

## CARBON DEPOSITS IN GAS TURBINE INJECTORS

**N. TIDJANI, G.H. MARTIN, F. ROPITAL**  
Institut Français du Pétrole (IFP)  
BP 3 - 69390 Vernaison Cedex  
France

**G. GRIENCHE, H. VERDIER**  
Turbomeca  
64511 Bordes Cedex  
France

## ABSTRACT

The formation of carbon deposits in gas turbines is a recurring problem to which a lot of important work has been dedicated. These deposits cause a lot of problems and have a direct impact on the performance of gas turbines both from an environmental point of view and on the energetic efficiency and on hot parts life. In the combustion chambers of gas turbines, two different types of deposits may appear, one inside the fuel injectors and the other in the flame tube. The understanding of the formation of these deposits as well as their characterization is of up most importance for the design of the combustion chambers of gas turbines.

The study presented in this paper summarizes the recent work carried out in IFP (Institut Français du Pétrole) on the formation of these deposits on the materials currently used in the design of the combustion chambers and injectors of gas turbines. A micro-pilot thermogravimetric unit operating at cracking temperatures to the order of 900°C allows us to define the parameters influencing the formation of these deposits. Thus, the influence of the nature of the material, of the composition of the charge and of the operating conditions (temperature, flow rate,...) on the formation of the deposits and their morphology was shown. This work was carried out by testing a turbine injector during several hours on a test bench reproducing the working conditions of medium power industrial gas turbine. Different physico-chemical characteristics of common turbine fuels have been tested in an inert atmosphere. The characterization of the deposits (obtained with an electronic microscope), shows their morphology, as well as their elementary composition.

For different fuels and various operating conditions, this work allows also to compare different types of materials used in the construction of gas turbines.

## NOMENCLATURE

SMD : Sauter Mean Diameter,  
Mc : gain in mass per unit surface after 5 hours in  $g/m^2$ ,  
Md : mass deposited after 10 hours,  
P : pressure of test chamber in bars,  
r : nitrogen to fuel ratio,  
ts : residence time of gas in the injector in ms,  
 $T_{N_2}$  : temperature in test chamber in °C,  
 $T_p$  : wall temperature in °C  
V : asymptotic rate of deposit in  $g/m^2.h$ ,

## INTRODUCTION

The design and the construction of gas turbines have much evolved in the last twenty years. The phenomenon linked to combustion are today much better understood mostly thanks to the use of numerical simulation. On the other hand, the combustion efficiency is directly linked to the quality of the air/fuel mixture and to the temperature of the flame. Innovations in the preparation and injection of the air/fuel mixture have resulted in a relatively low level of pollutant emissions. Also, the preparation of the air/fuel mixture has a direct repercussion on the formation of carbon deposits in the combustion chamber.

These deposits have a high effect on the performance of the combustion chamber. In fact, these deposits form just as well in the flame tube as they do in the system of fuel injection and vaporization system. These deposits modify the surface of the material constructing the combustion chamber. As a consequence they affect the speed of vaporization of the fuel and the transfer of heat between the flame and the walls of the combustion chamber. Moreover the formation of these deposits modify the

temperature distribution of the combustion chamber walls at the combustor outlet and in doing so add supplementary thermal stress to the already existing mechanical stress of the design and cause significant damages to engine hot parts. This can affect in an irreversible manner the lifetime of the combustion chamber. The formation of deposits in vaporization tubes modifies the characteristics of the fuel spray and therefore the quality of the air/fuel mixture. The immediate result of this modification is an increase of the pollutant emission levels and of the temperature heterogeneity at the combustor exit.

The aim of the work presented in this article is to contribute to the understanding of the physical phenomenon which causes the formation of carbon deposits in the combustion chambers of gas turbines. The available literature on this subject identifies two possible paths for the formation of deposits. The first possible path is due to the thermal effects of cracking or to the formation of unburnable carbons within the flame [1] (pyrolytic reactions). The second path is due to direct contact between the liquid fuel and the walls of the combustion chamber [2,3,4]. The first type of deposit is often encountered in the flame tube while the second is encountered inside the injector system but also in the flame tube in case of fuel droplets impingement on combustor walls.

The use of a micro-pilot thermogravimetric unit allows an understanding of the first type of deposit while tests on a bench injector allow the characterization of the second type of deposit.

### DEPOSITS DUE TO THE CRACKING OF THE CHARGE

Thermogravimetric study enables the following of the kinetics of formation of this type of deposit on a sample of metal representative of the combustion chamber. For this, the sample is suspended by a thread of Kantal of 0.3 mm in diameter, in a quartz reactor heated by an oven (see figure 1). The thread of Kantal is connected to a balance, which measures the gain in mass with time of the sample. The balance has a range 0-20g with a precision of 1 µg.

The charge is a mixture of toluene and decane, and their proportions can be modified. Therefore the characteristics of the fuel kerosene (20% aromatics and 80% alkanes) can be represented and also the aromatic content of the charge can be varied. This can lead to a better understanding of the type of fuel constituents influencing the formation of deposits. With the use of argon the charge is introduced into the reactor in the form of vapor.

The oven enables the temperature of the reactor to be increased to 950 °C, which corresponds to the wall temperature generally encountered in combustion chamber of gas turbines. For safety reasons these tests are carried out in the absence of combustion, instead oxygen is introduced into the reactor by water.

The temperature in the test chamber is not constant and depends on the location. On the first 5 cm length, the charge is cracked at 850 or 900 °C. After this it exists three locations where the temperature is respectively 700 °C, 500 °C and 300 °C. In these areas, we place the sample according to the required temperature.

In steady state conditions we suppose that the sample temperature is equal to the location temperature. The total input gas flow rate is varied with temperature in order that the velocity remains constant near the sample.

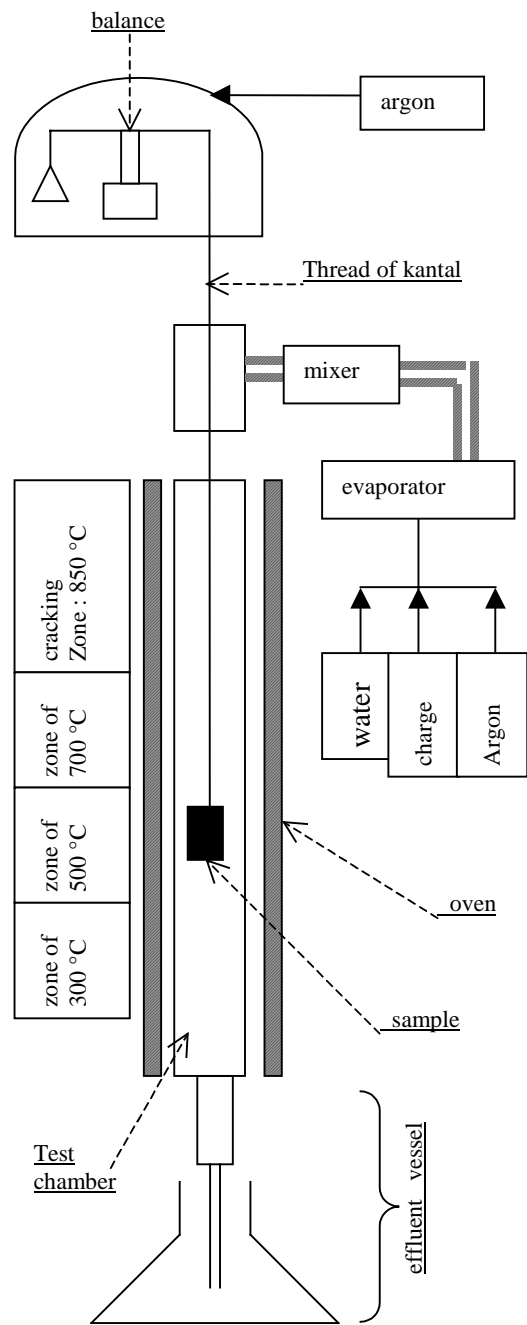


Fig. 1. Schematic drawing of the IFP Thermogravimetric test rig

With this installation we have studied the influence of the nature of the material on the processes and on the nature of the deposit. The results permit the determination of the following parameters:

- $M_c$ , which is the gain in mass per surface area of the sample after 5 hours of test, in  $g/m^2$ ,

- V, which is the asymptotic speed of deposit, in  $g/m^2.h$ ,

### Effect of the sample composition on the deposit

The experiments are carried out on blends of the alloy H75 composed of 75% nickel, 20% chrome and 5% iron. In order to know the influence of each component of the alloy, tests were carried out on samples of the pure metals, nickel, chrome and iron. The test conditions are as follows:

- The volumetric flow rates of the charge and of the water vapor are chosen to have a residence time of 85 ms at the sample level.
- The sample temperature is 500 °C and the cracking temperature is 900 °C,
- The charge is composed of 20 % toluene and 80 % decane, a composition representative of kerosene.

The results of these tests are shown in figure 2, which represents the gain in mass per unit surface of the sample over a period of 5 hours.

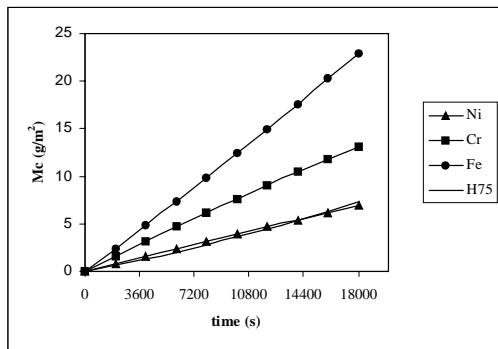


Figure 2 : Effet of constituents metals on the gain in mass per surface of the sample.

The asymptotic speed and the final mass gain for each material are shown in table 1.

	V	Mc
Ni	1.23	6
H75	1.46	7.34
Cr	2.58	13.4
Fe	4.87	22

Table 1. Final values of asymptotic speed and mass deposit for different samples.

Concerning the pure metals we can state that nickel is the most effective at limiting the formation of deposits followed by chrome and last iron which has developed the most deposits. In connection with the behavior of each of the pure metals, we can then analyze the performances of the H75 sample.

The behavior of the H75 alloy seems a little worse than that of nickel, but better than that of chrome and iron. Given that the nature of the material has an effect on the formation of deposits, we have examined using an electronic microscope the morphology of these deposits (see figure 3). This enables us to compare their appearance and eventually to show the differences in their mode of growth.

The deposits formed on the iron-based sample don't have a well-defined structure (fig 3.a). By comparison the deposits formed on the nickel-based sample are made up of conglomerates of spherical particles (fig 3.b). The structure of the deposits formed on the H75 sample is close to the structure of those formed on nickel due to the fact that these two samples show similar behavior (fig 3.c).

Analysis of the composition of the deposits shows that they are made up of 99% carbon with traces of hydrogen and oxygen. This composition is similar to that of graphite.

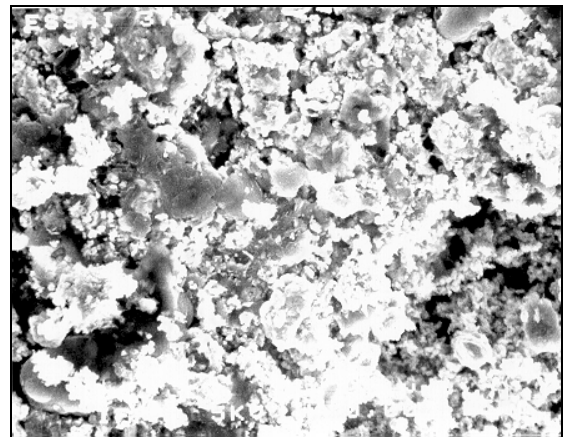


Fig. 3.a. Morphology of deposit formed on iron.

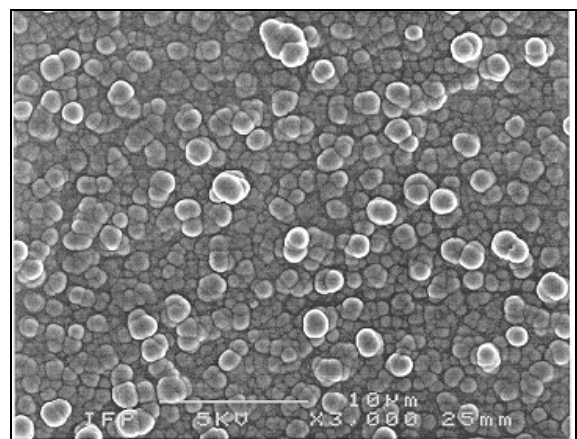


Fig. 3.b. Morphology of deposit formed on nickel.

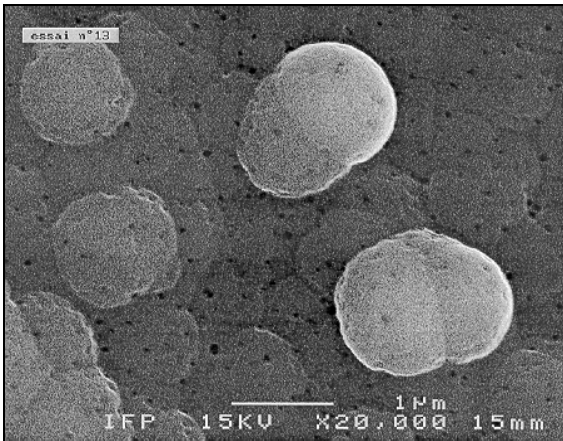


Fig. 3.c. Morphology of deposit formed on H75.

### Effect of cracking temperature

Figure 4 shows the mass deposited on the H75 sample for two cracking temperatures. All the others operating conditions are the same in these two cases and the sample temperature is 500 °C.

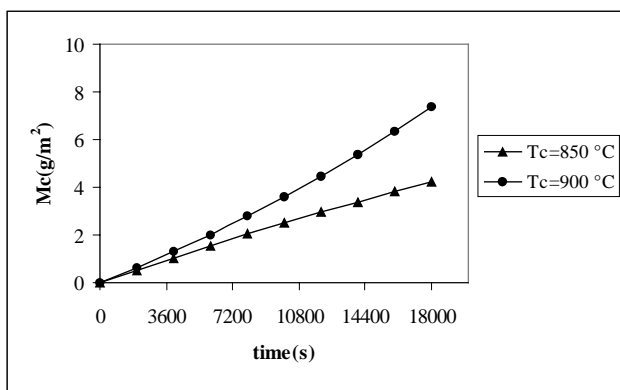


Fig.4. Influence of cracking temperature on deposit.

The cracking temperature has an important effect on the final mass deposited and on asymptotic speed of mass deposit. But the cracking temperature does not have an effect on the initial speed of mass deposited. The final mass deposit is 4.2 g/m<sup>2</sup> for Tc=850 °C and 7.34 g/m<sup>2</sup> for Tc=900 °C. The mass of deposits increase as the cracking temperature increase.

### Effect of the sample temperature

Figure 5 shows the results obtained on H75 for different temperatures of the sample. The cracking temperature was imposed at 850 °C. The mass of deposit and the asymptotic speed growth in time with an increase of sample temperature. The asymptotic speeds are respectively 0.3 for Tp=300 °C, 0.6 for Tp=500 °C and 1.53 for Tp=700 °C.

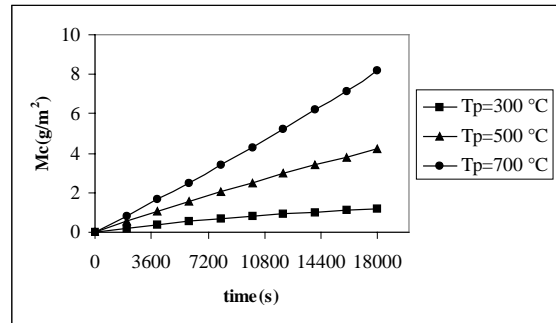


Fig.5. Influence of the sample temperature.

## DEPOSITS IN THE INJECTOR

Complementing the previous study we have studied the formation of deposits in an injector of a gas turbine. This time the tests are carried out under conditions similar to the operating conditions of a gas turbine of medium power (1MW). The injector tested is an aerodynamic type, therefore the material is H75. This injector is actually used, without any problem in the combustion chamber of some aeronautical gas turbines of Turbomeca burning kerosene fuel. The fuel is injected independently via a calibrated orifice opening in a premix tube equipped with an axial swirler. The premix tube contains orifices openings which allow the injection of air, the air/fuel mixture thus formed is sent to a vaporization tube. In the processes of mixture and vaporization, deposits are formed on the walls of the injector and these modifying his performances. Therefore a study on the formation of these type of deposits necessitates the formation of the air/fuel mixtures under conditions close to real operating conditions.

The bench tests carried out on the injector at IFP, permit the characterization of gas turbine injectors both on the aerodynamics of the spray by optical diagnostics as well as the problems linked to the formation of carbon deposits. Figure 6 shows the principal elements of this installation.

Certain deposits observed in the gas turbine injectors are not linked to combustion due the absence of a flame in the injectors. The mechanisms of formation of these deposits are lead by the direct contact between the liquid fuel and the injector walls. In order to eliminate the problems linked to combustion, these tests are carried out with nitrogen instead of air. The characteristics of this installation are given in table 2.

nitrogen flow rate	< 100 kg/h
fuel flow rate	< 14 kg/h
test temperature	< 450 °C
test pressure	< 5 bars
fuel pressure	< 100 bars

Table 2. Characteristics of the IFP test rig.

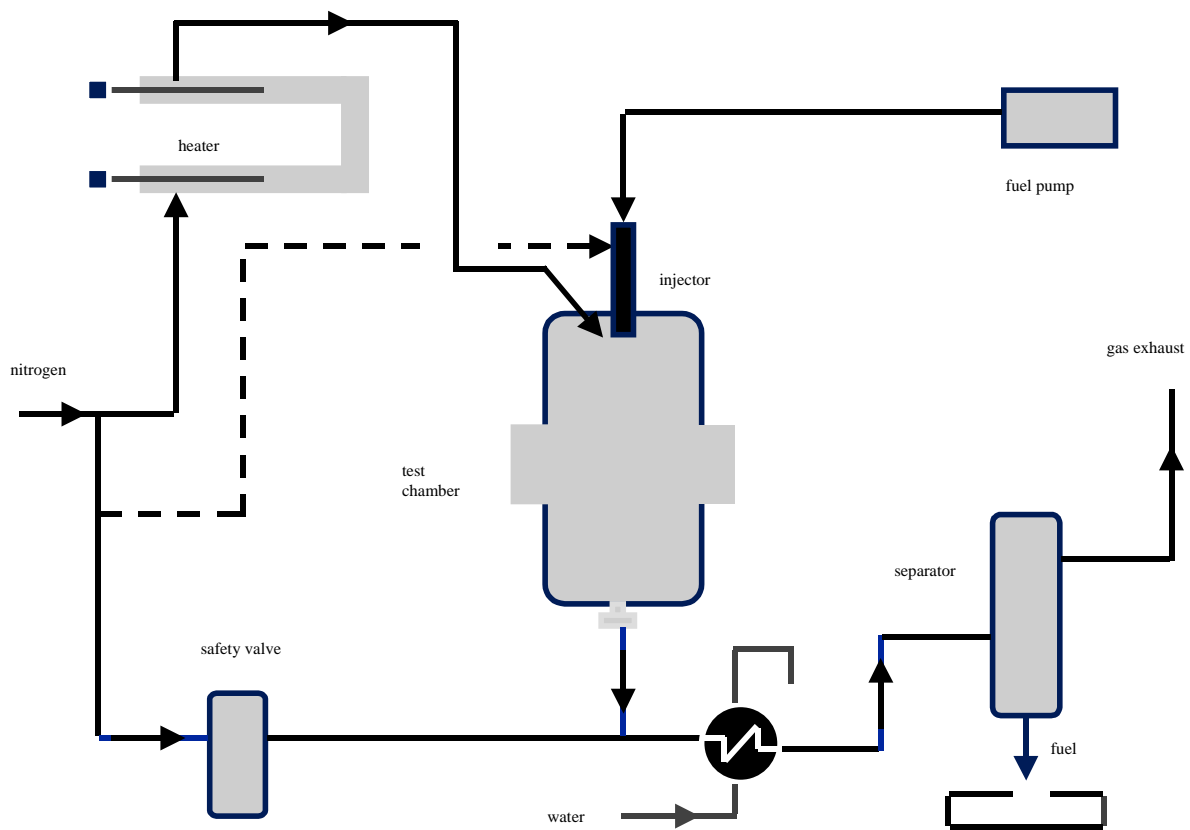


Fig 6. Schematic drawing of the IFP test rig injector.

The tests are carried out with domestic fuel oil under different conditions of pressure and temperature for a duration of 10 hours. The conditions of the tests are shown in table 3.

$T_{N_2}$	P	$t_s$	SMD	r	$T_p$
415	3	3	27.8	20	535
450	3	3	28.7	20	560
375	5	6	70	20	500
415	5	6	73.2	20	550
450	5	6	74.7	20	530

Table 3 : Tests conditions for Turbomeca injector

The characteristics of the fuel used are determined by an atmospheric distillation. The aromatic content is 33 %, the conradson carbon is 0.16 % and the density is 0.84; this is therefore a classic charge used in industrial turbines. Figure 7 shows a photo of the injector and of the vaporization tube after 10 hours of tests. The mass of deposits is obtained by weighing at the end of the test.

The results shown in figure 8 show that at a fixed pressure of 5 bars the mass of deposits decrease as the temperature increases. This tend is confirmed at 3 bars but the effect is less than that observed at 5 bars. In fact, at a fixed pressure an increase in nitrogen temperature corresponds to an increase of wall injector

temperature and to a reduction in the contact time between the liquid fuel and the wall and therefore to a decreased formation of deposits. The wall temperature at the vaporizing tube exit is fitted to a realistic value taking into account the combustor flame radiation. In the injector bench this temperature is obtained by an electrical induction heater device.

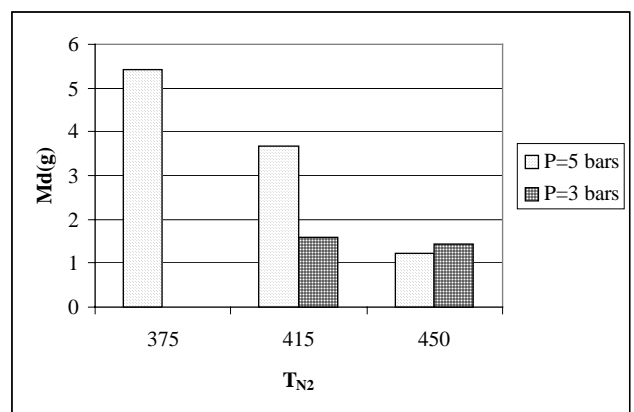


Fig.8. Mass deposit after 10 hours on turbomeca injector.

The mechanism of formation of this type of deposit seems to be different to that studied previously. The formation of this type of



deposit is linked to the direct contact between the liquid fuel and the walls of the injector. The characteristics of the spray delivered by the injector are known as a function of temperature and pressure. Due to the mass air-flow limitation of the rig, the air velocity inside the injector is lower at 5 bar than at 3 bar. Therefore at a fixed temperature, the average Sauter mean diameter of the spray droplets is greater at 5 bars than at 3 bars.

At 415 °C, the mass deposited at a pressure of 5 bars is greater than that deposited at 3 bars, this is due to the fact that the atomization deteriorates at 5 bars, and this leads to more deposit. At 450 °C the differences observed in the mass of deposits at 3 bars and 5 bars doesn't allow a clear conclusion to be drawn on the effect of the pressure.



Fig 7.a. View of the Turbomeca injector



Fig 7.b. View of the exit of vaporization tube of the injector. P=3 bars and T=415 °C

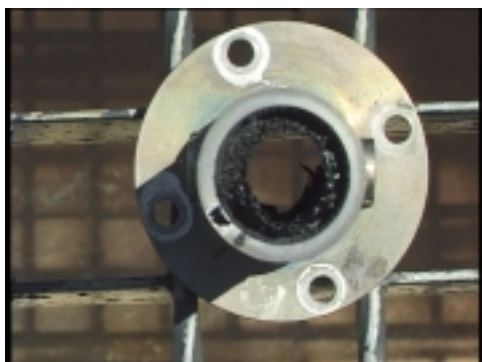


Fig 7.c. Bottom view of the exit of vaporization tube of the injector. P=5 bars and T=415 °C.

In the combustion chamber of a gas turbine, the presence of oxygen in air can modify the phenomenon of deposition via oxidation of the deposit during its formation. To confirm the validity of our tests, thermogravimetric analysis have been carried out on one sample of the deposit. Figure 9 shows the mass loss of deposit versus time. It appears that the oxidation of the deposit begins at 380 °C, which corresponds to a compressor output temperature of a medium power gas turbine. The oxidation of the deposit ends at about 575 °C.

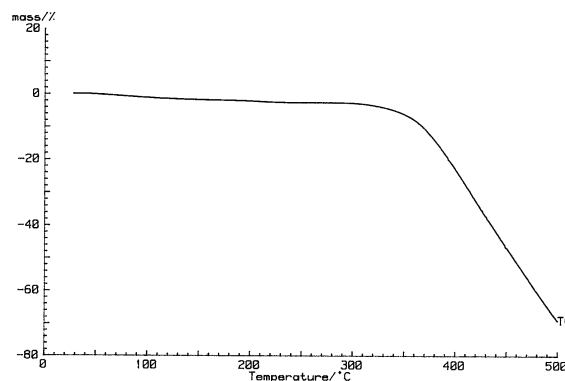


Fig 9. oxidation of deposit sample.

Analysis of the deposits show that they are composed of 83.5 % carbon, 12 % hydrogen, 2.5 % oxygen and traces of nitrogen and sulfur.

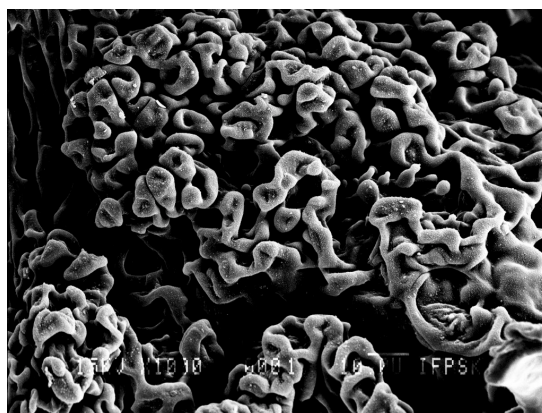


Fig 10. Morphology of carbon deposit in the injector.

Analysis of the morphology (fig 10) of the deposits shows that they are amorphous.

## CONCLUSION

The formation of carbon deposits in combustion chamber of gas turbines remain an important subject for designing efficient machines both from environmental and energetic efficiency. The results presented here show that two mechanisms of deposit can occur in the flame tube or on the walls of the combustion chamber.

Thermogravimetric micro-pilot shows that it is possible to characterize the deposit formed by cracking the charge. But this deposit depends a lot on the operating conditions of the combustion chamber. Tests carried out on alloy of nickel, chrome and iron show that iron tend to form more deposit than nickel. The mass deposit increases as the cracking temperature or sample temperature increase. The deposit composition is like carbon graphite.

The second type of deposit has been studied on IFP test rig injector in similar operating conditions than real aerodynamic injector. It seems that the main path for forming this deposit is the direct contact between liquid fuel and the wall of the injector. At constant pressure, the mass of deposits decreases as the wall temperature increase. This type of deposit seems to be different than that observed by cracking the charge. Analysis of this type of deposit shows that it contains more hydrogen than which obtained by cracking the charge.

The nature of the fuel, particularly its content of aromatics, is confirmed to be a very important factor explaining that fuel injectors currently used in aeronautic gas turbines with kerosene must be drastically adapted to burn diesel fuel on an aeroderivative industrial gas turbine.

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