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Development and validation of a semi-empirical model for the estimation of particulate matter in diesel engines

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ABSTRACT

A semi-empirical correlation for the estimation of PM (particulate matter) emissions in diesel engines, as a function of significant engine operating variables, has been developed and validated on a GM (General Motors) Euro 5 diesel engine.

The experimental data used in the present study have been acquired at the dynamic test bench of ICEAL-PT (Internal Combustion Engine Advanced Laboratory at the Politecnico di Torino), in the frame of a research activity with GMPT-E (General Motors PowerTrain-Europe) for the calibration of a Euro 5 prototype 2.0 liter diesel engine equipped with a twin-stage turbine and a piezo-driven Common Rail injection system. The experimental data were acquired for six key-points representative of the engine working conditions over a NEDC (New European Driving Cycle). The experimental tests have been carried out according to the Design of Experiment approach and for each point several variation lists of the main engine variables have been considered.

As a first step, the main engine variables which are expected to be related to the formation and oxidation of PM have been identified. An exponential mathematical model has then been introduced and a detailed statistical analysis has been carried out for each key-point in order to identify the most robust combination of the input variables among all the possible ones.

It was verified that PM emissions are correlated to a great extent to the value of the chemical heat release at the end of the injection of the main pulse. This quantity is in fact related to the mass of burned gases which is generated by the oxidation of the pilot pulses that precede the main injection. Such a mass can have a large impact on the local oxygen concentration and temperature of the charge in which the fuel of the main pulse is injected, with a consequent effect on PM formation. Additional quantities have also been considered in the investigation: the relative air-to-fuel ratio λ, the intake charge oxygen concentration, the accumulated fuel mass, the equivalence ratio of the spray at the main pulse start of combustion and some combustion metrics related to the heat release rate.

At the end of the statistical analysis, the most influencing parameters have been selected and a semi-empirical model to predict the in-cylinder formed PM mass has been developed. The model has hence been tested under both steady-state and transient conditions.

1. Introduction

Several studies have been carried out on a scientific basis on the effect of the particulate matter (PM) emissions on the human health as well as on the climate changes [1–8] and it is worth observing that diesel engines highly contribute to the overall PM emissions. Thus, the reduction of diesel emissions holds a key role for further penetration of the diesel engine in the automotive market. The emission legislations have become even more stringent and have resulted into increasing interest into the understanding of the mechanisms of PM formation and oxidation in internal combustion engines.

PM is made up of clusters of spherical particles, which widely vary in size, on which several compounds are absorbed [9,10]. The insoluble fraction of the diesel particulate matter is usually referred to as soot, and consists of solid carbonaceous substances carrying unburned hydrocarbons, metals and superficially absorbed sulfates [11]. The mechanism that leads to the formation of soot from the liquid- or vapor-phase hydrocarbons is generally related to six fundamental processes [11], namely pyrolysis, nucleation, coalescence, surface growth, agglomeration and oxidation. Several experimental studies, conducted in the past years with

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Nomenclature

a reduction coefficient of the spreading angle of the idealized spray model
AC alternating current
BMEP brake mean effective pressure
c coefficient of sensitivity
C PM mass emissions in mg/Nm3
C_a contraction area coefficient
C_d discharge coefficient
C_v velocity coefficient
CA crank angle
CFD Computer Fluid-Dynamics
CN combustion noise
CO Carbon Monoxide
d nozzle hole diameter
DI Direct Injection
DoE Design of Experiment
ECU Electronic Control Unit
EGR Exhaust Gas Recirculation
EOI end of injection
EOI_{main} end of injection of the main pulse
EVO Exhaust Valve Opening
FSN filter smoke number [0–10]
GM General Motors
GMPT-E General Motors PowerTrain-Europe
HRR heat release rate
ICEAL-PT Internal Combustion Engine Advanced Laboratory at the Politecnico di Torino
IMEP Indicated Mean Effective Pressure
IVC intake valve closing
k coverage factor
m mass; coefficient of the spray model
$\dot{m}_a$ air mass flow rate
$\dot{m}_f$ fuel mass flow rate
m_{PM} net formed mass of particulate matter per cycle/cylinder
MFB5 crank angle at which 5% of the fuel mass fraction has burned
MFB50 crank angle at which 50% of the fuel mass fraction has burned
MFB70 crank angle at which 70% of the fuel mass fraction has burned
MFB80 crank angle at which 80% of the fuel mass fraction has burned
MFB95 crank angle at which 90% of the fuel mass fraction has burned
N engine rotational speed; mole number
N_{cyl} number of cylinders
NEDC New European Driving Cycle
NOx Nitrogen Oxides
O_2 Intake charge oxygen concentration
OPA opacity [0–100%]
p pressure
p_a ambient pressure
p_f injection pressure
pil pilot injection
PM particulate matter
PMA pilot-main-after injection strategy
p_n Standard pressure
PPM pilot-pilot-main injection strategy
PPMA pilot-pilot-main-after injection strategy
q injected fuel volume
q_{aft} injected fuel volume quantity of the after injection
$q_{av,max,main}$ maximum value of the accumulated fuel mass after SOImain
$q_{f,inj}$ total injected fuel volume quantity
q_{pil2} injected fuel volume quantity of pil2 injection
q_{pil1} injected fuel volume quantity of pil1 injection
Q_{ch} chemical energy release
$Q_{ch}(EOI_{main})$ chemical energy release at the end of the injection of the main pulse
R gas constant; correlation coefficient
R_{corr} adjusted correlation coefficient
$R_{corr,best}$ adjusted correlation coefficient of the best combinations
R_{exh} gas constant of the exhaust gases
SOC start of combustion
SOI start of injection
t time
t^+ characteristic time
$\tilde{t}$ dimensionless time
T temperature
T_b(MFB95) temperature of the burned gases at MFB95 crank angle
THC total unburned hydrocarbon
T_n standard temperature
u^2 variance
U expanded uncertainty
UEGO Universal Exhaust Gas Oxygen sensor
u_{EGR} EGR valve duty-cycle signal
U_f fuel velocity at nozzle exit
WG wastegate
x generic axial spray coordinate
x^+ characteristic spray length
$\tilde{x}$ dimensionless distance
$x_{SOC,main}$ axial spray coordinate at the SOC of the main pulse
$x_{u,ivc}$ unburned air mass concentration at IVC
$x_{u,evo}$ unburned air mass concentration at EVO

Greek symbols
α air-to-fuel ratio; spreading angle of the idealized spray model
α_{st}^{u} stoichiometric ambient-to-fuel ratio
ΔCA_{comb} combustion duration parameter
ΔCA_{diff} diffusive combustion duration parameter
ΔMFB_{70-95} difference between MFB95 and MFB70 parameters
ϕ equivalence ratio
$\phi_{SOC,main}$ equivalence ratio of the spray at SOC_{main}
λ relative air-to-fuel ratio
θ spreading angle of the spray
ρ mass density
ρ_a ambient density
ρ_f fuel density
τ_{char} characteristic mixing time coefficient
τ_{HL} half-life parameter
τ_{id} ignition delay
$\tau_{id,main}$ ignition delay of the main pulse

the laser-sheet imaging technique, have led to a deeper insight into understanding of the combustion process and PM formation in DI diesel engines. On the basis of these results, Dec has introduced a novel conceptual scheme for diesel combustion, which is currently considered as the reference one in the literature [12]. According to the Dec scheme, diesel combustion is basically a two-stage process, made up of a fuel-rich premixed phase (ϕ = 2–4), which leads to the formation of products of incomplete combustion (soot, CO, THC), and a stoichiometric diffusive phase located at the jet periphery, in which the oxidation of the previously formed products takes