

A New Approach for Inlet Diffuser of Automotive Catalytic Converter Considering Conversion Efficiency of Pollutants

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Abstract

The monolithic catalytic converter is still the main pollution control device for modern vehicles in order to reach the ever-increasing legislative demands for low emission standards. The catalytic converters require a large expansion from the exhaust pipe to the front face of the monolith. Unfortunately, packaging constraints often do not permit the use of long diffusers. Hence, flow separation within the diffuser leads to a non-uniform flow distribution across the monolith. A uniform flow distribution at the inlet monolith face is favorable for the conversion efficiency as well as the durability of the catalytic converter. Therefore, the main problem is to optimize the flow distribution at the catalytic converter. It should be noted that due to flow maldistribution in an enlarged inlet of catalytic converter, some parts of the monolith would be non effective. In this research, a new design for inlet diffuser of catalytic converter has been proposed and fabricated. The new inlet diffuser is composed of some tube to tube cones that distribute the flow uniformly at the entrance face of monolith. Temperature, pressure drop, and concentration of pollutants, before and after the catalyst, have been measured. The results show that the new design for inlet diffuser tends to a less uniform temperature field at the entrance of monolith but the flow distribution becomes more uniform. Therefore, an increased conversion efficiency of the catalyst will be obtained.

Keywords: *Catalytic Converter, Inlet Diffuser, Pollutant, Conversion Efficiency, Flow Distribution*

Introduction

Monolith catalytic converter systems have demonstrated potential in enabling vehicle to comply emission standards. The monolith surface is coated with a resin that contains noble metals like Platinum (Pt) and Palladium (Pd) that allow oxidation and Rhodium (Rh) that is used in reduction. One of the most important parts in catalytic converters is inlet diffuser. The inlet diffuser has an important effect on distribution flow at the entrance face of the monolith. One of the most important problems that occur in the catalytic converter is maldistribution flow. Large diffuser cone angles lead to non-uniform inlet velocity distribution flow; therefore, the turbulent exhaust gas flow from the exhaust pipe into the diffuser separates from the walls and tends to enter the central channels of the monolith [1]. Thus, the highest portion of the exhaust flow passes through the center of the monolith with a velocity that is significantly higher than the ideal form. In an ideal converter, the flow at the exit of the inlet diffuser would be uniform and, thus, would be evenly distributed to all monolith passages. The flow distribution across the monolith frontal area depends on the geometry of a specific design of inlet diffuser.

Experimental techniques have been employed to visualize the internal flow structure of a prototype monolith converter [1], concluding that the uniform flow is a function of the inlet flow and Reynolds number. Since then, computational methods relying mostly on computational fluid dynamics (CFD) software have been widely used to provide more detailed information on the flow field as a function of various designs and operating parameters. 3-D flow field simulations at steady state conditions have been presented, including validation of the results with measurements [2]. The effect of inlet geometry on flow distribution has been studied by CFD and a flow uniformity index has been defined as a criterion to quantify the results [3]. More recent studies [4] have employed a CFD-based modeling in order to predict the steady state performance of the catalytic converter, including the effects of heat and mass transfer in the monolith, oxidation reactions, heat generation and ambient heat losses. There are a lot of limitations for experimental studies; therefore, the number of experimental researches are limited.

In this research, a new geometry for inlet diffuser of catalytic converter has been investigated with CFD code with the aim of improving uniform flow distribution at the inlet surface of monolith. In order to save time and cost all

the investigations in the CFD field have been conducted by the commercial software, FLUENT 6. Then, the best efficient geometry of inlet diffuser, with the aim of uniform flow has been fabricated. In order to investigate all effects of this new geometry on the performance of catalytic converter, a new test rig was installed in engine investigation laboratory of Sharif University of Technology. All data about concentration of pollutants pre and post converter as well as temperature in different positions of converter and pressure drop have been measured by experimental method.

Governing equations

To obtain the velocity distribution at the monolith entrance, equations governing the flow inside the converter were solved using the computational fluid dynamic software. The flow through the converter was modeled as steady, i.e. no flow pulsations were considered. In high engine load and speed, flow fluctuations are small compared to the mean gas velocity. Furthermore, the Mach number in all flow regions is not expected to exceed 0.1. Therefore, treating the exhaust gas as incompressible is a reasonable approximation [5]. Engine exhaust flow is highly turbulent. Therefore, gas flow is turbulent upstream and downstream of the monolith. However, the turbulent flow leaving the diffuser laminarizes in the monolith channels due to their very small hydraulic diameter about 1mm (in channels Reynolds number are unlikely to exceed 500) [5].

The conservation equations are as follows [6]:

$$\frac{\partial}{\partial x_j} (\rho u_j) = 0 \quad (1)$$

$$\frac{\partial}{\partial x_j} (\rho u_j u_i + \tau_{ij}) = -\frac{\partial p}{\partial x_i} \quad (2)$$

in which the stress tensor τ_{ij} for Newtonian turbulent flow is:

$$\tau_{ij} = -\mu \left(S_{ij} + \frac{2}{3} \frac{\partial u_i}{\partial x_j} \delta_{ij} \right) + \overline{\rho u'_i u'_j} \quad (3)$$

where δ_{ij} is the Kroneker delta and S_{ij} is the rate of strain tensor:

$$S_{ij} = \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \quad (4)$$

In order to determine the Reynolds stresses and turbu-

lent scalar fluxes, a $k-\epsilon$ turbulence model has been used, comprising differential transport equation for the turbulent kinetic energy k and its dissipation rate. The conventional form of ϵ model assumes that the turbulent Reynolds stresses and scalar fluxes are linked to the time-averaged flow properties by:

$$\overline{\rho u_i u_j} = -\mu_t S_{ij} + \frac{2}{3} \left(\mu_t \frac{\partial u_i}{\partial x_j} + \rho k \right) \delta_{ij} \quad (5)$$

where the turbulent viscosity μ_t is linked to k and ϵ by:

$$\mu_t = \frac{C_\mu \rho k^2}{\epsilon} \quad (6)$$

The transport equation used to determine the turbulence energy and its dissipation rate is:

$$\frac{\partial}{\partial x_j} \left(\rho \mu_j k - \frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x_j} \right) = \mu_t S_{ij} \frac{\partial u_i}{\partial x_j} - \rho \epsilon - \frac{2}{3} \left(\mu_t \frac{\partial u_i}{\partial x_j} + \rho k \right) \frac{\partial u_i}{\partial x_j} \quad (7)$$

$$\frac{\partial}{\partial x_j} \left(\rho \mu_j \epsilon - \frac{\mu_t}{\sigma_\epsilon} \frac{\partial \epsilon}{\partial x_j} \right) = C_{\epsilon 1} \frac{\epsilon}{k} \mu_t S_{ij} \frac{\partial u_i}{\partial x_j} - \frac{2}{3} \left(\mu_t \frac{\partial u_i}{\partial x_j} + \rho k \right) \frac{\partial u_i}{\partial x_j} - C_{\epsilon 2} \rho \frac{\epsilon^2}{k} + C_{\epsilon 3} \rho \epsilon \frac{\partial u_i}{\partial x_i} \quad (8)$$

In which C_μ , σ_k , σ_ϵ , $C_{\epsilon 1}$, $C_{\epsilon 2}$ and $C_{\epsilon 3}$ are further empirical coefficients where values are given in Table 1.

Table 1. Empirical coefficients for $k-\epsilon$ turbulent model [6]

C_μ	σ_k	σ_ϵ	$C_{\epsilon 1}$	$C_{\epsilon 2}$	$C_{\epsilon 3}$
0.09	1.0	1.2	1.44	1.92	-0.33

The gas flow in parallel channels of monolith can be regarded as a laminar flow whose governing equation is given by Hagen-Poiseuille equation to calculate the pressure loss through the monolith as follows [7]:

$$-\frac{\partial p}{\partial x} = \frac{32 \mu}{\phi D_h^2} u \quad (9)$$

By assuming quasi-steady, incompressible flow, the energy equation for the exhaust gas is written as [8]:

$$\frac{\partial T_g}{\partial t} + u \frac{\partial T_g}{\partial x} = \frac{-q_{gp}}{\rho C_{Pg} V} \quad (10)$$

The heat transfer from exhaust gas to the diffuser wall of catalytic converter is expressed by the following equation [8]:

$$q_{gp} = h_{gp} \pi d \Delta x (T_g - T_p) \quad (11)$$

h_{gp} is calculated by the following equations [8]:

$$h_{gp} = \frac{Nu k_g}{d} \quad (12)$$

for

$$Nu = \frac{(f/8) Re Pr}{1.07 + 12.7(f/8)^{1/2} (Pr^{2/3} - 1)} \quad (13)$$

for $10^4 < Re < 5 \times 10^6$

$$Nu = \frac{(f/8)(Re - 1000) Pr}{1.07 + 12.7(f/8)^{1/2} (Pr^{2/3} - 1)} \quad (14)$$

for $Re < 10^4$

The friction factor (f) is determined by the following equation [8]:

$$\frac{1}{\sqrt{f}} + 2 \log \left(\frac{e}{3.7d} + \frac{2.51}{Re \sqrt{f}} \right) = 0 \quad (15)$$

The surface roughness (e) is typically $2.59 \times 10^{-4} m$ for cast iron tube and $1.52 \times 10^{-6} m$ for steel tube.

The modified model for the inlet diffuser of catalytic converter

In order to improve the flow distribution at the inlet surface of monolith, a new geometry for inlet diffuser has been proposed in this research. The original catalytic converter (O.C.C) used in this research is shown in Fig. 1.

The modified catalytic converter (M.C.C) is shown in Fig. 2. This model was composed of some annular cones that distribute the flow uniformly at the entrance surface of monolith.

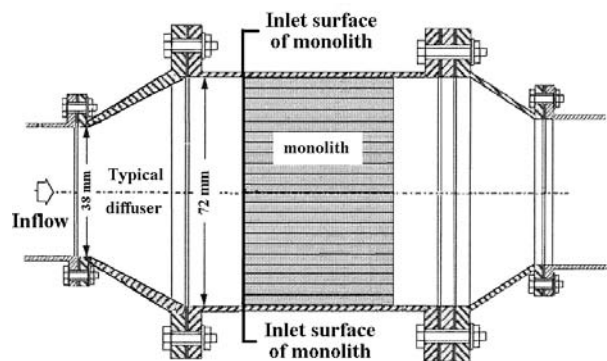


Fig 1. Schematic of original catalytic converter

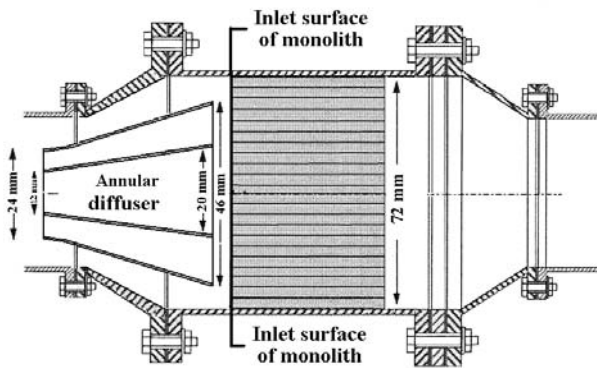


Fig. 2. Schematic of modified catalytic converter

The 2-D flow model to an axi-symmetric flow was developed to calculate the flow field at inlet diffuser. After determining the effect of this model on improving the flow distribution at the inlet surface of monolith, it has been fabricated and other tests were performed in real conditions to measure temperature distribution at the inlet surface of monolith as well as pressure drop and catalytic converter efficiency. This geometry is shown in Fig. 3.

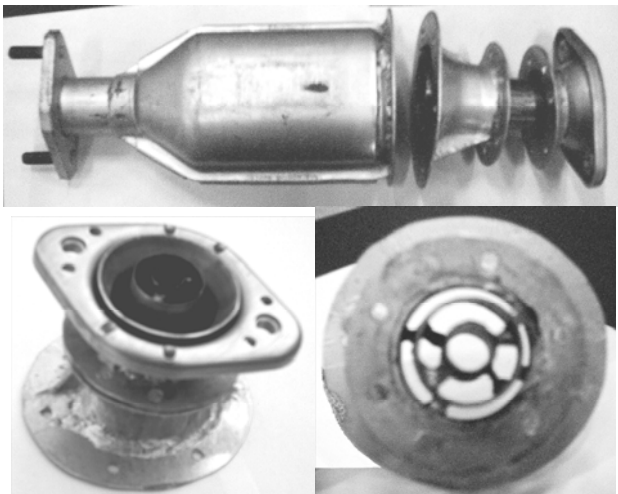


Fig. 3- Modified inlet diffuser of

Fig 3. Modified inlet diffuser of catalytic converter

Experimental test rig

In order to perform experimental tests, the engine was connected to an Eddy Current dynamometer. The objective is to simulate realistic vehicle operating conditions in the test bed. As shown in Fig. 4, two axial fans with accompanied ducting were employed to generate the air flow over moving vehicle. The engine was SI type, L-4, 1.3 liter with a multi point fuel injection (MPFI) system.

The catalytic monolith was a three-way catalyst model in which its properties are summarized in Table 2. The thickness of NiCr thermocouples used in the experiment was 1 mm. Several thermocouples protruded their heads 5 mm out of the channels for measuring the inflow gas temperature. Along radial direction, they were located at the positions with r coordinates of $0.2R$, $0.5R$ and $1R$. The differential pressure transducer was a digital type with diaphragm sensor calibrated between 0-50 mbar. Exhaust gas velocity was measured by vane. Torque and engine speed were measured by the Eddy Current dynamometer. Pollutant concentrations, namely CO and HC were measured by an AVL model 4000 gas analyzer before and after catalytic converter in order to determine its conversion efficiency in different conditions of engine load and engine speed. A schematic installation of thermocouples, differential pressure transducer, and gas analyzer is shown in Fig. 5. The catalytic converter under the test is shown in Fig. 6.

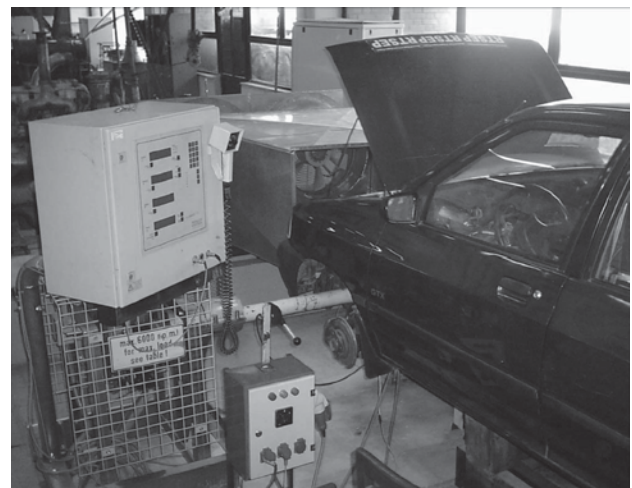


Fig 4. Experimental test rig

Table 2. Properties of catalytic converter

Parameter	Specification	Units
Monolith diameter	72	mm
Monolith length	120	mm
Channel density	400	channel/in ²
	62	channel/cm ²
Monolith type	TWC -metallic	----
Precious metals	Pt/Rh	----
Surface area	2.41	m ²
Wash coat	45	gr/ m ²

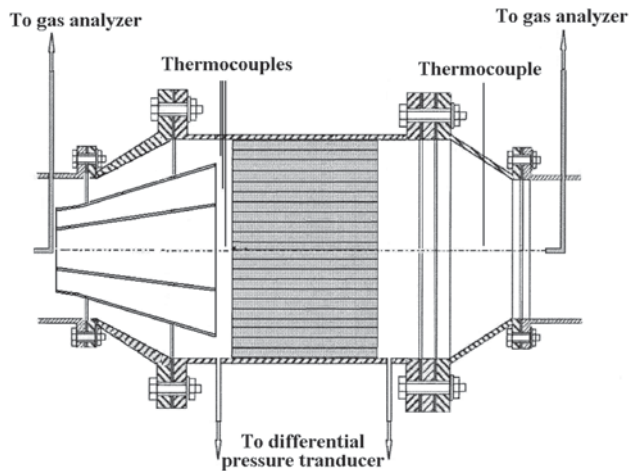


Fig 5. Schematic installation of test facilities

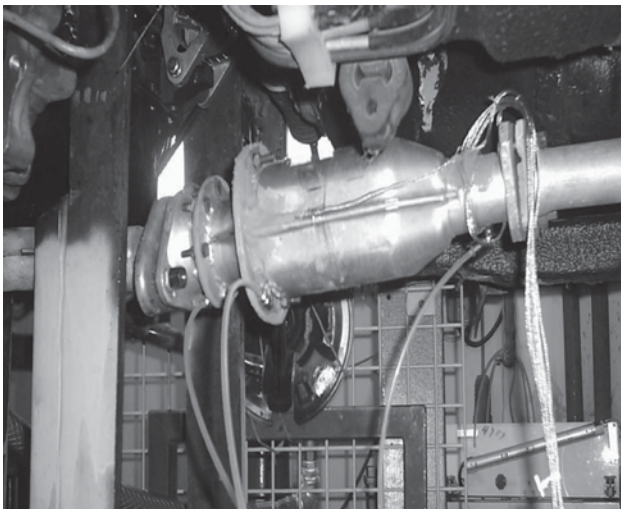


Fig 5. Catalytic converter under the test

Results and discussion

Velocity distribution at the inlet diffuser of catalytic converter was determined for both O.C.C and M.C.C converters for inlet gas velocities of 10 and 40 m/s. The gas velocity of 10 m/s was chosen to examine the effects of new geometry on low engine speed condition and velocity of 40 m/s for high engine speed condition that is a critical condition for catalytic converter performance due to high gas velocity in monolith channel and pure conversion efficiency. The boundary condition of inlet velocity for CFD analysis was measured in real condition of engine working in laboratory. The velocity distribution in x direction for both O.C.C and M.C.C diffusers are shown in Fig.7 to 10.

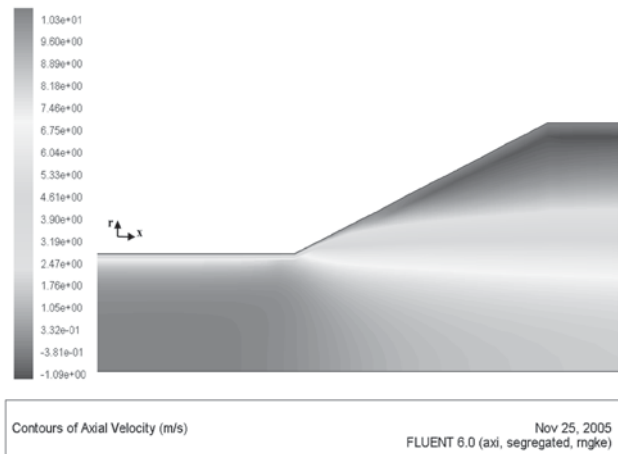


Fig 7. Velocity distribution in O.C.C diffuser for inlet gas velocity of 10 m/s (wide open throttle (WOT) – 1000 rpm)

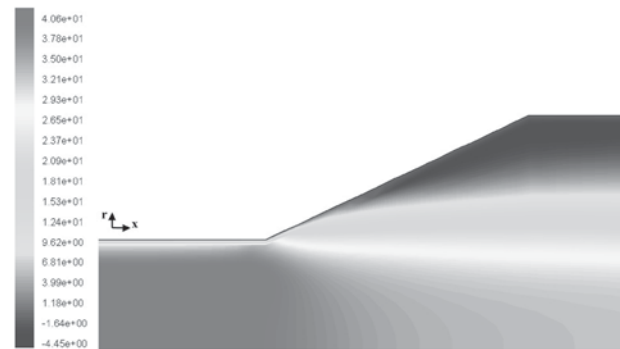


Fig 8. Velocity distribution in O.C.C diffuser for inlet gas velocity of 40 m/s (WOT – 3000 rpm)

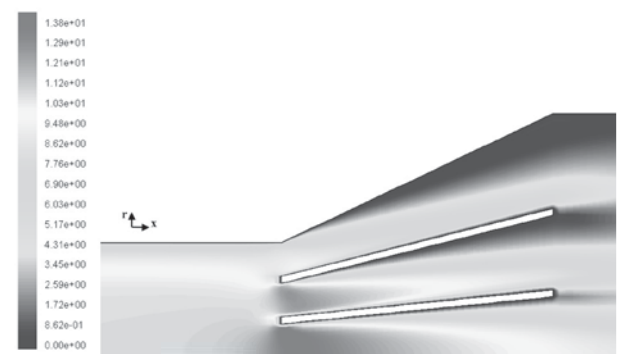


Fig 9. Velocity distribution in M.C.C converter for inlet gas velocity of 10 m/s (WOT – 1000 rpm)

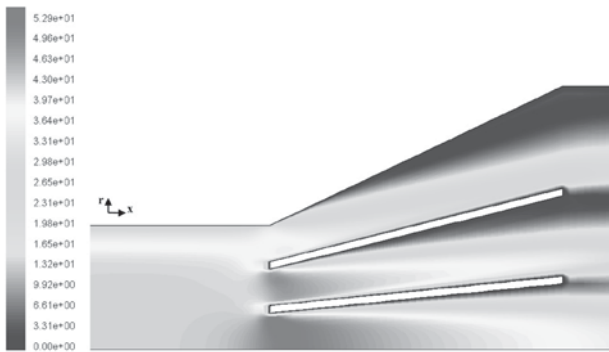


Fig 10. Velocity distribution in M.C.C diffuser for inlet gas velocity of 40 m/s (WOT – 3000 rpm)

The effect of annular cones on velocity distribution (in x direction) is shown in Fig 9 and 10. According to these results, the maximum velocity in middle channels of monolith has been decreased in new geometry. Besides, **the negative velocity and flow recirculation have been diminished near the wall.**

The **gas velocity profiles at the inlet surface of monolith** for inlet gas velocity of 10 and 40 m/s, in both O.C.C and M.C.C diffusers are shown in Fig.11 and 12. These figures show that **under such flow field conditions, large portion of monolith channels that gas velocity is in reverse direction, is not actually utilized (periphery of monolith) in O.C.C converter, so these channels are not involved in exhaust gas after-treatment.** The gas velocity at central channels of monolith in M.C.C converter decreased about 20% in comparison with O.C.C converter. This property increased the resident time in monolith so that the rate of chemical reactions and conversion efficiency of catalytic converter would be increased.

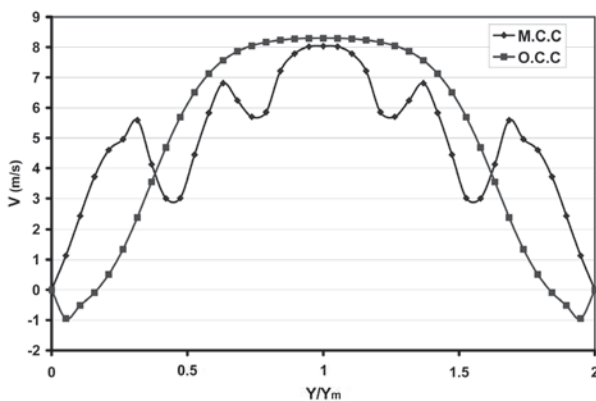


Fig 11. The gas velocity profiles at the inlet surface of monolith for inlet gas velocity of 10 m/s (WOT - 1000 rpm)

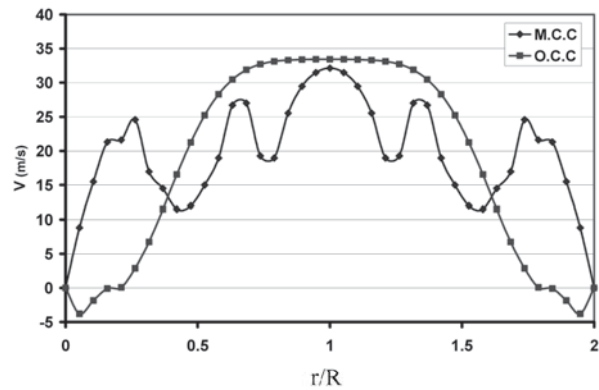


Fig 12. The gas velocity profiles at the inlet surface of monolith for inlet gas velocity of 40 m/s (WOT - 3000 rpm)

The temperature profiles at the inlet surface of monolith are shown in Figs. 13, 14 and 15 for both O.C.C and M.C.C converters in WOT and different engine speeds. In these figures, the vertical axis is T/T_{max} that shows the proportion of gas temperature (T) in different points of inlet surface of monolith to gas temperature in monolith centre (T_{max}). **Temperature profile in O.C.C converter was more uniform in comparison with M.C.C converter.** The gas temperature near the wall is 95% of maximum gas temperature in O.C.C converter but it is 80% in M.C.C converter. Therefore, **the velocity distribution at M.C.C converter was more uniform and gas velocity near the diffuser wall was greater in comparison with O.C.C converter; therefore, according to equation (13) and (14), the convection heat transfer coefficient between gas flow and diffuser wall and the convection heat transfer (q_{gp}) would be increased. It resulted in decreasing the gas temperature in layers near the wall and temperature gradient would be increased at the inlet surface of monolith.**

The **pressure drop in monolith versus inlet gas velocity** for both O.C.C and M.C.C converters is shown in Fig. 16. According to equation (9), **pressure drop in monolith depends directly on gas velocity in monolith channels.** Flow distribution at M.C.C converter was more uniform than O.C.C converter and **the gas velocity in peripheral channel was more considerable in comparison with O.C.C converter; therefore, the pressure drop in M.C.C converter would be increased about 9%.**

The catalytic converter efficiency is defined by equation (16):

$$\text{Catalytic Converter Efficiency} = \frac{C_{in} - C_{out}}{C_{in}} \quad (16)$$

Where C_{in} is the pollutants concentration in inflow and C_{out} is the concentration of pollutant in outflow of the catalytic converter. The conversion efficiencies of HC and CO are shown in Figs. 17 and 18 for both O.C.C and M.C.C converters in WOT condition and various engine speeds.

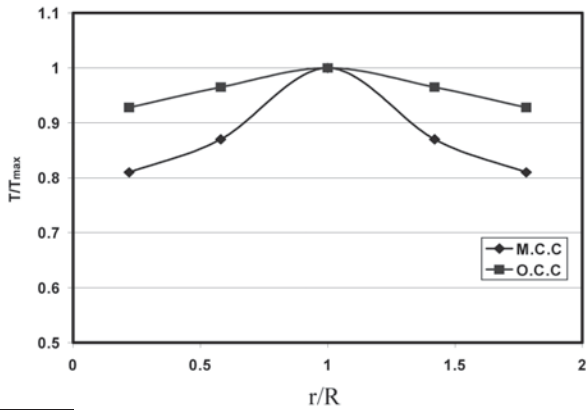


Fig 13. Temperature profiles at the inlet surface of monolith vs. r/R (WOT - 1000 rpm)

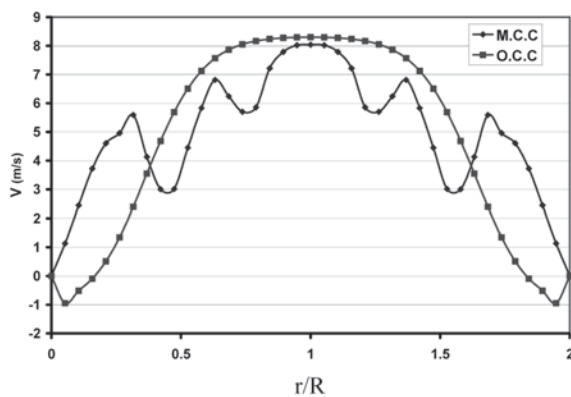


Fig 14. Temperature profiles at the inlet surface of monolith vs. r/R (WOT - 2000 rpm)

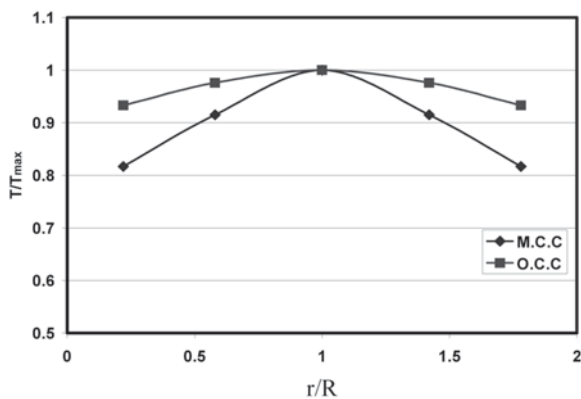


Fig 15. Temperature profiles at the inlet surface of monolith vs. r/R (WOT - 3000 rpm)

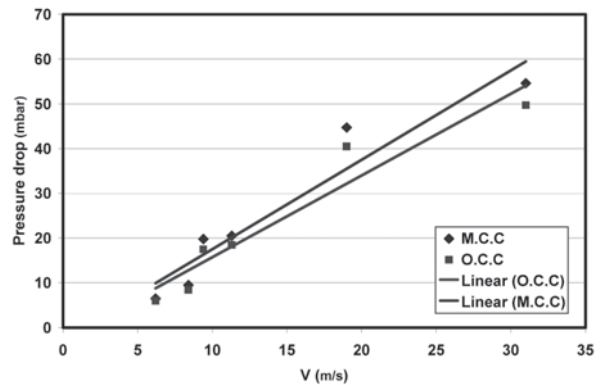


Fig 16. Pressure drop in monolith vs. inlet gas velocity

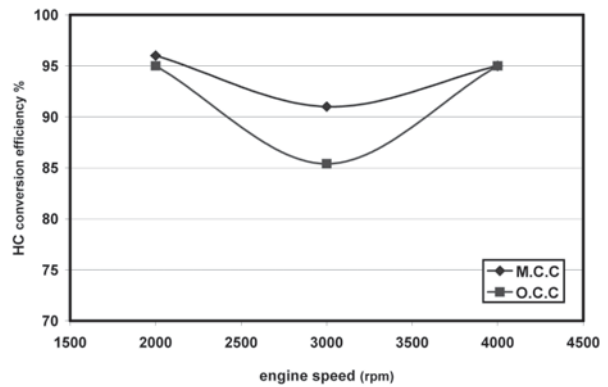


Fig 17. HC conversion efficiency vs. engine speed (WOT)

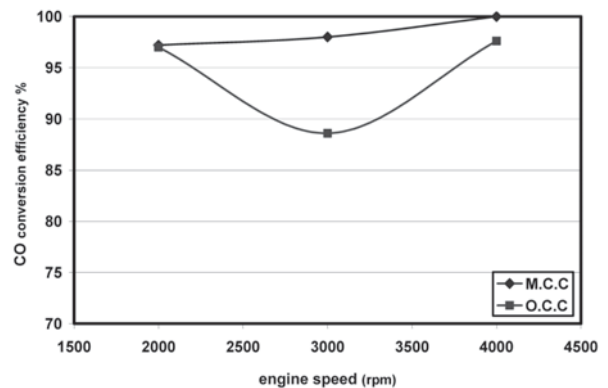


Fig 18. CO conversion efficiency vs. engine speed (WOT)

In order to identify the effect of this new geometry on catalytic converter treatment in other engine condition, the conversion efficiencies of HC and CO were measured and shown in Figs. 19 and 20 for both O.C.C and M.C.C converters for 50% load condition and various engine speeds.

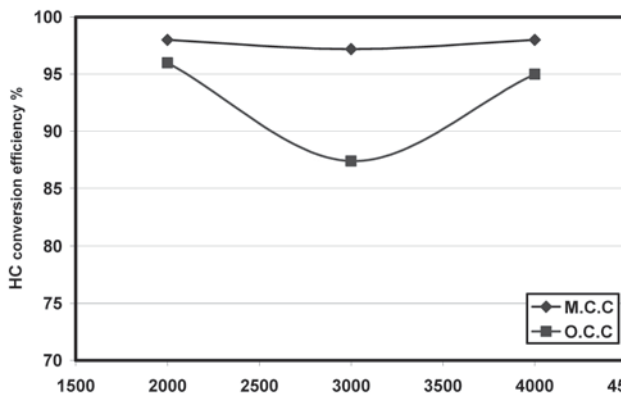


Fig 19. HC conversion efficiency vs. engine speed (50% load)

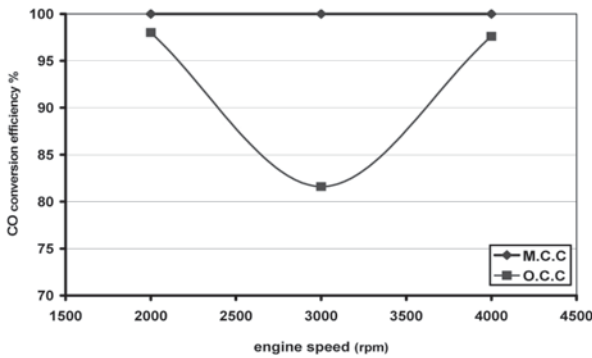


Fig 20. CO conversion efficiency vs. engine speed (50% load)

As shown in figures 17, 18, 19 and 20, the conversion efficiency of HC and CO have been increased 5 to 20% at M.C.C converter in comparison with O.C.C converter. Therefore, the flow distribution at M.C.C converter was more uniform in comparison with O.C.C converter so the chemical reaction rate and conversion efficiency of catalytic converter would be increased.

Conclusion

The flow distribution in a catalytic converter is one of the most important parameters that affects conversion efficiency. A simple diffuser used in typical catalytic converter for decreasing gas velocity and distributing flow on the monolith surface has side effects on making reverse flow near the wall. So a large part of monolith channels would not be used and this leads to decrease catalytic converter efficiency. The new geometry introduced in this research shows a significant effect on flow distribution in catalytic converter. In this geometry, the flow temperature gradient

is increased at inlet surface of monolith. In addition, the back pressure is increased about 9% in the worst condition compared with the typical one. But our results show that the gas velocity distribution in different channels of monolith is more effective on improving conversion efficiency than gas temperature and back pressure. The new geometry improves catalytic converter efficiency 5 to 20% compared with typical one.

Nomenclature

- C_{pg} specific heat of gas at constant pressure ($J/kg K$)
- d pipe diameter (m)
- D_h hydraulic diameter of monolith channel (m)
- e surface roughness (m)
- f friction factor
- h_{gp} heat transfer coefficient between exhaust gas and wall surface ($W/m^2 K$)
- k turbulent kinetic energy (m^2 / s^2)
- k_g gas thermal conductivity ($W/m K$)
- p pressure (Pa)
- C_{in} pollutant concentration before catalytic converter (volumetric percentage)
- C_{out} pollutant concentration after catalytic converter (volumetric percentage)
- Pr Prandtl number
- q_{gp} convection heat flux between exhaust gas and wall surface (W/m^2)
- R monolith radius (m)
- r r- coordinate of monolith (m)
- Re Reynolds number
- T_g gas temperature (K)
- T_p pipe temperature (K)
- t time (s)
- u_i velocity in direction x_i (m/s)
- u_i fluctuating velocity components in direction x_i (m/s)
- V control volume of gas in the exhaust pipe (m^3)
- x axial coordinate of the exhaust system (m)
- x_i Cartesian coordinate ($i=1,2,3$)
- μ gas viscosity ($kg/m s$)
- ϕ monolith porosity
- ε dissipation rate (m^2 / s^2)
- ρ mass density (kg/m^3)
- ($_$) time-averaged quantity

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