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PAFC demonstration plants in Europe: first results

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Abstract

In the past two years, over 100 fuel cell plants have gone into service worldwide, over 90% using PAFCs. So far, PAFCs have been the only technically mature and turnkey design available on the market. This paper gives an overview of the status of PAFC plants installed in Europe. Emphasis is laid on the experience gained from the operation of the 200-kW plant of Ruhrgas AG. The plant was commissioned in September 1992 at the Ruhrgas R and D facility and is presently being subjected to extensive testing. Ruhrgas not only measures the electrical output and corresponding efficiencies, but also simulates different user requirements. It further examines the effect of different gas properties on plant performance. The plant is operated on group L ($\sim$9.2 kWh/m^3) gas, group H ($\sim$10.8 kWh/m^3) gas and peak shaving gas. With this approach, overall efficiency and environmental compatibility of the fuel cell plant are thoroughly investigated and potential areas of improvement can be found.

Introduction

With the detrimental effects of anthropogenic emissions on the environment and the associated risk of climate changes, CHP (combined heat and power) generation has gained more and more importance over the past ten years.

In Germany, more than 1400 gas-engine and more than 100 gas-turbine packaged CHP systems are already in operation. The total power installed is 600 MW for engine-driven plants and approximately 1500 MW for turbine-driven plants [1, 2]. The trend towards CHP systems reflecting a growing interest in energy efficiency and low emissions will continue to rise not only in Germany but throughout Europe.

Over the last few years, R&D in the field of CHP systems not only concentrated on conventional gas engines and gas turbines but also on fuel cell technology with a substantial financial input.

The electrical efficiencies of fuel cells are considerably higher than the efficiencies of conventional energy generation systems. Fuel cells can meet the requirements of the entire CHP sector up to the MW range. An important advantage is the high electrical efficiency obtained for part-load operation. With combustion being replaced by electrochemical reactions, the extremely low emission of pollutants is another essential factor speaking in favour of fuel cell technology. Figure 1 shows a comparison of the efficiencies of different energy conversion technologies as a function of system's size.

In the past two years, over 100 fuel cell plants have gone into service worldwide, over 90% using PAFCs (phosphoric acid fuel cells). So far, PAFCs have been the

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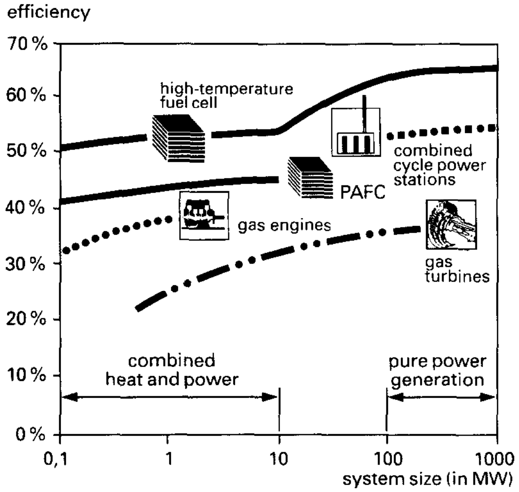

Fig. 1. Comparison of efficiencies of different energy conversion technologies as a function of system's output.

only technically mature and turnkey design available on the market. Presently, there are only two companies marketing PAFCs: Fuji Electric, Japan, which offered a 50-kW plant until recently, and ONSI, USA, with a small-scale production of a 200-kW plant. These two companies have already supplied 13 plants for trial operation to major European energy suppliers (Table 1) committed to supporting the introduction of this new CHP technology into the commercial market.

There are two further PAFC demonstration plants: an 80-kW plant of Solar–Wasserstoff–Bayern GmbH, based on Fuji/Kinetics Technology International/Linde technology, operating in Bavaria, Germany, and a 1100-kW plant in Milan, Italy, based on International Fuel Cells/Ansaldo/Haldor Topsøe technology, which is to be installed and scheduled to be commissioned by Aem, the Milan utility.

This paper gives an overview of the status of PAFC plants installed in Europe. Emphasis is laid on experience gained from the operation of the 200-kW plant of Ruhrgas AG, Germany.

PAFC project status in Europe

The following description gives the status of the PAFC demonstration projects in Europe as from July 1993. Unfortunately, it has not been possible to obtain the full data from all operators, so that the following tables are partly incomplete.

50-kW PAFC plant of Fuji Electric (FP 50)

Of the extensive PAFC development programme of Fuji Electric, the FP 50 is the smallest cell available as a compact unit. The FP 50 was designed for use in CHP systems. The development of the FP 50 was initiated by Tokyo Gas Company which also lent its active support to the project [3]. Of the more than 40 plants delivered by early 1993, four were installed in Europe. The FP 50 design data are listed in Table 2.

TABLE 1

PAFC demonstration plants in Europe

Operator	Country	Manufacturer	Capacity (kW)	Cooperating partners
Sydkraft	Sweden	Fuji	50	
Sydkraft	Sweden	ONSI	200	NUTEK
Vattenfall	Sweden	Fuji	50	
Ruhrgas	Germany	ONSI	200	Gasunie, Netherlands
HEAG	Germany	ONSI	200	State of Hesse, Germany
Thyssengas	Germany	ONSI	200	Gasunie, Netherlands
Naturgas Syd/SH	Denmark	ONSI	200	
Imatra Voima Oy	Finland	ONSI	200	EA Technology, UK
Austria Ferngas	Austria	ONSI	200	
Enagas	Spain	Fuji	50	
SNAM/Eniricerche	Italy	Fuji	50	
Services Industriels de Genève (SIG)	Switzerland	ONSI	200	
Acoser/Bologna	Italy	ONSI	200	
Solar–Wasserstoff–Bayern	Germany	Fuji/KTI/Linde	80	Bayernwerk, BMW, Siemens, Linde, DASA
Aem/Milan	Italy	IFC/Ansaldo/Haldor Topsøe	200	

TABLE 2

Design data of the 50-kW Fuji PAFC (FP 50) plant

Item	Specification
Power capacity (kW)	50
Thermal capacity (kW)	50
Power range (kW)	0–50
Electrical efficiency (%)	up to 40 (LHV)
Overall efficiency (%)	up to 80 (LHV)
Operation	atmospheric pressure water cooled fully automatic natural gas/peak shave gas grid connected/grid independent indoor/outdoor
Size (l×w×h)	2.9 m×1.6 m×2.2 m
Weight (t)	5

The FP 50 is suitable for indoor and outdoor installation. An important feature is the very compact design (cf., dimensions given in Table 2). The power density of 4.9 kW/m^3 is very high compared with other PAFC plants in operation. The plant includes all electrical and process components required for converting natural gas to power and heat. The compact design, however, has one major drawback: maintenance work, more frequently required during demonstration phases, is made difficult due to the restricted access. Figure 2 shows the FP 50 installation at the headquarter of Enagas in Madrid, Spain.

The operating data of the four FP 50 plants installed in Europe are summarized in Table 3. The FP 50 plants were commissioned in the period from November 1991 to May 1993.

Most of the problems occurred due to software problems in the plant controller [4]. Frequent startups and shutdowns (thermal cycling), of course, had also detrimental effects on the performance of the cell stack (decay of stack voltage) explaining the relatively low efficiencies listed in Table 3. Desulfurization of the natural gas, that is normally odorized in Europe with tetrahydrothiophene, turned out to be another problem.

The results obtained from the trial operation of the plants in Europe, however, are not typical of the FP 50. Several plants installed in Japan have since completed more than 10 000 operating hours.

Fuji has already given feedback to the results of European operators. The plants in Europe were retrofitted with modified components and improved software. An increased availability of the FP 50 plant can therefore be expected for the future.

200-kW PAFC plant of ONSI (PC 25)

The PC 25 of ONSI, a subsidiary of IFC International Fuel Cells, is a recent development of the 40-kW PAFC plant (PC 18). In the mid-80s the PC 18 was subjected to extensive field testing largely demonstrating its technical maturity [5].

Like Fuji FP 50, PC 25 is used in CHP systems. The first plants were delivered in 1992. So far, 56 plants have been ordered worldwide, and will be commissioned by mid 1994. According to ONSI, further orders are expected for some 40 plants. In

Fig. 2. Installation of the Fuji FP 50 plant at Enagas, Spain.

Europe, nine PC 25 plants are currently in operation (cf., Table 1). Table 4 shows the most important technical data of the PC 25 plant.

Like Fuji FP 50, ONSI PAFC includes all components required for operation. Only gas and power and the piping of the heat output to the user must be connected. The power density of 2.5 kW/m^3 is almost half the power density of the Fuji plant. Maintenance is also quite difficult due to restricted access to several components. Figure 3 shows the ONSI PC 25 plant installed at Ruhrgas AG.

If the heat output is not fully utilized, ONSI provides a cooling unit that is connected in parallel to the heat-consuming unit of the customer, and automatically transfers excess heat to the environment. The 5 m × 2 m × 2.5 m cooling unit weights 3.2 tons.

Table 5 lists the first results of the plants operating in Europe. The plants were commissioned in the period from June 1992 to June 1993. Shutdowns were mainly due to the failure of conventional components such as pumps and valves. Moreover, excess heat from the boost regulator and the inverter was a problem that was solved

TABLE 3

50-kW Fuji PAFC (FP 50) plant in Europe: first results (July 15, 1993)

User	I	II	III	IV
First operation date (dd-mm-yy)	01-11-91	19-05-93 (after retrofit work)	02-02-93	12-05-93 (after retrofit work)
Indoor/outdoor	Indoor	Indoor	Indoor	Outdoor
Fuel (natural gas/LPG)	NG	NG	NG	NG/LPG
Calendar time since first startup (h)	13752	1368	3168	1536
Operating hours (h)				
load time	2825	1238	1189	562
hot time	3210	1350		618
Longest continuous operating hours (h)	502	1150	701	348
Cumulative electricity produced (kWh net)	127127	36360	57300	23320
Net electrical efficiency (%) (at 50 kW)	34.3 (at 40 kW)	28.0 (at 40 kW)	36.0	36.5

TABLE 4

Design data of the 200-kW ONSI PAFC (PC 25) plant

Item	Specification
Power capacity (kW)	200
Thermal capacity (kW)	220
Power range (kW)	0–200
Electrical efficiency (%)	up to 40 (LHV)
Overall efficiency (%)	up to 85 (LHV)
Operation	atmospheric pressure water cooled fully automatic natural gas/peak shave gas grid connected/grid independent indoor/outdoor
Size (l×w×h)	7.5 m×3.0 m×3.5 m
Weight (t)	28

by retrofitting all plants with improved heat pipes. Plant operation was somewhat restricted due to gases with a low calorific value sometimes used in parts of Europe (group L gas: LHV ~9.2 kWh/m^3). Corrosive deposits were found in the cooling system which could negatively affect heat extraction from the cell stack. As remedial actions, the control software will be improved and the cooling system modified.

Fig. 3. Installation of the ONSI PC 25 plant at the R&D Facility of Ruhrgas AG, Germany.

80-kW PAFC plant of Solar–Wasserstoff–Bayern GmbH

In late 1986, Bayernwerk AG (60%), BMW INTEC, DASA, Linde AG and Siemens AG (10% each) founded the Solar-Wasserstoff-Bayern GmbH (SWB). SWB operates a demonstration plant in Bavaria, Germany, to test solar–hydrogen techniques [6].

The SWB demonstration project also included an 80-kW PAFC plant with natural gas reforming, CO conversion and pressure-swing adsorption (PSA).

The fuel stack was delivered by Fuji Electric, Japan. The balance of plant was provided by Kinetics Technology International BV (KTI), The Netherlands. The PSA was supplied by Linde AG, Germany and serves to produce pure hydrogen (at least 99.9% by volume), together with the reformer and CO converter. This plant concept simulates the operation on a solar–hydrogen basis possible in a future solar–hydrogen energy economy. For hydrogen, higher net efficiencies are obtained than for natural gas, because no reformer is required.

The PAFC of SWB is also designed for the simultaneous generation of power and heat. The most important technical data are summarized in Table 6 [7, 8].

TABLE 5

200-kW ONSI PAFC (PC 25) plant in Europe: first results (July 15, 1993)

User	I	II	III	IV	V	VI	VII	VIII	IX
First operation date (dd-mm-yy)	10-06-92	30-09-92	15-10-92	27-11-92	14-12-92	26-01-93	Feb. 93	05-04-93	30-06-93
Indoor/outdoor	Outdoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Outdoor	Outdoor	Outdoor
Fuel (natural gas/LPG)	NG	NG/LPG	NG	NG	NG	NG	NG	NG	NG
Calendar time since first startup (h)	9240	6912	6552	5520	5088	4057	n/a	2520	1250
(Reference date)	(01-07-93)							(20-07-93)	(24-08-93)
Operating hours (h)									
load time	6932	4667	5532	4464	4252	4026	2935	2473	1250
hot time	7040	4697	5634	4579	4302	4057	3012	2509	1250
Longest continuous operating hours (h)	1830	1320	2311	1730	1657	2103	n/a	864	1250
Cumulative electricity produced (kWh net)	1354000	792466	969840	843767	847900	798740	540000	478000	251000
Net electrical efficiency (%) (at 200 kW)	38.7	37.5	38.7 (at 140 kW)	40.0	39.0	40.0	40.0	40.0	n/a

TABLE 6

Design data of the 80-kW SWB PAFC plant

Item	Specification
Power capacity (kW)	71.1/79.3 (d.c.)[a]
Thermal capacity (kW)	30[a]/60[b]
Power range (%)	25–100
Electrical efficiency (%) (without inverter)	up to 48 (LHV)[b]
Overall efficiency (%) (incl. inverter, inverter efficiency ~94%)	up to 87 (LHV)[b]
Operation	pressurized water cooled fully automatic natural gas/hydrogen

[a] Operating on natural gas/air anode/cathode.
[b] Operating on H_2/air + 50 vol.% O_2, anode/cathode.

The cell stack was performance tested in Japan in November 1990. The tests confirmed the design data specified by the manufacturer; in some cases, recorded figures were even better. Trial operation, warranty testing and acceptance of the overall plant by SWB were delayed by two years and only took place in the spring of 1993 due to major problems during interfacing of the individual components of the plant. Due to the extended shutdown period the cell stack degraded by some 10%. Commissioning of the demonstration plant is scheduled for autumn 1993.

1300-kW PAFC plant of the city of Milan

To demonstrate the potential of the PAFC technology for an efficient and clean energy generation also in the range of several MW, Ansaldo Ricerche, ENEA (Italian organization for new technologies, energy and the environment) and Aem (Milan utility) launched a joint 1300-kW PAFC project.

Ansaldo started project planning in 1988. The construction of the buildings was commenced in June 1990. In the spring of 1991, the individual components of the plant were assembled. Ansaldo was responsible for the overall concept and the balance-of-plant. The fuel cell stacks were delivered by IFC and the gas treatment plant by Haldor Topsøe [9].

Due to numerous problems, including administrative problems, acceptance testing of the individual technical systems was delayed until 1993 [10]. Commissioning is scheduled for late 1993.

First test results of the Ruhrgas PAFC plant

To support the commercial introduction of the fuel cell technology, Ruhrgas — like other major European energy producers and suppliers — have purchased a 200-kW PAFC plant from ONSI. The plant was commissioned at the Ruhrgas R&D facility, Dorsten, in September 1992, and will be subjected to extensive testing over a period of about 18 months.

The crucial subject of authority's approval and the test programme with the first results are given below. The following briefly raises some questions regarding approval by the authorities and procedures required for obtaining the official permission for plant operation.

Plant approval

Since the PC 25 plant had been designed to meet US codes and standards, the approval of individual plant components had first to be obtained from the German authorities before the plant could be put into operation.

The Material Test Report (MTR) and the Manufacturer's Data Report (MDR), which are the US standards applicable to the materials used and to the plant manufacture, are largely compatible with the German standards.

Safety testing and safety valve pressure testing carried out during installation at the Dorsten facility did not reveal any weak points and the plant was successfully commissioned in September 1992.

Test programme

The fuel cell plant is currently being trial operated at the Ruhrgas R&D facility at Dorsten for a period of approximately 18 months. The plant is then scheduled to be field tested by a public utility.

Ruhrgas AG and Thyssengas GmbH, Germany, which is also operating a PC 25 plant, have concluded an agreement to coordinate test projects and programmes. Moreover, both companies have agreed to cooperate with the NV Nederlandse Gasunie, Groningen.

Testing at Ruhrgas AG focuses on the effects of different gas properties. In particular, the following gases are to be examined for their influence on the functioning of the PC 25 plant.

(i) group L gas; LHV $\sim$9.2 kWh/m^3, not odorized;
(ii) group H gas; LHV $\sim$10.8 kWh/m^3, not odorized;
(iii) LPG/air admixture; different admixture rates, and
(iv) CO_2 admixture.

Thyssengas GmbH [11] tested the influence of the sulfur-containing odorant THT.

The heat produced during the electrochemical power generating process is recovered and channelled to the user by a heat exchanger. The useful supply temperature is maximum 90 °C. Since the heat generated by the PC 25 is a function of the electrical power produced, Ruhrgas AG is examining the useful heat available at different load conditions.

To this end, the heat generated is fed to a cooling system making supply and return temperatures and flow rates adjustable over a wide range. With this test setup, varying user requirements can be simulated to determine the thermal outputs and efficiencies that can be obtained for changing temperature differentials and electrical capacities.

On the basis of these data, characteristic curves can be developed to adjust automatically the electrical output versus the thermal output. The operation of the fuel cell plant is then practically heat controlled.

The plant is grid connected. Normally, the power generated is used at the Ruhrgas facility. In the case of low load, the Ruhrgas plant exports a portion of the power to the utility grid.

Test results

The PC 25 fuel cell plant of Ruhrgas AG was commissioned on September 30, 1992. By April 30, 1993, operating hours were at 4600, i.e., plant availability was more than 90%. From late April to mid-July 1993 the plant was shut down due to a defect in the cooling system. The plant was again started on July 23, 1993, after repair work had been carried out under the supervision of an ONSI engineer.

In the following, the first results from plant operation on gas with low calorific values (group L gas) will be described.

Electrical output

To demonstrate the good part-load behaviour of fuel cell plants, the electrical and thermal efficiencies, useful heat and the emission behaviour as a function of the electrical output were examined.

Figure 4 shows the electrical efficiency as a function of the electrical output of the group L gas. This Figure makes it clear that the electrical efficiency virtually remains constant over a wide range of electrical outputs. Below $P_{el} = 100$ kW, i.e., at 50% full load, internal power consumption is relatively high, thus reducing net efficiencies.

Thermal output

Figures 5 and 6 show the results of the Ruhrgas simulations of different user requirements for two electrical outputs ($P_{el} = 200$ kW and 100 kW). The data only reflect the useful heat made available to the user and not the additional heat discharged to the atmosphere by the ONSI cooling system.

The Figs. clearly show how thermal output is affected by the interdependence of thermal output on the one hand and return temperature and flow rate on the other. When comparing the two Figs., the influence of the electrical output on useful heat becomes more obvious. At $P_{el} = 200$ kW and a supply-to-return temperature ratio of 60 to 40 °C, Fig. 5 shows a thermal output of $P_{th} = 235$ kW which corresponds to a thermal efficiency of ~45%. For the same temperature ratio and $P_{el} = 100$ kW, Fig. 6 shows a thermal output of $P_{th} = 90$ kW which corresponds to a thermal efficiency of about 36%.

Emissions

With electrochemical reactions replacing combustion, only extremely low emission of pollutants occurs during fuel cell operation. In particular NO_x emissions are greatly

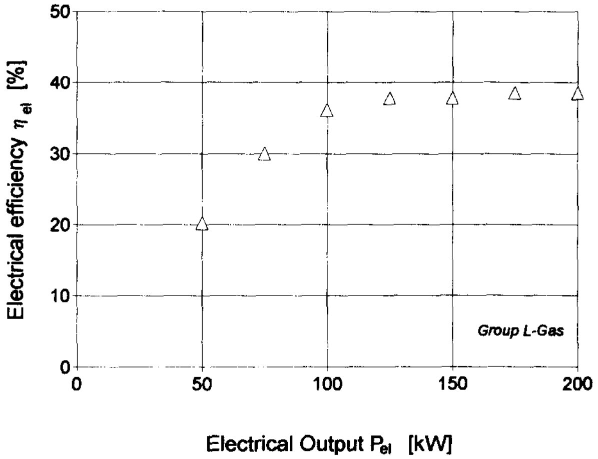

Fig. 4. Electrical efficiency as a function of electrical output.

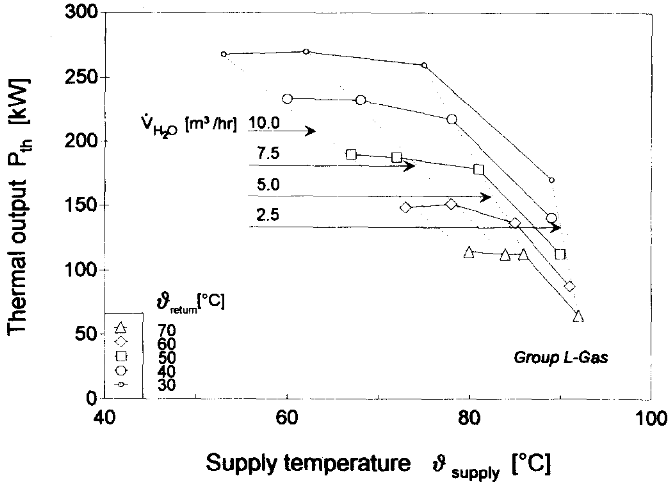

Fig. 5. Thermal output as a function of supply temperature at $P_{el}=200$ kW.

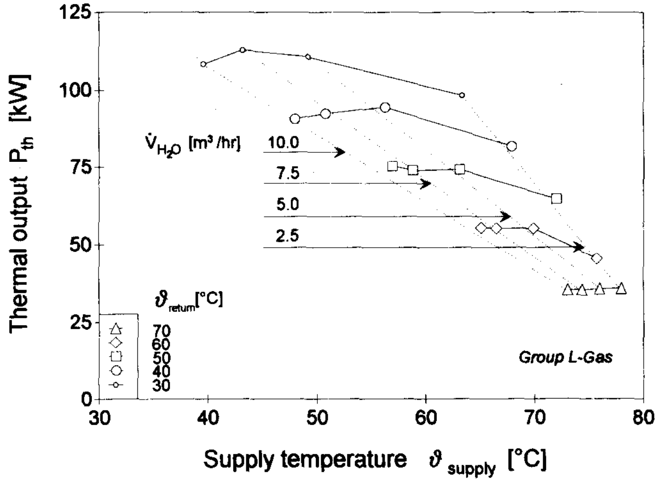

Fig. 6. Thermal output as a function of supply temperature at $P_{el}=100$ kW.

reduced due to low process temperatures; they are exclusively attributable to the NO_x produced by the reformer. Moreover, with the high electrical efficiencies compared with conventional gas-driven CHP systems, some 10% less CO_2 (referred to energy content) is released per kWh.

Figure 7 shows total pollutant emissions from the PC 25 plant as a function of electrical output for group L gas (NO_x, CO and hydrocarbons including methane). Pollutant emissions are referred to 5 vol.% of O_2 in the waste gas and thus are directly comparable with the limit values stipulated by the German Clean Air Code for gas engines.

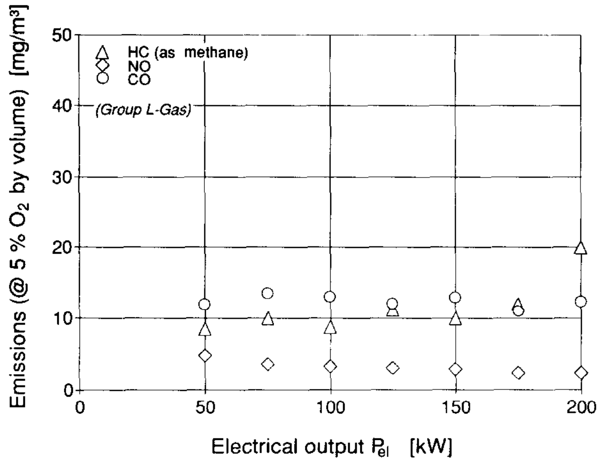

Fig. 7. Pollutant emissions as a function of electrical output.

Testing showed that the emissions from fuel cells are lower by several orders of magnitude than the values stipulated by the Clean Air Code (500 mg/m^3 for NO_x (NO_2); 650 mg/m^3 for CO; 150 mg/m^3 for non-methane hydrocarbons (NMHCs); as for hydrocarbon emissions, the Clean Air Code only sets limit values for NMHCs, however, Fig. 7 includes total hydrocarbons (shown as methane)). The interdependence of pollutant emissions and electrical output is to be explained by the fact that the reformer burner is not optimized for small ratings.

Measurable noise emission from the PC 25 plant are exclusively attributable to associated units such as pumps, fans and cooling systems. The electrochemical process as such does not produce any noise.

Outlook

The highly efficient gas-driven CHP systems will strengthen their foothold on the market. PAFCs as currently being introduced will certainly become strong competitors of the conventional gas engine and gas turbine, in particular for a plant size of less than 10 MW. With their high electrical efficiencies, fuel cells will certainly be most suitable for high-consumption users such as hospitals. However, fuel cells could also be used in administrative buildings, schools, swimming pools and hotels.

To support the market introduction of fuel cells, major European energy suppliers have taken up independent projects to operate demonstration plants.

The operators of the 50-kW PAFC plants of Fuji Electric and of the 200-kW PAFC plants of ONSI in Europe have reported very encouraging results so far. They all confirmed the high electrical efficiencies, the good part-load behaviour and the virtually negligible emissions and thus the 'ecological potential' of the fuel cell technology. No final assessment can yet be made on cell-stack life, which, according to manufacturers, amounts to 40 000 operating hours (at 10% loss in efficiency).

On the basis of the test results obtained so far, the European operators define the following areas of improvements:

- increase reliability of balance-of-plant
- reduce space requirements without restricting access to plant components
- modify control to account for European user requirements (heat-controlled operation)
- recover heat at higher levels of temperature (chillers, process steam)

Only a few years ago, specific capital outlay exceeded 9500 US\$/kW$_{el}$; it has markedly decreased since and is presently at ~1500 to 4000 US\$/kW$_{el}$. However, specific capital outlay is still twice as high as for conventional gas engine-driven CHP plant.

Capital outlay is, however, expected to decrease further in the medium term when rising demand will spur mass production to replace costly small-scale production. According to plant manufacturers, a new improved and less costly plant is scheduled to enter the market by the end of 1995.

References

1 Blockheizkraftwerke-Grundlagen, *Informationsschrift der Arbeitsgemeinschaft für sparsamen und umweltfreundlichen Energieverbrauch e.V., Hamburg, Germany,* 1992.
2 Anon., *Energiespektrum, 1* (1993) 11–13.
3 R. Anahara, *J. Power Sources, 37* (1992) 119–131.
4 A. Molin, *Proc. 4th Workshop Meet. European Fuel Cell Group, Malmö, Sweden, June 3–4, 1993,* submitted for publication.
5 40 kW On-Site Fuel Cell Field Test Program, *Final Rep., Jan. 1982–May 1986,* Gas Research Institute, Chicago, IL, USA, 1986.
6 Novum Neunburg, *Energiespektrum, 9* (1993) 11–16.
7 A. Szyska, G. Schimpf und J. Tachtler, *VDI-Berichte 912,* VDI-Verlag, Düsseldorf, 1992, pp. 147–161.
8 A. Szyska, personal communication.
9 R. Vellone, F. DiMario, V. Cincotti and M. Brocco, *J. Power Sources, 37* (1992) 111–116.
10 E. Ferrari, *Proc. 4th Workshop Meet. European Fuel Cell Group, Malmö, Sweden, June 3–4, 1993,* submitted for publication.
11 H. Knappstein and H. Nymoen, *Gaswärme Int., 42* (1993) 139–144.