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Methodology to estimate the threshold in-cylinder temperature for self-ignition of fuel during cold start of Diesel engines

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ABSTRACT

Cold startability of automotive direct injection (DI) Diesel engines is frequently one of the negative features when these are compared to their closest competitor, the gasoline engine. This situation worsens with the current design trends (engine downsizing) and the emerging new Diesel combustion concepts, such as HCCI, PCCI, etc., which require low compression ratio engines. To mitigate this difficulty, pre-heating systems (glow plugs, air heating, etc.) are frequently used and their technologies have been continuously developed. For the optimum design of these systems, the determination of the threshold temperature that the gas should have in the cylinder in order to provoke the self-ignition of the fuel injected during cold starting is crucial. In this paper, a novel methodology for estimating the threshold temperature is presented. In this methodology, experimental and computational procedures are adequately combined to get a good compromise between accuracy and effort. The measurements have been used as input data and boundary conditions in 3D and 0D calculations in order to obtain the thermodynamic conditions of the gas in the cylinder during cold starting. The results obtained from the study of two engine configurations -low and high compression ratio- indicate that the threshold in-cylinder temperature is a single temperature of about 415 °C.

1. Introduction

High speed DI Diesel engines are widely used for powering passenger cars basically thanks to the high degree of development reached by this type of engine in the recent years. The Diesel is considered an environmentally friendly engine mainly due to its reduced CO_2 emissions consequence of its low consumption. Moreover, the increasingly restrictive emission standards have been met thanks to the continuous development of novel technologies for combustion control and exhaust gas after-treatment. In the last decade, the Diesel engine performance and driveability have significantly improved with these latest technologies. The increase in boosting pressure and the improvement of the air management actually permit to reach specific powers higher than 60 kW/L, which makes them very competitive with spark ignition engines.

Nevertheless, one of the critical problems of this type of engine is related to the difficulties for starting at cold conditions, particularly in places where the ambient temperature is below 0° C [1]. Under these unfavourable conditions, very low cranking speeds and quite high blow-by levels [2,3] are caused by the increase of the oil viscosity [4] and the decrease of battery performance and, additionally, fuel-air mixing is hindered due to the weak air motion [5].

Combustion chamber and injector design has a strong effect on the fuel-air mixing and hence on engine startability [6]. Additionally, the fuel injection strategy plays a crucial role not only for startability improvement, but also for emissions reduction during engine starting [7,8]. Taking advantage of the flexibility of current injection systems, experimental [9] and theoretical [10,11] studies have been reported in which feasible strategies for cold start enhancement are proposed. The potential of the exhaust gas recirculation to improve combustion and emissions during engine starting has been also evaluated [12].

Together with these difficulties, the low temperature of the gas in the cylinder —which delays ignition— affects negatively the startability of Diesel engines [13]. Moreover, due to the lower compression ratio required in new combustion concepts such as HCCI, PCCI, etc., currently in development to comply with the near-future emission standards without efficiency penalties [14], this last effect is even more detrimental to engine cold starting [15].

To assist engine cold start external aid systems are frequently used for supplying the required thermal energy to the charge needed to provoke the self-ignition of the fuel. With this purpose, two pre-heating procedures have been commonly employed in

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Nomenclature

a	acceleration, m s^{-2}
A	contact area, m^2
C_1, C_{w1}, C_{w2}	Woschni correlation coefficients
C	discharge coefficient
c_m	mean piston velocity, m s^{-1}
c_u	instantaneous tangential velocity, m s^{-1}
D	bore, m
E	Young's modulus, N m^{-2}
h	specific entalphy, J kg^{-1}
h	film coefficient, W m^{-2} K^{-1}
K_{def}	constant strain
L_0	length from the crank up to the piston head height, m
m	mass, kg
$\dot{m}$	mass flow rate, kg s^{-1}
p	pressure, Pa
Q	heat, J
R	universal constant of perfect gas, J kg^{-1} K^{-1}
T	Temperature, K
u	specific internal energy, J kg^{-1}
V	volume, m^3

Greek symbols:

α	crank angle, deg
γ	adiabatic exponent
Γ	compressibility coefficient
δ, Δ	variation
ξ	correction function of the instantaneous tangential velocity
ρ	density, kg m^{-3}
Φ	swirl coefficient
Ψ	in-cylinder variable

Subscripts

bb	blow-by
cc	combustion chamber
ckc	crankcase
f	fuel
f, ev	evaporated fuel
f, g	evaporated fuel at in-cylinder conditions
f, inj	fuel injection conditions
g	gas
i	inertial efforts
p	pressure efforts
pp	piston pin
r	reciprocating motion elements
ref	reference
res	residual gas
s	swept
sc	short circuit
steel	steel
w	wall

Abbreviations:

BDC	bottom dead centre
CFD	computational fluid dynamics
CFPP	cold filter plugging point
CR	compression ratio
deg	degree
DI	direct injection
EGR	exhaust gas recirculation
EVO	exhaust valve opening
HCCI	homogeneous charge compression ignition
imep	indicated mean effective pressure
IVC	intake valve closing
IVO	intake valve opening
MSN	mean swirl number
PCCI	premixed charge compression ignition
SN	swirl number
TDC	top dead centre
UD	upwind differencing

Diesel engines: generating a hot spot in the combustion chamber or heating all the gas entering in the cylinder.

In the first procedure a glow plug is assembled in the cylinder head, so that the gas around its tip is heated. With the injector located close to the plug, part of the fuel injected evaporates quickly around the glow tip leading to a region where ignition can occur [16]. Glow plugs, which are a solution imported from IDI Diesel, are extensively used in small and medium sized engines [17,18]. However, since the glow plug is an intrusive element protruding in the combustion chamber, it has an adverse influence on the combustion process in normal engine operating conditions.

In the second solution a heater in the intake system is used for warming up all the air aspirated by the cylinder, so that the temperature required for the self-ignition of the fuel can be reached during the compression stroke. With this purpose either an electrical heater or manifold burners have been employed in medium and large Diesel engines; these should have in principle less difficulties than small engines for cold start, since they are more adiabatic. However, electrical air heaters were also successfully evaluated for cold starting of small modern Diesel engines [19,20]. Advantageous features of this technology for emissions reduction during engine warm up were also reported [21]. Moreover, the extreme difficulties encountered to start small engines of low compression ratio with state-of-the-art glow plugs in cold conditions have led engine developers to consider the intake air heating technology as an aid system complementary to the glow plugs. Especially, since the air heaters perform very well in controlling the engine stability after starting [22,23].

In order to provoke the first combustion for cold starting, it is important to determine accurately the thermal condition of the gas at injection time. This leads to the optimal design of the above mentioned technologies. In addition, the thermal condition of the gas must be related to the threshold temperature at which the self-ignition of the fuel occurs. Therefore, the design of the pre-heating system is based on its capacity to supply the required energy to heat up the gas in the cylinder from the current up to the threshold temperature.

In this paper, a novel methodology to estimate the threshold in-cylinder temperature for self-ignition of the fuel during cold start in modern DI Diesel engines is proposed. Experimental and theoretical procedures were adequately combined to obtain a good compromise between accuracy and effort. With the aim to evaluate the reliability of the proposed methodology, a 1.9 L engine with low and high compression ratio configurations was analysed in this study. Cold starting tests were performed for the two configurations in a dedicated climatic chamber. Three-dimensional calculations were executed to simulate the intake process during engine starting, while the gas conditions in the cylinder during the closed cycle were calculated by means of a thermodynamic model. In this model, the relevant phenomena occurring during cold start, such as heat transfer and blow-by, were considered. Hence, it is possible to correct the significant errors that are usually made in peak