Advanced Catalysts Substrates and
Advanced Converter Packaging

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PREFACE

A renewed cultural interest in environmental awareness and more stringent global legislation have required vehicle manufacturers to strive towards continually lower tailpipe emission standards. Technological improvements in each area of the drivetrain system along with computerized powertrain control and on-board diagnostics/monitoring have produced a new breed of cleaner, safer, more efficient, more powerful, and lastly more durable vehicles. These drivetrain and total system considerations aside, unquestionably one component (the catalytic converter) has become the major device that allows the free ranging-internal combustion automobile to meet past, current, and future tailpipe emission standards. Each catalyst that is installed on a vehicle creates a net positive effect for our atmosphere and the air quality level of millions of metropolitan families in symbiosis with millions of vehicles. This SAE Special Publication, Advanced Catalysts Substrates and Advanced Converter Packaging (SP-1532), distills some of the systemic advances in catalyst and substrate design, technology, materials, construction, modeling, and testing which make the modern catalytic converter a feasible device in a harsh environment.

The emphasis on emission control has shifted from individual component design to an integrated system design approach in which the aspects of heat management, the management of thermo-mechanical forces and the feedback control are combined with the advanced catalyst formulations and the advanced substrates to maximize performance. These new systems designs also enable the global automotive industry to realistically achieve such low emission levels. Environmental and social responsibility for pollution control has incremented the material fixed cost and labor variable cost of the finished vehicles, but there is a large unmeasurable payback for this investment – sharing and passing down a well maintained renewable resource for our future generations – clean air!

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TABLE OF CONTENTS

2000-01-0215

Heat Insulation Methods for Manifold Mounted Converters

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ABSTRACT

The introduction of the catalytic converter into the engine compartment has led to severe requirements for thermal insulation. The converter and the exhaust manifold constitute significant heat sources that increase the underhood air temperature and the direct radiation to surrounding components with limited heat tolerance.

In the present study, various methods of converter thermal insulation are investigated, and recommendations for minimizing heat transfer are presented. The basic heat transfer mechanisms from the converter are first reviewed to provide a basis for understanding the most effective means of insulation. Ceramic fiber insulation with various thermal conductivities are evaluated at several different thicknesses. This type of internal insulation, which is often used for catalytic converters, is compared to heat shielding. It is found more effective.

Experiment and/or simulation have been used to evaluate the various insulation methods. Simple one-dimensional heat transfer models have been used to support the experimental approach. These simple models have been found to be a very powerful tool for product design because they provide a means to quickly evaluate several competing scenarios.

INTRODUCTION

The introduction of the catalytic converter into the engine compartment became a necessity in order to meet the very low Euro 4 emissions limits that will be imposed for any certification in Europe by 2005.

The first step in improving emission performance was to move a fraction of the total required catalyst volume into the engine compartment to take better advantage of the hot exhaust gases for early catalyst light off. These so-called warm up systems were already efficient enough to avoid the usage of more complex external supplemental heat systems.

The next step consists of installing the total catalyst volume in the engine compartment and welding it directly to the manifold [1, 2] (Figure 1). This solution offers the best efficiency/cost compromise compared to other passive systems or to active systems like secondary air injection, or electrically heated converters [3]. However, this concept presents several challenges.

Figure 1: Manifold mounted converter

The catalyst must be able to tolerate continuous bed temperature of 950 °C or higher. The recently developed washcoats using Pd only or Pd/Rh demonstrate this ability even after severe aging [4, 5]. Figure 2 shows the emissions of a manifold mounted converter after dynamometer aging equivalent to 80 000 km on a vehicle. The washcoat stability insures that the tailpipe emissions stay well below the legal limits.

The available space in the engine compartment of modern vehicle has been reduced because of the increasing amount of equipment installed on today's cars, the more space required for the passenger compartment for its comfort in detriment of the engine and because of shape changes in the hood area for improved aerodynamics. The space available to install a close coupled converter is very limited. Furthermore, the catalytic converter, with a skin temperature of 400ºC or higher, will be surrounded by components that require skin temperatures lower than 150 °C, such as plastics, coolant hoses etc.

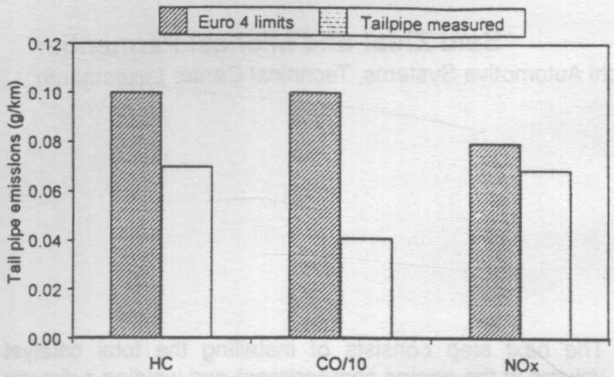


Figure2: Typical manifold converter tailpipe emissions.

It is therefore very important to pay special attention to thermal management and to look for insulation methods that can reduce the amount of heat transferred from the converter as much as possible while taking up as little space as possible.

Even when located under the vehicle, the catalytic converter is treated carefully from the thermal management standpoint because of the exothermic reactions that take place during all engine-operating modes. Under conditions of misfire, a large amount of energy is released by the oxidation of the unburned fuel. The temperatures will then exceed the ceramic melting point. Another common requirement is the grass ignition temperature limit. A converter should not have a skin temperature exceeding the level that auto-ignites dry grass.

In order to define the most efficient insulation method, the heat transfer modes need to be analyzed. In the past, catalytic converters have been insulated internally by the mat surrounding the ceramic substrate but also by adding an external heat shield. The insulation mat is a mixture of ceramic fiber and vermiculite, which expands at high temperature and mechanically holds the catalyst to compensate for the difference in expansion between the ceramic substrate and the metallic can. Later, the internal insulation alone was found to be sufficient. This allowed removal of the heat shield, which was often a source of audible noise.

In the present study internal and external insulation methods will be compared, their relative advantages or disadvantages will be highlighted. Using a validated numerical model, a detailed analysis of the heat transfer modes will be presented and their relative importance will be discussed.

RELEVANT HEAT TRANSFER MECHANISMS

The various components surrounding the manifold converter are subjected to heat transfer from the converter shell directly by radiation and indirectly through the ambient air that is heated up to temperature levels as high as 100°C.

The free convection heat transfer can be reduced by having a lower skin temperature. The heat transfer by radiation will depend on the skin temperature but also on the emissivities of the materials involved. The impact of these parameters will be discussed in more detail later.

The external shell might be heated by:

- Convection and radial conduction from the catalyst brick which is kept at a temperature between 900 and 1000°C by the engine exhaust gas flow and by the exothermic chemical reactions occurring in the catalyst. The exhaust gases transfer heat to the walls of the catalyst channels by laminar convection and by radial conduction through the substrate material. Between the center of the brick and the periphery, a temperature gradient up to 100°C is observed. If the converter shell is in direct contact with the substrate without any insulation, the surface temperatures can be as high as 850 to 950°C.

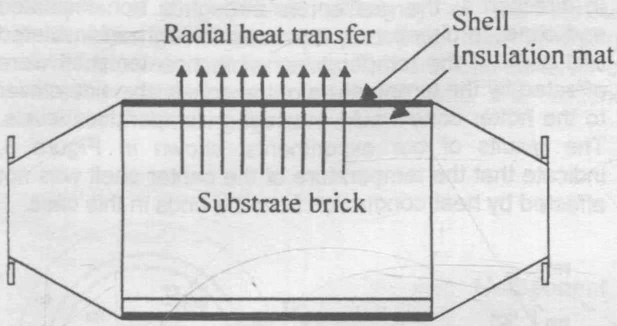
- Axial heat conduction from the exhaust manifold and from the converter outlet cone to the outer shell. The exhaust manifold, usually heat shielded, will be at 750 – 800 ºC and the outlet cone at 450 – 500 ºC while the converter shell will be kept at 350 – 400 ºC. If these sources are important enough, they can significantly reduce the insulating effect achieved by adding layers of mat. The decrease in radial heat transfer from adding mat may be overshadowed by heat conduction from the two ends of the converter. In such a case adding more insulation may not result in any reduction of temperature on the converter shell.

To be able to efficiently design heat insulation for the catalytic converter, it is important to evaluate the relative importance of the above mentioned modes.

RADIAL HEAT TRANSFER

As discussed previously, the exhaust gas out of the engine combined with the exotherm from the chemical reactions will heat the substrate. The substrate outer circumference temperature will be determined by the spatial distribution of the temperature and flow at the substrate front face, and also by the radial heat conduction from the center of the brick. The converter shell will be heated by conduction through the insulation.

To evaluate the amount of heat lost by the shell to the surroundings, a 100 in3 ceramic round converter, insulated with 4mm of ceramic fiber is considered.



A simple numerical model of the heat transfer was built and validated with experimental measurements. The heat balance, assuming one dimensional heat transfer by convection from the gas to the surface of the brick, by conduction through the mat and by natural convection and radiation from the outer converter shell, can be expressed as follows:

$$Nu_{gas} \frac{\lambda_{gas}}{D_{ch}} A_b (T_{gas} - T_b) = \frac{2\,\lambda_{mat}}{L_n(R_b/R_s)} (T_b - T_s)$$

$$= f_s(Gr, Pr)\, A_s\, (T_s - T_{amb}) + \sigma\, \varepsilon\, A_s\, (T_s^4 - T_{env}^4)$$

Where Nu_{gas} is the Nusselt number of the laminar flow in the substrate channels, F_s is the free convection heat transfer from the shell to the ambient air. For f_s a general heat transfer correlation for a vertical tube is used [6]. The other variables and parameters are defined in the nomenclature section. The radial temperature gradient in the converter metallic shell is neglegted due to its high thermal conductivity.

From these heat balances, given T_{gas}, T_{amb}, T_{env}, geometric characteristics and the temperature dependant air and insulation mat properties , it is possible to compute the brick temperature, T_b, and the shell temperature T_s.

T_{gas} is assumed to be the gas temperature at the periphery of the substrate. This is a difficult parameter to obtain since it is linked to the exhaust flow and temperature distribution, which requires a 3D model to be obtained. In the present study, the temperature is assumed to be 100 °C less than the bed temperature in the center.

To validate this very simple model, a catalytic converter was installed on an engine dyno and the skin temperatures where measured and compared to the ones computed for similar conditions. The agreement is quite good as shown in Figure 3 for various insulation thicknesses and bed temperatures. However, the prediction quality depends on the exhaust gas temperature used. Since the model will be used mainly for sensitivity studies, it is only important to capture the basic phenomena that are taking place. The one dimensional assumption also limits the model accuracy if the axial heat conduction from the exhaust manifold and from the outlet cone is significant. The following section will discuss this issue and we will show that this heat transfer mode is not significant and the one dimensional approximation is valid.

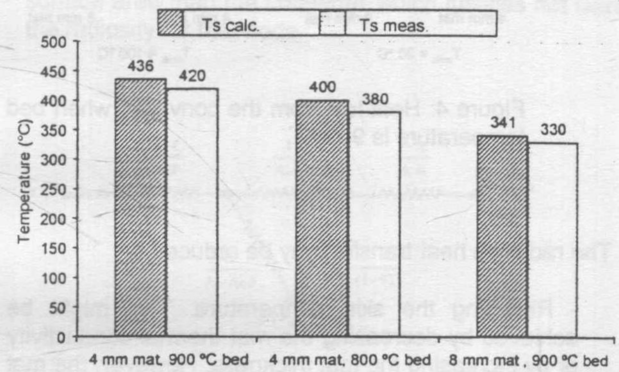


Figure 3: Model validation

The computed heat fluxes from the outer shell of the converter are given by figure 4 for two mat thicknesses and for two ambient temperatures. In all cases, the radiated heat represents 70 to 80 % of the total heat lost. The contribution of free convection is further reduced for high ambient temperatures. Forced convection will help to remove more heat and to reduce the skin temperature and consequently the heat radiation. However, vehicle soak after a high load driving schedule is the critical condition considered as the ultimate test and in these conditions only free convection will take place. It is therefore important to concentrate the insulation efforts on reducing the radiative part of the heat transfer.

It is important to notice from the data shown in Figure 4 that the total heat loss from the catalytic converter is in total of about one kilowatt. This is relatively low compared to the amount of heat convected by the exhaust gas from the engine which could reach several kilowatts. Therefore the converter outlet gas temperature is not significantly modified by the changes in the converter thermal insulation.

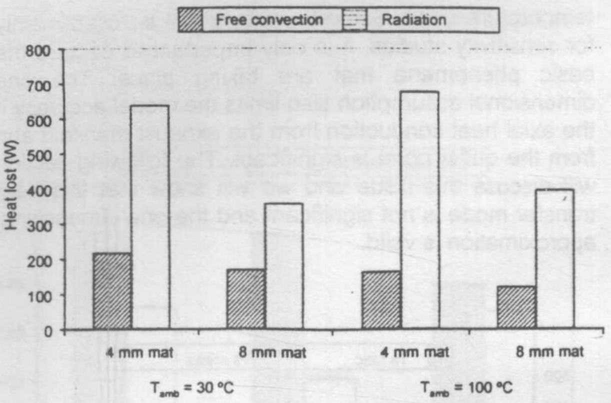


Figure 4: Heat lost from the converter when bed temperature is 900 ºC.

The radiative heat transfer may be reduced by:

- Reducing the skin temperature. This might be achieved by decreasing the mat thermal conductivity or by increasing the mat thickness. However, the mat thickness increase will increase the shell diameter and consequently the surface area for radiation.

- Reducing the shell emissivity. The emissivity of steel could vary from 0.4 for an austenitic stainless steel to 0.7 for a ferric stainless steel. This represents a 75% increase in the amount of heat radiated.

In a later section, we will analyze the effect of the above measures on a given component located close to the converter.

HEAT CONDUCTED FROM THE EXHAUST MANIFOLD OR THE OUTLET CONE

To evaluate the effect of heat conducted from the ends of the catalytic converter, the following test was conducted:

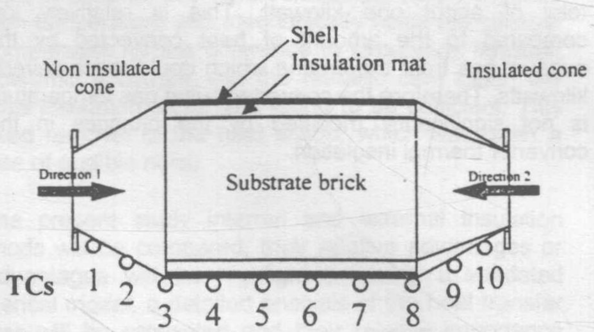


Figure 5: Configuration tested to analyze the heat conduction from the ends to the center shell.

A converter was built such that exhaust gas could be directed into either end under the same flow conditions. In direction 1, the gas enters through a non insulated end cone. In direction 2, it passes through an insulated end cone. If the temperatures of the center shell were affected by the temperature of the cones, the side closer to the hotter cone would see higher temperature levels. The results of our experiments, shown in Figure 6, indicate that the temperature of the center shell was not affected by heat conduction from the ends in this case.

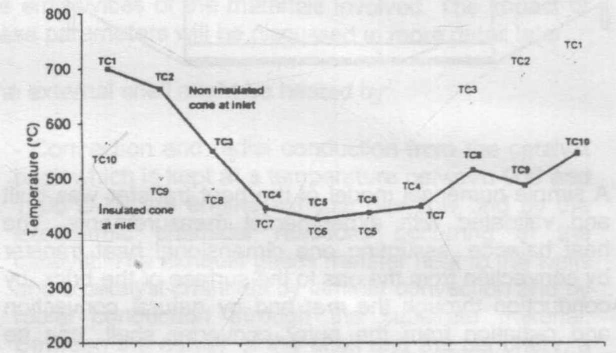


Figure 6: Influence of heat conduction from the cones,

HEAT INSULATION DESIGN

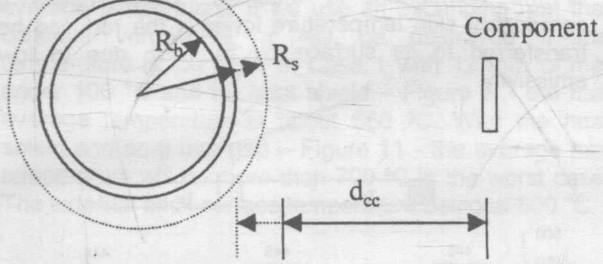
The manifold converter located in the engine compartment will contribute to increase the underhood ambient temperature, particularly during the soak conditions where there is no air circulation. This will be the primary impact on the thermal load of the surrounding components since a high ambient temperature will reduce the heat removed from their surfaces by free convection which is proportional to (T_c - T_{amb}).

The most efficient insulation that could reduce this contribution would be more internal insulation that could reduce the catalytic converter surface temperature.

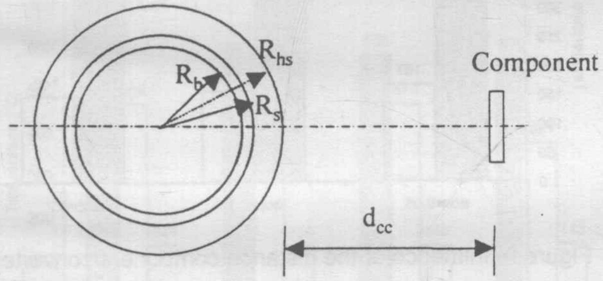
The surrounding components will be heated by heat radiation most directly from the catalytic converter and from the exhaust manifold. This was found to be the predominant mode of heat transfer in our case. The heat radiated from the catalytic converter surface to any component located in its vicinity will be a complex combination of the emissivities, the view factors and the surface temperatures.

The most common means of protecting an adjacent component from heat radiation is by interposing a heat shield between the radiative surface and the component. Below we discuss this technique as compared to increased internal insulation.

The following two cases will be considered in the analysis of the relative efficiency of the various parameters: insulation mat thickness, heat shielding, view factors and emissivities. The first one consists of increasing the internal insulation and the second consists of shielding the converter.



Case1: Internally insulated – variable mat thickness



Case2: Heat shielded

The heat shield is installed around the converter because we assume that several components, represented here by just one for our generic study, could surround the converter. Heat shielding each component individually is a complex and expensive solution.

The heat balance for the above presented case 1 and case 2 could be written as follows:

$$N_{ugas}\frac{\lambda_{gas}}{D_{ch}}A_b(T_{gas}-T_b) = \frac{2\ \lambda_{mat}}{L_n(R_b/R_s)}(T_b-T_s)$$

$$\text{For case1} \quad = f_s(G_r, P_r)\,A_s\,(T_s-T_{amb})+q_{rad,\,s}$$

$$\text{For case2} \quad = \frac{2\pi L\,\lambda_{gap}}{L_n(R_s/R_{hs})}(T_s-T_{hs})+q_{rad,\,s/hs}$$

$$= f_{hs}(G_r, P_r)\,A_{hs}\,(T_{hs}-T_{Amb})+q_{rad,\,hs}$$

The balance for the component is expressed as:

$$f_c(G_r, P_r)\,A_c\,(T_c-T_{amb})+q_{rad,\,c}+q_{contact}=0$$

The radial temperature gradient in the converter metallic shell and in the heat shield are again is neglegted due to their high thermal conductivity.

$q_{rad,s}$, $q_{rad,hs}$ and $q_{rad,c}$ are respectively the net heat radiated from the converter (in case 1), from the heat shield (in case 2) and from the component. They are calculated by solving the Kirchhoff Law in the following network (Figure 7) and assuming all surfaces to be gray. The environment is assumed to have a much higher surface area than the converter which justifies not using the radiosity for that node.

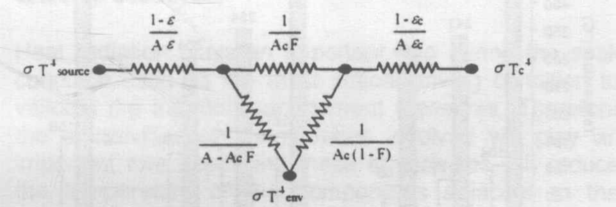


Figure 7: Heat radiation network used to solve case1 and case 2.

The heat source for the component is the converter for Case 1 and it becomes the heat shield for Case 2. The view factor F depends only on geometric parameters.

The heat radiated from the converter to the heat shield, $q_{rad,s/hs}$, is calculated assuming a view factor of one.

The heat conduction between the converter and the heat shield is calculated using a modified air conductivity given by [1].

$$\lambda_{gap} = \lambda_{air}.0.386\left[\frac{L_n(R_{hs}/R_s)}{(R_{hs}-R_s)^{3/4}.(D_s^{-3/5}+D_{hs}^{-3/5})^{5/4}}\right] * (\Pr/(0.861+\Pr))^{1/4} R_{ah}^{1/4}$$

The heat lost by the adjacent component, supposed to be attached to the vehicle body, is evaluated by $q_{contact}$ which is expressed by:

$$q_{contact} = h_c\,A_c\,(T_c - T_{body})$$

Where, h_c is the contact heat transfer coefficient.

EFFECT OF MAT THICKNESS AND CONDUCTIVITY

In Case 1, the mat thickness is increased from 4mm to 12mm with ambient temperatures of 30 ºC and 100 ºC. The main effect is the reduction of the skin temperature, but there is also an increase in the view factor between the converter and the component. However, the net radiated heat is reduced overall and the component's temperature is lower as shown below. The converter skin temperature is not significantly changed when increasing the ambient temperature. The component's temperature increases more significantly. This is in line with the fact that convective heat transfer from the component represents an important part of its heat loss while for the converter the radiated heat portion predominates.

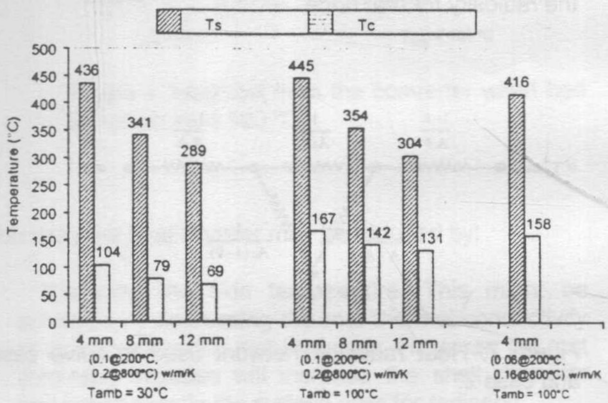


Figure 8 : effect of insulation thickness, ambient air temperature and insulation mat conductivity.

Reducing the insulation mat thermal conductivity can also play an important role. From the reference mat that has a conductivity of (0.1@200°C, 0.2@800°C) w/m/K, to a mat with lower conductivity of (0.06@200°C, 0.16@800°C) w/m/K but with the same wall thickness (Figure 8), the temperature is reduced by 5%. Doubling the mat thickness gave a 15% decrease but reducing the thermal conductivity is more attractive, since adjacent component's temperature is reduced without increasing the size of the converter. However, insulation materials having low thermal conductivity are always more expensive.

EFFECT OF EMISSIVITIES AND VIEW FACTOR

One way to reduce the component temperature is to move the component away from the converter. Figure 9 shows that this method has only limited potential, particularly in the engine compartment.

Reducing the converter emissivity by any treatment that will remain after aging will help to reduce the component skin temperature. Going from an emissivity of 0.8 to an emissivity of 0.4 will reduce the component temperature by 15 °C while the converter temperature has increased. Figure 10. That shows that the converter skin temperature should not be the only parameter taken in account in assessing a nearby component's temperature. However, increasing the converter skin temperature will increase the heat transferred by convection to the ambient air, which will increase its temperature.

If the component emissivity is reduced from an emissivity 0.1 to an emissivity of 0.01 the component temperature is reduced by 60°C. This method seems to be more effective compared to thicker insulation mat. It is interesting to notice that the converter skin temperature has not changed in this case, because the total heat lost is not affected much when the emissivity of the component is modified. What makes the component skin temperature lower is the reduced heat transferred to its surface by radiation due to lower emissivity.

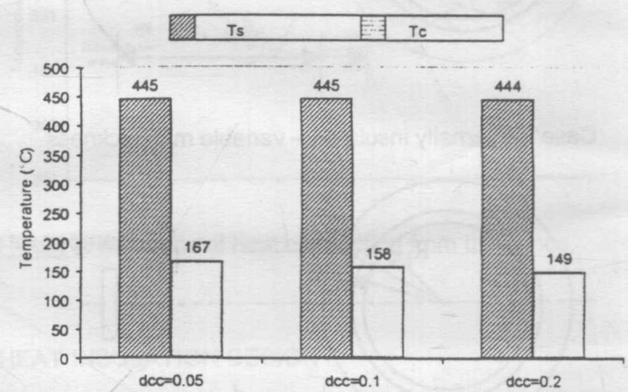


Figure 9: Influence of the distance component/converter

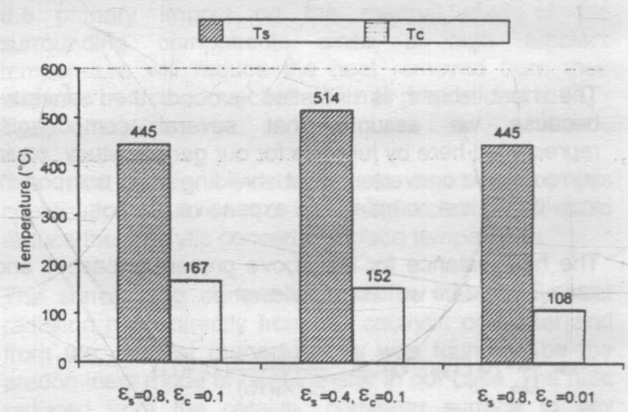


Figure 10: Influence of component and shell emissivities.

HEAT SHIELD PROTECTION

In Case 2, a heat shield is installed over the converter insulated with 4 mm of mat. If the gap between the converter and the heat shield is kept between 4 and 8 mm, the distance from the heat source to the component is similar to Case 1, where the mat thickness was increased from 4 mm to 12 mm. The component temperature for the same distance from heat source to component is lower with the heat shield. We have assumed here that the heat shield will maintain an emissivity of 0.4 on both faces. If the emissivity increases for any reason on one of its faces, the advantage of having a heat shield will be reduced.

The main drawback to using the heat shield is the mat average temperature. If we use an expanding mat that contains vermiculite, it will be destroyed if the temperature is too high. In Case 1 with 12 mm of mat under 100 °C and no heat shield – Figure 8 - the mat average temperature is about 550 ºC. With the heat shield and an 8 mm gap – Figure 11 - the average mat temperature will be more than 700 ºC in the worst case. The external brick surface temperature being at 800 °C.

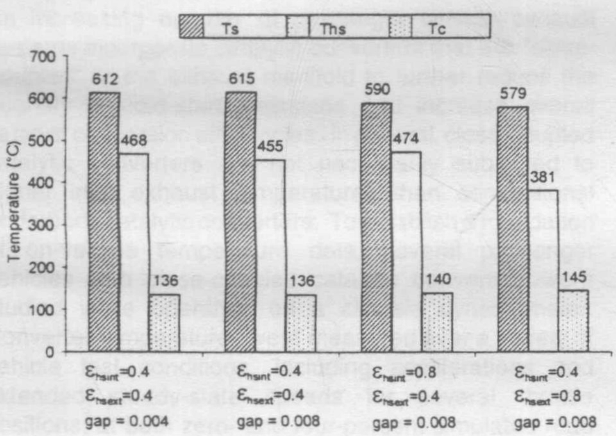


Figure 11: Skin temperature with heat shield.

CONCLUSION

The introduction of the catalytic converter into the engine compartment needs to be accompanied with special care to limit the thermal load on the surrounding components. Only a system approach and a combination of measures could be successful and will insure a good thermal management of the underhood.

The converter skin temperature can be reduced using more insulation material. Even though its external surface is increased, which will tend to increase the radiation and convection heat transfer, the net benefit on the component's temperature is still positive.

Using insulation material with lower thermal conductivity has a limited value as compared to an increase of the thickness of the regular insulation mat because their cost is very high. This can only be of an interest if severe packaging problems cannot allow just an increase of the thickness of the regular insulation material.

The heat conduction from the converter ends, exhaust manifold and outlet cone, to the center shell is not significant. This allows to take full advantage of the insulation mat thickness increase, since it will not be overshadowed by heat conduction from the ends.

Placing a heat shield over the catalytic converter is not significantly more beneficial than increasing the insulation mat thickness. Furthermore, installing a heat shield will increase the insulation mat temperature to levels where the mixture ceramic fiber and vermiculite could be destroyed.

Heat radiation plays an important role during the soak condition used as the most critical driving condition to validate the thermal management measures. Therefore the emissivities of the surfaces involved will play an important role. Reducing these emissivities will reduce the temperature of the components adjacent to the manifold converter and the component's emissivity is the most influencial one.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

A_b Substrate surface area (m^2)
A_c Component surface area (m^2)
A_{hs} Heat shield surface area (m^2)
A_s Converter shell surface area (m^2)
D_{ch} Substrate channels diameter (m)
D_b Substrate diameter (m)
D_{hs} Heat shield diameter (m)
D_s Converter shell diameter (m)
F Converter or heat hield to component view factor (-)
f_c Free convection coefficient over the component
f_{hs} Free convection coefficient over the heat shield
f_s Free convection coefficient over the converter shell
Gr Grashoff number (-)
L Catalytic converter length (m)
Pr Prandtl number (-)
$q_{rad.c}$ Total heat lost by radiation from the component (w)
$q_{rad.hs}$ Total heat lost by radiation from heat shield (w)
$q_{rad.s}$ Total heat lost by radiation from the converter shell
$q_{rad.s/hs}$ Heat transfer by radiation from the converter shell to the heat shield (w)
Ra Railegh number (-)
R_b Substrate radius (m)
R_{hs} Heat shield radius (m)
R_s Converter shell radius (m)
T_{amb} Ambient temperature (K)
T_b Converter brick skin temperature (K)
T_c Component temperature (K)
T_{env} Environment temperature
T_{gas} Gas temperature (K)
T_{hs} Heat shield temperature (K)
T_s Converter shell temperature (K)

ε_s Converter shell emissivity (-)
ε_{hsint} Internal heat shield face emissivity (-)
ε_{hsext} external heat shield face emissivity (-)
ε_c Component surface emissivity (-)
λ_{mat} Insulation mat thermal conductivity (w/m/K)
λ_{gas} Exhaust gas thermal conductivity (w/m/K)
λ_{air} Ambient air thermal conductivity (w/m/K)
λ_{gap} Air gap equivalent thermal conductivity (w/m/K)

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Catalytic Converter Thermal Environment Under Dynamometer Simulated Roadloads

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Southwest Research Institute

Richard Beason, Andrew Montalbano and Jonathan Kisenyi
Ford Motor Company

ABSTRACT

An increasing number of passenger vehicle exhaust systems incorporate catalytic converters that are "close-coupled" to the exhaust manifold to further reduce the quantity of cold-start emissions and increase overall catalyst conversion efficiencies. In general, close-coupled catalytic converters are not necessarily subjected to higher inlet exhaust temperatures than conventional underbody catalytic converters. To establish a foundation of on-vehicle temperature data, several passenger vehicles with close-coupled catalytic converters were studied while operating on a chassis dynamometer. Converter temperatures were measured over a variety of vehicle test conditions, including accelerations and extended steady-state speeds for several throttle positions, at both zero- and four-percent simulated road grades.

INTRODUCTION

Typical catalytic converter assemblies for gasoline vehicles consist of a catalyzed ceramic substrate mounted in a stainless steel container. Substrate mounting materials include wire mesh and intumescent mats. Mounting materials must maintain a positive pressure on the substrate over a wide range of temperatures. The gap between the substrate and the container usually increases with temperature, due to an order-of-magnitude difference in thermal expansion coefficient of the container steel compared to the ceramic substrate. The catalytic converter assembly must be carefully designed to protect the substrate mounting material and steel container from excessive thermal exposure. Failure of one component that affects holding pressure will lead to a mechanical failure of the converter.[1]

Recent clean air legislation has tightened emissions requirements on passenger vehicles and increased the durability requirements of emissions control devices. Beginning in 1994, passenger car emission standards were incrementally lowered from the 1985 EPA standards to the EPA Tier I standards. Tier I rules included emissions standards for 50,000 and 100,000 miles of vehicle use, effectively extending the useful life of the catalytic converter and other emission control devices to 100,000 miles.[2]

As a result of the increased emission control requirements, automobile manufacturers have incorporated exhaust systems that use close-coupled catalytic converters in conjunction with (or sometimes even replacing) the underbody catalytic converter. By placing the converter at the exhaust manifold, the catalyst can typically achieve operating temperature more quickly than an underbody converter, thereby substantially reducing cold-start emissions, if the engine air-fuel ratio is controlled properly. While not justified by the findings of this study, it is nevertheless sometimes assumed that close-coupled converters may be subjected to higher exhaust gas temperatures than conventional underbody converters. Additionally, current technology vehicles with close-coupled converters may have higher exhaust temperatures than earlier vehicles with close-coupled converters that benefited from fuel-richening catalyst cooling strategies.

To obtain an understanding of the temperature environment for close-coupled and underbody catalytic converters, exhaust temperatures were measured on five 1998 model year vehicles with various engine and exhaust system designs. All vehicles were gasoline-fueled, and the converters on these vehicles contained ceramic monolith substrates. Vehicles were driven on a 48-inch roll chassis dynamometer using driving conditions selected to provide a complete vehicle profile of typical and extreme operating conditions.

TEST VEHICLES

Three North American and two European vehicles were selected for testing. A listing of vehicle engine type, transmission type, and converter location is given in Table 1. These 1998 production vehicles were tested with production engine calibrations. New catalytic converters were obtained and installed for vehicle testing.

Table 1. Test Vehicles for Catalytic Converter Temperature Study

Vehicle No.	Engine Type	Transmission Type	Converter Location
1998 North American Vehicles			
1	2.0L I-4	Automatic/ 4-speed	1 close-coupled
2	2.5L V-6	Automatic/ 4-speed	2 close-coupled 1 underbody
3	4.2L V-6	Automatic/ 4-speed	2 close-coupled 2 underbody
1998 European Vehicles			
4	2.0L I-4	Manual/ 5-speed	1 underbody
5	1.25L I-4	Manual/ 5-speed	1 close-coupled

INSTRUMENTATION

For each catalytic converter tested, exhaust gas and converter container temperatures were recorded using Type-K (chromel-alumel) thermocouples. Thermocouples were generally installed on the converter container surfaces at the locations illustrated in Figure 1. Six thermocouples were installed around the circumference of the container spaced at equal distances from each other, and 25.4 mm downstream of the substrate edge. One thermocouple was installed on the inlet cone 25.4 mm upstream of the substrate edge on the minor axis. One thermocouple was placed at mid-dimension of the substrate on the minor axis. Converter heat shields were removed for thermocouple installation, and later replaced before installing the converter onto the vehicle.

Figure 2 contains the exhaust gas thermocouple locations inside the converter substrate. Converter inlet and outlet exhaust gas temperatures were measured at 25.4 mm upstream and downstream of the substrate surfaces using 3.2 mm diameter thermocouples. Three small diameter (1.0 mm fast response) thermocouples were inserted into the converter substrates to measure mid-stream temperature at a depth of 25.4 mm from the inlet face, substrate skin temperature (first cell adjacent to substrate mount at minor axis) at a depth of 25.4 mm from the inlet face, and mid-bed temperature at one half the depth of the substrate. For converters with two substrates, exhaust gas temperature was measured between substrates using a 3.2 mm diameter thermocouple.

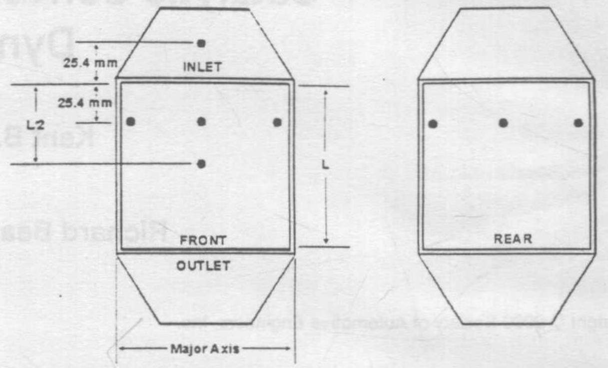

Figure 1. Thermocouple Locations for Catalytic Converter Container Temperature Measurement

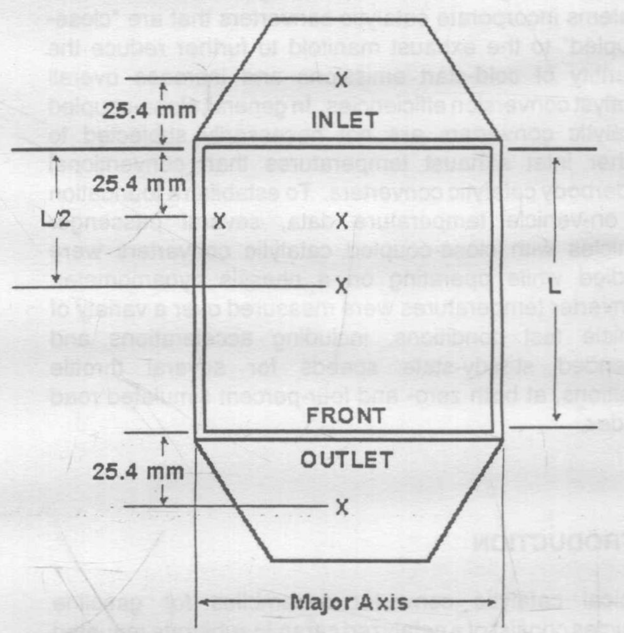

Figure 2. Thermocouple Locations for Catalytic Converter Exhaust Gas Temperature Measurement

In addition to the temperatures, vehicle speed and engine speed were recorded. Vehicle speed output was a voltage signal proportional to the dynamometer roll speed. The engine speed voltage signal was proportional to a frequency signal from the engine crank angle sensor. Engine inlet air mass flowrate and engine air-fuel ratio also were recorded. The engine air mass flowrate was measured from the vehicle mass air flow sensor (MAFS). Intake air flowrate sensor calibration information was obtained from the vehicle manufacturer.