CHEMICAL ANALYSIS OF THE IMPROVED FLOW IN AN AUTOMOTIVE CATALYTIC CONVERTER

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Abstract. *This work studied emissions flowing out of an automotive catalytic converter where the exhaust gas flow is improved by means of metallic screens. Due to boundary layer separation on the walls of the inlet catalytic diffuser, the flow occurs in the form of a " jet ", with high speeds in the center. The non-uniform distribution of the flow causes an irregular use of the catalytic area, among other problems. The insertion of metallic screens in the diffuser perpendicular to the flow reduces the adverse pressure gradient, avoiding separation of the boundary layer. The experiments showed that this method of flow control is capable of producing a good uniform velocity profile and influences catalytic efficiency favorably.*

Keywords: *catalytic converter, boundary layer separation control, screens, experimental fluid mechanics.*

1. INTRODUCTION

In general, diffusers used in the entrance of automotive catalytic converters have wide divergence angles. The characteristics of combustion gas flow inside this diffuser are related to its geometry. Farell and Xia (1990) shows that the critical geometry of the diffusers with divergence angle (2θ) is above 10º. Mehta (1977) also defined as critical those that presented abrupt increase of the transverse section, whose ratio between the entrance area and exit area “A” exceeded 2,5. Such conditions are very often found in automotive catalytic converters, in which the boundary layer separation can only be avoided with use of some control method. The catalytic converter used in the present study had a divergence angle 2θ = 42º and A = 4.

In this case, the boundary layer separation inside of the diffuser becomes a problem, because the flow distribuition an the catalytic section is not uniform. This non-uniformity of the flow produces high temperature gradients on the honeycomb and, consequently, high thermal stress, as demonstrated by Wendland and Matthes (1986) and Guojiang and Song (2005). These factors also contribute to decrease the fluid dynamic efficiency and catalytic conversion.

To avoid this effect, many control methods of boundary layer separation were studied, mainly in aerodynamic research, because this phenomenon modifies aircraft performance, nozzle efficiency, wind tunnel performance and others like this. In view of this, many devices or control methods were analyzed and proposed, such as vanes and splitter plates (Bella and Maggiore, 1991). These devices are already used in catalytic converters, but are not very efficient and are difficult to install. Another disadvantage is the great heat absorption of the exhaust gas, mainly during cold starts and where there exists high back pressure (Day and Socha, 1991).

In the exit of the catalytic converters is also mounted a nozzle, however, this is the convergent kind with favorable pressure gradient, which does not significantly affect the flow inside of the honeycomb, as discussed by Karvounis and Assanis (1993) and Lemme and Gives (1974). Therefore, the objective of this study is on flow inside of the diffuser, in which the pressure gradient is unfavorable.

The present work shows experimental results of the flow using a metal screen with correct mesh and installed inside of the diffuser, as well as the influences on catalytic efficiency. Such a technique is used to control boundary layer separation, decreasing the unfavorable pressure gradient. As in Arantes (2001), the use of screens in automotive catalytic converters has showed an increase in fluid dynamic efficiency, because of the control of the boundary layer separation inside of the diffuser.

The results obtained in these tests confirmed the expectations and they will be presented in detail. The fluid dynamics and chemical analyses were performed at the PUC-Minas and UMICORE laboratories, respectively.

2. METHODOLOGY

2.1. Screen theory

Screens are recognized as a means of controlling turbulence levels in wind tunnels and associated with boundary layer control. Schubauer and Spangenberg (1948) studied separation control by means of screens in wide angle diffusers and after that, a comprehensive review of this study was carried out by Mehta (1976). The tables and graphs presented in these works also were used to define the correct mesh of the screen, based on geometric parameters. The idea is to match the screen head loss to the diffuser pressure recovery and so keep the pressure gradient reduced. The loss provided by the screen is given as in Eq. (1).

$$\Delta p = k\rho \frac{u^2}{2} \tag{1}$$

Where k is a function of the screen open area ratio, but is affected by the Reynolds number, u (m/s) is the velocity on screen and ρ is especific mass (kg/m^3). The open area ratio (β) is given as Eq. (2)

$$\beta = (1 - \frac{d}{l})^2 \tag{2}$$

where d (m) is the wire diameter and l (m) is a screen mesh length.

Mehta (1977) gives the pressure drop coefficient (k) as Eq. (3) and Eq. (4).

$$k = 6{,}5 \frac{1-\beta}{\beta^{5/3}} \mathrm{Re}^{-1/3} \quad \text{for } u < 10 \text{ m/s} \tag{3}$$

$$k = \frac{c(1-\beta)}{\beta^2} \quad \text{where } 0{,}9 \le c \le 1{,}0\text{; for U} > 10 \text{ m/s} \tag{4}$$

The Reynolds number ($Re = Ud/\nu$) is a function of the screen wire diameter (d).

Table 1 gives the characteristics of selected screens used during the test, considering the speed above 10 m/s incident on the screen.

Table 1: Data of the main screens tested.

Screen BWG	Wire diameter (mm)	Screen mesh length (mm)	Open area ratio (β)	k
18/32	0,23	1,18	0,70	0,58
26/30	0,30	0,67	0,47	2,28
28/32	0,23	0,67	0,56	1,33

In the table above, the “BWG” (Birmingham Wire Gauge) are: the first numbers (xx/) mean the amount of the wires per linear inch and the second numbers (/xx) are related with the wire diameter of the screen.

Certainly, the number of screens installed to prevent boundary layer separation completely depends on both diffuser area ratio (A) and divergence angle (2θ). In the present work, such a screen was mounted to simplify the group installation. As in Arantes (2001), a well-selected screen can improve the uniformity coefficient (γ) of the flow inside of the catalytic converter.

As proposed by Bressler et al. (1996), the standard deviation of the speed along the profile provides a measure of the flow uniformity coefficient (γ), as Eq. (5).

$$\gamma = 1 - \frac{1}{n}\sum_{i=1}^{n} \frac{\sqrt{(u_i - \overline{u})^2}}{\overline{u}} \tag{5}$$

where $\overline{u}$ is the speed averaged (m/s) over the velocity profile in the exit of the honeycomb and u_i (m/s) is the local velocity, where $\gamma = 1$ is a fully uniform profile.

2.2. The catalytic converters tested

A couple of identical catalytic converters were used during the tests. Basically, these were a VW catalytic converters part number 377131701C, manufactured to allow the introduction of the metallic screen inside of the inlet diffuser. To achieve this, they had a "flange" which facilitated the installation of the screen. On the other side there was a larger flange for access after the honeycomb, allowing measurement of the velocity profiles with a Pitot tube. Figure 1 show the catalytic converter model used in the tests, where both flanges can be seen.

Figure 1: Detail of the catalytic conveter used in the tests.

The honeycomb dimensions were 4,6" x 6,0" (diameter x length) with a density equal to 400cpsi (cells per square inch). Both catalytic converters analyzed had the same technology and metal loads.

The flange to screen installation was located immediately in the inlet diffuser. This is the place where the abrupt angle variation of the inlet diffuser is situated. As in Mehta (1977), this is the preferred point to install the screen in order to control boundary layer separation in wide angle diffusers. Arantes and Medeiros (2008) reached the same conclusion after several tests with screens and catalytic converters, that is to say, a screen could be mounted directly in the diffuser entrance. Figure 2 shows in detail a metallic screen with stainless steel wires and mesh 26/30 mounted inside the diffuser.

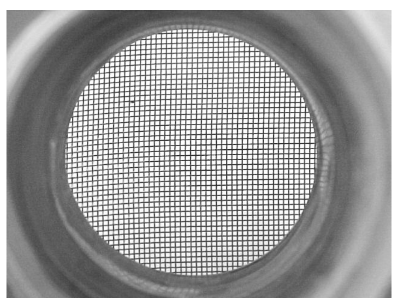

Figure 2: Screen installed inside the catalytic converter diffuser.

Having removed the wide flange, access was made possible to the exit face of the honeycomb, as can be seen in Fig. 3. In this way it was possible to analyze the velocity profiles for the honeycomb by mean of Pitot anemometry. This device was mounted on a mobile table (positioner) and connected to a líquid manometer.

Figure 3: The catalytic converter without cover. This picture shows the exit side of the honeycomb. Velocity profiles were analyzed on this side.

2.3. Flow test bench measurements

The catalytic converters were tested on a flow bench installed at the fluid dynamic laboratory at PUC-Minas (Pontifícia Universidade Católica de Minas Gerais), using air at an average temperature of 22°C. In these conditions the velocity profiles were measured with and without a screen, maintaining Reynolds number equal to $78x10^3$ in the diffuser inlet.

After testing with some selected screens and configurations inside the diffuser, the best application was chosen. Then a screen with 26/30 mesh was used, made of stainless steel. This material had been tested previously, resisting high temperatures very well, which is essential for use in automotive applications.

The velocity profile measured without any screen can be seen in the Fig. 4. Near to the center of the honeycomb the peak velocity was 11 m/s and the average velocity was 7,6 m/s. The flow uniformity coefficient calculated during this test presented a relatively low value equal to 0,76. The measurements were obtained at 30 mm from the honeycomb surface (distance to Pitot probe).

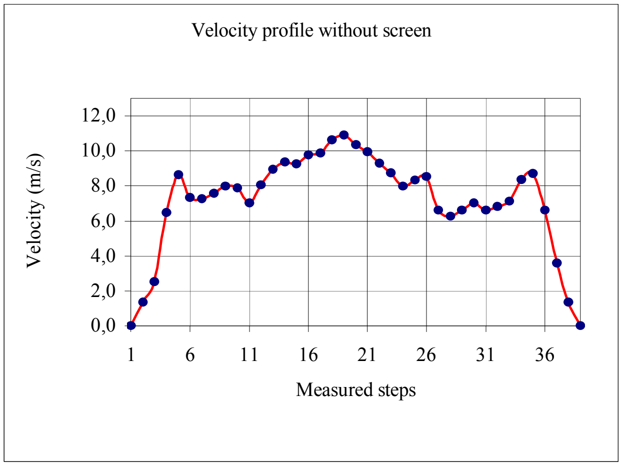

Figure 4: Velocity profile in honeycomb exit without screen.

Under the same conditions, the velocity profile was analyzed with a screen 26/30 inside of the diffuser. In this case, the velocity peak was equal to 8,5 m/s and the average velocity 7,0 m/s. The flow uniformity coefficient (γ) improved to 0,82, showing a significant gain in the fluid dynamic efficiency. Figure 5 shows a more uniform velocity profile when compared with Fig. 4. In this condition, the high velocities in the center of the honeycomb do not exist, showing a better performance of the flow than previously.

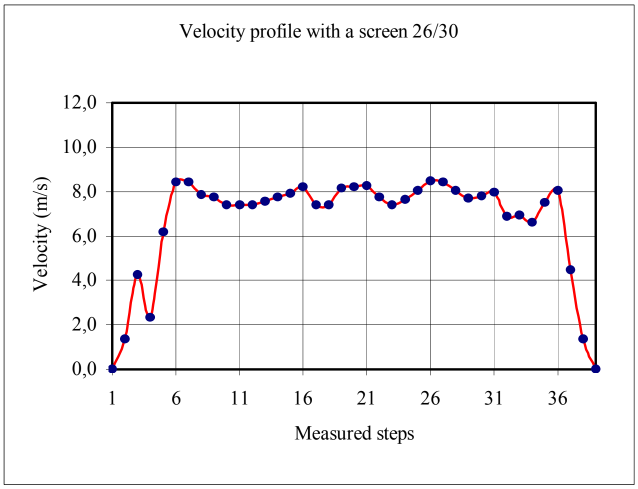

Figure 5: The velocity profile optimized by a screen inside of the diffuser.

3. RESULTS

Both catalytic converters were stabilized on an engine test bench and then the tests proceeded. The catalytic converters were identified as CC 01 (with a screen) and CC 02 (without a screen). The work steps proceeded: Light-off test (is defined as temperature at which the conversion of a specific exhaust gas component reaches 50%); sweep test (test by mean gas analyzer); ageing (partial deactivantion on the catalytic surface when submitted at temperatures higher than 900°C); sweep test aged and light-off aged. All these experiments were made a test bench using a gas analyzer system and a gasoline engine 2.0 litres (VW), just as gas generator and heat. Soon after, the both catalytic converters were installed in two different vehicles and proceeded other experiments as USA test cycle - FTP 75 (Federal Test Procedure). Basically, the FTP 75 consists of three phases that represent conditions measured on the streets of Los Angles in morning commuter traffic. Figure 6 shows the test results where the light-off temperatures with both pieces stabilized can be seen. The gases HC (hidrocarbons), CO (carbon monoxide) and NO_X were analyzed during the emission tests.

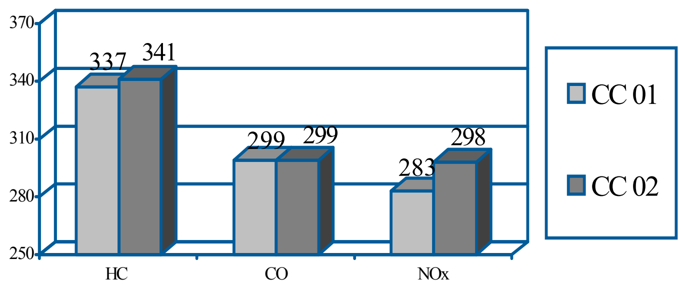

Figure 6: Light-off (ºC) with both catalytic converters stabilized, considering emissions of HC, CO and NO_x.

In these tests, the catalytic converter with a screen inside of the diffuser (CC 01) showed a gain in light-off performance of HC (4°C) and NO_x (15°C).

The sweep tests were done with the honeycombs average temperatures of 350°C and 450°C, respectively. The HC catalytic efficiency increased during these experiments, but the other gases did not show significant variations. Figure 7 shows the HC catalytic efficiency with lambda (λ) variations around 0,99 and 1,01. Figures 8 and 9 show CO and NO_x catalytic efficiency, respectively.

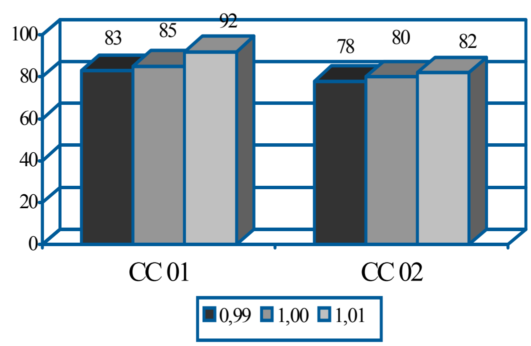

Figure 7: HC efficiency with lambda variations during sweep tests at 350°C.

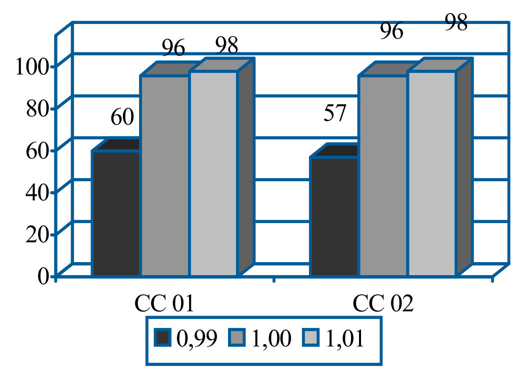

Figure 8: CO efficiency with lambda variations during sweep tests at 350°C.

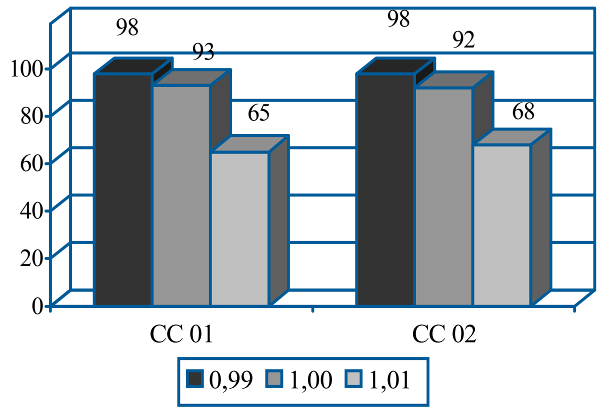

Figure 9: NO_x efficiency with lambda variations during sweep tests at 350°C.

The next step in the experiments was analyzed sweep tests at 450°C. In these cases there was an increase in the catalytic efficiency of all gases. Figure 10 shows HC catalytic efficiency with a honeycomb average temperature of 450°C. In the same conditions, Figs. 11 and 12 show the tests results of the efficiency of CO and NO_x respectively.

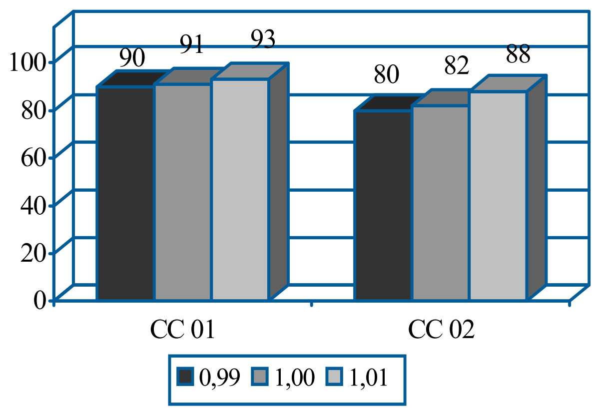

Figure 10: HC efficiency with lambda variations during sweep tests at 450°C.

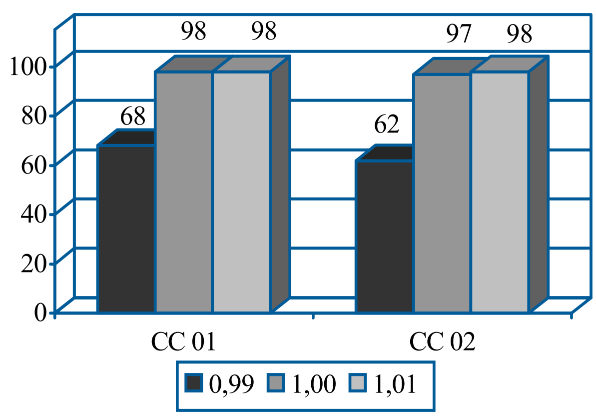

Figure 11: CO efficiency with lambda variations during sweep tests at 450°C.

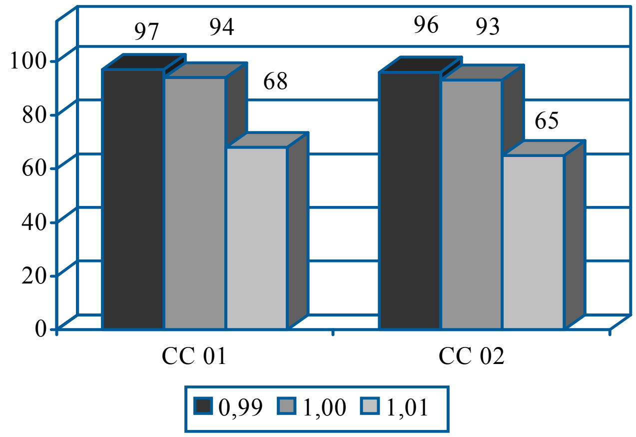

Figure 12: NO_x efficiency with lambda variations during sweep tests at 450°C.

During light-off aged the catalytic converter with a screen (CC 01) showed a significative increase in the activation temperature of the CO emission, as show in Fig. 13.

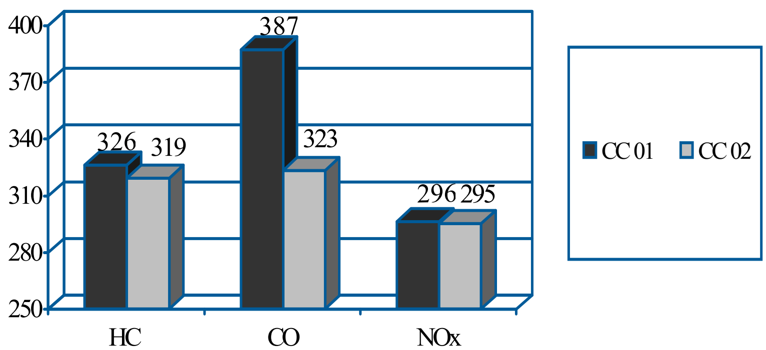

Figure 13: Results of the light-off aged (ºC).

As expected, in the sweep tests aged at 350°C happened the same behavior as that of the sweep tests 350°C showed previously. In Figures 14, 15 and 16 the catalytic converters efficiencies to HC, CO and NO_x, respectively can be seen.

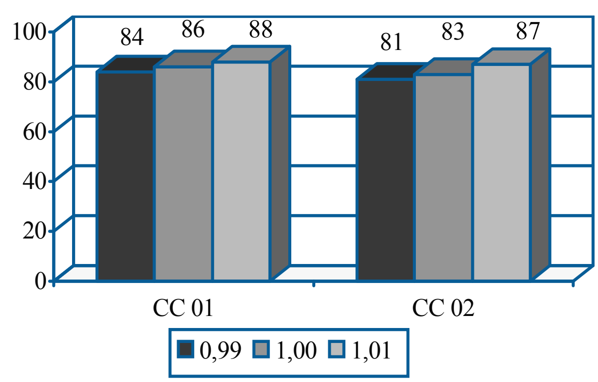

Figura 14: HC efficiency with lambda variations during sweep tests aged at 350°C.

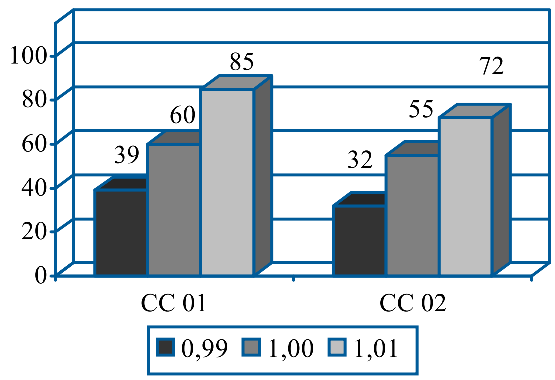

Figure 15: CO efficiency with lambda variations during sweep tests aged at 350°C.

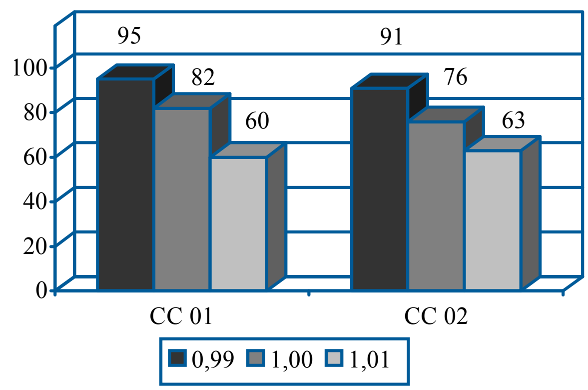

Figure 16: NO_x efficiency with lambda variations during sweep tests aged at 350°C.

In fact, the CO efficiency is the smallest when compared with HC and NO_x during the sweep tests aged at 350ºC, showing the more critical convertion at low temperatures. The same occurs during the light-off aged analyzed in the Fig. 13, where the CO activation temperature was 387ºC.

With larger temperatures the CO and NO_x efficiencies increased relatively. These behaviors are present in Figs. 17, 18 and 19 (sweep tests aged 450ºC), further confirming the beneficial effect of the screen inside of the catalytic diffuser.

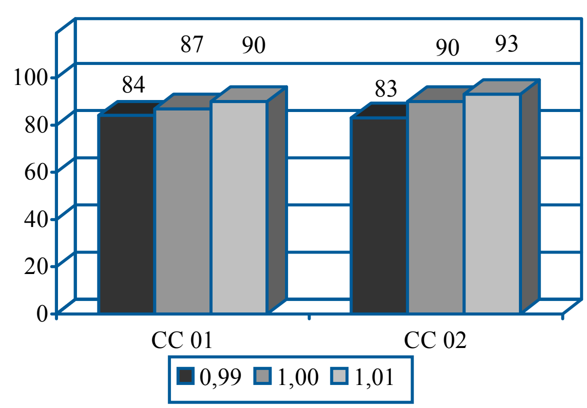

Figure 17: HC efficiency with lambda variations during sweep tests aged at 450°C.

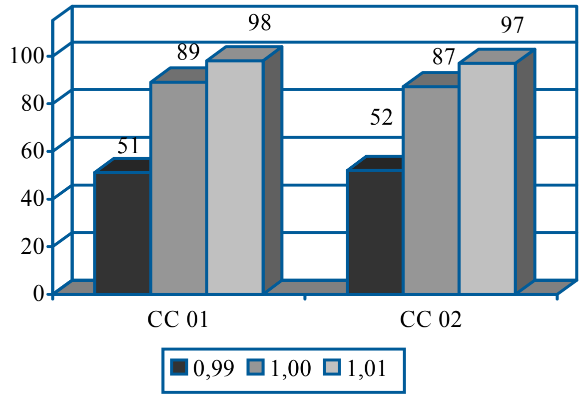

Figure 18: CO efficiency with lambda variations during sweep tests aged at 450°C.

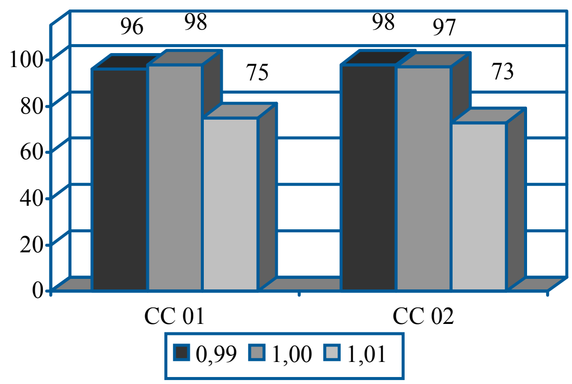

Figure 19: NO_x efficiency with lambda variations during sweep tests aged at 450°C.

After being submitted to the experiments already described, both catalytic converters were tested as cycle FTP 75 in two different vehicles on the engine test bench: Audi 1.8 turbo (gasoline+22% ethanol) and Astra GM 2.0 (gasoline+22% ethanol). Table 2 shows the results of the HC tests on the vehicles. The Audi 1.8 turbo with CC 01 showed lower emissions as compared with the Astra GM 2.0 (without turbo) with the same catalytic converter.

Table 2: Total HC bag (g/km) as three phases cycle of the FTP 75 norm.

Emission (g/km)	Audi turbo 1.8 (CC 01)	Audi turbo 1.8 (CC 02)	Astra GM 2.0 (CC 01)	Astra GM 2.0 (CC 02)
Phase 1	0,091	0,109	0,060	0,049
Phase 2	0,014	0,015	0,028	0,019
Phase 3	0,021	0,022	0,013	0,012
Total emission	0,126	0,146	0,102	0,080

The Tables 3 and 4 show the results of the CO and NO_x tests on the same vehicles as FTP 75 norm, respectively. In CO test the Audi 1.8 turbo presented significant efficiency increase with the catalytic converter CC 01, although with the Astra GM 2.0 the gain was less evident. In the NO_x test the emissions had an efficiency decrease with the use of the catalytic converter CC 01.

Table 3: CO bag (g/km) as three phases cycle of the FTP 75 norm.

Emission (g/km)	Audi turbo 1.8 (CC 01)	Audi turbo 1.8 (CC 02)	Astra GM 2.0 (CC 01)	Astra GM 2.0 (CC 02)
Phase 1	0,529	0,645	0,347	0,385
Phase 2	0,006	0,037	0,068	0,039
Phase 3	0,079	0,173	0,036	0,048
Total emission	0,615	0,855	0,452	0,471

Table 4: NO_x bag (g/km) as three phases cycle of the FTP 75 norm.

Emission (g/km)	Audi turbo 1.8 (CC 01)	Audi turbo 1.8 (CC 02)	Astra GM 2.0 (CC 01)	Astra GM 2.0 (CC 02)
Phase 1	0,052	0,058	0,099	0,081
Phase 2	0,084	0,049	0,052	0,047
Phase 3	0,052	0,060	0,076	0,069
Total emission	0,188	0,168	0,228	0,196

4. CONCLUSION AND DISCUSSION

The experiments on the flow test bench confirmed that non-uniformity of the velocity profile in the honeycomb can be improved by mean of a correctly selected screen. With this screen inside of the catalytic diffuser it showed an increase in performance of the uniformity coefficient (γ), even in extreme flow cases as analyzed in this work (Re= $78x10^3$ inside of the inlet diffuser). The screen is a cheap device, easy to install inside of the catalytic converter and it possesses an insignificant mass. The device has been registered at INPI – Brazil under the number PI0303014-8 as “Control Method of Boundary Layer Separation inside Catalytic Converters” and PCT/BR2004/161.

The chemical analysis presented and tested on a specific test bench and on vehicles showed a good performance and improvement of the results with a screen and added an improvement in the flow efficiency. It was possible to improve the efficiency with both new (stabilized) and aged catalytic converters. Some results as light-off aged showed an efficiency decrease, mainly in CO temperature. This was possibly caused by gain uniformity of the flow with the screen, although the catalytic converters were not prepared for such a condition. A partial deactivation of the catalytic area by precious metals sinterization, as studied by Taylor (1984), could have happened. It is possible that an optimization of the precious metals impregnation to a more uniform flow would improve the results and should be studied in detail in future works.

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