EXPERIMENTAL STUDY OF THE EFFECT OF HYDROCARBON CONDENSATION ON THE FOULING DEPOSITS OF EXHAUST GAS RECIRCULATION COOLERS

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ABSTRACT

The use of exhaust gas recirculation (EGR) coolers reduces the temperature of the recirculated exhaust gases, leading to the reduction of NOx pollutants. The particulate matter deposition and hydrocarbon condensation that occur in the gas-side of these compact heat exchangers cause the deposit build-up that results in cooler effectiveness loss and pressure drop.

To analyze the wet fouling deposits formation, this study presents an experimental evaluation of the effect of hydrocarbon condensation on deposits under controlled conditions. An experimental setup, developed to recreate the soot particle generation and hydrocarbon vapor injection, has been used to analyze the fouling layer generation. The test section has been especially designed to inspect the final appearance of the fouling deposit and the final fouling layer thickness has been measured locally employing an optical profiler. Likewise, the evolution of the outlet gas temperature, thermal efficiency and pressure drop have been monitored during the test.

The effect of hexadecane ($C_{16}H_{34}$) condensation has been evaluated under high hydrocarbon concentration and low coolant temperature. It has been detected that hydrocarbon condensates changes the deposit properties causing a fouling layer more thermally conductive leading to an improvement of the thermal efficiency and causing the reduction of the outlet gas temperature from 95.1°C to 92.2°C. In addition, hexadecane condensation has been examined varying the coolant temperature between 30 and 90°C and it has been noted that the test with the lowest coolant temperature is the most affected by hexadecane condensation and an increase of 2% in thermal efficiency has been detected after the beginning of hydrocarbon injection.

INTRODUCTION

European emission standards and new vehicle test procedures define more stringent acceptable limits for polluting emissions of new vehicles. The exhaust gas recirculation (EGR) system plays an important role in the reduction of the emissions of nitrogen oxides and its use has really taken off in the past few decades [1].

Fouling deposits that appear in the compact heat exchanger of the EGR system, formed by particulate matter (PM) and hydrocarbons (HC), cause the decrease in thermal efficiency and the increase in pressure drop along the device [2]. These hydrocarbons are derived from unburned and partially burned fuel and lube oil of the engine that leave the combustion chamber and become a part of the exhaust gas flow. The condensation of the hydrocarbon vapor exacerbates the formation of fouling deposits inside the EGR system. Thus, particulate matter deposition coupled with hydrocarbon condensation results in the formation of wet deposits that can clogged the cross sectional area of the heat exchanger, compromising the function of the system.

Inside EGR coolers, the hydrocarbon condensation is function of the vapor pressure and the concentration of the HC species [3]. Various authors [4, 5] have found that hydrocarbons in the range C_{11} - C_{23} have been deposited and retained inside EGR coolers of diesel engines and up to 10% of the deposit mass are volatiles. Hydrocarbon condensate changes the structure of dry soot deposits modifying their properties, such as the thermal conductivity, the density or the heat capacity [6–8].

Owing to the importance of the effect of hydrocarbon on the fouling deposit formation inside EGR coolers, different experimental studies have evaluated the changes that hydrocarbon causes in particulate matter characteristics and in fouling layer growth [9–11]. They have reported that as coolant temperature decreases the effect of hydrocarbon on the growth of particulate matter deposits increases and that "wet" aggregates — with hydrocarbons— are more effective in forming deposits inside EGR coolers.

Although it is acknowledged that water vapor condensation also affects the fouling layer formation inside the EGR system, as several authors have reported [12–15], this study is focused in particular on the analysis of the effect of hydrocarbon condensation inside a test section. The aim is to study the fouling layer formation under high hydrocarbon concentrations employing an experimental layout developed to recreate the exhaust gas flow. It is planned to monitor the evolution of the outlet gas temperatures, thermal efficiency and pressure drop inside the test section during the test. Using an optical profiler, it is intended to acquire the topography of the fouling deposit to evaluate the final deposit thickness along the plate and examine the appearance of the outer surface of the fouling layer.

EXPERIMENTAL EQUIPMENT

The experimental test bench used in this study has been designed to reproduce the fouling phenomenon under controlled conditions and some of its important elements have been presented in detail in previous studies [16, 17]. Figure 1 depicts the scheme of the test facilities, where the soot generator, the heating zone, the hydrocarbon injector, the test section, the

diluter, the scanning mobility particle sizer (SMPS) and the opacity meter are the main parts.

The MiniCAST 5203 Type C soot generator, that provides particles in the range of 20-200nm (mean mobility diameter) and particle concentrations up to 108 part/cm³, generates the exhaust gas flow with a maximum flow rate of 200L/min. Downstream the soot generator, the heating zone, which is made up of a ceramic furnace and a heating cable, has been installed to heat the exhaust gas to reach the working temperature of EGR systems (200-800°C).

In order to study the fouling process under high hydrocarbon concentration, the Syringe pump NE-500 system has been added to the test bench. This dispensing system allows to inject hydrocarbon into the exhaust gas line with a volume flow in the range 0.73μ L/h-2120mL/h. In order to ensure that all the injected hydrocarbon is vaporized, a heating resistance has been added downstream the hydrocarbon injector.



Fig. 1. Scheme of the fouling test bench.

The SMPS device (TSI 3936L75-N), coupling with a dilution system that guarantees the suitable conditions for accurate particle measurements, has been used to determine the particulate matter distribution upstream the test section. Moreover, the opacity meter Texa Opabox has been used to register the opacity values of the exhaust flow during the test.

Various thermocouples type K have been employed to monitor the temperature along the entire path of the gas stream and a differential pressure sensor has been installed to control the pressure drop inside the test section.

The coolant circuit provides water flow inside the coolant housing of the test section. To prevent local coolant boiling, a coolant flow high enough (1500L/h) has been selected.

In order to capture the surface topography of the fouling deposit, an optical profiler (*PLu Neox Sensofar Optical Profiler*) has been used. Employing non-contact methods, this optical profiler acquires the spatial coordinates of the surface of the deposit allowing the characterization of the fouling layer. Through data processing, the fouling profiles have been extracted from topographies and the final fouling layer thickness has been computed.

TEST SECTION

In order to inspect the final fouling layer appearance, a device with removable parts has been selected. The test section is made up of two ribbed plates that are mounted in a coolant housing creating a rectangular channel with a hydraulic diameter of 13.97mm through which exhaust gas flows (Figure 2). The plates, that have been designed to create non-uniform gas flows, allows to examine the fouling deposit that grows over the different regions of the rib-roughened surface.



Fig. 2. Test section.

EXPERIMENTAL PROCEDURES

The test plates have been tested following an eight-steps methodology, as Figure 3 illustrates. Before starting the test, the plates are scanned using the optical profiler to acquire the topography of the plate under clean conditions. After that, the couple of ribbed plate are assembled inside the test device. The soot generator, the heating zone and the coolant circuit are running until they are working under controlled conditions, and when operating conditions are reached, the gas line is opened and the test begins. During the test, the gas temperatures and pressure drop inside the test section are monitored. Moreover, using the SMPS, the particulate matter distribution is measured upstream the test section. After the first 70 minutes of the test, the syringe pump is activated and the hydrocarbon injection begins. After three hours, the test ends and the ribbed plates are disassembled from the heat exchanger. The topography of the fouled plates is measured and the fouling layer profiles are extracted.



Fig. 3. Test methodology

Applying this methodology, the experiments have been conducted based on the test matrix shown in Table 1. Due to, in diesel deposits, the major alkanes species are in the range C_{11} - C_{23} [4, 5], these test include the presence of hexadecane ($C_{16}H_{34}$). Moreover, tests with different coolant temperatures have been carried out.

Table 1. Operating conditions

Test	Gas flow	Gas temp.	Coolant	C ₁₆ H ₃₄ injection
	rate [L/min]	[°C]	temp. [°C]	flow [µL/min]
А	115	200	30	-
В	115	200	30	100
С	115	200	60	100
D	115	200	90	100

RESULTS AND DISCUSSION

In all tests the outlet gas temperature, the thermal efficiency and the pressure drop evolution have been monitored. Likewise, the deposit profile and the fouling layer thickness have been evaluated in a local manner.



Fig. 4. Evolution of the outlet gas temperature, thermal efficiency and pressure drop along the test section. Dashed vertical line represents the beginning of HC injection (70min).

HC CONDENSATION EFFECT

In order to study the effect of hydrocarbon condensation on the fouling deposit, the tests A and B consider, under low coolant temperature (30°C), the absence and presence of hydrocarbon respectively. For the selected hydrocarbon injection flow (100 μ L/min) the concentration of hexadecane in the main flow is around 1100ppmC, similar to the one encountered in a diesel engine working with an air/fuel ratio of 25:1 [3]. Under this working conditions, the dew temperature of hexadecane is 61.5°C, therefore, hydrocarbon condensation is likely to occur in some areas of the plates.

The injection of a high concentration of hexadecane in the exhaust gas causes the drop of the outlet gas temperature, as Figure 4 shows. Although the evolution of the outlet gas temperature in both cases is similar during the first 70 minutes, immediately after beginning hydrocarbon injection, the outlet gas temperature of test B falls from 95.1°C to 92.2°C. At the end of the test, the difference in the outlet gas temperature between both test is 13.4°C. This effect, that has been also detected in the evolution of thermal efficiency, could be caused by two factors: the increase of the thermal conductivity of the deposit due to the diffusion of the hydrocarbon condensate in the fouling layer; and the fragmentation and removal of some deposit areas encouraged by the accumulation of large amounts of condensate.

On the one hand, the hydrocarbon condensate changes the fouling layer nanostructure collapsing the porous of the deposit, increasing its density and hence its thermal conductivity [6, 8, 18–20]. This increase in thermal conductivity, improves the thermal efficiency of the heat exchanger, reducing the outlet gas temperature, as Figure 4 illustrates.

On the other hand, the accumulation of large amounts of condensate in regions where deposit is thinner can wash-out the deposit causing the removal of some areas of the fouling layer. Just like water condensation [21],[13], a large amount of liquid hydrocarbon over the soot deposit can drag the particles of the soot layer removing some regions of the deposit.

In both tests, the evolution of the pressure drop along the test section is similar and significant differences have not been observed. Since this is a device with a larger hydraulic diameter (13.97mm), in both cases the growth of the fouling layer does not cause a large increase in the pressure drop.

Analyzing the deposit thickness at the end of the test in a local manner, it has been observed that the deposit exposed to hydrocarbon condensation —test B— shows two differentiated parts, as Figure 5 shows. The first half of the plate —where the thickness of the deposit is higher than the test A— and the second half of the plate —where the fouling thickness is abruptly reduced—. The average fouling thickness of the test A ranges from 252.8µm in the inlet region to 187.1µm in the outlet region, while in the test B, the average fouling thickness ranges from 292.0µm in the inlet region to 74.3µm in the outlet region, as Table 2 reports.

Both the deposition of aggregates and the increase of particle sticking probability on the fouling deposit, due to the presence of hydrocarbon in the fouling layer, produces the growth of the

Table 2. Results of tests A and B.

Test	Average fouling thickness [µm]		Standard deviation [µm]	
	Inlet region	Outlet region	Inlet region	Outlet region
А	252.8	187.1	68.0	46.5
В	292.0	74.3	64.6	29.1



Fig. 5. Deposit profiles (a) and fouling layer thickness (b) at the end of the test.



Fig. 6. Final appearance of fouling deposit of test B and details of the topographies of the fouling layer.

fouling layer in the first half of the plate. In this region, the deposition of the particulate matter, formed by the combination of soot particles and condensed hydrocarbons, is driven by the thermophoretic effect causing thicker deposits than ones caused by dry soot particles —test A— [22]. Likewise, the hydrocarbon condensation increases the particle sticking probability giving rise to a larger amount of deposited particles on the first half of the plate. Moreover, it has been detected that the reduction of the rolling of particulate matter over the deposit due to the presence of hydrocarbon in the deposit, reduces the fouling layer thickness in the particle accumulation areas, such as the foot of the ribs, as Figure 5 shows.

The abruptly reduction of the thickness of the deposit in the second half of the plate could be caused by the large amount of condensate that appears on the regions where the fouling layer is thinner. The lower gas temperature and slower increase in the surface temperature of the deposit encourage the hydrocarbon condensation in the outlet region [23],[24]. In this area, the accumulation of large amount of condensate could wash-out the particles of the deposit causing the reduction of the thickness of the fouling layer. As Figure 6 illustrates, the mud cracks that appear on the fouling surface reveal that the volatilization of the condensed hydrocarbons causes the degradation of the fouling layer and changes its physical structure [22]. As Lance et al. [7] have reported, the mud cracks are formed as the muddy deposit dries and contracts providing a fractured deposit. Compared with the smooth appearance of the sections of the inlet region, the sections analyzed in the outlet region show a cracked appearance with more grooves as it moves towards the end of the plate. This effect may be the origin of the spontaneous regeneration that has been registered in the thermal efficiency evolution and that has been reported by various EGR manufacturers [7].

COOLANT TEMPERATURE EFFECT

Tests B, C and D have been conducted under the same gas condition and, in order to analyze the effect of coolant

temperature on the hexadecane condensation, the coolant temperature has been fixed in 30, 60 and 90° C, respectively.



Fig. 7. Evolution of the outlet gas temperature, thermal efficiency and pressure drop along the test section. Dashed vertical line represents the beginning of HC injection (70min).



Fig. 8. Deposit profiles (a) and fouling layer thickness (b) at the end of the test.

As would be expected, the evolution of the outlet gas temperature shows that the lower the coolant temperature, the lower the outlet gas temperature, as shown in Figure 7. It has been noted that only the test B -with the lowest coolant temperature- shows a change in trend when hexadecane injection begins. In the same manner, the graph of the evolution of the thermal efficiency, which also registers this effect, exhibits an increase of 2% 6 minutes after the beginning of the HC injection. On the contrary, the evolution of the outlet gas temperature and the thermal efficiency of the tests C and D have not been affected by the presence of hexadecane in the exhaust gas flow. Since for the selected hydrocarbon injection flow (100µL/min) the hexadecane dew temperature is 61.5°C, hydrocarbon condensation does not occur in tests C and D and, in these test, the amount of hydrocarbon in the fouling layer is not large enough to change the structure of the deposit.

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Test	Average fouling thickness [µm]		Standard deviation [µm]	
	Inlet region	Outlet region	Inlet region	Outlet region
В	292.0	74.3	64.6	29.1
С	255.8	220.9	47.3	63.0
D	218.2	244.4	50.7	75.7

Analyzing the local fouling layer thickness it has been noted a strong relationship between the fouling thickness and the coolant temperature in the first half of the plate. The test B —with the lowest coolant temperature— presents the highest average fouling layer thickness, as Table 3 reports. This effect is causes by the strong thermal gradient that appear in the inlet region of the plate and that is more pronounced in the test with the lowest coolant temperature. Thus, in accordance with previous studies [24–26], thermophoresis effect plays an important role in the particulate matter deposition giving rise to thicker deposits when the coolant temperature is lower.



Fig. 9. Final appearance of fouling deposit of tests B, C and D.

Scratching the fouled deposits allows to detect that the fouling layer of test B is an oleaginous deposit, especially in the

outlet region, as Figure 10 shows. In the outlet region —where condensation is more persistent— deposit becomes "wet" and its appearance becomes lacquer-like [20]. Deposits of tests C and D, both at the inlet region and at the outlet region, show brittle appearance and, although they are mainly made up of dry fluffy soot particles, trace amounts of oleaginous material have also been found.



Fig. 10. Scratched of the fouling deposit of tests B, C and D.

CONCLUSIONS

This study presents the experimental results of the fouling layer formation considering the condensation of the hydrocarbon hexadecane. The evolution of the outlet gas temperature, thermal efficiency and pressure drop inside the test section have been monitored during the test and the topography of the deposits has been captured using an optical profiler.

On the one hand, in the analysis of the effect of hexadecane condensation during the deposit formation, it has been noted an increase of the thermal efficiency when hexadecane condensation occurs. A spontaneous regeneration has been registered when hydrocarbon injection begins. Likewise, it has been noted an abruptly reduction of the fouling layer thickness on the outlet region of the plate when it is exposed to hydrocarbon condensate.

On the other hand, it has been detected a strong relationship between low coolant temperature and thicker deposits and it has been noted that, for the selected operating conditions, hexadecane condensation mainly affects the test with the lowest coolant temperature.

These results have allowed to examined the hexadecane condensation inside a test section under specific operating conditions and, although the presented tests do not reflect an exhaust gas flow produced by a specific engine operating point, results can provide useful data on the hydrocarbon condensation that occurs inside EGR coolers.

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