G. Symko, M. Aliramezani, C. R. Koch, and R. E. Hayes. Axial insulation rings - testing and simulation of pressure drop and temperature transients in engine exhaust catalysts. In *Combustion Institute/Canadian Section (CI/CS) Spring Technical Meeting , Toronto*, page 6, May 2018

Proceedings of Combustion Institute – Canadian Section
Spring Technical Meeting
Ryerson University, Toronto, ON
May 14-17, 2018

Axial insulation rings – testing and simulation of pressure drop and temperature transients in engine exhaust catalysts

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1. Abstract

To reduce engine-out emissions and to meet the stringent emission regulations, a typical Diesel Compression Ignition (CI) engine relies on multiple catalysts and a particulate filter . The result of adding an insulation ring to the interior of the Diesel oxidation catalyst (DOC) on pressure drop and light-off characteristics is investigated by injecting a ceramic material into the channels of the monolith forming a circular ring. The steady state pressure drop is recorded as a function of the mass flow rate while the transient temperature response is recorded as a function of time. The experimental results are compared with a numerical model created using ANSYS Fluent. The experimental results show no statistical difference in pressure drop with the addition of an insulation ring as the pulsations in the exhaust flow, created by the engine, results in uncertainty larger than the expected difference in pressure drop. The experimental results indicate that the addition of an insulation ring increases the heat capacity of the DOC requiring more energy and time to reach steady state. However, the numerical model indicates that the increase in time to reach steady state is due to the slow rate of heating of the insulation ring, while the rate of heating of the monolith is increased, with the exception of a small area directly adjacent to the insulation ring. With the addition of an insulation ring, the light-off characteristics of the DOC may be improved as the rate of heating is increased across the monolith, except directly adjacent to the insulation ring which shows a decreased rate of heating. Whether the decrease in the rate of heating adjacent to the insulation ring is offset by the benefits of the increase for the remainder of the monolith for improving emission reduction during light-off needs to be further explored.

2. Introduction

Governments worldwide are acting to decrease harmful emissions and decrease the amount of CO_2 produced by automotive engines, requiring manufacturers to both optimize current systems to minimize the emissions produced and to develop new methods of eliminating emissions produced by the engine. The Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) have issued rules to reduce greenhouse gases (GHG) emissions for model year vehicles 2017-2025. The EPA regulations are expected to result in an average combined production of no more than 101.28 g/km (163 g/mile) of CO_2, equivalent to an average fuel consumption of 4.32 L/100 km (54.5 mpg) by the end of 2025 [1]. The advances in engine technology will require corresponding advances in exhaust aftertreatment technology [2]. A typical exhaust setup for a CI engine includes a Diesel Oxidation Catalyst (DOC) to reduce HC emissions, Selective Catalytic Reduction (SCR) catalyst or Lean NO_x Trap (LNT) to reduce NO_x emissions, and Diesel Particulate Filter (DPF) to reduce PM emissions.

The primary function of the DOC is to oxidize CO, HC and portions of the NO emissions. As the oxidation of NO is equilibrium limited, the DOC oxidizes only portions of the NO to alter the NO/NO_2 ratio in the exhaust to meet the downstream requirements of the SCR or LNT [3, 4]. Precious metals are the most commonly used catalysts in the DOC, typically platinum or palladium [4, 5]. Each provide different advantages and disadvantages depending on the operating conditions of the engine and the exhaust composition and temperature.

The objective of this research is to characterize the flow of exhaust gas through the DOC without considering

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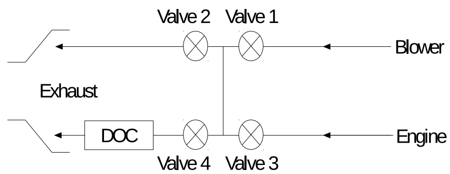
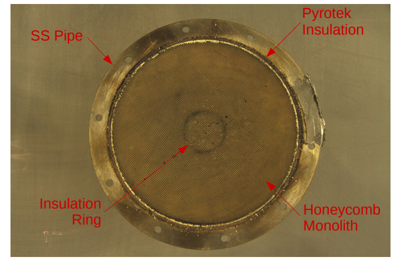


(a) Schematic of the experimental setup



(b) Structure of the DOC (shown in cross section)

Figure 1: Experimental setup and DOC

catalytic reactions. To understand the flow through the DOC and its effect on the DOC, a number of key aspects are observed including the pressure drop, the heating characteristics affecting the light-off temperature, and the effect of altering the internal geometry. The experimental results are compared to numerical simulations for a greater understanding of the internal flows inside the monolith and to aid in developing a numerical model of the DOC for future work.

By characterizing the flow through the DOC, the DOC construction can be optimized to minimize the pressure drop and improve the light-off characteristics. By decreasing the pressure drop, the back pressure on the engine is reduced improving the overall efficiency and leading to a decrease in fuel consumption. Improved light-off characteristics can lead to a significant reduction in tailpipe emissions, as it has been found that as much as 50% to 80% of emissions are produced during cold start prior to the catalyst reaching light-off temperature [6–8]. Finally, by characterizing the flow through the DOC, the results can be used to validate the numerical models. These models will provide a greater understanding of the flow characteristics and will allow for better optimization of the DOC by manufacturers and provide more efficient control of the system by the engine controller. As it is expected that auto manufacturers will meet emissions regulations through improvements in engine control and aftertreatment systems [1], the ability to optimize these systems is crucial to meeting regulations.

3. Experimental setup

The primary objective of the experiment was to characterize the flow of exhaust gas as it passed through the DOC and to determine the heating characteristics of the DOC. The DOC is connected to a stock Cummins 4-cylinder Diesel engine and a Tornado centrifugal fan with 6.5 HP electric motor, giving the option of directing hot exhaust gas from the engine or cold air from the blower through the DOC. By opening or closing the correct configuration of valves, as shown in Figure 1a, the gas passing through the DOC can be easily switched between hot from the engine or cold from the blower.

The hot exhaust gas can be bypassed around the DOC allowing the engine to reach steady state operation with a constant exhaust temperature prior to directing the gas through the DOC. After passing through the DOC, the exhaust gases pass through a muffler and then are exhausted into an open exhaust conduit drawing exhaust in at slightly lower pressure than the ambient room pressure, as shown in Figure 1a. The engine specifications are outlined in Table 1.

For testing four monoliths with similar construction are used and only differ by containing an insulation ring of a different diameters. The insulation ring is a ceramic material injected into the square channels of the monolith creating a ring approximately 5 mm in thickness. The diameters of the insulation rings are specified in Table 2 and the location of the insulation ring is illustrated in Figure 1b. None of the four monolith have had a washcoat applied as the flow characteristics through the monolith is of interest and not the reaction kinetics, therefore no active catalyst is present.

Orientation	In-Line
Cylinders	4-Cylinder
Displacement	4.5 L
Horsepower	109-170 hp (81-127 kW)
Torque	360-460 ft-lb (488-624 kW)
Aspiration	Turbocharged

Table 1: Engine Specifications

DOC	Description	ID (mm)	OD (mm)
1	No Insulation Ring	N/A	N/A
2	Small Insulation Ring	41 ± 2	46 ± 2
3	Medium Insulation Ring	70 ± 2	75 ± 2
4	Large Insulation Ring	99 ± 2	104 ± 2

Table 2: Inside and outside diameters of monolith insulation rings

The thermocouples used are OMEGA 20G K-Type and are connected to a NI9213 analog input module and read by the computer using LabVIEW. The radial distance of each thermocouple is the same for all of the transient tests (from radial location of 0 to 90 mm) allowing comparison of the heating characteristics for each of the 4 DOC configurations tested. The differential pressure sensor is a stock automotive pressure sensor with a linear relationship between the voltage output and a change in pressure. The pressure taps are located 0.15 m upstream and downstream of the DOC. Fourteen engine operating points were selected to span the engines operating range by varying both the speed and load [9]. A schematic of the measurements is shown in Figure 2.

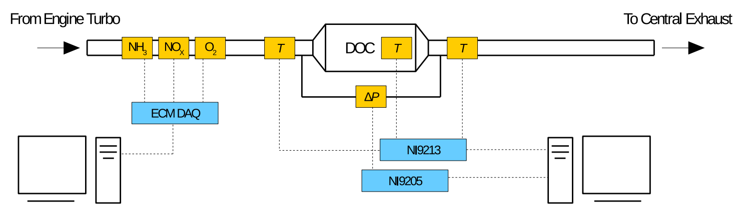


Figure 2: Exhaust setup showing the sensors and data acquisition equipment

4. Simulation

To simulate the flow of exhaust gas through the DOC and the heat transfer from the system, a two-dimensional axisymmetic model in ANSYS Fluent 16.2 was used. The DOC was modeled and meshed using ANSYS ICEM CFD. The monolith is composed of square channels approximately 0.81 mm^2 seperated by cordierite walls approximately 1 mm in thickness. To simplify the model, the exhaust flow through the DOC is assumed to be: a variable density ideal gas, incompressible for the purpose of flow modeling, steady state such that flow pulsations are ignored and premixed such that diffusion is ignored.

The axisymmetric geometry of the model is shown in Figures 3 with dimensions listed in Table 3. All four of the DOC insulation rings were combined into a single model, leaving only the boundary conditions to be altered to give each of the different models. This ensured an identical mesh for each of the four simulations.

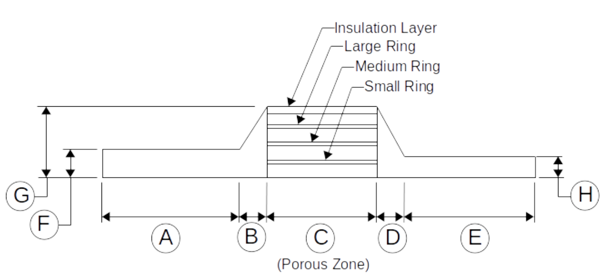


Figure 3: Axisymmetric model used for numerical model of DOC

Dimension	Length (mm)
A	225
B	75
C	105
D	75
E	220
F	35
G	20
H	95

Table 3: Dimensions of DOC as illustrated in Figures 3

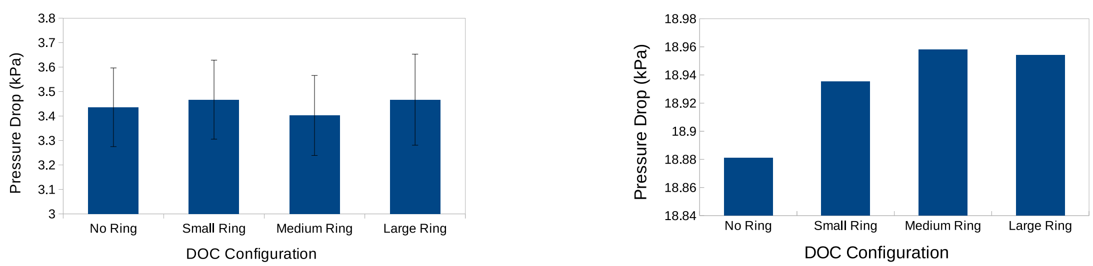
More information about the materials, properties, heat transfer, turbulence and porous zone modelling is available in [9].

5. Results and discussions

Steady State Pressure Drop

Engine tests were carried out to determine what effect adding an insulation ring to the monolith of the DOC would have on the overall pressure drop and the radial temperature profile. Steady state operation is achieved when the exhaust temperature downstream of the DOC reaches a constant value $\pm 1°$C. The differential pressure across the DOC is sampled at 1 Hz with the pressure drop calculated as the mean over the subsequent 10 seconds. Each test is repeated six times for each of the 14 operating points and for each of the four DOCs. The uncertainty in the pressure drop is calculated using a *t*-distribution with a 95% confidence interval.

The effect of the insulation ring on the pressure drop across the DOC for the blower tests is shown in Figure 4a. Any difference in pressure drop between the various sizes of insulation ring in the DOC is smaller than the uncertainty in the pressure drop. The effect of the insulation ring on the pressure drop remains inconclusive as neither the engine nor blower tests indicated any statistically significant difference in pressure drop. The pressure drop results for each of the four DOC configurations are taken from the numerical analysis and shown in Figure 4b. The results indicate that the addition of an insulation ring to the monolith increases the overall pressure drop across the DOC. The increase in pressure drop is expected as the insulation ring decreases the cross-sectional flow area while the overall mass flow rate remains constant. This leads to an increase in the viscous resistance due to the increase in fluid velocity causing an increase in pressure drop.



(a) Experimental

(b) Simulation

Figure 4: Pressure drop across the DOC for each of the DOC configurations

DOC energy absorption and light-off

To determine the effect of the insulation ring on the energy absorbed by the DOC, the energy absorbed by each of the four DOCs was found for each operating points. The energy absorbed by the DOC, $\dot{E}$, is given by,

$$E = \int_0^t C_p(T)\dot{m}\Delta T \, dt \tag{1}$$

where $C_p(T)$ is the temperature dependent specific heat capacity of the exhaust, $\dot{m}$ is the mass flow rate of exhaust through the DOC, ΔT is the temperature difference between the exhaust measured upstream and downstream of the DOC, and t is the time. The specific heat capacity of the exhaust is approximated using the specific heat of air from [10]. Energy transfer from the DOC to the surroundings is calculated by determining the rate of energy absorption by the DOC at steady state since the energy absorbed by the DOC at steady state is equal to the energy lost to the surroundings. To calculate the energy transfer to the surroundings during the transient phase, a linear interpolation is used to give an approximate rate of energy transfer. Because the rate of energy transfer to the surroundings is not linear with temperature, some degree of error is introduced, but because the rate of heating is approximately the same for each of the four DOCs for the same operating point, the relative difference between the DOCs can be compared.

The time required to reach 75% of the steady state temperature is greater for the three DOC configurations containing an insulation ring as shown in Figure 5. The delay in heating of the DOC is likely to negatively affect the light-off characteristics of the DOC since increasing the time to reach light-off increases the amount of NO_x, CO, and HC being emitted to the atmosphere during cold start. However, it is hypothesized that the insulation ring tends to direct greater amounts of the exhaust flow through the central region of the DOC increasing the rate of heating for the core of the DOC. This in turn decreases the time required to reach light-off as the majority of the emissions will be converted in the central portion of the DOC with only a fraction of the exhaust passing through the radial portions of the DOC. This effect needs to be further explored to fully determine whether the insulation ring increases or decreases the time required to achieve light-off using a monolith with a washcoat and active catalyst.

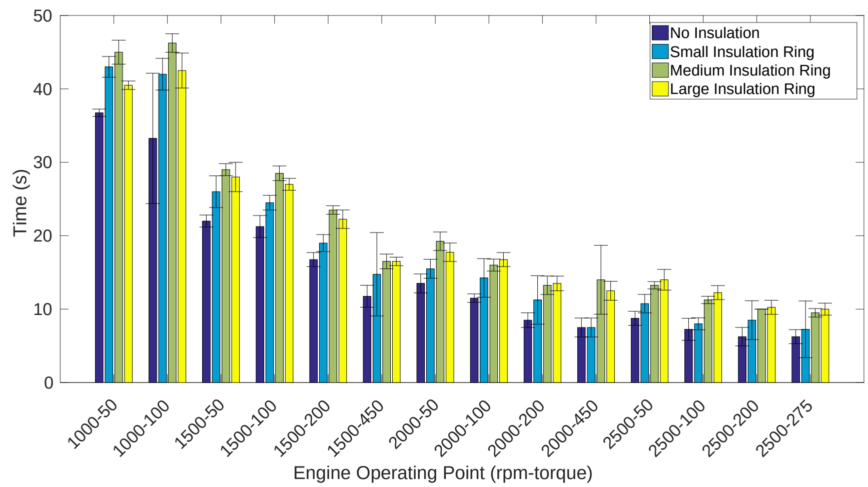


Figure 5: Time required for DOC to reach 75% of steady state temperature. The engine operating points are denoted xxxx-yyy with xxx being the engine rpm and yyy being the engine torque in N.m

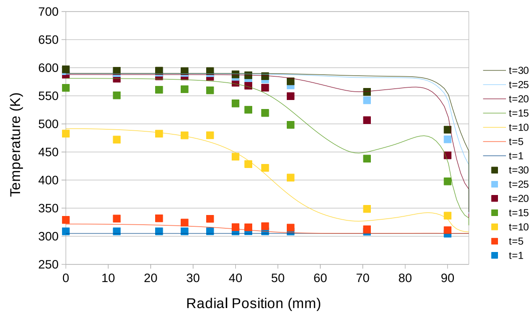
The heating characteristics predicted by the numerical model for each of the four DOC configurations are shown in Figures 6. The heating profile demonstrates that the DOC undergoes the highest rate of temperature increase at the centre of the monolith with the rate of heating decaying with increasing radial distance. The insulating ring reduces the rate of heating adjacent to the ring and shown in Figure 6b to 6d. The decreased rate of heating next to the insulation ring is expected as the flow directly adjacent to the insulation is reduced and the thermal capacity of the ceramic ring is higher than the remainder of the monolith requiring a greater amount of energy to reach steady state.

The numerical model is generally able to predict the heating characteristics of the monolith, showing approximately the same heating profile as the experimental results. The numerical model however underestimates the time required for the monolith to reach the steady state temperature, showing a much faster rate of heating than the experimental data. As the numerical model shows a similar profile to the experimental data, the discrepancy is likely due to incorrectly estimating one of bulk density of the monolith, heat capacity of the exhaust or thermal conductivity of the exhaust.

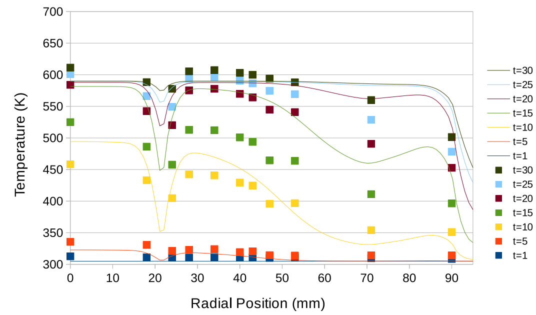
Overall, the ability of the numerical model to predict the transient temperature of the monolith is sufficient for a simple model of the DOC. The ability to use commercial software to obtain good results allows for the optimization of the DOC without requiring each DOC to be tested experimentally.

6. Conclusions

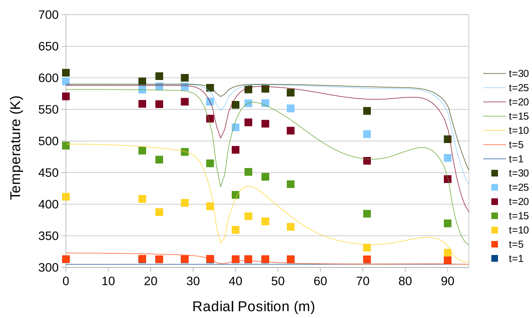
Experimental results show no statistical difference in pressure drop while the numerical model indicates an increase in pressure drop due to decreasing the cross-sectional flow area increases back pressure. Increased back pressure decreases the engine efficiency. Energy absorbed by the monolith increased resulting in a longer time to reach steady state. Numerical model indicates both local increases and decreases in the rate of heating. The insulation ring requires longer to reach steady state. The combination of the local increase and decrease in rate of heating needs to be explored to determine the overall effect on light off.



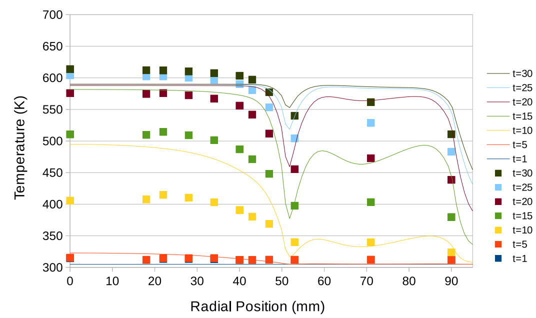
(a) No Insulation Ring



(b) Small Ring at r = 20.5-23 mm



(c) Medium Ring at r = 32.5-35 mm



(d) Large Ring at r = 49.5-52 mm

Figure 6: Heating characteristics of the DOC monolith

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