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Asymptotic characteristics of particulate deposit formation in exhaust gas recirculation (EGR) coolers

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HIGHLIGHTS

- EGR coolers would profoundly reduce NO_x emission from diesel engines.
- An explanation of fouling asymptote in EGR coolers.
- Proposes a critical velocity above which fouling can substantially be suppressed.

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ABSTRACT

The objective of this research is to shed some light into the asymptotic behavior of fouling process in EGR coolers based on a theoretical hypothesis that is verified experimentally. This is important for a successful simulation of particulate fouling in EGR coolers and to develop appropriate fouling mitigation approach. The experimental results showed that the development of fouling layer causes i) the thermal resistance of the fouling layer to increase as well as decreased temperature difference between the gas side and the fouling layer, which subsequently decreases the deposition rate, ii) the tube cross-sectional area to decrease thus the average gas-side temperature increases, consequently the gas velocity and deposit removal would increase. At a certain moment of time a balance occurs between the decreasing deposition rate and the increasing removal rate such that the fouling process ceases and an asymptotic behavior is approached.

1. Introduction

Diesel engines emissions, especially nitrogen oxides (NO_x) pose a major threat to the environment. The widely used measure to reduce NO_x emissions in diesel engines is to return part of the exhaust gas after cooling it to the intake of the engine. This is usually done through a heat exchanger known as the exhaust gas recirculation (EGR) cooler [1]. Many researchers, e.g. Kowada et al. [2], McKinley [3] have shown that NO_x emissions are significantly reduced by using EGR coolers. However EGR coolers are subjected to severe fouling dominantly due to particulate matter in the exhaust gas, i.e. soot particles. Moreover, other fouling mechanisms such as solidification and chemical reaction may also take place. Nevertheless in the present study the focus will be on particulate deposition as primary mechanism. Particulate fouling is defined as the deposition of unwanted materials on the heat transfer surface forming an insulating layer that reduces the heat transfer coefficient. The fouling layer decreases the thermal efficiency and increases the pressure drop in the EGR cooler. Kim et al. [4] examined the fouling behavior of a shell and tube EGR cooler, and showed that severe clogging in the tubes can happen just after 62 h of operation. Zhan et al. [5] measured fouling in an EGR cooler connected to a 7.3 L V8 diesel engine, and found that if the exhaust gases are fed directly into the cooler without any treatment then the pressure drop in the EGR cooler increased by 61% from its initial state within 42 h of operation. This is mainly due to clogging of the tubes by the formation of a deposit layer. Fouling of EGR coolers tends to be one of the predominant factors of EGR systems failure, and introduces a major uncertainty into the design and operation of EGR coolers.

Zhang et al. [6] and Malayeri et al. [7] investigated the influence of particulate matter on the performance of EGR coolers. It was

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found that the fouling had a significant impact on the performance of the EGR cooler during only the first 12 h of operation. The thermal resistance increased by 100% in approximately 3 h and by 150% in 12 h. The thermal resistance of the cooler increased continually throughout the test period, but the rate of increase of the thermal resistance decreases with time until it reached an asymptote. Zhang et al. [6] concluded from the performed experiments that the rate of change in the fouling resistance is initially quite large but the resistance normally asymptotes to a constant value after a long time, which is known as the asymptotic behavior of the fouling process. This phenomenon has been reported by many researchers, e.g. Garrett-Price et al. [8], Abd-Elhady et al. [9] and Warey et al. [10], and many attempts have been done to explain it.

Ismail et al. [11,12] performed a series of experiments to characterize soot deposition profile in EGR coolers using a non-destructive technique [13] to measure the three-dimensional thickness profile of deposited soot in diesel engine exhaust systems. They concluded that the asymptotic behavior in EGR coolers is due to fact that the deposition and re-entrainment of the soot become approximately equal. This physical explanation of the asymptotic behavior was not supported by any scientific reason. Abraham et al. [14] made a review of soot deposition and removal mechanisms in EGR coolers, and tried to explain the exponential approach of the fouling layer in EGR coolers. They concluded that as the fouling builds up in the cooler, its surface temperature increases that cause higher kinetic energy of soot particles at the gas deposit surface, such that thermal forces acting on particles may overcome van der Waals forces between them, which makes the outer layer of deposit fluffier and more prone to removal. They also reported that the mechanism responsible for the asymptotic behavior of fouling in EGR coolers is due to the increased removal rate of particles as the FL builds up such that a balance between the deposition and removal of particles occurs. However, this hypothesis still needs to be verified. Paz et al. [15] developed a numerical simulation procedure for studying soot particle deposition in diesel exhaust systems, with a particular focus on the fouling layer thickness evolution. Paz et al. [15] developed a numerical approach based on the Kern and Seaton model [16] that the net fouling process is the difference between the deposition rate $\dot{m}_d$ and the removal rate $\dot{m}_r$. They also assumed that the deposition rate $\dot{m}_d$ is constant while the removal rate $\dot{m}_r$ is proportional to the fouling layer thickness, such that at a certain moment of time the deposition rate becomes equal to the removal rate and an asymptotic behavior is approached. Both assumptions, i.e. deposition rate is constant and the removal rate is proportional to the fouling layer thickness, have been applied solely as hypotheses.

The objective of this research is to explain the asymptotic behavior of the fouling process in EGR coolers based on a theoretical hypothesis that is verified experimentally. This explanation is quite important for a successful simulation of particulate fouling in EGR coolers as well as the design of EGR coolers. Simulating the fouling process in EGR coolers without a thorough understanding of the fouling behavior would lead to peculiar results that cannot be explained. The proposed hypothesis is discussed in the next section. An experimental setup has also been used where soot particles of nano-size are produced by a particle generator, which are then mixed with injected air, and the whole mixture is heated up in a tube furnace, to simulate the conditions of exhaust gasses from diesel engines. The gas–particle mixture is cooled by a tubular EGR cooler which is commonly used in diesel engines due to its simple design and operation, and then fouling of the cooler is monitored. Detailed description of the experimental setup can be found in Ref. [9]. The experimental procedure is given in the Section 3, followed by the experiments performed and discussion of its results.

2. Proposed hypothesis for the asymptotic fouling behavior in EGR coolers

2.1. Particle transport and deposition

The stages of particulate fouling are illustrated in Fig. 1. The thermal resistance R_f of the fouling layer is related to its thermal conductivity k and thickness Δ by

$$R_f = \frac{\Delta}{k} \tag{1}$$

The change in the fouling layer thermal resistance with time indicates the growth rate of the fouling layer. The initial deposit layer (**a**) is likely to be of fine particles, which are transported by the thermophoresis mechanism (Wagoner and Yan [17]). Fine particles in the flue gases experience a force in the direction toward the cooler surface, i.e. a thermophoretic force (Raask [18]), due to the temperature gradient between the hot gasses and the cold surface of the heat exchanger. This force arises from the fact that hotter gas molecules have higher velocity. Thus, in a thermal gradient the gas on the hot side of the particle hits with higher force than the gas from the cooler side, and a net force is created toward the cooler region. As particles are transported from the bulk gas flow into the boundary layer near the surface, they enter a region of large thermal gradient and thus are thermophoretically driven toward the wall.

This so-called thermophoretic effect augments the transport of sub- to micro-meter particles toward the heat exchanger surface, but hardly influences the transport of large particles, as found by De Best [19]. For small particles, approximately sub to a few microns in diameter, transport is controlled by diffusion and thermophoresis, while for large particles, transport rate increases since inertia becomes important. Inertial impaction takes place when large particles, usually have a large inertial momentum to follow the gas stream lines, and instead impact the surface. A measure for the importance of the inertia of the particle is given by the particle relaxation time τ_p, the time scale in which a particle can adapt to a change in the fluid velocity and is defined as (van Beek [20]):

$$\tau_p = \frac{\rho_p d_p^2}{18\mu_g} \tag{2}$$

The different modes of particle transport as a function of the particle diameter d_p are given in Fig. 2. Transport by inertial impaction becomes important when the particle is not capable anymore to follow the smallest fluid fluctuations that are characterized by the Kolmogorov time scale τ_K, so when $\tau_p > \tau_K$.

The Kolmogorov time scale τ_K is the time scale required to generate the smallest hydrodynamic length scales in turbulent flows, and it is defined as (Lesieur [21]):

$$\tau_K = \sqrt{\frac{\nu_g L}{U^3}} \tag{3}$$

L and U denote the length and velocity scale of the most energetic eddies and ν_g the gas kinematic viscosity. L is taken equal to the radius of the tube and U to the main stream velocity. Small particles are defined based on their relaxation time τ_p, such that the particle can follow the smallest fluid fluctuations that are characterized by the Kolmogorov time scale τ_K, i.e. $\tau_p < \tau_K$. The critical particle diameter defining the inertial-impaction regime, $d_{p,c}$, can be found by substituting τ_K for the particle relaxation time τ_p in Eq. (2). It can be concluded that the critical diameter, $d_{p,c}$, for soot particles in exhaust gases in EGR coolers at an average gas temperature of 400 °C and velocity of 30 m/s is 1 μm. The diameter of