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"Advances in Catalytic Carbon Monoxide Oxidation at Ambient Temperatures: A Short Review"

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Abstract
The oxidation of carbon monoxide (CO) is essential in maintaining life and safety in various specialized environments like submarines, underground mining works and space missions, where the buildup of the poisonous gases may cause serious complications. Moreover, the discriminatory oxidation of CO in gas streams with hydrogen is required to have the efficient functioning of the fuel cells, as any traces of CO may greatly impair their performance. CO oxidation at room temperature is a complicated chemical process; its practical significance is hard to overestimate. Elimination of the dangerous pollutants, especially carbon monoxide and unburnt hydrocarbons, in the atmosphere is one of the most urgent environmental issues of the day. Such toxic gases are emitted in several industrial and combustion-related processes, and they lead to air pollution as well as health risks to people. A good and sustainable method to remove these pollutants is by catalytic total oxidation, which transforms them into less harmful substances such as carbon dioxide and water. The given research is devoted to the CO oxidation in ambient conditions and discusses the main parameters that determine the catalyst activity. It also talks of the various methods of preparing the catalysts, the types of catalysts used, the source of materials and the various applications of these catalysts in practice. When these aspects are addressed, the work would seek to support the development of catalytic technologies to help in achieving environmental protection and enhancing the quality of air.

Key Words: *Carbon monoxide oxidation; Catalysis; Ambient temperature reactions; Air pollution control; Toxic gas removal; Fuel cell efficiency; Preferential oxidation (PROX); Catalyst activity; Environmental protection; Clean energy technologies.*

Introduction

The oxidation of carbon monoxide (CO) is vital for human safety and survival in extreme environments such as submarines, underground mining operations, and space missions, where toxic gas accumulation can be fatal. In addition, selective removal of CO from hydrogen-rich streams is essential for efficient fuel-cell operation, as even trace amounts of CO can severely poison fuel-cell electrodes.

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Although CO oxidation at room temperature is chemically complex, its environmental and practical importance is considerable. The removal of toxic air pollutants, particularly carbon monoxide and hydrocarbons, has become a major global concern. Catalytic total oxidation provides an effective method for converting these harmful gases into less hazardous products. Increasing emissions of CO, hydrocarbons, nitrogen oxides, sulfur oxides, volatile organic compounds, and particulate matter have intensified research into catalytic CO oxidation under ambient conditions. Carbon monoxide, often termed the "unrecognized poison of the 21st century," is colorless, odorless, and non-irritating, making detection difficult (Université de Bourgogne, France, 1998). Large quantities of CO are released worldwide from transportation, power generation, industrial activity, and domestic combustion, driving continued interest in low-temperature catalytic oxidation as a cost-effective pollution-control strategy.

1. Sources of CO emission

Nearly 90% of hydrocarbon and carbon monoxide emissions measured during a vehicle test drive occur during the cold-start phase, when the engine and catalytic converter have not yet reached optimal operating temperatures (Tang et al., 2009). During this stage, incomplete combustion leads to the release of large quantities of unburned pollutants until emission- control systems become fully effective. Carbon monoxide sources are not limited to vehicles alone. Elevated CO exposure may occur in warehouses and fruit-packing facilities using propane-powered forklifts, as well as on construction sites where small gasoline-engine equipment is operated. Kerosene space heaters, natural-gas cooking appliances, and propane- driven floor polishers also emit CO. While outdoor use is generally safe, operation in enclosed or poorly ventilated spaces can rapidly result in toxic or fatal CO accumulation, often without warning due to its colorless, odorless, and non-irritating nature.

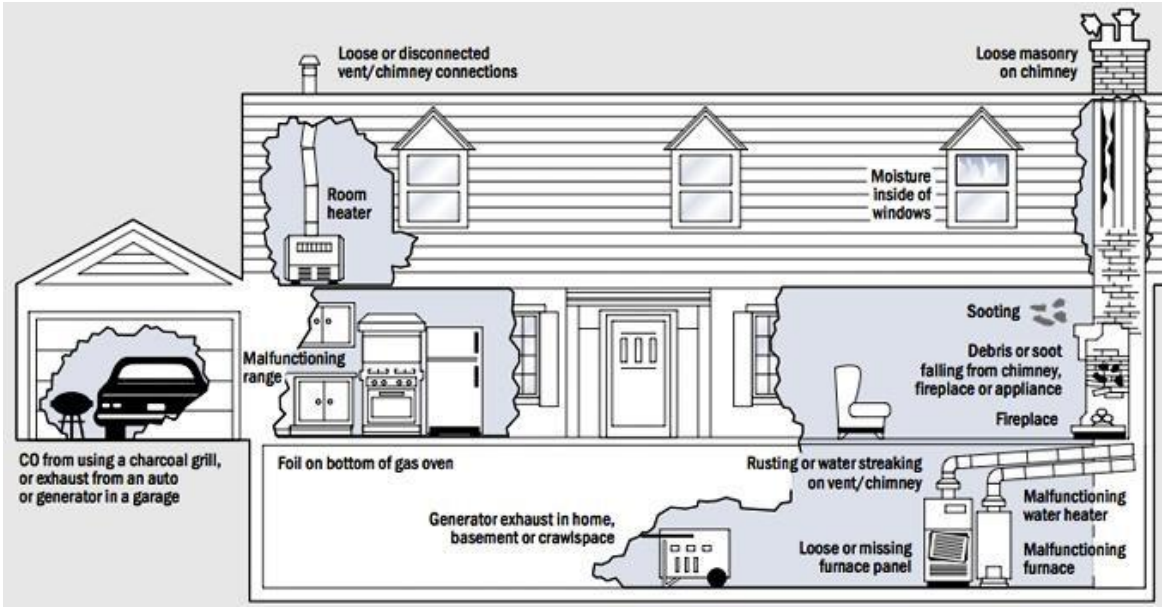

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Fig. 1. Diagrammatic representation showing Common sources of CO.

2. Effects of CO

Carbon monoxide (CO) is extremely toxic to aerobic life and is rapidly absorbed through the respiratory system (Ernst & Zibrak, 1998). Even low concentrations can cause cellular hypoxia, neurological damage, and potentially fatal outcomes. Individual susceptibility to CO exposure varies and is influenced by factors such as physical exertion, ventilation rate, metabolic activity, altitude, and underlying medical conditions, including cardiovascular disease, anemia, and blood disorders (Raub et al., 2000; Carbon Monoxide, 2008; Lipman, 2006; Env. Heal. Crit. 213, 1999). Continuous exposure to levels at or above 100 ppm poses serious health risks (Prockop & Chichkova, 2007). The toxic action of CO arises from its strong binding to hemoglobin, as first demonstrated by Claude Bernard. Occupational exposure limits established by OSHA restrict long-term exposure to 50 ppm and require immediate removal at 100 ppm (Kao & Nanogas, 2006; OSHA Fact Sheet, 2009; Carbon Monoxide-1917.24, 2010). Long-

term exposure is linked to cardiac injury and reduced lifespan, and CO poisoning remains the leading cause of fatal air poisoning worldwide (Henry et al., 2006; Omaye, 2002).

Table 1. The acute effects produced by carbon monoxide relative to ambient concentration in parts per million are listed [Goldstein, 2008; Struttmann et al. 1998]:

3. Emission testing

The state of California became the first state to use a standardized cycle of vehicle emission testing in 1966 to measure the tailpipe emissions in parts per million (ppm). Since then, the development of monitoring techniques has changed the way the emissions of vehicles are measured. Emission detection system: A laser-based emission detector invented by Dr. Donald Stedman of the University of Denver is used in many cities. This new technology enables the measurement of exhausts outside the car as the cars are working in real conditions on the roads, and the participants do not have to visit special inspection and testing facilities. The laser- related remote sensing technique that was initially developed by Stedman has gained prevalence in cities to measure the level of on-road vehicle emissions because of its effectiveness and non-invasive characteristics (Swayne, 1999).

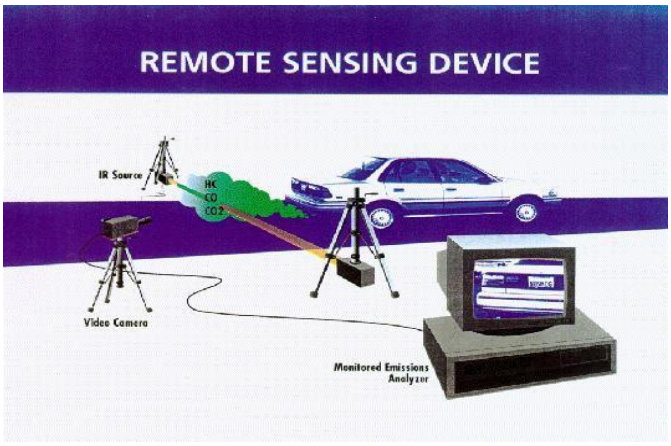

Fig.2. A remote sensing device for CO emission testing.

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4. CO emission checking:

The room temperature oxidation of carbon monoxide is of paramount importance in the respiratory protection applications where extremely efficient oxidising catalysts are needed to lower the CO concentration to very low levels and maintain this activity over long durations.

Turning carbon monoxide into carbon dioxide is also one of the most effective approaches to the CO in the air-pollution control system. The invention of catalytic converters has also been a great provocation in the research on metal catalysts in the last five decades. A catalytic converter is a device that is fitted in the exhaust system of a vehicle to convert hydrocarbons, carbon monoxide and nitrogen oxides into less harmful gases using platinum, palladium and rhodium. Three-way catalysts have the capacity of storing oxygen at low air-fuel lean conditions (Brandt et al., 2000). In the case of diesel engines, diesel oxidation catalysts make good use of the excess oxygen in exhausts so that CO and hydrocarbons are effectively oxidised with a maximum conversion efficiency of 90 percent.

5. Chemistry of CO

Carbon monoxide is made up of an oxygen atom and a carbon atom, which are bound together by a triple bond. This bond comprises two covalent bonds and one dative covalent bond. It is the simplest oxocarbon. The carbon monoxide in coordination complexes is known as carbonyl. There are three resonance forms of carbon monoxide as indicated in fig 3. This is one of the explanations with regard to its outstanding adsorption characteristics and reactivity on metal and oxide surfaces.

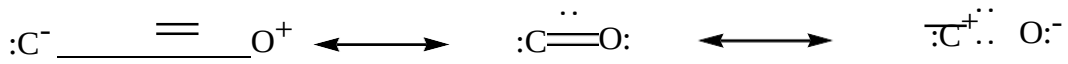

Fig. 3. Resonance structure of CO.

6. Catalysts for CO oxidation

Commercially available carbon monoxide catalysts fall into three types:

1. Hopcalite is an effective catalyst for CO oxidation, but it becomes inactive in the presence of water vapor.
2. Supported platinum (Pt), palladium (Pd), and tin dioxide (SnO_2) catalysts resist water but require high amounts of Pt and Pd to be effective at high CO concentrations.
3. Gold nanoparticles supported on oxides are very active at high humidity, but they have only recently become available on the market (Mintek in Randburg, South Africa, and 3M).

All CO oxidation catalysts can be grouped into two categories under normal conditions:

1. Plain metal oxides
2. Mixed metal oxides

Here are a few brief descriptions.

a. Plain metal catalysts

The current body of literature relating to the oxidation of carbon monoxide over base metal oxide catalysts can be broadly divided into the two stages, which are (a) an early phase of high scientific activity between the years of about 1965 and 1980 before the introduction of base metal catalysts into

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automotive exhaust treatment; and (b) a revival phase of interest in the area over the last few years since the year 1980 which has seen catalysts of the second generation employed to replace the noble metals, which are generally considered to be cost.

i. Cobalt oxides

1. Unsupported cobalt oxides

Even though one of the first materials to be used in terms of carbon monoxide oxidation was cobalt(III) oxide, spinel phase Co_3O_4 is the most catalyzed one. Such oxide bears two oxidation states, (+2 and +3). Which add to its high redox activity. At a temperature of about 350 C to 900 C, Co_3O_4 is thermodynamically stable, but at higher temperatures it loses its oxygen and is reduced to CoO. In 1974, Yu Yao explored the oxidation of CO and hydrocarbons on different unsupported Co_3O_4 catalysts and established that they were very active. Nevertheless, it was discovered that these catalysts were extremely susceptible to sulphur dioxide poisoning, and that even a few parts per million of SO_2 would lead to a total deactivation of the catalyst at low temperatures. Recently, Xie et al. (2009), have noticed that Co_3O_4nanorods had extraordinary CO oxidation activity in ambient conditions. Complete conversion of CO at room temperature resulted in almost 60 hours of stay and high activity, which indicates both high activity and maximum stability in the presence of a limited amount of moisture.

Supported cobalt oxides CoOx/Al2O3 catalysts

When cobalt oxide reacts with alumina, its catalytic performance is greatly increased, but a significant reduction in its catalytic activity is seen when alumina is impregnated with cobalt nitrate. However, when impregnated with cobalt acetate or cobalt ammine precursors, the catalytic activity is significantly greater. Also, the thermal stability of cobalt oxide is increased by physically combining Co_3O_4powders with alumina, and its catalytic activity is further increased. Co_3O_4/γ-Al_2O_3 serves as a highly active catalyst for low-temperature CO oxidation. However, when the reaction occurs at room temperature, deactivation is common due to strong CO adsorption on cobalt oxide and the formation of surface carbonates.

ii. Copper Oxide Unsupported copper oxides

Compared to Co_3O_4, unsupported copper oxides are less commonly applied in CO oxidation. This is mainly because cobalt oxide contains both Co^{2+} and Co^{3+} species, whereas CuO and Cu_2O generally involve only Cu^{2+} or Cu^{+} ions. Copper oxides also exhibit lower stability, with oxidation states changing during reaction conditions. Early systematic studies by Bray, Draper, Garner et al. (1952), and Jennings and Stone (1957) demonstrated the activity and kinetics of Cu_2O in room-temperature CO oxidation.

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iii. Ceria-supported catalysts

Ceria is widely incorporated into automotive emission-control catalysts because of its high oxygen storage capacity and its strong promotional effect in carbon monoxide (water–gas shift) and hydrocarbon reforming reactions in the presence of steam. It also enhances metal resistance to sintering. When combined with catalyst supports, ceria alters reaction kinetics through a cooperative dual-site mechanism, where CO adsorbs on metal sites. At the same time, oxygen is activated on adjacent ceria sites, reducing competitive adsorption.

iv. Other oxides

Titanium dioxide is generally considered ineffective for direct carbon monoxide oxidation; however, it is an excellent support for several metals, particularly gold (Christmann et al., 2010). Recent studies have shown that finely dispersed Ir/TiO_2 catalysts display high catalytic activity for CO oxidation at room temperature (Zhang et al., 2005). Similarly, size-controlled supported gold nanoparticles exhibit strong low-temperature activity (Haruta et al., 1993; Valden et al., 1998). The catalytic performance of Ir/TiO_2 is highly dependent on pretreatment conditions and the nature of the support, with metallic iridium formed by hydrogen reduction being significantly more active than its oxidized form (Zhang et al., 2005).

b. Mixed metal oxide catalysts

i. Perovskite (ABO3)

Perovskite-type metal oxides with the general formula ABO_3, where the A-site is occupied by a rare-earth element and the B-site by a transition metal, have been extensively explored as alternatives to noble-metal catalysts for controlling automotive exhaust emissions (Voorhoeve et al., 1977). These materials offer several advantages, including lower cost, good thermal stability, and adjustable redox properties. However, only a limited number of perovskite compositions reported to date exhibit significant catalytic activity for carbon monoxide oxidation under ambient or near-ambient conditions. Meilin et al. (2011) reported that gold- supported lanthanum manganite (Au/$LaMnO_3$) demonstrated notable low-temperature performance, achieving approximately 60% CO conversion at 50 °C. This finding indicates that appropriately modified perovskite catalysts have promising potential for low-temperature CO oxidation applications.

ii. Hopcalite

For several decades, hopcalite, a mixed copper–manganese oxide, has been regarded as one of the most effective catalysts for carbon monoxide oxidation (Taylor et al., 1999). Its high low- temperature activity was first reported by Lamb et al. in 1920. Hopcalite is largely amorphous at room temperature but loses activity above 773 K due to spinel $CuMn_2O_4$ formation, although crystalline $CuMn_2O_4$ can also be catalytically active (Schwab & Kanungo, 1977; Veprek et al., 1986; Kanungo, 1979, Singh &

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Prasad, 2016). Improvements through metal-oxide additions have been modest (Haruta & Sano, 1983; Jaworska-Galas et al., 1994).

Chemistry of Hopcalite

In CO oxidation, its high activity is typically attributed to the resonance system Cu2+Mn3+/Cu+Mn4+ and the strong adsorption of CO on Cu2+/Mn4+ and O2 on Cu+/Mn3+ [Fortunato et al. 2001]. The catalyst exhibits high activity in its amorphous form, even at room temperature, but its performance declines above approximately 500 °C due to crystallization into $CuMn_2O_4$ (Kanungo a, 1979; Kanungo b, 1979). Its exceptional oxidation activity is attributed to electron transfer between multiple valence states of copper and manganese within the spinel structure. This charge-transfer mechanism has been widely discussed, although determining the precise structure and oxidation states remains challenging (Padalia, 1973; Dollimore & Tonge, 1970; Radhakrishnan & Biswas, 1977; Vanderberghe, 1978).

a. Gold-based catalysts

Bulk gold has long been considered catalytically inert. However, in recent years, it has been highly active in low-temperature CO oxidation when it is finely dispersed on appropriate oxide supports (Gomez et al., 2009). After the breakthrough realised by the pioneer study of Haruta et al. (1989), gold-based catalysts are remarkably active and tolerate moisture (Date et al., 2004; Oh & Hoflund, 2007). Addition of gold to hopcalite forms new active sites and stabilises catalyst reducibility; the more active the catalyst, the greater is the mobility of lattice-oxygen (Cole et al., 2010). Again, La2O 3 - supported Au 3 + complexes and newlydeveloped 3M nanogold catalysts also reveal the ability to remover CO effectively under humid and low-temperature conditions. This is usually because the surface gold atoms are under-coordinated, which is believed to be the high activity of gold (Min & Friend, 1994).

Table 1: CO Oxidation Catalysts Performance

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CO oxidation Catalyst	**Temperature**	**Activity in presence of moisture**	**Reaction conditions**	**% CO conversion**	**References**
Metal oxides					
Ag/meso-SiO_2	**30 °C**	**–**	**1 atm, 50 ml/min**	**100**	**Liu et al. 2008**
α-ZrP-$Rh_{0.42}$	9 °C	–	–	0.60 mmol	Date & Haruta, 2001
Co_3O_4	Room temperature	Active (3–10 ppm);	1% CO + 2.5% O_2 + He	100	Merrill & Scalone, 1921;

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		Deactivated (<1 ppm)			Yu et al. 2009; Xie et al. 2009
20 wt.% Bi_2O_3–Co_3O_4	Up to −89 °C	–	–	100	Lou et al. 2011
CeO_2–Co_3O_4	45 °C	–	5% CO + air; 66.7 mL min^{-1}	100	Xu et al. 2006

Table 2: Supported Pt/Pd/tin oxide catalysts

Pd-Cu-Cl_x/Al_2O_3	**27 °C**	**Active**	**–**	**100**	**Dongsheng et al. 2010**
Pd/ZrO_2	41 °C	–	–	50	Faticanti et al. 2005

Table 3 : Nanoparticle gold on oxide support

Au/Co_3O_4	**Below 0 °C**	**Active**	**CO/O_2/He**	**100**	**Haruta et al. 1993**
2.9% Au/Mn_2O_3	−62 °C	–	1% CO + 20% O_2; 50 cm^3 min^{-1}	50	Wang et al. 2009
Au/TiO_2	0 °C; up to −70 °C; at room temp	Active	CO/O_2/He (1:2:25)	90	Yan et al. 2006; Boccuzzi & Chiorino, 2000
Au/γ-Al_2O_3	0 °C	Active	CO/O_2/He	100	Juan et al. 2005
Au/SBA-15 (mesoporous silica)	Below 0 °C	–	–	100	Zhu et al. 2006
Au/Fe_2O_3	Up to −70 °C; 43.2 °C	Active	–	90	Ruihui et al. 2010
Au/α-Fe_2O_3	−50 °C; ~10 °C	Active	CO/O_2/He	90; 100	Haruta et al. 1993
Au/CeO_2-x	5 °C	–	CO/O_2/He	100	Juan et al. 2005
0.52 wt.% Au/CeO_2 nanoparticle	0 °C; 20 °C	–	CO in air; 48,000 mL h^{-1} g^{-1}	80; 100	Han et al. 2010
Au/La_2O_3	25 °C	–	CO/O_2/He	100	Juan et al. 2005
$Au/La_2O_3/Fe_2O_3$	28.9 °C	Active	–	90	Ruihui et al. 2010
Au-Fe_3O_4/C	50 °C	–	–	100	Yin et al. 2008

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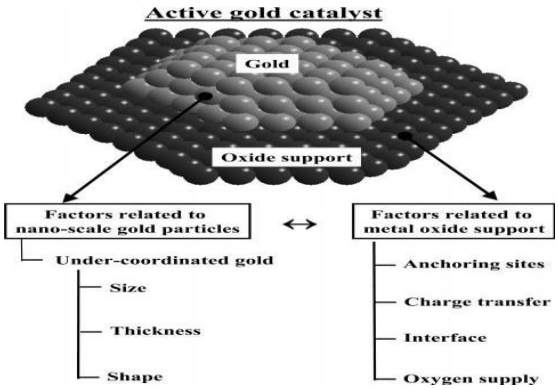
Au/NiO	Up to −70 °C	Active	$CO/O_2/He$	100	Haruta et al. 1993
$Au/Be(OH)_2$	Below 0 °C	–	$CO/O_2/He$	100	Haruta et al. 1993
$Au/Mg(OH)_2$	Below 0 °C	–	$CO/O_2/He$	100	Haruta et al. 1993
Au/ZnO	−13 °C	–	$CO/O_2/He$	100	Boccuzzi & Chiorino, 1994

7. Applications of CO oxidation catalyst

a. As emergency breathing masks

The principal applications of carbon monoxide (CO) oxidation catalysts operating at ambient temperature are emergency respiratory protection devices and life-support systems used in confined environments, including spacecraft cabins. For land-based emergency breathing masks, hopcalite has traditionally been employed due to its effectiveness in CO removal. However, during the 1970s, NASA selected a catalyst consisting of 2% platinum supported on carbon for use in the Space Shuttle. This material was preferred because it demonstrated higher catalytic activity and greater resistance to deactivation by water vapor compared to hopcalite (Nalette et al.).



b. Destruction of carbon monoxide

For light gaseous pollutants such as H_2, CO, and CH_4, which cannot be effectively captured by activated carbon, catalytic oxidation is considered the most efficient removal technique. This method converts these gases into CO_2 and H_2O, which can be readily eliminated. Hopcalitehas long been used for this purpose, particularly in submarines, though it has notable limitations. Recent studies have reviewed hopcalite catalysts for low-temperature CO oxidation, focusing on activity, reaction mechanisms, and deactivation causes (Jiling et al., 2007; Maier & Saalfrank, 2004). The lowest CO oxidation temperature reported is approximately 220 K using Au_4/TiO_2 catalysts.

c. Ozone removal

Ozone is a highly reactive and corrosive gas that can damage a wide range of materials, including most plastics, rubber, and non-stainless metals. Continuous exposure to ozone pollution is associated with adverse health effects and can also reduce tree growth and agricultural productivity (Clear Air Counts,

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2003). To remove ozone from gas streams, a composite catalytic material has been developed using a support matrix coated with fine hopcalite particles, primarily containing manganese oxide. As ozone passes through a manganese dioxide catalyst bed, it is converted back into oxygen in a heat-releasing catalytic reaction. This thermal-catalytic destruction process does not consume the catalyst, allowing the catalyst bed to remain effective for one to five years, depending on operating conditions and the carrier gas.

d. Oxidation of ammonia

The accumulation of biologically generated ammonia in closed cabin environments poses a serious health risk during long-duration missions. Urine is the primary source of ammonia, and although control measures are applied at the source, trace amounts still enter the cabin air. To maintain a safe atmosphere, spacecraft trace contaminant control systems must effectively remove ammonia. Catalytic oxidation is a preferred method, converting ammonia into water and nitrogen. NASA supported research at Texas Tech University (NAS 1-9506) to examine ammonia transformation pathways in catalytic oxidizers, where conversion to nitrogen is favored due to the toxicity of nitrogen oxides (Johnson, 1972).

e. Volatile organic compounds (VOCs) abatement

Volatile organic compounds (VOCs) are widespread pollutants found in residential environments and numerous industrial sectors, including dry cleaning facilities, food processing units, petroleum refineries, airports, service stations, and chemical and electronics industries. These substances evaporate easily into the atmosphere and contribute significantly to air pollution, while rainfall and snowmelt can transport them into soil and groundwater (Rusu & Dumitriu, 2003). VOC exposure poses serious risks to human health, vegetation, and wildlife (Minnesota Dept. of Health, 2003). In catalytic converters, oxidation reactions involving CO and hydrocarbons are complex, and extensive research has focused on the total oxidation of alkanes—particularly methane—due to its role as a major greenhouse gas (Prasad et al., 1984; Zwinkels et al., 1993; Zwinkels et al., 1998; Choudhary et al., 2002; Gelin & Primet, 2002).

i. Propane oxidation

Controlling dioxin emissions from waste incinerators remains a major environmental challenge (Balldvhmiter et al., 1986; Buchert & Ballschmiter, 1986). Conventional methods, such as increasing exhaust-gas temperature to enable catalytic oxidative decomposition, are effective but involve high capital costs and complex mechanical systems, making them

unsuitable for small-scale incinerators (Duwel et al., 1990). An alternative approach involves catalytic oxidation of dioxins at the dust filter stage. Studies show that ternary catalysts such as Au/Fe_2O_3–Pt/SnO_2–Ir/La_2O_3 exhibit significantly enhanced activity for o-chlorophenol and dioxin oxidation at 423 K, with Ir/La_2O_3 acting as an effective promoter despite its low standalone activity (Okumura et

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al., 2003).

ii. Oxidation of thiophene

Sulfur-containing volatile organic compounds (VOCs) are major contributors to offensive odors in the environment and are increasingly recognized for their potential health risks under prolonged exposure (Kosmider et al., 2002; Le et al., 2004). Growing public concern and complaints regarding odor emissions from industrial and municipal sources have intensified research into effective odor-control technologies. Among the available approaches, catalytic oxidation has emerged as a promising method for the removal of odorous gases from the atmosphere (Wang & Weng, 1998; Wang et al., 2002). Commercial catalysts used for VOC combustion typically include supported noble metals, metal oxides, and hybrid systems combining noble metals with metal oxides (Garetto et al., 2004; Malley & Hodnett, 1999; Kim, 2002; Ferrandon & Bjornbom, 2001). In particular, both conventional hopcalite and hopcalite modified with noble metals such as platinum, palladium, and gold have been investigated for thiophene oxidation, showing promising catalytic performance (Szynkowska et al., 2009).

iii. Oxidation of halogenated hydrocarbons

Purifying air that contains a variety of low-concentration contaminants has become increasingly important, especially as people spend long periods in enclosed spaces. Nineteen halogenated hydrocarbons mixed with air were tested using a Hopcalite catalyst in a laboratory-scale catalytic burner under conditions similar to those in submarine burners.

iv. Low temperature oxidation of ethene

Several studies have focused on developing catalysts capable of achieving complete oxidation of volatile organic contaminants at relatively low temperatures. In particular, catalysts used for carbon monoxide oxidation have also been evaluated for the removal of ethene in fruit storage environments, where ethene accelerates ripening. A range of catalysts was tested using a mini-reactor coupled with a mass spectrometer and a total hydrocarbon analyzer. Under reaction conditions of 300 ppm ethene and 0.6% oxygen in nitrogen at a fixed space velocity, all oxide catalysts exhibited activity at temperatures above 300 °C. Platinum on asbestos and palladium on alumina achieved 50% ethene conversion at approximately 145 °C. In contrast, platinum- and palladium-supported zeolites reached complete conversion at around 100 °C. HZSM-5 also demonstrated excellent performance, achieving full ethene oxidation at 200 °C. The PtCsNaY(T) catalyst maintained stable reactivity even after processing 5 g of ethene per gram of catalyst (Parker & Patterson, 1994).

f. Study of the adsorption of water vapor and carbon dioxide

Previous studies have demonstrated that manganese dioxide, either alone or combined with other metal oxides, functions as an effective oxidation catalyst. Although these catalysts may vary in composition, they are generally characterized by a highly porous structure, which enables efficient adsorption of

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gaseous vapors. This porosity enhances catalytic performance

but can also create vulnerability under conditions of high moisture. When gases contain elevated levels of water vapor, catalyst deactivation may occur if liquid water condenses within the pores. For this reason, it became essential to investigate the adsorption behavior of various substances, particularly water vapor and carbon dioxide, better to understand their influence on catalyst performance and stability (Lanning, 1930).

g. Water gas shift reaction (WGSR) Activity

The water-gas shift reaction was discovered by the Italian physicist Felice Fontana in 1780. In this reaction, carbon monoxide reacts with water vapor to produce carbon dioxide and hydrogen:

$CO\ (g) + H2O\ (v) \rightarrow CO2\ (g) + H2\ (g), \quad \Delta H = -41.09$ kJ/mole.

This reaction is significant in industry. It is often used alongside steam reforming of methane or other hydrocarbons, crucial for producing high-purity hydrogen for ammonia synthesis. The reaction is slightly exothermic, releasing 41.1 kJ (10 kcal) per mole.

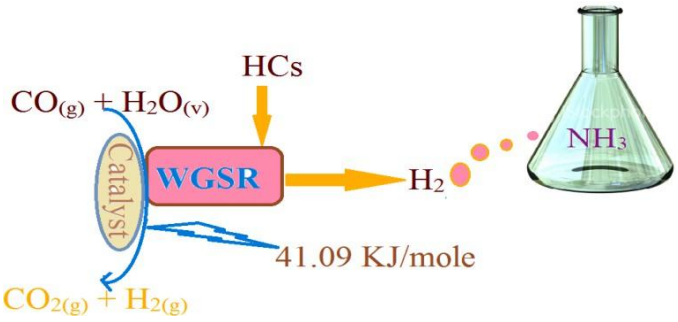

Fig. 7. Schematic diagram showing use of catalyst in WGSR & NH3 synthesis.

The reduction of Cu–Mn spinel oxides to form copper–manganese oxide catalysts has been widely investigated to improve the performance of copper-based systems in the water–gas shift reaction (WGSR). Optimized Cu–Mn spinel catalysts have demonstrated excellent WGSR activity under high carbon monoxide concentrations, similar to conditions encountered during hydrocarbon reforming. However, the presence of carbon dioxide in the reformate gas was found to suppress WGSR activity at temperatures below 200 °C, whereas stable CO conversion was achieved at 200 °C in the absence of CO_2 (Tanaka et al., 2003).In related studies, noble metals supported on various oxide materials have been evaluated for high-temperature WGSR. Platinum exhibited enhanced catalytic performance when supported on U_3O_8 and CeO_2–ZrO_2, while rhodium showed superior activity on Fe–Cr oxide and Cr_2O_3 supports. These improvements are attributed to increased reaction rates occurring at the interface between the promoter metal and the oxide support, highlighting the importance of metal–support interactions in WGSR catalysis (Science Daily, 2011).

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h. **Photocatalytic reactions (Water Detoxification)**

Photocatalytic water purification using semiconductor materials has emerged as an advanced oxidation technique and has undergone significant development over the past two decades (Hsiao et al., 1983; Pruden & Ollis, 1983; Nguyen & Ollis, 1984; Al-Ekabi & Serpone, 1988). Titanium dioxide (TiO_2) has attracted considerable attention due to its strong photocatalytic properties. The incorporation of metallic gold onto TiO_2 surfaces further enhances photocatalytic efficiency by preventing reaction-rate decline at higher phenol concentrations. During photocatalysis, phenol is progressively degraded and completely mineralized into CO_2 and H_2O. Consequently, Au/TiO_2 catalysts demonstrate superior performance compared to pure TiO_2 in aqueous phenol removal (Dobosz & Sobczynski, 2001).

8. **Epoxidation of Styrene**

Controlling dioxin emissions from waste incineration plants remains a major challenge in environmental protection (Balldvhmiter et al., 1986; Buchert & Ballschmiter, 1986). Although increasing exhaust-gas temperatures to promote catalytic oxidation has been applied (Duwel et al., 1990), the high capital cost and mechanical complexity limit its use in small incinerators. A more practical alternative is catalytic oxidation at the dust- filter stage. Ternary catalyst systems such as Au/Fe_2O_3 combined with Pt/SnO_2–Ir/La_2O_3 exhibit significantly enhanced activity for oxidizing o-chlorophenol and dioxins at 423 K, indicating a strong promotional role of Ir/La_2O_3 (Okumura et al., 2003).

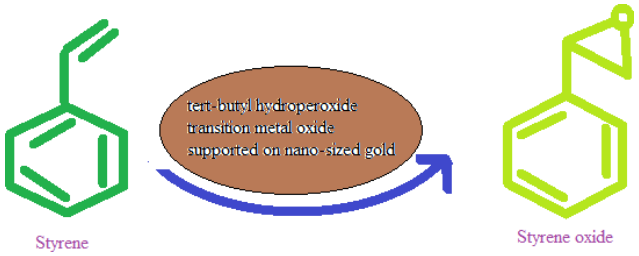

Fig. 8. Conversion of styrene to styrene oxide using CO oxidation catalyst.

9. **Oxidative decomposition of Dioxins**

Controlling dioxin emissions from waste incinerators remains one of the most serious challenges in environmental protection (Balldvhmiter et al., 1986; Buchert & Ballschmiter, 1986). Existing control methods include increasing flue-gas temperatures to promote catalytic oxidative decomposition; however, high capital costs and mechanical complexity limit their applicability in small-scale incinerators (Duwel et al., 1990). An alternative strategy involves catalytic oxidation directly at the dust-filter stage. Ternary catalyst systems such as Au/Fe_2O_3–Pt/SnO_2–Ir/La_2O_3 exhibit significantly enhanced activity for oxidizing o-chlorophenol and dioxins at 423 K, indicating a strong promotional role of Ir/La_2O_3 despite its low standalone activity (Okumura et al., 2003).As Biological Probes

Bond and co-workers proved that the supported gold catalysts are quite active in hydrogenation reactions of olefinic hydrocarbons (Bond et al., 1973; Bond & Sermon, 1973). Specifically, impregnated gold catalysts supported on silica or 300 C alumina were identified to be useful in hydrogenating 1-pentene at 373 C (Bond et al., 1973; Bond & Sermon, 1973; Sermon et al., 1979). These are findings that emphasised the possibility of using gold as an active catalytic material, despite the age-old belief that it is chemically inactive. Chen and

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others have also reported further progress in this by producing a new Au/SiO 2 catalyst and were able to use this catalyst in the reduction of a variety of aromatic nitro compounds; this is evidence of the generality of the gold catalytic system (Chen et al., 2006).

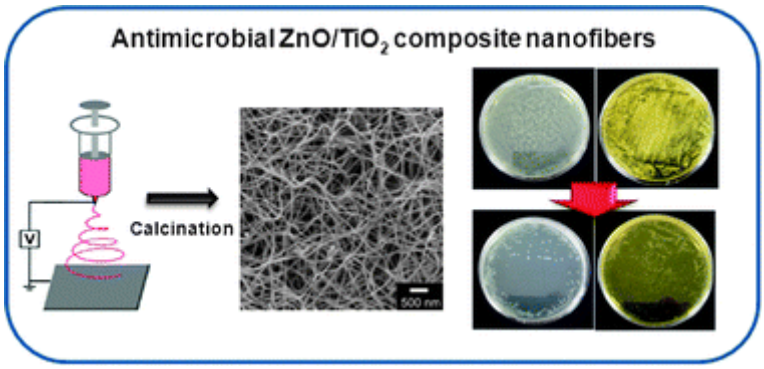

Fig.9. Electrospun ZnO/TiO2 composite nanofibres exhibited excellent bactericidal performance against E. Coli, S. aureus with and without light irradiation.

10. Hydrogenation reactions

Bond and co-workers established that supported gold can be a good catalyst to perform hydrogenation reactions with olefinic hydrocarbons (Bond et al., 1973; Bond & Sermon, 1973). Silica or 3-alumina supported gold catalysts synthesised by impregnating with gold are found to have high activity in the hydrogenation of 1-pentene at temperatures of 373 K (Bond et al., 1973; Bond & Sermon, 1973; Sermon et al., 1979). Increasing the use of gold-based catalysts, Chen and co-workers eventually came up with a new type of catalyst, Au/SiO2 and were able to test its ability of the reduction of various aromatic nitro compounds (Chen et al., 2006).

11. Poisoning and Masking of Catalyst

Various factors can negatively influence the performance of a catalytic system; these are mechanical vibrations, abrasion due to the presence of particulate matter, catalyst poisoning, surface masking, and thermal ageing. Catalyst poisoning happens when a chemical reaction between catalystic sites and phosphorus, halogen or heavy metals is experienced, and the resulting compounds are inactive, resulting in the loss of activity. On the other hand, masking is a physical barrier to the active sites of the catalyst caused by deposition of solids upon it. These deposits could either be of airborne dust, metal oxides or carbonaceous residues in which the reactor is under insufficiently low temperatures (Kohl & Nielsen, 1999).

12. Conclusion

Although numerous catalysts have been explored for carbon monoxide oxidation, many suffer from serious limitations such as moisture-induced deactivation, high costs associated with noble metals like platinum, palladium, and ruthenium, and concerns regarding long-term stability and availability. These challenges have intensified the search for efficient CO oxidation catalysts that can operate under ambient conditions. In this context, gold-based catalysts have attracted considerable interest. When properly prepared, gold catalysts

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exhibit superior low-temperature CO oxidation activity compared to conventional noble metals and show strong resistance to sulfur poisoning, particularly when dispersed as nanoparticles on transition-metal oxide supports.

13. Future Aspects

The role of water in the increasing oxidation of carbon monoxide over various catalyst systems is a phenomenon that is still open and under active discussion, and is probably going to be an issue of research in the future. Nevertheless, very few studies have been conducted so far to monitor the behaviour and impact of trace levels of ammonia incatalytic oxidation systems, despite its possible application in the real operating conditions. Experimental data also show that CO oxidation can be greatly accelerated by the presence of moisture, which implies that water can either be a direct or an indirect participant in the mechanism. Catalysts made of gold-based material have been observed to hold great promise as they are very active catalysts at ambient temperature. Simultaneously, there has been an increasing interest on non-noble metal catalysts because they can serve as a cheaper substitute of precious noble metals and can also present a more sustainable way forward in future catalytic research.

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