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Synthesis of ammonia directly from wet air at intermediate temperature

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1. Introduction

Nitrogen fertiliser has supported approximately 27% of the world’s population over the last century, equivalent to around 4 billion people born (or 42% of the estimated total births) since 1908 [1]. Although over 78% of the atmosphere is composed of nitrogen, it is difficult to use N₂ directly by plants as plants can only use fixed nitrogen. The breakthrough in nitrogen fixation took place a century ago, the well-known Haber–Bosch process, operating at high temperature (∼500 °C) and high pressure (150–300 bar) [2]. Fritz Haber and Carl Bosch won Nobel prize in chemistry in 1918 and 1931 respectively for their contributions in industrial production of ammonia.

In the Haber–Bosch process, the required hydrogen is produced through the steam reforming of natural gas or coal and consumed more than 1% of world power generation [3]. In addition, 1.87 tons of CO₂ is released per ton of ammonia produced [4]. Globally 131 million tons of ammonia was produced in 2010 [5]. 245 million tons of CO₂ was released from ammonia industry which is equivalent to 0.77% of the world total CO₂ emission (31.78 billion tons) in 2010 [6]. In order to reduce the current dependency on the fossil fuels and to reduce carbon emissions associated with their use, it is essential to introduce new ammonia synthesis process and break the link between fossil fuels and ammonia industry [7]. The electrochemical synthesis processes are among the promising alternatives in particular if the hydrogen required for ammonia synthesis is produced from non-fossil fuel resources [2,8–11]. Recently, it has been reported that ammonia can be directly synthesised from air and water at ambient conditions, bypassing the N₂ separation and hydrogen production stage [2]. In a recent experiment, it was found that ammonia formation rates were even higher at 80 °C than those at room temperature which means reasonably higher working temperature facilitates the ammonia formation [3]. Thermodynamic analysis shows that the equilibrium conversion of ammonia decreases with temperature. Therefore, the higher the temperature, the higher the extent of ammonia decomposition [2]. However, it has been widely reported that ammonia can be synthesised at a temperature as high as ∼600 °C [8,10,12–15]. The possible reason is that, the decomposition of ammonia at high temperature is kinetically slow thus ammonia can still be collected if it is removed from the reactor in time. Synthesis of ammonia directly from air and water at elevated temperatures would be possible if the oxidation of ammonia is also slow. In this paper, for the first time, we report the synthesis of ammonia directly from wet air at 400 °C and ambient pressure. For comparison, ammonia was also synthesised from wet N₂ under the same conditions. Double chamber reactors were previously used for electrochemical synthesis of ammonia from N₂ and H₂O [10] or air and H₂O [2,3]. In this study, a simple single chamber reactor was used to simplify the synthesis process.

In our previous papers, we reported electrochemical synthesis of ammonia from N₂ and H₂ using CeₓGa₄SmₓO₁₂₋ₓ−(Li,Na,K)₂CO₃ composite electrolyte, (Li,Na,K)₂CO₃ ternary molten salts have an eutectic point of 396 °C [16,17]. The low melting point of
mixed (Li,Na,K)$_2$CO$_3$ salts makes the composite to exhibit high ionic conductivity at relatively low temperature which can minimise the operating temperature of the cell, reducing the potential thermal decomposition of ammonia. It has been reported that the ionic conductivity of Ce$_{0.8}$Sm$_{0.2}$O$_{2.6}$-(Li,Na,K)$_2$CO$_3$ composite reached 0.1 S/cm at a temperature around 400°C [18]. The total ionic conductivity composed those from Li$^+$, Na$^+$, K$^+$, H$^+$, HCO$_3^-$, CO$_3^{2-}$ and O$_2^-$ ions. Good fuel cell performance based on Ce$_{0.8}$Sm$_{0.2}$O$_{2.6}$-(Li,Na,K)$_2$CO$_3$ composite electrolyte indicates high H$^+$/O$_2^-$ ionic conductivity in this type of composite materials [18–21]. Either H$^+$ or O$_2^-$ ionic conduction can be used for electrochemical synthesis of ammonia [22]. Therefore a similar composite electrolyte Ce$_{0.6}$Gd$_{0.4}$O$_{2.6}$-(Li,Na,K)$_2$CO$_3$ was used as electrolyte in this study. As for electrocatalysts, ammonia was successfully synthesised using Fe-containing perovskite oxide La$_{0.6}$Sr$_{0.4}$Fe$_{0.8}$O$_{1.98}$ [14]. Barium is a well known catalytic promoter for ammonia synthesis catalysts therefore strontium was replaced by barium in the new perovskite [23]. Lanthanum was also replaced by multi-valent praseodymium to improve the electronic conductivity. Therefore a new perovskite Pr$_{0.6}$Ba$_{0.4}$Fe$_{0.8}$Cu$_{0.2}$O$_{3.6}$ (PBFCu) was synthesised as electro-catalyst for synthesis of ammonia from air/N$_2$ and water. Pr$_{0.6}$Ba$_{0.4}$Fe$_{0.8}$Cu$_{0.2}$O$_{3.6}$ was used as both cathode and anode and a single chamber reaction was used for the synthesis. The concept for synthesis of ammonia directly from wet air at intermediate temperature has been successfully demonstrated.

2. Experimental

2.1. Materials synthesis

For synthesis of Ce$_{0.8}$Gd$_{0.2}$O$_{2.6}$, calculated amounts of Gd$_2$O$_3$ was dissolved in hot dilute nitric acid to form gadolinium nitrate aqueous solution. Then an appropriate amount of Ce(NO$_3$)$_3$·6H$_2$O was added into the solution. 1 M (NH$_4$)$_2$CO$_3$ solution was slowly added dropwise with vigorous stirring until pH value reached 7–8, after that vigorous stirring was continued for another 30 min. The formed precipitate was then collected by vacuum filtration and washed several times with deionised water then dried at 100°C overnight. The obtained powder was calcined in air at 650°C for 2 h to obtain ultrafine CGO powder.

Ce$_{0.8}$Gd$_{0.2}$O$_{2.6}$ and ternary carbonate mixture (Li,Na,K)$_2$CO$_3$ (32.1 wt% Li$_2$CO$_3$; 34.5 wt% K$_2$CO$_3$; 33.4 wt% Na$_2$CO$_3$) powders were mixed together with weight ratio of carbonate 7:3. The mixture was put in ball miller (Planetary Mono Mill Pulverisette 6) for mixing with speed of 400 rpm for 4 h. The ball-milled powder was then heated at 600°C for 1 h.

For synthesis of Pr$_{0.6}$Ba$_{0.4}$Fe$_{0.8}$Cu$_{0.2}$O$_{3.6}$, praseodymium oxide (Pr$_{0}$O$_{1.1}$) was dissolved in dilute nitric acid to form praseodymium nitrate under heating and stirring. Calculated amounts of nitrates Ba(NO$_3$)$_2$, Fe(NO$_3$)$_3$, 9H$_2$O and Cu(NO$_3$)$_2$·2.5H$_2$O were dissolved in deionised water and were added to the above prepared solution. Appropriate amounts of citric acid and EDTA (ethylenediaminetetra-acetic acid) were then added as complexing agents with a molar ratio of citric acid:EDTA:metal cations of 1.5:1:1. Dilute aqueous ammonia solution was then added to the mixed solution to adjust the pH value to around 6. By further heating and calcined in air at 900°C for 2 h, single phase Pr$_{0.6}$Ba$_{0.4}$Fe$_{0.8}$Cu$_{0.2}$O$_{3.6}$ was obtained.

2.2. Materials characterization

TG/DSC analyses were performed using a Stanton Redcroft STA/TGTH series STA 1500 operating through a Rheometric Scientific system interface controlled by the software RSI Orchestrator in flowing air at a flow rate of 50 ml min$^{-1}$.

X-ray data were collected on a PANanalyticalXpert Pro in the Bragg-Brentano reflection geometry with a Ni Kα source (1.5405Å), fitted with a X'Celerator detector and an Empyrean CuLFF XR&D tube. Absolute scans in the 2θ range of 5–100° with step sizes of 0.0167° were used during data collection.

Conductivity measurements were carried out by a pseudo-four-terminal method using a computer-controlled SolartronAnalytical® SI 1470E electrochemical interface by applying a constant current. The Pr$_{0.6}$Ba$_{0.4}$Fe$_{0.8}$Cu$_{0.2}$O$_{3.6}$ powder fired at 900°C was pressed into pellets with diameter of 13 mm and thickness of around 2 mm then fired at 1100°C for 5 h. A silver coated pellet was fitted into the measuring apparatus and measurement was carried out in ambient air.

2.3. Fabrication of the single cell

The cell for ammonia synthesis was a tri-layer single cell which fabricated by a cost-effective one-step dry-pressing and co-firing process. The anode and cathode material was 0.8 g Pr$_{0.6}$Ba$_{0.4}$Fe$_{0.8}$Cu$_{0.2}$O$_{3.6}$ plus 0.2 g composite electrolyte to form a composite electrode materials. The composite anode, composite electrolyte and composite cathode (PBFCu/CGO-(Li,Na,K)$_2$CO$_3$/PBFCu) were fed into the die, layer by layer, with the aid of a sieve to ensure uniform powder distribution, and then uniaxially pressed at pressure of 300 MPa by cold pressing into 13 mm pellets. The pellets were sintered at 600°C for 2 h. The thickness of the anode, electrolyte and cathode was approximately 0.6, 1.0 and 0.6 mm respectively. The catalyst surface area of the cathode and anode was 1.281 cm$^2$. Silver paste was painted on each electrode surface of the cell as a current collector. Ag wires were used as output terminals for both electrodes.

2.4. Ammonia synthesis and measurement

The as-prepared cell was put inside a quartz tube sealed by a rubber bung at the cold end. The schematic diagram of the single chamber reactor used for ammonia synthesis is shown in Fig. 1. Compressed air or N$_2$ was passing through room temperature water before imputing to the single chamber reactor. The flow rate of air (or N$_2$) was 50 ml min$^{-1}$. The steam concentration in air (or N$_2$) was 3 mol%. A dc voltage was applied to the cell using a Solartron 1287E electrochemical interface. The synthesised ammonia was absorbed by 25 ml of diluted sulphuric acid (0.001 M) for 60 min as described before [2,14]. The concentration of NH$_4^+$ in the absorbed solution was analysed using Orion Application solution for low adjusting ISA. The produced ammonia was detected using an ammonia meter (ISE Thermo Scientific Orion Star A214) and the rate of ammonia formation was calculated using the following equation [2].

$$\text{Rate} = \frac{\text{NH}_3}{\text{Vol} \times \text{Time} \times \text{Area}}$$

where $\text{NH}_3$ is the measured NH$_4^+$ ion concentration, $\text{Vol}$ is the volume of the dilute H$_2$SO$_4$ for ammonia collection, $\text{Time}$ is the adsorption time, $\text{Area}$ is the effective area of the cell.
3. Results and discussion

3.1. Structure and conductivity of Pr0.6Ba0.4Fe0.8Cu0.2O3-δ

As for preparation of Pr0.6Ba0.4Fe0.8Cu0.2O3-δ, STA analysis of ash indicates the reaction completes at a temperature around 820 °C (Fig. 4A) therefore a firing temperature of 900 °C has been chosen (Fig. 3A). XRD analysis of the powder after firing at 900 °C indicates it is a single phase (Fig. 2). It exhibits an orthorhombic structure with space group Pnma(62); a = 5.5447(6) Å, b = 7.8070(3) Å, c = 5.3937(6) Å, V = 239.80(4) Å3 (Table 1). In our previous report, perovskite oxide La0.6Sr0.4FeO3.03-δ exhibits a cubic structure with space group Pm-3m (221). The ionic size of Ba2+ ions (1.61 Å) is much larger than that for Sr2+ ions (1.44 Å) at coordination number of 12 but ionic size of Pr3+ (n = 3, 4) is just slightly smaller than La3+ ions [24]. When Sr2+ ions are replaced by larger Ba2+ ions, lattice distortion becomes significant resulting in lower symmetry. Perovskite oxides PrFeO3 and Pr1-xSrFeO3-δ also exhibit orthorhombic structure with space group Pnma(62) [25]. It was reported that perovskite oxide PrBaCuFeO3.5y exhibits the ordering of both A- and B-sites with a space group P4/mmm(123). This is a tetragonal structure with a = ap, c = 2ap where ap ≈ 4 Å, in which ap is the lattice parameter of primitive cubic structure. The possible A-site ordering of Pr3+ and Ba2+ ions was not observed in Pr0.6Ba0.4Fe0.8Cu0.2O3-δ as A-site ordering will lead to cubic or tetragonal structure [26]. The lattice parameters a and b in Pr0.6Ba0.4Fe0.8Cu0.2O3-δ are significantly different indicating it is orthorhombic rather than tetragonal structure. Therefore Pr0.6Ba0.4Fe0.8Cu0.2O3-δ exhibits an orthorhombic structure without cation ordering.

The electronic conductivity of Pr0.6Ba0.4Fe0.8Cu0.2O3-δ is very important in order to be used as both cathode and anode for the electrochemical cells for ammonia synthesis. Dc conductivity measurement indicated that the conductivity increased before 425 °C, reached a value of 5.25 S/cm then started to decrease (Fig 3). This is probably due to the semi-conductor to metal transition which is a common phenomenon in perovskite oxides [27]. Thermal analysis of Pr0.6Ba0.4Fe0.8Cu0.2O3-δ in air indicated the gradual loss of oxygen at a temperature above 350 °C (Fig 3B). The semiconductor to metal transition could be related to the loss of oxygen. No obvious thermal effect was observed on the DSC curve indicates Pr0.6Ba0.4Fe0.8Cu0.2O3-δ does not exhibit first order phase transition up to measured 800 °C (Fig 4B). As for the operating temperature of the cell, the lowest working temperature of the CGO-(Li,Na,K)2CO3 composite electrolyte is 400 °C, very close to the highest conductivity of Pr0.6Ba0.4Fe0.8Cu0.2O3-δ. To minimise potential thermal decomposition and oxidation of ammonia, 400 °C has been selected as the operating temperature of the cell. In terms of the stability of the (Li,Na,K)2CO3 molten salts, it has been reported that the (Li,Na,K)2CO3 carbonates is stable in air up to 530 °C [17]. Therefore an operating temperature above 530 °C should be avoided.

3.2. Synthesis of ammonia directly from wet air

As for the first step, wet air was used as the precursor for ammonia synthesis. Compressed air was passing through room
Table 1
Structure parameters of Pr0.5Sr0.5Fe0.8Cu0.2O3−δ.

<table>
<thead>
<tr>
<th>Atom</th>
<th>Site</th>
<th>Occupancy</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>Uiso/Å²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pr</td>
<td>4c</td>
<td>0.6</td>
<td>0.0078(7)</td>
<td>0.25</td>
<td>0.9947(23)</td>
<td>0.0180(4)</td>
</tr>
<tr>
<td>Ba</td>
<td>4c</td>
<td>0.4</td>
<td>0.0078(7)</td>
<td>0.25</td>
<td>0.9947(23)</td>
<td>0.0180(4)</td>
</tr>
<tr>
<td>Fe</td>
<td>4b</td>
<td>0.8</td>
<td>0.5</td>
<td>0</td>
<td>0.0165(6)</td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>4b</td>
<td>0.2</td>
<td>0.5</td>
<td>0</td>
<td>0.0165(6)</td>
<td></td>
</tr>
<tr>
<td>O1</td>
<td>4c</td>
<td>1</td>
<td>0.485(6)</td>
<td>0.25</td>
<td>0.053(5)</td>
<td>0.008(9)</td>
</tr>
<tr>
<td>O2</td>
<td>8d</td>
<td>1</td>
<td>0.277(6)</td>
<td>0.243(3)</td>
<td>0.733(7)</td>
<td>0.039(5)</td>
</tr>
</tbody>
</table>

Note: Space group Pnma (62); a = 5.5447(6) Å, b = 7.8070(3) Å, c = 5.5397(6) Å, V = 239.80(4) Å³, R_p = 3.94%, R = 3.74%, χ^2/ν = 1.43.

The gas composition was approximately 3 mol% H2O, 97 mol% air. The effect of the applied potential on ammonia formation rate was investigated at 400 °C and the order for applied voltage was from low to high, between 1.2 and 1.7 V with 0.1 V interval. Fig. 5A shows the recorded current change against time for electrolytic cell during the ammonia synthesis process at different potentials at 400 °C over a period of 1 h. As can be seen, at lower applied voltages, the current tends to decrease. The electrolytic cell demonstrated good stability under applied voltage between 1.4–1.6 V. Furthermore, it was found that the current density decreases with increasing applied potential. These could be related to the ‘blocking effect’ of ions as observed in a previous study [3]. As mentioned above, in theory, Li⁺, Na⁺, K⁺, H⁺, HCO3⁻, CO3²⁻ and O2⁻ ions are all mobile in the CGO–(LiNaK)2CO3 composite electrolyte. When a dc voltage is applied, the cations tends to move to the cathode while anions tends to move to the anode. As the Li⁺, Na⁺, K⁺ ions are blocked by the electrodes; this will form a positively charged layer on the electrolyte side of the cathode/electrolyte interface. HCO3⁻, CO3²⁻ ions could be partially blocked. Accordingly, a negatively charged layer will be formed on the electrolyte side of the anode/electrolyte interface. The charged layer at the electrode/electrolyte interfaces may block the transfer of H⁺ or O2⁻ ions leading to reduced current density. Therefore, the current density gradually decreased when a dc voltage was applied. As the first measurement was carried out at 1.2 V, therefore the blocking effect was most significant. The higher the applied voltage, the more significant blocking effect is expected. Therefore, the current density may decrease at higher applied voltage. Following the ion blocking effects observed in the electrochemical cell using Li⁺/H⁺/Na⁺ mixed conducting electrolyte at 20 and 40 °C [3], similar effects was observed at 400 °C when CGO–(LiNaK)2CO3 composite electrolyte was used for electrochemical synthesis of ammonia.

Ammonia was successfully synthesised directly from wet air at 400 °C and atmospheric pressure. As can be seen in Fig. 6A, the ammonia formation rate increased significantly with the increased applied potential and reached a maximum value at 1.4 V (1.07 × 10⁻⁹ mol s⁻¹ m⁻² at 400 °C), showing that 1.4 V was the optimum potential for ammonia synthesis in this study. The same tendency was observed for both wet air and wet N2. This could be attributed to nitrogen chemisorption hindered by the high rate of electrochemically supplied H⁺, which in turn poisoned the catalyst (cathode surface) [22,28].

In terms of catalyst weight, the ammonia formation rate was 1.72 × 10⁻¹⁰ mol/s gcat. This is more than two orders of magnitudes higher than the reported ammonia formation rates (around 1.0 × 10⁻¹² mol/s gcat at ~600 °C) when either a H⁺ (SrCe0.95Yb0.05O3−δ) or O2⁻ (8 mol% yttria-stabilized zirconia) conducting was used electrolyte, an industrial Ru/MgO catalyst was used at the cathode [10]. The difference is possibly due to the operating temperature, while it was 400 °C in our experiment which is roughly 200 °C lower than that reported by Skodra and Stoukides [10]. Higher working temperature may cause the thermal decomposition of ammonia.

3.3. Synthesis of ammonia directly from wet N2

For comparison, ammonia synthesis was also carried out on the same cell using wet nitrogen as the precursor. Fig. 5B shows the recorded current change against time for electrolytic cell during the ammonia synthesis process at different potentials at 400 °C. As can be seen, the electrolytic cell demonstrated reasonably good stability under applied voltages. In addition, at the higher voltage (1.7 V), the current is relatively stable but also low amount at the all period of time.

As expected, ammonia was also successfully synthesises directly from wet N2 at 400 °C under atmospheric pressure (Fig. 5A). Again the effect of the applied potential on ammonia formation rate was investigated at 400 °C and the order for applied voltage was from
4. Discussion

The key finding from our experiments is that, ammonia can be synthesised directly from wet air at intermediate temperature. When a single chamber reactor is used, the key to obtain ammonia from the electrochemical cell is to avoid the possible thermal decomposition and oxidation of ammonia. Although thermodynamically ammonia may decompose to N₂ and H₂ according to reaction (2) at a temperature above 175 °C when the partial pressure of all the gases is 1 bar [2], the real thermo-decomposition temperature is much higher, roughly around 500 °C [29] which makes it possible to synthesise ammonia at a temperature below 500 °C. The possible reason is that, thermo-decomposition of ammonia is kinetically slow. It has been reported that, even at a temperature of 827 °C, short reaction time prevents large decomposition of NH₃ through a homogeneous reaction [30]. At a lower temperature, ammonia decomposition could be minimised if it is removed from the reactor in time.

\[ 2\text{NH}_3 = \text{N}_2 + 3\text{H}_2 \]  \hspace{1cm} (2)

As for ammonia oxidation at high temperatures, the normal products are N₂ at T<800 K and NO at T> 800 K [31].

\[ 4\text{NH}_3 + 3\text{O}_2 = 2\text{N}_2 + 6\text{H}_2\text{O} \] \hspace{1cm} (3)  
\[ 4\text{NH}_4 + 5\text{O}_2 = 4\text{NO} + 6\text{H}_2\text{O} \] \hspace{1cm} (4)

The oxidation of ammonia in the presence of supercritical water is quite slow at low temperatures. Without a catalyst, at 24.6 MPa, conversion for ammonia oxidation was only 3.4% at 640 °C when the residence time was 11.8 s [32]. At lower temperatures, with absence of ammonia oxidation catalyst, the oxidation of ammonia could be negligible [32].

The slow kinetic processes on decomposition and oxidation of ammonia make it possible to synthesise ammonia directly from wet air. Compared to wet N₂, the N₂ separation from air stage is not required which may save costing on energy and separation device. This will make the synthesis process simpler and more efficient.

As mentioned in previous report, ammonia production is completing with hydrogen production when water was used as a precursor [2]. If the proton conduction of the CGO–(Li,Na,K)₂CO₃ electrolyte was utilised for the electrochemical reactions, then, at the anode:

\[ 2\text{H}_2\text{O} = 4\text{H}^+ + \text{O}_2 + 4\text{e}^- \] \hspace{1cm} (5)

At the cathode, H⁺ ions may combine with N₂ in air to form NH₃,
\[ \text{N}_2 + 6\text{H}^+ + 6\text{e}^- = 2\text{NH}_3 \] \hspace{1cm} (6)

The H⁺ ions at cathode can also receive electrons and produce H₂ instead of NH₃,
\[ 2\text{H}^+ + 2\text{e}^- = \text{H}_2 \] \hspace{1cm} (7)

Reactions (5) and (6) are in parallel and competing with each other. A good catalysts should be in favour of ammonia formation and suppress the H₂ production.

If the O²⁻ ion of the CGO–(Li,Na,K)₂CO₃ electrolyte is used, then the half-cell reaction at the cathode is:

\[ \text{N}_2 + 3\text{H}_2\text{O} + 6\text{e}^- = 2\text{NH}_3 + 3\text{O}_2^- \] \hspace{1cm} (8)

At the anode, O²⁻ ions release electrons and form O₂,
\[ 2\text{O}_2^- = \text{O}_2 + 4\text{e}^- \] \hspace{1cm} (9)

However, water splitting reaction may also happen at the cathode,
\[ \text{H}_2\text{O} + 2\text{e}^- = \text{H}_2 + \text{O}_2^- \] \hspace{1cm} (10)

Under the circumstance, H₂ instead of NH₃ will be produced.
Therefore, no matter either H⁺ or O²− conduction of the CGO–(Li,Na,K)₂CO₃ composite electrolyte is used for the electrochemical reactions, productions of NH₃ and H₂ are always completing with each other. This ends up with high requirements on the electrochemical catalysts. A good catalyst must meet the following standards: it must be a good ammonia synthesis catalyst and, at the same time, a poor catalyst for hydrogen production, ammonia thermal decomposition and ammonia oxidation. Fortunately, it has been observed that the optimal catalyst for ammonia synthesis is never the optimal catalyst for ammonia decomposition [33]. This makes it possible to identify good ammonia synthesis catalysts while not worrying too much on the ammonia decomposition under the same conditions.

Based on the amounts of synthesised ammonia, the Faraday efficiencies of the electrochemical synthesis process under different conditions are also calculated. As shown in Fig. 5B, when wet air was used, the highest Faraday efficiency was 0.77% when a voltage of 1.5 V was applied. In the case of wet N₂, the highest Faraday efficiency was 5.33% at a voltage of 1.7 V. Considering both the ammonia formation rates and Faraday efficiency, an applied voltage of 1.4 V is ideal for both wet air and wet N₂.

The Faraday efficiency for ammonia synthesis was not high when wet air was used as the precursor. Only a small amount of the supplied electricity was used for ammonia production according to reactions (5) or (7) while the major part of was used for hydrogen production according to reactions (6) or (9).

The circulating of H₂ or O₂ across the cell may cause the decrease in Faraday efficiency as well. When wet air was used, theoretically the O₂ in the air may be pumped from anode to the cathode (oxygen pumping effect), the current used for pump of oxygen is wasted and has no contribution to the production of NH₃ or H₂. From this point of view, to use a proton-conducting electrolyte ammonia synthesis directly from wet air is a better choice. The hydrogen produced in the electrochemical process will be brought out from the reactor then will not be circulated. This also explains why the Faraday efficiency for ammonia production is much higher when wet N₂ was used. In general, the current density of hydrogen is much higher when both anode instead of wet N₂ was fed in the reactor (Fig. 5). This could be related to the high O²− conductivity in the CGO–(Li,Na,K)₂CO₃ composite electrolyte. In wet N₂, due to the lack of O₂, the current contributed from migration of O²− ions will be significantly lower, leading to lower current density. The absence of O₂ minimised the oxygen pumping effects, particularly the O²− ionic conductivity of CGO–(LiNa,K)₂CO₃ is pretty high at the operating temperature. It is expected that this oxygen pumping effect will be minimised if a proton-conducting (instead of O²− ionic conducting) electrolyte is used then faraday efficiency will be achievable.

The typical equilibrium conversion is in the range of 10−15% for the Haber–Bosch process when operating at 430−480 °C [8,34]. When wet N₂ was used, the efficiency is fairly close to that of the Haber–Bosch process. Although the Faraday efficiencies in our experiments are lower than the high efficiency of 78% when H₂ and N₂ was used as the precursor [8], but steam instead of N₂ was used as the precursor in this study, by-passing the hydrogen production and N₂ separation stages.

5. Conclusion

In conclusion, after our previous reports on ammonia synthesis from air and water at ambient temperature and up to 80 °C [6,13], for the first time, ammonia was synthesised directly from wet air at intermediate temperature (400 °C) using Pr₀.₄Ba₀.₆Fe₀.₈Co₀.₂O₃−δ as both anode and cathode catalysts. The maximum ammonia formation rate using wet N₂ (1.83 × 10⁻⁶ mol s⁻¹ m⁻² at 400 °C) was better than the maximum rate of ammonia production using wet air (1.07 × 10⁻⁶ mol s⁻¹ m⁻² at 400 °C). After normalised by the weight of catalysts used, the values are two to three orders of magnitude higher than the reported ammonia formation rates when synthesised from N₂ and H₂O at 600 °C [10]. Our perovskite catalysts are also low cost compared to the Ru/MgO catalysts in previous report [10]. As the ammonia formation rate for wet air still slightly lower than that for wet N₂ indicating partial oxidation. In future, it is necessary to synthesise ammonia at a temperature lower than 400 °C; however, to identify a good proton-conducting electrolyte at this temperature range, also with good chemical compatibility with basic ammonia will be a challenge.

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