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# Solid Oxide Direct Carbon Fuel Cell Electrochemical Performance Using Wheat and Spruce Carbon Fuels

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A single cell solid oxide electrolyte direct carbon fuel cell with two biomass carbon fuel performances is presented in this article. The performances of the wheat carbon fuel are better than those of the spruce fuel. At 800°C the open circuit voltage of wheat fuel (1.18 V) was slightly higher than spruce (1.16 V). The peak power density recorded for wheat fuel was 66.92 mW/cm$^2$ while spruce fuel was lower at 57.40 mW/cm$^2$. On the contrast spruce fuel (156.20 mA/cm$^2$) gave a maximum current density with wheat fuel lower at 138.52 mA/cm$^2$. Other electrochemical performances are presented.

*Keywords*: biomass, open circuit voltage, power and current density, solid oxide direct carbon fuel cell, spruce, wheat

## 1. INTRODUCTION

The operation of solid oxide fuel cell is at a temperature at which certain oxidic electrolytes become oxygen ion, $O^{2-}$, conducting. It is the same effect that is experienced in the Lambda sensor supplied with three-way catalytic converters in spark ignition automobiles, and Lambda sensors are used as convenient lab models for solid oxide fuel cells (SOFCs). The oxides normally employed are a mixture of yttria and zirconia (Hoogers, 2003; Larminie and Dicks 2003). The electrode reactions are given by Eqs. (1) and (2) (Hoogers, 2003; Larminie and Dicks 2003:

$$H_2 + O^{2-} \rightarrow H_2O + 2e^-, \tag{1}$$

$$\tfrac{1}{2}O_2 + 2e^- \rightarrow O^{2-}. \tag{2}$$

The overall cell reaction is similar to that of molten carbonate fuel cell (MCFC) with standard reversible potential and water generated at the anode. The SOFC benefits from excellent kinetics at the anode and cathode. For thermodynamic reasons, the reversible potential at the operating temperature is lower in SOFC than for low-temperature fuel cells. The inherent advantages of the SOFC are the solid-state design with no water management problems. The main problems encountered with SOFC are materials problems relating to sealing and thermal cycling. The searches for the right stack design for SOFC are still a focal point of some research work (Cao et al., 2007; Cherepy et al., 2005; Hoogers, 2003). This article reports on the investigations carried out on a direct carbon fuel cell (DCFC) using two major biomasses (wheat and spruce). The DCFC

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could be integrated in a power plant for the generation of electricity and heat energy, thus using biomass makes it sustainable (Adeniyi and Ewan, 2011).

## 2. METHODOLOGY

The design that was developed for the electrochemical cell system of the solid oxide electrolyte direct carbon fuel cell (SODCFC) is schematically represented in Figures 1 and 2. Button cells from Fuel Cell Materials Ltd. (USA) were used. The composition of the cell includes lanthanum oxide, manganese oxide, strontium oxide, cerium (IV) oxide, gadolinium oxide, nickel (II) oxide, zirconium oxide, yttrium oxide, and scandium oxide. The cells consisted of a Ni/Yttrium-stabilized zirconium (YSZ) anode support layer, Ni/scandium-stabilized zirconium (ScSZ) anode active interlayer, ScSZ electrolyte layer, and lanthanum strontium manganese (LSM)/ScSZ cathode layer. The anode and the cathode layers are 1.2 cm in diameter and the cells are 2.5 cm in diameter with an active surface area of 1.1 $cm^2$. Because of their relatively simple experimental setup and good reproducibility, these button cells were employed in the SODCFC experiments (Li et al., 2011a, 2011b; Liu et al., 2010; Wu et al., 2009; Ihara et al., 2004; Zhu, 2003; Nakagawa and Ishida, 1988). Figure 2 shows the button cell with gold mesh bonded on each side to serve as the current collector.

Wheat straws and spruce wood chips were cut into small pieces and ground in the Cross Beater Mill (Model 16-150, Glen Creston Ltd.) with a sieve size of 2.0 mm. The proximate, ultimate, and calorific value analyses were carried out on the biomass and carbon. The ash and volatile content were carried out using a Carbolite furnace (AAF 1100) at a temperature of 750 and 950°C, respectively. Other analyses were previously reported (Adeniyi and Ewan, 2011).

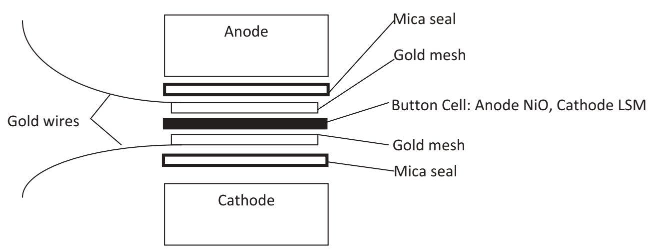


FIGURE 1 SODCFC button cell electrode assembly.

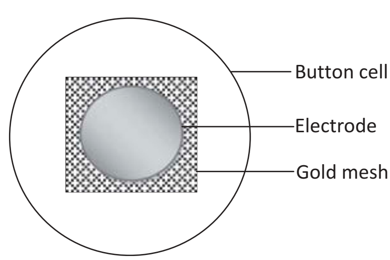


FIGURE 2 Button cell bond with gold mesh on each side as the electrolyte.

## 3. RESULTS AND DISCUSSION

The results of the analyses carried out on the carbon produced from these biomasses after pyrolysis are shown in Table 1. The calorific values (CV) of the biomasses presented in Table 1 are key factors to consider in the DCFC performance. The CV value of spruce is higher than that of wheat and one would expect higher electrochemical performances of spruce carbon in the DCFC. The results of the biomass carbons, after pyrolysis, include higher values for spruce (33 MJ/kg) and lower values for wheat (23 MJ/kg). Spruce has higher carbon and hydrogen contents and for application in the DCFC the higher carbon content is of significance.

### 3.1. SODCFC Performance with Biomass Carbon Fuels

Figures 3 and 4 show the voltage, power, and current densities behavior of the SODCFC for wheat and spruce carbon particle fuels for the operating temperatures of 700 and 800°C. The average particle sizes for spruce and wheat are 8 and 3 μm, respectively. Figure 3 shows an interesting pattern, which was referred to as the curve back phenomena. This curve back phenomena pattern of the fuels is attributed to the overconsumption of the carbon fuel at the anode compartment giving rise to gaps between the fuel contact and the electrolyte layers (Jia et al., 2010). The active surface area of the SODCFC was 1.1 cm$^2$; this was used in the calculation of the current and power

TABLE 1
Moisture, Calorific Value, and Ultimate Analyses of Biomass Carbon Fuel

| *Biomass* | *Moisture Contents, wt%* | *Calorific Value, MJ/kg* | *Carbon, wt%* | *Hydrogen, wt%* |
|---|---|---|---|---|
| Wheat | 5.96 | 23.36 | 65.35 | 0.51 |
| Spruce | 2.41 | 32.53 | 90.72 | 1.11 |

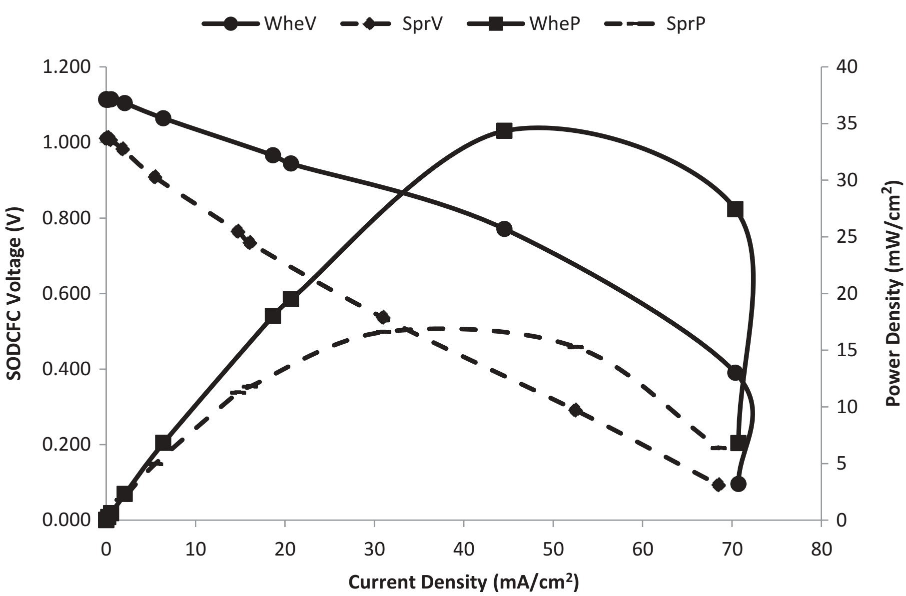


FIGURE 3 Biomass carbon fuels electrochemical performances at 700°C.

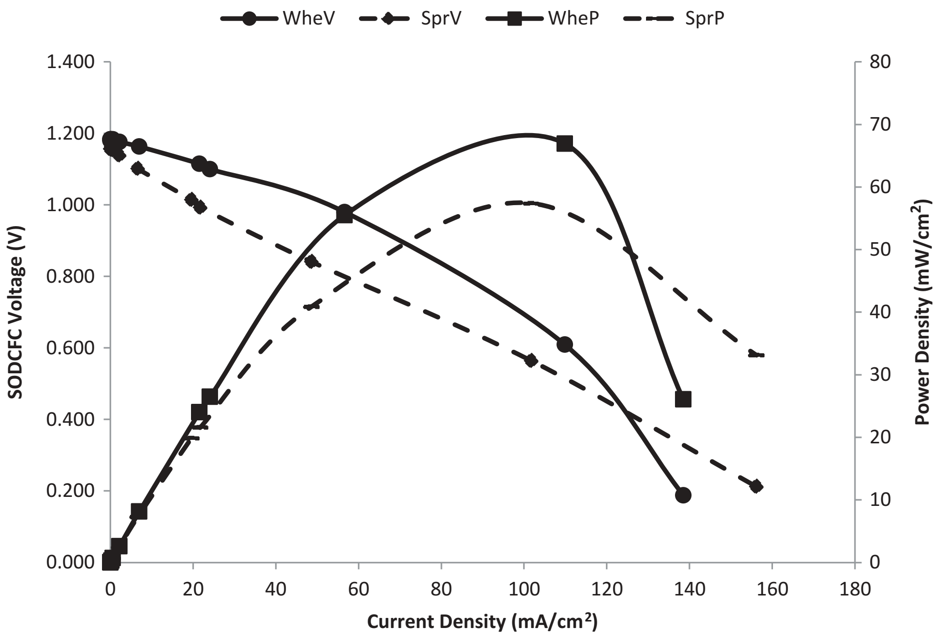


FIGURE 4 Biomass carbon fuels electrochemical performances at 800°C.

densities. The curve back phenomena lead to reduction in this active surface area bringing about lower values of the current and power densities and the patterns experience by some of the graphs presented (Adeniyi and Ewan, 2011; Jia et al., 2010). The SODCFC power density and current density increases with an increase in temperature, reaches a maximum, and finally falls at higher current densities (Li et al., 2009; Hackett et al., 2007). At 800°C the performances improved.

The effects of temperature on the performance of the SODCFC using the two biomass carbon fuels are shown in Figure 5. There is a sharp rise in the open circuit voltage (OCV) above 200°C, indicating ionic conduction in the SODCFC. This shows that the electrochemical reactions of the carbon fuels in the SODCFC started at lower temperatures. The performance of the fuel cell was greatly enhanced as the temperature increases up to 800°C; this is attributed to the decrease in the viscosity of the molten carbonate fuel phase and a corresponding enhancement of the ionic conduction rate of the electrolyte and the electrochemical reactions at the two electrodes (Jia et al., 2010; Li et al., 2009; Jain et al., 2008; Hackett et al., 2007; Cherepy et al., 2005).

Table 2 presents the summary of the current, power, voltage, and other electrochemical characteristic behavior of a single cell solid oxide electrolyte direct carbon fuel cell (SODCFC). The effective OCV, peak power, current density, and the area specific resistance (ASR) behaviors of the fuel cell are shown. Table 2 reveals that the OCV, power, and current densities increase with an increase in temperatures while the area specific resistance (ASR) decreases with a rise in temperature. Wheat has the higher power efficiency of 69% at 700°C with spruce at 53%.

Table 2 summarizes the results of the SODCFC electrochemical performances for wheat and spruce biomass carbon fuels at 600, 700, and 800°C. At 800°C the open circuit voltage for wheat fuel (1.18 V) was slightly higher than spruce fuel (1.16 V). The best peak power density was recorded for wheat fuel (66.92 mW/cm$^2$) and spruce fuel (57.40 mW/cm$^2$). On the contrary, spruce fuel (156.20 mA/cm$^2$) gave the maximum current density while spruce fuel (138.52) gave the minimum. For the current density at 80% voltage efficiency, wheat fuel (90 mA/cm$^2$ at 800°C) was higher than spruce fuel (60 mA/cm$^2$ at 800°C). Wheat fuel (0.61 V) shows the higher voltage at

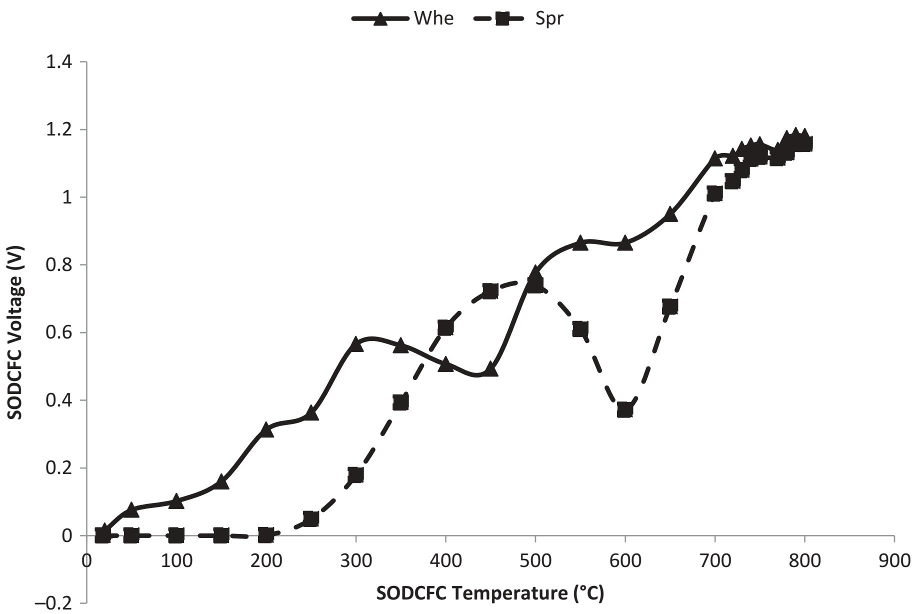


FIGURE 5 SODCFC voltages of the biomass carbon fuels at different temperatures.

TABLE 2
SODCFC Electrochemical Performances for Wheat and Spruce Carbon Fuels

| | *Wheat* | | | *Spruce* | | |
|---|---|---|---|---|---|---|
| | *Temperature, °C* | | | *Temperature, °C* | | |
| *SODCFC Parameter* | *600* | *700* | *800* | *600* | *700* | *800* |
| Open circuit voltage (V) | 0.87 | 1.11 | 1.18 | 0.37 | 1.01 | 1.16 |
| Peak power density (mW/cm$^2$) | 2.80 | 34.35 | 66.92 | 1.34 | 16.60 | 57.40 |
| Maximum current density (mA/cm$^2$) | 17.68 | 70.73 | 138.52 | 13.26 | 68.52 | 156.20 |
| Current density at 0.8 V (mA/cm$^2$) | 1.51 | 54.00 | 90.00 | 0 | 14.75 | 60.00 |
| Voltage at peak power (V) | 0.38 | 0.77 | 0.61 | 0.15 | 0.54 | 0.56 |
| Area specific resistance (Ω cm$^2$) | 40.26 | 7.24 | 3.69 | 21.58 | 13.28 | 5.66 |
| Efficiency at peak power (%) | 44.00 | 69.00 | 52.00 | 41.00 | 53.00 | 48.00 |

peak power than spruce fuel (0.56 V). The ASR evaluation shows that wheat fuel gave a lower value (3.69 Ω cm$^2$ at 800°C) than spruce (5.66 Ω cm$^2$ at 800°C); the reduction in the ohmic resistance could have been responsible for the higher peak power efficiency observed for wheat fuel.

## 3.2. Industrial Application of Electricity Generation by DCFC Route

Part of the benefits of using biomass in the DCFC is that electricity and heat can be generated from the system at higher conversions (80%) when compared to the thermal steam cycle of 35%. Biomasses are renewable and sustainable and thus they provide a good alternative to the traditional DCFC fuel of coal, which is a fossil fuel, nonrenewable, and presenting challenges to $CO_2$ emission, climate change, and global warming. Considering two major routes of electricity generation from biomass, the first is the conventional route of burning biomass in a power plant to generate electricity from a steam cycle having a conversion efficiency of 35%. The second alternative is the DCFC integrated route in which the pyrolysis gas and liquid are used to power gas turbine cycle (50% conversion efficiency) to generate electricity and the biomass char used in the DCFC to further generate electricity with a higher efficiency of 80%. The highest peak power efficiency reported in this article is 69% (Table 2) using wheat carbon fuel. Using 1.0 kg of biomass, the conventional route will generate 6.5 MJ of electricity while the DCFC integrated route would double that to give 12.8 MJ (Adeniyi and Ewan, 2011; Desclaux et al., 2010; Cao et al., 2007; Cherepy et al., 2005; Cooper, 2004; Zecevic et al., 2004).

## 4. CONCLUSION

The electrochemical performance of wheat and spruce biomass carbon fuels in a single cell solid oxide electrolyte direct carbon fuel cell have been investigated and presented in this article. Biomasses are environmentally friendly and when applied in the SODCFC would help generate electricity and heat energy for the growing world population. It would also significantly help to reduce the problems of climate change and global warming associated with fossil fuels. In most of the biomass fuel electrochemical cases, wheat fuels perform slightly better than spruce in the SODCFC. At 800°C operating conditions the open circuit voltage of wheat fuel (1.18 V) was slightly higher than spruce (1.16 V). The peak power density recorded for wheat fuel was 67 mW/$cm^2$ while spruce fuel was 57 $mW/cm^2$. On the contrary, spruce fuel (156 $mA/cm^2$) gave the maximum current density while wheat fuel gave a slightly lower value of 139 $mA/cm^2$. For the current density at 80% voltage efficiency, wheat fuel (90 $mA/cm^2$) was superior to that of the spruce fuel (60 $mA/cm^2$). The voltages at peak power for the SODCFC were close for the two biomasses. The peak power efficiency evaluated shows that wheat fuel (69%) gave a higher value than spruce carbon fuel (53%).

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