# **RSC Advances**





Cite this: RSC Adv., 2015, 5, 3581

## Salen ligand complexes as electrocatalysts for direct electrochemical reduction of gaseous carbon dioxide to value added products

Surya Singh,<sup>a</sup> Bedika Phukan,<sup>b</sup> Chandan Mukherjee<sup>\*ab</sup> and Anil Verma<sup>\*c</sup>

 $CO_2$ , being a linear and centrosymmetric molecule, is very stable, and the electrochemical reduction of  $CO_2$  requires energy. Moreover, the  $CO_2$  electroreduction proceeds at a significantly higher applied voltage than thermodynamically required. In this concern, salen ligand,  $H_2L^{NO_2}$ , and its corresponding Ni(II) and Cu(II) complexes are synthesized and reported for the first time as electrocatalysts for  $CO_2$  electroreduction. Both the metal complexes are active for  $CO_2$  reduction and surprisingly result in formation of  $C_1$  and  $C_2$  hydrocarbons. The complexes are found to be very efficient to minimize overpotential required for the reaction as compared to their pure metal counterparts. Thus, the present study opens up a new class of metal complexes for the efficient electrochemical reduction of  $CO_2$  having the potential to generate hydrocarbons at lower overpotentials.

Received 4th September 2014 Accepted 24th November 2014

DOI: 10.1039/c4ra09818h

www.rsc.org/advances

## 1. Introduction

Utilization of  $CO_2$  for curbing the global warming menace is one of the highly investigated fields in the present scenario. In this respect, the electrocatalytic reduction of  $CO_2$  (ERC) may pave possibly a better way to mitigate and utilize  $CO_2$ , along with the generation of high calorific value fuels. Moreover, the use of renewable energy required for the  $CO_2$  reduction can be stored in the form of fuels.<sup>1–5</sup> Eqn (1)–(3) represent formation of a few of the high calorific value products using electrochemical reduction of  $CO_2$ . The equations show a full cell reaction, where 2, 8, and 12 moles of electrons are utilized for the formation of one mole of CO,  $CH_4$ , and  $C_2H_4$ , respectively, at corresponding standard cell potentials. Thus ERC may be helpful not only for the reduction of  $CO_2$  and generation of the conventional energy resources but also for the storage of renewable energy.

$$2CO_2 + H_2O \rightarrow 2CO + O_2 + H_2O, E^\circ = -1.33 V$$
 (1)

$$CO_2 + 2H_2O \rightarrow CH_4 + 2O_2, E^\circ = -1.06 V$$
 (2)

$$2CO_2 + 2H_2O \rightarrow C_2H_4 + 3O_2, E^\circ = -1.15 V$$
 (3)

Though the electrochemical reduction of  $CO_2$  offers advantages for the formation of value added products but the process is quite energy intensive. Most of the energy is used up towards conversion of  $CO_2$  by utilizing one-electron to form a  $CO_2^-$  anion radical, which has bent geometry. Generally, metals, such as Cu, Ru, and Mo, have been studied for the ERC process because of their ability to undergo multi-electron reduction of CO<sub>2</sub>, forming higher hydrocarbons and/or alcohols.<sup>6-8</sup> However, large activation overpotential is required for the formation of such reaction products using metals.9 Therefore, metal complexes are being studied in order to reduce the activation overpotential using well designed ligand and central metal atoms.<sup>2,9,10</sup> Macrocyclic metal complexes, such as Fe porphyrins; Mn, Cu, Zn phthalocyanines; and Ru bipyridines, have been extensively studied for CO<sub>2</sub> electroreduction.<sup>11-17</sup> Most of the systems resulted in the two-electron reduction of CO<sub>2</sub>, forming CO and/or HCOO<sup>-</sup>. A few of the workers also reported six and eight-electron reduction mechanism of ERC resulting in CH<sub>3</sub>OH and CH<sub>4</sub> formation using Mn, Zn porphyrins and Cu, Ga and Ti phthalocyanines, respectively.<sup>18-20</sup> Thus, the synergetics of suitable metal and ligand in metal complexes may have a greater role in the formation of high calorific value products as well as lowering down the overpotential. In the present study, for the first time, the use of salen ligand metal complex is reported as the electrocatalyst for direct electrochemical reduction of the gaseous CO<sub>2</sub>.

Salen ligand complexes are well known for their ability to chemically catalyze various reactions.<sup>21–24</sup> Therefore, Gambarotta *et al.* studied the bifunctional salen ligand complex containing nucleophilic cobalt(1) and an alkali cation for CO<sub>2</sub> capture. They have found very encouraging results, where acidic–basic (bifunctional) sites present in the metal complex played a role in binding the CO<sub>2</sub>.<sup>25</sup> In fact, this inculcated the idea to bind the CO<sub>2</sub> at the site and simultaneously reduce it at the electrode. Moreover, there is no study on such complexes for CO<sub>2</sub> electroreduction. Hence, the potential of salen complexes

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<sup>&</sup>lt;sup>a</sup>Centre for the Environment, Indian Institute of Technology, Guwahati-781039, India <sup>b</sup>Department of Chemistry, Indian Institute of Technology, Guwahati-781039, India. E-mail: cmukherjee@iitg.ac.in

<sup>&</sup>lt;sup>c</sup>Department of Chemical Engineering, Indian Institute of Technology, Delhi-110016, India. E-mail: anilverma@iitd.ac.in; Fax: +91-11-26581120; Tel: +91-11-26597304

needs to be explored in the field of ERC. In this effort, the primary objective of the paper is to evaluate the salen metal complexes for the electrochemical reduction of  $CO_2$  for the formation of value added products. To establish and evaluate the ERC, Ni and Cu were used to form salen metal complex electrocatalysts. Cu is well known to facilitate the formation of hydrocarbons, whereas Ni mostly results in undesired H<sub>2</sub> production with meager formation of CO.<sup>26–28</sup> Therefore, these metals were chosen to understand the effect of salen metal complex over ERC. It may be noted that the direct use of gaseous  $CO_2$  for the electrochemical reduction of  $CO_2$  (dERC) is being used.<sup>29</sup>

### 2. Experimental

#### 2.1 Materials

4-Nitro-*o*-phenylenediamine was procured from Alfa Aesar. Potassium bicarbonate (KHCO<sub>3</sub>), *N*,*N*-dimethylformamide (DMF), NiSO<sub>4</sub> · 6H<sub>2</sub>O and CuSO<sub>4</sub> · 5H<sub>2</sub>O were purchased from Loba Chemie. Acetonitrile (CH<sub>3</sub>CN), NiCl<sub>2</sub> · 6H<sub>2</sub>O, CuCl<sub>2</sub> · 2H<sub>2</sub>O, triethylamine (Et<sub>3</sub>N), ethanol (EtOH) and salicylaldehyde were procured from Merck. CDCl<sub>3</sub> for NMR spectroscopy was purchased from Sigma Aldrich. Pt/C (40 wt% Pt) was purchased from ElectroChem, Inc. USA. All the chemicals were used without further purification and de-ionized water was used in all the experiments unless stated otherwise. Gas diffusion layer from CeTech was used as a backing layer for electrocatalyst film to form an electrode. Nafion membrane was procured from DuPont, USA.

#### 2.2 Method

2.2.1 Characterization techniques. The synthesized ligand and metal complexes were characterized using Fourier transform infrared spectroscopy (FTIR), nuclear magnetic resonance spectroscopy (NMR), high-resolution mass spectrometry (HRMS), CHN analysis, and electrochemical half-cell studies. FTIR spectra were recorded in the range of 500–4000 cm<sup>-1</sup> using a Perkin Elmer FTIR spectrometer by grinding the sample with KBr (IR grade). The NMR spectrum was recorded at a 400 MHz frequency using a Varian, Mercury Plus nuclear magnetic resonance spectrometer. To know the mass of the ligand, the spectrum was obtained using an Agilent high-resolution mass spectrometer. CHN analysis was carried out using a EuroEA elemental analyser. Electrochemical tests (cyclic voltammetry (CV) and chronoamperometry) were performed using a potentiostat/galvanostat (CH Instruments Inc.). Product analysis was carried out using gas chromatography (GC) (Nucon 5765).

2.2.2 Synthesis of the salen ligand  $(H_2L^{NO_2})$  and corresponding complexes. 4-Nitro-*o*-phenylenediamine (A) contains a highly electron withdrawing  $-NO_2$  group at the *-para* position of one of the two amine groups (Scheme 1), and hence, the  $-NO_2$  group reduces the nucleophilic character of the amine group. Therefore, the ligand,  $H_2L^{NO_2}$ , was synthesized by reacting a large excess (6 equivalents) of salicylaldehyde with A in ethanol under refluxing condition. The ligand upon reacting with equivalent amounts of NiCl<sub>2</sub>·6H<sub>2</sub>O/CuCl<sub>2</sub>·2H<sub>2</sub>O in acetonitrile

in the presence of  $Et_3N$  provided Ni complex/Cu complex, respectively. The synthesis route of the ligand and the metal complexes is shown in Scheme 1.

2.2.2.1 Synthesis of salen ligand  $(H_2L^{NO_2})$ . A suspension of 4-nitro-o-phenylenediamine (1.53 g, 10 mmol) was prepared in ethanol solution (20 mL). Salicylaldehyde (7.33 g, 60 mmol) was added dropwise into the prepared suspension to form a mixture. The resulting mixture was heated to reflux for 20 hours. A yellow precipitate appeared after cooling the mixture at 30 °C. The precipitate was filtered, washed thoroughly with EtOH, and finally air dried to get  $H_2L^{NO_2}$ . Yield: 78%. FTIR (KBr pellet cm<sup>-1</sup>): 3447, 1615, 1566, 1511, 1478, 1341, 1277, 1194, 1153, 910, 843, 765. <sup>1</sup>H NMR (CDCl<sub>3</sub>, 400 MHz):  $\delta$  6.97 (td, J = 7.6 Hz, 1.2 Hz, 2H), 7.05 (t, J = 8.0 Hz, 2H), 7.33 (d, J = 8.8 Hz, 1H), 7.41–7.46 (m, 4H), 8.15 (d, J = 2.4 Hz, 1H), 8.18 (dd, J = 8.8 Hz, 2.4 Hz, 1H), 8.65 (s, 1H), 8.73 (s, 1H), 12.50 (s, 1H), 12.56 (s, 1H). HRMS (+) m/z for [C<sub>20</sub>H<sub>15</sub>N<sub>3</sub>O<sub>4</sub> + H]: calcd, 362.1135; found, 362.1115.

2.2.2.2 Synthesis of metal complexes  $[Ni^{\prime\prime}L^{NO_2} and Cu^{\prime\prime}L^{NO_2}]$ . In a CH<sub>3</sub>CN solution (10 mL) of H<sub>2</sub>L<sup>NO<sub>2</sub></sup> (0.180 g, 0.5 mmol), NiCl<sub>2</sub>·6H<sub>2</sub>O (0.120 g, 0.50 mmol)/CuCl<sub>2</sub>·2H<sub>2</sub>O (0.090 g, 0.50 mmol) and triethyl amine (0.2 mL) were added, and the resulting solution was stirred at 30 °C for five hours. During this time the color of the solution changed to reddish-brown (for Ni complex)/yellowish-brown (for Cu complex) with concomitant precipitation of the solid with the abovementioned color. Furthermore, the solid was filtered, washed thoroughly with CH<sub>3</sub>CN, and air dried.

*Ni complex.* Yield: 80%. FTIR (KBr pellet cm<sup>-1</sup>): 3433, 1610, 1576, 1509, 1335, 1279, 1248, 1198, 1155, 914, 836, 768. Anal. calcd for  $[C_{20}H_{13}N_3O_4Ni]$ : %C, 57.55; %H, 3.14; %N, 10.07. Found: %C, 59.46; %H, 3.14; %N, 9.66.



Scheme 1 Synthesis route to formation of the ligand and corresponding Ni(II) and Cu(II) complexes (A = 4-nitro-o-phenylenediamine).

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*Cu complex.* Yield: 82%. FTIR (KBr pellet cm<sup>-1</sup>): 3320, 1612, 1575, 1509, 1334, 1259, 1189, 1154, 875, 818, 760. Anal. calcd for  $[C_{20}H_{13}N_3O_4Cu \cdot CH_3CN \cdot 0.5H_2O]$ : %C, 55.93; %H, 3.63; %N, 11.87. Found: %C, 56.04; %H, 3.26; %N, 11.92.

2.2.3 Preparation of electrodes and membrane electrode assembly. Pt/C (40 wt% Pt), with Nafion dispersion (5 wt%) as binder, was used to prepare the anode electrocatalyst ink. The ink was coated over the gas diffusion layer using spraying technique and dried to get the anode. For the cathode (or working electrode), the ink was prepared by dispersing the metal complex electrocatalyst in an appropriate solvent along with Nafion dispersion. The electrocatalyst ink was then coated over the gas diffusion layer followed by drying. For the preparation of pure metal electrocatalysts (cathode) of Ni and Cu, electroplating was done over the gas diffusion layer using electroplating baths of NiSO4 · 6H2O and CuSO4 · 5H2O respectively. Suitable additives were added in respective baths to get the smooth deposition of metals over the gas diffusion layer. The electrocatalyst loading for anode and cathode was kept as  $0.5 \text{ mg cm}^{-2}$  and  $2 \text{ mg cm}^{-2}$ , respectively. The cation exchange membrane (Nafion-117) was treated using the standard procedure<sup>30</sup> before the experiments. The membrane electrode assembly was prepared by sandwiching the Nafion membrane in between anode and cathode at a particular temperature and pressure.

2.2.4 Electrochemical tests. The half-cell studies were conducted in a three-electrode cell assembly using Ag/AgCl as a reference electrode and Pt wire as a counter electrode. The working electrode was prepared using a 2 mg cm<sup>-2</sup> electrocatalyst loading supported over the gas diffusion layer. The cyclic voltammetry test was carried out in aqueous (0.5 M KHCO<sub>3</sub>) and non-aqueous (dimethylformamide, DMF) electrolytes at the scan rate of 0.01 V s<sup>-1</sup>. In all the half-cell studies, the potential is reported with respect to standard hydrogen electrode (SHE), unless stated otherwise. The full cell studies were carried out in an electrochemical reactor as described elsewhere.<sup>31,32</sup> The electrode area of  $3 \times 3 \text{ cm}^2$  was used for both anode and cathode of the electrochemical reactor. The cathode side of the reactor was fed with  $CO_2$  gas (99.995%) with the flow rate of 20 mL min<sup>-1</sup> adjusted by a rotameter. Deionized water was used as proton source at the anode with the flow rate of 1.5 mL min<sup>-1</sup>. The experiment was conducted using chronoamperometry technique (pulse width 5 s) at 8 different electrode potentials and the reaction products were collected at the cathode outlet and analyzed by GC. The electrochemical experiments were carried out at 30 °C and at atmospheric pressure.

### 3. Results and discussion

#### 3.1 Metal complex characterization

The salen ligand and metal complexes were characterized using FTIR spectroscopy along with other characterization techniques as described in Section 2.2.2. However, an ESI-MS measurement for the complexes was not possible due to insoluble nature of the complexes in the measurement friendly solvents. The infrared spectrum of ligand  $H_2L^{NO_2}$  showed a broad band

centered at 3447 cm<sup>-1</sup> due to v(O-H) stretching of two -OH groups. The broadness of the band indicated hydrogen bonding in the ligand. The aldamine C=N stretch appeared at 1615 cm<sup>-1</sup>. A sharp band at 1566 cm<sup>-1</sup> was found because of a phenyl asymmetric  $\nu(C=C)$  stretch. The existence of bands at 1511 cm<sup>-1</sup> and 1341 cm<sup>-1</sup> consolidated the presence of  $-NO_2$ functional group in the ligand. The phenolic  $\nu$ (C–O) band appeared at 1277 cm<sup>-1</sup>. In Ni and Cu complexes, the aldamine C=N stretch shifted slightly to a lower value and appeared at 1610 cm<sup>-1</sup> and 1612 cm<sup>-1</sup>, respectively. After complexation, an asymmetric  $\nu(C=C)$  stretching band for the phenyl ring appeared at 1576 cm<sup>-1</sup> and 1575 cm<sup>-1</sup> for the Ni complex and Cu complex, respectively, and the value was  $\sim 10~{
m cm}^{-1}$  higher compared to the value observed in the free ligand. This indicated more aromatic character inside the phenyl rings in the complexes compared to the ligand. In addition, a lower phenolic  $\nu$ (C–O) stretching value in the complexes (1248 cm<sup>-1</sup> in Ni complex and 1259 cm<sup>-1</sup> in Cu complex) compared to free ligand (1277 cm<sup>-1</sup>) supported further the higher aromatic character of the phenolate moiety. In the IR spectra of both the complexes, no appreciable changes were observed in 1511 cm<sup>-1</sup> and 1341 cm<sup>-1</sup> stretching bands. This indicated an undisturbed and non-interacting nature of the -NO<sub>2</sub> group in both Ni and Cu complexes. Interestingly, in Cu complex a relatively weak and broad band appeared at 3321  $\text{cm}^{-1}$ . The band is attributed to the  $\nu$ (O–H) stretching of H-bonded lattice water. Microanalysis data further supported the presence of lattice water.

#### 3.2 Half-cell studies

To find out the feasibility of the synthesized metal complexes for electrochemical reduction of CO2, half-cell studies were carried out. Metal complexes were studied in both aqueous and non-aqueous medium. In aqueous medium, the test was conducted in 0.5 M KHCO<sub>3</sub> solution, which was saturated with N<sub>2</sub> or CO<sub>2</sub> gases, to compare the voltammograms in inert and CO<sub>2</sub> environments, respectively. The pH of the saturated solution with N<sub>2</sub> and CO<sub>2</sub> was 8.5 and 7.5, respectively. The cyclic voltammograms (CVs) of the Ni and Cu complexes in the potential range of 0 to -3 V vs. SHE are shown in Fig. 1. The CVs were recorded in inert gas  $(N_2)$  as well as in CO<sub>2</sub> environment for both the complexes. It can be seen that a significant amount of current density is observed in both environments. However, the current density in the CO<sub>2</sub> saturated system is higher than the corresponding current density in the N2 saturated system for both complexes. The current density observed in the inert atmosphere is due to the reduction of water into H<sub>2</sub> gas. The onset potential (potential at which 0.1 mA  $cm^{-2}$  current density is observed) was found to be  $\sim$ 1 V for both complexes. It can be seen that with the increase in the applied voltage beyond onset potential, the current density increases (Fig. 1). It can be seen that the current density was found to be more, up to some extent, in the CO<sub>2</sub> environment as compared to the inert environment for both complexes. The higher current density in the CO<sub>2</sub> saturated environment may signify that electrocatalysts are able to reduce CO2. However, in aqueous medium the increase in current density is not only from the CO<sub>2</sub> reduction but also



Fig. 1 Cyclic voltammograms of the Ni complex (a) and Cu complex (b) in N<sub>2</sub> (broken line) and CO<sub>2</sub> (solid line) saturated in aqueous solution.

due to the reduction of H+ at the cathode, which is evident from Fig. 1. Moreover, the different pH level of the saturated solutions also affect the cathodic process as low pH favours the water reduction to hydrogen gas.<sup>33</sup> Therefore, efficacy of the metal complex electrocatalysts may not be truly ascertained by the abovementioned study. It may also be noted that the CV was conducted, and the products were evaluated using only the salen ligand (without metal). It was found that only hydrogen gas was evolved, which rules out the possibility that the salen ligands themselves are decomposing under reducing conditions to give the value added products. Hence,  $CO_2$  electroreduction was also carried out in non-aqueous medium to get more information about the electrocatalysts.

To further confirm the electrocatalytic activity of the complexes towards  $CO_2$  reduction, the half-cell tests were conducted in a non-aqueous environment (DMF solvent) to avoid any effect due to H<sup>+</sup> reduction to form H<sub>2</sub> gas.<sup>34</sup> The CV scans in a non-aqueous environment for both the metal complexes are shown in Fig. 2. It can be seen that the scan was recorded in absence of  $CO_2$ , and thus, only the charging current could be observed as there is no possibility of electron transfer between the electrolyte and electrode in the absence of any redox species ( $CO_2$ ). Furthermore,  $CO_2$  was bubbled in DMF, and the pH was maintained so as to have the same pH when  $CO_2$  was saturated

in the aqueous electrolyte.<sup>34</sup> Fig. 2 shows that the current density increases in the presence of CO2 because of the transfer of electrons from the electrode surface to the dissolved CO<sub>2</sub>. This increased current density in CO<sub>2</sub> environment confirms the reduction of CO<sub>2</sub>, as there is no other electroactive species present in the medium. Hence, the increase in current density is solely attributed to the CO<sub>2</sub> reduction. It was also seen that there is no increment in current density after -2.8 V vs. SHE and -2.6 V vs. SHE in CV of Ni complex and Cu complex, respectively. Moreover, on comparing the corresponding current densities in Fig. 1 and 2, it can be seen that the magnitude of the current density is significantly low in the case of Fig. 2. In the case of  $CO_2$  saturated aqueous system (Fig. 1) a significant amount of current density was due to the reduction of water into hydrogen gas at the cathode apart from the CO<sub>2</sub> reduction. In the case of DMF (Fig. 2), the  $CO_2$  was bubbled only up to a certain level to maintain the pH instead of CO2 saturation in the DMF. Moreover, the electroreduction might not be completed due to the absence of other reactants to combine with the reduced or activated  $CO_2$ . In turn, the low level of  $CO_2$  in the electrolyte along with increased mass transport resistance and scarcity of the co-reactant reduces the current density, which does not increase even with the increase in the applied voltage. Apart from other reasons, the difference (in the order of 10<sup>3</sup>) in



Fig. 2 Cyclic voltammograms of the Ni complex (a) and Cu complex (b) in the absence (broken line) and presence of CO<sub>2</sub> (solid line) in dimethyl formamide.



Fig. 3 Effect of applied voltage on current density (a) and Faradaic efficiency (b) for dERC using metal complex electrocatalysts.

electrical conductivities of the media (mS cm<sup>-1</sup> in case of KHCO<sub>3</sub>, whereas  $\mu$ S cm<sup>-1</sup> in case of DMF) also affects the performance.<sup>34</sup> Therefore, these studies confirm qualitatively the efficacy of the metal complexes, however, cannot be used for quantifying the role of the electrocatalysts. Therefore, further study was conducted to evaluate and quantify the products obtained out of the dERC using Ni and Cu complexes.

## 3.3 Electrochemical reduction of CO<sub>2</sub> using metal complexes in electrochemical reactor

Once the activity of the synthesized metal complexes was proved for the electrochemical reduction of  $CO_2$  in preliminary half-cell studies, the full cell studies were attempted for the qualitative and quantitative information regarding the products formed in dERC using the complexes. The reactions were carried out in aqueous solution and above the onset potential range, which is ~1 V in all the cases. The products formed were collected at definite time intervals from the cathode outlet and analyzed using gas chromatography. It may be noted that the experiments without the cathode (electrocatalyst) (that is, with only carbon paper) hardly produce any product. **3.3.1 Effect of applied voltage on current density and Faradaic efficiency towards total CO<sub>2</sub> reduction.** For both the metal complex electrocatalysts, the experimental results obtained are presented in Fig. 3. Fig. 3 shows the current density and Faradaic efficiency corresponding to various applied voltages at the terminals of the electrochemical reactor. It can be seen that the current density increases with the increase in the applied voltage for both the complexes. It depicts that with increase in the applied voltage the current density increases, which in turn signifies the increased rate of various electrochemical reactions including  $H_2$  gas generation at the electrode surface.

Fig. 3(b) shows the Faradaic efficiency for electrochemical reduction of  $CO_2$  using metal complexes. It can be seen that the Faradaic efficiency for the Ni complex is quite high *viz.* 74% at 1.5 V. On further increasing the voltage, the Faradaic efficiency decreases sharply. The Faradaic efficiency for the Cu complex increases initially and attains maxima at 1.8 V and then subsides gradually with the increase in the voltage. The highest Faradaic efficiency of 25% is achieved at 1.8 V for the Cu complex electrocatalyst. It may be noted that the Faradaic efficiency using the complexes is the result of cumulative



Fig. 4 Effect of applied potential on Faradaic efficiency of the products using Ni-complex (a) and Cu-complex (b).



Fig. 5 Comparison of Faradaic efficiency of metal complexes (solid line) with corresponding pure metals (broken line); Ni complex vs. Ni metal (a) and Cu complex vs. Cu metal (b).

efficiencies for the formation of various products from electroreduction of  $CO_2$ . To determine the energy utilized (Faradaic efficiency) for the various reaction products, it is necessary to quantify the reaction products at the cathode of the electrochemical reactor.

**3.3.2 Effect of applied potential on Faradaic efficiency of individual products.** To get more insight into the metal complex performance for the formation of various products, studies were conducted to find the Faradaic efficiencies of individual products of dERC as well as hydrogen production. Fig. 4 shows the Faradaic efficiency for the various products formed for dERC using Ni and Cu complexes.

It can be seen in Fig. 4 that using metal complex electrocatalysts, the main products of dERC are hydrocarbons and carbon monoxide. The Ni complex resulted in better Faradaic efficiency than the Cu complex. In the case of Ni complex, Faradaic efficiency for CH4 and C2H6 is considerably high with the maximum for CO formation (Fig. 4a). It is to be noted that CO, CH<sub>4</sub> and C<sub>2</sub>H<sub>6</sub> show the highest Faradaic efficiency at 1.5 V. However, C<sub>2</sub>H<sub>4</sub>, which was minor, formed at 1.4 V with Faradaic efficiency of 2.1%. In the case of Cu complex, CH<sub>4</sub> was the major product along with considerable Faradaic efficiency of CO (Fig. 4b). Moreover, C<sub>2</sub>H<sub>4</sub> was formed feebly with Faradaic efficiency of 1%. It can be seen that the Faradaic efficiency (23%) for CH<sub>4</sub> is highest at 1.5 V; however, CO attains its maxima at 1.8 V with Faradaic efficiency of 10.5%. Apart from the products resulting from CO<sub>2</sub> reduction, H<sub>2</sub> formation was also found in both the complexes, which approximately compensate for rest of the Faradaic efficiency at any particular voltage.

In order to find the role of the salen ligand in the metal complex, the experiments were also carried out using pure Ni and Cu metal electrocatalysts and were compared with the metal complex electrocatalysts. The comparison of Faradaic efficiency of metal complexes with corresponding pure metals is shown in Fig. 5. Fig. 5 shows a few of the very interesting results. It can be seen that the Faradaic efficiency towards the generation of the undesired  $H_2$  gas is reduced significantly using any of the metal complexes as compared to the pure metal electrocatalyst, which in turn increased the Faradaic efficiency towards

other useful products. Moreover, the Faradaic efficiency of CO and hydrocarbons were significantly higher for the metal complexes as compared to the pure metal electrocatalysts. Thus, the metal complexes show low operating voltage values and formation of  $C_2$  hydrocarbons as compared to pure metals, where only a meagre amount of CH4 and CO could be formed at a high operating voltage. In the case of Ni metal, two products were formed with Faradaic efficiency of 1.4% for CO and 1.2% for CH<sub>4</sub>. However, in the case of Cu metal, the Faradaic efficiency for CH4 and CO was found to be 4.9% and 0.3%, respectively. C<sub>2</sub> hydrocarbons were not formed in any of the pure metals, and most of the supplied energy was inadvertently used for the H<sub>2</sub> generation. In contrast to this, metal complexes resulted in efficient CO<sub>2</sub> reduction with significantly low Faradaic efficiency towards H<sub>2</sub> generation. It can be said that the ligand has profound impact over the process as it is evident from the performance of Ni and Cu as pure metals and in the complexed form with salen ligand. Thus, drastic change was found in the efficiency of the metals and corresponding metal complexes. Table 1 shows the applied voltage for a few representative reaction products at maximum Faradaic efficiency using the metal (Ni or Cu) and metal complexes. It can be seen that the metal complexes use lower voltages corresponding to

Electrocatalysts	Applied voltage (V) corresponding to maximum Faradaic efficiency of the product		
	$CH_4$	CO	$C_2H_6$
Ni	2	1.8	_
Ni-complex	1.5	1.5	1.5
Reduction in operating voltage (V)	0.5	0.3	_
Cu	2	2	_
Cu-complex	1.5	1.8	_
Reduction in operating voltage (V)	0.5	0.2	_



Scheme 2 Representation of redox behaviour of salen ligand complex.

their metal counterparts for the product formation at their maximum Faradaic efficiency. It is very interesting and worth noting that the operating voltage of the reaction reduced significantly using the salen ligand metal complex as compared to the pure metal electrocatalyst. The reduction in operating voltage shows the reduction in overpotential of the reactions.

It is evident that both the Ni and Cu complexes were active towards CO<sub>2</sub> reduction and underwent multi-electron reduction of CO<sub>2</sub> resulting in C<sub>1</sub> and C<sub>2</sub> hydrocarbons, which was usually rare in case of other metal complexes. It happened because incorporation of the anchoring  $-NO_2$  group in the ligand (H<sub>2</sub>L<sup>NO<sub>2</sub></sup>) backbone provides better interaction of salen complexes to the electrode material and hence facilitates an efficient electron transfer during the conversion of CO<sub>2</sub> to the products. In addition, during the conversion process, when M<sup>*n*+</sup> reduces to M<sup>(*n*-1)+</sup> state (M stands for metal), the decrease in Lewis basicity of the central metal ion due to an increase in metal-to-ligand(imine)  $\pi$ -back donation is compensated by two strong  $\sigma$  donations by two phenolate donors as shown in Scheme 2. This is due to a more aromatic character inside the phenyl rings of the complexes, which was depicted in the FTIR spectra. Moreover, the operating voltage required for the reaction was quite low for both the metal complexes as compared to pure metals (Table 1). It is because of the initial reduction of the metal complex itself ( $M^{n+}$  to  $M^{(n-1)+}$ ) and subsequent reaction with CO<sub>2</sub>. Thus, metal complexes act as a redox couple, which help to reduce the operating voltage for the CO<sub>2</sub> electroreduction as well as help in multielectron transfer resulting in C<sub>1</sub> and C<sub>2</sub> hydrocarbons.<sup>35</sup>

Overall, Ni complex was found to perform considerably better than Cu complex, which can be explained in terms of the stability of the Ni(1) and Cu(1) intermediate species. As it is known, the optimum stability or binding of metal-CO<sub>2</sub> bond is crucial for multi-electron reduction during dERC. The strong binding of metal-CO2 may poison the electrocatalyst, whereas weak bonding may result in higher overpotential for the reaction along with dissociation of product from the reaction site by utilizing only a few electrons. During the CO<sub>2</sub> reduction process, Ni(II) and Cu(II) converts to Ni(I) and Cu(I) species, respectively. Ni(I) being less stable, coordinates with CO<sub>2</sub> yielding stable Ni-CO<sub>2</sub> complex<sup>36</sup> thus resulting in effective multi-electron reduction of  $CO_2$  with high efficiency; however, Cu(1) is comparatively more stable and hence does not bind with CO<sub>2</sub> with the same efficacy, which in turn results in lower performance. Based on the products formed, an elementary reaction mechanism is proposed for the formation of hydrocarbons and CO as shown in Scheme 3. Scheme 3 shows that initially the metal complexed to the salen ligand is in +2 state and reduced to +1 state by taking up an electron from the electrode. The addition of CO<sub>2</sub> in the system receives the electron from the reduced metal, which was in +1 state, and binds with it. However, the stability of the system was maintained by the phenolate groups of the ligand. Simultaneously, H<sup>+</sup> ions were transported through the membrane from the anode side to the cathode during the full cell reaction and reacted with the metal complex-CO<sub>2</sub> along with some internal rearrangements in the complex to form either the adsorbed CO (COad) or free CO, which escapes from



Scheme 3 Proposed elementary mechanism for the formation of reaction products using salen metal complexes.

the cathode. The  $CO_{ad}$  may further participate in the reaction to form hydrocarbons<sup>37,38</sup> as shown in Scheme 3. Ultimately, the metal in the complex reverts to its previous oxidation state (+2). This redox behaviour of the salen metal complex is very peculiar and needs further investigation. The intermediate steps are not completely elucidated and are under investigation. Moreover, these metal complexes offer immense opportunity to study and improve the selective formation of hydrocarbons. Further work needs to be done to get more insights into the detailed reaction mechanism and to understand the salen metal complex.

## 4. Conclusions

The electrocatalytic property of the salen ligand was unexplored in the field of ERC in spite of its ability to bind the CO<sub>2</sub>. Hence, the salen ligand and its corresponding Ni and Cu complexes were synthesized and reported for their application as electrocatalysts in direct electrochemical reduction of CO<sub>2</sub> using halfcell and full cell studies. The complexes were found to be quite efficient for the process and resulted in the production of hydrocarbons (C<sub>1</sub> and C<sub>2</sub>) and CO. The total Faradaic efficiency was found to be 74% for Ni complex and 25% for Cu complex at 1.5 V and 1.8 V, respectively. The better performance by the Ni complex as compared to the Cu complex was attributed to the low stability of Ni(1) as compared to Cu(1). It was also seen that Cu complex was more selective towards hydrocarbons as compared to Ni complex. Moreover, the Ni-complex showed better efficiency towards CO formation as compared to Cucomplex. The activity of complexes was also compared with the corresponding pure metals to understand the effect of the ligand. It was found that the redox behaviour of the metal complex is responsible for their better performance, and hence, the complexes were able to decrease the overpotential up to a great extent. The overpotential using metal-complexes was reduced significantly ranging from 10% to 25% against their pure metal counterparts for formation of different products. Moreover, a reaction pathway was proposed for formation of the various reaction products. It was observed that the formation of hydrocarbons using metal complexes is rather rare, and hence, these complexes offer an immense scope for future research in this field.

## Acknowledgements

Authors are thankful to the 'National Program on Carbon Sequestration Research', Department of Science and Technology (DST), New Delhi for the financial support (project grant number DST/IS-STAC/CO<sub>2</sub>-SR-139/12(G): Project Investigator: Anil Verma, IIT Delhi) and the Central Instruments Facility (CIF), IIT Guwahati, for providing the NMR facility for carrying out this work.

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