EXPERIMENTAL ANALYSIS OF SOOT PARTICLE FOULING ON EGR HEAT EXCHANGERS: EFFECT OF VELOCITY ON THE DEPOSITED PARTICLE SIZE DISTRIBUTION

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ABSTRACT

The problem of fouling in the EGR cooler has yet to be resolved. New more stringent regulations have made the fouling one of the major problems affecting the design of these systems as their performance must be warranted over a long period of time. This type of fouling process is dominated by particulate deposition, and should be studied until stable or asymptotic conditions are reached.

In this paper, an experimental setup is used to study the fouling process in technologies commonly employed in EGR coolers. The technology selected has been “plate and fins” tube, a technology broadly used to fit European Emissions Regulation. Inside the test section particulate matter is deposited making a soot fouling layer.

A soot generator, mini-CAST burner, has been used to reproduce the soot particles emitted from diesel engines. The diameter of soot particles varies in the range 10 nm to 650 nm while soot particle concentration range is 0 to 5E+08 part/cm³, values which are common in current diesel engines. The concentration and particle size of soot particles were controlled, obtaining a type of very dry fouling, with negligible amount of hydrocarbons (HC).

In order to analyse different velocities inside the tested probe, minor modifications were carried out in the samples. Size particle distribution has been analysed using a scanning mobility particle sizer (SMPS). The distribution of the particle size has been counted upstream and downstream the heat exchanger probe. Variations on particle size distribution have been confirmed during experimental test under different boundary conditions and mean deposited and removed particle diameters have been identified under different exhaust gas flows. It has been investigated the evolution of the diameter of the particles that have been deposited and removed and the critical flow velocity has been studied to analyse the removal mechanism inside this technology.

INTRODUCTION

Asthma, lung cancer and mortality have been associated with particulate matter exposure in recent medical studies (Brunekreef et.al, 2002; Pope III et.al, 2002). These investigations have demonstrated clear associations between ambient fine particulate air pollution and elevated risk of serious disease (Pope III, 2006). Both Diesel and gasoline engines generate exhaust particles that have been classified as carcinogenic to humans by the World Health Organization (WHO) based on research made by the International Agency for Research on Cancer (Cancer, I.A., 2014).

In order to reduce the air pollutants generated by road traffic, European Union has created the Euro emission standards. Since 2005, this Regulation controls the emissions of atmospheric pollutants such as particulate matter and nitrogen oxides for vehicles sold in EU Market. Actually, Euro VI emission standards require the greatest emission reduction of any previous stage along European regulatory pathway (Mattarelli et.al, 2017).

Exhaust gas recirculation (EGR) systems have been implemented in diesel and gasoline engines to reduce NO_x emission (Zheng et.al, 2004). Nowadays, fouling in EGR coolers is one of the most important problem that manufacturers are faced with. Soot particles and unburned hydrocarbon, that are part of the exhaust gas, produce fouling deposits inside the heat exchanger devices deteriorating thermal efficiency and increasing pressure drop across the cooler (Abd-Elhady et.al, 2004). The thermal efficiency of the EGR cooler decreases with the growth of the fouling thickness (Sluder et.al, 2008) and in some cases, fouling is so severe that deposits form plugs strong enough to occlude the gas passages (Lance et.al, 2014).

The study of soot particle deposition has generated interest in different industrial areas for a long time. Due to this fact, various authors have done theoretical investigations about soot particle deposition in the presence of thermal gradients (Cha et.al, 1974; Epstein et.al, 1997; Talbot et.al, 1980) emphasising that thermophoresis is one of the most important mechanisms that causes fouling deposits (Abarham et.al, 2009; Housiadas et.al, 2005; Lin et.al, 2008). In another way, there have been many recent experimental investigations related to EGR cooler soot particles which are focused on the examination of the particle size distribution and primary soot particle diameter produced under different EGR conditions (Mathis et.al, 2005; Srivastava et.al, 2011).

The use of new tools that allow the measurement of the size of the particles inside the common range in current engines, has occasioned the appearance of several studies which have the purpose of research the deposition and removal mechanism through those measurements. Making an example of this, the studies carried out by Hong et al. (2011) and Bika et al. (2012) have intended to clarify the particle behaviour inside a heat exchanger using a scanning mobility particle sizer (SMPS) and

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to identify the particles that are deposited or removed from the fouling layer.

With the aim of contributing to the study of fouling process that takes place inside the EGR coolers and making use of the new measurement technology, the main objective of this research is to analyse the evolution of the soot particle distribution before and after a geometry typically applied in EGR heat exchangers. It is intended to define the particles behaviour inside these devices under different flow gas velocities and to identify the size of the particles that are deposited or removed from the fouling layer. Particle size distribution of removed and deposited particles will be studied with the purpose of analyse the soot diameters that are likely to build up fouling deposits and critical flow velocity will be calculated to study particle removal rate.

EXPERIMENTAL SETUP

An experimental test bench has been designed to reproduce the exhaust gases of current diesel engines and to recreate the fouling conditions inside an EGR cooler. This new layout has been integrated into the facility that was developed in a previous study (Paz et.al, 2016) and the group of devices used in this test bench have been specifically selected to generate and monitor the exhaust gas flow which are common in diesel engines. The soot generator, the heating zone, the test section, the gas analyser, the diluter and the scanning mobility particle sizer (SMPS) are the most significant parts of this experimental arrangement and they have been depicted in the schematic of Figure 1.

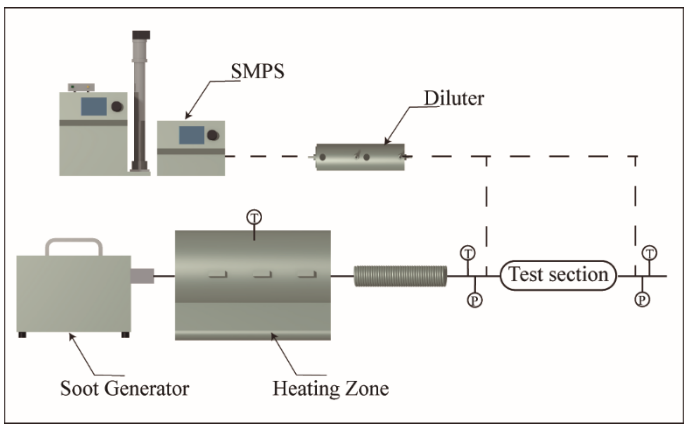

Figure 1: Schematic of the fouling test stand

Instead of selecting a diesel or a gasoline engine to generate the exhaust gas flow, a soot generator has been chosen to work under controlled conditions. This avoid the influence of other variables such as lubricants or fuel composition, and repeatability and accuracy in soot particle generation have been guaranteed. MiniCAST 5203 Type C soot generator has been the device used and it is analogous to the one selected in similar research (Hong et.al, 2011; Moore et.al, 2014; Xu Chen et.al, 2014). The operating mode of this equipment is based on the generation of a diffusion flame using propane, air and nitrogen, in which soot particles are formed during pyrolysis (Jing et.al, 2014). Varying the combustion conditions, different particle diameter and concentration can be obtained. With a particle concentration up to 108 part/cm³, this device can be adjusted to produce particle size in the range of 20-200 nm (mean mobility diameter). It generates a total exhaust gas flow rate of 200 l/min and a maximum mass particle output of about 1.5 g/h.

Since gas temperature at the outlet of the soot generator varies between 80 and 140°C, it is necessary to heat the gas to reach normal temperatures in EGR systems (250 - 800 °C). To carry out the heating of exhaust gas and to avoid any heating system in the emitted particles, a ceramic furnace and a heating cable have been chosen to heat the pipe by conduction and radiation.

A Scanning Mobility Particle Sizer (SMPS, model 3936L75-N, TSI) has been employed to measure the properties of the particles of the flow, similar to the one use in similar research (Gulijk et.al, 2004; Mathis et.al, 2005; Wong et.al, 2003). Particle size and number distributions have been measured upstream and downstream of the test section. Using this equipment, it is possible to measure a wide range of particle sizes (10-1000 nm) and concentrations up to 10^7 particles/cm³. Because of high gas flow temperatures and elevated particle concentration, it is necessary to dilute the gas flow to carry out the measurement. A PALAS PMPD 100 dilution system has been employed to dilute a portion of the exhaust gas stream with flow of clean air. The process dilution has been carried out in two stage with 1:10 dilution ratio. To avoid hydrocarbon condensation and nucleation, the first dilution takes places at high temperature, with an outlet temperature around 150°C. Then, using ambient temperature gas, a second dilution occurs, obtaining a non-condensing, cool and suitable gas flow for accurate particle measurements.

To ensure temperature control throughout the entire path of the gas stream, various thermocouples type K (class-2, 1.5mm diameter) have been added to the test bench. Three thermocouples have been installed inside the tube in star layout in each measurement section. All thermocouples have been arranged forming an L, with the tip of the thermocouple towards the flow to guarantee accurate temperature measurements. The mean value of the three measurements has been calculated to ensure precise temperature values and to avoid any deviation.

TEST SECTION

The plate and fins technology is one of the most employed technology in current EGR coolers, thanks to the good ratio of heat transfer enhancement to additional pressure loss (Bravo et.al, 2006). Because of this, it has been selected to carry out this study and an EGR heat exchanger made up of one plate and fins tube has been designed, similar to the one used in previous studies (Malayeri et.al, 2011; Jang et.al, 2012). This technology is characterised by the use of fins at gas side that produce channels completely separated. These fins increase the turbulence of the gas flow and generate extra heat exchange surface in a compact way, increasing the efficiency of the tube. Both the plate and fins has been made of stainless steel due to this is the most common used material in High Pressure EGR devices (Bravo et.al, 2013).

Inside this heat exchanger, exhaust gas flow produces particulate matter deposition over the internal surfaces making a soot fouling layer while, on the other side, water from the coolant circuit cools the external tube wall.

With the goal of evaluating the effect of velocity on the deposited particle size distribution, four similar probes have been tested. Exhaust gas mass flow has been kept constant and, to vary flow velocity inside the tube, some channels have been clogged in the same way as occurs in strong fouling conditions. Inside the test sections with clogged channels, and due to the reduction of inlet area, exhaust gas is forced to go through the remaining channels so, gas velocity will be higher. In this manner, particulate matter deposition will be analysed under different velocity conditions. Figure 2 shows a schematic of the four geometries used during this experimental study.

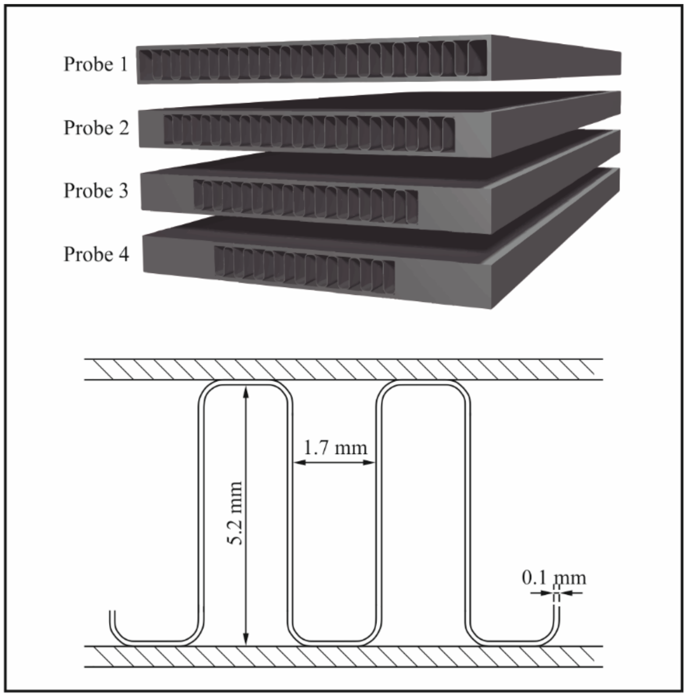

Figure 2: Schematic of the inlet test section

EXPERIMENTAL PROCEDURE

All experimental tests have been carried out under steady-state conditions. The gas mass flow rate has been selected in 8.8kg/h and gas inlet temperature has been fixed in 250°C. Coolant temperature has been kept constant at 90°C.

The procedure for each test is describe below:

- The probe is mounted inside the EGR cooler shell.
- Soot generator and heating zone system are started and allowed to run until steady-state conditions were reached.
- Exhaust gas starts to flow through the experimental section.
- The temperature, pressure drop and thermal efficiency are monitored during the test.
- Every 30 minutes, using the SMPS, particle size distribution is measured upstream and downstream from the test section.
- Test is carried out during 3 days. Every day, 10 hours are tested, reaching a total of 30 hours.
- At the end of the test, the probe is cleaned in an ultrasound cleaning bath.

The measurements of the SMPS device have been interpreted using the software Aerosol Instrument Manager (A.I.M. v9.0).

RESULTS AND DISCUSION

The experimental measurements have been carried out during 162 days. Using the same experimental configuration several test have been conducted with each probe to ensure accurate results and repeatability and to avoid any particularity. After take measurements, the results obtained in these test have been studied and examined to acquire relevant information about the distribution and behaviour of soot particles inside the EGR cooler.

Figure 3 shows the inlet particle diameter of all test that have been carry out in this study, with a typical statistical boxplot representation. The bottom and the top of the box represent the first and the third quartile respectively (Q_1, Q_3). The lower and upper whisker, represent the maximum and minimum respectively, and the line inside the box represent the median or second quartile, Q_2 (82.9 nm).

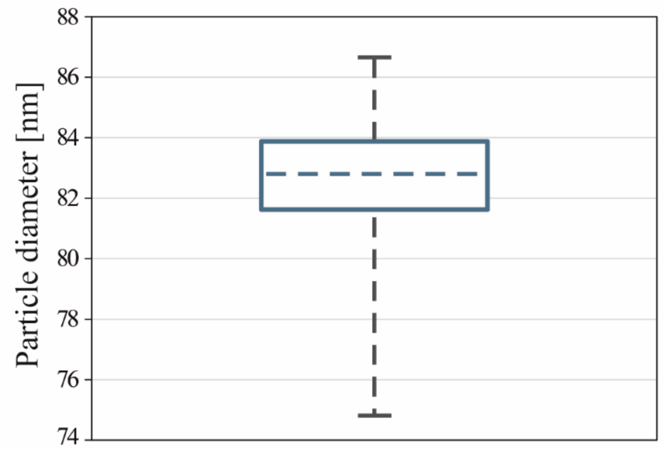

Figure 3: Mean particle diameter

The particle number distribution measured upstream of the probe section are similar to the particle distribution generated by diesel engines. Figure 4 shows the number weighted mobility diameter distribution of particulate matter generated by a diesel engine running at 1500 rpm under different EGR conditions (Harris et.al, 2001). Dotted line depicts the SMPS measurements of soot particle used in this study. They show a lognormal distribution form and the average diameter is inside the usual range of diesel soot particle diameters.

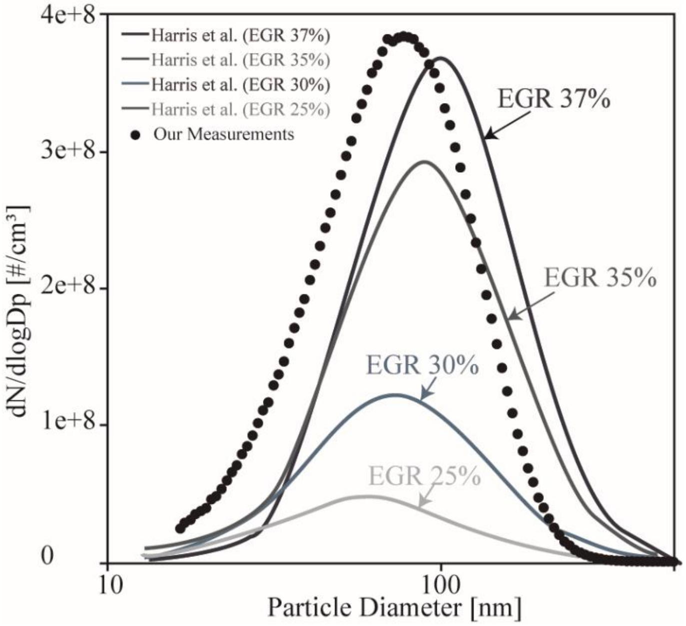

Figure 4: Number weighted mobility diameter distributions of PM emissions from diesel engine from Harris et al. (2001)

In order to identify the evolution of the particle behaviour inside the EGR cooler, particle number distribution have been plotted for downstream and upstream measurements. In all tests that have been done in this study, a different pattern has been identified for particles measured at the inlet and at the outlet, as Figure 5 shows. Solid line depicts particle number distribution measured before the test section and dashed line represents particle number distribution after the test probe. Inlet particle distribution reveals an upward trend for mean diameters, while outlet particle distribution presents lower values. Dotted line reproduces the difference between particle number distribution before the test section and particle distribution after that.

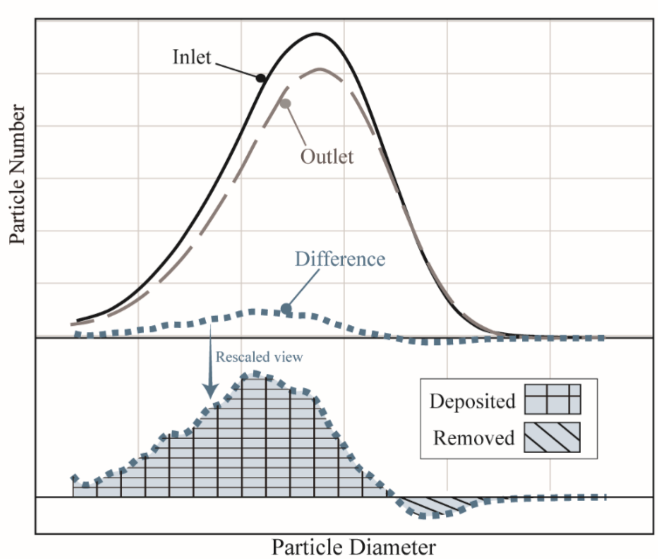

Figure 5: Example of analysis of particle number distribution downstream and upstream of the test section

It is known that size particle distribution can slightly vary inside the heat exchanger due to multiple factors like particle agglomeration or breakup. In any case, and after an exhaustive analysis of the results generated in all test of this study, it has been verified that deposition and removal are the most important causes that produce the evolution of the particle size distribution. For this reason, the remaining mechanisms that could influence the particle distribution in a minor scale are neglected and, deposition and removal mechanisms have been identified as the cause of the evolution of particle distribution. In this manner, when the difference between particle number distribution before and after the test section takes positive values, i.e. particle diameters that have been registered at the inlet of the cooler but they have not been registered at the outlet, particles could be identified as deposited particles. On the contrary, when the difference takes negative values, i.e. when some particle diameters have left the test probe but they have not been registered at the inlet, particle could be designed as removed particles. This simplified way of characterization of deposited and removed particle allow us to examine, in a clear manner, the behaviour inside the different test probes used in this study. The rescaled view of the Figure 5 shows in an amplified manner the dotted line, which clearly describes the diameters which represent the particles that could have been deposited and those that could have been removed.

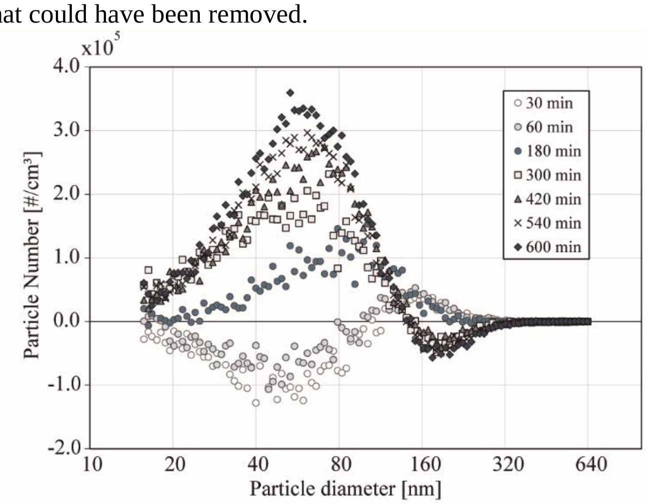

Figure 6: Difference between particle number distribution upstream and downstream of the probe at different moments of the test

Examining the results obtained in this research, it has been observed that, as Figure 6 shows, the difference between particle number distribution upstream and downstream the probe varies with time. During a one-day standard test, the diameter of the particles that are deposited or removed changes considerably. It has been detected that, during the first minutes of the test, the littlest diameters have been classified as removed particles while the biggest ones are deposited. As the test progresses this tendency is inverted. Then, the biggest particles are removed and the littlest are deposited.

This phenomenon has been observed, to a greater or lesser extent, in all results obtained with the four test sections. Variations on deposited and removed diameters have been identified and the amount of particles has been studied in both cases. In order to examine the behaviour of deposited and removed particles under the influence of different gas velocities, the results obtained are listed below.

DEPOSITION

Studying particle deposition, based on the SMPS results, some variations in the evolution of the deposited particle size have been detected. Figure 7 shows the size evolution of the particles that have been deposited throughout test duration. The image depicts, for the 4 probes, the results obtained during the 3 days of the test. The size of the circles is directly proportional to the number of particles that have been deposited.

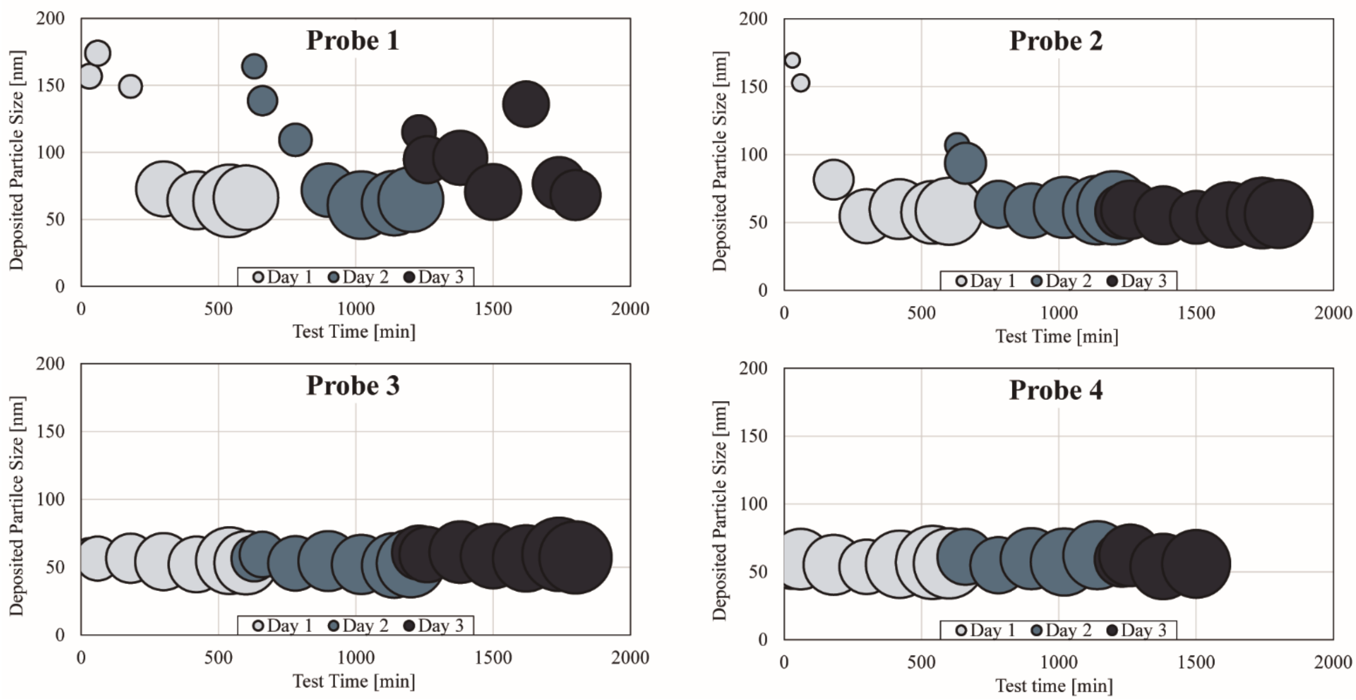

Figure 7: Evolution of Particle deposition during test time. Size of circles represents the number of particles that have been deposited.

Decreasing behaviour has been observed in the evolution of the deposited particle size. This effect is clearly observed in Probes 1 and 2, the test sections that present the lowest gas velocity (8 and 11 m/s respectively), while Probes 3 and 4, assessments with the highest gas velocity (18 and 23 m/s respectively), do not present this tendency. As the gas velocity is increased, Probe 1 to 4, this behaviour is mitigated, so, it can be said that this conduct is only detected with low gas velocity.

Some authors like Reza et.al. (2016) have studied the particle deposition under various gas velocities and they have achieved similar results when flow gas velocity is increased. Their numerical model shows that, for higher gas velocities, the sticking probability of soot particles colliding with a clean surface decreases abruptly, especially for the biggest diameters. They have identified that higher gas velocities and large particle sizes correspond to lower sticking probability and, so, when the velocity of the gas flow is high enough, the biggest particles cannot be deposited due to the loss of sticking probability.

As graphs shows, it has been identified that, inside probes where gas velocity is lower, as the time passes, the size of deposited particles is gradually reduced until it reaches an asymptotic value. It has been quantify that the diameter of particles that have been deposited during the early stages of the test are included between 180 and 100 nanometres. As the test progresses particle diameter is gradually decreased until an asymptotic value of around 60 nanometres is reached. This effect is observed during the first minutes at the beginning of the test and it can be also seen in the restart point of the second and the third day. It has been measured that this transient effect appeared in Probe 1 and 2 approximately during the first 180 minutes of each day. One of the cause of this phenomenon, among others, could be the increase of the gas velocity due to the reduction in the cross sectional area induced by the fouling layer growth (Abd-Elahdy et.al, 2004). As deposition progresses and the deposit thickness grows, the gas velocity increases due to the reduction in the cross sectional area of the tube as well as the density effect imposed by the reduction in heat transfer. As time passes, the increase of the gas velocity in Probes 1 and 2 causes that deposition mechanism tends to be similar to the one that takes place in Probes 3 and 4, where gas velocity is higher. Inside these probes this effect is not detected because, when velocity exceeds a threshold value, little increases in gas velocity do not affect meaningfully the deposition process.

It has been also recognised that, under low gas velocity conditions, even though the mean size of the deposited particles during this first moments of the test is bigger than in the rest of the test, the number of deposited particles is less numerous. The amount of deposited particles that have been registered in early stages is between 4 and 6 orders of magnitude smaller than in the steady state phase. Test results obtained in Probes 3 and 4 do not exhibit this tendency.

To analyse the evolution of the particle distribution during the test, the distribution of the deposited particles has been plotted, as Figure 8 shows. The graphs depict the size particle distribution for the four probes at different moments of the test during a one-day standard test.

It has been observed that in probes with high gas velocity the particle size distribution hardly vary. In Probes 3 and 4 the particle size distribution keeps constant during the test, however, measurements made in Probes 1 and 2 show changes in particle distribution. In these test sections, where gas velocity is lower, as the test progresses, deposited particle distribution moves to littler diameters. During the time of the test, especially between 30 and 180 minutes, particle size distribution of deposited particles progresses towards littler diameters and, at the same time, the range of diameters is narrowed due to the reduction of the standard deviation, passing from 45 nm to 32 nm.

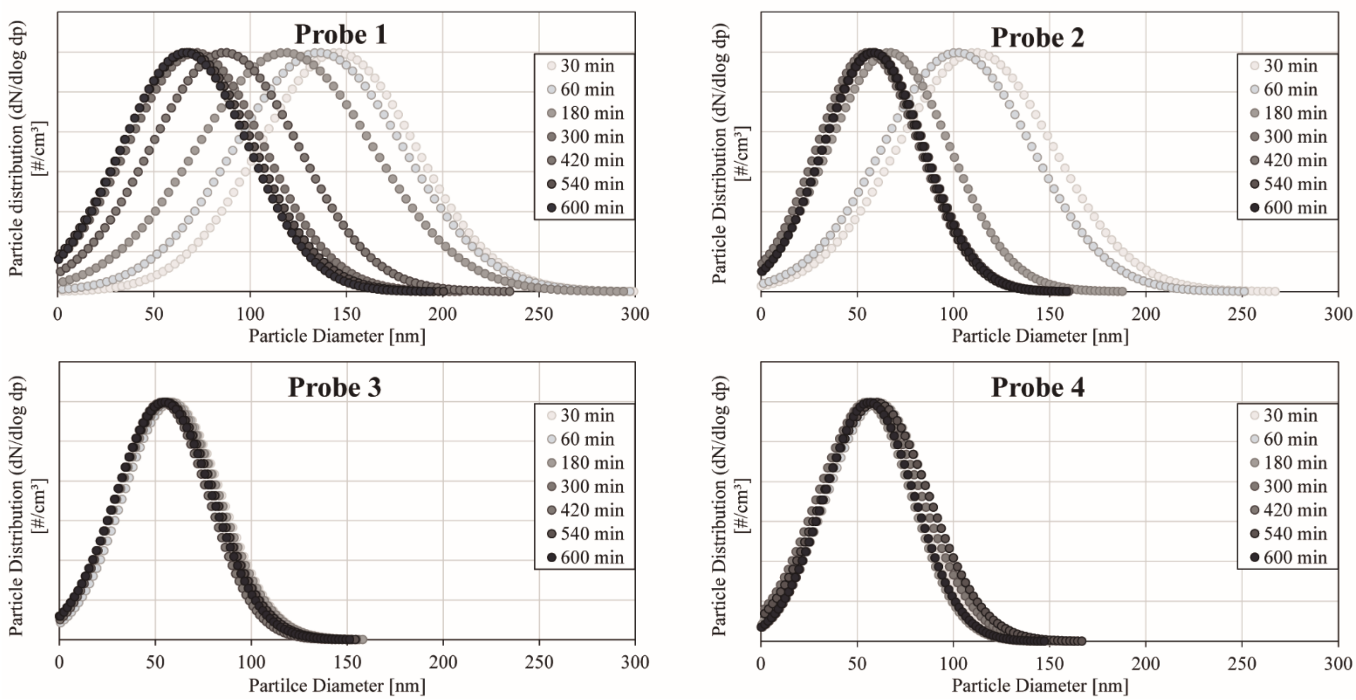

Figure 8: Lognormal distribution of the deposited particle of the four probes at different moments of the test.

These results seem to indicate that under lower flow gas velocities the range of particle diameter that are deposited is larger than when the gas velocity is higher. This assumption is in agreement with the conclusions achieved by others authors whose studies have demonstrated that increasing gas velocities lead to lower rates of deposition of particulate inside EGR cooler tubes (Abd-Elhady et.al, 2004; Abd-Elhady et.al., 2011; Sluder et.al, 2008).

REMOVAL

Figure 9 depicts, for the 4 probes, the results obtained during the 3 days of the test, where the size of the circles is directly proportional to the number of particles that have been removed. It has been observed different tendencies in the probes studied when flow gas velocity is increased. The results show that in probes with the lowest gas velocities (Probes 1 and 2) both the amount and the diameter of the particles that have been removed are smaller than in the other probes. Increasing the flow gas velocity it can be observed an escalation in the size of the removed particles and, at the same time, an intensification in the number of them.

One possible explanation for this behaviour is that flow gas velocity is the cause of these different tendencies. The shear force leads to the detachment of the particles that are part of the fouling deposits. At the same time, particles can also be removed due to the impact of incident particles when kinetic energy is high enough. It should be pointed out that these deductions are in agreement with other previous studies about particle removal. Sluder et al. (2013) have investigated that removal process increases markedly with the gas velocity and the high wall shear stress, caused by the increase in gas velocity, motivates the particle re-entrainment in the flow. Abd-Elhady et.al. (2002), Abarham et al. (2012) and Badr et al. (2005) have reached similar conclusions and they have also identified that high gas velocities intensify removal activities.

The large amount of big particles registered downstream the Probes 3 and 4 could be caused by the increase in gas velocity, which prevents the particles from being deposited. The loss of sticking probability induced by high gas velocity explained in the previous section seem to be the cause of this phenomenon. Given that big particles could not be deposited under these conditions, they would leave the test section and they would be registered by the SMPS downstream of the probe. In this way, these particles would not be “removed”, they would be “not deposited”.

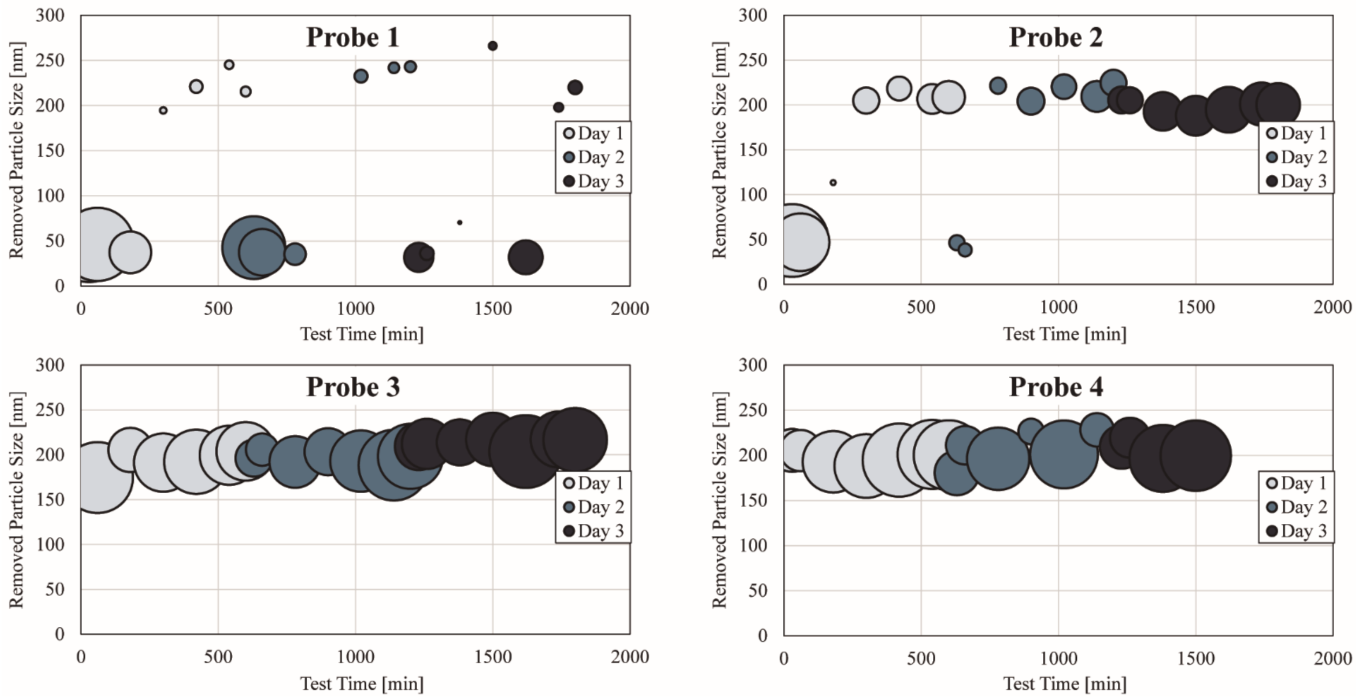

Figure 9: Evolution of particle erosion during test time. Size of circles represents the number of particles that have been removed.

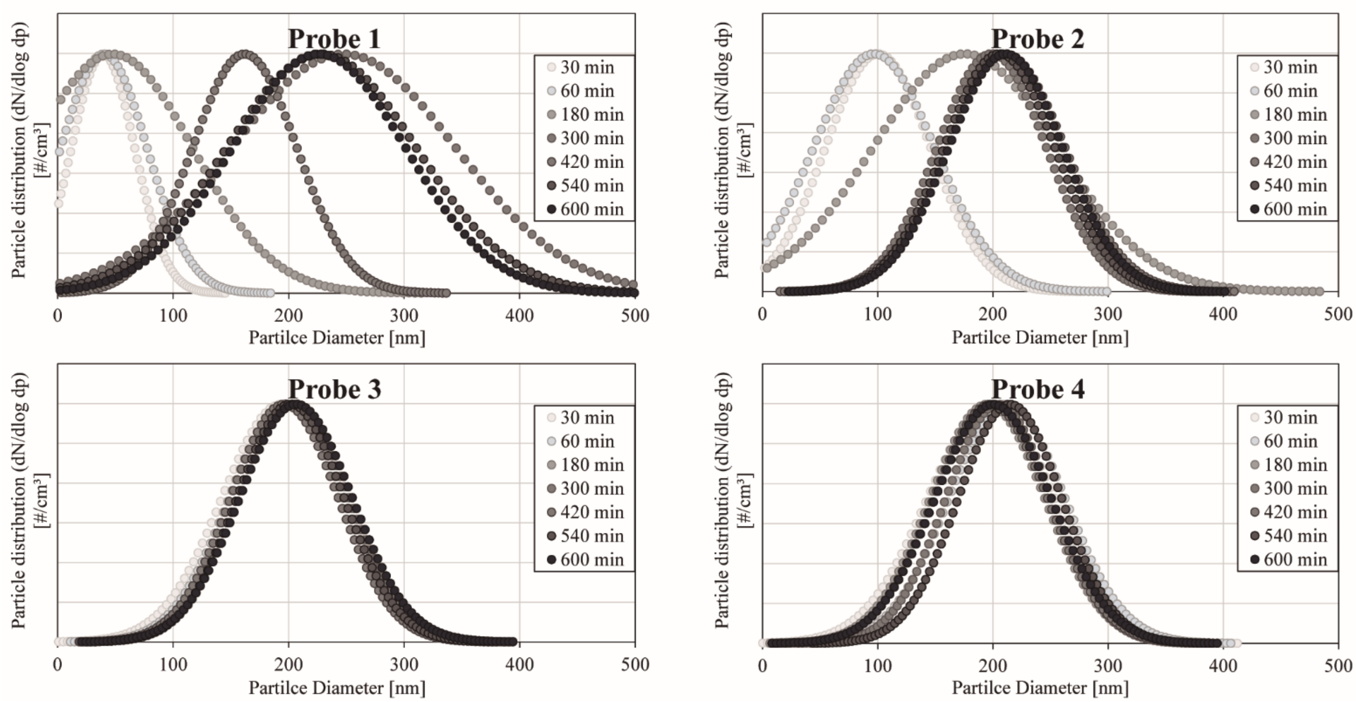

Figure 10: Lognormal distribution of the removed particle of the four probes at different moments of the test

In contrast to Probes 3 and 4, in the probes with the lowest gas velocity, and especially in the Probe 1, during the test it can be observed an evolution of the removed particle diameter. As test progresses, the diameter of the particles grows and it takes values close to 200 nanometres and the amount of particle that have been removed decreases significantly. After the first minutes of the test of each day, the total amount of removed particles is reduced, achieving a state where only some big particles are detached. This evolution of the removal particle size detected in Probes 1 and 2 at the beginning of each day of the test could be caused by the sintering of the fouling layer (Abd-Elhady et.al, 2004). Sintering of deposit takes place when particles accumulate and build up the fouling layer. Sintering is a function of time and of the hot gas temperature flowing over the fouling layer that causes a solid stable structure strongly attached to the heat exchanger surface. During the progression of the test, the fouling layer is compacted complicating the removal effect and, therefore, reducing the number of particles that are removed. When the flow gas ceases at the end of each day, the fouling layer gets back to a powdery structure making easier the removal activity at the beginning of the next day. This phenomenon is clearly identified in cases with low gas velocity but it does not takes place in which gas velocity is higher because, when gas velocity reaches a threshold value, the sintering effect is not strong enough to retain the soot particles.

To analyse the evolution of the removed particle distribution during the test, Figure 10 shows the particle size distribution of the removed particles at different moments of the test representing the evolution of the particle distribution in a one-day standard test.

In Probes 3 and 4, the geometries with the highest gas velocity, the size distribution of removed particles hardly vary. During the test, the size of the particles that have been removed keeps constant around a mean diameter of 200 nanometres and the standard deviation registered in the test does not change markedly keeping its value around 48 nanometres. In Probe 2, and especially in Probe 1, it has been identified an evolution of the removed particle size. Inside these test sections, as time passes, the mean diameter of the removed particles grows and, at the same time, the standard deviation is increased. This corroborates that, under the lowest flow gas velocities both the mean diameter of the particles and the standard deviation of them vary. The increase of flow gas velocity due to the reduction in the cross sectional area of the tube could be the cause of this change. A wide range of particle diameters that are part of the fouling deposits which have been generated inside the probes with the lowest gas velocity seems to be easily influenced under little variations in gas velocity. In contrast, those deposits that have grown under high gas velocities show a stable range of particle which can be removed.

Based on the analysis of the measured results, the Figure 11 shows the average diameter of the particles that have been deposited and removed in the four probes at different times of the test. The graph illustrates, by solid bars, the diameter of the particles that have been deposited and dotted bars show those that have been removed. It can be seen that, in agreement with the results previously presented, probes 1 and 2 show a noticeable evolution of the mean diameter during the test both in deposition and removal analysis. The diameter of the removed and deposited particles under low gas velocities varies significantly as test progresses until they reach similar values of those of the remaining probes. In contrast to this, the diameters of deposited and removed particles under high gas velocities hardly vary, keeping constant during all the test. These results show that, under high flow gas velocities, the particle size distributions involve both in particle deposition and removal mechanism remain uniform during all the time of the test.

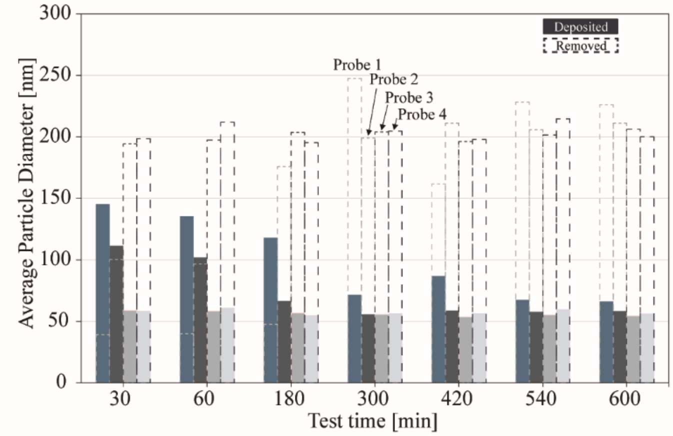

Figure 11: Average diameter of deposited and removed particles of the four probes at different moments of the test

Probe	1	2	3	4
Average deposited particle diameter [nm]	98.82	72.99	56.14	57.55
Average removed particle diameter [nm]	141.55	171.48	200.51	203.29

Table 1: Average particle diameter of deposited and removed particles

To complete this study the critical flow velocity inside the geometries has been analysed and some relevant connections have been detected with the results of removed particles.

Considering spherical particles, the critical flow velocity is the main stream velocity required to roll a particle resting on a flat surface (Abd-Elhady et.al, 2005). This variable is a function of the surface material, particle material and size. The critical flow velocity can be calculated from a moment balance for a spherical non-charged particle when assuming that hydrodynamic rolling moment due to drag force (F_d), lift force (F_l) and buoyancy force (F_b), is greater than the resting adhesion moment due to surface adhesion force (F_a) and the force of gravity (F_g). The hydrodynamic rolling moment (Eq. 1), defined by Zhang et al. (2000), tries to rotate the particle in the direction of flow, while the adhesion resting moment tries to stick the particle to the surface. In the equation of the rolling moment R, δ, and d (Eq. 2) represent the particle radius, the deformation of the particle and the contact diameter respectively.

$$RM = \frac{Hydrodynamic\ rolling\ moment}{Adhesion\ resting\ moment} = \frac{F_d(1.399\ R - \delta)}{(F_a + F_g - F_b - F_l)d/2} \qquad \text{Eq. 1}$$

$$d^3 = 6r_p\left(\frac{1-v_p^2}{E_p} - \frac{1-v_s^2}{E_s}\right)\left\{L + 3\pi\Gamma r_p + \left[3\pi\Gamma r_p L + (3\pi\Gamma r_p)^2\right]^{1/2}\right\} \qquad \text{Eq. 2}$$

The critical flow velocity has been calculated for the four probes of this study. Dashed lines of Figure 12 depict the ratio between the stream velocity and the critical flow velocity for the inlet particle sizes. The comparison is based on a surface energy coefficient of 0.14 J/m², which has been taken from the study of Kuznetsov et al. (2001).

It has been detected that Probe 3 and 4 show several particle diameters with a critical velocity rate bigger than 1, i.e. particle diameters whose critical velocity is under the stream velocity and that are prone to be removed or not to be deposited. The particles affected by this criterion are those with the biggest diameters. The 22.7% of the diameters of the Probe 3 and the 47.2% of the diameters of the Probe 4 are susceptible to be removed.

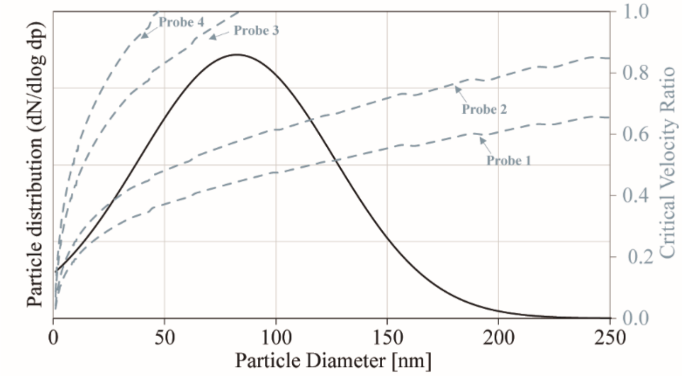

Figure 12: Particle distribution and critical velocity rate when surface energy is 0.14 J/m²

These results are in agreement with the measurements previously mentioned. Since the beginning of the test, the diameter of the particles that have been registered downstream the Probes 3 and 4 shows values around 200 nanometres, while in the remaining probes, whose stream velocity do not exceed the value of the critical flow velocity, the size of the removed particles are smaller. Furthermore, the amount of removed particles in the Probes 3 and 4 is bigger than in the probes with the lowest gas velocity, mainly during the first stage of the test.

Figure 13 depicts the removal ratio, which has been defined as the ratio of the number of inlet particles and removed particles, versus the coefficient of the gas flow velocity between the 50% of the critical velocity, and these results show a clear tendency.

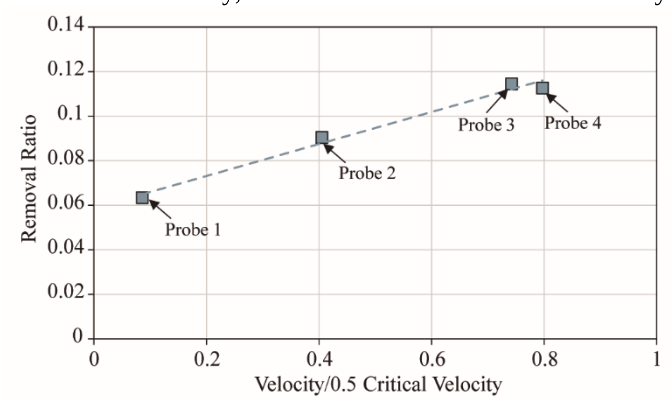

Figure 13: Removal ratio versus critical velocity ratio

In view of these results, and as other researchers have reported (Abd-Elhady et.al, 2002; Abd-Elhady et.al, 2004; Paz et.a., 2012; Sluder etal., 2013), there is a limiting flow velocity above which fouling is reduced because of the strong removal mechanisms induced by high gas velocities. They have been identified that, increasing the flow gas velocity above a certain limit, the induced shear force and the incident particle impact produce high removal rates.

CONCLUSIONS

In this study an experimental setup has been designed and built for investigating particulate fouling inside an EGR heat exchanger under different flow gas velocities. Using a scanning mobility particle sizer (SMPS) the size distribution of soot particle has been measured ant it has been found that, during the test, the particle size distribution varies downstream from the probe.

Increasing the gas flow velocity inside the tube, it has been detected that the size of deposited particles is gradually reduced until it reaches an asymptotic value around 60 nm. Inside probes with low gas velocity, transient effects have been detected during the first minutes of the test while, in probes with high gas velocity, it has been observed that, as test progresses, deposited particle distribution hardly vary.

Analysing the particle removal mechanism that takes place inside the tube, it has been detected that, as gas velocity increases, an escalation in the size and in the number of the removed particles has been identified. The detachment of the particles that are part of the fouling deposits generated by the shear force and the loss of the sticking probability of the biggest particles produce that, increasing the gas flow velocity, a big amount of particles can be measured downstream from the test section. In addition, the critical flow velocity of the inlet particles has been analysed for the four probes of this study and it has been measured that particle diameters with higher critical flow velocity correspond with higher removal ratios.

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