fuel is delivered by the injection system in modern diesel engines affects not only the performance, but also the noise and the pollutant emissions [2]. A fundamental characteristic of the fuel injection process is the fuel mass flow rate as well as the total amount of fuel injected into the combustion chamber [3]. Therefore, measurement and control of these parameters is one of the most important objectives in engine research and many studies have been carried out to understand the behavior of the flow in the most used nozzle types [4,5].

The real flow through the nozzle under general operating conditions (where cavitation can be present) is determined by the velocity and density profiles, which are complex and unknown [6]. However, it is possible to characterize this real flow by an effective area, A_{eff}, lower than the geometric one, through which the fluid exits with a uniform effective velocity, u_{eff}, and with a density equal to the one of the liquid fuel, ρ_f; in a way that the simplified flow characterized by these parameters leads to mass and momentum rates equal to the real ones, which can be experimentally measured [7].

The effects of the internal flow on the mass flow rate and momentum flux can be summarized in three different dimensionless coefficients: the velocity coefficient, C_v, the area coefficient, C_a, and the discharge coefficient, C_d [8]. All of them are widely described in Section 3.

Lichtarowicz et al. [9] performed a wide review of discharge coefficient measurements versus the Reynolds number for different nozzles under non-cavitating conditions. A compilation of parametric equations for C_d is shown in that paper. However, all

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Nomenclature

A_{eff}	effective area at the outlet of the nozzle
A_{geom}	geometric area at the outlet of the nozzle
C	conicity of the nozzle
C_a	area coefficient
C_d	discharge coefficient
C_v	velocity coefficient
d	outlet diameter of the nozzle
D	inlet diameter of the nozzle
ET	energizing time
K	proportionality constant between the thickness of the boundary layer and the Reynolds number referred to the direction of the flow
L	nozzle length
P	pressure
r	radius of rounding at the inlet of the nozzle
Re	Reynolds number
u	velocity profile inside the boundary layer
u_{eff}	effective velocity at the outlet of the nozzle
u_{th}	theoretical maximum velocity at the outlet of the nozzle
u_{∞}	velocity outside the boundary layer
x	axial direction of the nozzle
y	radial direction of the nozzle
δ	thickness of the boundary layer
ΔP	pressure difference between the rail and the outlet of the nozzle
ϵ	percentage deviation in C_d between experimental and theoretical results
$\lvert\bar{\epsilon}\rvert$	mean relative deviation between experimental and theoretical results
μ	viscosity
ξ	pressure drop coefficient caused by the recirculation zone in the inlet of the nozzle
ρ	density

Subscripts

aSOE	after start of injection
back	referred to downstream the nozzle
exp	referred to experimental results
inj	referred to injection conditions (in the rail)
out	referred to the outlet of the nozzle
SOE	start of injection
th	referred to theoretical results

of them are empirical correlations and, therefore, the expressions cannot guarantee their validity out of the range of the experimental measurements. Similar studies have been performed by Kent and Brown [10] and Ohrn et al. [11].

Schmidt and Corradini [12] also published a review about the internal flow of diesel fuel nozzles. Different analytical and multi-dimensional models are shown, focusing on the cavitation behavior. However, cavitation is a phenomenon that normally is avoided in automotive engines and, to this aim, convergent non-cavitating nozzles are usually installed in current engines.

Payri et al. [13] studied the influence of the flow regime on the mass flow rate and momentum flux, and how it affects the spray development in diesel nozzles. Experiments were carried out in three tapered nozzles and spray visualization tests revealed a change in the behavior of the angle and penetration of the spray related to the change of the flow nature. Finally, the authors related these macroscopic parameters to those describing the internal flow (area, velocity and discharge coefficients) and with the geometry of the nozzle. The macroscopic characteristics of direct-injection multi-hole sprays have also been studied by Zeng et al. [14] by using dimensionless analysis, including the discharge coefficient and penetration.

The influence of the injector technology (solenoid or piezoelectric) on the area, velocity and discharge coefficients and on the development of the spray was also studied by Payri et al. in [15,16]. The authors characterized the hydraulic behavior of different nozzles by means of mass flow rate and momentum flux measurements. It was found that under steady-state conditions, the differences in nozzle geometry dominate on the injector technology. Therefore, the hydraulic characteristics of a nozzle can be studied under steady-state conditions independently of the injector.

Desantes et al. [7] analyzed the flow behavior inside the nozzle for five different nozzles under different injection conditions. The area, velocity and discharge coefficients were obtained under non-cavitating and cavitating conditions and they were related to the spray tip penetration. The authors found that the experimental discharge coefficient decreases when the diameter of the nozzle is increased, probably due to a higher proneness to cavitation.

Vergnes et al. [17] studied the injector nozzles performance (by means of the discharge coefficient) under low-temperature environment conditions. The authors correlated the discharge coefficient with the Reynolds number by an empirical relationship. Therefore, a wide range of experimental data was needed to fit the parameterization of C_d. Moreover, the authors showed the relevance of the discharge coefficient, since the development of the spray (in terms of spray tip penetration) can be deduced from it.

Finally, Dober et al. [18] developed numerical models for investigating the effect of injection hole geometry on the internal nozzle flow, focusing on the injection rate and spray geometry predictions. The authors found that the flow efficiency can be increased up to a 7% by grinding the inlet of the nozzle, proving the high dependence of the maximum discharge coefficient on the inlet geometry.

The main objective of this study is to obtain and validate an alternative theoretical procedure to determine the discharge coefficient of a convergent nozzle under non-cavitating ans steady-state conditions. The study has been done with diesel fuel, but the results can be extrapolated to any other fuel. Despite the fact that the effects of the nozzle geometry on the discharge coefficient are known, most of the correlations available for C_d are mere experimental correlations, obtained by applying a mathematical fitting. An expression that can be used to predict the value of the discharge coefficient avoiding the experimental setup is intended to be defined here. Thus, once the theoretical expressions will be obtained, some experimental results from different nozzles will be used to validate the equations.

Despite the fact that CFD studies can provide a very good approximation to the discharge coefficient of a real nozzle under steady-state conditions, even a simple CFD study needs much more working and computing time than a 0-D correlation like the one presented in this paper. Moreover, the working time needed is highly increased if the hydraulic characterization of the nozzle (variation of C_d with the Reynolds number) wants to be known, hence the interest in developing theoretical 0-D expressions.

It should be noted that realistic conditions can be studied by analyzing the internal flow through a diesel nozzle. It has been proved that the injector needle does not have any effect on the outlet flow when the needle lift has reached around 100 μm, which is a value by far overcome in most real operating conditions, especially during the main injection [19]. Moreover, Salvador