Catalyst conversion comparison efficiency from the use of transition metallic catalytic converters: A literature review

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Abstract. Exhaust emissions have a severe impact on human health and the environment. Emission control using catalytic converters is a smart solution to reduce the number of exhaust emissions. Currently, the catalytic converter most widely installed in motor vehicles is a three-way catalytic converter (TWC) made from precious metals. TWC can reduce CO and HC emissions by 98-99% and > 95%. However, due to the very high production costs, research is needed to find other alternative materials. This study focuses on catalytic converters made from transition metals. Data collection techniques are carried out by studying literature by prioritizing primary libraries. Data analysis using the Miles and Huberman model was carried out in four stages involving the process of data reduction, data display, data verification, and concluding. Experimental analysis based on the results of literature studies on catalytic converters such as copper, chrome, manganese, brass, nickel, and oxides from several metals have been carried out so far. The study results show that the use of transition metals can significantly reduce exhaust emissions starting from 16% -96.36% for CO and 32.54% -94.74% for HC. Mn-coated Cu catalytic converters can reduce CO and HC emissions by 96.36% and 94.74%, although this result still cannot defeat the ability of platinum-group metals (PGM).

1 Introduction

Nowadays, air pollution has been fully recognized as one of the factors causing various health problems in humans [1]. This is undoubtedly a consequence that must be accepted due to the rapid industrial growth in all countries and the world [2]. International Energy Agency (IEA) [3] reports that the energy sector contributes significantly to air pollution generated by human activities, whereas much as 30% of pollution is produced by exhaust emissions. It should be noted that motor vehicle emissions produce several hazardous substances such as a sulfur oxide (SO_x), carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons (HC), and particulate matter (PM) [4]. The increasing population of motor vehicles is directly proportional to the increase in air pollution generated to the environment [5]. Besides, air pollution that is suspended in the air also has the potential to cause several dangerous diseases to human health if exposed to both the long and short term. Short-term chronic illnesses, such as respiratory and cardiovascular diseases, neuropsychiatric complications, eye irritation, and skin diseases. Meanwhile, long-term chronic diseases, such as cancer [6].

Many technologies have been developed to reduce the levels of exhaust emissions [7]. Dobrzyńska et al. [8] explain that there are at least three efforts that can be made to reduce the number of exhaust emissions, such as changing the design of the engine, treating exhaust gases, and modifying fuel. Providing treatment for exhaust gas is one alternative that has been developed by researchers. The application of this exhaust gas treatment is to install catalytic converter technology in motor vehicle exhaust systems [9]. Nowadays, automotive manufacturers use platinum-group metals (PGM) or precious metals such as Platinum (Pt), Ruthenium (Rt), Rhodium (Rh), and Palladium (Pd) as catalysts, where these metals have specific activities and higher ability than other types of metals [10]. However, the weakness in the use of this type of precious metal is the cost required is quite expensive to manufacture [11]. Also, exhausts equipped with catalytic converters with valuable metal materials are generally designed to be built up or cannot be assembled [12].

The smart solution offered to minimize these weaknesses is to use a catalytic converter using metals such as copper (Cu), brass (CuZn), and stainless-steel (FeCr). This material has not received much attention. The reason, the ability factor in increasing exhaust emissions is not favored by precious metals [13]. This literature review discusses the conversion of efficiency between precious metals and transition metals in catalytic converters to reduce exhaust emissions. Then, the primary purpose of this conversion is to test the ability of each catalyst material when used as a catalytic converter.

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2 Catalyst material and method

2.1 Catalytic converter

Catalytic converters installed in motorcycle and car exhaust systems are one of the latest technologies to meet the stringent demands of exhaust emission standards [15]. Flue gas emissions are the most significant contributor to air pollution. In motor vehicles, the exhaust pipe emits some harmful gases such as CO, HC, and NO [16]. If calculated, the exhaust pipe emits 65% to 85% of the total gas emissions coming out into the environment, and of course, these emissions will be hazardous if inhaled by humans [16]. The use of catalytic converters in motorized vehicles to reduce exhaust emissions and convert them into harmless gases. The cross-section of the catalytic converter is shown in Fig. 1.

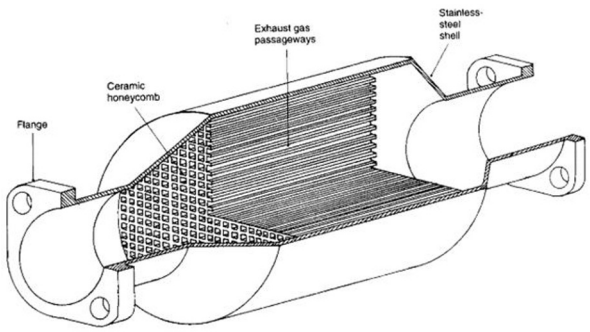

Fig. 1. Honeycomb type catalytic converter section [14].

2.2 Catalyst material

Material can be said as a catalyst metal and can be used as a catalytic converter if it can provide a reduction and oxidation reaction to a dangerous gas produced by combustion in the cylinder. Hazardous gases coming out of the exhaust tip must be converted to harmless gases so that they do not cause adverse effects when inhaled by humans. In theory, the oxidation process occurs when CO gas passes through the oxidizing catalyst metal. At that time, CO gas takes oxygen (O_2) from copper oxide, so CO gas combines with O_2 to form carbon dioxide (CO_2) gas. The same thing happened with HC gas. When passing through the oxidizing catalyst metal, HC gas takes oxygen from copper oxide so that the HC gas combines with O_2 to produce water (H_2O) and CO_2 [18]. Several catalysts that are known to be active for the oxidation of CO and HC emissions to CO_2 and H_2O are platinum, palladium, plutonium (precious metals); manganese, copper, chrome, nickel, iron, vanadium, cobalt, and their oxides [16]. The oxidation ability of catalyst material to temperature is shown in Figure 2.

2.3 Method

This research is a type of literature review that uses literature as a basis for developing new models, theories, or concepts [19]. Data sources using secondary data obtained from the study of scientific papers, both from international/national journals/proceedings, websites, and other relevant and valid sources [20]. The collected data is then verified and analyzed qualitatively using the Miles and Huberman models [21]. Data analysis using the Miles and Huberman model was carried out in four stages involving the process of data reduction, data display, data verification, and concluding [21].

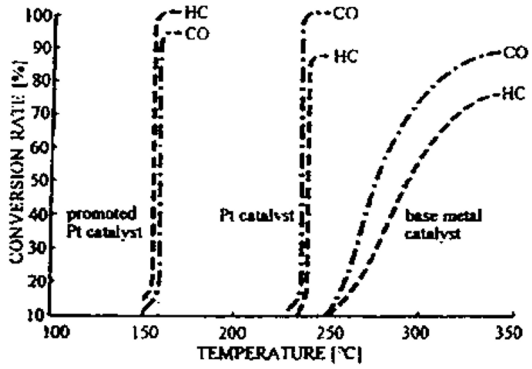

Fig. 2. Graph of catalyst material for temperature [17].

3 Discussions

The most catalytic converter installed in vehicles is the precious catalytic metal or platinum-group metal (PGM) with TWC type [22]. Precious metals commonly used, such as Platinum (Pt), Palladium (Pd), or Rhodium (Rh) [23]. Of the three metals, Pt is the most active precious metal and is both an oxidation and reduction catalyst. Pd is better if used as an oxidation catalyst, while Rh is more suitable as a reduction catalyst. Following the theory and facts, the use of precious metals as catalytic converters is beneficial and efficient in reducing exhaust emissions. Khivantsev et al. [24] explained that noble metal catalysts only need at temperatures> 180–200°C to reduce CO emissions by 99%, while at the same temperature, HC emissions can be reduced to 95% [23]. But on the contrary, Heisler [14] states that precious metal catalysts work at temperatures of 300°C to reduce CO emissions by 98-99% and HC emissions above 95%. However, for temperatures below 300°C the catalyst is not practical [13]. The reactions that occur in the Pt, Pd, and Rh catalytic converters are explained in Fig. 3.

Pt	→	$C_xH_{2x+2} + \frac{(3x+1)}{2} O_2 \xrightarrow{Pt} x\,CO_2 + (x+1)H_2O$
Pd	→	$2\,CO + O_2 \xrightarrow{Pd} 2\,CO_2$
Rh	→	$2\,NO_x \xrightarrow{Rh} O_2 + N_2$

Fig. 3. PGM catalytic converter reaction in the exhaust system [24].

Judging from its ability to reduce exhaust emissions, it would certainly be natural if many automotive manufacturers were more interested in using catalytic converters made from precious metals compared to other types of materials. However, because the production process is costly, it certainly makes automotive manufacturers and some researchers from

universities continue to conduct research to find alternative materials that have relatively lower production prices with abundant quantities. As a solution to this problem, the use of transition metals is one of the promising options for oxidizing CO, HC, and NOx emissions. Besides, transition metals are no less effective when used as a catalyst for both oxidation and reduction. Strengthening the statement Bagus Irawan, Purwanto, & Hadiyanto [26] stated that useful metals as catalysts for reduction and oxidation were Pt, Pd, Ru> Mn, Cu> Ni> Fe> Cr> Zn and their oxides.

Based on some transition metals that have been mentioned, copper (Cu) metal is the most widely used material as a catalytic converter. Lower costs, abundant material availability, and several other benefits make Cu a right choice as a catalyst material [27]. Besides, the ability of a catalytic converter that is quite effective in reducing exhaust emissions is also one of the strong reasons this type of metal is starting to be in high demand. Choudhury & Deo [28] showed that the use of catalytic converter copper plate was able to reduce HC emissions by 55.44%, CO emissions by 62.96%, and NOx emissions by 40.41% under full load conditions. Research Udhayakumar et al. [29], which employed a Cu-Zn coated catalytic converter on a diesel engine, demonstrated a reduction in hydrocarbon emissions by 72%, carbon monoxide by 60%, and nitrogen oxides by 65% under full-load conditions compared to an engine without a catalytic converter.

Besides, when combined with other materials, the ability of copper catalytic converters to reduce exhaust emissions also increases. Penelitian oleh Yakoumis [30] mengembangkan katalis berbasis tembaga yang terdiri dari nanopartikel tembaga, paladium, dan rhodium sebagai fase aktif, menunjukkan aktivitas katalitik tinggi terhadap oksidasi CO dan CH4 serta reduksi NO. Further research conducted by Yakoumis, Polyzou, & Moschovi [31] conducted a study on a copper-based polymetallic catalyst named PROMETHEUS. The results show that CO oxidation efficiency can reach 100%, while CH_4 oxidation efficiency can reach 87-95% under rich fuel conditions ($\lambda = 0.99$). Furthermore, the catalyst successfully replaced 85% of noble metals with copper while maintaining high performance. Rathore, Thakur, & Deepak [32] researched copper catalytic converters coated with nano-particles. The results showed that by using a copper catalytic converter coated with nanoparticles CO emissions decreased from 1.25% vol to 0.8% vol, and HC emissions were reduced from 962 ppm to 862 ppm as well. Whereas NOx and CO2 emissions are also consistently cut. Shan et al. [33] conducted a comprehensive study on Cu-SSZ-13 catalysts for selective catalytic reduction. The results demonstrate excellent catalytic activity for NO_x reduction with high hydrothermal stability, providing a theoretical basis for the application of copper catalysts in vehicle emission control systems.

The next transition metal that is effectively used to reduce exhaust emissions is Manganese (Mn). Generally, manganese is a powder-shaped metal so that in its application as a catalytic converter, other materials are needed as support. Li et al. [34] conducted a study on the effect of iron doping on a Pd-only three-way catalyst. The results demonstrate that the Pd/CZFe(1%) catalyst exhibits the best performance for eliminating CO, HC, NO, and NO_2, and provides the widest operating window. The 1% iron doping promotes the formation of a homogeneous solid solution, facilitates the creation of oxygen vacancies, and enhances the oxygen storage capacity, leading to superior catalytic activity. Furthermore, Zulfugarova et al. [35] conducted a study on cobalt-containing oxide catalysts synthesized via a sol-gel method with auto-combustion for low-temperature CO oxidation. The results demonstrate that the binary Co-Cr (2:1) and triple cobalt-containing oxide systems were highly active, achieving complete CO conversion at temperatures as low as 145-160 °C, with the mutual reinforcing effect of oxide and spinel phases being key to their performance.

Complementing this research on thermal catalysis, Usman et al. [36] conducted a comprehensive review of cobalt-based electrocatalysts for the electrochemical reduction of CO_2. The results demonstrate that various structures, including single-atom cobalt and cobalt-based metal–organic frameworks (MOFs), show significant promise in converting CO_2 into valuable fuels with high Faradaic efficiency, highlighting cobalt's versatility in both CO oxidation and CO_2 conversion. Furthermore, research into other non-precious metals shows parallel advancements. Li et al. [37] conducted a review of manganese-based catalysts for the removal of NOx and CO. The results demonstrate that Mn-based catalysts exhibit excellent low-temperature activity, and their performance is heavily influenced by factors such as valence states and morphology, which provides a valuable framework for understanding and improving other metal oxide catalysts like cobalt.

Finally, pushing the boundaries of manganese catalysis, Zhang et al. [38] conducted a study on a halogen and nitrogen-coordinated manganese electrocatalyst for CO2RR. The results demonstrate an exceptional CO Faradaic efficiency of 97% and a record-high turnover frequency, proving that the electronic structure modulation of earth-abundant metals is a powerful strategy for developing high-performance catalysts for carbon dioxide conversion.

4 Conclusions

Based on the literature review and discussion, it is known that the PGM catalytic converter has an excellent ability in reducing exhaust emissions, namely 98-99% for CO and > 95% for HC. However, due to its costly production, automotive manufacturers, and researchers at universities continue to conduct research to find alternative materials that are relatively inexpensive with abundant material availability. So, catalytic converters made from transition metals began to be analyzed for their ability to reduce levels of exhaust emissions. The test analyzes on copper, chrome, manganese, brass, titanium dioxide, nano-particle, nickel, and oxide catalytic converters of several metals have been carried out so far.

The results show that CO and HC emissions can be significantly reduced even though they cannot defeat the ability of PGM. The use of catalytic converters made from copper can reduce CO emissions by 62.96% and HC emissions by 55.44%. If it is coated with chrome, it can reduce CO emissions by 95.35% and HC emissions by 79.28%. Meanwhile, if covered with TiO_2, CO emissions can be reduced by 57.27%, and HC emissions can be reduced by 70.74%. From an economic standpoint, catalytic converters made from brass are the cheapest catalyst metals. The ability of this type of catalytic converter is no less impressive where CO and HC emissions can be reduced by up to 80.28% and 59.52%. Based on literature studies, the experimental results show that the use of transition metals can significantly reduce exhaust emissions ranging from 16% -96.36% for CO and 32.54% -94.74% for HC.

The manganese-plated copper catalytic converter is by far the best catalyst in reducing CO and HC emissions compared to other transition metals. This catalytic converter can reduce CO and HC emissions by 96.36% and 94.74%. Therefore, transition metals can be used as an alternative catalyst material to reduce exhaust emissions of motorized vehicles. However, this result still cannot defeat the ability of platinum-group metals (PGM).

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