ABSTRACT

The solid oxide fuel cell can be configured to allow recovery of carbon dioxide, which can then be sequestered underground. The efficiencies of gas fueled power generation systems using tubular SOFCs designed for full separation and re-injection of carbon dioxide have been simulated. The simulations show that the overall process will incur only a small power loss for recovery and re-injection. The cost of power generation with recovery of the CO₂ using solid oxide fuel cells indicates that this technology can be considered viable as a significant contributor to reducing world CO₂ emissions.

INTRODUCTION

Concerns about the impact of anthropogenic CO₂ on global warming have invigorated the search for technologies to reduce the amount of CO₂ that is released to the atmosphere during power generation. A unique solution to the problem is offered by SOFCs that are configured to allow recovery of carbon dioxide, which can then be sequestered underground. Such permanent underground disposal could be in depleted gas/oil reservoirs, aquifers or coal seams. Furthermore injecting CO₂ into producing oil reservoirs can be a means to enhance oil recovery. Gas production from some coal seams can also be enhanced by CO₂ injection. Schemes to generate power with collection and sequestration of the produced carbon dioxide can suffer from high cost and low efficiency due to the addition of the CO₂ recovery equipment. In order to assess the economic viability of using SOFCs in this way, simulations of the overall process have been made.
THE CO$_2$ SEPARATING SOLID OXIDE FUEL CELL

The configuration favoured for the CO$_2$ separating fuel cell is based on the tubular SOFC design in which controlled leakage rather than seals are used to separate the fuel side from the air side of the cell. This is the design which has been pioneered by Westinghouse and involves the use of tubular electrodes closed at one end. In the conventional, non-CO$_2$ separating design, exhaust air and exhaust fuel are allowed to mix through controlled leakage of fuel through baffle boards which separate air and fuel in the generator. By introducing additional baffle boards and careful management of internal flows and pressure drops, it is possible to arrange for the exhaust fuel to be withdrawn as a separate stream without the need to apply high temperature sealants.

Fuel cells do not burn all of their fuel. To keep the electrochemical reaction progressing at reasonable speed requires a certain partial pressure of unburned fuel to be maintained resulting in a practical limit to the fuel utilisation of 80 – 90%. To achieve CO$_2$ separation in the exhaust stream it is necessary to after-burn the unused fuel without directly mixing with air which would introduce nitrogen. To do this, as shown in Fig. 1 the spent fuel is passed over a bank of oxygen ion conducting tubes very similar in configuration to the SOFC tubes, in the main stack of the fuel cells.

Figure 1. Configuration of CO$_2$ separating SOFC.
The Integrated System

Flow schemes and cost models have been developed for the integrated system of fuel supply, fuel cell, CO$_2$ recovery and re-injection. By careful integration of the fuel supply, air supply and exhaust gas recovery system the process can be optimised in terms of cost or efficiency. CO$_2$ has to be brought to high pressure (at least 200 bar) for re-injection and the fuel gas itself may be available at very high pressure from the gas field. Turbo expansion of the fuel can be used to generate some of the power for CO$_2$ recompression. The temperature drop created by the expansion process could be used to assist in the liquefaction of the recovered CO$_2$ so that it can be pumped rather than compressed into the reservoir.

The optimum conditions for the process are to operate the SOFC under pressure. Apart from improving the specific power output of the stack this significantly reduces the compression power for the CO$_2$ recovery and results in smaller CO$_2$ and water separation equipment. Exhaust air can still be passed through an expander to recover power as in the conventional SOFC/turbine combination and this form of integration increases overall efficiency significantly. For simplicity it is possible to run the process at atmospheric pressure as the extra compression costs for the CO$_2$ are not great compared with the overall power output of the fuel cell. They amount to a 2-3% additional loss in overall electrical efficiency. This configuration is however not the optimum with regard to either cost or efficiency.

New technology will be used for compact in-line drying of the recovered CO$_2$ allowing cheaper materials to be used in the rest of the CO$_2$ compression and re-injection system. Wet CO$_2$ is very corrosive and requires the use of stainless steel equipment whereas carbon steel can be used in dry CO$_2$ service.

The Simulation Model

For an energetic analysis of the SOFC power plant concept the commercial flow sheet simulator PRO/II (Simsci) is used. This program simulates the components mass flows and conditions and calculates the energy demand or energy production of common peripheral units. For special components like injector, pre-reformer, stack reformer and oxygen separation tubes design data of Siemens Westinghouse are used. A SOFC stack modelling program is integrated as a FORTRAN subroutine. Based on a planar model [1], an equivalent model for a tubular SOFC with an air feed tube was developed. For calculation of the ohmic resistance, the equations of an analytical solution given by Nisancioglu [2] were used.
The performance characteristic of the simulated tubular fuel cell is described in Fig. 2. Three curves are shown for pressure levels of 1, 5 and 10 bar. The mean fuel temperatures are in the range between 950 and 1000 °C. These simulated performance characteristics are in good agreement with experimental data published by Singhal [3]. The current-voltage curve for a pressure of 5 bar shows that the cell voltage at 0.7 V leads to a relatively high mean current density of about 300 mA/cm².

In Fig. 3, the components of the plant simulation model are shown. The natural gas stream is expanded and recuperatively heated before entering the SOFC module. Within an anode gas recycle loop, which is realized with an injector, the pre-reformer and the stack reformer convert the fuel to a hydrogen rich gas. The anode gas flows outside the tube walls in co-flow with the cathode gas. The fresh air is compressed to about 6 bar and recuperatively pre-heated to about 600 °C. The spent fuel is afterburned with pure oxygen. This oxygen is produced in oxygen separation tubes. These are modelled as tubes effectively in open circuit and thus neither contribute nor draw electrical power in the modelling work done so far. The pressurized depleted air is expanded in a turbine to produce work (used for the air compression) and ac power in a generator. The completely converted fuel is cooled down to separate the water. Then the CO₂ rich gas is compressed to about 60 bar for liquefaction. In this liquid phase it can easily be pumped to even higher pressure levels. In the diagram in Figure 3, a pool of work and power is shown. The incoming and outgoing energy flows describe qualitatively the energy balance.
The energy produced in the SOFC, the fuel gas expander and the exhaust air expander contribute positively to the net power, whereas the energy demand for air compression, O₂ separation and CO₂ compression lower the net power production.

Initial simulation results and estimations indicate the main parameters which influence the overall net system efficiency. The main contributor to power production is the tubular SOFC module. Depending on the pressure level (5-8 bar) and the chosen current density (200-300 mA/cm²) a cell voltage in the range of 650-750 mV is reached. This results in a gross electric efficiency of about 50-60 %, if a fuel utilization of 85 % is assumed. The main contributors to power consumption are air compression, recompression of recovered CO₂ and the conversion of DC to AC power. Depending on the development status of different types of oxygen separation tubes and the special design with respect to oxygen flux densities a more or less high portion of energy converted has to be taken into account for this process step. This process may either be a contributor or consumer of power. For each 0.1 volt consumed or produced a plant efficiency change of about 1.5 % points results (in case of 85 % fuel utilization, 15 % of the incoming fuel is burned with pure oxygen). The other power producing and consuming components in sum contribute to the net electrical plant efficiency, for which a value approaching 55 to 60 % seems feasible. Further work has to be done to optimize the flowsheet, the design of the key components (tube bundles, expanders and recuperative heat exchangers) and of the operation parameters of the cells and the peripheral components (fuel utilization, pressure and temperature levels).
PLANS FOR DEMONSTRATION

The current plans for developing this technology center around a demonstration of the CO₂ separating fuel cell at the 100kW level. SOFC technology is modular and this scale is considered sufficient to prove the concept for any power level. The demonstrator will not re-inject the recovered CO₂ as the quantities produced by a 100kW unit during the test are too small to justify drilling an injection well. Subsequent to a successful test, consideration will be given to scaling up the technology to achieve a power output of several 10’s of MW, probably in an oil field application.

CONCLUSIONS

Fuel cells are a reality but so far they have struggled to compete on cost with alternative electricity generating systems, particularly low efficiency turbines and engines. However comparisons on a $/kW basis do not take into account other aspects such as turndown, emissions, noise and reliability on which some customers place a high value. Fuel cells do have many features, which differentiate them significantly from other power delivery systems. The CO₂ separating fuel cell system described in this paper is an example of an application in which the fuel cell can provide functionality that other generation systems will find difficult to match. It is through these special applications that major breakthroughs into the marketplace can be achieved.

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