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Experimental evaluation of the critical local wall shear stress around cylindrical probes fouled by diesel exhaust gases

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ABSTRACT

The problem of fouling in the heat exchangers of exhaust systems has yet to be resolved. This results in enormous costs for engine manufacturers due to the required over-sizing during design and due to unscheduled maintenance needs.

This article presents an experimental layout developed for measuring fouling in diesel engine exhaust gas systems. This facility was based on a circular cylindrical cross-flow device, with one straight and smooth stainless steel probe positioned transverse to the flow of exhaust gases. The probe can be cooled from the inside with water and fouled on the outside as a result of particle deposition from exhaust gases.

The tests were conducted under constant engine operating conditions. Therefore, the asymptotic depth of the fouling layer could be measured at different angular positions at the end of each test.

The critical wall shear stress rate is proposed as the controlling mechanism of the local removal process that leads to different fouling depths around each probe. This is in contrast to the critical velocity concept, which cannot be applied at a local scale due to its formulation. The experimental results, although subject to the usual uncertainties of fouling processes, seem to support this idea.

1. Introduction

In recent years, the requirements imposed on exhaust systems have rapidly increased; turbochargers, intercoolers, catalysts, regenerators, filters, heat exchangers, and a growing number of antipollution devices are now required. All of these systems suffer from a common problem: they are damaged by fouling, one of the most important design parameters in exhaust gas systems [1].

Fouling is defined as the presence of any foreign substance that is adhered to the heat transfer surface and causes negative effects. It is a complex phenomenon that is influenced by factors such as design, operating conditions, fuel, and oil. The deposition of fouling material on the heat transfer surface decreases thermal transmission [2] and, in most cases, creates an additional layer of material that reduces the flow section and thereby results in pressure losses [3]. Monitoring the evolution of this pressure loss to account for the fouling layer requires expensive control loops and sensors. An understanding of the mechanisms involved in the process and a characterisation of the properties of the accumulated mass are important for the development of effective mitigation techniques.

In this research, a test bench was developed to measure the amount of mass deposited and the local thickness of the fouling layer on devices exposed to diesel exhaust gases. Examination of the deposits adhered to the walls of the probes showed that solid carbon and condensed hydrocarbons were the main constituents of the fouling layer, as observed by other authors [4], and that particle deposition seemed to be the most important mechanism during fouling [5].

In general, the growth of the soot layer can be driven by different physical mechanisms, including sedimentation, interception, diffusion, inertial impaction, electrostatic attraction, thermophoresis and gravitational settling. These mechanisms depend on the nature and size of the particles present and the operating conditions. Fouling is commonly divided into three steps, as proposed by Bott [6]; Epstein expanded this division to include five steps [7]. First, particles are transported from the duct core toward the vicinity of the walls. This transport is related to the particles' relaxation time t_p^+, which characterises the extent to which the drag forces experienced by a particle are affected by fluid velocity changes caused by turbulence. After reaching the proximity of the boundary layer, the particles may travel through this layer because the turbulent effects are substantially decreased and become deposited on the surface. Deposition is a strongly size-dependent process. For $t_p^+ < 0.1$–0.2 (in air, particles diameter below 0.1–0.2 μm), the deposition rate is mainly controlled by Brownian diffusion and turbulent dispersion when the temperature gradient is zero. When a temperature gradient exists in the above range, the thermophoretic force becomes important [5]. In the range

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Nomenclature

A	cross-sectional area (m^2)
d	contact diameter (m)
D_h	hydraulic diameter (m)
E	Young's modulus (Pa)
f	friction factor, $f = \frac{2\tau_w}{\rho u^2}$, dimensionless
F_d	drag force (N)
F_{adh}	adhesion force (N)
F_g	gravity force (N)
F_l	lift force (N)
F_b	buoyancy force (N)
L	load (N)
$\dot{m}$	mass flow rate (kg/s)
r_p	particle radius (m)
Re	Reynolds number, $\mathrm{Re} = \frac{\rho u D_h}{\mu}$, dimensionless
RM	rolling moment ratio, dimensionless
T	temperature (K)
t_p^+	particle relaxation time, $t_p^+ = \frac{2\rho_p r_p^2 \rho_g u_\tau^2}{9\mu}$, dimensionless
u	velocity (m/s)
u_τ	friction velocity (m/s)
v	Poisson's ratio, $v = -\frac{d\tau_{transverse}}{d\tau_{axial}}$, dimensionless

Greek symbols

δ	particle deformation (m)
ε	thermal efficiency, dimensionless
Γ	surface energy (J/m^2)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
τ_w	wall shear stress (Pa)

Subscripts and superscripts

c	coolant
g	gas
in	inlet
out	outlet
p	particle
s	surface
∞	free-stream (far away from the walls)
$*$	critical

$0.1 < t_p^+ < 10$, (particle diameter between 1 and 10 μm in air), thermophoretic effect decreases as t_p^+ approaches 10, while turbophoresis and lift force may become relevant. The impaction regime starts for $t_p^+ > 10$–20 (about 10–20 μm in air); here, particles are too large to respond to the eddies fluctuations near the wall, therefore, turbophoretic effects becomes less important [8].

Soot particles in diesel exhaust gases are in the range of 10^{-8}–10^{-5} m, with most typical values on the order of 10^{-8}–10^{-7} m [4]. The submicron scale of these particles and the high temperature gradients typical in exhaust systems make thermophoresis the most important deposition effect [9]. When the particles reach the wall at low velocities, chemical and electrostatic forces, such as van der Waals forces, enable sticking or adhesion [10].

In the reverse process, particles are removed and detached from the fouling layer. This process was described by Epstein [11] as dissolution, erosion and spalling. This step, which has likely received the least amount of attention from researchers, involves several mechanisms including turbulent bursts, electrostatic double layer forces [10], and the impacts, rolling and scrubbing actions associated with particles [12,13]. Removal is considered to be strongly linked to velocity [14]. Finally, the last process is the change of residue properties with time, a process referred to as ageing.

When fouling is dominated by particulate deposition, a stable or asymptotic thickness may be reached [15]. Several researchers, including Messerer et al. [16] and Grillot and Icart [5], have studied the evolution of asymptotic fouling. The most accepted explanation of this phenomenon is that, in confined flows, deposits attenuate heat transfer and increase shear stress. This reduces temperature gradients, which thereby decreases thermophoretic deposition and increases the removal effect, leading to an equilibrium situation [15].

Most previous research has evaluated fouling at a global scale under controlled conditions with plastic or metal particles. In this study, the real working conditions of a diesel exhaust device were reproduced to generate a fouling layer on a cylindrical probe. The local depth of the deposited layer was compared with the local levels of thermophoresis and shear stress, which oppose these forces at a local scale.

2. Experimental set-up

Several reasons justified the experimental setup chosen: the fouled surface can be extracted for its weight and optical inspection, the system generates low backpressure to the engine assuring its stable operation during the test, the shear stress distribution over a cylindrical probe is well documented, it is easy to generated cases with different level of refrigeration, and the geometry generated the range of Reynolds and t_p^+ we were looking for. In addition, it is easy to simulate numerically which can be useful for the validation of fouling submodels.

The gases used in this fouling study were produced with a CGM10DW generator set composed of a Lombardini LDW 702 and a single pole alternator. In this system, gases were exhausted from a two-cylinder engine working at 3000 rpm submitted to a 6 kV A resistive load. The engine supplied a constant mass flow of approximately 60 kg/h up to approximately 650 K. The exhaust gases supplied by the engine arrived through a bifurcation that split the gases between two parallel pipelines, in which two identical automotive EGR coolers were positioned. Before and after each EGR cooler, cylindrical probes were exposed to the gas. The measuring section is shown in Fig. 1.

The pressure and temperature measurements were collected with thermocouples and pressures gauges, the locations of which are shown in Fig. 1. The positions of the sensors were selected according to the recommendations of each manufacturer. The pressure sensors were of the membrane type and had an accuracy of ±0.05 mbar, a relative maximum of 500 mbar and an absolute maximum of 10 bar absolute. The temperature sensors were A class sensors designed for high temperatures (up to 600 °C). In the coolant circuit, three wire PT100 temperature sensors were used. When necessary, the check valves at the entrance of the test section could be closed to derive the entire mass flow rate of exhaust gases through a single section of the arrangement (60 kg/h); opening both sides introduced 30 kg/h of exhaust gas into each section.

With this layout, the probes positioned before the heat exchanger (the precooler probes) were subjected to conditions similar to those found at the entrance of EGR coolers, while the probes positioned after the heat exchanger (the postcooler probes) operated under conditions typical of the colder parts of EGR coolers. Due to the weakness of the fouling layer, several attempts to introduce an insertion probe into the heat exchanger to directly measure fouling were unsuccessful.

Finally, the gas under the desired conditions crossed the instrumented section, with the thermocouples and pressures gauges connected to a CPU control system to guarantee stability of the test