Practical experience with a fuel cell unit for Combined Heat and Power (CHP) generation on the building level

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Introduction

The previous REHVA Journal article "Micro-Combined Heat and Power (Micro-CHP) Appliances for one- or two-family houses for more energy efficiency" [1] described the common technologies "Stirling Engine"," Internal Combustion Engine" and "Fuel Cell" with the help of available CHP-units. With this article the authors would like to discuss their experience with a fuel cell-based micro-CHP Unit that is highly efficient in terms of electrical output. This experience was gained during research work at the laboratory of heating technology at Cologne University of Applied Sciences [2]. Some of the findings were already presented in 2012 ([3] and [4]).

Figure 1. The test arrangement of the BlueGEN natural gas fired fuel cell-based CHP unit manufactured by Ceramic Fuel Cells. Data sheet performance: 0.5–1.5 kW electrical output and 0.3–0.54 kW thermal output. The heating water buffer tank is oversized for test purposes. Laboratory of Heating Technology at Fachhochschule Koeln.

The Tested Fuel Cell Unit

Figure 1 shows the test arrangement of the investigated fuel cell unit. This unit is called BlueGEN and is manufactured by CFC Ltd. an Australian-German company. It simultaneously generates heat and power. On the electrical side it is connected, in parallel, to the public grid in order to export power or obtain power. On the fuel side it is connected to the public natural gas grid. A heating water circuit delivers the generated heat from this fuel cell unit directly to the connected 680 L heating water buffer tank displayed below. The thermal performance of this unit is being tested by buffer tank heat loading via the fuel cell unit and the heating water circuit. **Figure 2** shows the schematic depiction of how the test arrangement works.

Electrical Performance

Several fuel cell stacks have been tested. **Figure 3** shows the data for the tested fuel cell unit after a new fuel cell stack was installed after roughly 9 800 hours of operation. The electrical export of this fuel cell has been set at a constant value of 1 500 W from the beginning. With a fuel input of around 2.5 kW the power was generated with an electrical efficiency of around 60%, see also the calculation. Due to degradation of the fuel cell, the gas input has to be increased after approximately 2 000 hours in order to maintain 1 500 W of power export. After 6000 hours of fuel cell operation,

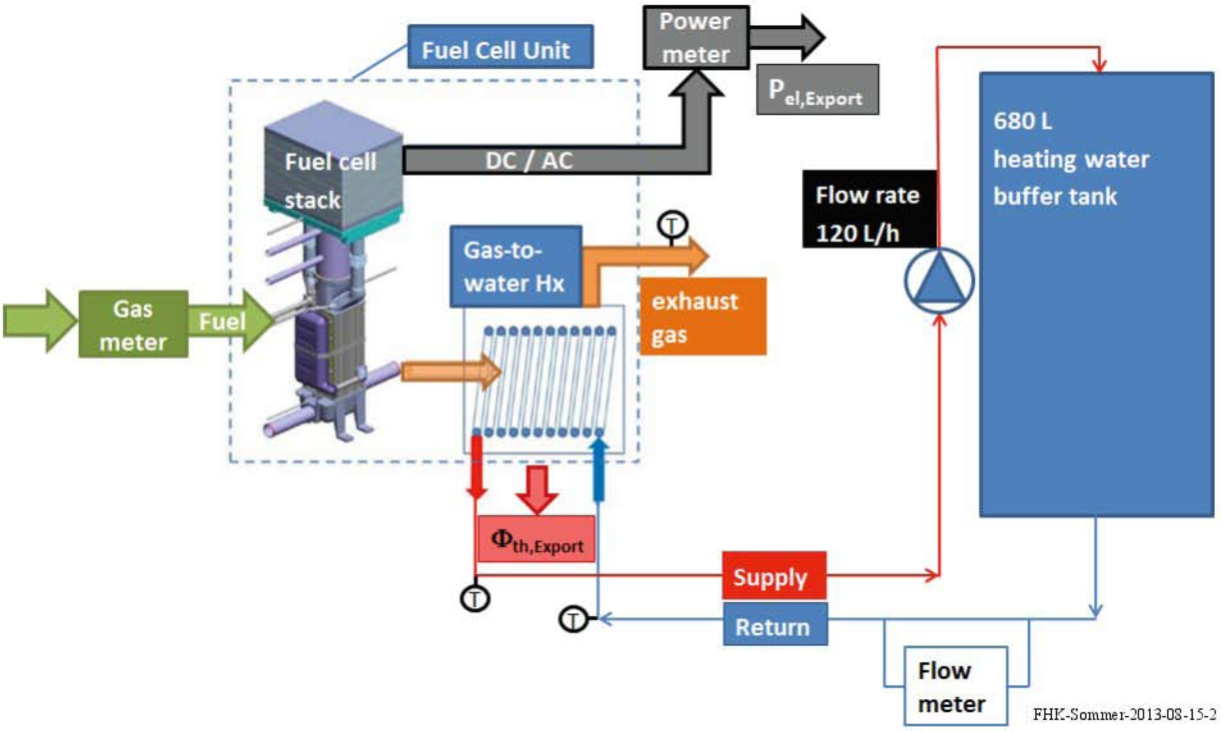

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Figure 2. Schematic depiction of the test arrangement presented in figure 1. The fuel cell unit began to be operated in the laboratory of heating technology on October 10, 2011, it had previously been in operation for 150 hours. In the meantime the unit has been tested for more than 16 000 hours of operation. A number of high temperature solid oxide fuel cell stacks have been installed for test purposes during this time. Additional details regarding this fuel cell unit can be found in [1].

2.67 kW of fuel input are required to achieve the same output and the electrical efficiency has decreased to a value of around 56%.

Calculation of the electrical efficiency η_{el} of the fuel cell unit:

$$\eta_{el} = \frac{P_{el,Export}}{\dot{V}_{Gas} \cdot LHV_{Gas}}$$

where

$P_{el,Export}$: Net power (AC) to grid

$\dot{V}_{Gas}$: Flow rate of fuel (standard conditions)

LHV_{Gas}: Lower heating value for this test arrangement ≈ 9.1 kWh/m³ (standard conditions)

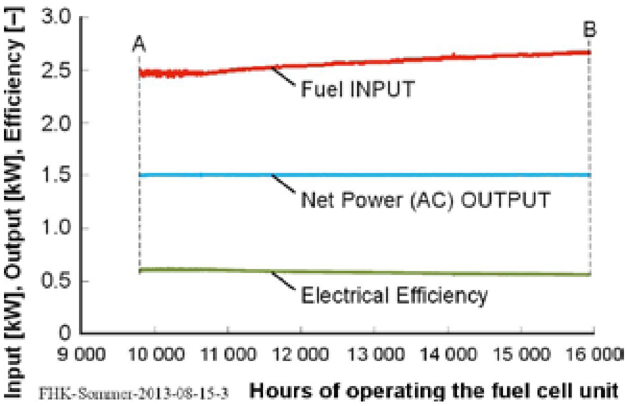

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Figure 3. Electrical performance of the fuel cell unit together with a newly installed stack that started working at "A" and was taken out of operation at "B".

The development of the stack's efficiency from the first hour of operation at "A" to "B" has been quantified as follows:

$$\eta_{el,A} = \frac{1.5\,\mathrm{kW}}{2.50\,\mathrm{kW}} = 0.6 \text{ or } 60\%$$

$$\eta_{el,B} = \frac{1.5\,\mathrm{kW}}{2.67\,\mathrm{kW}} = 0.56 \text{ or } 56\%$$

Figure 4 demonstrates another one of the fuel cell stacks that was installed and tested for over 3 000 hours from "A" to "B". Here the focus of the test was on the part load capability of the fuel cell stack for the following levels of exported power (AC): 0.1 kW; 0.3 kW; 0.5 kW; 0.7 kW; 0.9 kW; 1.0 kW; 1.1 kW and 1.3 kW.

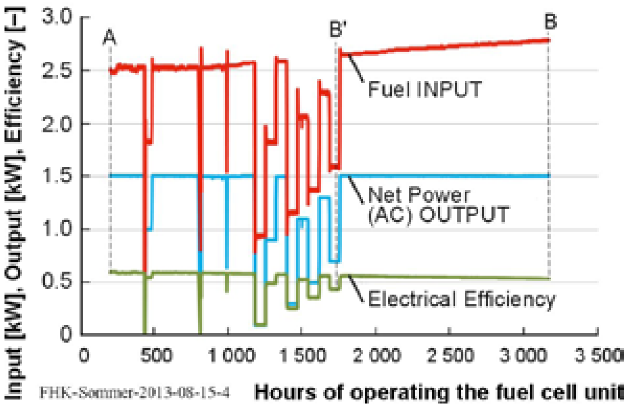

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Figure 4. Electrical performance of the fuel cell unit together with the first installed stack that started working at line A and was taken out of operation after line B. Note: Experimental data registered by the unit's power management system and provided by the manufacturer.

These tests were rather stressful for this newly installed fuel cell stack. Hence, after around 700 hours of operation, the new stack ("A" + 700 hours) already required increasing fuel input in order to maintain 1 500 W of power export. At "B" this fuel stack required 2.78 kW of natural gas for 1.5 kW of electrical output, which equates to an electrical efficiency of 54%. The decrease of the performance of this fuel cell was faster than that of the fuel cell in figure 3 because of degradation along with the various part load operation levels to which it was subjected.

Figure 5 displays the part load efficiency versus the net power (AC) export for the time range "A" to "B' " in **Figure 4**.

The higher the power export of the fuel cell unit, the higher the electrical efficiency of the fuel cell. The curve of **figure 5** is described by the following equation:

$$\eta_{el} =$$

$$0.1177 \cdot (P_{el,Export})^3 - 0.542 \cdot (P_{el,Export})^2 + 0.9257 \cdot (P_{el,Export}) + 0.0222$$

In order to achieve optimal electrical efficiency and to reduce stress on the fuel cell, the unit should always be operated at a constant level of 1.5 kW power (AC) export.

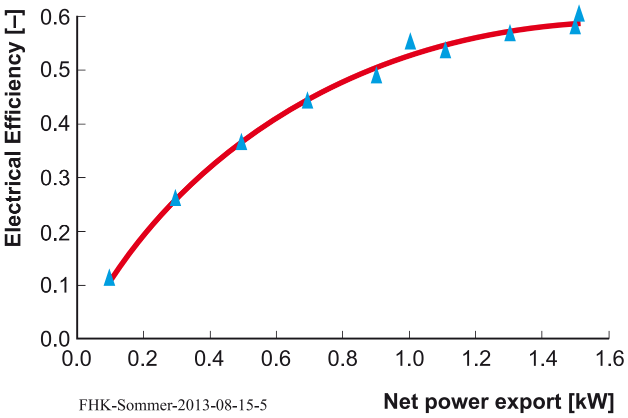

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Figure 5. Electrical efficiency of the fuel cell unit versus the net power (AC) exported to the grid for the range of A to B' in figure 4. Note: Experimental data generated by the unit's power management system and provided by the manufacturer.

Thermal Performance at 1500 W net power (AC) export

The thermal output of the fuel cell unit has been measured in a very practical way (thermocouples in thermowells in the heating water loop between the fuel cell and the heating water buffer tank, thermocouples directly in the exhaust gas and an electromagnetic flow meter to measure the heating water loop flow rate), see **figures 1 and 2**. The thermal loading process of the buffer tank is very slow because the water loop flow rate is only 120 litres per hour (manufacturer's recommendation) between the fuel cell unit and the 680 L buffer tank.

The thermal performance of the fuel cell has only been tested at 1 500 W power (AC) export because electrical efficiency for this fuel cell unit is highest under these conditions. **Figure 6** displays the exhaust gas, supply and return temperatures of the fuel cell unit versus time during the thermal loading of the buffer tank by the fuel cell unit (see also **Figure 2**). Starting the loading process with a return temperature of around 17°C from the buffer tank, the fuel cell unit requires around 2 800 minutes to heat up the supply heating water to around 47°C; by this time the return heating water reaches a temperature of around 44°C. No further increase in the temperatures will take place because, from this point on, the thermal output of the fuel cell unit only serves to compensate for the heat losses of the heating water loop and the heating water buffer tank.

The fuel cell unit generates temperature differences of 6 K at the beginning of the loading process, which gradually fall to 3 K at the end of the loading process. **Figure 7** demonstrates a very close relationship between the temperature of the return heating water and the temperature of the supply heating water when leaving the fuel cell unit.

In **Figure 8** the data from **Figure 6** have been used to calculate the heat export of the fuel cell versus the return heating water of the buffer tank. These results clearly illustrate that the lower the temperature of a heating water buffer tank, the higher the thermal benefit that results from the fuel cell unit.

The example illustrated in **Figure 8** indicates that in order to achieve 500 W of thermal output from the fuel cell unit, the returning heating water of the hydronic system should not exceed 40°C.

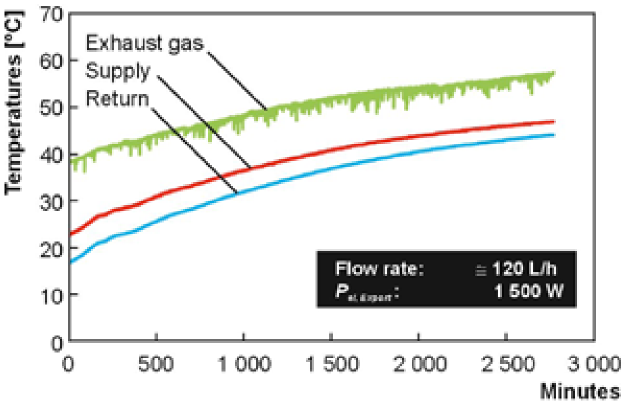

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Figure 6. Measurement of the thermal performance of the fuel cell unit by means of thermal loading of the 680 L heating water buffer tank (see also figure 2). Fuel INPUT = 2,6 kW for the fuel cell unit.

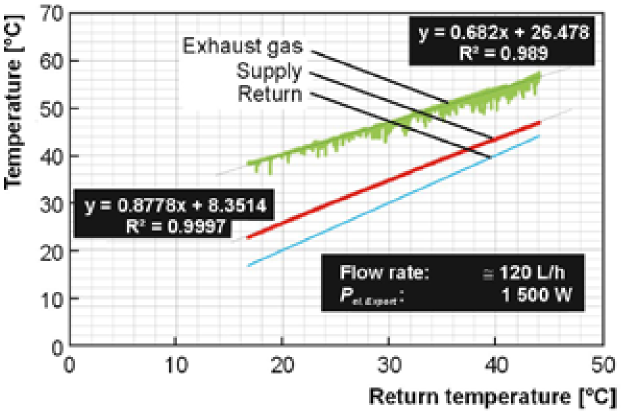

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Figure 7. Measured temperatures from figure 6 plotted here against the return temperatures.

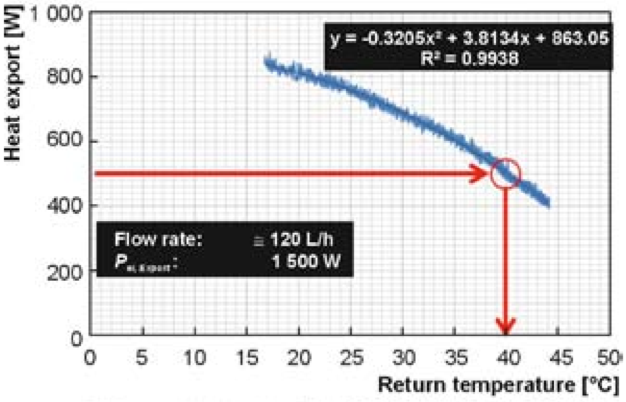

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Figure 8. Thermal export of the fuel cell unit versus the return temperature of the heating water from the heating water buffer tank. This result has been derived from the data in figure 6.

The thermal efficiency η_{th} can be calculated in a manner similar to the electrical efficiency mentioned above.

$$\eta_{th} = \frac{\Phi_{th,\,Export}}{\dot{V}_{Gas} \cdot LHV_{Gas}}$$

where

$\Phi_{th,\,Export}$: Thermal output to the system

$\dot{V}_{Gas}$: Flow rate of fuel (standard conditions)

LHV_{Gas}: Lower heating value of this test arrangement ≈ 9.1 kWh/m³ (standard conditions)

For the example presented in **Figure 8** this means:

$$\eta_{th} = \frac{0.5\,\text{kW}}{2.6\,\text{kW}} = 0.19 \;\; or \;\; 19\%$$

Or for the total energy efficiency of this example:

$$\eta_{tot} = \eta_{el} + \eta_{th} = \frac{1.5\,\text{kW}}{2.6\,\text{kW}} + \frac{0.5\,\text{kW}}{2.6\,\text{kW}}$$

$$= 0.58 + 0.19 = 0.77 \;\; or \;\; 77\%.$$

Figure 9 shows η_{tot}, η_{el} and η_{th} for the whole range of data from **Figure 8** versus the returning heating water of the hydronic system (buffer tank). The electrical efficiency is not influenced by the return temperature but the lower the returning heating water, the higher the total efficiency.

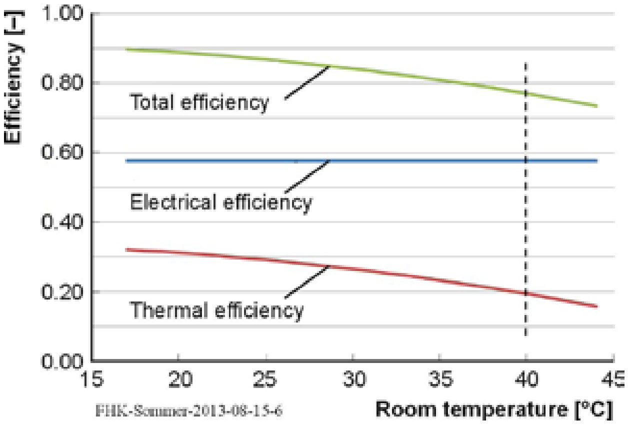

Figure 9. Electrical, thermal and total efficiency of the tested fuel cell unit derived from the data in Figure 8.

Lessons learned

The BlueGEN fuel cell CHP unit manufactured by Ceramic Fuel Cell Ltd. that was tested achieved an electrical efficiency of around 60% when it is new and when exporting 1 500 W net power (AC). This represents its peak efficiency and is outstanding. Degradation reduces the electrical efficiency during the time of operation. When the unit is constantly operated at peak efficiency, degradation reduces the electrical efficiency from 60% to 56% after 6 000 hours of operation. Electrical part load operation leads to additional reductions in electrical efficiency by subjecting the fuel cell stack to stress, thus further accelerating the loss of electrical efficiency over the long term.

The thermal output of the fuel cell depends on the return temperature of the heating water from the connected hydronic system (heating water buffer tank). The lower this return temperature, the higher the thermal efficiency of this fuel cell. Operation at peak electrical efficiency and return heating water temperatures of 35°C from the connected hydronic system lead to a total efficiency of around 81% (LHV). Under these conditions, the net power (AC) export of the fuel cell is 36 kWh per day, or 13 140 kWh per year, with a simultaneous thermal output of 14.5 kWh per day, or 5 290 kWh per year, when providing supply heating water temperature of 39°C. ■

References

[1] Sommer, Klaus: Micro-Combined Heat and Power (Micro-CHP) Appliances for one- or two-family houses for more energy efficiency. REHVA Journal, December 2011.

[2] Two-year research project (2011-2013) "Analysing of the real operating characteristics of a high-efficient fuel cell based micro-CHP unit in order to find out the best possible application for residential buildings and to get real system characteristics"; project leader Prof. Dr. Klaus Sommer. Funded by KlimaKreis Koeln (www.klimakreis-koeln.de), Rheinenergie AG (www.rheinenergie.com) and Fachhochschule Koeln/Cologne University of Applied Sciences (www.fh-koeln.de).

[3] Sommer, Klaus: Describing the Real Energy Efficiency of a Fuel Cell-Based Micro-CHP Unit in Residential Buildings. Presentation on ASHRAE Winter Conference in Chicago, January 22, 2012.

[4] Sommer, Klaus: Thermal Performance of a Fuel Cell-Based Micro-CHP Unit for Residential Buildings. Presentation on IEA/ECBCS Annex 54, 6th Experts Meeting, Tokyo University, Japan, October 9-12, 2012.