ABSTRACT

In this paper, the design and construction of a 1 - 5 kW SOFC test system is presented together with initial test results obtained during the first 1080 hours of operation. The main purpose of the test system is to analyse and demonstrate a complete SOFC system including fuel and air supply systems, heat exchangers, fuel processing units, power electronics etc., as well as be a platform for testing and evaluation of individual BoP components. The study describes basic design criteria and properties of the test system. Characteristics of major sub-systems such as fuel and air supply, steam supply, purge gas, exhaust heat-recovery, power electronics and control system are also explained.

The system will be used for system testing and modelling purposes for several years to come. It will also support product development and designing of an upcoming alpha-prototype and other prototype units.

INTRODUCTION

In August 2002, Wärtsilä Corporation and Haldor Topsøe A/S entered into a co-operation agreement to start a joint development program within the planar SOFC technology. This program aims to bring highly efficient, clean and cost competitive fuel cell products to the market in the power range above 200 kW. The products will be designed for both stationary power generation and marine applications. Within the program, a conceptual study of a 250 kW planar SOFC system for CHP applications was presented in 2003 (1) along with strategies to counteract stack ageing (2). This paper presents a program phase where the principles presented in the conceptual study have been implemented in a working test system operating at a lower power output.

The test system was started with one 1.2 kW stack on September 16, 2004. The first continuous test run had a duration of 1080 hours. Generated power was supplied to the Finnish national grid. System was shut-down in order to change and test new balance of plant components. Four new 1.2 kW stacks are planned to be installed in February 2005 bringing the peak electrical power up to 5 kW. Meanwhile, testing will continue with one 1.2 kW stack.

SYSTEM DESCRIPTION

The SOFC test system is a natural gas (NG) fuelled power system including all the required balance of plant (BoP) components. Pressurised natural gas is supplied to a
sulphur removal unit. The sulphur-free natural gas is partially reformed by an adiabatic pre-reformer prior to entering the stack. The reformer is a fixed bed reactor where all higher hydrocarbons are converted with steam into methane, hydrogen and carbon oxides. In the initial test phase, anode circulation has not been included. Steam required in the steam reformer is supplied from an external water supply. The system flow sheet is presented in Figure 1.

![Figure 1. Basic flow sheet of the SOFC test system.](image)

Cathode air is supplied by a blower and preheated in a heat exchanger prior to entering the stack. Heat exchanged cathode off-gas is used as oxidant and coolant in the catalytic burner. An additional air supply line (dashed line in Figure 1) will be constructed to provide extra air for burner cooling purposes, since it became evident that cathode off-gas flow alone is not sufficient to keep the burner at its operating temperature at off design operating points. Overview of the system is presented in Figure 2.

![Figure 2. Overview of Wärtsilä - Haldor Topsoe 1-5 kW SOFC test system (3).](image)

In addition to the air and fuel management systems, water management, purge gas, exhaust heat recovery, back-up power, power conversion and control systems are included in the system.
CELL AND STACK TECHNOLOGY

Cell and stack technology used in the system is based on the planar SOFC technology developed by a consortium of Haldor Topsøe A/S and Risø National Laboratory. The cell consists of ceramic materials where the active cell components are encased by metallic interconnects and end plates. Cell properties and performance are described elsewhere (4). Cells and interconnects with minimal thickness are used to provide high power density, low weight and low cost of the stack. The interconnect plates providing internal gas distribution channels in-between the cells are made of ferritic stainless steel. The metallic plates are pre-coated to protect the material against hot corrosion and to ensure optimal electrical contact at the interfaces.

In the stack assembly, up to 75 anode-supported cells with the dimensions 12 x 12 cm² are positioned together with seals and metallic interconnect plates. In the system, 1.2 kW stacks with internal manifolding and cross flow arrangement are used. Power density of the utilised stacks is ca. 820 W/l.

The system was started with one 1.2 kW stack on September 16, 2004. Four new 1.2 kW stacks are scheduled to be installed in February 2005. All the stacks are located in an electric furnace, which compensates for heat losses and is the heat source during the start-up phase. A 75 cell stack is presented in Figure 3. Stack performance is discussed further in the Results section.

![Figure 3. 75 cell, 1.2 kW stack.](image)

FUEL REFORMING TECHNOLOGY

Russian natural gas is filtered and fed into the fuel processing system using a standard mass flow controller. The natural gas has a methane content of 98% and small amounts of ethane, propane and butane. Up to 6 ppm of THT is used as odorant. The THT, which is rather refractory and difficult to process without hydrogen present, is removed using a special catalyst, ST-101, in a fixed bed reactor operating at 300°C. The sulphur-free gas is pre-reformed by an adiabatic steam reformer at approximately 500°C. Both sulphur removal and pre-reformer reactors are electrically heated in order to compensate for heat losses and assist during start-up.

The sulphur removal reactor has two separate heating zones. Since no heat is generated nor consumed in the chemical reactions taking place within the reactor, same temperature is maintained in both zones.

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The pre-reformer has inlet and outlet heating zones as well as three adiabatically controlled zones around the catalyst bed as presented in Figure 4. Adiabatic control of this physically rather small reactor has turned out to be challenging. In adiabatic control, temperature measurements from inner layers of the reactor are used as temperature set points for the heating elements placed on the outer layers. Heating elements provide compensation for external heat losses. Since the thermal mass of the reactor is rather small, it both cools down and warms up rapidly. Due to this, reactor temperatures have a tendency to drift in adiabatic control mode. The reactor is currently operated in non-adiabatic control mode, using fixed temperature set points determined by the system operator. Pre-reformer temperature profile and reforming capabilities are discussed further in the Results section.

Figure 4. Schematic diagram of the pre-reformer with heating resistors.

BALANCE OF PLANT

Steam Supply

Since anode recycling system has not yet been implemented, normal tap water is used to provide a constant steam flow for the reformer. The water is filtered, de-ionised and pressurised prior to supplying it into a steam generator operating at a pressure of 2.5 bar(g). The generated steam is further superheated up to 500°C by an electrical heater prior to the steam reformer. A pressure difference measurement over a measuring flange is used to determine the rate of steam flow. The flow is adjusted by a pneumatic control valve in a range of 0.4 - 2.5 kg/h. Steam to carbon ratio is maintained above 0.8 (H₂O/total C) in order to avoid carbon formation in the pre-reformer.

There have been some difficulties in obtaining a stable steam flow. Upward spikes with duration of some seconds occur approximately every five minutes. This instability is most likely caused by small pressure fluctuations within the pressure vessel of the steam generator.

Heat Exchangers

Main heat exchanger of the system is an air recuperator which preheats the cathode air up to 700°C. While the catalytic after burner is in operation, natural gas is heated from room temperature to 300°C prior to the sulphur removal unit using the heat contained in the burner off-gas. Pre-reformed fuel gas is further heated up to 650°C prior to the stacks using the heat of anode off-gas.
The remaining exhaust heat is recovered by water cooled plate heat exchangers located at both fuel and air side exhaust lines. Cooling water temperature measurements and flow rates are used to determine the amount of waste heat recovered.

The currently utilised gas-to-gas heat exchangers have been manufactured from a high temperature steel alloy by using a semi-commercial plate heat exchanger concept where the plates are connected to each other through brazing. Thermal cycling seems to present significant challenges for this type of technology. Leakages between cold and hot sides have been witnessed in some of the units. Testing of different heat exchanger concepts is currently under way.

Importance of sufficient thermal insulation has been highlighted during the first test runs. Since the overall size of the apparatus is notable, and the distances between BoP components are long, electrical trace heating must be placed along some of the pipelines to compensate for heat losses.

Air Supply

Both a vane compressor and a side channel blower have been tested at the system air supply. The tested side channel blower is capable of providing 0 - 85 Nm³/h of ambient air at a maximum pressure of 0.3 bar(g). Physically considerably smaller vane compressor is capable of providing roughly the same amount of air at a higher counter pressure. Compressor’s drawbacks include significantly louder operating noise and fluctuating pressure. The compressor hasn’t proven to be as reliable as the standard side channel blower.

Air flow rate on the cathode side of the system is measured using a thermal mass flow meter. Automation system controls the rotational speed of the blower or the compressor with a PID controller.

Catalytic Burner

The system includes a catalytic after burner in which anode off-gases leaving the fuel cells are combusted. Using a catalytic burner ensures extremely low emissions with varying fuel compositions. Burner flue gas temperature is maintained around 700°C. Cathode off-gas is used to cool the burner.

Catalytic after burner has not been in use during the first 1080 hours of operation, since it became evident that cathode off-gas flow alone is not sufficient to cool the burner to 700°C. A separate air supply line will be constructed in order to be able to provide enough air directly into the burner for cooling purposes.

When the burner is in operation, the temperature of its flue gas will determine the temperature of heat exchanger E1 and thus the temperature of the pre-heated fuel gas entering the sulphur removal unit. While the burner has been out of operation, electrical trace heating has been utilised in heating the natural gas prior to the sulphur removal unit.

Purge Gas Supply

In addition to natural gas supply, the system is equipped with hydrogen and nitrogen supply lines. The gases are used in different mixtures for the reduction of the pre-
reformer catalyst as well as for protecting the catalyst and stacks from oxidation during idling, start-up and shut-down phases. Hydrogen and nitrogen are filtered before preparing the purge gas mixture (95-97% N₂, 3-5% H₂) using standard mass flow controllers. In emergency shutdown situations, readily mixed purge gas (97% Ar, 3% H₂) is provided at a predetermined flow rate set by a manually adjustable rotameter. All purge gas pressures are reduced onto a safe level using pressure regulators.

AUTOMATION AND CONTROL SYSTEM

The test system has been automated using a standard industrial PLC. The modular PLC consists of separate CPU and I/O modules. Automation and control system includes various voltage, temperature and pressure measurements, as well as flow indication and control of fuel, air, steam and purge gas streams. Fuel and air flows can be controlled according to process temperatures and stack voltages which vary according to electrical loading.

The system includes close to 90 temperature measurements and over 10 pressure measurements. In total, the system has 115 analogue and 11 binary inputs, as well as 7 analogue and 46 binary outputs. Data logging and man-machine interfacing is realised with a PC based operator station software. The software package consists of various different components including SQL and OPC servers. Connection between the PLC and the PC is established over TCP/IP connection via an OPC server.

In addition to normal system control which is done using the PLC, a back-up control system for emergency shut-down situations is provided. Back-up control will ensure safe operation of the system under all circumstances. A hardwired emergency shutdown sequence of the whole system is initiated in case a failure, which can damage the unit or cause danger to surroundings, is detected.

A great deal of attention has been paid to choosing the measurements and limits that trigger a system shut-down. Minimising the risk of unnecessary system trips is important from system reliability point of view. During the first continuous test run, the system was under autonomous operation for 1080 hours without experiencing any unnecessary trips.

Instrumentation

The amount of instrumentation is excessive due to the experimental nature of the apparatus. Identifying the critical measurements required in efficient and reliable system control is an important objective.

Due to high operating temperatures, most temperature measurements are carried out using K type thermocouples. Obtaining reliable temperature measurements as close to stack inlets and outlets as possible has presented some challenges.

Since pressure drops over the BoP components are small, attention has been paid to the accuracy of pressure sensors. This is an important factor from data collection point of view. Due to the significant amount of steam present in the anode side fuel flow, delicate pressure sensors had to be protected with hydroseals.
Concentration of combustible gases is monitored both in the furnace and the ambient air as a security precaution. Possible pipe breaks and other leakages can be quickly detected and automatic countermeasures taken.

Several voltage and current transducers are used in determining electrical characteristics of the stacks. Due to the rapidity of fuel cells' electro-chemical reactions, stack voltages are critical measurements from system control point of view.

**Actuators**

The system has been equipped with a significant number of shut-off valves and by-pass pipelines. In order to minimise pressure drops within the system, full-bore ball valves have been utilised. Valves can be used to isolate subsections of the system providing the possibility to operate different sections separately. This has been a highly beneficial feature during initial testing and commissioning. Since the price of high temperature ball valves is prohibitive considering future products, system simplification is a prime objective.

**POWER ELECTRONICS**

The low voltage generated by individual stacks is transformed up to a range of 595 - 650 Vdc using DC/DC converters. The high voltage DC current is transformed into a three phase 400 Vac current by a line inverter. After the inverter, voltage is connected to a standard 50 Hz grid through an LC filter and an isolating AC/AC transformer.

A standard UPS unit is used to ensure uninterrupted power supply for the control system and the operator station during a possible black-out of the grid. A schematic picture of the power electronics is shown in Figure 5.

![Figure 5. Power electronics system.](image-url)
The line inverter detects frequency and amplitude of the grid voltage with special algorithms. After a successful detection routine, the inverter synchronizes the output voltage to the detected grid voltage. Phase order doesn’t affect the success of grid synchronization. The line inverter is protected with several hardware and software implemented protection features, namely, over current protection, over- and under voltage protection, over- and under temperature protection, earth fault protection, short circuit protection and phase supervision protection.

The size of the power conversion unit is notable due to the presence of three DC/DC converters. The converters are required to boost the low voltage generated by individual stacks up to a range required by the line inverter. In addition to affecting the size of the power conversion unit, the DC/DC converters have a negative impact on the overall electrical efficiency of the system.

RESULTS

Some of the test results obtained during the first 1080 hours of operation are presented below.

Stack

The 75 cell, 1.2 kW stack running with pre-reformed natural gas has the voltage-current characteristics presented in Figure 6. Fuel composition, at the time the measurements were recorded, was the following: natural gas 470 Nl/h, Steam 0.85 kg/h, Nitrogen 470 Nl/h.

Figure 6. UI curve for 1.2 kW, 75 cell stack.

Fuel Reforming

The small amounts of sulphur compounds, which manage to pass through the sulphur removal unit, are caught by the pre-reforming catalyst. The catalyst is slowly deactivated
by the resulting catalyst poisoning. Progress of this poisoning is monitored by measuring the temperature profile of the pre-reformer catalyst bed. Temperature profile recorded after one month of operation is presented in Figure 7.

The catalyst is located between 80 and 160 cm. Natural gas is fed into the reactor from the top with a temperature of approximately 470°C. The endothermic reforming reactions take place at the top part of the catalyst bed where rapid cooling is witnessed. Gas temperature rises slowly after the reforming due to the current non-adiabatic control logic.

Catalyst poisoning causes the zone where rapid cooling is witnessed to gradually migrate towards the bottom section of the reactor. This change in temperature profile is caused by catalyst deactivation, progressing from reactor inlet towards reactor outlet. Catalyst poisoning was not observed, as the temperature profiles recorded during the first 1080 hours of operation were compared. The sulphur removal catalyst is, therefore, working well. Less than 0.1 ppm of sulphur is expected to reach the pre-reformer.

![Pre-reformer temperature profile after one month of continuous operation](image)

Comparison between calculated and experimental gas composition at the pre-reformer outlet is presented in Table I. The pre-reforming catalyst is performing as expected, converting the gas to equilibrium. Almost all the conversion takes place at the very top part of the pre-reformer as indicated by the measured temperature profile.
Table I. Calculated and experimental gas composition at the pre-reformer outlet.

| Dry Vol% | Experimental output | Calculated output |
|---------|---------------------|-------------------|
| Temperature | ~ 400 °C | 409 °C |
| H₂       | 25.7 %            | 27.65 %           |
| N₂       | 31.8 %            | 31.80 %           |
| CO       | 0.3 %             | 0.27 %            |
| CO₂      | 6.3 %             | 6.85 %            |
| CH₄      | 33.4 %            | 33.43 %           |

CONCLUSIONS

The system design phase has brought up a number of development areas. These will be concentrated on during the ongoing development program. Reducing the amount of instrumentation by identifying the critical measurements required in efficient and reliable system control is crucial. Since the price of high temperature valves and other actuators is significant, system simplification is also of great importance.

Power conversion system development requires further attention. Increasing the voltage level by electrically connecting several stacks in series will improve the overall efficiency of the system, as DC/DC converters can be omitted.

As a result of the project a working SOFC test system has been constructed. The system will provide an extensive platform for the development of SOFC system technology and related BoP components.

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