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Communication

Role of copper grid mesh in the catalytic oxidation of CO over one-step synthesized Cu-Fe-Co ternary oxides thin film

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ABSTRACT

The effective valuation of catalyst supports in the catalytic oxidation makes the contribution to understand the support effect of great interest. Here, the role of active substrate in the performance and stability of Cu-Fe-Co ternary oxides was studied towards the complete catalytic oxidation of CO. The Cu-Fe-Co oxide thin films were deposited on copper grid mesh (CUGM) using one-step pulsed-spray evaporation chemical vapor deposition method. Crystalline structure and morphology analyses revealed nano-crystallite sizes and dome-top-like morphology. Synergistic effects between Cu, Fe and Co, which affect the surface Cu^{2+}, Fe^{3+}, Co^{3+} and chemisorbed oxygen species (O^{2-} and OH^{-}) of thin films over the active support and thus result in better reducibility. The thin film catalysts supported on CUGM exhibited attractive catalytic activity compared to the ternary oxides supported on inert grid mesh at a high gas hourly space velocity. Moreover, the stability in time-on-stream of the ternary oxides on CUGM was evaluated in the CO oxidation for 30 h. The adopted deposition strategy of ternary oxides on CUGM presents an excessive amount of adsorbed active oxygen species that play an important role in the complete CO oxidation. The catalysts supported on CUGM showed better catalytic conversion than that on inert grid mesh and some literature-reported noble metal oxides as well as transition metal oxides counterparts, revealing the beneficial effect of the CUGM support in the improvement of the catalytic performance.

Catalytic oxidation of CO has aroused the interest of researchers for its importance in practical applications and speculative studies in the area of catalysis due to its low operative temperature, high conversion efficiency, economical technology and eco-friendly [1]. Recently, a huge amount of CO is universally produced mainly from chemical plants, transportation, petroleum refineries, automobile manufacturing and pharmaceutical plants, which is regarded to be vastly toxic and dangerous for human health even at the level of 9 ppm [2]. There are two kinds of catalysts frequently used for the catalytic CO oxidation, namely those based on transition metal oxides (TMOs) and noble metals. The noble metals based catalysts have been extensively used for CO oxidation owing to their high activity at low temperature [3]. It is generally accepted that noble metals are more active than TMOs. Nevertheless, the TMOs are easily available, highly thermally stable, less expensive and exhibit good resistant to the poisoning tendency [4]. Consequently, attentions are increasingly being paid to the replacement of precious metals and the preparation of cheap transition-metal based mixed oxides [5,6].

Among TMOs, copper-based catalysts have been found active in the oxidation of CO and attracted significant attention in recent years [7,8]. Copper oxide catalysts supported on niobium oxide have been successfully tested in the CO oxidation and achieved remarkable results by Leung *et al.* [7]. Stoyanova *et al.* prepared $CuCo_2O_4$ spinel supported on Al_2SiO_5 and achieved complete oxidation of CO to CO_2 at ~230 °C [9]. Liu *et al.* used Fe-based catalysts loaded with Cu and Mn for oxidation of CO and observed that interaction between Cu and Mn, Mn/Cu molar ratio and reducibility considerably influenced the catalytic performance [10]. Choi *et al.* evaluated Mn-Cu-Co ternary oxides catalyst for low temperature CO oxidation and found that the oxygen mobility and also textural properties of the catalysts constructively influenced on the catalytic activity [11].

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Recently, Carrillo *et al.* reported that the supported catalysts on halloysite have better catalytic activity than unsupported catalysts, revealing the crucial role of support in the enhancement of catalytic activity [12]. In general, the performance of a catalyst in oxidation reaction depends upon the physicochemical properties and active component of the used support, such as surface area, crystal structure, thermal stability and chemical composition. According to literature, the presence of single and binary structure of copper oxide, iron oxide and cobalt oxide could play a key role in the catalytic oxidation of CO over TMOs catalysts [13–15]. On the other hand, it is also significant to use an active support for the Cu-based catalysts in order to improve their catalytic performance for oxidation of CO. Among the possible active metal supports, CUGM is a promising candidate in terms of oxidation, sheet resistance and also has ability of calcination in a temperature range of 400–700 °C in air [16]. It is nearly non-porous having a very small specific surface area; it offers high thermal conductivity with value of 385.0 W m^{-1} K^{-1} which is higher than their counterparts [17], porosity, stability and mass transferability which facilitates better storage and easy mobility of reactive oxygen species [18]. These advantages make the CUGM more promising as support for Cu-Fe-Co ternary oxides thin film to exhibit better catalytic performance for the complete oxidation of CO. However, to the best of our knowledge, there is no pervious reported work on an active support for thin films through pulsed spray evaporation chemical vapor deposition (PSE-CVD). Therefore, the study on the support effects to understand the effective valuation of catalyst over an active support for CO oxidation would be of valuable interest in the absence of any other oxygen promoter and nobel metals support such as Au/SiO_2, Nb_2O_5, Pt/Pb, Al_2O_3, and TiO_2.

In the present work, the investigation of one-step synthesis of thin film Cu-Fe-Co ternary oxides supported on an active CUGM *via* PSE-CVD synthesis method was performed. The physicochemical properties of the deposited thin film were systematically characterized. Furthermore, the attention was paid to investigate the role of CUGM as an active support in the catalytic performance towards complete CO oxidation over Cu-Fe-Co ternary oxide. Moreover, an attempt to associate the durability of Cu-Fe-Co ternary oxides with the effect of support and structural features was discussed.

The synthesis of Cu-Fe-Co ternary oxides thin film was performed by PSE-CVD synthesis method. The experimental procedure and details of the setup can be seen in our earlier works [19,20]. In the current work, copper acetylacetonate (Cu(acac)$_2$), iron acetylacetonate (Fe(acac)$_3$) and cobalt acetylacetonate (Co(acac)$_2$) precursors were individually dissolved in ethanol with concentrations of 2.5 mmol/L as a feedstock to prepare the thin film catalyst over active support at appropriate percentage of 50:25:25 after attaining an attractive performance on inert support [21]. The feedstock was attained through PSE delivery route by using a four-pinhole injector with a frequency of 4 Hz and a valve opening time of 1.0 ms. The mixed feedstock was injected as a fine spray, with O_2 and N_2 flow rates of 0.50 and 0.25 standard liter per minute (slm) into evaporation chamber at 200 °C, by keeping the total pressure in deposition chamber at around ~2 kPa. Thin film catalyst was deposited on numerous substrates of bare glass (BG), stainless steel (SS) plate and CUGM at appropriate 320 °C using a flat resistive heater.

Numerous techniques were used to characterize the Cu-Fe-Co ternary oxides thin film. X-ray Diffraction (XRD) analysis with the 2θ of 15°-90° and scanning step of 0.02° was carried out by using the Phillips X'Pert Pro MDR diffractometer with PW3830 X-ray generator Cu Kα radiation under ambient conditions. The XRD database (JCPDS-ICDD) was used as a reference to identify the crystalline phases. Hitachi SU 8020 with ultra-high resolution of 1.5 nm (15 kV) was employed to obtain the surface morphology by Scanning Electron Microscope (SEM). Chemical compositions were determined by the Energy Dispersive X-ray Spectroscopy (EDS). Electrical resistivity measurement of Cu-Fe-Co thin film was carried out by using home-made four-point probe setup. A DC current source meter was used to apply current through the outer two probes and inner two probes was used to measure a voltage through voltmeter, probe spacing between each probe is about 1.5 mm. X-ray photoelectron spectroscopy (XPS) was used to examine the chemical and ionic states of the obtained thin films, with transmission energy of 80 eV and analysis voltage of 15 kV through AXIS ULTRA DLD (Shimadzu Kratos).

The catalytic performance of the deposited film as a catalyst, was evaluated using a fixed bed flow reactor for CO oxidation. The detail of the apparatus has been described elsewhere [19]. The as-prepared thin film catalyst (~12 mg) was supported on a copper grid mesh. A gaseous mixture consisted of 1% CO, 20% O_2 in Ar, with a total flow rate of 15 mL/min, corresponding to the gas hourly space velocity (GHSV) of ~75,000 mL cat g^{-1} h^{-1}. The furnace temperature was increased with a ramp of 5 °C/min by using a digital electrical furnace. The composition of the exhaust gas was measured by FTIR spectrometer coupled with KBr cell for qualitative and quantitative analysis. The data treatment is based on the Bouguer–Beer–Lambert's law can be found in our previous work [5]. Moreover, a time-on-stream test of the as-prepared thin film was carried out under the same inlet conditions for 30 h continuously at ~75% conversion of CO (~181 °C).

The purity and crystalline structure of the Cu-Fe-Co ternary oxides were studied by XRD, as shown in Fig. 1. The as-prepared ternary oxide showed clear peaks, indicated that the deposited oxides exhibited crystalline phases which fit well with the XRD database of (JCPDS No. 50-1452) and (JCPDS No. 49-1399). The ternary oxide showed high purity in crystallite because there was no peak of impurity phases.

The micro-strain and the crystallite size of Cu-Fe-Co ternary oxide among two most intense diffraction peaks were calculated by applying Scherrer's formula. The micro-strain was found to be 0.251% and the crystallite size was calculated to be 12 ± 2 nm respectively, as shown in Fig. 2 [13,22–25]. Compared to results reported in the literature [13,26,27], it can be seen that the crystallite size decreases while micro-strain increases, as displayed in Fig. 2. Iqbal *et al.* reported that this kind of behavior might be ascribed to the slightly larger ionic radii of dopant as compared to host ions [28]. In the present work, the crystallite size tends to be small and the micro strain increases as shown in Fig. 2, which could be due to agglomeration of larger ionic radii of Cu^{2+} (0.73 Å), Fe^{3+}

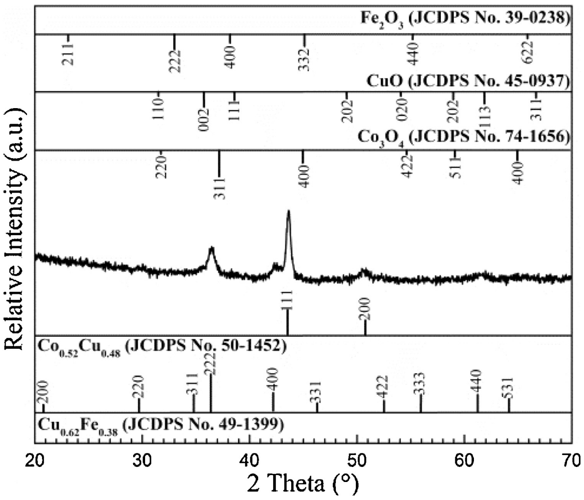

Fig. 1. XRD pattern of the Cu-Fe-Co ternary oxide.

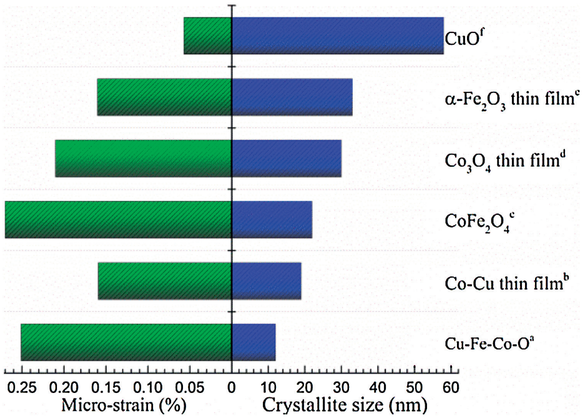

Fig. 2. Crystallite sizes and micro-strains of different systems: (a) Cu-Fe-Co-O in this work; (b) Co-Cu thin film [13]; (c) $CoFe_2O_4$ [22]; (d) Co_3O_4 thin film [23]; (e) α-Fe_2O_3 thin film [24]; (f) CuO [25].

(0.78 Å) and Co^{3+} (0.61 Å). The crystallite size of the oxides supported on copper was found to be smaller than the inert support and supported with other TMOs [29,30], suggested that copper support could adequately benefit the high dispersion of ternary oxides as a support. In addition, it was reported that the small grain size exhibited a favorable effect on active sites dispersion and the efficiency of catalytic performance might be increased [31]. Therefore, the synergetic effect among Cu, Fe and Co species and the small crystallite size was expected to play together decisive role in the catalytic performance for CO oxidation.

The surface morphology of the as-prepared thin film was studied by SEM and the representative images are shown in Fig. 3. Before deposition, the CUGM owns yellow golden color (not shown here). It was reported that copper is very active and it can be easily shaped with different colors, including black, red, blue and metallic lusters [32]. In the current work, CUGM turns into dark gray or blackish color after deposition of the ternary oxide (Fig. 3a) which is in good agreement with Britt [32]. In general, Cu-Fe-Co ternary oxide exhibited agglomerated dome-top-shaped structures and no other particular defined geometry was observed due to the loss of the crystallinity. Furthermore, the as-prepared ternary oxide film dispersed uniformly on the support owning porous, open-like surface and very small grain size that is in somehow accordance with obtained ones from XRD results. Besides the dome-top shapes, a number of hollows were also observed. In fact, the rates of nucleation and growth process were not parallel to more continuous nucleation of the films [33]. This observed morphology might be due to the agglomeration of copper oxide (ball-like morphology), iron oxide (nano-plate structures) and the aggregation of the corresponding cobalt oxide (cubic-shape morphology), which gives small distinct particles [25,34,35]. Moreover, the fast growth rate of copper oxide (1.84 nm/min) over iron oxide (0.71 nm/min) and cobalt oxide (1.55 nm/min) were reported in our earlier works [23–25] and the high content of copper composition tends to lead morphology close to copper oxide. The deposited film showed hollows, small grain size and open porosity that may provide a high surface area with highly accessible active catalytic sites and the ability to contain a significant amount of oxygen, which plays a crucial role in the catalytic oxidation of CO [36,37].

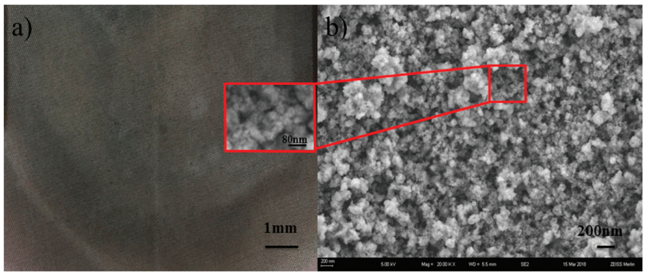

Fig. 3. Images of Cu-Fe-Co ternary oxide, (a) low-resolution and (b) high-resolution.

The chemical composition of the deposited thin film was examined using EDS to understand the properties of the active layer. A comparison was made by using EDS images between non-coated CUGM and Cu-Fe-Co ternary oxide shown in Fig. 4, it could be clearly seen the co-existence of elements of Cu, Fe, Co and O after incorporation into the ternary oxide structure and the presence of Cu element on non-coated CUGM, showing that Cu, Co and Fe were successfully dispersed in bulk of the prepared material. The comparison of the composition of non-coated CUGM and Cu-Co-Fe ternary oxides are listed in Table 1.

In addition, the higher quantity of oxygen species presented in the produced thin film catalyst could play a beneficial role in the catalytic oxidation [20], thus the observed high amount of O in the as-prepared ternary oxides after deposition on active substrate could be beneficial to enhance the catalytic performance. Consequently, the observed abundance of oxygen due to oxygen vacancies have been introduced into transition metal oxides by cation doping of agglomeration metals, solution processing [38,39] and (hollows and open porosity morphology) in the as-prepared ternary oxides thin film structure could lead to very good catalytic activity with respect to the complete CO oxidation.

In order to obtain the composition of the surface, XPS was performed. Fig. 5 shows the XPS spectra of Cu 2p, Fe 2p, Co 2p and O 1s. As shown in Fig. 5a, the Cu $2p_{3/2}$ peak is centered at 932.0 eV and the Cu $2p_{1/2}$ peaks at 951.8 eV. Strong intensity satellite peaks were perceived at higher binding energy, which clearly indicates the existence of Cu^{2+} on the as-prepared ternary oxide surface [40]. As exhibited in Fig. 5b, The Fe 2p spectrum of as-prepared thin film showed a wide peak at ~711.4 eV, which is in good agreement with the value of Fe_2O_3 reported in the literature and indicated the existence of Fe^{3+} [41]. Fig. 5c presents a doublet with peaks at approximately 779.0 and 793.9 eV due to the presence of oxidized species. The main two peaks are located at 794.0 and 779.1 eV, corresponding to Co $2p_{3/2}$ and Co $2p_{1/2}$, respectively. The O 1s spectrum exhibiting two peaks is displayed in Fig. 5d. The higher energy peak is assigned to the adsorbed oxygen (OH^- or defective oxygen), and the lower peak at ~529.5 eV could be attributed to the lattice oxygen species (O^{2-}). Waqas *et al.* [21] reported ternary oxide material release oxygen at relatively low temperature as compare to single and binary oxide materials counterparts during the reaction, causing oxygen species to move from lattice to the surface. Therefore, it is expected that the lattice and adsorbed oxygen present on the surface of the prepared thin film have a favorable influence on the complete CO oxidation.

The catalytic activity of the Cu-Fe-Co ternary oxide thin film grown on CUGM was studied for complete CO oxidation at atmospheric pressure using fixed-bed quartz flow reactor. The light-off curves of CO conversion over Cu-Fe-Co ternary oxides are shown in Fig. 6 [21–23,25,34,42]. It was observed that the conversion of CO was visible at about 110 °C and that complete conversion was attained at 222 °C on the deposited Cu-Fe-Co oxide film. The deposition of copper, iron, and cobalt species on the CUGM provided adequate surface active sites, leading to an increase of CO to CO_2 conversion. The comparison of CO oxidation over Cu-Fe-Co oxide film grown on CUGM, single oxide, binary oxide, ternary oxide reported in the literature and non-coated (active and inert) support is displayed in Fig. 6b. The obtained Cu-Fe-Co oxide film grown on GCGM showed better activity than Cu-

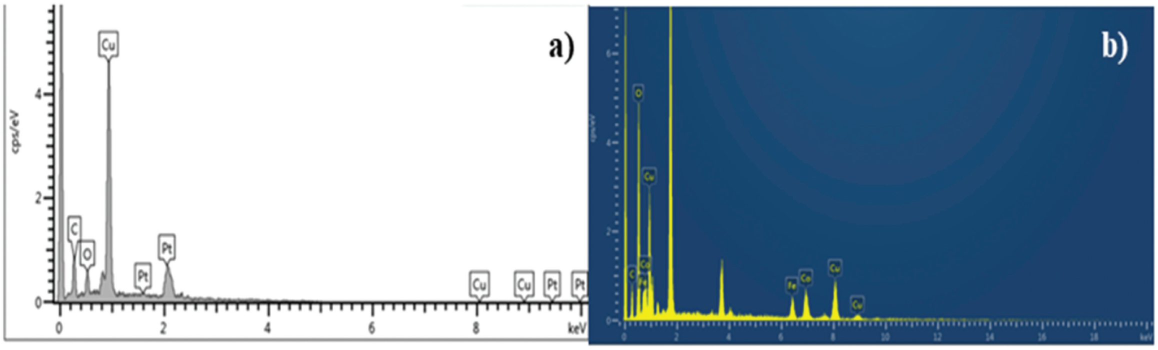

Fig. 4. EDS pattern of the non-coated CUGM (a) and Cu-Fe-Co oxide thin film (b).

Table 1
Relative chemical composition of non-coated CUGM and Cu-Fe-Co oxide thin film.

Catalyst	Cu (at%)	Fe (at%)	Co (at%)	O_{tot} (at%)
Non-coated CUGM	96.92	–	–	3.08
Cu-Fe-Co-O thin film	10.88	3.40	5.12	80.60

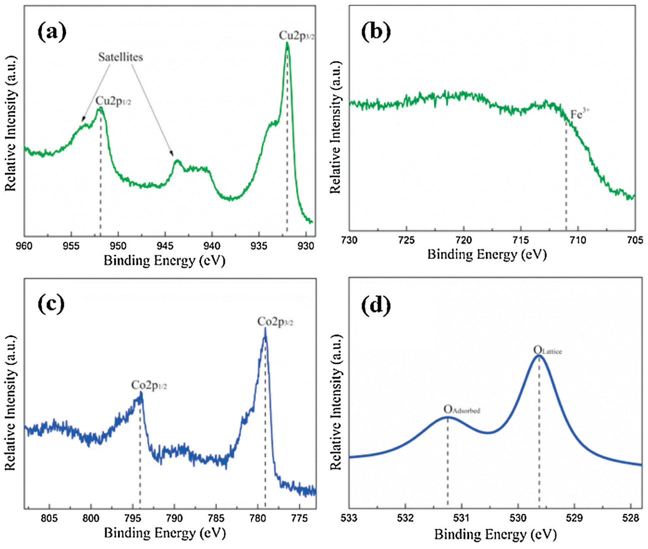

Fig. 5. XPS spectra of the Cu-Fe-Co-O thin film: (a) Cu 2p (b) Fe 2p; (c) Co 2p; (d) O 1s.

Fe-Co-O coated on inert support. Moreover, it was observed that non-coated active support showed much better activity than non-coated inert support towards complete CO oxidation. These results revealed that the active support greatly contributed in the performance of Cu-Fe-Co oxide film by providing excessive adsorbed active oxygen species for the oxidation reaction.

Compared with the single metal oxide [43], noble metal oxide [44], binary metal oxide [37] and Cu-Fe-Co ternary oxide thin film supported on inert support [21] reported in the literature, the as-prepared thin film ternary oxide exhibited better catalytic activity. The 90% conversion temperature T_{90} (Fig. 7a) over Cu-Fe-Co oxides (200 °C) as a thin film catalyst coated on CUGM observed higher than that over Cu-Fe-Co-O/SSGM (224 °C), $CoFe_2O_4$ (260 °C), $Co_{1.8}Fe_{1.2}O_4$ (250 °C), CuO/CoO (247 °C), Co_3O_4 (350 °C), Fe_2O_3 (366 °C) for the oxidation of CO [21–23,37,45,46]. Törncrona *et al.* reported [42] $Pt/CoO_x/Al_2O_3$ (340 °C) and Pt/Al_2O_3 (304 °C) catalysts and observed much higher 50% conversion temperature T_{50} of CO than that observed with Cu-Fe-Co oxide (162 °C) in the present work, which indicated that Cu-Fe-Co oxide grown on CUGM was more active at low temperature. The complete CO conversion was attained at a much lower temperature compared to stated metal oxide catalysts, even at a high GHSV. The comparisons of test conditions above mentioned metal oxides are listed below in Table 2.

Hertl and Farrauto studied the oxidation mechanism of CO with respect to spinel-type mixed oxide [47] and two reaction mechanisms were proposed. On the one hand, the oxidation of CO occurred at low temperature (80–200 °C) by decomposition of the carbonyl group on the surface of the catalyst. Hertl *et al.* reported the reaction occurred at low temperature came from the CO reaction with the lattice oxygen [47]. On the other hand, the

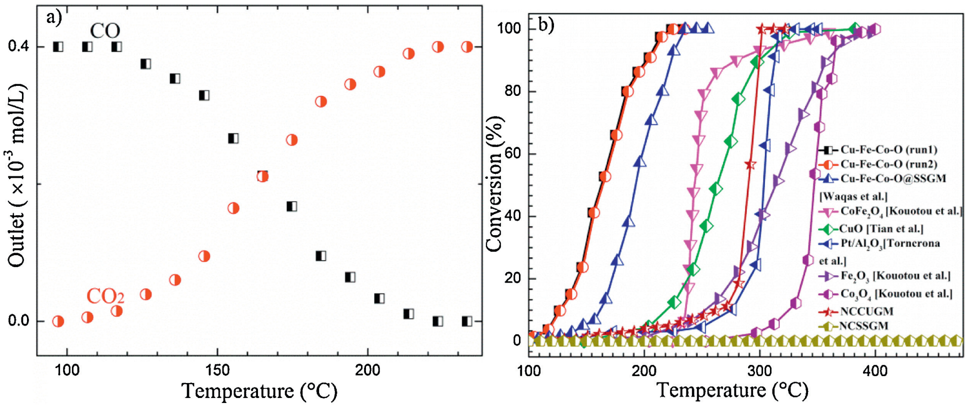

Fig. 6. Light-off curves of CO conversion over Cu-Fe-Co ternary oxide (a) and comparison of the catalytic performance for CO total oxidation over Cu-Fe-Co-O (run1 and run2, this work), Cu-Fe-Co-O@SSGM (stainless steel grid mesh) [21], $CoFe_2O_4$ [22], CuO [25], Pt/Al_2O_3 [42], Fe_2O_3 [34] and Co_3O_4 [23] (b).

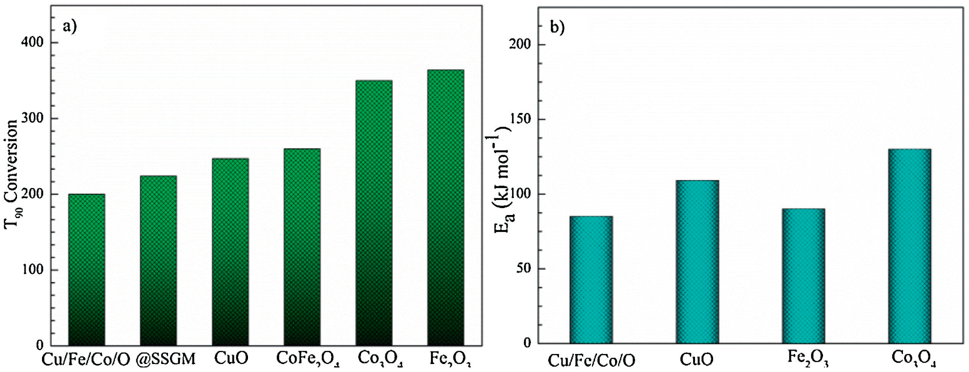

Fig. 7. (a) Comparison of the 90% conversion temperature (T_{90}) and (b) Apparent activation energy (E_a) for the CO oxidation with some other catalysts: CuO [25], Fe_2O_3 [34] and Co_3O_4 [23].

Table 2
Test conditions comparison of different metal oxides.

Catalysts	Weight (mg)	Gas composition	GHSV (mL g^{-1} h^{-1})	Ref.
Cu/Fe/Co/O (CUGM)	12	1% CO/20% O_2 in Ar	75,000	TW
NC-CUGM	–	1% CO/20% O_2 in Ar	–	TW
NC-SSGM	–	1% CO/20% O_2 in Ar	–	TW
CuO	12	1% CO/10% O_2 in Ar	75,000	[25]
Co_3O_4	12	1% CO/10% O_2 in Ar	75,000	[23]
Fe_2O_3	20	1% CO/10% O_2 in Ar	45,000	[34]
CuO/CoO	20	1% CO/10% O_2 in Ar	45,000	[37]
$CoFe_2O_4$	20	1% CO/10% O_2 in Ar	45,000	[22]
Cu/Fe/Co/O (SSGM)	12	1% CO/20% O_2 in Ar	75,000	[21]
Au/SiO_2	100	1% CO/99% in dry air	12,000	[46]
Pt/Al_2O_3	2/200	1% CO/1.38% O_2 in N_2	90,000	[42]

Note: GHSV refers to the gas hourly space velocity; TW stands for the results obtained in this work.

oxidation occurred at above 200 °C temperatures by decomposition of carbonate groups, which was from adsorbed oxygen. Moreover, according to our recent published work based on experimental and DFT calculations of CO reaction [48,49], it is plausible that a Eley-Rideal (ER) mechanism can be implemented to the complete CO oxidation on Cu-Co-Fe thin film oxide, having excessive amount of absorbed oxygen as an active oxygen species. This finding demonstrated that CUGM as an active substrate significantly affected the physicochemical properties of the Cu-Fe-Co oxides of by providing excellent thermal conductivity [17] and scattering of the charge carrier by agglomeration of copper, iron and cobalt are probably the effect leading to better electrical resistivity as compare to non-coated CUGM and SSGM as shown in Table 3. According to Verwey [50] proposed mechanism, polaron jumps lead to the electrical conductivity of the spinel oxide between the neighboring octahedron cations. Therefore, anionic vacancies close to octahedron cations can be appropriate sites to trap oxygen species, which can lead to increase the electrical resistivity due to stretching the distance between octahedral sites anions; also mass transferability for the transmission of reactive oxygen species and improved their catalytic performance. In the literature, it was reported that numerous parameters of metal oxide catalyst such as crystal size and structure, morphology, chemical composition, surface metal content and oxygen species could strongly affect the properties of catalytic performance for CO oxidation [51,52]. Furthermore, the catalytic performance could also benefit from easy mobility of reactive oxygen species, high active surface area and good porosity which results in a long contact-time between catalyst and reactants providing by as-prepared ternary oxide grown on CUGM and the synergetic effects of (Cu, Fe, and Co) metal species. Moreover, the effect of synergistic effects among Cu^{2+}, Fe^{3+}, Co^{3+} is reflected in the Fig. 6. Complete conversion of CO was observed at much higher temperature over single oxide (CuO, Fe_2O_3, Co_3O_4) thin films. The temperature for the complete conversion of CO decreased when binary oxide ($CoFe_2O_4$) was used due to synergistic effects between Co and Fe. The further role of synergistic effects among Cu^{2+}, Fe^{3+} and Co^{3+} was enhanced the catalytic activity when ternary oxide (Cu-Fe-Co-O) thin film was used for the CO conversion. Complete conversion of CO was attained at much lower temperature comparing to single oxide and binary oxide thin film. Moreover, the dome-top-like morphology with hollows illustrated by the microstructure analysis could adsorb more oxygen and expose more surface area, which would cause the oxidation at relatively low temperatures.

Furthermore, the catalytic activity was compared using the apparent activation energies (E_{appa}), which was determined by the Arrhenius equation based on the light-off curve in the region where the CO conversion was less than 15% [5]. The attained E_{appa} in current work was compared to the apparent activation energies in the literature, as displayed in Fig. 7b. The E_{appa} of Cu-Fe-Co oxide was found to be 85 kJ/mol, which was shifted to lower value as compared to corresponding values of pure copper oxide (109 kJ/mol), iron oxide (90 kJ/mol) and cobalt oxide (130 kJ/mol) in CO reaction. The E_{appa} of as-prepared ternary oxide reveals that the agglomeration of corresponding oxide results in dramatically decreasing of E_{appa}, which in turn is accompanied in enhancing the catalytic performance as aforementioned.

Moreover, the durability test is very significant criteria of the catalyst required for potential applications and it recently attained much more attention. In this work, the stability of as-prepared thin film gown on CUGM was examined by carrying out the oxidation reaction of CO for 30 h. As displayed in Fig. 8, it can be clearly seen that the conversion capability of the Cu-Fe-Co ternary oxides is

Table 3
Electrical resistivity of non-coated SSGM, CUGM and Cu-Fe-Co oxide thin film over copper mesh.

Current (mA)	Resistivity of non-coated SSGM (Ω cm)	Resistivity of non-coated CUGM (Ω cm)	Resistivity of Cu-Fe-Co over CUGM (Ω cm)
100	13	25	30
500	24	40	55
1000	38	73	95

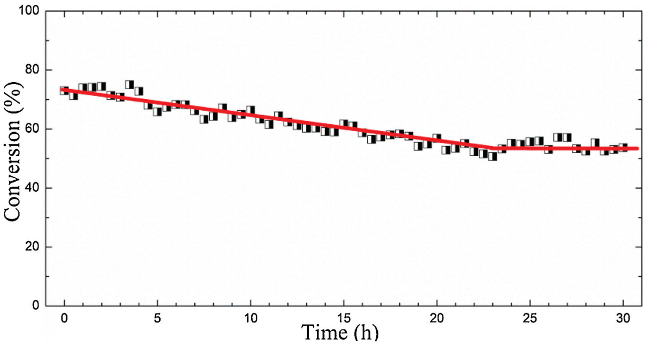

Fig. 8. Durability test of Cu-Fe-Co ternary oxide.

getting decreased after starting the reaction at 75% conversion and a loss of 26% conversion was observed in time-on-stream after 23 h, before getting improved later to achieve ~55% conversion at the end of the reaction, which can lead the reaction toward stability even after 23 h. The observed decrease in durability of as-prepared oxides can be ascribed due to the reaction products resulting from the deposition and accumulation during the oxidation process might be responsible for the corresponding reduction of the catalyst activity. Kouotou *et al.* [24] reported the decrease in durability of oxides due to the coverage of the active surface sites of the catalyst. Comparing to other results in literature, it is noteworthy to show that even a degradation has been seen during a reaction of as-prepared oxide in durability test that stabilized at 55% of conversion corresponds to 168 °C which shows prepared ternary oxide over CUGM is still more reactive than other counter parts, at similar temperature of 168 °C, as CuO with a conversion of ~2% [25], Fe_2O_3 (~0.4%) [34] and no conversion was observed over Co_3O_4, $CoFe_2O_4$ and Au/SiO_2 [22,23,46]. Thus, the as-prepared ternary oxide in present study remains very active catalyst at low temperature even after 30 h of time-on-stream reaction.

In colusion, thin film of Cu-Fe-Co ternary oxides for CO oxidation was homogeneously deposited on CUGM by one-step synthesis method named PSE-CVD and their properties were thoroughly characterized. Systematic characterizations showed that as-prepared thin film grown on CUGM revealed nano-sized crystallites, dome top-like morphology and chemisorbed oxygen species. The catalytic tests indicated that Cu-Fe-Co oxide thin film supported on GUGM found much active and presented competitive performance to single and mixed metal oxides supported on SSGM (stainless steel grid mesh) and reported precious metal supported on Al_2O_3, CoO_x and SiO_2 counterparts. Moreover, a slight decrease in the performance of as-prepared ternary oxides supported on copper mesh was observed during the time-on-stream experiment for 30 h. The attractive catalytic performance was attributed to the attractive synergistic effects with combination of (Cu^{2+}, Fe^{3+}, Co^{3+}) and chemisorbed oxygen species due to open porosity and hollows observed in morphology over as-prepared thin films, electrical resistivity, easy mass transferability, and higher quantity of oxygen species that provided the active sites which are suitable for the oxidation reaction. These findings provided a new generation of ternary oxides catalyst supported on a CUGM for the CO oxidation, which showed potential application at industrial level due to its high efficiency, energy saving and environmentally friendly properties.

Acknowledgments

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