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Modeling a resistive soot sensor by particle deposition mechanisms

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ABSTRACT

Soot sensors are used for the diagnosis of Diesel Particulate Filter (DPF) failures that will result in exceedance of Particulate Matter (PM) emission limits defined by increasingly stringent regulations for diesel vehicles. Accumulating sensors, also known as resistive electrode sensors, are considered to be a practical and low-cost approach to estimate soot concentration in diesel engine exhaust, as part of the vehicle On-Board Diagnostics (OBD). This paper presents a physical model describing soot particle deposition mechanisms that was developed to interpret and predict the soot sensor behavior.

Initially, the range of parameters that affect sensor output is defined after analyzing vehicle driving cycle measurements. Next, a set of steady-state measurements is conducted and Computational Fluid Dynamics (CFD) simulations are performed to investigate the flow field inside the sensor tip. Data from measurements and simulations feed the developed physical model of the soot deposition on the sensor electrode plate. The investigated deposition mechanisms include thermophoresis, electrophoresis, inertial impaction, and convective diffusion. The model results are validated with several sets of measurements of a diesel engine equipped with DPF based after-treatment system. The developed model is found capable of predicting the behavior of the sensor for a range of exhaust gas conditions, taking into account sensor geometry.

1. Introduction

Purpose of soot sensors is to correctly diagnose a DPF malfunction that leads to emissions exceeding a certain threshold. The advantage of using a resistive electrode soot sensor, in comparison with other type of sensors, is its low cost and inherent simplicity that makes it suitable for mass production and use for vehicle OBD purposes. The Differential Pressure (Delta-P) sensors have been used for years in order to detect the soot load status of the DPF via the DPF pressure-drop measurement. However, until recently, they are not sufficiently accurate (Masoudi & Sappok, 2014). Radio-Frequency (RF) sensors rely on measurement of the absorption of an RF signal (Masoudi & Sappok, 2014) and Electric Charge sensors measure an electrical current e.g. generated after charging particles with a corona charger (Ntziachristos, Fragkiadoulakis, Samaras, & Janka, 2011).

In the direction of improving a resistive sensor design, a physical model has been developed to assist the understanding of the underlying soot deposition mechanisms. The sensor is expected to monitor the DPF malfunction against a specific OBD Threshold Limit (OTL) and for this reason, the operational range of the sensor was defined. Representative levels of parameters that affect sensor output were determined after analyzing data from driving cycles measurements of a vehicle equipped with a failed DPF. Subsequently, a set of steady-state measurements was conducted and in combination with CFD simulations. The results were used as inputs to the physical model. After the calibration of the deposition mechanisms, a Sensor Constant is introduced, which can be used

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Nomenclature

A_{pl}	Sensor electrode plate area [m^2]
A_b	Sensor body external area [m^2]
C	Particle mass concentration [kg/m^3]
c_b	Sensor body specific thermal capacity [J/(kg K)]
C_C	Cunningham correction factor [dimensionless]
C_m	Velocity jump coefficient [dimensionless]
C_{pl}	Sensor plate specific thermal capacity [J/(kg K)]
C_S	Thermal creep coefficient [dimensionless]
C_t	Temperature jump coefficient [dimensionless]
$\mathfrak{D}$	Particle diffusion coefficient [m^2/s]
d_0	Primary particle diameter [m]
d_f	Mass-mobility exponent [dimensionless]
D_j	Jet radius (impaction) [m]
d_p	Particle diameter [m]
dz	Distance covered by particles vertical to the plate [m]
E	Electric field intensity [V/m]
E_I	Impaction efficiency [dimensionless]
h_{amb}	Ambient convection coefficient [W/(m^2 K)]
h_{gas}	Exhaust gas convection coefficient [W/(m^2 K)]
h_m	Mass transfer coefficient [m/s]
J	Particle number deposition flux [#/(m^2 s)]
J_t	Total particle deposition flux at time t [#/(m^2 s)]
$\overline{J_t}$	Average particle deposition flux [#/(m^2 s)]
J_{el}	Particle deposition flux (electrophoresis) [#/(m^2 s)]
J_{imp}	Particle deposition flux (impaction) [#/(m^2 s)]
k_b	Sensor body thermal conductivity [W/(m K)]
k_B	Boltzmann's constant [J/K]
k_g	Exhaust gas thermal conductivity [W/(m K)]
Kn	Knudsen number [dimensionless]
k_p	Particle thermal conductivity [W/(m K)]
k_{pl}	Sensor plate thermal conductivity [W/(m K)]
K_{th}	Thermophoretic coefficient [dimensionless]
L	Sensor plate characteristic length [m]
M	Particle mass [kg]
n_0	Particle number concentration [#/m^3]
N_0,N	Particle number [#]
$n_{0,t}$	Particle number concentration at time t [#/m^3]
n'_A	Sensor Constant point estimate [#/m^2]
$\overline{n'_A}$	Sensor Constant [#/m^2]
ne	Particle electric charge (expressed as a multiple of elementary charge) [Cb]
Nu_{gas}	Nusselt number (exhaust gas) [dimensionless]
p	Exhaust gas pressure [kPa]
Pr	Prandtl number (exhaust gas) [dimensionless]
R^2	Coefficient of determination [dimensionless]
$R_{cond,b}$	Sensor body conduction thermal resistance [K/W]
$R_{cond,pl}$	Sensor plate conduction thermal resistance [K/W]
$R_{conv,g}$	Exhaust gas convection thermal resistance [K/W]
$R_{conv,amb}$	Ambient gas convection thermal resistance [K/W]
Re_L	Reynolds number [dimensionless]
RT	Response Time [s]
$RT_{modeled}$	Modeled Response Time [s]
Sc_p	Schmidt number [dimensionless]
St	Stokes number [dimensionless]
t', t_1, t_2	Time interval, time [s]
T_g,T	Exhaust gas temperature [K]
T_1,T_2, T_3	Temperature at nodes 1, 2, 3 (thermal model) [K]
V_b	Sensor body volume [m^3]
V_{dep}	Deposition velocity [m/s]
$V_{dep,total}$	Total deposition velocity [m/s]
$V_{dep,total,t}$	Total deposition velocity at time t [m/s]
V_{diff}	Deposition velocity due to diffusion/convection [m/s]
V_{el}	Electrophoretic deposition velocity [m/s]
V_{gas}	Exhaust gas velocity [m/s]
V_{imp}	Inertial impaction deposition velocity [m/s]
$V_{parallel}$	Velocity component parallel to the plate [m/s]
V_{pl}	Sensor plate volume [m^3]
V_{TE}	Terminal electrostatic velocity [m/s]
V_{th}	Thermophoretic deposition velocity [m/s]
V_{turb}	Turbulent impaction deposition velocity [m/s]
V_Z	Exhaust gas velocity vertical to the plate [m/s]
w	Particle deposit yield [kg]
Z	Electrical mobility [m^2/(V s)]

Nomenclature (Greek symbols)

Δt	Simulation/measurement time step [s]
Δx_{pl}	Distance between two consecutive nodes of the sensor plate (1D thermal model) [m]
Δx_b	Distance between two consecutive nodes of the sensor body (1D thermal model) [m]
η_g	Dynamic viscosity [Pa s]
λ	Exhaust gas mean free path [m]
λ_{ref}	Exhaust gas mean free path reference [m]
μ_g	Geometric mean of particle diameter [m]
ν_g	Exhaust gas kinematic viscosity [m^2/s]
ρ	Exhaust gas density [kg/m3]
ρ_0	Primary particle density [kg/m^3]
ρ_b	Sensor body density [kg/m^3]
ρ_p	Particle density [kg/m^3]
ρ_{pl}	Sensor plate density [kg/m^3]
σ_g	Geometric standard deviation of particle diameter [dimensionless]
τ_W	Wall shear stress (at plate surface) [N/m^2]

for the prediction of the sensor response.

A resistive soot sensor typically includes a plate which is positioned vertically to the exhaust flow direction. The plate is made from a highly insulating ceramic material, such as aluminum oxide, which is used as substrate (Hagen et al., 2010). Upon the ceramic layer, the electrodes are thin conductor tracks made of platinum (Hagen et al., 2010), which are intertwined in a comb-like manner. As soot particles accumulate on the interelectrode channels, dendrites and "bridges" are formed, which produce conductive pathways, which in turn change the electrical properties of the two electrodes.

The operation of the sensor consists of three phases (Fig. 1). During the first phase or dead-band period (A→B), conductive pathways have not been formed yet. During the second phase or sensing period (B→C), the sensor conductivity passes an internal threshold and a signal is generated, which has increasing monotony as the electrode conductivity increases. During the third phase or

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