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Biogas in PEM Fuel Cells

Using biogas in fuel cells advantageously combines a cost effective renewable energy source with a technology, which promises high efficiency and low environmental impact. Within the framework of a research project, the suitability of proton exchange membrane fuel cell systems (PEMFC) for generating electricity from biogas has been experimentally confirmed for the first time. Measurements taken from a 650 W_{el} test stand show a cell efficiency of 58% in operation, with a low power density of 0.14 W/cm^2. A particularly problematic component is the steam reformer with a thermal efficiency of about 38%. A model calculation based on an optimised PEM fuel cell system shows that an electrical system efficiency of over 40% can be obtained.

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Keywords

Fuel cell, PEM, biogas, steam reformer

Literature

Literature references can be called up under LT 05104 via internet http://www.landwirtschaftsverlag.com/landtech/local/literatur.htm.

The development of fuel cell technology offers a promising alternative to the conventional use of gaseous hydrocarbons in combined heat and power plants (CHP). Fuel cells produce less noise and pollutant emissions while achieving higher electrical efficiency, particularly in partial load operation. The fuel predominantly used in stationary application is natural gas. Biogas is particularly suitable for use with fuel cells as it's properties are similar to natural gas and it is by far the most cost effective renewable fuel. However, biogas has a lower power density, a noticeably higher carbon dioxide content and contains various other harmful components such as sulphur compounds and ammonia [1].

Of the six different types of fuel cell in total, the molten carbonate fuel cell (MCFC), the solid oxide fuel cell (SOFC), the phosphoric acid fuel cell (PAFC) and the proton exchange membrane fuel cell (PEMFC) come into consideration for use with biogas [2, 3]. The PAFC is already commercially available and is used in several 200 kW_{el} pilot plants for the generation of electricity from sewage gas, whereby its economic prospects are assessed unfavourably [4, 5, 6]. In the last three years, the suitability of the MCFC and the SOFC for biogas and sewage gas have been experimentally proven with more or less success [7, 8]. Despite intense efforts this has yet to be verified for the PEMFC.

Materials and methods

The fuel cell test stand is supplied with biogas from two solid state fermenters operating with manure and forage maize silage. The methane content is varied by adding manufactured gases (CH_4, CO_2). The test plant consists of the reformer unit with internal desulphurisation and the fuel cell unit with integrated electronic load. The latter has two independent fuel cell stacks. The test stack with four cells (150 W_{el}) is intended to examine the effect of harmful gases and the operating stack with 14 cells (650 W_{el}) serves to examine the performance and characteristic values. The fuel processor, which has been developed in the USA, consists of a steam reformer, a two stage water-gas shift and a selective oxidation reactor. The apparatus includes gas compression, desulphurisation and steam generation and has internal heat recovery (*Fig. 1*). Gas measurement technology consists of a process gas analyser and a drum gas meter. Process gases are taken from three sample ports to analyse and

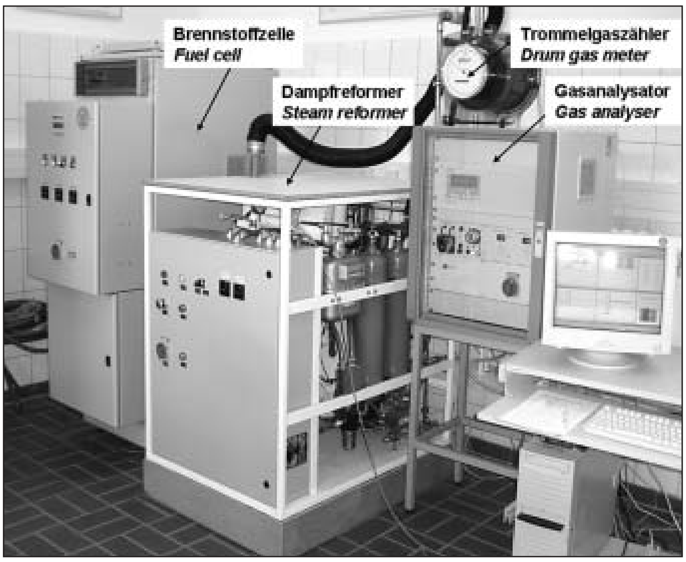

Fig. 1: Fuel cell test stand of the ATB

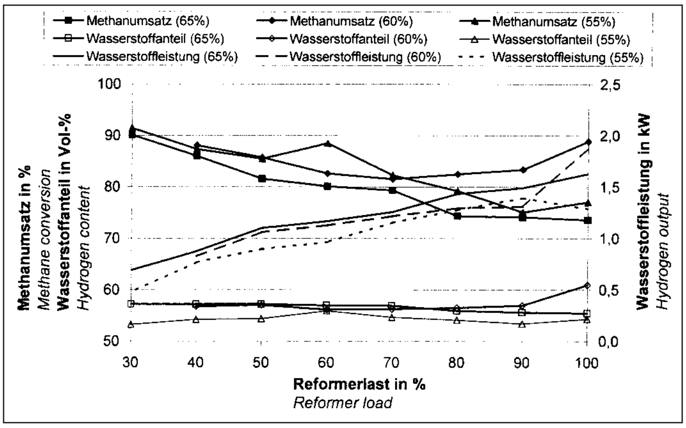

Fig. 2: Conversion methane in the reformer and hydrogen content and capacity versus load and methane content of biogas

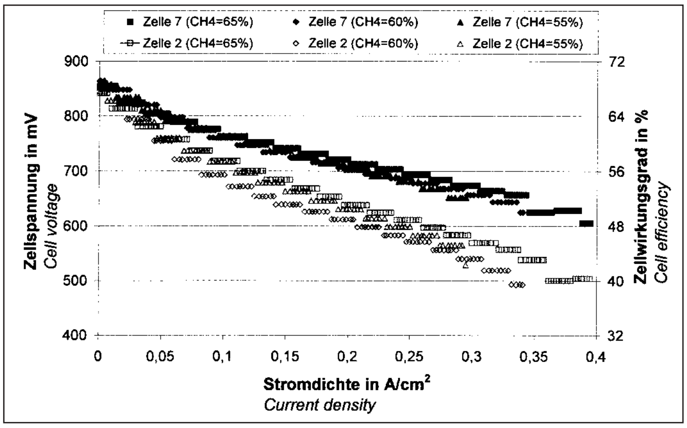

Fig. 3: Characteristic curves of current density and voltage of selected single cells

record the composition of biogas, reformate and anode off-gas (CH_4, CO_2, CO). The concentrations of oxygen (O_2) and the hydrogen sulphide load (H_2S) are controlled by a standard landfill gas monitor.

Reformer performance

In contrast to the high temperature fuel cells (MCFC and SOFC), the PEMFC requires a fuel that is largely free of carbon monoxide. To reduce the content of carbon monoxide formed during reformation to below 10 ppm, the reformed gas is purified by selective oxidation (adding atmospheric oxygen). Reformate entirely free of carbon monoxide is obtained by adding a volumetric air flow rate of more than 5% of the reformate flow rate. Stochastic CO maximum values of >250 ppm occur when less than 2.5% air is added. The reason for this is not known [9].

The intended aim of the reformation is to produce hydrogen. A high hydrogen output requires a high methane conversion rate. Measurement results show a clear decrease in the methane rate with increasing reformer load, which is a sign of insufficient catalyst activity. Depending on the percentage of methane in the biogas, the conversion rate of more than 90% at partial load decreases to less than 80% at full load. This is assumed to be due to the relatively low reformation temperature of 700 to 740 °C (*Fig. 2*). The hydrogen output and the hydrogen content of the reformate are to a small extent determined by the methane content of the biogas. An increase of the CH_4 content in the biogas from 55% to 65% causes an increase in H_2 content in the reformate of 53% to 56%.

Polarisation curve

The operating performance of fuel cells is characterised by polarisation curves. Increasing current density lowers the voltage and hence decreases cell efficiency. This behaviour leads to difficulties in determining the rated power, since there is a conflict between high output and high efficiency. The characteristic curves of the entire operating stack for different compositions of raw gas (55% to 65% CH_4 content) show currents barely deviating from each other at current densities of up to 0.25 A/cm^2. In contrast, the polarisation curves of different single cells clearly diverge. A comparison of the curves for the most efficient cell 7 and the weakest cell 2 shows a difference in voltage, which rises with increasing electrical output, being more than 100 mV at a current density of 0.35 A/cm^2. This corresponds to a difference in cell efficiency of more than 8% (*Fig. 3*).

Efficiency

A power balance is established for different operating points to assess the performance of the test plant. The measurements show an electrical gross system efficiency η_{Sys} of 12% at a current density of 0.29 A/cm^2 and a fuel utilisation μ_f of 70%. At partial load the efficiency is $\eta_{Sys} = 11\%$ at $\mu_f = 62\%$.

The reason for the unsatisfactory system efficiency η_{Sys} is to be found in the inefficient reformer which has a thermal efficiency of less than 38% and in the process design, as a large part of the chemically bound energy leaves the system unused as anode off-gas. The amount of auxiliary electrical energy is estimated at 3% to 5% of the output [10, 11].

The attainable gross system efficiency η_{Sys} for the generation of electricity from biogas with PEM-fuel cells is estimated based on the experimental results and reliable published data [9]. A particular process design, such as the one developed and tested at the Bergakademie TU Freiberg, uses the anode off-gas to supply thermal energy to the reformer [12, 13]. The calculation assumes an optimised system (fuel utilisation: 71% or 83%; reformer efficiency: 68% according to manufacturers data for the laboratory reformer used or 80% according to literature data; methane conversion rate: 97%; inverter efficiency: 95%). In the results, a system efficiency of 39% to 42% is calculated for the most favourable operating parameters. However, this does not take into consideration fundamental improvements expected in the development of the still young fuel cell technology mainly in the field of membrane development.

Conclusions

The suitability of PEMFC technology for generating electricity from biogas has been proven. As measurements on an unoptimised 650 W_{el} test plant show, cell efficiencies of up to 58% are obtained at a current density of 0,2 A/cm^2. However, this value is only achieved by individual cells. Reasons for this are assumed to be due to irregular gas flow and humidification of the cells.

The steam reformer proves to be a particularly problematic component with a thermal efficiency of approximately 38% and a methane conversion rate of 75% to 90%. A calculation on the basis of the strongest individual cell results in an electrical gross system efficiency of more than 40% at a power density of 0,14 W/cm^2 in an optimised system using the anode off-gas to supply thermal energy to the reformer. However, considerable efforts in research and development are needed to attain this degree of efficiency.