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Analysis and Mathematical Prediction for the Practical Behavior of Proposed and Optimized Catalytic Converter Implemented on a Test Rig of Four Stroke Spark Ignition Engine to Control Emissions

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Abstract

This research is pivoted on a comprehensive behavioral model of a four stroke engine, achieved through advanced simulation techniques. The model accurately reproduces the engine's operational traits, combustion processes, and emission generation under diverse operating conditions. A distinctive element of this research involves integrating a catalytic converter coated with copper nanoparticles, aimed at leveraging copper's catalytic properties to enhance the conversion of harmful exhaust pollutants into less noxious substances. The primary objective of this investigation revolves around assessing the efficacy of the specially designed copper nano-coated catalytic converter in mitigating environmental pollution. This assessment entails a thorough analysis of how the converter interacts with exhaust emissions to effectively diminish air pollutants. By combining both simulation and empirical inquiries, this study thoroughly evaluates the performance of the copper nano-coated catalytic converter, quantifying its prowess in catalyzing and transforming pollutants. This, in turn, contributes to a cleaner exhaust and a lessened environmental impact. The implications of the research findings are of significant importance to environmental sustainability, particularly concerning the management of pollution stemming from internal combustion engines. The successful implementation of the copper nano- coated catalytic converter presents a pioneering and efficient avenue for addressing the adverse consequences of vehicular emissions on both air quality and public health. The achievements of this research work are the identification of an effective method for controlling air pollution from spark ignition engine automobiles using the capabilities of copper nanoparticles. The limitations of copper nanoparticles like supplementing to the structure complexity and concerns of heat management are trivial as compared to the significant benefits offered by the implementation of this method.

Major Findings: *This major finding of this research work entails a thorough analysis of how a nano-particles coated catalytic converter interacts with exhaust emissions to effectively diminish harmful air pollutants. By combining both simulation and empirical inquiries, this study thoroughly evaluates the emission control potential of a catalytic converter, quantifying its prowess in catalyzing and transforming pollutants. 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, Copper Nanoparticles, Four Stroke Engine, Public Health, Vehicular Emissions*

**Author for correspondence*

1.0 Introduction

The ever-increasing demand for efficient and eco-friendly automotive technologies has spurred a new era of research and innovation. In this context, the present study unveils a pioneering approach towards enhancing the environmental compatibility of internal combustion engines. Focusing on the four stroke engine, a fundamental component of vehicular propulsion, this research delves into the development of an intricate behavioral model. This model, meticulously crafted through advanced simulation techniques, serves as a reliable representation of the engine's multifaceted characteristics, encompassing its operational behavior, combustion dynamics, and emission generation profiles across a spectrum of operating conditions. A notable and distinctive facet of this study lies in the integration of a catalytic converter embellished with copper nanoparticles. The rationale behind this innovation rests on the catalytic prowess exhibited by copper nanoparticles, offering a gateway to amplify the conversion efficiency of noxious exhaust pollutants into less harmful byproducts. Central to the investigation is the evaluation of the novel copper nano-coated catalytic converters efficacy in ameliorating environmental pollution. This evaluation unfolds through an exhaustive analysis, meticulously examining the converter's intricate interactions with exhaust emissions. Its role in diminishing air pollutants takes center stage. A comprehensive evaluation for copper nano-coated catalytic converters performance is a two-pronged endeavor, intertwining simulation-based predictions with empirical investigations.

Through this meticulous approach, the study rigorously quantifies the converter's adeptness in catalyzing and transforming pollutants, thereby driving towards a cleaner exhaust emission profile and a correspondingly reduced environmental impact.

The implications of this research reverberate with profound significance in the realm of environmental sustainability. As concerns mount over air quality deterioration, the successful integration of the copper nano-coated catalytic converter offers a promising and effective countermeasure. By curbing the adverse repercussions of vehicular emissions, particularly from internal combustion engines, this innovation presents a pioneering pathway toward safeguarding air quality and public well-being. As the study's findings unfold, they stand to reshape the discourse surrounding pollution control strategies, thereby contributing to a cleaner and healthier future for all. The world is currently in the midst of an environmental crisis, brought about by the steady increase in population growth and the resulting demand for resources. This has led to a rapid escalation of urbanization and commercial activities, exacerbating the tragic issue. The detrimental impacts include heightened levels of noise, air, and water pollution. The term "air pollution" refers to the suspension of one or more hazardous emissions in air over an extended period. This pollution jeopardizes not only human health but also the well-being of plant and animal life. To predict and manage air pollution stemming from transportation, innovative models have been developed on a global scale[1-3].

Unfortunately, the process by which engines convert fuel into water and carbon dioxide is far from optimal or fully efficient. Consequently, arrange of policies and regulations has been instituted to address this pressing issue. Emission standards restrict the quantity of harmful substances emitted by vehicle exhausts. The pollutants covered by these laws encompass particulate matter, carbon monoxide, nitrogen oxides, and hydrocarbons. Among these, carbon monoxide poses the most serious threat and can be effectively reduced through the application of catalytic converters[4-6].

Incomplete combustion in automobile engines results in the release of unburned hydrocarbons. The measurement of these unconsumed hydrocarbons, expressed in parts per million, allows for the calculation of combustion efficiency. The process of purifying exhaust gases before they are released into the environment is known as "exhaust gas treatment"[7-8]. Carbon monoxide, when inhaled, obstructs the transportation of oxygen to vital organs such as the brain and heart, posing significant health risks. Sulfur dioxide (SO_2) is produced through the combustion of sulfur present in automobile fuels, notably diesel. When released into the atmosphere, sulfur dioxide can form fine particles that pose health risks, especially to young children and individuals with asthma. Harmful air pollutants consist of chemical compounds emitted by various sources, including automobiles, trucks, refineries, and gas pumps[9-13]. Two commonly employed methods for purifying ambient air are catalytic converters and air injection systems. Catalytic converters are extensively used to mitigate the pollution emanating from vehicle exhaust emissions. Nanoparticles are proposed as potential inhibitors of harmful combustion product formation, with copper catalysts facilitating oxidation and reduction reactions within the converter.

The goal is to construct a catalyst system that maximizes catalyst surface area exposed to exhaust gases while minimizing catalyst usage[14-18].

Among the precious materials explored in nanotechnology, copper and copper-based compounds, along with Au, Ag, Pd, and Pt, hold particular significance. Recent interest has grown in incorporating copper metal, consistently segregated within silica layers, into nonlinear optical devices and systems. As new applications emerge, the need to scale up synthesis to a bulk level becomes increasingly important. Most synthetic procedures involve high temperatures and pressures for particle recycling, often leading to diminished catalytic activity or irregular particle characteristics[19-26]. Copper nanoparticles are synthesized using sodium borohydride reduction of copper ions, allowing particle size manipulation through reactant and capping agent concentration adjustments[27]. The updated converter design, characterized by a small input or output diameter and high inclination angle, demonstrates improved exhaust emission reduction due to increased efficiency. Catalytic reactions occur at the nanoscale surfaces when exhaust gases interact with the catalyst bed. Copper oxide nanoparticles, possessing porous structures and heightened catalytic effectiveness for hydrocarbon and carbon monoxide oxidation, are integrated into the catalytic converter[28-32].

Of the noble metals like Silver (Ag), Gold (Au), Palladium (Pd) and Platinum (Pt) and on which many researches on nanotechnology have been carried out, copper has become a prime player in manufacturing electronics and electrical circuits due to of its excellent electrical and thermal conductivity along with lesser cost[33]. Nano-copper particles were synthesized by the use of sodium borohydride reduction of copper ions, facilitating particle size manipulation through reactant and capping agent concentration adjustments. The results obtained by experiments conducted indicated that nano-sized copper catalyst particles significantly enhanced overall combustion reaction performance[34].

This research work targets to cover 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 directed towards achieving an environmental friendly solution to mitigate the issue of rising air pollution from petrol engine automobiles so that the environment can be made cleaner and air quality may be improved.

2.0 Materials and Methods

2.1 A New Proposed Catalytic Converter for Emissions Control from S.I. Engine Automobiles

A catalytic converter was proposed based on the specified design, featuring a tubular structure with an inner circular grid as shown in Figure 1. This design significantly enhances surface area, gas-catalyst interaction region, and interaction time.

To assess its effectiveness, exhaust emissions of CO and unburned HC were analyzed and compared across different engine loads using an exhaust gas analyzer. To prolong the interaction time between exhaust gases and the catalyst, various modifications and improvements were implemented in this research. The goal of these changes is to facilitate increased oxidation time for exhaust gases, ultimately leading to a reduction in harmful emissions. After experiment, modeling was conducted to estimate the functioning of the system mathematically and simulation model was developed and tested for validation of obtained modeling results.

2.2 Experimental Setup of Four Stroke S.I. Engine Test Rig for Testing the Catalytic Converter

The following Figure 2 shows the various components of the four stroke S.I. engine test rig used for checking the effectiveness of the proposed catalytic converter.

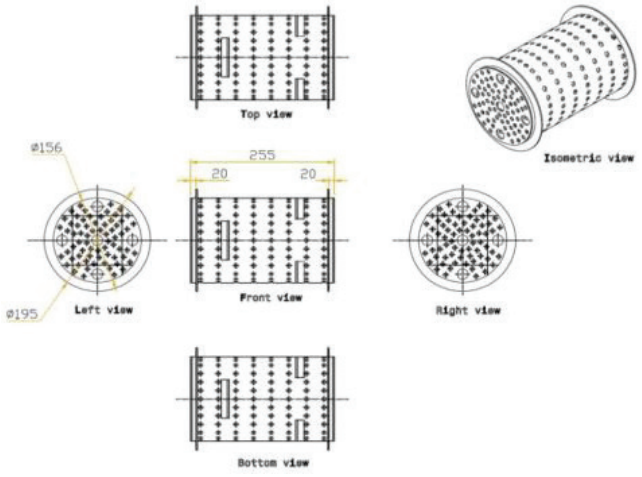


Figure 1. Different views of a new proposed catalytic converter.

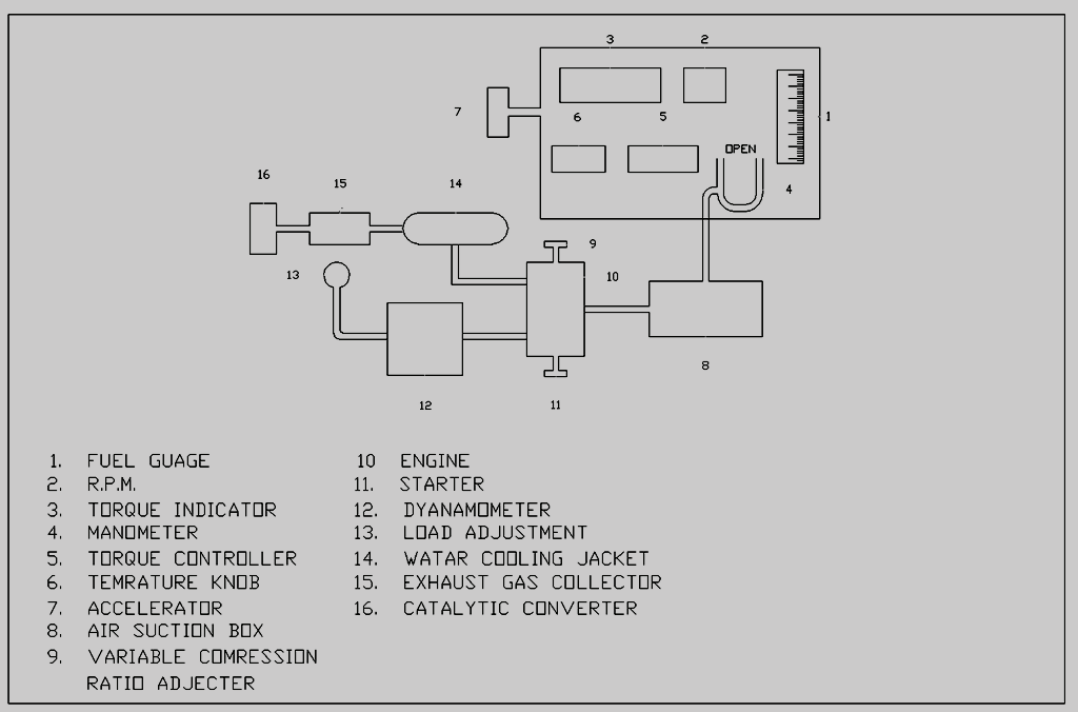


Figure 2. Experimental setup of four stroke S.I. engine test rig

The above experimental set up was used to test the effectiveness of the new proposed 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 withand without using the new proposed catalytic converter in a four stroke S.I. engine test rig at different 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.

2.3 Behavioral Modeling

Motivation behind adopting a behavioral approach is to establish a systematic framework for analyzing systems that remains consistent with the fundamental principles of physics. Even if a combination of ideal or theoretically unrealistic components is utilized, as long as the resulting simulation accurately reproduces the behavior of the system being studied, the behavioral approach achieves its objective. In the first step, the behavior of the S.I. engine test rig equipped with the proposed catalytic converter was implemented and approximated using mathematical equations. These equations serve as a representation of the target system's behavior. Once these mathematical equations were derived, the subsequent step involved their implementation within the MATLAB Simulink platform. The final stage encompasses a validation process, which entails running simulations on the developed model to ensure its accuracy and fidelity.

2.3.1 Modeling for the Four Stroke S.I. Engine Only

Following steps describe the process of incorporating modeling of the 4-stroke S.I. engine only:

1. Understanding experimental results: In the first step, the experimental values of CO and HC obtained at different loads from the engine only were considered as shown in the Table 1 below
2. Plotting graphs for experimental variations: From Table 1, the output variables CO and HC which were experimentally obtained against the 16 different values for the input variable applicable load in running condition of engine.

Table 1. CO and HC for different loads on the S.I. engine only

S. No.	Load (kg)	CO (%)	HC (PPM)
1	5	1.3	1155
2	6	1.2	1100
3	7	1.1	947
4	8	1	880
5	9	0.9	856
6	10	0.85	830
7	11	0.8	790
8	12	0.72	750
9	13	0.79	770
10	14	0.8	780
11	15	0.85	810
12	16	0.9	852
13	17	1	895
14	18	1.2	957
15	19	1.3	1126
16	20	1.4	1150

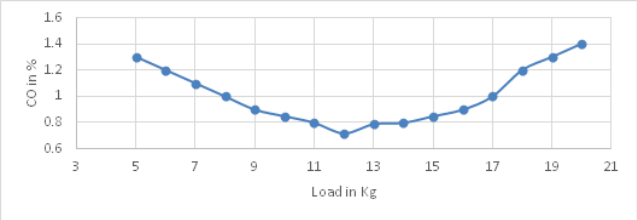


Figure 3. CO *vs* load variation for engine only.

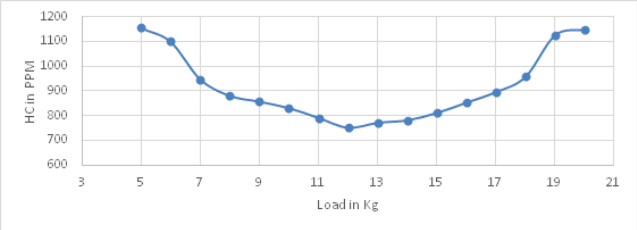


Figure 4. HC *vs* load variation for engine only.

Now, in order to, efficiently mimic the mathematical behavior of each of the outputs CO and HC versus the applied load, this work utilize curve-fitting tool of the MATLAB (version 2020A) software plat form on the curve shown in above Figures 3 and 4. The final mathematical equations obtained for CO and HC after proper fitting of the curve are given as:

$$CO = \begin{cases} -0.0005777x^4 + 0.01961x^3 - 0.2377x^2 + 1.126x - 0.4809, & \forall 5 \le x \le 12 \\ -0.0009659x^4 + 0.06128x^3 - 1.432x^2 + 14.69x - 55.21, & \forall 13 \le x \le 20 \end{cases} \quad (1)$$

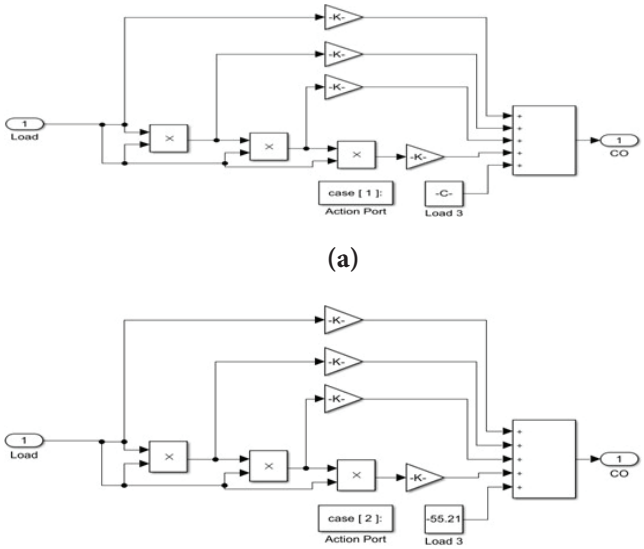
$$HC = \begin{cases} -0.892x^4 + 29.33x^3 - 342.7x^2 + 1611x - 1437, & \forall 5 \le x \le 12 \\ -0.1397x^4 + 6.766x^3 - 109.8x^2 + 650.2x, & \forall 13 \le x \le 16 \\ 53.5x^2 - 1811x + 1.621 \times 10^4, & \forall 17 \le x \le 19 \\ 24x + 670, & \forall 19 \le x \le 20 \end{cases} \quad (2)$$

Where x= Load values of engine.

3. Modeling for CO and HC: Figures 5 and 6 show the modeling of output variables CO and HC respectively for the four stroke engine.

2.3.2 Modeling for New Proposed Catalytic Converter

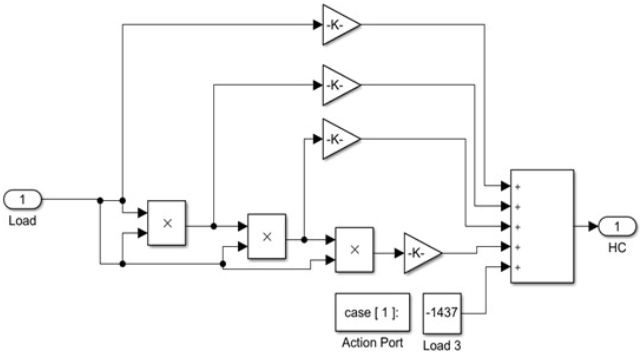
1. Understanding experimental results after using new proposed catalytic converter: The change in the concentrations of CO and HC after the use of new proposed catalytic converter is shown in Figures 7 and 8.



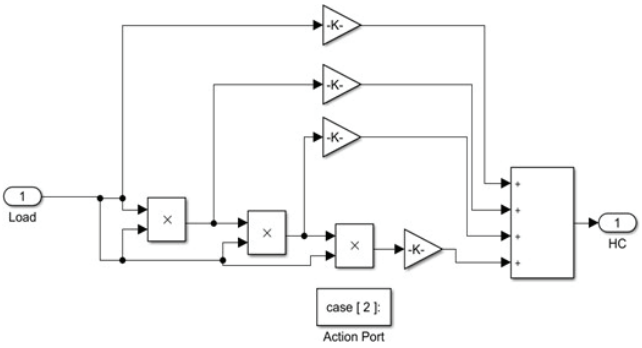
(a)

(b)

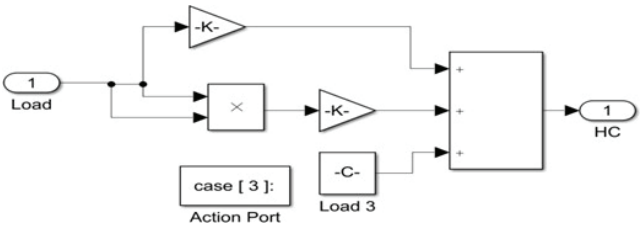
Figure 5. Actual simulation model for output variable CO of stroke engine. **(a)** For 5≤x≤12 **(b)** For12≤x≤20.



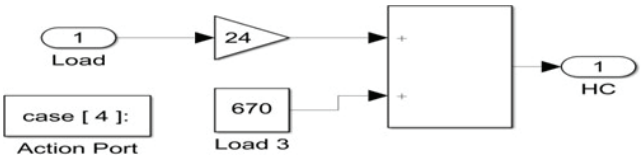
(a)



(b)



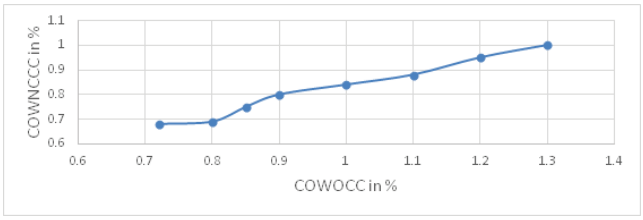
(c)



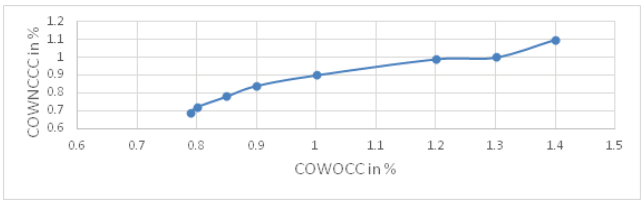
(d)

Figure 6. Actual simulation model for output variable HC of stroke engine. **(a)** For $5 \le x \le 12$ **(b)** For $13 \le x \le 16$ **(c)** For $17 \le x \le 19$ **(b)** For $19 \le x \le 20$.

2. Conversion of graphical variation of CO and HC for new proposed catalytic converter in terms of equations:

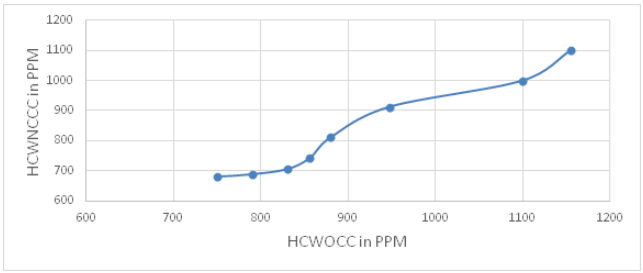


(a)

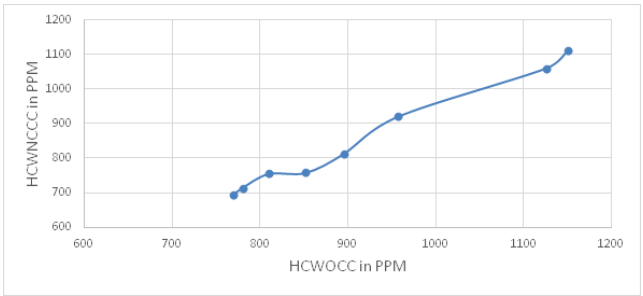


(b)

Figure 7. Plot of COWNCCC with respect to COWOCC. **(a)** For $5 \le Load \le 12$ **(b)** For $12 \le Load \le 20$.



(a)



(b)

Figure 8. Plot of HCWNCCC with respect to HCWOCC. **(a)** For $5 \le Load \le 12$ **(b)** For $12 \le Load \le 20$.

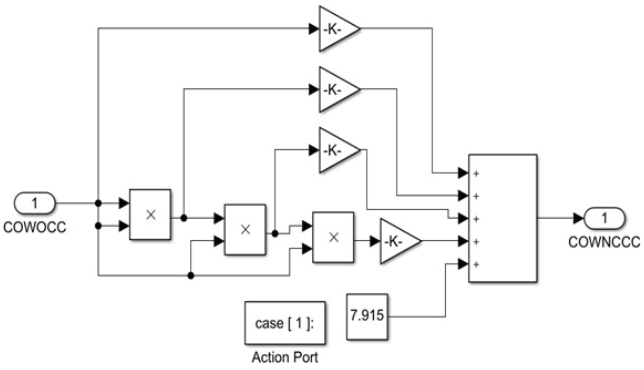
$$COWNCCC = \begin{cases} 8.312x^4 - 33.42x^3 + 49.55x^2 - 31.52x + 7.915, & \forall 5 \le Load \le 12 \\ 4.853x^4 - 17.41x^3 + 21.24x^2 - 9.087x + 1.314, & \forall 12 \le Load \le 20 \end{cases} \quad (9)$$

Where x = COWOCC of engine.

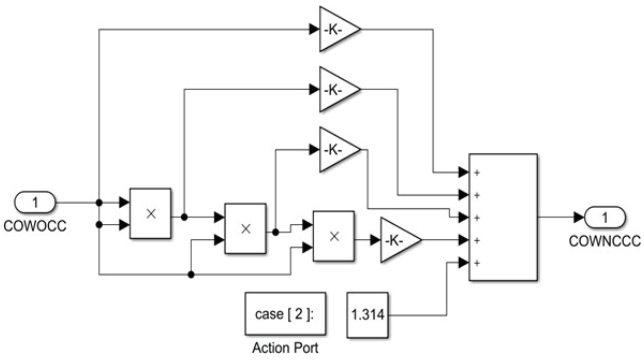
$$HCWNCCC = \begin{cases} 1.818x - 1000, & \forall 5 \le Load \le 6 \\ 1.507x - 515.6, & \forall 6 \le Load \le 8 \\ 1.423x - 472.6, & \forall 8 \le Load \le 10 \\ 0.2x + 530, & \forall 10 \le Load \le 12 \\ 1.9x - 768, & \forall 12 \le Load \le 14 \\ 0.07143x + 697.1, & \forall 14 \le Load \le 16 \\ 1.742x - 747, & \forall 16 \le Load \le 18 \\ 2.125x - 1333, & \forall 18 \le Load \le 20 \end{cases} \quad (3)$$

Where x=HCWOCC of engine.

3. Modeling of above equations in Simulink of MATLAB.

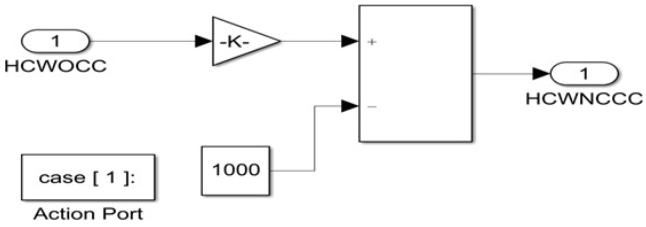


(a)

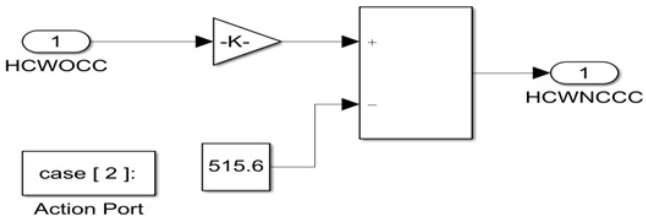


(b)

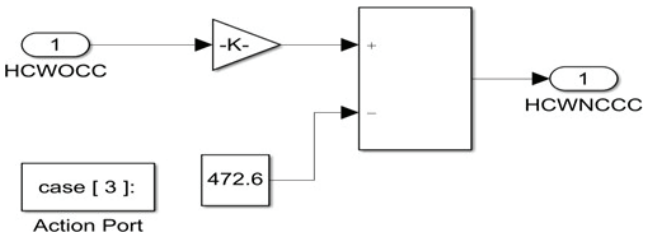
Figure 9. Actual simulation model for output variable COWNCCC of new proposed catalytic converter: **(a)** For $5 \le x \le 12$ **(b)** For $12 \le x \le 20$.



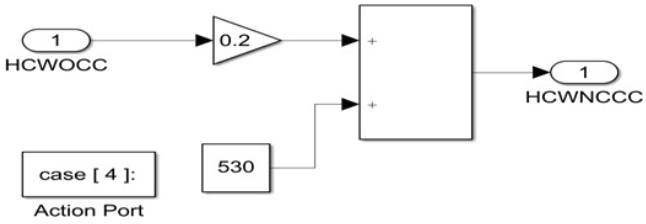
(a)



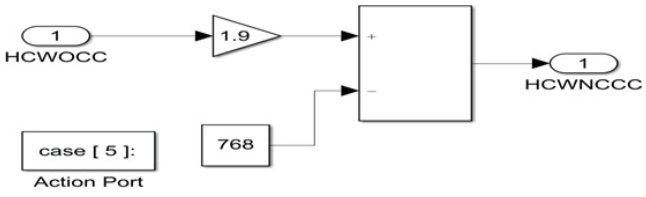
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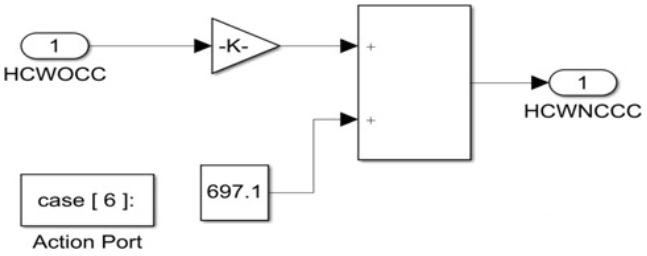


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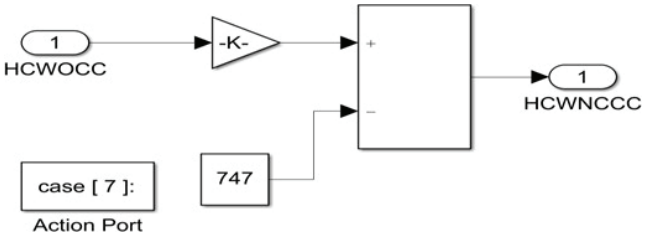


(e)

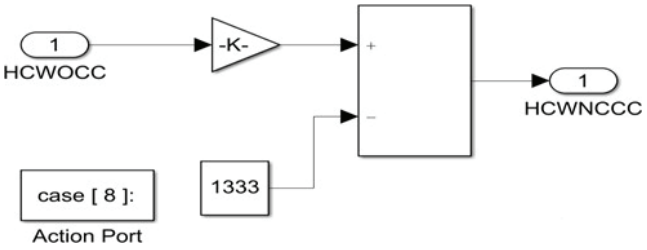
Figure 10. Actual simulation model for output variable HCWNCCC of conventional catalytic converter: **(a)** For $5 \le x \le 6$ **(b)** For $\le x \le 8$ **(c)** For $8 \le x \le 10$ **(d)** For$10 \le x \le 12$ **(e)** For $12 \le x \le 14$ **(f)** For $14 \le x \le 16$ **(g)** For $16 \le x \le 18$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



(f)



(g)



(h)

Figure 10. (Continued)

2.3.3 Modeling for Complete Model

The complete behavioral model for new proposed catalytic converter including the S.I. engine was developed and is shown in the following Figure 11.

3.0 Results and Discussion

The outcomes obtained from experimentation were collated with the outcomes obtained from the behavioral model for practical validation of the developed behavioral model. The comparative table of the different values of CO and HC are depicted in the following Table 2.

4.0 Conclusion

The research integrates advanced simulation techniques to develop an accurate behavioral model of the engine, capturing its operational characteristics, combustion processes, and emission generation across various operating conditions. The main conclusions of present research are as below:

1. The primary motive is to evaluate the potential of this novel catalytic converter in reducing environmental pollution, specifically targeting pollutants like Carbon monoxide (CO) and Hydrocarbons (HC).
2. The investigation employs a combination of simulation and empirical analysis to comprehensively evaluate

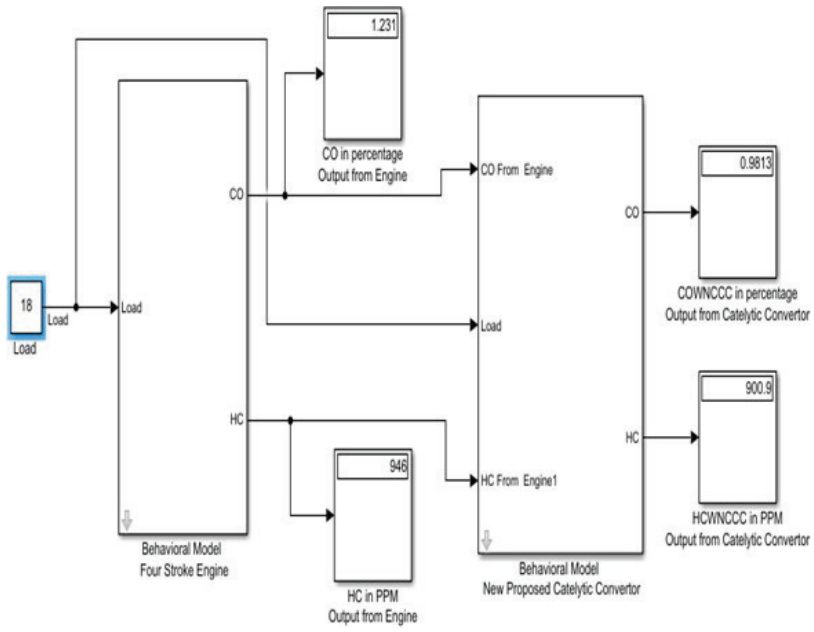


Figure 11. Complete model of four stroke S.I. engine with new proposed catalytic converter.

Table 2. Comparison of practical and simulated values for CO and HC from the four stroke S.I. engine with new proposed catalytic converter

Load	COWNCCC (%)			HCWNCCC (PPM)		
	Practical	Simulation	% Error	Practical	Simulation	% 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

the converters performance, quantifying its ability to catalyze and transform pollutants, resulting in cleaner exhaust emissions and reduced environmental impact.

3. The research findings hold significant implications for environmental sustainability, particularly in addressing pollution stemming from internal combustion engines.
4. The study's outcomes could potentially reshape pollution control strategies and contribute to a cleaner, healthier future for society.
5. Since, the behavioral model has close proximity with experimentation outcomes, so the model can conveniently be applied to estimate the reduced values of CO and HC outcomes at different loading conditions on the four stroke S.I. engine.
6. In summary, the new proposed catalytic converter showcases a novel approach to combat environmental pollution, emphasizing the importance of innovative technologies in promoting cleaner and more sustainable automotive systems.
7. The long term durability of catalytic converter coated with copper nano particles depends on the employability conditions of the engine and the temperatures developed inside the catalytic converter. For a well maintained engine and warming temperatures of above 300° C approximately, the catalytic converter coated with copper nanoparticles can perform effectively for emissions concentrations control up to 1-1.2 lakh kilometers covered by the automobile installed with copper coated catalytic converter. However, at irregular working conditions and temperatures below 300° C in the catalytic converter, the efficiency might be lesser.

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Nomenclature

CO	Carbon Monoxide
HC	Hydrocarbons
S. I.	Spark Ignition
COWNCCC	Carbon Monoxide concentrations With New Proposed Catalytic Converter
COWOCC	Carbon Monoxide concentrations Without Catalytic Converter
COWNCCC	Hydrocarbons concentrations With New Proposed Catalytic Converter
COWOCC	Hydrocarbons concentrations Without Catalytic Converter