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In-situ visualization of exhaust soot particle deposition and removal in channel flows

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HIGHLIGHTS

- ▸ A unique apparatus for in-situ observation of thermophoretic particle deposition.
- ▸ In-situ measurement of the deposit layer (formed by nano-particles) thickness.
- ▸ Practical methods for removal of the formed layer in laminar channel flows.
- ▸ Observing micron size particle in diesel exhaust in contrast to conventional wisdom.

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ABSTRACT

Exhaust gas recirculation (EGR) coolers are used in diesel engines to reduce emissions of nitrogen oxides. Thermophoretic particle deposition occurring in EGR coolers causes a significant degradation in the cooler effectiveness generally followed by the stabilization of cooler effectiveness after long exposure times. Mechanisms responsible for this stabilization are not clearly understood. To investigate the stabilization trend, a visualization test rig was developed to track the dynamics of diesel exhaust soot particulate deposition and removal in-situ. A digital microscope records surface characteristics. A medium duty engine is used to generate the exhaust stream. A steady state condition was selected to run the engine for the deposition tests. In contrast to conventional understanding, large particles (tens of microns) were observed in diesel exhaust. Interesting results are observed for flaking/removal of the deposit layer during designed removal experiments. Water condensation at a low coolant temperature and bombardment of large particles resulted in a significant removal of deposit in the form of flakes while thermal expansion or shear force (low velocities) alone did not remove the deposit layer.
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1. Introduction

Petroleum fuels are heavily used in the U.S. transportation system. Beside the massive consumption of these fuels, vehicles produce CO_2 emissions that have a significant effect on global warming. While diesel engines are very efficient and consequently produce less CO_2, one of their main shortcomings is their high level of nitrogen oxides (NO_x) emissions. Cooled exhaust gas recirculation (EGR) has proven to be an effective way of reducing NO_x formation in diesel engines; however, the performance of the EGR cooler has been shown to significantly degrade with fouling.

In practical engine coolers, a portion of exhaust gas, known as EGR, is returned to the engine and mixed with incoming fresh air. Through the use of EGR, peak in-cylinder and flame temperatures can be lowered, leading to drastically lowered engine out NOx emissions. The EGR cooler is a heat exchanger in which engine coolant is used to cool the exhaust gas, which enhances the reduction of NO_x emissions (Hoard et al., 2009). The presence of cooled surfaces will cause soot deposition and condensation of hydrocarbons and acids. The buildup of deposits in EGR coolers causes drastic degradation in heat transfer performance (Hoard et al., 2009). However, future emission standards will require increased EGR flow rates and reduced temperatures, forcing particulate deposition within the EGR cooler to be reduced or prevented.

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Particle deposition in general occurs due to various mechanisms including Brownian diffusion, turbulent impaction, electrostatic and gravitational forces, diffusiophoresis, and thermophoresis. Particle diameter is a critical factor in determining the deposition mechanism. Our scaling analysis (Abarham et al., 2010) show that thermophoresis is dominant among the aforementioned deposition mechanisms for submicron particles (i.e. exhaust gas flow carrying particles ranging from a few nano-meter to 300 nm (Harris and Maricq, 2002). Thermophoresis is a particle motion generated by thermal gradients. In a thermal gradient, gas molecules on the hot side of the particle collide with higher force than the molecules from the cooler side, and a net force is created toward the cooler region i.e. the channel or tube wall. The well known Talbot formula (Talbot et al., 1980) describes thermophoretic deposition of particulates as:

$$V_{th} = -\frac{K_{th}\nu}{T}\nabla T \tag{1}$$

where is K_{th} thermophoretic coefficient (Talbot et al., 1980), ν is gas kinematic viscosity, and ∇T is the temperature gradient. In internal flows, thermophoretic velocity in the axial direction is significantly smaller than the gas velocity in the axial direction and can be ignored. In tube flows, the radial component of thermophoretic velocity becomes important while in channel flows the components in the directions perpendicular to the axial direction are comparable with the flow field velocity.

It is shown in previous publications that the layer formed due to particulate deposition in duct flows tends to stabilize after a long exposure time (Epstein, 1997; Stolz et al., 2001; Lepperhoff and Houben, 1993). The mechanisms leading to this stabilization are not clearly understood. There may be deposit removal mechanisms, or it may be that the rate of deposition decreases as deposits build (or both) along with the variation of the deposit layer properties. There are a few articles in literature discussing deposit removal of submicron particles in the sub-sonic flow range (Abd-Elhady et al., 2011; Sluder et al., 2011). Although particle removal is seen in the aforementioned work due to the shear force, the gas velocity in the experiments (30–75 m/s) is noticeably larger than that of in operating conditions of real EGR coolers. Therefore, it is unlikely to be the reason for stabilization of real EGR cooler deposits.

There are many experimental studies of particle deposition and hydrocarbon condensation in EGR coolers including effectiveness reduction and pressure drop increase due to fouling (Sluder et al., 2008; Chang et al., 2010; Abd-Elhady et al., 2009; Ismail et al., 2005) or ex-situ measurements of the deposit thermal properties after the layer was exposed to the ambient and the sample was cut (Lance et al., 2010; Lance et al., 2009). Despite the very good quality of these studies, the dynamics of the fouling process is not clear from them. Also, there have been a few attempts at simulation, prediction, and measurement of deposit growth in a combustion chamber by extensive micrographic study (Price et al., 1997; Cheng, 1996; Price et al., 1995) but the novel investigation in this research study is performed to observe in-situ the dynamics of particle deposition, layer formation, and removal.

In our previous work, the deposition mechanism of exhaust soot particulates in internal flows was studied by proposing an analytical correlation (Abarham et al., 2010) and numerical CFD models (Abarham et al., 2009; Abarham, 2011) to estimate effectiveness drop of surrogate tubes and deposit mass gain inside the tubes due to thermophoretic deposition of soot particles up to 12 h of exposure time. We compared our model prediction of deposit mass gain and effectiveness drop of the tube to experimental measurements done at Sluder's Laboratory, and the results are in a satisfactorily agreement. Those experiments were performed so that effectiveness was measured in-situ but deposit mass was measured ex-situ after the tests were complete and the sample cooled down to the ambient temperature. Despite the good agreement for short exposures, the results of the models show a deviational trend for longer exposure times. Therefore, we started investigating the physics of long exposure experiments and deposit stabilization mechanism(s) by monitoring the deposit layer in-situ. The aim of this study is to investigate enhancing mechanisms for deposit removal and effectiveness recoveries in EGR coolers by visualizing the events happening in different designed conditions. In the following section the experimental test fixture and the experiments are described.

2. Experimental apparatus

A unique visualization experimental apparatus was designed and constructed in order to observe the mechanism of particulate deposition/removal in-situ. A 2008 model year medium duty diesel engine is used to generate exhaust for the visualization test fixture. Hot engine exhaust carrying soot particles flows through a rectangular channel with one wall made of Pyrex® and the other of stainless steel 316L (metallic wall). The Pyrex® wall provides the opportunity to monitor the deposit growth on the opposite wall made of stainless steel (Fig. 1).

If thermophoresis were the only deposition mechanism for submicron particles, imposing a zero temperature gradient (in the direction perpendicular to the axial direction $(\partial T/\partial y = 0)$—see Fig. 2) on the Pyrex® wall should result in no deposition. One side of the Pyrex® wall is exposed to the hot exhaust stream and the other side

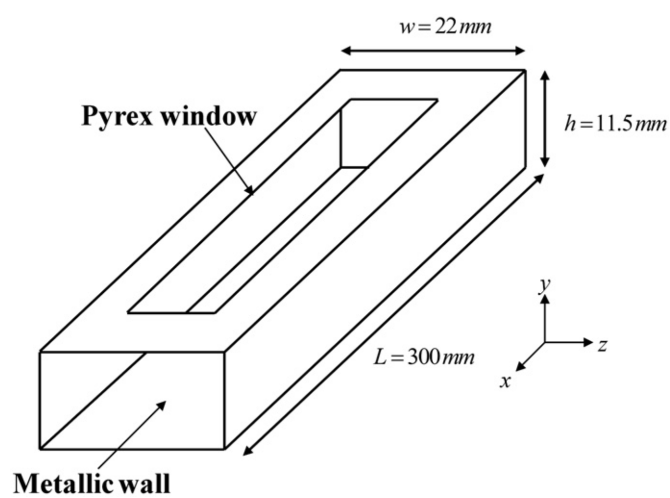

Fig. 1. Schematic of the channel (isometric view).

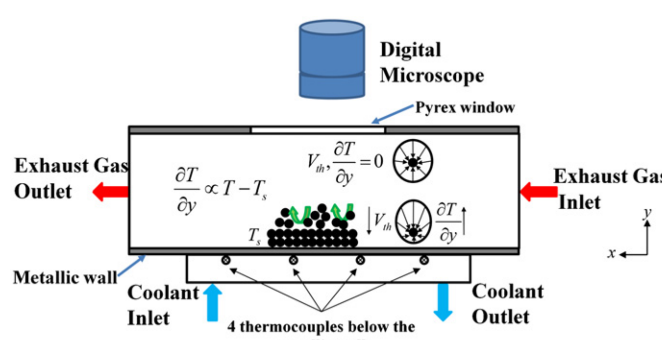

Fig. 2. Principle of the visualization test rig (side view)—metallic channel caries exhaust (or compressed air) and glass window allows visualization.

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