HIGH POWER DENSITY CELL DEVELOPMENT AT SIEMENS WESTINGHOUSE

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ABSTRACT

High Power Density (HPD) solid oxide fuel cells are being explored for an enhancement in power densities over the current state-of-the-art cylindrical solid oxide fuel cell (SOFC). The HPD solid oxide fuel cell modifies the tube geometry in order to decrease the ohmic polarization of the cell while maintaining the seal-less properties of the cylindrical SOFC cells. Several geometries are being considered, for instance an HPD cell with ten channels (HPD10) increases the cell power density by about 58%. This increased performance is due to geometry alone and does not include any further enhancement of power achievable if more advanced materials were to be used. This paper reviews the fabrication and performance of different geometries of HPD cells to date.

INTRODUCTION

Siemens Westinghouse is recognized as a global leader for innovation in cylindrical solid oxide fuel cells (SOFC). In the past years, several generators have been built and tested. SOFCs of the seal-less tubular type have demonstrated great longevity, thermal cycling robustness, and negligible performance degradation over several years of operation. In recent years, Siemens Westinghouse has embarked on several initiatives in order to reduce the cost of SOFC generators. The main focus is to reduce the dollar per kilowatt ($/kW) of SOFC units produced. There are two main ways to achieve this goal. The first approach is to increase the cell power so that fewer cells are required for a generator of given capacity or the capacity can increase without an increase in the number of cells. The second approach is to decrease the materials cost and use more effective manufacturing processes. This paper discusses a portion of the power enhancement activities in which the tube geometry is modified in order to decrease the cell ohmic resistance. Several tube geometries are being explored through mathematical modeling and electrical testing.

The present configuration of the air electrode supported solid oxide fuel cell is shown in Figure 1. The cathode or air electrode tube acts as the mechanical support of the cell as well as the porous media that allows the oxidant to reach the triple phase boundary. A thin dense layer and narrow strip of interconnection (IC) is applied to the tube allowing connection in series with the fuel electrode (anode) of the next cell. A thin layer of electrolyte (yttria stabilized zirconia (YSZ)) covers the rest of the tube and overlaps the IC. Together with the IC, the electrolyte prevents fuel and air from mixing and acts as...
the ionic conducting media. An interlayer is applied between the cathode and electrolyte in order to provide mixed conductivity for enhanced electrochemical activity on the air side. The fuel electrode covers the electrolyte except for a narrow margin on each side of the IC. This constitutes the active area of the cell and provides the porous media for fuel to diffuse and reach the reactive region as well as for the product to diffuse out. The oxidant (air) is delivered to the bottom or closed end of the cell by means of an air feed tube (AFT) that is concentric with the cell. The depleted air exits from the top or open end of the cell. Fuel flows on the anode side from the closed end towards the open end.

A new type of air electrode supported cell under development is shown in Figure 2. This type of cell is called a high power density (HPD) solid oxide fuel cell. A number at the end indicates the number of channels that the support tube has i.e., an HPD5 and an HPD10 have 5 and 10 channels, respectively. This cell geometry still maintains the seal less design and has the same functional layers as in a cylindrical SOFC. The new geometry provides an increased electrical performance because of the shorter current path and additional paths that are provided by the ribs. The oxidant can be delivered in two different ways, by means of air feed tubes as is custom for the standard cylindrical SOFC or by using some of the channels between the ribs for the air inlet and the others for exhausting the depleted air. The increased cell performance and possible removal of the air feed tubes can reduce the $/kW of SOFC units.

EXPERIMENTAL

The approach used to reduce the ohmic losses is to change the support tube geometry such that the current path is shorter and additional paths are introduced by means of ribs. In cylindrical cells, only two circumferential current paths are possible as shown in Figure 3. Current enters and distributes radially in the anode and at the same time crosses the electrolyte layer reaching the cathode. The current collects within the cathode and exits though the interconnection before entering the next cell connected in series. The shortcoming of this geometry is the long current path and limited numbers of paths. In addition, the cathode thickness is a significant variable as current flows circumferentially and can not be too thin.

For SOFC, we can write the cell voltage as shown in Equation 1 (1). Here $V_N$ represents the Nemst equation and is shown in Equation 2 (2). The ohmic drop is represented by the second term in Equation 1 or $j R_{Cell}$, where $R_{Cell}$ is the total cell ohmic resistance. The third and fourth terms in Equation 1 are the polarization at the cathode and anode respectively and also play a significant role in the cell performance; however such terms are not the focus of this paper and will be not discussed here.

$$V_{Cell} = V_N - j R_{Cell} - \eta_{Cathode} - \eta_{Anode}$$  \hspace{1cm} [1]$$

$$V_N = E^0 + \frac{RT}{2F} \ln \frac{P_{H_2}}{P_{H_2O}} + \frac{RT}{4F} \ln P_O$$  \hspace{1cm} [2]$$

In order to keep the cell voltage high one must minimize the losses or the last three terms in Equation 1. Therefore a benefit in cell performance is achieved by lowering the total
cell ohmic resistance. In the design of HPD fuel cells, two variables are very important; a) the current path length and b) the number of paths. The cell ohmic resistance is the sum of the ohmic resistance of each functional layer (interconnection, cathode, electrolyte, and anode). This is shown in Equation 3 where $R_i$ represents the resistance of each layer (3). Since the support tube contributes to the cell resistance, the smaller the tube path length, $L_{tube}$, the lower the cell resistance. Also, the tube cross-sectional area, $A_{tube}$, decreases the cell resistance but needs to be optimized commensurate with strength requirements and cell weight. The materials used determine the functional layer resistivities $\rho_i$. This also affects the cell ohmic resistance but for all practical purposes the benefit of geometry would apply to any choice of materials.

$$R_{Cell} = \sum_i R_i = \sum_i \rho_i \frac{L_i}{A_i} \quad \text{(3)}$$

The benefit of increased number of conductive paths can be seen from Equation 4 as the cathode ribs act as parallel connected resistors (3). Here $R_j$ represents the resistance of each rib. Therefore as the number of ribs increases, the cathode equivalent resistance decreases.

$$\frac{1}{R_{tube \, eq}} = \sum_j \frac{1}{R_j}$$

Figure 4 further illustrates the benefit of decreasing the conductive path length and increasing the number of paths, while maintaining relatively high cell voltage as given in Equation 1. As current enters the anode and crosses to the cathode side, it has several paths to the reach the interconnection.

Figure 5 shows the three cell geometries currently under investigation. The cylindrical cell on the left is the standard SOFC while the HPD5 (center) and HPD10 (far right) are the focus of efforts to improve cell performance. As presently fabricated, both HPD5 and HPD10 are half the length of standard cylindrical cells. Another benefit of the HPD cell geometry is the power per volume (kW/cm³). In Figure 6, three bundles are shown. One is the standard cylindrical cell bundle while the others are HPD5 bundles with different number of cells. A flat geometry enjoys a higher packing density than the cylindrical counterpart, significantly increasing the power per volume.

Siemens Westinghouse is aggressively pursuing newer technologies in cell manufacturing. The electrochemical vapor deposition, EVD (4), process has recently been replaced with the atmospheric plasma spray (APS) process. It is believed that this process has low cost to bring tubular SOFC to a viable commercial product. All cells, cylindrical and HPD, are currently being produced using the APS process and all cells reported here are APS cells.

The APS process is shown in Figure 7. Gases are introduced within a small chamber where two electrodes provide the electrical charge to create a plasma. The plasma reaches a very high temperature and therefore can melt, or partially melt, ceramic materials with very high melting temperature, i.e., $\text{ZrO}_2 \, \text{mp} = 2677^\circ\text{C}$ (5). The feed powder is introduced in the plume either internally or externally to the APS gun whereupon it
becomes molten before hitting a substrate at high velocity. The microstructure of
different functional layers can be tailored to produce dense or porous structures. Figure 8
illustrates different layers of the SOFC made by the APS process. On the left is shown
the electrolyte layer where a relatively dense layer is obtained. A few pores are still
present but the porosity is closed and does not affect the cell performance. On the right
the anode layer is shown; a very porous structure with good electrical contact between Ni
particles is obtained using the APS process.

The state-of-the-art materials used in the tubular SOFC and respective manufacturing
processes are the following:

1. Cathode: Doped LaMnO₃ Extruded and sintered
2. Interlayer: Various Slurry coating
3. Interconnection: Doped LaCrO₃ APS process
4. Electrolyte: Yttria Stabilized Zirconia APS process
5. Anode: Ni-YSZ APS process

Both cylindrical and HPD tubes are currently extruded and sintered to achieve the desired
properties such as porosity, electrical conductivity, and mechanical strength. Different
types of interlayers are used either as a barrier for unwanted reactions or as a mixed
conductor for enhanced electrochemical activity (6). For instance the standard cylindrical
 cell uses cerium oxide while the HPD cell uses a composite interlayer (mixed ionic and
electronic conducting phases). The interconnection, electrolyte, and anode are the same
for both cylindrical and HPD cells and both use the APS process to deposit each layer.

RESULTS AND DISCUSSION

Cylindrical cells are routinely fabricated with the APS process, and electrical test data
extends to several years of operation in single cell test articles. Currently cylindrical cells
are being fabricated in large quantities for several demonstration units. To date several
HPD5 cells have been fabricated for development purposes and for a small 5 kW unit that
will use 36 cells. Many HPD5 cells have been electrically tested as well. A few HPD10
cells have been made and one has been electrically tested. Figure 9 plots the voltage
and power density of the three geometries as a function of current density. The advantage of
the HPD geometry can be readily seen. For instance a typical cylindrical cell operates at
a cell voltage of 0.65 volt and 300 mA/cm² while a HPD5 can operate at a cell voltage of
0.65 volt and 400 mA/cm². This translates to a 33% improvement in power density. The
multiple HPD5 electrical tests indicate that the performance is reproducible and the
manufacturing processes are well controlled. The first HPD10 cell test shows
improvement over the HPD5 cell and confirms the benefit of increasing the number of
conductive paths or ribs. The result is encouraging as the HPD10 can operate at a cell
voltage of 0.65 volt and 475 mA/cm². This translates to a 58% improvement in power
density over cylindrical cells. It is worth noting that this is the first HPD10 cell test and
further improvement is to be expected as the manufacturing process matures.

In Figure 10, the cell voltage and cell power is plotted against cell current. The benefit is
more evident when one compares the cell power for different geometries. A typical full
length cylindrical cell can produce about 190 Watts at maximum power. At the same
conditions an HPD5 cell can produce about 270 Watts and a HPD10 reaches about 300 Watts. These improvements have been achieved with HPD cells having half the length of cylindrical cells.

Low temperature operation is also of interest at Siemens Westinghouse. The ultimate target is 800°C. The current materials used are not suitable for operation at 800°C but can achieve respectable power densities at 900°C with the HPD geometry. Figure 11 illustrates cell test data at 900°C. The standard cylindrical cell operates poorly but an enhanced interlayer provides better performance even for cylindrical cells. Again the HPD geometry improves the performance further as is shown for the HPD5 and HPD10 curves. For instance at a cell voltage of 0.65 volt, the cylindrical standard cell operates at about 200 mA/cm²; with the composite interlayer, a cylindrical cell can operate at about 250 mA/cm², the HPD5 cell at about 320 mA/cm², and the HPD10 at about 350 mA/cm². Ultimately the combination of advanced materials with the HPD geometry will allow Siemens Westinghouse SOFCs to operate at 800°C.

Siemens Westinghouse is justifiably proud of the longevity of cylindrical cells as exhibited by cells that have been on test for several years with negligible voltage degradation. This also applies to HPD cells, where at the time of writing, the cumulative testing hours have exceeded 15,000 hours. Figure 12 shows the lifetime plot of an HPD5 cell test. Good stability is observed at relatively high current densities and 212 Watts.

To further demonstrate the electrical performance of HPD cells, a five-cell HPD5 bundle was assembled and tested. The bundle was assembled using the standard Ni felt technology. A secondary objective of this test was to qualify the bundling technology to be used in the 5 kW generator. Figure 13 illustrates the lifetime plot of this bundle test. At a current density of 300 mA/cm², the bundle was able to produce about 900 Watts. This corresponds to 180 Watts per cell and little difference is seen when compared to a single HPD5 cell test.

CONCLUSIONS

The power density of the tubular type cell has been improved by modifying the geometry from cylindrical to HPD tubes. The geometry has reduced the cell resistance and in turn lowered the ohmic losses. The power enhancement at 1000°C is due to geometry alone and does not include the benefit if more advanced materials were to be used. Though HPD cells have respectable power densities at 900°C, further temperature reduction is desired. It is expected that a combination of advanced materials and the HPD geometry will bring Siemens Westinghouse SOFCs performance for operation at 800°C up to par.

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Figure 1. Standard air electrode supported (AES) cylindrical solid oxide fuel cell.

Figure 2. Air electrode supported high power density (HPD) solid oxide fuel cell.
Figure 3. Current path in a cylindrical solid oxide fuel cell.

Figure 4. Improved current path in an HPD solid oxide fuel cell.

Figure 5. Different types, cylindrical and HPD, of air electrode supported (AES) solid oxide fuel cells fabricated by the Atmospheric Plasma Spray (APS) process.
Figure 6. Different size bundles of cylindrical and HPD5 cells by the APS process.

Figure 7. The Atmospheric Plasma Spray (APS) process.

Figure 8. Typical microstructure of APS solid oxide fuel cells.
Figure 9. Cell electrical performance with 89% H₂/11% H₂O and 85% fuel utilization in terms of current density.

Figure 10. Cell electrical performance with 89% H₂/11% H₂O and 85% fuel utilization in terms of cell current.
Figure 11. Cell electrical performance with 89% H₂/11% H₂O and 85% fuel utilization in terms of current density.

Figure 12. Lifetime plot for Test 1000.
Figure 13. HPD5 bundle electrical performance at 1000°C with 89% H₂/11% H₂O and 80% fuel utilization.