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Characterization of the Exhaust Flow in the Catalytic Converter of a Spark-Ignition Engine Using Infrared Thermography

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ABSTRACT

The paper reviews an infrared (IR) thermographic study that was implemented to evaluate the performance of a catalytic converter in a 1.6 liter fuel-injected spark ignition gasoline engine from Renault. Part of a 10-year ongoing research and development effort, this collaboration involves the research center IMST within the Department of the Universidad Politécnica de Valencia and the engineering center of Renault in Valladolid, Spain.

Experimental tests were carried out at the engine test bench using an infrared camera. Infrared thermography data made it possible to compare the actual internal temperature of the exhaust gases at different engine speeds and loads with values calculated using heat transfer theory, and corresponding correlations of external free convection, external radiation, and internal forced convection into the catalyst.

The comparison between theoretical calculations and the experimental exhaust gas temperatures shows striking consistency. It proved possible to develop some interesting conclusions about the flow of exhaust gases in the interior of the catalytic converter as a function of the exhaust mass flow rate. A major finding was that the distribution of the exhaust gases inside the catalytic converter is not uniform, but flows mostly through the central part of the device, so the rest of the swept volume acts as insulating material, where relatively still exhaust gases remain in the cells of the structure, depending on the load and the engine speed.

The paper emphasizes the use of thermal imaging techniques in two aspects of particular interest in this engineering field:

- The estimation of the internal temperature of the gas flowing through pipes or ducts
- The use of temperature measurements to complete the energy balance of the engine

Some basic heat transfer concepts necessary to analyze these aspects are also briefly described.

Keywords: Engines, internal gas temperature, catalytic converter, energy balance, infrared, IR, and thermal imaging.

INTRODUCTION

For fifteen years the Institute of Energy Engineering of the Universidad Politécnica de Valencia has been closely collaborating with different car companies in Spain, such as SEAT-WOLKSWAGEN and RENAULT ESPAÑA. The following results could be pointed out as the most important features of these Research Projects:

- The design of the intake manifold valves for some engines manufactured at the Spanish factories
- Quality monitoring of the cylinder head characteristics, such as discharge and swirl coefficients
- Consultant services on different issues related with engine test benches.

In October 2000, a FLIR ThermaCAM® SC 2000 infrared camera was acquired for the laboratory of the Institute, allowing it to be used in the numerous projects developed by the different research groups. This camera has been used at the engine test benches of the described Spanish car companies as the support tool to carry out the research work presented in this paper.

ESTIMATION OF THE INTERNAL GAS TEMPERATURE

The determination of the surface temperatures of some engine components using the infrared camera enables a good estimate of the internal temperature of the fluid flowing inside. To establish and confirm the precision of the estimate, experimental measurements or a good estimation of the mass flow rate through the specific element are necessary.

Some heat transfer calculations are required, beginning with the calculation of the internal and external convection coefficients, using the available Nusselt number correlations [1,2].

Usually natural convection conditions are assumed to estimate the external convection coefficient on the engine surface. The required thermal properties of the air are calculated using the average value between the surface and the air temperature [1,2].

The heat losses from the engine surfaces are caused by convection and radiation:

$$Q_{total} = Q_{convection} + Q_{radiation}$$

$$Q_{total} = \varepsilon \cdot \sigma \cdot (T_{\mathrm{sup}}{}^{4} - T_{surrounding}{}^{4}) + h_{conv} \cdot (T_{\mathrm{sup}} - T_{air})$$

With the assumption that the internal gas temperature is approximately constant along the length of the element analyzed, Q_{total} is transmitted as forced convection from the internal gas flow to the inside surface:

$$Q_{total} = h_{conv\_\mathrm{int}} \cdot (T_{gases} - T_{\mathrm{sup}})$$

The internal convection coefficient is calculated assuming forced and turbulent flow conditions (Reynolds number > 2300). The proposed correlations (Dittus-Boelter expression) [1,2] are the following:

$$\mathbf{Nu_D} = \mathbf{0.023} \cdot \mathbf{Re_D}^{\mathbf{0.8}} \cdot \mathbf{Pr}^{\mathbf{n}} \qquad n \begin{cases} 0.3 \text{ if the flow is cooled} \\ 0.4 \text{ if the flow is heated} \end{cases}$$

The calculation of the Reynolds number requires knowing the gas speed or the mass flow rate through the pipe.

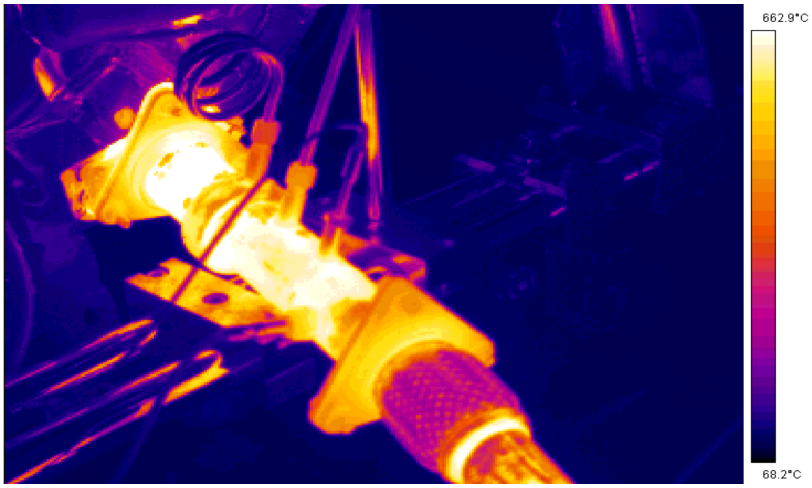

Figure 1. Infrared thermogram showing the supplementary element between the exhaust manifold valve and the collector.

Considering that the temperatures of the inside and outside surfaces of the pipe are close to each other, it is possible to estimate the internal gas temperature. That assumption is accurate for thin wall metal pipes, like for example, exhaust manifold collectors, but it is not appropriate for plastic ducts commonly used in the intake system of the refrigeration circuit in which the corresponding conduction resistance must be taken into consideration. A great part of our experimental research focuses on the exhaust system in which an accurate estimation of the gas temperatures is important for different purposes, such as the determination of the amount of energy available in the turbocharger.

Finally, the thermal properties of the fluid used in the convection coefficient correlations — Prandtl number, kinematic viscosity, thermal conductivity, etc. — are determined to estimate the gas temperature. Therefore, to calculate these factors an iterative method easily developed with conventional commercial software is used.

The procedure described above has been used to estimate the gas temperature of the engine element shown on the infrared image of Figure 1. A special pipe between the exhaust manifold valve and the collector is used to measure the gas temperatures and pressures. The gas temperatures are measured with thermal resistances. The experimental data of engine mass flow rates were available from the usual acquisition system of the engine test bench.

The comparison between the external surface temperatures and the internal gas temperatures shows substantial differences, close to 200 K for the highest engine speeds.

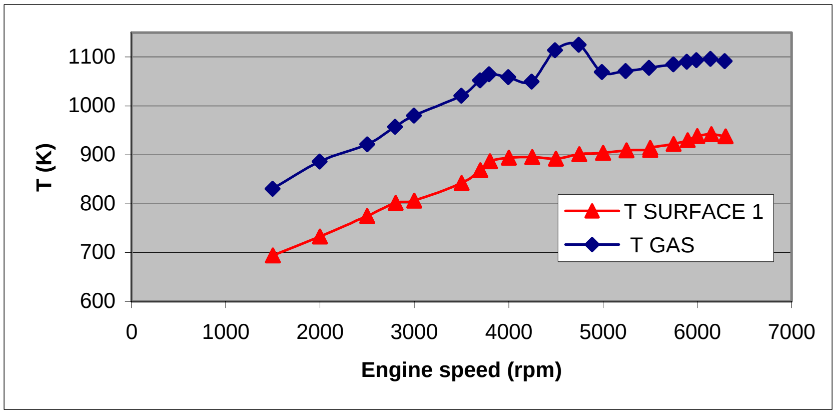

Figure 2. Comparison between external surface temperatures and internal gas temperatures under full load conditions.

Figure 3 shows the comparison between the experimental and the calculated results. This estimation has been carried out using the methodology already described. The best results are obtained at high engine speed. Under these conditions the correlation is really very high. Thus, this procedure could be useful to estimate the gas flow temperature, from the surface temperatures obtained with the thermograms.

This methodology has also been utilized for other types of flows and geometries, for example the exhaust gas recirculation system (EGR). Very satisfactory results have also been obtained, confirming the usefulness of this procedure.

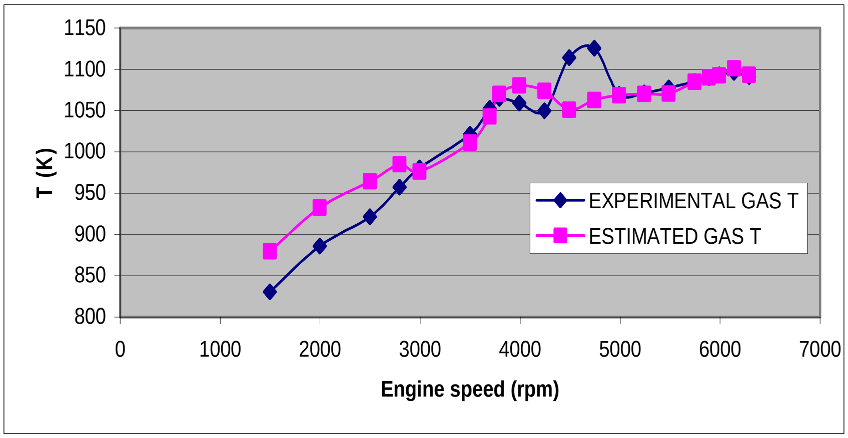

Figure 3. Comparison between experimental and estimated exhaust gas flow temperatures.

CHARACTERIZATION OF THE FLOW AT THE CATALYTIC CONVERTER

The image in Figure 4 shows the infrared thermogram of the catalytic converter of a spark ignition engine of 1.6 liters of displacement. The test conditions are full load and maximum engine speed. The first important question from this thermogram focuses on the apparent temperatures on the surface of the catalytic converter — are they real or are they caused by low emissivity? To find out, an emissivity test was carried out using a special kind of paint resistant to the high temperatures common in this exhaust system component.

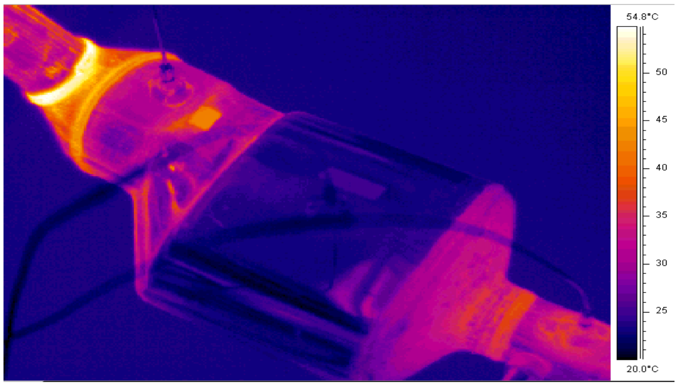

Figure 4. Thermogram of the catalytic converter under full load and maximum engine speed conditions.

As shown in Figure 4, the painted square zone on the top of the connecting pipe presents a higher apparent temperature, showing in this way that the real emissivity of this surface is lower. But on the catalytic converter the painted zone is similar to the rest of the surface; this means that the emissivity is really high, close to the value of the painted zone.

Figure 5: Sectioned view of a honeycomb type catalytic converter.

As shown in the photograph in Figure 5, the catalytic converter is composed of a stainless steel shell which contains the ceramic honeycomb on which the catalytic active material is deposited. The ceramic honeycomb is surrounded by a thin layer of insulation fiber to maintain high gas temperatures and thus improve the catalytic reaction. In fact, this is the reason for the low temperature of the external surface of the steel shell. This insulation layer causes an important temperature drop between the internal and the external surfaces of the wall. Therefore, it is not accurate to assume that the temperature of both surfaces is similar.

The external temperature of the steel shell has been determined using the thermogram data. The heat losses, convection and radiation, are estimated by using the methodology described in the previous section. This thermal power is transferred from the internal gas. Its temperature has been experimentally determined with the use of thermocouples.

The internal convection coefficient is calculated using the correlations available for forced laminar convection conditions [1,2], taking into account the small size of the exhaust gas passageways.

The overall heat transfer process between the internal gas and the external environment is characterized as follows:

- Internal forced laminar convection from the exhaust gases to the inside wall surfaces.
- Conduction through the different layers of the catalytic converter.
- Convection and radiation from the external surface of the steel shell towards the external environment.

The heat transfer between the internal exhaust gases and the external surface of the catalytic converter could be written in an analytical form, using the concept of equivalent thermal resistances [1,2]:

$$Q_{total} = \frac{(T_{gas} - T_{\sup\_ext})}{\frac{1}{S_{\text{int}} \cdot h_i} + R_{conduction}}$$

As the remainder terms in this expression are known, it is possible to determine the corresponding equivalent conduction resistance $\boldsymbol{R_{conduction}}$. In the conventional configurations, this conduction resistance is approximately constant and depends mainly on the thermal and geometric properties of the materials.

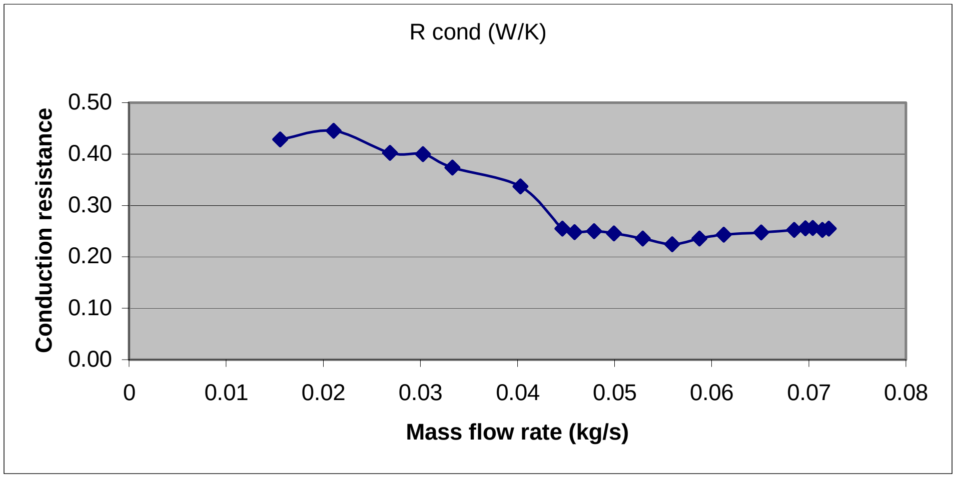

Figure 6: Estimated conduction resistance of the catalytic converter wall vs. the mass flow rate of exhaust gases.

But, as shown in Figure 6, the calculated conduction resistance for the catalytic converter is not constant. The tendency shows a strong dependence on the mass flow rate of the exhaust gases. As this parameter increases, the conduction resistance drops down to certain uniform level for mass flow rates larger than 0.05 kg/s.

The conduction resistance for the highest mass flow rates is approximately 0.25 W/K. This value could correspond to the conduction resistance of a real insulation material, for example, a layer 5 mm thick and thermal conductivity of 0.035 W/m K. These magnitudes seem reasonable for the real thermal insulation layer close to the steel shell used in the catalytic converter (see Figure 5).

The *excess* of conduction resistance for low mass flow rates has a maximum value (0.45) for the minimum gas flow rate. This value progressively decreases with increasing mass flow rates. This behavior could be characterized as a *decreasing insulation effect*.

Such a tendency can be understood by observing Figure 7, a cross-sectional view of the catalytic converter. The honeycomb structure of this element could cause an insulating effect if still gas occurs inside the passageways. Under real operating conditions this condition is possible only if the gases flow only through the central part of the honeycomb section, for example, if the mass flow rate is very low. The remainder part of the section would be filled with still gas, which could be the responsible for the insulating effect.

From this point of view it is even possible to estimate the effective flow section of the catalytic converter, as a function of the engine speed, as it is shown in Figure 8.

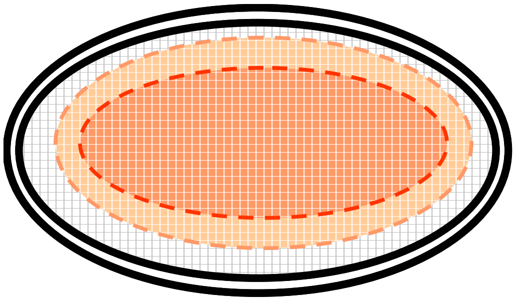

Figure 7. Scheme showing the progressive "filling" of the catalytic converter section with increasing mass flow rates

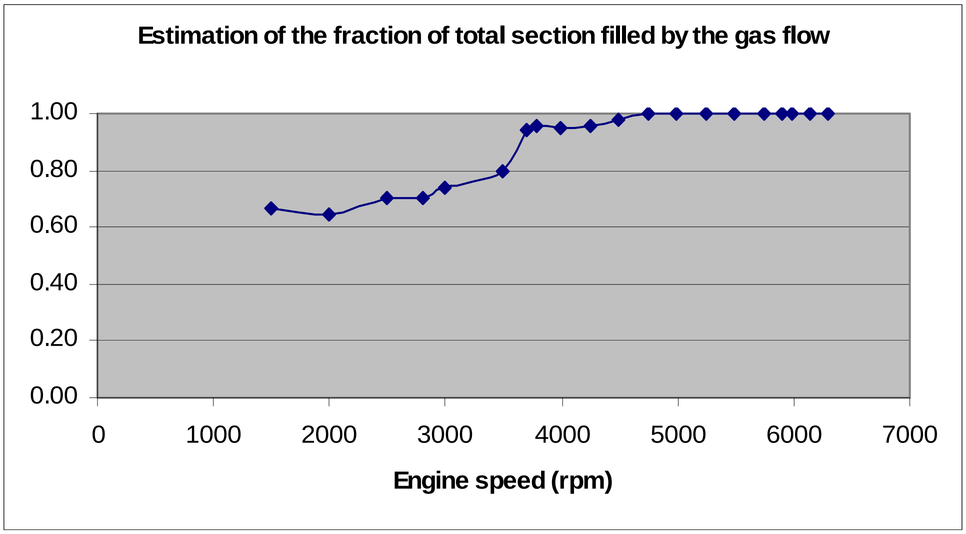

Figure 8: Estimation of the fraction of effective flow section of the catalytic converter vs. the engine speed.

For the lowest engine speeds, the flow fills about 60% of the section of the catalytic converter. The now active passageways, filled with still gas, could have an insulating effect.

This analysis could be applied to optimize the predesign of the catalytic converter, because it clearly shows if inadequate sizes are utilized, as two opposite tendencies:

- Too small size: the effective section is completely filled for very low mass flow rates.
- Too large size: partial section filling for the maximum mass flow rates.

OTHER APPLICATIONS AT THE ENGINE TEST BENCH: ENERGY BALANCE FOR THE ENGINE

There are some applications in which an accurate estimation of the engine heat losses is necessary. A very typical case is the predesign of the climatization system of the engine test bench, required to maintain specific ambient conditions during engine testing.

The overall thermal power of the engine corresponds to the “chemical energy” released during the combustion process. This energy is calculated from the reaction heat of the specific fuel, and the consumption of the engine. One part of this energy, as large as possible, is converted to useful power by the engine (a maximum value of about 30% for the most favorable conditions). The remaining part consists of heat losses as follows:

- Energy of the exhaust gases leaving the engine.
- Energy to the coolant water from different engine components (exhaust valves, cylinder head, liners, etc.)
- Energy released from the external surface of the engine.

For the climatization of the engine test bench, this last term is particularly important.

The calculation procedure is very similar to the methodology described in previous sections:

- Determination of the surface temperature in the different zones of the engine (using the infrared thermograms)
- Measurement of the temperature of the air inside the test bench

From these experimental values, it is possible to estimate the overall heat losses as:

$$\boxed{\begin{aligned}&Q_{total}=Q_{convection}+Q_{radiation}\\&Q_{total}=\varepsilon\cdot\sigma\cdot(T_{\sup}{}^{4}-T_{ec}{}^{4})+h_{conv}\cdot(T_{\sup}-T_{aire})\end{aligned}}$$

As in the previous cases, it is also necessary to calculate the convection coefficient between the external surface of the engine and the air inside the test bench, normally as natural convection conditions [1,2]. From the studies carried out for different types of engines (spark ignition and Diesel engines), the following conclusions were obtained:

- At full load conditions, heat losses from the surface of the engine could be quantified as 50% of the maximum engine power.
- The maximum heat losses are produced at the exhaust part of the engine, where the radiation intensity is really very high.
- The temperature of the main part of the engine surface is about 95–100ºC, similar to the temperature of the coolant water. This is reasonable taking into account the high thermal conductivity of the materials used nowadays in the engine walls (aluminum).
- For the turbocharged Diesel engines common in Europe, the zone surrounding the turbine could reach 600ºC. It is very important to take into account these thermal levels, because it involves a high thermal charge even if the heat transfer surface is not too large.

SUMMARY

The use of some basic heat transfer concepts allows the calculation of several important parameters in the car engine, such as:

- The temperature of the gas flowing through different systems
- The heat losses from the surface of the engine
- The flow characterization inside the catalytic converter or the EGR system.

REFERENCES

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