Journal of Aerosol Science 124 (2018) 41–53

Contents lists available at ScienceDirect

Journal of Aerosol Science

journal homepage: www.elsevier.com/locate/jaerosci

The impact of voltage and flow on the electrostatic soot sensor and the implications for its use as a diesel particulate filter monitor

M. Matti Maricq*, David Bilby

Research & Advanced Engineering, Ford Motor Company, P.O. Box 2053, MD 3179, Dearborn, MI 48121, USA

ARTICLE INFO

Keywords:
PM sensor
Soot sensor
Electrostatic trap
On board diagnostics
Electrically charged aerosol

ABSTRACT

This paper takes a detailed look at the operation of the electrostatic soot sensor and its potential use to monitor motor vehicle particulate matter emissions. Charged soot particles entering the sensor are trapped and grow into dendritic soot structures aligned with the electric field. Above a critical length, the electrostatic force fractures the dendrites, producing fragments that carry sufficient charge between the electrodes to generate nanoamp level currents. While proportional to soot concentration, this current also responds to flow variations, which limits the sensor's application in areas such as motor vehicle on-board diagnostics. The present work demonstrates that this flow dependence is closely related to the sensor's response to variations in electric field. The measured response to step changes in applied voltage agrees very well with a kinetic model of electric field induced dendrite growth and fragmentation. Variations in flow induce fluctuations in sensor current as dendrites reorient in response to the drag force and find themselves above or below the critical length for fragmentation. This mechanism qualitatively fits the experimental data. In engine exhaust applications, variation of exhaust flow with engine operation interferes with time resolved soot measurement. This interference partially cancels out when averaged over time, rendering the electrostatic soot sensor a potentially viable means to distinguish diesel particulate filter performance.

1. Introduction

As motor vehicle emissions regulations become more stringent, they drive new technology not only for exhaust aftertreatment, but also for the sensors required for the on-board diagnostics (OBD) mandated to monitor their performance (California ARB, 2015). The United States Environmental Protection Agency (EPA) 2007 heavy duty standards and the European Union (EU) Stage 5b light duty diesel standards dramatically reduced particulate matter emissions limits to 10 mg/bhp h and 6×10^{11} solid particles/km, respectively (DieselNet, 2018). These levels are too low to meet by engine design changes alone; hence, they ushered in the age of diesel particulate filter (DPF) equipped diesel vehicles. The subsequent EU Stage 6 regulations and California Air Resources Board (CARB) LEV III 2025 1 mg/mi PM standard have extended the need for exhaust filtration to gasoline direct injection vehicles and led to the development of gasoline particulate filters (GPF).

Thanks to ceramic and cordierite wall-flow filter technology (Guan, Zhan, Lin, & Huang, 2015), DPF implementation into vehicle exhaust systems proceeded more facilely than prior aftertreatment components, catalytic converters for example, and overachieved the particulate matter (PM) and particle number (PN) standards. The same cannot be said for OBD PM sensors. A decade after introduction of the EPA heavy duty and EU 5b standards, the currently used resistive sensor suffers many limitations. This sensor

---

* Corresponding author.
E-mail address: mmaricq@ford.com (M.M. Maricq).

https://doi.org/10.1016/j.jaerosci.2018.07.002
Received 17 April 2018; Received in revised form 7 June 2018; Accepted 11 July 2018

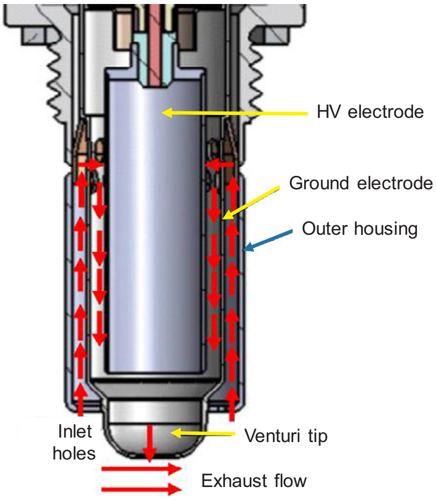

Fig. 1. Emisense PMTrac electrostatic soot sensor. Arrows show gas flow path. The electric field is across the inner portion of the flow.

records soot by conductive pathways formed as it deposits onto a pair of interlaced electrodes plated onto a heatable substrate (Grob, Schmid, Ivleva, & Niessner, 2012; Malik et al., 2011; Ochs, Schittenhelm, Genssle, & Kamp, 2010). The time span for the current to rise to a pre-established value serves as a measure of soot emissions, after which the sensor needs thermal regeneration prior to beginning another measurement. The result is a periodic relative assessment of PM emissions that will likely lack sufficient sensitivity as OBD limits are tightened.

The electrostatic soot sensor presents a potential alternative means to monitor soot emissions. Hall and coworkers initially developed this sensor concept (Diller, Hall, & Matthews, 2008; Diller, Osara, Hall, & Matthews, 2009; Steppan et al., 2011; Warey & Hall, 2005; Warey, Hendrix, Hall, & Nevius, 2004). They recorded nanoamp currents as diesel engine exhaust flowed past a parallel pair of electrodes held at 1 kV potential difference. Hauser (2006) independently designed a similar sensor, one with multiple parallel plates that extend into the exhaust pipe. EmiSense Technologies LLC later refined the Hall and coworker sensor into a coaxial electrode design (Fig. 1), which increased sensor response by roughly an order of magnitude (Allmendinger et al., 2013; Allmendinger, 2011; Steppan et al., 2014).

This electrostatic trap based sensor detects soot because the chemistry of rich flames naturally produces ions and, thereby, a Boltzmann distribution of charged soot particles (Maricq, 2006, 2008). The surprising thing is that the sensor registers nanoamp level currents under conditions in which the trapped soot particles carry only enough charge to produce picoamp currents. In previous work, we visually demonstrated that dendrite growth followed by fragmentation is the mechanism for this current amplification (Bilby, Kubinski, & Maricq, 2016). The sensor preferentially detects soot particles, because they undergo electric field induced growth into dendritic structures, whereas other charged particles, such as organic or ash, have little if any propensity to do so (Riehle & Wadenpohl, 1996).

Interestingly, we also observed that the sensor exhibits a cross sensitivity to flow transients. This is not a problem in applications where the flow through the sensor is kept constant. However, sensors for motor vehicle emissions applications are designed to operate without a pump, and instead draw sample via the pressure drop generated as the exhaust flows past the sensor. Because of this, flow through the sensor varies with exhaust flow, and it becomes difficult to distinguish sensor response to soot from its response to flow changes.

The present paper takes a detailed look via experiment and model calculations at this flow dependence and the sensor's closely related dependence on applied voltage. The next section describes a model for the sensor mechanism. The comparison of model and experimental results for voltage steps helps confirm our model of the sensor mechanism and extend it to flow steps. The results then present measurements of diesel engine exhaust that investigate the PMTrac's ability to distinguish different DPF leak rates in the presence of vehicle speed / load induced flow variations.

2. Sensor description and model

Fig. 1 shows a cross sectional view of the EmiSense PMTrac sensor examined in this work. It is designed for insertion into an engine exhaust pipe to monitor soot. It consists of three concentric cylinders: outer housing, ground electrode, and high voltage electrode. Exhaust flow past the sensor tip causes a pressure drop at the peripheral inlet holes. This draws in exhaust, which passes through the outer annulus, turns 180 degrees, flows through the electric field, and exits the hole at the tip. Soot is detected as an electrical current across the high voltage and ground electrodes.

In the electric field, charged soot agglomerates acquire a transverse drift velocity and some fraction, depending on particle size and flow rate, reaches the electrodes. There they grow into electric field induced dendrites, such as illustrated in Fig. 2. Our model approximates these as stacks of unit soot “blocks”, which are subject to electrostatic and drag forces (Bilby et al., 2016). Dendrite