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Investigating the Performance of a Car Catalyst Cooling Converter Equipped with an Electromechanical Temperature Control System

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Abstract

Controlling the temperature of an automotive catalytic converter is one of the key factors in improving its efficiency. For optimal exhaust gas conversion, the catalyst must operate within a specific temperature range. Theoretical and experimental results indicate that the catalyst achieves its highest conversion efficiency within the temperature range of 300 °C to 600 °C. In this study, a theoretical approach is proposed to prevent the catalyst temperature from exceeding the specified limits. To mitigate excessive temperature increases, a double-walled converter with an asymmetric flow configuration is employed upstream of the main catalytic converter. The exhaust gases pass through this device before entering the catalyst. The cooler was designed with four different lengths: 0.5 m, 1 m, 1.5 m, and 2 m. Its performance was numerically investigated using a commercial finite-volume code. Heat transfer characteristics and their effects on exhaust gas temperature reduction were evaluated. According to the results, the 0.5 m-long cooler reduced the exhaust gas temperature to 291.6 °C. Furthermore, by incorporating the temperature-reduction converter and automatically activating fluid circulation when the critical temperature is reached, the performance of the sensor- and actuator-based electromechanical system was investigated.

Keywords

Car catalyst, Temperature control, Reducing emissions, Control unit, Temperature reducing converter; Numerical simulation

1. Introduction

A vehicle's emission levels depend on several factors, including the type of fuel consumed, the type of engine used, and the emission control systems employed. One of the most important components contributing to the reduction of vehicle emissions is the catalytic converter, which can reduce engine emissions by up to approximately 90%[1-2]. The catalytic converter is an exhaust after treatment device installed in the exhaust gas flow path, between the exhaust manifold and the muffler [3]. Temperature is one of the key parameters affecting the optimal performance and service life of a catalytic converter. It is influenced by several factors, including the installation location, engine load, and air–fuel ratio. When the catalyst surface temperature exceeds 900 °C, the precious metals present on the catalyst surface gradually deteriorate, resulting in a decline in catalytic activity [4]. Figure 1 shows that rapidly heating the catalytic converter during the initial startup period reduces the hydrocarbon (HC) content of the exhaust gases from 800 ppm to 115 ppm. It also reduces the CO concentration from 4% (v/v) to 0.07% (v/v). At low engine startup temperatures, the conversion of exhaust gases is not sufficiently effective. However, once the catalyst temperature reaches 398 °C, the conversion of NOx into N_2 and O_2, as well as CO into CO_2, proceeds effectively. The study also reports that at temperatures above 593 °C, the catalyst substrate undergoes thermal damage, resulting in reduced catalytic efficiency [5].

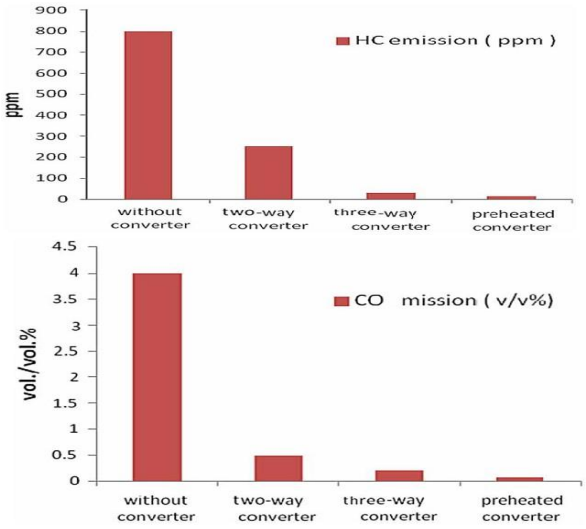


Figure 1. Reduction in exhaust emissions using a catalytic converter equipped with a heater [8].

An automotive catalytic converter exhibits its highest effectiveness in converting pollutant gases within the temperature range of 300–500 °C, which is considered its optimal operating temperature range. The catalytic converter operates in two distinct phases. During the first phase (cold start), the catalyst temperature must be raised to its operating temperature of 300 °C in the shortest possible time to ensure that the conversion of pollutant gases begins with adequate efficiency. In the second phase, the catalyst exceeds its initial operating temperature and, during continuous engine operation, may reach a critical temperature of 600 °C. Exceeding this temperature leads to a decline in catalytic converter performance. The proposed cooling system in the present study is therefore intended to improve catalyst performance during the second phase of operation by controlling and reducing its temperature to the desired range, thereby enhancing the efficiency of pollutant gas conversion.

2. Methodology

As illustrated in Figure 2, the temperature-reducing heat exchanger is a double-pipe type, consisting of two separate flow passages for the fluids. The inner passage carries the pollutant-laden exhaust gases, while the outer passage carries the cooling fluid. The double-pipe configuration was selected because of its simple design and manufacturing process, as well as its relatively low maintenance and repair costs. To enhance the cooling effectiveness and maximize heat transfer from the exhaust gases to the cooling fluid, the two fluids flow through their respective passages in a counter-current (counter flow) arrangement. The designed heat exchangers exhibit different effects on the temperature of the flowing exhaust gases depending on the length of the heat transfer section in contact with the cooling fluid [6]. Accordingly, shorter heat exchangers provide a lower cooling effect, whereas increasing the heat exchanger length enhances its cooling performance. In this study, temperature-reducing heat exchangers with lengths of 0.5 m, 1 m, 1.5 m, and 2 m were analyzed. Among these configurations, the 0.5 m heat exchanger provided the required temperature reduction to maintain the exhaust gas temperature within the desired range of 300 °C to 600 °C.

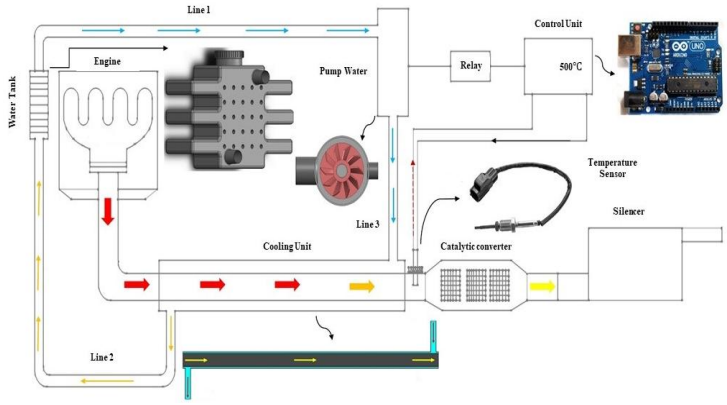


Figure 2. Schematic diagram of the cooling system for exhaust gases entering the automotive catalytic converter.

2-1. Investigation of the Temperature Reduction of Exhaust Gas at the Heat Exchanger Outlet and the Temperature Increase of the Cooling Fluid

The governing equations were solved using the finite volume discretization method in ANSYS Fluent software Figure 3.

The following assumptions were considered for the heat transfer analysis:

1. The fluid flow was assumed to be incompressible and steady-state.
2. Changes in kinetic and potential energy were assumed to be negligible.
3. The combustion products were assumed to behave as an ideal gas.

As shown in Figure 4, the 0.5 m heat exchanger provides sufficient cooling capacity to effectively reduce the temperature of the exhaust gases. When the exhaust gas temperature at the heat exchanger inlet reaches 500 °C (773 K), the cooling system is activated. As the exhaust gases flow from the inlet to the outlet passage, their temperature decreases to 291.6 °C (564.8 K). Meanwhile, the temperature of the cooling fluid increases from 25 °C (298.15 K) to 27.38 °C (300.53 K).for both types of fuel used in the vehicle, the catalytic converter exhibits an appropriate average conversion efficiency within the temperature range of 300 °C to 600 °C. Based on its cooling capacity, the 0.5 m temperature-reducing heat exchanger can maintain the catalytic converter within its desired operating temperature range.

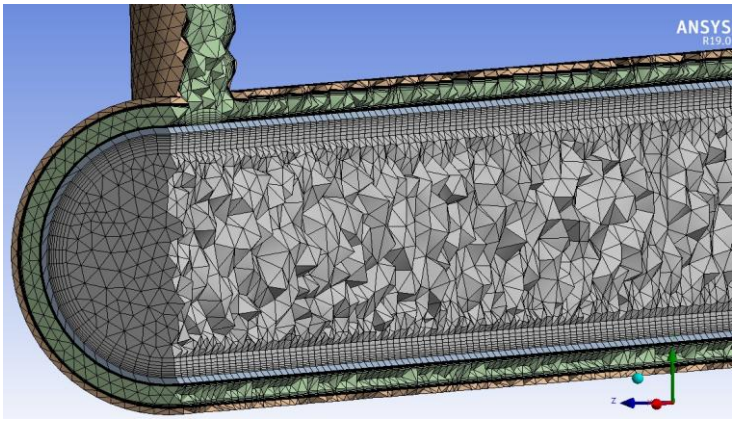


Figure 3. Meshed cross-sectional view of the temperature-reducing heat exchanger.

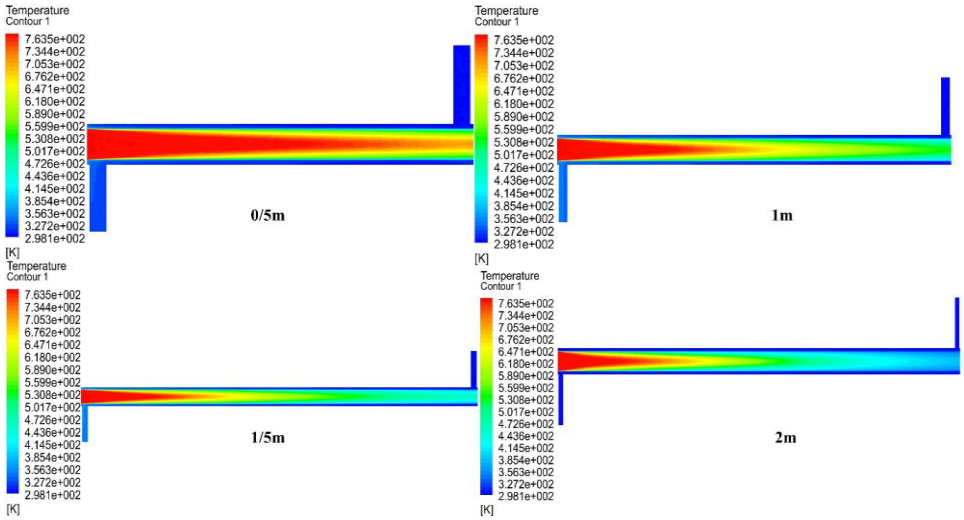


Figure 4. Effect of the cooling fluid on reducing the temperature of exhaust gases at the outlet of the temperature-reducing heat exchanger.

3. Results

The designed temperature-reducing heat exchanger is installed upstream of the automotive catalytic converter and is responsible for reducing the temperature of the exhaust gases entering the converter under critical operating conditions. To select a suitable heat exchanger with the desired cooling capacity, four configurations with lengths of 0.5 m, 1 m, 1.5 m, and 2 m were designed, and the required heat transfer analyses were performed for each configuration. The operating conditions were kept identical for all four heat exchangers, with the only difference being their lengths. The results obtained were used to determine the effect of increasing the heat exchanger length on reducing the temperature of the exhaust gases at the heat exchanger outlet. The exhaust gas temperature at the heat exchanger inlet was set to 500 °C (773 K), the cooling water mass flow rate to 0.1 kg/s, the exhaust gas mass flow rate to 0.00476 kg/s, and the cooling fluid temperature to 25 °C (298.15 K).

4. Conclusions

Based on the investigations conducted in this study, controlling the catalytic converter temperature within the range of 300 °C to 600 °C plays an important role in improving its performance. To regulate the temperature within this range, temperature-reducing heat exchangers with lengths of 0.5 m, 1 m, 1.5 m, and 2 m were designed. Subsequently, numerical simulations were performed to determine the cooling capacity of each heat exchanger. In addition, an electromechanical system was designed and simulated to circulate the cooling fluid and evaluate the feasibility of its implementation.

The main findings of this study are as follows:

1. The analyses demonstrated that increasing the length of the temperature-reducing heat exchanger has a positive effect on reducing the temperature of the exhaust gases entering the catalytic converter.
2. Based on the results obtained for the four heat exchanger configurations, the 0.5 m temperature-reducing heat exchanger can provide the optimum thermal conditions for the catalytic converter in accordance with its cooling capacity.
3. During operation with the 0.5 m heat exchanger, the cooling system reduces the temperature of the exhaust gases entering the catalytic converter by 208.4 °C, lowering their temperature from 500 °C at the heat exchanger inlet to 291.6 °C at its outlet.
4. The electromechanical catalytic converter temperature control system offers considerable flexibility and allows the activation temperature range to be adjusted according to the type of catalytic converter.

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