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OPTIMIZATION OF THE FLOW IN THE CATALYTIC CONVERTER OF INTERNAL COMBUSTION ENGINES BY MEANS OF SCREENS

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Abstract. *The flow in the automotive catalytic converter is, in general, not uniform. This significantly affects cost, service life and performance during cold start-up. The current paper reports on a device that provided a large improvement in flow uniformity, avoiding the effects mentioned. The device is to be placed in the converter inlet diffuser and is constructed out of ordinary screens. It is also cheap and easy to install.*

keywords: *catalytic converter, wide-angle diffuser, screens, boundary layer separation control, experimental fluid mechanics.*

1. Introduction

In the late sixties the legislations that control the emission of pollutants by vehicles drove the automotive industry into the use of the catalytic converter. Along the years the limits imposed became increasingly tighter and the service life required from the converter became longer. Currently the converter employs large amounts of noble metals, which renders the equipment very expensive.

The situation called for an effort aimed at improving the catalyst efficiency. However, in despite of the research devoted to this, there are aspects of the systems which can still be improved. As pointed out by various researchers (Howitt and Sekella, 1974; Wendland and Matthes, 1986), one of such aspects is the exhaust gas distribution in the catalytic converter. Perhaps the most commonly used configuration for the catalytic converter consists of a ceramic honeycomb structure wash-coated with a porous layer impregnated with the catalytic substance. A nonuniform distribution of the exhaust gases among the cells of the honeycomb brings a hole series of problems that reduce the efficiency of the system. The current work presents the results of an experimental investigation of a device that provided a significant improvement in the flow distribution of a typical catalytic converter. The device is built out of ordinary screens.

The chemical reactions within the honeycomb cells require a minimum residence time. With a nonuniform flow distribution the honeycomb length is dictated by the cells which receive fluid at higher velocity. It means that a uniform flow distribution would enable a reduction in the converter length with subsequent reduction in cost. Moreover, the cells with lower flow velocity do not fully exploit the catalytical material available. As a consequence, at the end of the converter service life, expensive substances are wasted.

The flow distribution also affects other aspects of the performance of the catalyst. The chemical reaction rates in the honeycomb are influenced by the temperature. It is only above a certain temperature that the catalyst reaches the required efficiency. This is related to the so called light-off temperature of the converter. Since the honeycomb is usually heated by the exhaust gases, a typical vehicle over the New European Driving Cycle or FTP-75 cycles produces about 60 to 80% of its emissions in the first 200s of the cold start-up phase. Associated with the flow maldistribution there is a maldistribution of temperature and they both contribute to an irregular heating of the honeycomb. In general the outer part of the honeycomb receives less gas flow and at the same time looses more heat to the environment. The combination of these effects may further reduce the catalytic efficiency during the cold start-up. Moreover the radial gradient of temperature in the honeycomb creates thermal stresses which may crack the ceramic material and reduce service life (Howitt and Sekella, 1974).

The back pressure of the engine may also be affected by flow in the converter. The catalytic converter represents a large proportion of the head loss in the exhaust system. Within the catalyst the head loss is related to the cells with higher flow velocity, which have already been lengthen due to flow maldistribution. The larger head loss imposes a higher back pressure and hence a reduction in the engine efficiency.

The reason for the flow maldistribution in the converter is related to the design of the device. In order to coupe with both severe space restrictions in the vehicle and the required residence time, often the honeycomb has a larger diameter than the exhaust ducts. Connection between the duct and the honeycomb is made via an inlet diffuser, figure 1. The diffuser angle is so wide that the high pressure recovered associated promotes the separation of the boundary layer that develops on the diffuser wall. As a consequence, the resulting flow is not evenly distributed over the frontal area of the honeycomb, but concentrates along the central part of the honeycomb, figure 2. Downstream of the honeycomb there is also an outlet nozzle but this does not affect the flow in the converter (Karvounis and Assanis, 1993; Lemme and Gives, 1974).

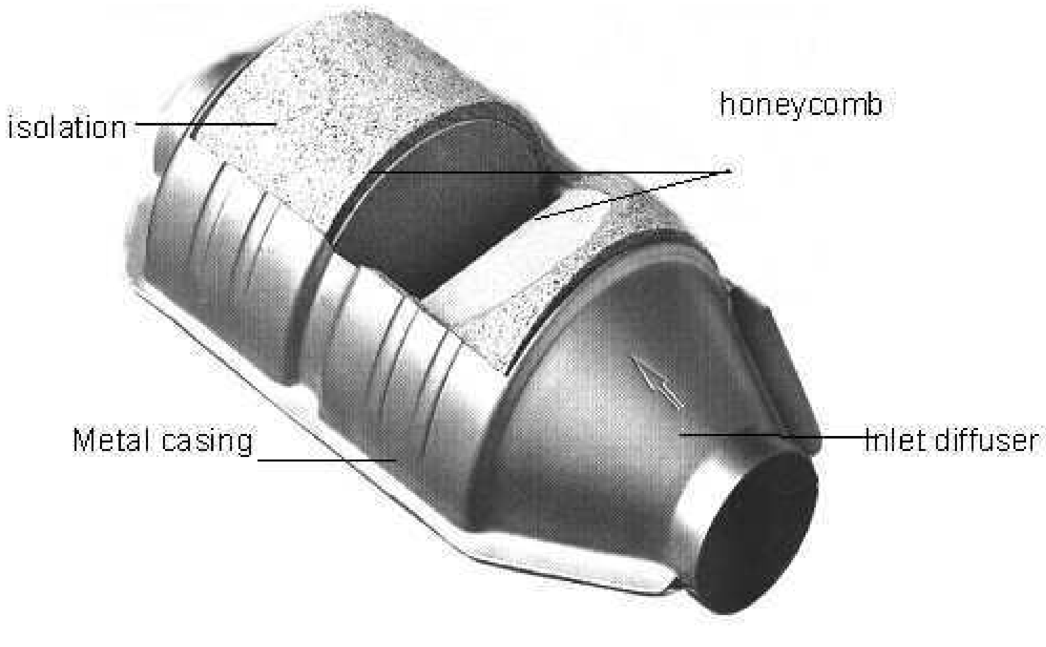

Figure 1: Scheme of a catalytic converter.

Boundary layer separation is an important aerodynamic phenomenon. It affects airplane performance and is dealt with in very many different ways in aeronautical research and development. One specific example where this phenomenon must be properly controlled is in the design of wind tunnels. These tunnels are experimental facilities consisting essentially of a duct where air is driven through in a controllable fashion. In this controlled air flow, airplane models can be tested under condition that simulated flight. In these tunnels, the existence of wide angle diffusers is common place but, in spite of that, a uniform flow must be produced as it is necessary for the usefulness of the experiment. In view of these, a hole series of techniques has been developed to inhibit boundary layer separation. From the various methods studied one, which involves the use of screens, has become the standard technique in the design of wide angle diffusers for wind tunnels.

Some os these methods, such as the use of vanes and splitter plates, are quite obvious and have already been tested in catalytic converters (Bella et al., 1991). However, often they are very complicated to install and not very efficient. In the context of the catalytic converter there are yet other undesirable effects, as for example, the large amount of heat that they extract from the exhaust gases during the cold start up and the large back pressure that they produce (Howitt and Sekella, 1974; Day and Socha Jr., 1991).

The current work presents the results of an experimental investigation into the use of screens to enhance flow uniformity in the catalytic converter. To the knowledge of the authors, this has not yet been carried out.

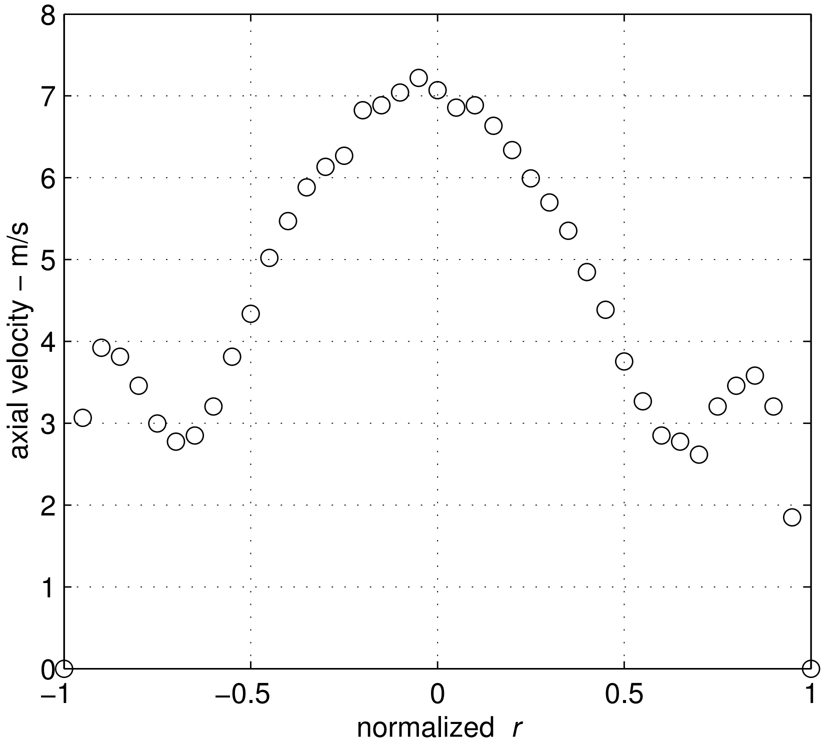

Figure 2: Typical axial velocity distribution in a catalytic converter.

Although, from the start of the work there was a great confidence that the method would work also in the current application, there were a few differences with respect to wind tunnel applications that could have an affect in the performance of the system. These differences were mainly the size of the duct and the fact that in the catalytic converter there is a honeycomb downstream of the diffuser. In view of this, a device was designed and tested. The results confirmed the expectations and are presented here in some detail. The analysis also included screen configurations that were simpler than those that led to optimum performance, but that could be more cost-effective.

2. Metodology

2.1. The tested converter

The severe restrictions on pollutant emissions sometimes call for the use of more than one catalytic converter. One is located close to the engine and another is placed under the car body. The main converter is usually the under-body one. The other, the closed-coupled converter, is particularly useful in the cold start-up as it receives hotter exhaust gases and is smaller, which both contribute to a faster warm-up. The current investigation is focused on the under-body catalytic converter, but it is expected that, under most circumstances, the results would also be useful for closed-coupled converter.

The under-body converter is the one usually associated to an upstream diffuser. As a rule, the included angle of these diffusers is above 40^o and can reach values of 90^o or more. The included angle is that between the opposite walls of the diffuser and is commonly represented by 2θ. Apart from the included angle, the flow uniformity is also affected by the diffuser area ratio (A), which is the exit area divided by the inlet area. In catalyst diffusers these can reach values beyond 4. Depending on the diffuser area ratio, an included angle above 5^o may already produce boundary layer separation. For $2\theta > 10^o$ and $A > 2.5$, boundary layer separation can be prevented only by the use of some means of separation control. These diffusers are normally referred to as wide-angle diffusers. In conical wide-angle diffusers the boundary layer separation yields the formation of toroidal vortices in the diffuser, which renders the flow very unsteady, and reduces the effective flow area. Under extreme conditions, the flow may behave like a jet, virtually ignoring the diffuser wall. Clearly the diffusers used in catalytic converters are of the wide-angle type.

The catalytic converter used in the current study had an included angle of 47^o and an area ratio of 4. It is by no means among the widest angle diffusers used by automotive industry in catalysts, but, already, works under the extreme conditions mentioned above. The honeycomb dimensions corresponded to those utilized in ordinary 1000cm^3 engines produced by the Brazilian automotive industry. The honeycomb cell was 1x1mm. Sometimes catalytic converters have an elliptical cross section, an curved inlet pipe and a not fully developed inflow. These aspects affect the flow in the converter. However, in order to reduce the number of parameters involved, none of them were here analyzed. The tests used a cylindrical converter, connected to a straight pipe so long that the flow could be considered a fully developed turbulent pipe flow at the diffuser entrance. Nevertheless, it is expected that the optimizing device to be described here can be adjusted to coupe with these perhaps more severe conditions.

2.2. Experimental aparatus

Despite the fact that the flow in the exhaust system of vehicles, owing to the valve motion, is pulsating, most studies of catalytic converter have considered steady flow. This is partially because it is more difficult to conduct either experiments or computations for pulsating flows, but, for the under-body converter, this is, in general, regarded as an acceptable simplifying assumption Bressler et al., 1996; Zhao, 1997; Jeong and Kim, 2001. In view of these, the current work also investigated only steady flow.

The experiments did not use the actual exhaust gases from the engine, but, instead, air at room temperature was employed. This had many obvious advantages, and is appropriate as long as dynamic similarity is maintained. The velocity in the exhaust system are relatively high, but the flow can be regarded as incompressible, in particular, in view that the temperatures involved are high which increases the speed of sound. Dynamic similarity is warranted if $Re_g = Re_a$. Re is the Reynolds number defined as $Re = \frac{UD}{\nu}$ where U is the flow speed, D is the pipe diameter and ν is the kinetic viscosity. The index g and a stand for gas and air, respectively. For a 1:1 scale, dynamic similarity yields

$$Q_a = Q_g \frac{\nu_a}{\nu_g}. \tag{1}$$

Applying this relation to the current experiment resulted that the test volume flow was about 5 times lower than the actual exhaust flow. The rotational speed range of 2000 to 5000 rpm for a 1000cm^3 engine corresponded to test volume flows in the range of about 0.007 to 0.02 m^3/s. These flow rates could be easily supplied by a domestic vacuum cleaner that was available in the laboratory and that was modified to blow air. The system, with the converter in place, provided a maximum volume flow of almost 0.025 m^3/s.

A gate valve was fixed to the vacuum cleaner and connected, via a flexible rose, to a 3000mm long PVC pipe. In order to promote flow uniformity in the pipe a screen was placed in the connection between the rose and the pipe. A metal rod was attached to the pipe to prevent bending. The pipe internal diameter, 45mm, was chosen to match the inlet of the converter diffuser. The converter was connected to the exit of the pipe. The downstream nozzle of the converter was removed, but the honeycomb was maintained in place. The measurements of the velocity profiles were carried out at the exit section of the honeycomb. Flow temperature was measured with a thermo-par placed close to the pipe entrance.

The streamwise velocity profiles were measured with a Pitot-tube connected to an inclined manometer. This provided an accuracy of ±0.25Pa. The Pitot-tube was positioned using a manual traverse system with an estimated accuracy of 0.5mm. The volume flow was adjusted using the gate valve and was measured with a calibrated pitot-static tube placed inside the pipe at 270mm from the pipe outlet. The pitot-static was connected to a digital manometer. Care was taken that the pitot-static tube did not affect the velocity profiles in the diffuser inlet. Prior to the tests, the dynamic pressure measured at the centerline of the pipe was calibrated against volume flow measurements made by integration of the velocity profiles measured at the pipe exit. An almost perfect quadratic relation between the dynamic pressure and the volume flow was obtained, figure 3. The apparatus could adjust and maintain a volume flow rate accurate to within 2% for the higher flow rates but decreased to about 10% at lowest flow rate studied.

2.3. The screens

Screens are often recognized as a means of controlling turbulence level in wind tunnels. It is less often associated with boundary layer control. However, study of separation control by screens in wide-angle diffusers started quite long ago, at least since the work of Schubauer and Spangenberg, 1948. A comprehensive review of this study was carried out by Mehta, 1977.

The idea underlying the control of boundary layer separation by the use of screens is to match the screen head loss to the diffuser pressure recover, and so keep the pressure gradient small in the the diffuser. The loss due to the screen is given by

$$\Delta p = K \frac{\rho u^2}{2}, \tag{2}$$

where K is mainly a function of the screen open-area ratio, but is also affected by Reynolds number. The

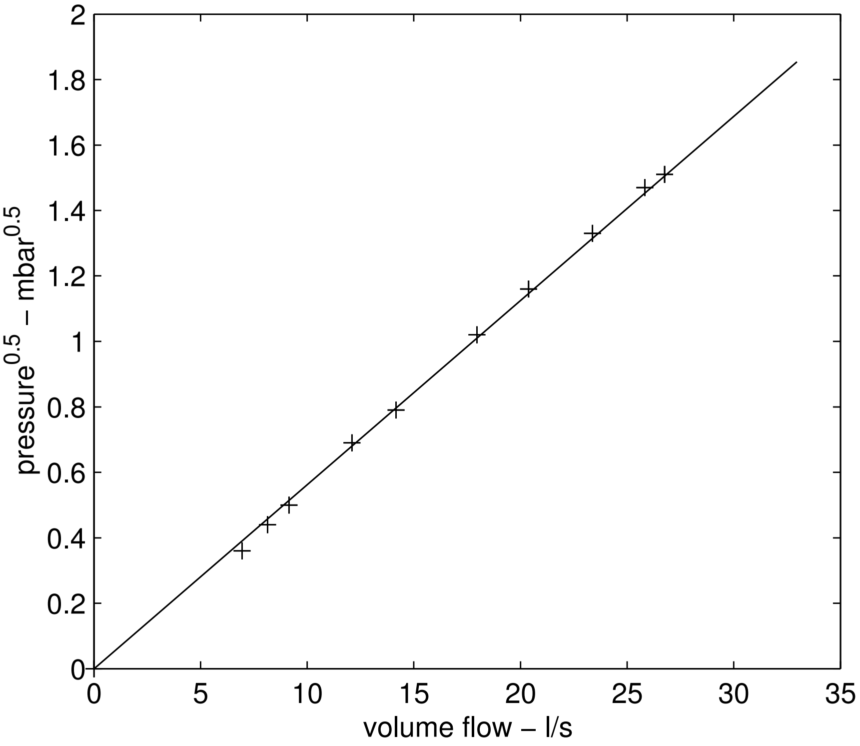

Figure 3: Calibration of Pitot-static readings versus volume flow.

open-area ratio is given by

$$\beta = (1 - \frac{d}{l})^2, \tag{3}$$

where d is the wire diameter and l is the screen mesh length. The open-area ratio is the complement of the solidity.

Mehta, 1977 suggests the use of the following formulae for K:

$$K = 6.5 \frac{1-\beta}{\beta^{5/3}} \frac{(Ud}{nu)}^{1/3} \quad \text{for } U < 10 \text{ m/s}, \tag{4}$$

where ν is the kinematic viscosity, and

$$K = C \frac{1-\beta}{\beta^2} \quad \text{for } U > 10 \text{ m/s}. \tag{5}$$

Note that the factor $\frac{Ud}{\nu}$ is a Reynolds number based on the screen wire diameter. When using more than one screen, the effective K is the sum of the K for each screen.

Mehta, 1977 compiled the data from wide angle diffusers used in wind tunnels throughout the world and, based on these results, prepared graphics that enable one to select the screens for a given diffuser geometry. He was able to fit a straight line:

$$\sum K = \frac{A-1}{1.14}, \tag{6}$$

given, as a function of diffuser area ratio, the minimum $\sum K$ for preventing flow separation. In the current work the values of $\sum K$ used were not much above that given by 6. That is because too large a value of $\sum K$ can lead to a divergence of the flow, that is, higher flow speed close to the diffuser wall, and low speed along the center. Since the objective was an uniform flow, it was thought that too large values of $\sum K$ should be avoided.

Mehta, 1977 also gives guidelines for the number of screens to be used in the diffuser. These are summarized in figure 6 of his paper. The number of screens depends on both diffuser area ratio and angle. Based on graphics produced by Mehta, 1977 the diffuser under investigation here would require 2 or 3 screens. The position of the screens is also of concern. For straight-walled diffusers, like the current one, the best screen positioning is where the diffuser wall changes angle, that is, at inlet and outlet. However, this is not essential for good performance. Owing to manufacturing difficulties, in the current study the screen closest to the inlet was placed at about

5cm from the inlet. This and the other three screen positions where separated from each other by about 10cm. They were named P05, P15, P25 and P35 and span the total length of the diffuser. Improved performance can also be gained by using curved screens (Mehta, 1977), but because they are more difficult to built and install, such screens where not considered in the current investigation.

A selection of 4 different flat screens was used in the investigation. According to equations 4 and 5, in the velocity range where the experiments had to be performed, the parameter K was not constant, except for the highest speeds which were above 10m/s. Below 10m/s K decreases with Reynolds number. Moreover, both the literature and the results given here show that the nonuniformity increases with Reynolds number. As consequence, the most demanding situation both in terms of flow uniformity and K parameter corresponds to the highest Reynolds number flow condition. Therefore the selection of the screens were based on this case.

Table 1 gives the characteristics of the screens used. According to equation 6, $\sum K$ needed for the diffuser here studied is 2.63. This is not achievable with one single screen from the selection given, which is consistent with the need of 2 or 3 screens, as discussed above.

Table 1: Characteristics of the screens tested

Screen BWG	Wire diameter - mm	Screen mesh length - mm	Open area ratio - β	K at above 10 m/s
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
30/32	0.23	0.61	0.53	1.59

2.4. Preliminary tests and experimental procedures

Prior to the tests it was deemed necessary to verify flow quality. This was carried out by removing the converter and taking measurements of the streamwise velocity profiles at the pipe exit for flow rates in the range of those to be used in the experiment. These were compared with the seventh-root law:

$$\frac{u}{u_{max}} = \left(\frac{y}{R}\right)^{\frac{1}{7}} \tag{7}$$

where R is the pipe radius and y is the distance from the wall. It is seen that the agreement is good (figure 4).

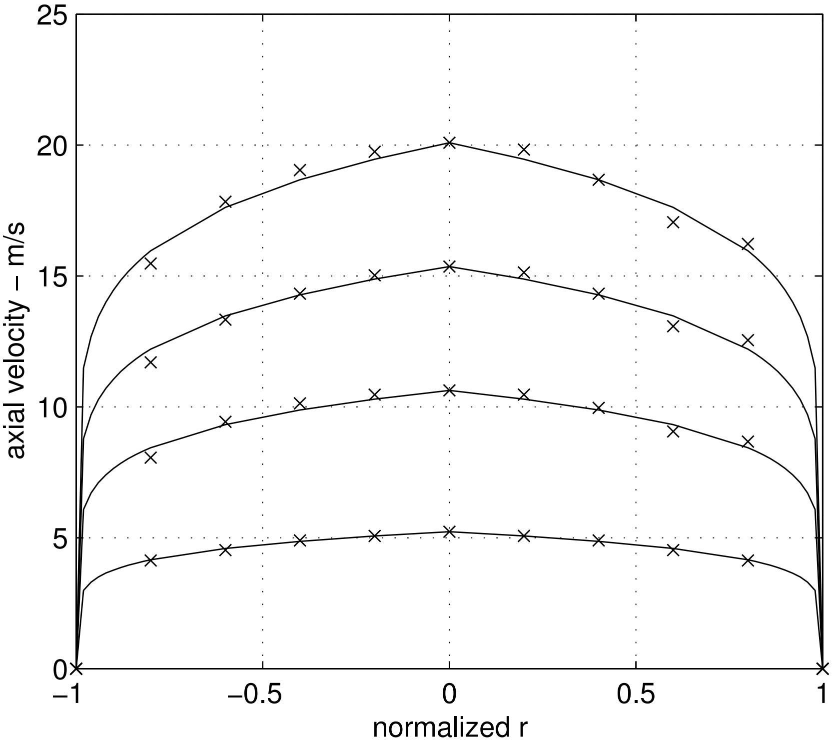

Figure 4: Velocity profiles at the diffuser entrance for various flow rates.

Preliminary tests where then performed with the converter in place. It was found that very close to the honeycomb exit, at about 10mm from it, the velocity profiles were not smooth. At 30mm they looked much better. The problem was attributed to a nonuniformity of the flow associated with the exit of the individual cells of the honeycomb, but this was not investigated any further. The velocity profiles were then obtained at 30mm from the honeycomb.

The repeatability of the experiment was also investigated. It was found that it could be reproduced to within the experimental uncertainty. A little asymmetry was noticed in the profile, which could be traced to misalignment of the diffuser and the honeycomb. Rotating the converter reduced the problem. Finally a two dimensional velocity profile on a plane perpendicular to the flow was taken which showed that the flow was reasonably axi-symmetric. This allowed that the analysis could be carried out using velocity profiles along one diameter of the honeycomb.

These tests also revealed that the temperature was almost constant from test to test. Therefore, dynamic similarity among tests with different screen arrangements could be warranted by ensuring a constant flow rate.

3. Results

Initially the velocity profile at the honeycomb exit was measured without the use of screens for a number of flow rates, figure 5. The flow rates were 7.6, 12.8 14.3 and 17.5, which roughly corresponded to engine operation at 2000, 3000, 4000 and 5000 rpm. The maximum flow rate that the experimental rig could provide, namely, 25 l/s, was also tested. Hereinafter the flow rates used are referred to by using the engine rotation, with the maximum flow rate case being called >5000rpm. As expected the flow was very nonuniform, in particular at higher velocities. The maximum speed occurred at the center, but local maxima were also found at the edges. Apparently, these local maxima have not been reported previously. Their origin was not deeply investigated here, but the result was very repeatable and there was a pattern linking the various curves. It is believed that they are not a result of experimental error. In any case, as is shown bellow, the screens were also able to reduce these maxima.

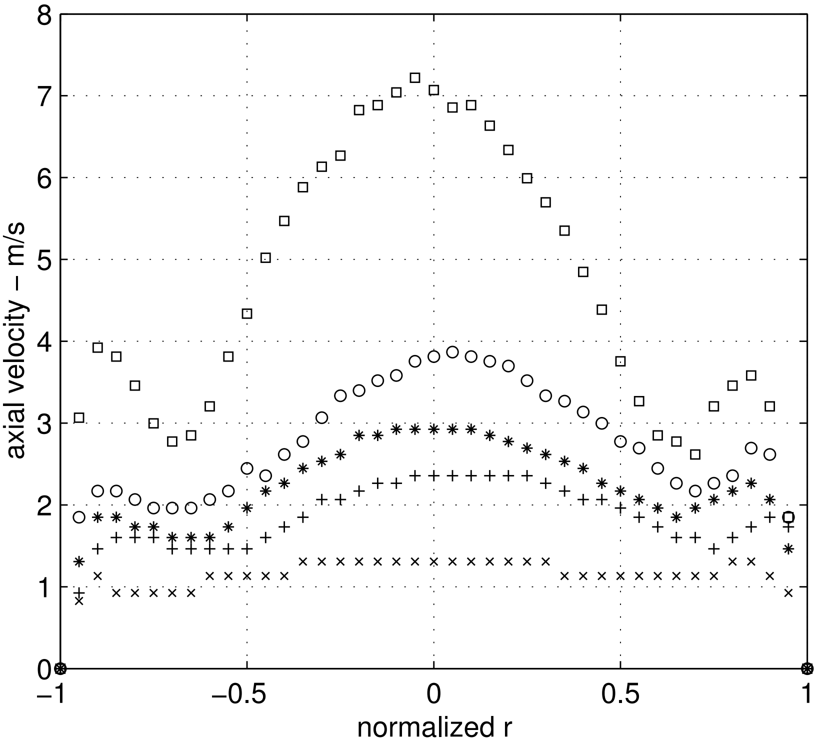

Figure 5: Velocity profiles at the honeycomb exit for various flow rates without the use of screens.

As proposed by Bressler et al., 1996, the standard deviation of the velocity along the profile provides a measured of flow uniformity. A coefficient was defined as

$$\gamma = 1 - \frac{1}{n} \sum_{i=1}^{n} \frac{\sqrt{(u_i - \bar{u})^2}}{\bar{u}}, \tag{8}$$

where $\bar{u}$ is the velocity averaged over the profile. $\gamma = 1$ indicates a uniform profile, and lower values indicate less uniformity. The values of γ for the rotational speeds from 2000rpm to >5000rpm were, respectively, 0.84, 0.78, 0.76, 0.74 and 0.66.

The guidelines given by Mehta, 1977 suggested the use of 2 or 3 screens, but, from a manufacturer point of view, it may be very important to check what can be achieved with a single screen. Therefore this analysis was also carried out. Figure 6 gives the results obtained with the use of screen 26/30 at position P05. The values of K stayed in the range 2.1 to 2.6, depending on flow speed. In general, these were below the value of 2.6 predicted by equation 6. For speeds from 2000rpr to >5000rpm, γ was found to be, respectively, 0.86, 0.90, 0.88, 0.864 and 0.84. Comparison of figures 5 and 6, and the values of γ, reveals a significant improvement in flow uniformity.

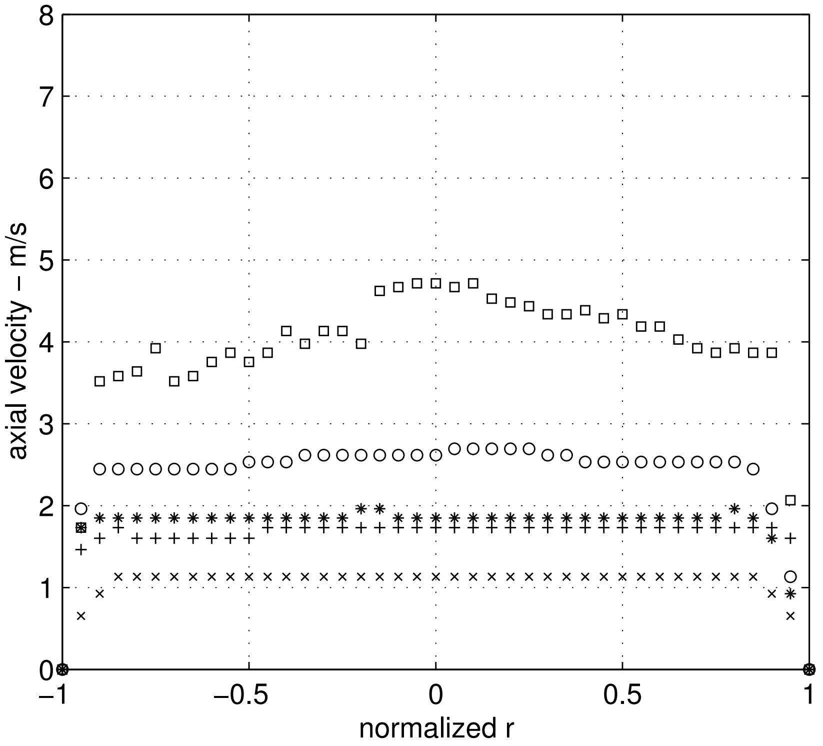

Figure 6: Velocity profiles at the honeycomb exit for various flow rates with the use of one screen in the inlet diffuser.

Another aspect that might be of interest to manufacturers is the sensitivity of the results to the position of the screen. That is shown in figure 7 for 5000rpm. For comparison, the case without the screen is also shown. For positions closer to the inlet of the diffuser, the flow quality was not sensitive to position. This was confirmed by the values of γ, which were very close to each other, namely, 0.864 and 0.866, respectively. The uniformity degraded for screens closer to the diffuser exit, giving $\gamma = 0.856$ and 0.844.

To achieve $\sum K$ above 2.6 at least two screen were needed. Tests were then carried out with screen 30/32 at position P05 and screen 18/32 at position P15, except for the case when the speed was higher than 5000rpm, which used two screens of the type 28/32. This yielded $\sum K$ in the range 2.4 to 3.2 for rpm from 2000 to >5000. Results are shown in figure 8. For speeds 2000 to >5000 rpm, γ was, respectively, 0.882, 0.884, 0.878, 0.870 and 0.86. In comparison with the use of a single screen, a little improvement was obtained, in particular for the higher rpm. However, it might not justify the extra cost of installing a second screen. The use of three screens was also tested but no measurable improvement was obtained.

4. Conclusion and discussion

The experimental results confirmed previous works in that the flow in the catalytic converter is very nonuniform, in particular for higher flow speeds. The expectation that the use of screens would improve the uniformity of the flow in the catalytic converter was also confirmed by the experiments. The improvement was seen not only from the velocity profiles shown, but also from the coefficient γ, which is a measure of flow uniformity. In extreme cases, the uniformity measured by this coefficient increased by 30%.

The results suggested that the use of one single screen may be enough for most applications, but in extreme conditions the use of more screens may provide further improvement. The results also indicated that flow quality is not very sensitive to the position of the screen, as long as it stays in the first portion of the diffusers. The

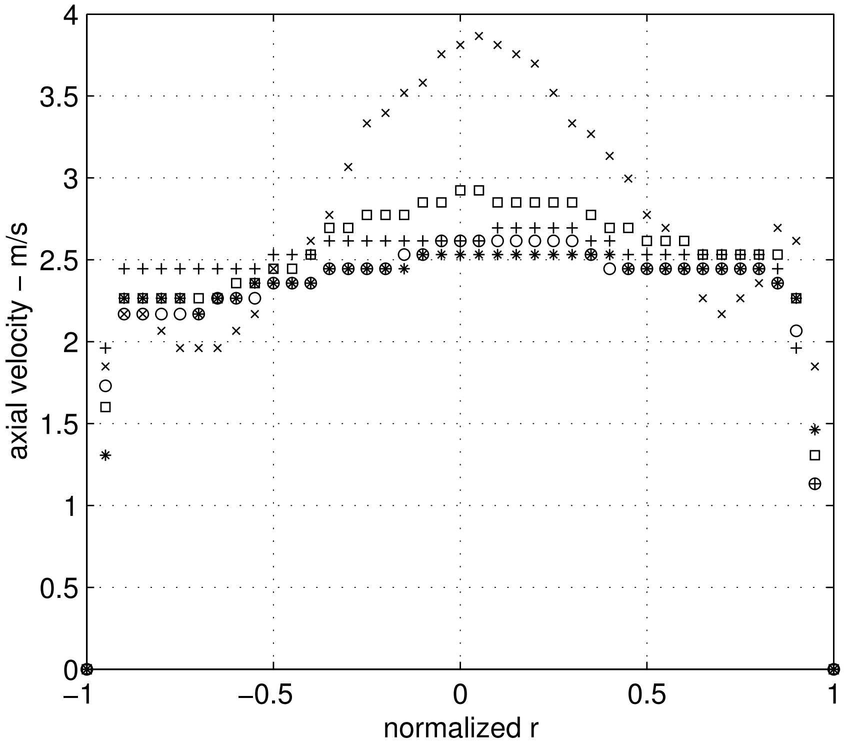

Figure 7: Velocity profiles at the honeycomb exit for a screen at different position in the inlet diffuser. The square corresponds to the at position P35; the circle, P25; the asterisk, P15; the cross, P05 and the times, no screens.

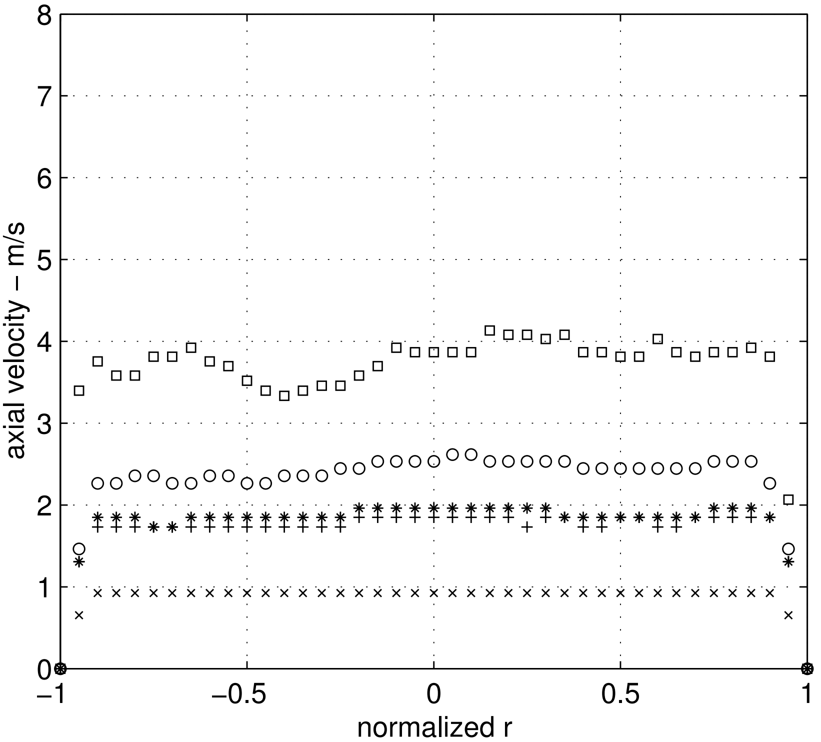

Figure 8: Velocity profiles at the honeycomb exit for various flow rates with the use of two screens in the inlet diffuser.

device is then both cheap and easy to install.

The investigation also included analysis of the engine back pressure provided by the converter. These results were not addressed in the current paper. However, it can be anticipated that the use of screen did not increase the back pressure significantly. In particular, with the use of 2 screens no measurable difference was found from the case without screens.

The device has been registered at INPI - Brazil under the number PI0303014-8.

5. Acknowledgements

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