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Experimental and empirical analysis of an optimized catalytic converter for reducing air pollution from automobiles

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ABSTRACT

The purpose of this research is to find an effective solution for reducing air pollution from automobiles by using the capabilities of copper nanoparticles. After decades of study, the catalytic converter's function in lowering pollution by introducing numerous adjustments to cars is now crystal clear. This research focuses on the advancements in the emissions control capability of catalytic converters utilizing copper nanoparticles in lieu of the noble materials currently utilized in catalytic converters. The prime reason for opting copper nanoparticles over its counterparts is its highly active surface area which facilitates effective reduction of exhaust emissions when they pass through the copper nanoparticles coated catalytic converter. Copper nano-particles have an excellent thermal and electrical conductivity apart from being non-toxic in nature. This research paper presents an experimental and empirical for analysis of performance an optimized catalytic converter coated with copper nanoparticles. From the obtained experimental and simulation results, it was found that the optimized catalytic converter with copper nanoparticles exhibited remarkable performance in restricting the emissions for different conditions of load on the considered four stroke spark ignition engine. The modeling and simulation performed in this research helps in analysis and replicating the results of the considered four stroke spark ignition engine set up with catalytic converter for all loading conditions in the range. The shortcomings of copper nanoparticles like increase in complexity of structure and issues of in heat management are faintly critical compared to its promising benefits for emission control. The research work leads to an effective and reliable solution for control of exhaust emissions from petrol vehicles using the capabilities of copper nanoparticles coated catalytic converter.

Keywords: Catalytic converter, modeling, performance, pollution, simulation.

INTRODUCTION

The world is presently experiencing an environmental crisis as a result of the rapid growth in population and the consequent need for resources, which has drastically intensified urbanization and commercialization. In order to forecast air pollution due to transportation, new and better models have been created internationally [Jonidi et al., 2021; Deepak et al., 2015]. The system that turns fuel into water and carbon dioxide inside of an engine is far from optimal or fully effective. To deal with this issue, several policies and regulations have been created. The quantity of hazardous substances that can be produced by an automotive exhaust is limited by emission rules [Hasan et al., 2021; Gendron et al., 2022; Borck et al., 2021]. Carbon monoxide and hydrocarbons may be effectively reduced with the use of catalytic converters [Manisalidis, 2020; Kumar et al, 2021; Glencross et al., 2020; Tainio et al., 2021]. The amount of hydrocarbons that have not been burnt is measured in parts per million of the hydrocarbon chains [Costa et al., 2020; Turner et al., 2020; Shepelev at al., 2021]. Two regularly used techniques for sanitizing or purifying ambient air are catalytic converters and air injection systems [Deepak et al., 2016; Thakur et al., 2013; Deepak et al., 2018, Manojkumar et al., 2021].

Catalytic converters are now employed to lessen the pollution that is spread by vehicle exhaust emissions [Kritsanaviparkporn at al., 2021; Rathore et al., 2018; Saravanakaumar et al., 2024].

The catalytic converter which possesses magnetic and chemical features that allow for use in biological nano-sensors, optoelectronic devices, nano devices, nano electronics, information storage, and catalysis is the most effective pollution-control technique [Deepak et al., 2017; Astruc, 2020; Chaudhary et al., 2022; Jamkhande et al., 2019]. Copper's exceptional conductivity, exceptional biocompatibility and high catalytic activity will be given significant importance [Hammami et al., 2021; Saleem at al., 2022; Taran et al., 2021]. Nanocrystal, nonlinear optical devices and systems, copper metal that is consistently segregated in silica layers has lately attracted a lot of interest [Alahdal et al., 2023; Madhusha et al., 2023; Luque et al., 2023]. Given that the size quantization effect results in the emergence of novel functionalities, these composite materials offer an exciting potential for usage in thin film electronics. It will becoming more and more important to be able to scale up synthesis to a bulk scale as new applications are developed. However, the majority of synthetic procedures call for high temperatures and pressures in order to recycle the particles, which either results in the loss of the particles' catalytic activity and capacity or in the development of an irregular shape and broad size dispersion [Al-Hakkani et al., 2020; Deepak et al., 2016; Samim et al., 2007].

Out of the main metals like silver (Ag), palladium (Pd), platinum (Pt), gold (Au) and on which many works on nanotechnology have been carried out, copper has become a significant player in manufacturing electronics and electrical circuits on account of its excellent electrical and thermal conductivity along with less cost [Feldheim et al., 2004]. Nano-copper particles were synthesized using sodium borohydride reduction of copper ions, allowing particle size manipulation through reactant and capping agent concentration adjustments. The results obtained by experiments conducted demonstrated that nano-sized copper catalyst particles significantly improved overall combustion reaction performance. All pollutants were reduced and the innovative fuel mix enhanced engine performance parameters [Rajesh et al., 2016].

This research work aims to fill the gap of identification of a suitable method for control of air pollutants from petrol engine vehicles by utilizing the capabilities of copper nanoparticles coated on the considered catalytic converter. The proposed method is targeted towards achieving an environmental friendly solution to mitigate the issue of rising air pollution from petrol engine automobiles.

METHODOLOGY

Design of a catalytic converter

In order to safeguard human health, carbon monoxide—one of the most harmful and hazardous gases in our atmosphere—must be entirely oxidized at room temperature. The catalytic converter being updated and improved in this study has a small input and output diameter and a high inclination angle. The model's updated design is more effective at lowering exhaust emissions from four-stroke spark-ignition engines owing to increased performance and efficiency.

The idea's fundamental tenet is that nanoparticles have the ability to minimize the concentrations of CO and HC emissions. In the converter, oxidation and reduction are accomplished using copper catalyst. The target of this research is to design and develop a structure that provides the biggest catalytic active surface to the exhaust gases while using minimum quantity of catalyst. The catalytic reaction occurs at nanoscale surfaces upon the interaction of automobile exhaust gases with a catalyst bed. Because tiny nanoparticles have a greater catalytic surface area than larger particles, copper oxides have a porous nature better catalytic effectiveness.

By passing exhaust gases via catalytic converters, the quantity of harmful emissions that are discharged into the environment during oxidation of carbon-containing products in motor vehicles is decreased, significantly lowering air pollution. The catalytic converter used in automobile exhaust is a pollution-control mechanism that converts more dangerous pollutants into less dangerous ones through catalytic reactions. The catalytic converters promote the formation of Carbon dioxide and help to ensure that they destroy more toxic compounds but on the issue of climate change, they produce an unfavorable effect. The design of catalytic converters will be improved by effective numerical simulation and mathematical modeling, which will decrease the number of trials and offer time-saving solutions. The catalytic converter's configuration is depicted in Figure 1 as a tubular structure with a circular grid on the inside surface. Because of its design, the system's surface area, the region where gases interact with it, and the time it takes for that contact to happen have all been greatly increased. Several changes and enhancements have been made to increase the holding period of exhaust emissions so as to facilitate more time for oxidizing and minimizing the concentrations of dangerous emissions.

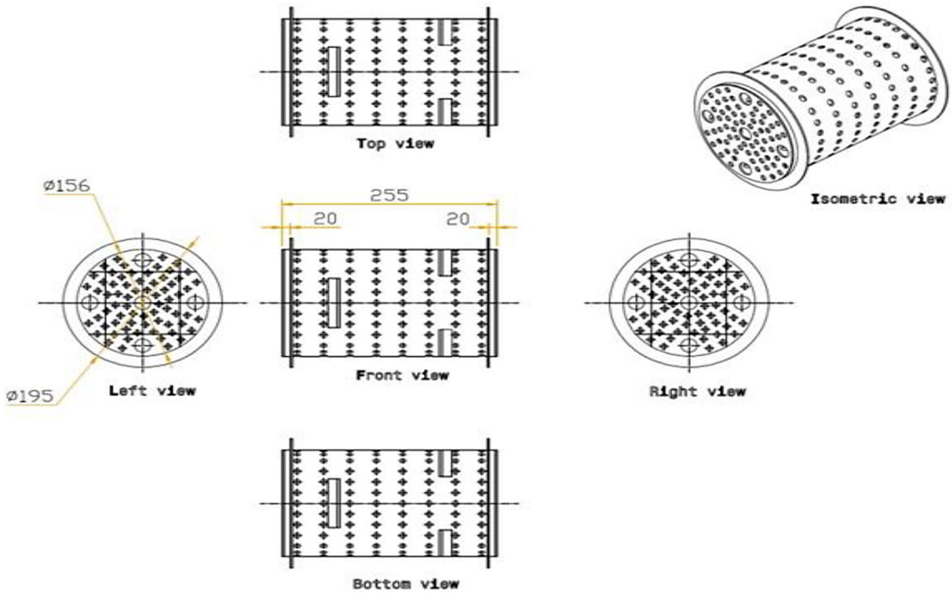


Figure 1. Different views with dimensions of designed catalytic converter (all dimensions in mm)

Size, coating method and morphology of copper nanoparticles coated on the catalytic converter

In this research work, a technique for reducing exhaust emissions from petrol, four-stroke, single-cylinder engines is presented. Copper nanoparticles having dimension range of 40–50 nm was used in solvent of Ethylene glycol and then applied on to the catalytic converter in multiple layers using drop casting method to obtain a uniformly distributed coat of copper nanoparticles. Then, the coat was dried at a temperature of about 200 °C for approximately two hours in an apparatus of a hot air oven. The above procedure was repeated again for proper adhesion of another copper nanoparticles layer over the previous obtained layer (Figure 2).

Experimentation using a four-stroke S.I. engine set up

The experimental set up used to the capability of considered catalytic converter by carrying out experimentation for measuring the concentrations of CO and HC emissions at various loads on the engine with and without using the new proposed catalytic converter. The procedure of the experimentation involves the measurement of emissions with and without using the catalytic converter at dynamic loading conditions on engine. The load was measured using a rope brake dynamometer attached with the test rig. The measurement of the exhaust emissions concentrations was done using a mutli gas analyzer. Behavioral modeling and simulation was then performed for mathematical analysis of the behavior of the new proposed catalytic converter for varying loading conditions on the S.I. engine.

The following Figure 3 shows the various components of the four-stroke S.I. engine test rig used for evaluating effectiveness of proposed catalytic converter and Figure 4 shows the used multi gas analyzer.

Specifications of engine:
- Type: S.I. engine
- Number of strokes: 4
- Bore: 0.07 m
- Stroke: 0.07 m
- Fuel: gasoline/petrol
- Cylinders in engine: 1
- Horse power of engine: 3

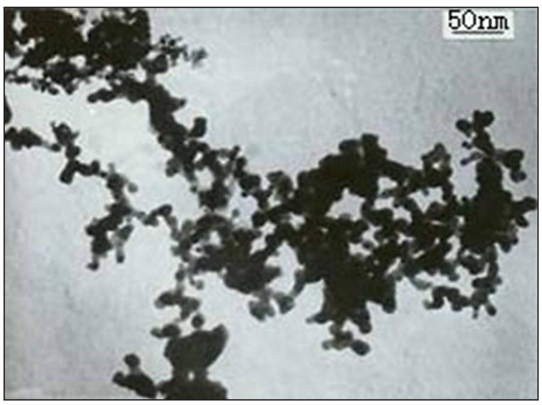


Figure 2. Image of TEM for copper nanoparticles

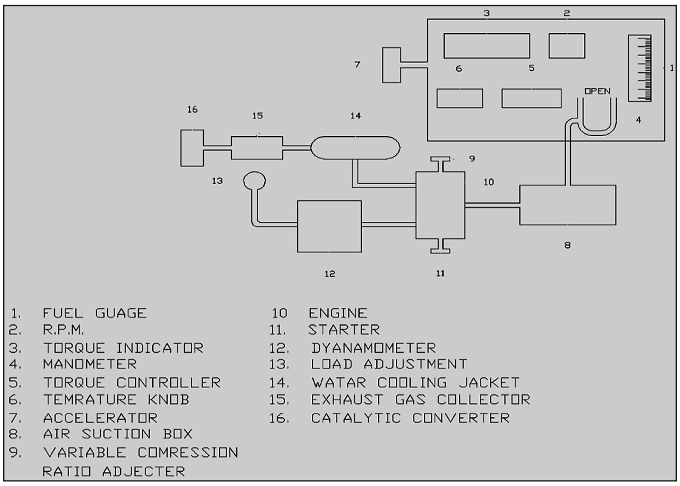


Figure 3. Experimental setup of four-stroke S.I. engine test rig

Figure 4. Multi gas analyzer for measuring the exhaust emissions concentrations

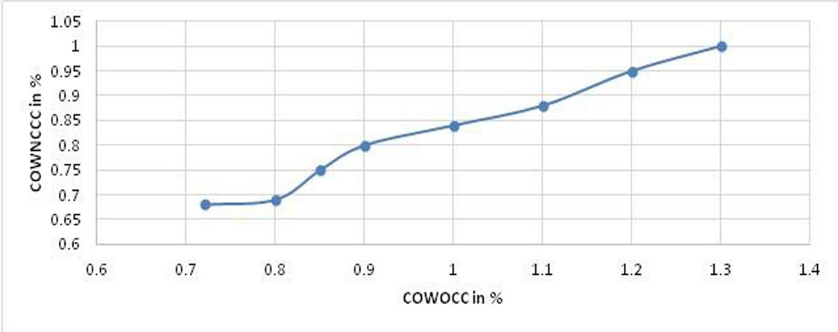
Behavioral modeling and simulation of an optimized catalytic converter

In this section, mathematical analysis of an optimized nano-copper coated catalytic converter is presented which was attached with a test rig of four-stroke spark ignition engine.

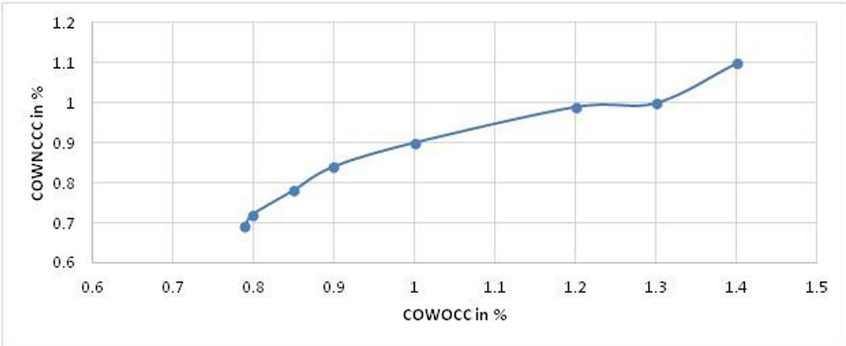
- Step 1 – behavior analysis: Figures 5 and 6 show corresponding plots.
- Step 2 – the obtained equations for reduced COWCCC and HCWCCC are shown in Equation 1, where: x = COWOCC of engine (Fig. 7) and Equation 2, where: x = HCWOCC of engine (Fig. 8).
- Step 3 – modeling of above equation in MATLAB Simulink.

$$COWNCCC = \begin{cases} 8.312x^4 - 33.42x^3 + 49.55x^2 - 31.52x + 7.915, & \forall\ 5 \le Load \le 12 \\ 4.853x^4 - 17.41x^3 + 21.24x^2 - 9.087x + 1.314, & \forall\ 12 \le Load \le 20 \end{cases} \quad (1)$$

$$HCWNCCC = \begin{cases} 1.818x - 1000,\ \forall\ 5\,kg \le Load \le 6\,kg \\ 1.507x - 515.6,\ \forall\ 6kg \le Load \le 8\,kg \\ 1.423x - 472.6,\ \forall\ 8\,kg \le Load \le 10\,kg \\ 0.2x + 530,\ \forall\ 10\,kg \le Load \le 12\,kg \\ 1.9x - 768,\ \forall\ 12\,kg \le Load \le 14\,kg \\ 0.07143x + 697.1,\ \forall\ 14\,kg \le Load \le 16\,kg \\ 1.742x - 747,\ \forall\ 16\,kg \le Load \le 18\,kg \\ 2.125x - 1333,\ \forall\ 18\,kg \le Load \le 20\,kg \end{cases} \quad (2)$$

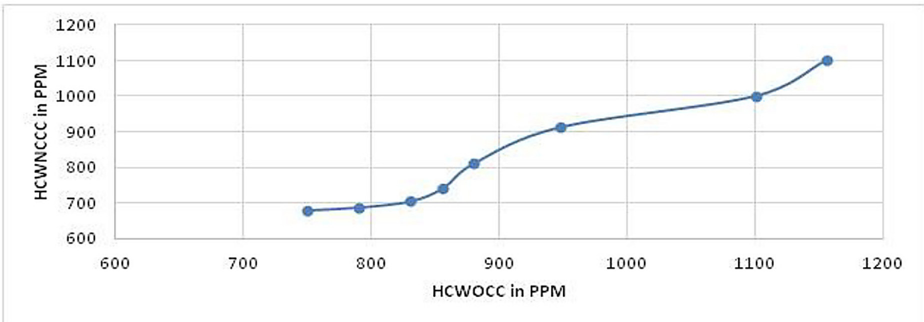


(a)

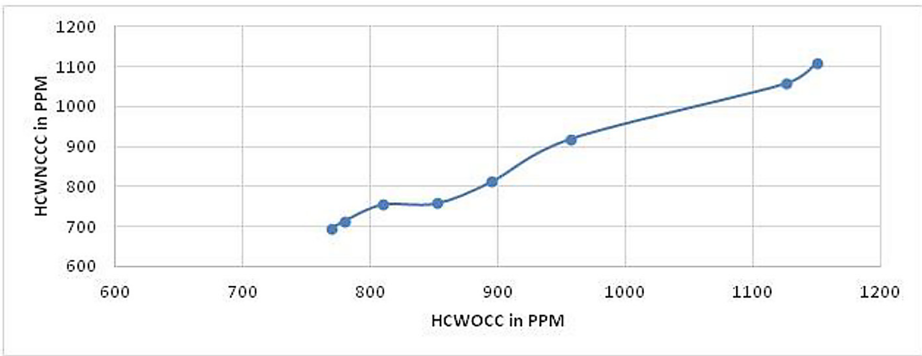


(b)

Figure 5. Plot of COWNCCC with respect to COWOCC: (a) for 5 kg ≤ load ≤ 12 kg, (b) for 12 kg ≤ load ≤ 20 kg. COWNCCC – carbon monoxide percent with new proposed copper catalytic converter; COWOCC – carbon monoxide percent with optimized catalytic converter

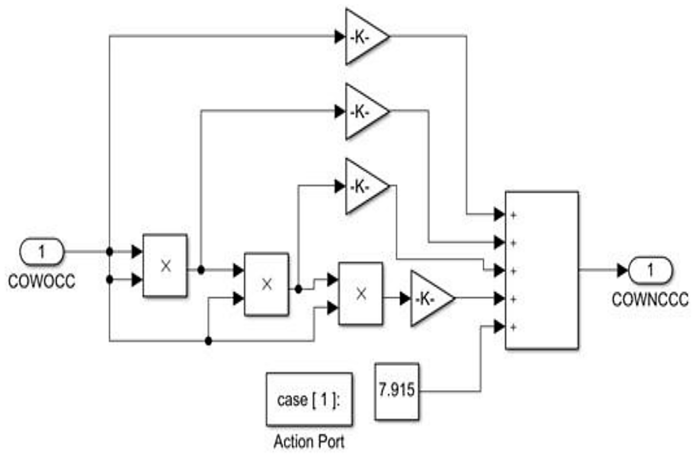


(a)

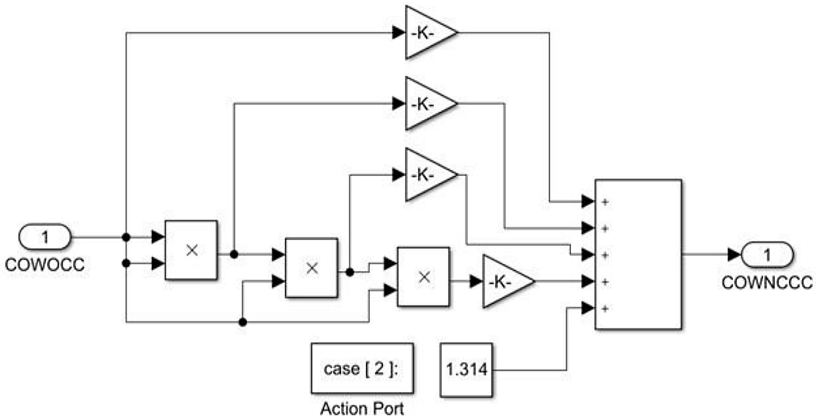


(b)

Figure 6. Plot of HCWNCCC with respect to HCWOCC: (a) for 5 kg ≤ load ≤ 12 kg, (b) for 12 kg ≤ load ≤ 20 kg. HCWNCCC – hydrocarbons emissions with nano copper coated catalytic converter; HCWOCC – hydrocarbons emissions without catalytic converter; PPM – parts per million



(a)



(b)

Figure 7. Actual simulation model for output variable COWNCCC of optimized catalytic converter: (a) for 5 kg ≤ x ≤ 12 kg, and (b) for 12 kg ≤ x ≤ 20 kg

RESULTS AND DISCUSSION

The final structure of the complete model of optimized catalytic converter is shown in Figure 9.

Simulation for the complete set up

The simulation for the complete set up is depicted in the following Figure 10. The jagged curves on COWNCCC vs COWOCC (as shown by Figure 5) and HCWNCCC vs HCWOCC (as shown by Figure 6) plots indicate that the values of CO and HC obtained by using the copper nanoparticles coated catalytic converter is far lesser as compared to those obtained without catalytic converter at all the loading conditions on the engine within the range. So, for all the loading conditions on the engine, the copper nanoparticles coated catalytic converter has the ability to reduce the CO as well as HC emissions concentrations.

A comparison of CO & HC values for the practical and simulation is shown in Table 1. The average deviation of the practical and experimental values for CO and HC as depicted in the previous table is very small. The minimum percent error for CO values has been obtained as 0.119% and the maximum percent error as 7.521%. The minimum percent error for HC values has been obtained as 0.0% and the maximum percent error as 0.054%.

The results clearly showcase the validity of the developed mathematical model in reproducing the performance of the considered four stroke S.I. engine test rig firstly with and then, without using optimized copper nanoparticles particles coated catalytic converter. The developed model may be used to obtain the values of reduced CO and HC concentrations by using the considered catalytic converter coated with copper nanoparticles for all values of load in the range.

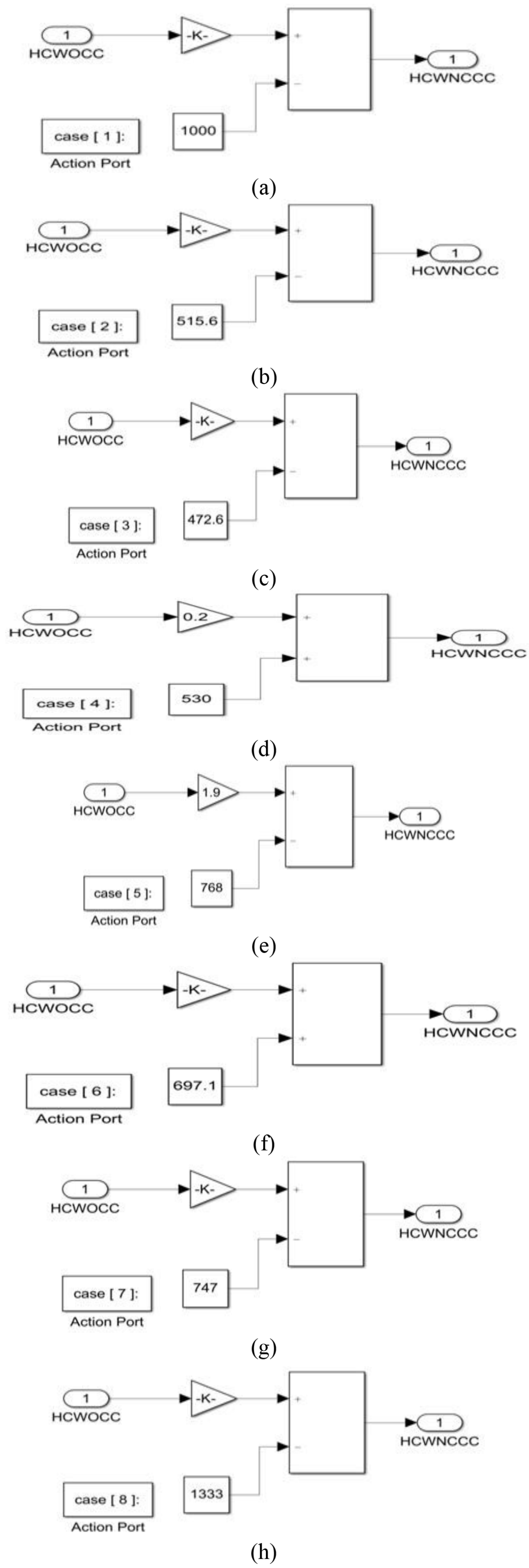


Figure 8. Actual simulation model for output variable HCWNCCC of conventional catalytic converter: (a) for 5 kg $\leq x \leq$ 6 kg, (b) for 6 kg $\leq x \leq$ 8 kg, (c) for 8 kg $\leq x \leq$ 10 kg, (d) for 10 kg $\leq x \leq$ 12 kg, (e) for 12 kg $\leq x \leq$ 14 kg, (f) for 14 kg $\leq x \leq$ 16 kg, (g) for 16 kg $\leq x \leq$ 18 kg (h) for 18 kg $\leq x \leq$ 20 kg

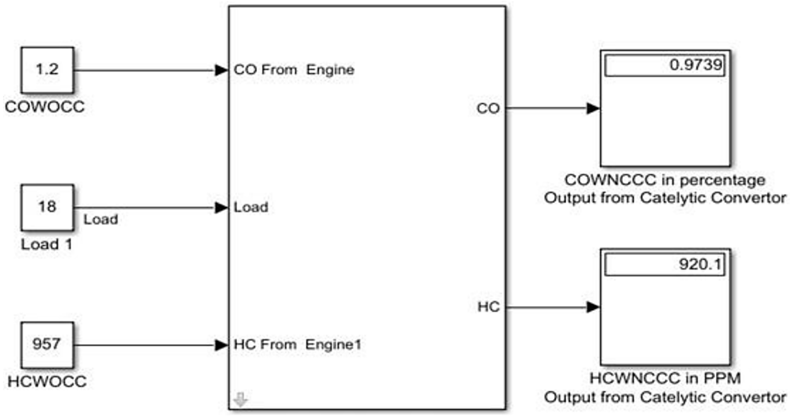


Figure 9. Complete model of optimized catalytic converter

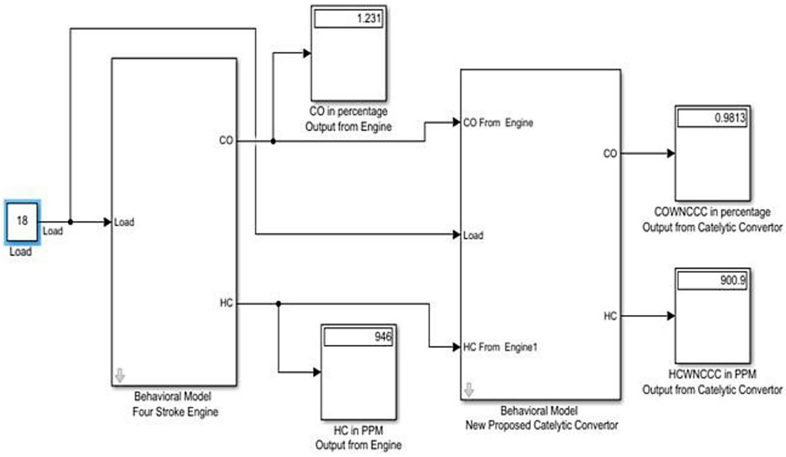


Figure 10. Complete model of four-stroke engine with optmized catalytic converter

Table 1. Comparison of CO and HC with optimized catalytic converter

Load (kg)	COWOCC			HCWOCC		
	Practical (%)	Simulation (%)	Error (%)	Practical (PPM)	Simulation (PPM)	Error (%)
5	1	1.00	0.134	1100	1100	0.019
6	0.95	0.93	1.789	1000	1000	0.020
7	0.88	0.89	1.145	912	912	0.052
8	0.84	0.84	0.119	811	811	0.054
9	0.8	0.78	2.897	742	742	0.015
10	0.75	0.74	1.102	705	705	0.016
11	0.69	0.71	2.689	688	688	0.000
12	0.68	0.67	1.305	680	680	0.000
13	0.69	0.70	1.815	695	695	0.000
14	0.72	0.71	1.590	714	714	0.000
15	0.78	0.74	4.906	755	755	0.006
16	0.84	0.78	7.521	758	758	0.005
17	0.9	0.84	6.556	812	812	0.011
18	0.99	0.93	5.757	920	920	0.010
19	1	1.00	0.134	1060	1060	0.024
20	1.1	1.14	3.264	1111	1111	0.023

Note: PPM – parts per million.

CONCLUSIONS

In this research work, the goal was to develop an effective method for controlling the air pollution from S.I. engine powered automobiles. The considered catalytic converter was designed, coated using nanoparticles of copper and then tested in experimental conditions for assessment of the fruitfulness of the developed method. The gap found during the literature review was the need for development of a suitable method for control of air pollution from automobiles that is effective, environmental friendly and easy to implement. After getting satisfactory results from experimentation, mathematical modeling was deployed to develop a framework of mathematical equations to generalize the behavior of the developed system. Simulation was done to validate the model developed.

Mathematical model developed in this research work gives minimal percentage errors for the values of Carbon Monoxide and Hydrocarbons with and without using Copper nanoparticles Coated Catalytic Converter when obtained values from mathematical model are compared with the experimental values of Carbon Monoxide and Hydrocarbons. This validates the mathematical model and hence, it can be used to find the values of emissions at different loading conditions on the engine. The range of loading conditions used in developing the modeling behavior equations for CO and HC from the engine and catalytic converter have been made on the basis of the curve fitting approach used on MATLAB to obtain well defined and accurate curves depicting clear variation of CO and HC for varying conditions.

The model has been developed on the basis of the employed experimental conditions and the equations have been developed entirely by applying the curve fitting approach in MATLAB by different iterations so as to give an accurate prediction of the actual experimental behavior of the considered practical setup. The model will be effective for all the permissible loading conditions on the Spark Ignition engine. The results obtained also disclose that after using copper nanoparticles coated catalytic converter, the automobile emissions have significantly decreased. So, considered nano-copper coated catalytic converter can be very effective in controlling the Carbon Monoxide and Hydrocarbons concentrations. Here, an efficient catalytic converter design is suggested in light of the growth of environmental pollution by vehicles, which is supported by research and analysis. Nano coating has been applied to the surface of a catalytic converter to lengthen the retention time of exhaust gases, which has been utilized to speed up the response rate of exhaust gas from four-stroke petrol engines. The effectiveness for long term along with durability of copper nanoparticles depends on the working conditions of the engine and the temperature inside catalytic converter. For a properly maintained engine and warming temperature of above 300 °C approximately, the catalytic converter coated with copper nanoparticles can work effectively up to 1–1.2 lakh kilometers covered by the vehicle installed with copper coated catalytic converter. However, at improper working conditions and temperatures below 300 °C in the catalytic converter, the efficiency may be lesser. The use of copper may lead to creation of Nitrogen Oxides (NOx) at high temperatures but the issue is of less concern for spark ignition engines. The chances of formation of NOx are high in compression ignition engines due to high temperatures developed.

Experimental conditions were used to create a simulation environment for the optimization of the obtained equation for the intended catalytic converter in the steady state for analyzing the ability to reduce Carbon Monoxide and Hydrocarbons emissions. Since, the proposed method can be adapted to any of the considered Four Stroke Spark Ignition engine; it is also scalable for commercial purpose. The optimized catalytic converter with copper nanoparticles coated on the surface gives and effective reduction in emissions concentrations when compared to other catalytic converters working on nobles metals. So, the proposed method is productive for air pollution control from spark ignition engine automobiles. The limitations of the research work include the experimental conditions affecting the results of the research work. The future course of work involves improvements in the method for increasing the efficiency of the developed method.

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