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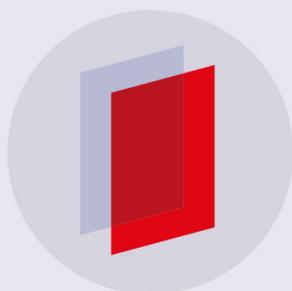
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The effects of Sn infiltration on dry reforming of biogas at solid oxide fuel cell operating conditions over Ni-YSZ catalysts

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Abstract. This work presents successful infiltration of Ni-YSZ-based catalysts for dry reforming of biogas over a temperature range of 600–800°C. Ni catalysts over YSZ support are commonly used as solid oxide fuel cell (SOFC) anode material to catalyse the fuel, normally hydrogen, in electrochemical oxidation reaction to generate electricity. The objective of this work is to find suitable SOFC anode catalyst materials to enable the SOFCs to operate on biogas as a renewable and low cost fuel. There are challenges when biogas is used as fuel; biogas dry reforming is slow and deleterious carbon deposition is unavoidable. The slow electrochemical reaction leads to low SOFC performance. While accumulation of carbon deposits may reduce the catalytic activity, decrease the SOFC performance and can lead to a complete failure of the SOFC operation. In this work, tin salt was used as a dopant in careful infiltration of Ni-YSZ catalysts. Characterisations of the catalysts were performed using SEM, XRF and XPS. Dry reforming reactions were carried out in a quartz tube reactor attached to a quadrupole mass spectrometer to monitor the product gases. Various compositions of CO₂:CH₄ mixtures were used to simulate biogas. It was observed that at small quantities of less than 1 weight % Sn/Ni loadings, dry reforming of biogas produced much higher level of the desired CO and H₂ gas products compared to that obtained over non-infiltrated NiYSZ catalyst. The developed Sn-Ni-YSZ catalysts were able to operate continuously for more than 48 hours without noticeable performance degradation. More work is still in progress; however, this work so far concludes that Sn-doped Ni-YSZ catalysts have improved dry reforming of biogas at SOFC operating temperatures and so promised successful operations of SOFCs using biogas, a renewable fuel source, to produce sustainable electricity with high efficiency.

Keywords: dry reforming; biogas; SOFC anode infiltration; carbon deposition; NiYSZ

1. Introduction

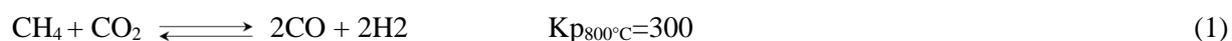
The Fuel cell technology is an attractive alternative to conventional methods of energy generation. Several of the attractive points of fuel cell technology are the very low or almost ‘zero’ level of pollutants such as NO_x, SO_x, and particle emissions, potential high efficiency operation, and the highly modular nature, which allows for distributed power generation. The solid oxide fuel cell (SOFC), which operates at 600-800°C, is one of several types of fuel cell which offers promising clean and efficient energy production with added benefit of being fuel flexible. The high operating temperature of SOFC allows for direct use of methane and hydrocarbons through internal reforming and is beneficial for recovering heat as a by-product for operating as a combined heat and power (CHP) generator [1-4]. The benefit of SOFC in being capable of utilising hydrocarbons as fuel is added especially when the hydrocarbons



come from renewable sources such as biogas. Modelling and evaluation of the economic value of operating an SOFC system in biogas fuel has shown promising results [5, 6]. Biogas is a methane rich gas phase product of anaerobic digestion of hydrocarbons and protein containing wastes. Biogas contains mainly CH₄ and CO₂ in various compositions plus other impurities depending on the source of the biomass.

The challenge for SOFC operation with direct biogas fuel is the low power produced originating from the lower heating value of the biogas compared to that of natural gas and the high possibility of carbon deposition on the anode catalyst surface which always accompanies hydrocarbon reforming and can lead to rapid SOFC performance degradation. Generally, carbon deposition is avoided by adding steam to the fuel feed with a ratio of 2 mole water to 1 mole carbon [7, 8]. However, this provision of steam in the feed supply adds complexity to the SOFC system and reduces overall efficiency.

Dry reforming is an endothermic catalytic reaction of methane and carbon dioxide, which produces CO and H₂. The reaction takes place above 400°C and can be represented by the overall reaction (1):



Two major steps are involved in reaction 1, methane decomposition (reaction 2) which produces carbon and hydrogen, followed by carbon oxidation by CO₂ (reaction 3) to form CO. Therefore, unreacted CH₄ and CO₂ plus CO, C, H₂ and H₂O as products are present in the system. In a reactor with the presence of CH₄, CO₂, CO, C, H₂ and H₂O, carbon accumulation is possible especially when carbon-forming reactions occur faster than carbon removal (or oxidation) reactions. Other possible reactions in the system are CO disproportionation and CO reduction by hydrogen as outlined in reactions 4 and 5 below. According to their low values of K_p, these two reactions are less likely to take place under normal SOFC operating conditions compared to the first three reactions. Another reaction, which may take place in an SOFC anode with hydrocarbon fuel, is water gas shift (WGS) reaction (reaction 6). This reaction produces H₂ from CO interaction with steam at high temperature.



Since all of the above reactions are reversible, it is possible to remove carbon in this system by promoting the reverse of carbon deposition reactions. Hence, provision of excess steam to the gas feed stream is needed during steam reforming to facilitate carbon removal through the reverse of reaction 5. Similarly, excess CO₂ is needed in dry reforming to facilitate reaction 3, which is the reverse of reaction 4. However, in practice, provision of excess H₂O or CO₂ complicates the SOFC system by adding a component to the fuel supply sub-system and leads to a consequence of lower electrical and overall power output due to dilution of the fuel gas stream.

The quantity of accumulated carbon is affected not only by the gas composition in the system, which is defined by the equilibrium constants, but also by the rate of carbon deposition and carbon removal, which are affected by the catalytic activity of the anode surface of the given system. Therefore, it is of paramount importance that the anode in an SOFC is designed to facilitate the desired reactions and to suppress or inhibit the undesired reactions. It follows that carbon accumulation can be reduced by not only adding excess H₂O or CO₂, but also by modifying anode catalytic properties. Various attempts have been made and successes have been achieved in modifying SOFC anode materials to enhance hydrocarbon reforming and electrochemical oxidations of the reforming products, and to improve the resistance to carbon deposition [9-12]. Hence, formulating and modifying the composition of anode material in SOFC can play an important role in minimising carbon deposition.

Despite the high activity of nickel towards carbon formation, to date NiYSZ cermets are still the most commonly used SOFC anodes. Other anode types, such as Cu-based anodes or mixed ionic-electronic conductive oxides, have shown better performance towards minimising carbon formation; however, they still suffer from several drawbacks such as low catalytic activity towards electrochemical oxidation and hydrocarbon reforming, low mechanical strength, or incompatible thermal coefficient of expansion with other SOFC components.

Infiltrating NiYSZ anodes with metals such as Ce, Mg, Mo, Sn and Rh have been reported as one of the methods attempted. Especially with Sn infiltration, work based on experiments and density functional theory (DFT) calculations have shown that the presence of approximately 1.0 wt% or less Sn/Ni in the form of Sn/Ni alloys showed significant effects on reducing carbon deposition during steam reforming [9-11]. Further investigations suggested that compared to NiYSZ, Sn/NiYSZ was reported to have a lower tendency to form C-C bonding [12-14] which led to Sn/NiYSZ catalysts demonstrating lower carbon deposition. The success of using Sn as a dopant for Ni-based catalysts in reducing carbon deposition during steam reforming operations such as reported by Trimm [9], Kan *et al.* [11], Kan and Lee [15], Nikolla *et al.* [10], Nikolla *et al.* [12], Nikolla *et al.* [13], Nikolla *et al.* [14] and Nikolla *et al.* [16] led to this investigation of using Sn as a dopant for direct-biogas SOFC operations in dry reforming mode as presented in this paper. Recent reports show that SnNi alloys demonstrated excellent performance on SOFC operating in biogas. Sn-infiltration on NiO powders for NiGDC anode and on NiYSZ nanoparticles for SOFC anode have been used by Myung *et al.* [17] and Hua *et al.* [18] respectively. These investigations support the proposition that high efficiency SOFC operation in pure biogas is promising.

As can be predicted from the C-H-O ternary diagram in Fig. 1 [19, 20], to prevent carbon deposition an SOFC operating with dry reforming thermodynamically needs a higher excess CO₂ or higher molar ratio of CO₂:CH₄ in the system compared to the need for excess H₂O in steam reforming operation. This paper presents results of investigating the ability of SOFC anode operating in biogas under dry reforming mode (without the addition of steam) with a low carbon dioxide to methane ratio of 1:2 CO₂:CH₄. This ratio represents a common biogas composition. This ratio also represents a biogas composition with high risk of carbon deposition.

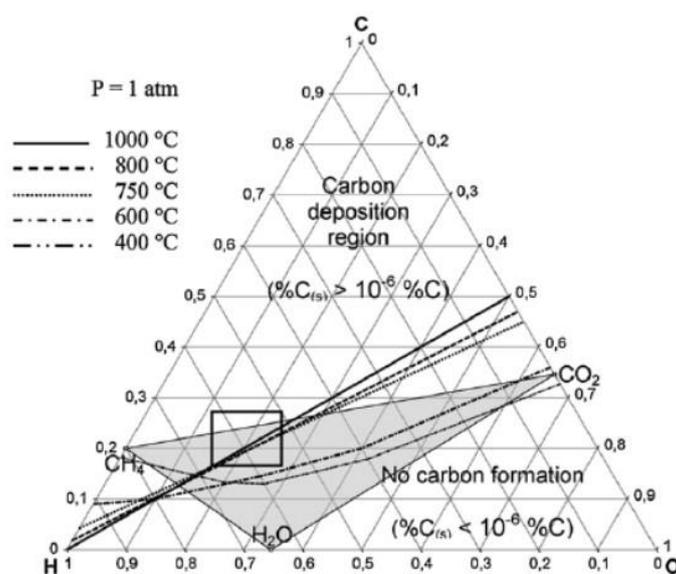


Figure 1. C-H-O ternary diagram at different operating temperature.

2. Materials and Methods

Commercially available Nickel Ytria Stabilized Zirconia (NiYSZ)-based pieces of planar SOFC anodes (NIMTE–Ningbo Institute of Materials and Energy Technology-China) with YSZ electrolyte layer (TOSOH TZ-8YSZ) were used as the catalyst material. The catalyst, weighing 500–785 mg for each charge, were placed in a quartz tube reactor. The reactor inlet is fed with simulated biogas at a certain ratio of CO₂:CH₄ with helium gas added as inert and partial pressure reference to enable calculation of other gases partial pressures. The SOFC anode outlet gas was fed to a Cirrus quadrupole mass spectrometer to allow for continuous monitoring of the anode gas composition.

Performance of the non-infiltrated and infiltrated catalysts in dry reforming reaction was observed. To prepare the Sn-dopant solution, SnCl₂·2H₂O (Fisher Scientific, UK) was used as the Sn precursor and was dissolved in 95% ethanol. Sn-anode infiltration was carried out on sintered anode surface using a simple pipette drop method. Each drops of dopant solution contains 1 mg of Sn. The infiltrated anode discs were then dried and calcined. Before being used as the dry reforming catalyst, the discs were crushed into small pieces of 2–4 mm diameter. Gravimetric analysis and SOFC anode surface characterisations using XRF, SEM/EDX, XRD and XPS were used to confirm the presence of Sn in the Sn-infiltrated SOFC anodes.

3. Results and Discussion

This section presents results of physical properties characterisations of the catalysts using SEM/EDX, XRF and XPS analysis and of observing the activity of NiYSZ-based SOFC anode pieces to catalyse dry reforming of biogas. The catalytic activity of NiYSZ was measured in terms of the amount of H₂ and CO gases produced and percentage conversion of CH₄ and CO₂. The effects of operating temperature and CO₂:CH₄ ratio in the feed composition on the H₂ and CO gases produced were observed.

3.1. Gravimetric analyses, SEM/EDX, XRF and XPS

3.1.1. *Gravimetric analysis.* As represented in Fig. 2 gravimetric analysis showed that a linear relationship is obtained between the number of drops of Sn-salt solution and the anode weight gain. For each number of Sn-salt solution 6 sample repeats were used.

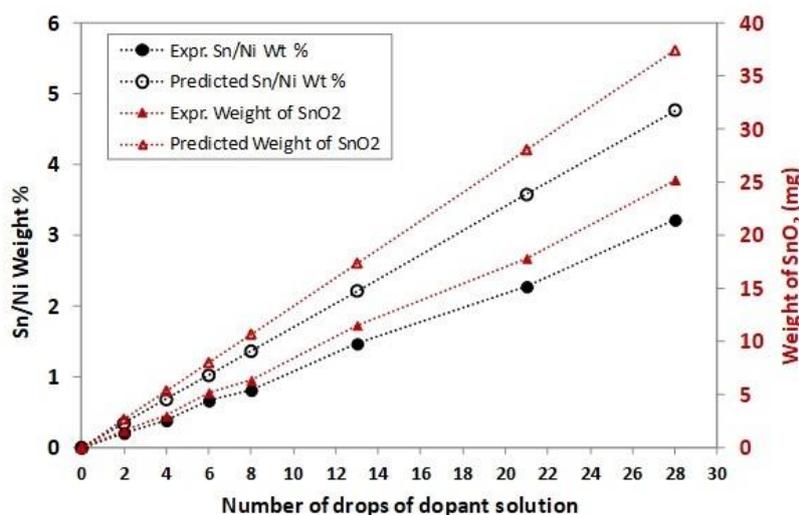


Figure 2. Results of gravimetric analyses of SOFC anode weight gain at different Sn loads.

3.1.2. *SEM and EDX.* SEM/EDX were used to characterise the cell microstructure. Detailed micrographs of the porous anode, dense electrolyte and porous cathode are described in [21]. The micrographs show that on the anode surface Zr-rich part forms more continuous part compared to Ni-rich part. They also

showed that anode pores are of less than 1 μm diameter. The EDX map confirms that Sn is present and well distributed over the Ni particle sites, and much less on Zr-rich sites.

3.1.3. XPS and XRF. An SOFC anode disk which had been infiltrated with 28 drops of Sn-salt was used as the sample for XRF analysis. The results are presented in table 1 and Fig. 3. The spectra in Fig. 3 show Ni, Zr, Y and Sn peaks of principal line KA1 accompanied by KB1. Although rhodium is not on the list of the SOFC anode component, it appears in these spectra since the XRF detector we used contained Rh.

Table 1. Chemical composition of 28D-Sn-infiltrated SOFC anode obtained from XRF.

Atomic symbol	Atomic Number	Weight %	Atomic
Ni	28	48.07	
Zr	40	46.48	
Sn	50	4.80	
Y	39	0.65	
Atomic ratio Ni:Sn			20.3 : 1
Atomic % Sn			4.71
Weight % of Sn/Ni		9.99	

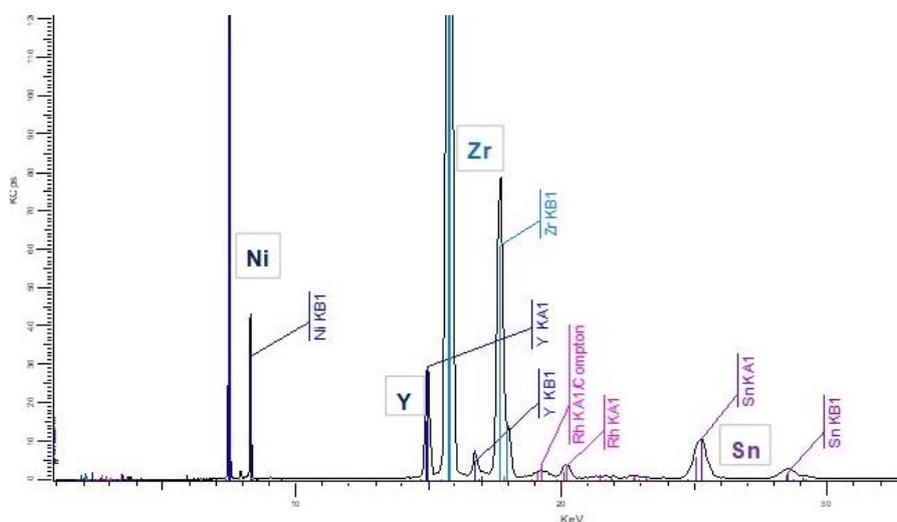


Figure 3. X-ray fluorescence spectra of 28D-Sn-infiltrated anode.

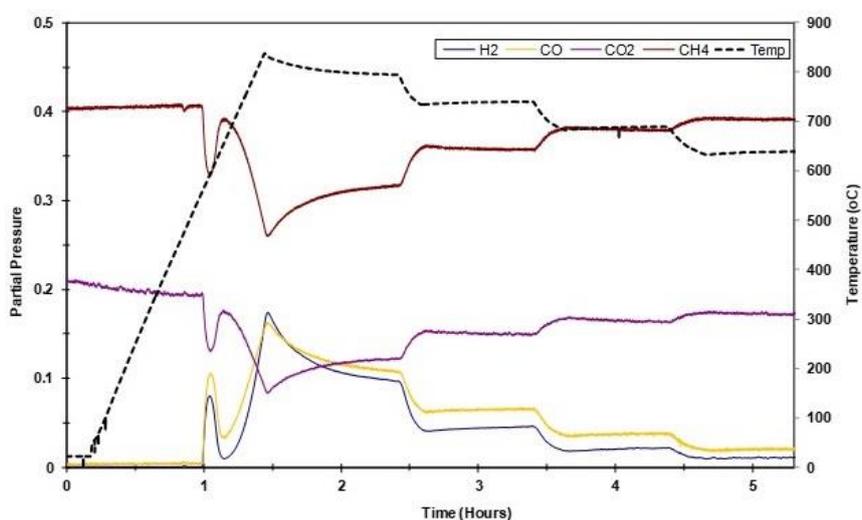
Table 2 shows the chemical composition obtained from XPS of the 28-drops 28D-Sn-infiltrated SOFC anode. It is shown that as high as 59.72 weight % Sn/Ni is identified by XPS. Since XPS analysis measures only a sample surface layer down to 20 nanometres deep, this high value of 59.72 weight % Sn/Ni indicates that the Sn content is highest on the anode surface. This is made clear when the value is compared to 9.99 weight % obtained from XRF and 4.77% obtained from gravimetric analysis which represent the Sn content in the bulk anode. The finding is in accordance with the observation presented by Nikolla *et al.* [13], Nikolla *et al.* [14].

Table 2. Chemical composition of 28D-Sn-infiltrated NiYSZ anode surface obtained from XPS.

Ni 2p %	O 1s %	Sn 3d %	Zr 3d %	At Ni:Sn	At % Sn	Wt % Sn/Ni
15.34	38.38	5.13	5.02	2.99 : 1	25	67.61

3.2. The effects of operating temperature

Fig. 4a and 4b show mass spectra of methane dry reforming product gases at different operating temperatures for non-infiltrated and Sn-infiltrated catalysts respectively. The biogas feed composition was 1:2:2 volume ratio of CO₂: CH₄: He which was the composition intended to be used for the SOFC operation. The spectra in Fig. 4a show almost equimolar H₂ and CO produced at 800°C but slightly higher CO produced at 750°C and 700°C. A similar trend is observed in Fig. 4a and 4b; that is the unreacted CO₂ and CH₄ are lowest at 800°C, and that the unreacted gas feed gradually increased and showed the highest values at 650°C. Both Fig. 4a and 4b also show that a decrease of 50°C resulted in the decrease of H₂ and CO produced by approximately 50%. The lower the temperature the less CO and H₂ were produced. At 650°C very little (less than 3%) CO and H₂ were produced which means that the activity of this NiYSZ catalyst at 650°C is very low hence this may not provide sufficient CO and H₂ for SOFC operation. At 750°C, the planned temperature to operate the fuel cell, approximately 5 vol.% H₂ and 7 vol.% CO are produced. These results show that at 750°C H₂ and CO are present as the dry reforming products and thus available for electrochemical reactions under fuel cell operation. It is interesting to compare the level of H₂ and CO partial pressures represented by the blue and yellow coloured curves in Fig. 4a and 4b. The results of dry reforming over Sn-infiltrated NiYSZ shows twice or higher H₂ and CO produced than that of non-infiltrated NiYSZ. This shows that Sn-infiltration improves dry reforming of CH₄ and increases the H₂ and CO production. Even at 650°C more CO and H₂ (between 5-7%) were produced over Sn-infiltrated catalyst than that over non-infiltrated catalyst.

**Figure 4a.** Mass spectra of outlet gases from dry reforming over non-infiltrated NiYSZ anode at 650-800°C.

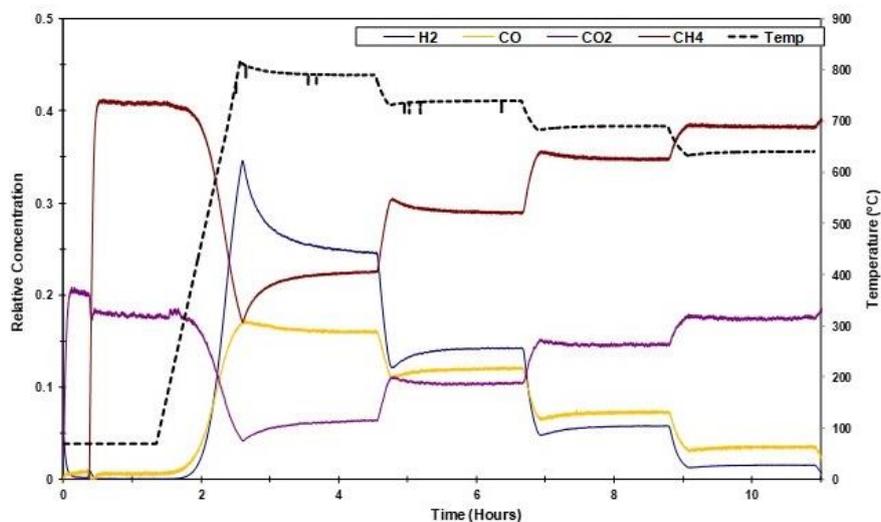


Figure 4b. Mass spectra of outlet gases during dry reforming over (6-drops) Sn-infiltrated NiYSZ anode at 650-800°C.

Fig. 5 shows % conversion of CO_2 and CH_4 over non-infiltrated catalyst at different temperatures while Fig. 6 shows partial pressures of CO and H_2 produced. Fig. 5 and 6 clearly show that dry reforming of CH_4 is significantly affected by temperature; increasing temperature from 750°C to 800°C resulted in two folds of increase of CO_2 and CH_4 conversion and twice the amount of CO and H_2 produced. The very low CO and H_2 produced at 700°C and especially at 650°C indicate dry reforming on this NiYSZ anode at 700°C and 650°C are not efficient. This finding is an important input in selecting suitable SOFC operating temperature for direct biogas reforming. In Fig. 5 it is shown that CO_2 conversion was higher than CH_4 conversion. At 800°C, CO_2 conversion was 40% while CH_4 conversion was only 20%. This phenomenon is in agreement with that observed by Stagg *et al.* [22]. Stagg and co-workers reported that ZrO_2 as a Pt catalyst support for dry reforming of CH_4 plays a good role in promoting CO_2 dissociation, compared to SiO_2 . In this work the ZrO_2 in NiYSZ may have acted as a promoter for CO_2 dissociation.

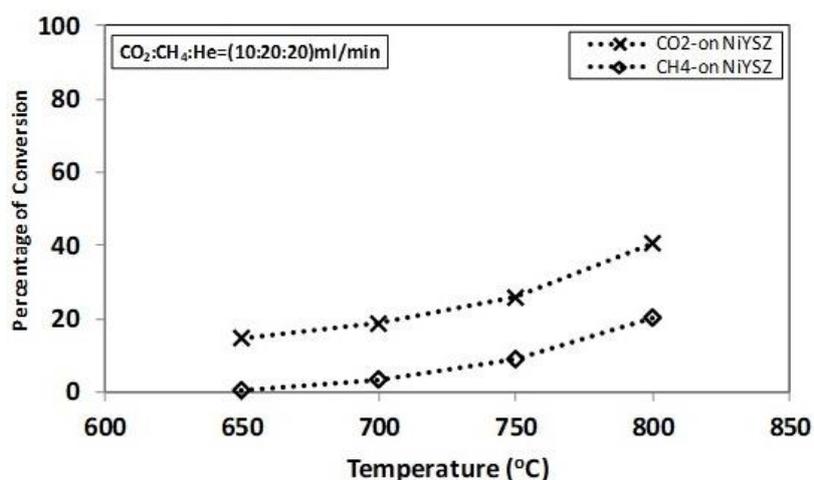


Figure 5. Percent conversion of CO_2 and CH_4 over non-infiltrated NiYSZ anode at 650-800°C.

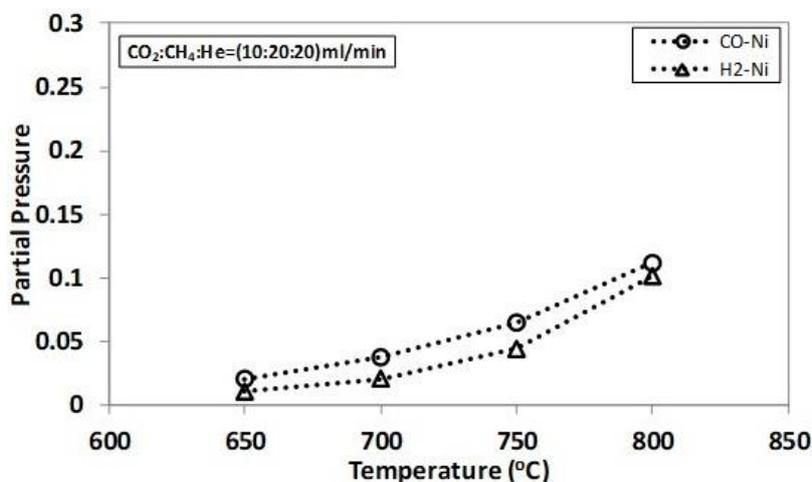


Figure 6. Partial pressure of CO and H₂ produced over non-infiltrated NiYSZ anode at 650-800°C.

3.3. The effects of different feed composition

Fig. 7 shows effect of different feed compositions on the outlet gas composition. The spectra were obtained from 500 mg Sn-infiltrated anode. The total volume of gas feed was kept at 50 ml min⁻¹ with constant 5 ml min⁻¹ helium flow and varied flow rates of CO₂ and CH₄. Fig. 7 shows that the highest level of H₂ and CO produced is at 1:1 ratio of CO₂:CH₄ feed which is expected from stoichiometry, but this is also in agreement with literature [22]. Fig. 7 also shows that at CO₂:CH₄=1:2 H₂ produced is slightly higher than that from CO₂:CH₄=1:1, and CO produced is only slightly lower. This is a good indication for the planned SOFC operation; in that the SOFC is feasible to operate at 750°C and with CO₂:CH₄=1:2 to produce sufficient amount of CO and H₂ for electrochemical oxidation.

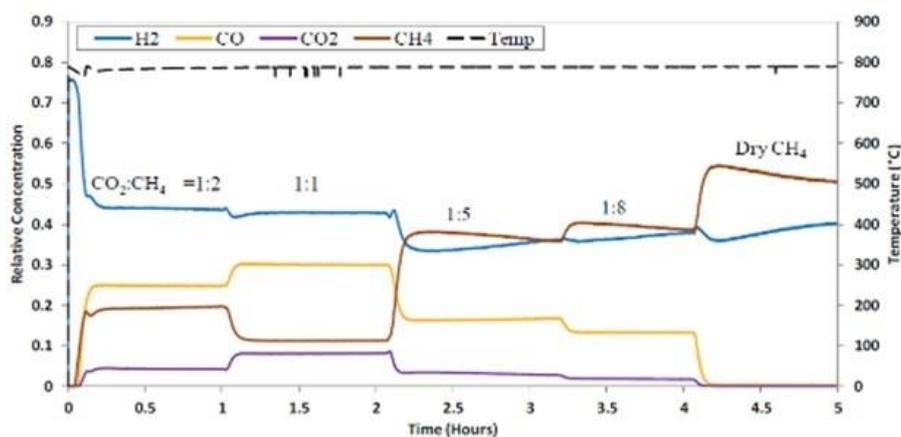


Figure 7. Mass spectra of outlet gases during dry reforming over (4-drops) Sn-infiltrated NiYSZ anode at 800°C and varied CO₂:CH₄ ratio.

Fig. 8 and 9 are the same experimental results with those in Fig. 7 but presented in bar charts to make comparisons of all gas partial pressures easier. Fig. 8 and 9 also show that it is the amount of CO produced which linearly corresponds to the different CO₂:CH₄ ratio in the feed; while H₂ produced was not linearly affected by CO₂:CH₄ ratio. The amount of CO produced decreases as the CO₂ concentration in the feed was decreased. This can be explained by the general understanding that dry reforming reaction, represented by equation 1, occurs via at least two reactions namely methane cracking, equation

2 which produces C and H₂, and oxidation of C by CO₂ to form CO which is also known as reverse Boudouard reaction (equation 3). Considering these three reactions it is clear that in a closed system, the amount of CO produced is directly affected by the available CO₂.

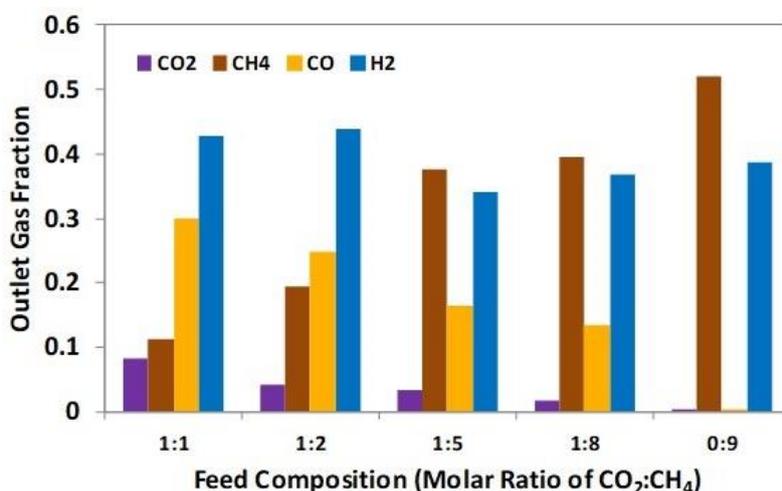


Figure 8. Dry reforming product gas fraction over 4-drops Sn-infiltrated NiYSZ anode at 800°C at varied CO₂:CH₄ ratio.

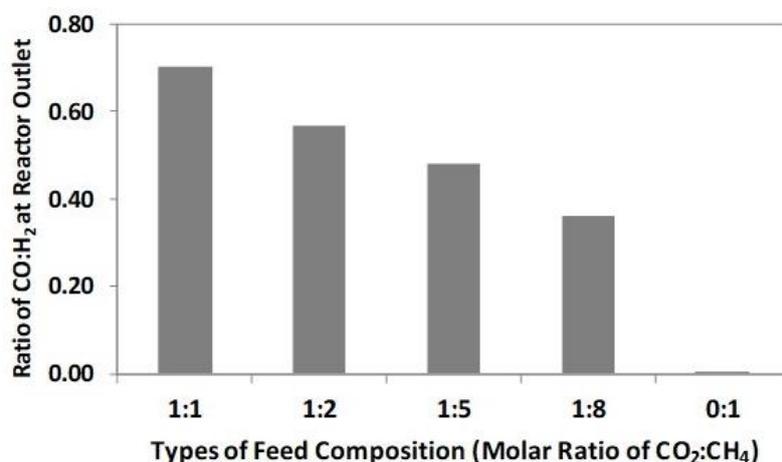


Figure 9. Ratio of CO:H₂ over 4-drops Sn-infiltrated NiYSZ anode at 800°C and varied CO₂:CH₄ ratio.

For an equilibrium dry reforming reaction without steam, the ratio of CO to H₂ present in the product stream is expected to be 1. Fig. 8 and 9 show that the ratio of CO:H₂ produced being less than 1 and the less CO₂ in the feed results in the less CO produced; this may indicate that carbon is formed during the dry reforming reaction and that the presence of CO₂ is essential to reduce carbon accumulation. The most important and promising result is that the Sn-infiltrated catalyst is able to catalyse methane dry reforming at 650–800°C with conversion at 750°C producing sufficient amount of CO and H₂ for electrochemical oxidation.

3.4. Overall discussion

Pieces of non-infiltrated SOFC and Sn-infiltrated SOFC anodes were tested as catalysts for dry reforming reactions. It was shown that at the observed temperature range (650°C to 800°C) Sn-infiltrated SOFC anodes converted more CO₂ and CH₄ and produced more H₂ and CO compared to non-infiltrated

ones. On both non-infiltrated and Sn-infiltrated anodes, more H₂ is produced at higher temperature (800°C) than at the lower temperatures of 650–750°C. It was observed that at 750°C and 1:2:2 ratio of CO₂: CH₄: He approximately 5 vol.% H₂ and 7 vol.% CO were produced on non-infiltrated NiYSZ SOFC anode while 15 vol.% H₂ and 13 vol.% CO were produced on Sn-infiltrated NiYSZ SOFC anode. These differences on the level of H₂ and CO produced from the dry reforming reaction and the fact that Sn-infiltrated anodes produced 2 to 3 times CO and H₂ compared to uninfiltrated anodes are considered sufficient for further investigation of the non-infiltrated and Sn-infiltrated SOFC anode electrochemical performance in the SOFC operation.

As expected from stoichiometry, observation of dry reforming at different CO₂:CH₄ ratios shows that equimolar feed of CO₂:CH₄ produced the highest amount of CO and H₂ compared to other feed compositions. The amount of CO produced is much affected by the composition of CO₂ in the feed. Rough comparison of dry reforming on 6-drops and 4-drops Sn-infiltrated SOFC anodes (Fig.s 4b and 7 respectively) shows that the Sn loading is another determining factors (other than temperature and gas composition) for the amount of H₂ and CO produced with 4-drops Sn-infiltrated anode showing better CO₂ conversion. This means that a very small quantity of Sn in NiYSZ anode makes a significant difference in the catalytic performance.

4. Conclusion

It was shown that Sn infiltration on anode surface significantly improved dry reforming of CH₄ over 650–800°C and methane to carbon dioxide ratio of 1:1 to all methane (90% CH₄ and 10% Helium) conditions. As a base for evaluation of SOFC operation with direct biogas feed, these results of dry reforming on SOFC anode pieces have shown that infiltration of SOFC anode with Sn dopant increased the yield of dry reforming products, namely CO and H₂, therefore Sn-infiltration is very promising to be used in improving electrochemical performance of SOFC operating on biogas. The Sn-infiltrated NiYSZ catalysts are expected to give higher electrochemical performance and less carbon accumulation when employed as SOFC anode.

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