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Progress with the development of a CO_2 capturing solid oxide fuel cell

M.R. Haines[a,*], W.K. Heidug[a], K.J. Li[a], J.B. Moore[b]

[a]Shell Global Solutions International, B.V., Oil and Gas Upstream Development, Visseringlaan 26, Rijswijk 2280, The Netherlands
[b]A/S Norske Shell, P.O. Box 40, 4098, Tanager, Norway

Abstract

In April 2000 Siemens Westinghouse started work under a co-operation agreement with Shell International to develop and demonstrate a natural gas fired 0.25 MW solid oxide fuel cell (SOFC) modified to enable capture of carbon dioxide. The basic principles of this development and initial plans for the demonstration, which is due to start up at a Norwegian location in 2003, have been presented in environmental and fuel cell forums during 1999/2000. This paper reviews the latest technical progress with this development and discusses the large potential market for stationary power generation using SOFCs with CO_2 capturing capability.

Keywords: Fuel cell; Carbon dioxide capture; Demonstration project; Solid oxide; After-burner

1. Introduction

With the growing awareness that green house gas emissions will have to be curbed, there is increasing interest within the oil and gas industry in processes that will capture the CO_2 emitted during combustion of hydrocarbons [1,2]. Development of economic processes to perform CO_2 capture during power generation and heating will enable large scale geological sequestration of CO_2 and a significant reduction in release of green house gases. Furthermore, by injecting CO_2 at high pressure into depleted oil reservoirs the recovery of oil can be increased by as much as 20%. At the same time a large part of the CO_2 becomes geologically sequestered thus contributing significantly to reduction of green house gas emissions. This combination of CO_2 capturing power plant and oil production operations has the potential to eliminate CO_2 emissions from electricity generation on a large scale. Capture of CO_2 during power generation can be achieved by three main classes of process: pre-combustion, oxy-combustion and post combustion. Pre-combustion uses fuel reforming to make hydrogen and CO_2 with recovery of CO_2 prior to combustion. Oxy-combustion uses pure oxygen to combust the fuel so that a steam/CO_2 exhaust, undiluted with nitrogen, is produced from which the CO_2 is easily recovered. Post combustion covers all those technologies which extract CO_2 from fuel gases, such as amine absorption.

These processes all suffer from high cost and reduction of generating efficiency because of their parasitic heat and electrical power needs. The post combustion processes are the most developed and have the lowest cost and smallest efficiency reduction. Nevertheless, they require massive fuel gas scrubbers and consume significant amounts of energy for regeneration of the absorption solvent.

2. CO_2 capture with a solid oxide fuel cell

2.1. Principle of CO_2 capture

The solid oxide fuel cell (SOFC) electrolyte transports exclusively oxygen ions from cathode to anode to provide oxygen for oxidation of the fuel (see Fig. 1). In doing this, it effectively separates oxygen from the air and can thus be seen as an oxy-combustion type process according to the preceding classification. The driving force for the oxygen separation is the oxidation reaction and hence the separation is performed without expenditure of additional energy. This puts the SOFC at a great advantage compared with other oxy-combustion processes, which pay a large energy penalty for the operation of a separate oxygen separation unit. Thus, the SOFC intrinsically lends itself to efficient power production with CO_2 capture.

The cost of electricity generated by this type of power plant is projected to become low enough to compete with the other methods of CO_2 capture from fossil fueled power generation plants.

2.2. Design adaptation for CO_2 capture

To take advantage of this intrinsic attribute of the SOFC to allow CO_2 capture, present designs need to be enhanced in

* Corresponding author. Tel.: +31-70-311-3484.
E-mail address: m.haines@siep.shell.com (M.R. Haines).

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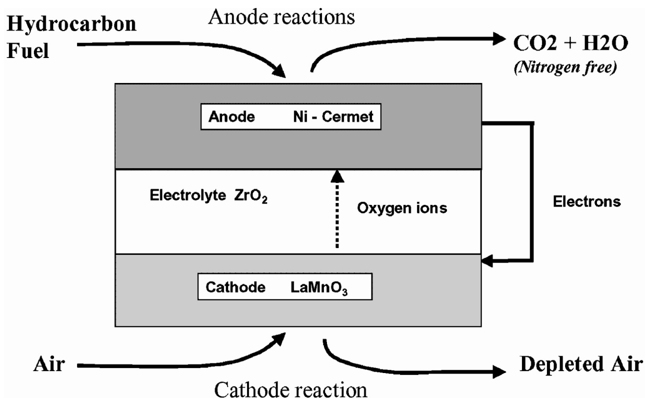

Fig. 1. Basic chemical processes in SOFC.

respect of two features. Firstly, the practice of completing the oxidation of unreacted fuel by direct oxidation with air has to be replaced by a method which does not introduce nitrogen from the air. Secondly, the sealing between the cathode and anode gases has to be maintained throughout the fuel cell system to the point at which the CO_2 in the exhaust has been separated from the other main component, which is water. A method of doing this has been developed which can most easily be applied to the SOFC design pioneered by Siemens Westinghouse Power Corporation (SWPC) [3,4]. It makes use of an additional ‘‘after-burning’’ section, which operates in a similar way to the main fuel cell stack. The after-burner makes use of an additional stack of tubes, which increase the fuel oxidation from the normal 85% leaving the main stack, to around 98%. The layout of this one is shown in cross-section in Fig. 2. The SWPC seal-less tubular SOFC already makes use of controlled leakage through a series of tube sheets in order to provide adequate sealing while allowing for movements caused by thermal expansion of the SOFC tubes during the operating cycle. The basic design of SWPC already includes a plenum chamber for re-circulating anode gas to the fuel reforming section. By improving the sealing arrangements here, but using the same principles to avoid the use of fixed sealing points, it is expected that the required segregation of anode from cathode gases to allow recovery of almost all of the CO_2 can be realized.

3. The demonstration project

3.1. Overall description

Since the principles of the CO_2 separating SOFC were proposed by Shell engineers in 1998, plans were put in place to develop and demonstrate the feasibility of the technology. In order to do this a co-operation agreement was entered into between Shell and SWPC in 1999. Under the framework of this agreement a contract for development and delivery of a 250 kW atmospheric CO_2 separating SOFC demonstration unit was placed in April 2000. Prior to placing this contract, studies were made on the feasibility and also the expected limits of overall system efficiency. [5–7] The results of these studies were particularly encouraging as it appears that the overall efficiency of the CO_2 separating SOFC can be close to that of a conventional SOFC (Fig. 3). In particular, the pressurized hybrid system is applicable and would allow efficiencies to exceed 60% and possibly reach 70% on larger units. This would overcome one of the principle objections to use of CO_2 capture and sequestration technology which is that it reduces overall efficiency and thus increase reliance on hydrocarbon fuels.

The demonstration project is funded mainly by A/S Norske Shell with some additional grant assistance from both the Norwegian Government and the US DOE. The technology is of particular interest to Norske Shell who are seeking a way to meet the Norwegian Government aspirations to reduce CO_2 emissions from offshore oil and gas production operations. The demonstration project will however be run at an onshore location. In line with sustainable development principles, a location was sought for the demonstration unit which would be of maximum advantage to stakeholders and community as a result of which agreement was reached to integrate the unit into a local fish farm.

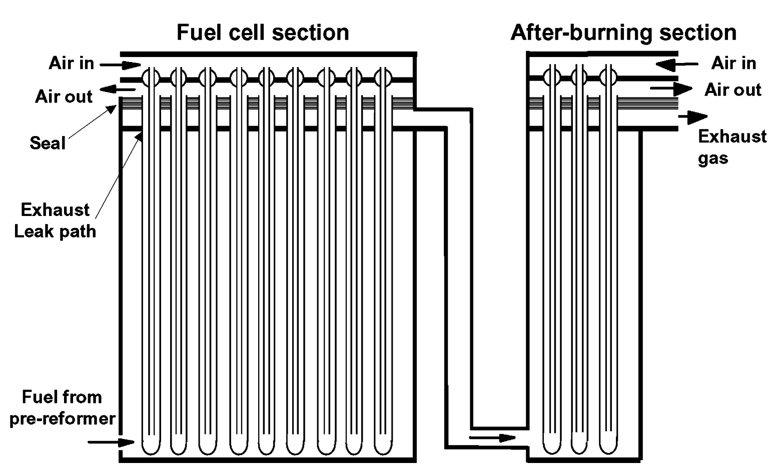

Fig. 2. CO_2 separating fuel cell concept.

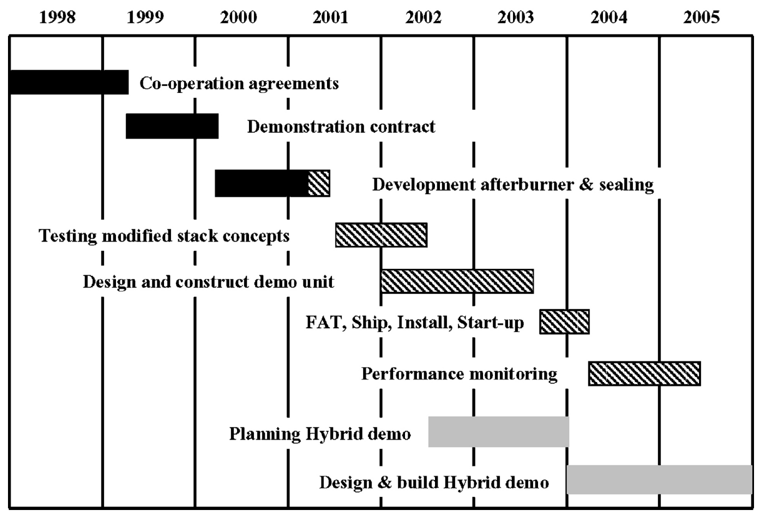

Fig. 3. CO_2 separating SOFC development plan.

3.2. Project schedule and progress

Work started on the project in April 2000 with the first and critical tasks being development of an effective after-burning section and sealing arrangement. These tasks involved production and testing of tubes made of new and modified materials for the after-burner section. The stability of operation had to be demonstrated by running tests of sufficient time and severity to give confidence in the materials selection. It was originally envisaged that this work would deliver a result by the end of 2000 whereas in the event it was not until May 2001 that a satisfactory combination for the after-burner was found. Several different concepts for the modified sealing system have been investigated. A selection of the preferred concept has recently been made and work is now under way to detail and test the chosen design. Prior to building the complete demonstration unit at the 250 kW scale, it is planned to conduct tests on a section of the complete bundle to verify design and performance expectations. This verification is scheduled to take place in the first part of 2002. The complete unit is scheduled for assembly and factory test in USA towards the end of 2003. Shipping to Norway and installation at site is expected last quarter 2003 with start-up planned late 2003 to early 2004. All efforts are being made to bring forward the start-up date of the demonstration in so far as they do not jeopardize the success of the project.

3.3. Test site

The diagram (Fig. 4) shows how the unit is planned to be integrated into a cod fingerling fish farm to be built near the Kollsnes gas terminal in Norway. It is proposed to use not only the electric power from the unit but also the low grade waste heat and the captured CO_2. Because of the relatively small scale of the power plant there is no point in demonstrating geological sequestration, instead the CO_2 will be used to enhance the growth of algae which is grown in the fish farm to feed to the growing fingerlings. The fish farm consists of a series of sea water filled tanks some of which have to be kept at above ambient temperature as shown in the figure. The fish farm design already makes use of heat pumps in order to minimize energy consumption. In addition, waste heat from the fuel cell will also be captured and used to further reduce the overall fuel consumption. The use of the CO_2 from the fuel cell for enhancing algae growth will give a small financial saving as it will displace externally supplied CO_2. The fuel cell will not be the only source of power for the fish farm as it requires somewhat more than the fuel cell can provide. The system will thus be configured so that the fuel cell runs as a base load provider with additional power brought in from the grid. However, at present it is not planned to set the system up for power export to the grid as little or no downtime of the fish farm is to be expected. Apart from the learning obtained from demonstrating the CO_2 capture capability of the fuel cell, it is expected that

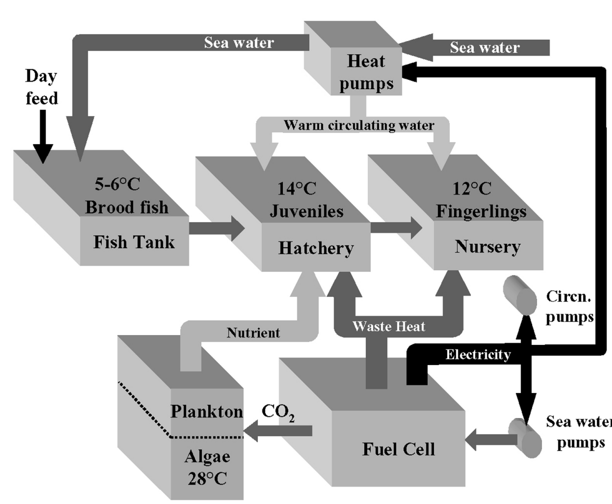

Fig. 4. Fuel cell integration with fish farm.

much will be learned about operational aspects of running a fuel cell as a power supply to a dedicated customer.

3.4. Technical objectives

The main technical objectives of the demonstration are to show that effective anode/cathode gas separation can be achieved and that a high degree of fuel utilization, preferably to 98%, can be achieved. This will allow an exhaust stream to be produced with a composition such that CO_2 can be recovered easily for geological sequestration, enhanced oil recovery (EOR) or other industrial applications. The expected net AC electrical efficiency of the unit is expected to be around 45%, similar to that of conventional atmospheric SOFCs of the same type. The results will also be used to project the expected performance of a pressurized hybrid design with CO_2 separation.

4. Applications

The first main application currently envisaged for this technology is offshore generation of electric power with CO_2 capture and re-injection. Oil and gas companies are well placed to integrate the injection of CO_2 into their operations. There are tax incentives in the Norwegian offshore Oil and Gas sector to implement CO_2 free production, thus Norway is the likely place for first implementation. The capacity of the units required is typically in the range of 10–50 MW. The fuel cell has a major advantage in the offshore sector because of its modularity and reliability. It is common practice when relying on gas turbine power plants to install either a complete 100% spare generator or three units of 50% capacity. With a fuel cell made up of modules, this spare capacity can probably be eliminated.

The ultimate goal of the development is to apply CO_2 capture in high efficiency hybrid SOFCs. Once confidence has been gained with the viability of the atmospheric design, it will be a logical next step to build a CO_2 separating pressurized hybrid SOFC perhaps on the larger scale of 1 MW. A suitable industry partnership will be needed to champion such a demonstration. A location where the captured CO_2 can be kept out of the atmosphere or put to beneficial use is needed. Projects to geologically sequester CO_2 from existing industrial point sources and to collect and use CO_2 for EOR are of increasing interest. [8–11] At the 1 MW scale, tie in to such a project allowing demonstration of completely zero emission power generation would be desirable. The confidence to formulate such plans should be gained by the time the testing activities planned in 2002 are complete.

Large scale capture and geological sequestration of CO_2 can play a significant role in alleviating the effect of consuming fossil fuels on the environment. Straight sequestration on its own is simply an additional cost of doing business. However, CO_2 is a valuable resource for EOR and has the advantage that after use in this process it remains sequestered in the depleted oil reservoir. [8–11] It is also possible to reuse the CO_2 which has been injected into an oil reservoir for CO_2 flood in an adjacent reservoir thus further increasing the value of the resource whilst freeing up additional sequestration capacity. It is also possible to use gas reservoirs for sequestration of CO_2 and it may be possible in some situations to increase gas recovery by displacing gas out of such reservoirs with CO_2. An additional process which is of interest is the displacement of coal bed methane by CO_2 in unmineable seams. More CO_2 can be taken up by the coal than is generated by burning the displaced methane making this a highly sustainable process with respect to green house gas emissions. Using the fuel cell to supply CO_2 for these application brings additional advantages which promote sustainable development. It will accelerate introduction of a significantly more efficient, less polluting, quieter and distributable power generation technology which is also ideally suited for use in a future hydrogen based economy.

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