Part I  
Design and Operation
1 MTU’s Carbonate Fuel Cell HotModule

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1.1 The Significance of Fuel Cells

Fuel cell technology and its applications are basic innovations, at best comparable to, e.g. implementations of steam engines in earlier decades of the century or the electrodynamic principle for energy conversion. For the first time in the history of energy technology fuel cells offer an alternative to thermodynamic power conversion without the efficiency limits imposed by Carnot’s law, i.e. their electrical efficiency is not mainly correlating to the range of operating temperatures.

The various fuel cell technologies cover a wide scope of applications ranging from battery applications through electrical propulsion up to power stations due to their inherent modularity, high efficiency, and cleanliness. Highly reliable energy supply of small units like laptops, consumer electronics, units in spacecrafts and aircrafts, applications for supply of automotive electrical propulsion systems and auxiliary power units (APU) and as modular basic building blocks for stationary power production systems as well as combined heat and power units (CHP) or tri-generation units (combined heat, power, cooling energy) can be realised with fuel cells. The fuel cell technologies in principle differ in the utilized electrolyte giving them their names and in operating temperatures, which basically determines the ranges of possible applications and the utilization of different fuels.

The list of possible usable fuels is long and comprises

- pure hydrogen,
- gaseous or gasified hydrocarbons (natural gas, biogas, sewage gas, coal mine gas, methane containing gas mixtures, etc.),
- synthesis gases (mixtures of hydrogen and carbon monoxide)

As oxidant both pure oxygen and air are used.

Fuel cells are operating inherently clean, produce hardly emissions and offer maximum electrical efficiency.

The basic functional mechanisms of the different fuel cell types already are addressed in literature, so we have only to discuss the differences of the two temperature classes of fuel cells:
• low temperature fuel cells,
  – alkaline fuel cell (AFC),
  – phosphoric acid fuel cell (PAFC),
  – proton exchange membrane fuel cell (PEM or PEMFC)
• high temperature fuel cells
  – carbonate fuel cell, often called molten carbonate fuel cell (CFC or MCFC)
  – solid oxide fuel cell, ceramic fuel cell (SOFC)

This classification of fuel cells already gives indications to their utilization and applications:
Due to their high operating temperature (approximately 600 °C up to 1000 °C) high temperature fuel cells can be equipped with facilities for internal reforming of the fuel gas and therefore are not limited to use pure hydrogen as fuel but can use gaseous or gasified hydrocarbons of all kinds. This leads to most simple system design and highest efficiency and useful high temperature heat for CHP, tri-generation and also poly-generation, which means additional use of the reaction products, e.g. utilization of CO₂ for fertilizing purposes or water vapour for humidification.

But due to their relatively high temperature the systems are thermally slow and consequently slow in load changes, which makes them mostly usable for stationary applications in the field of energy conversion.

Low temperature fuel cells due to their lower operating temperature have faster operational behaviour and higher dynamic in power output. Additionally they have higher energy density, meaning lower specific mass and volume. They are adaptable to the requirements of automotive propulsion, of APUs or to smaller and very small power supply units, which can never be realised by a MCFC system.

But of all existing or emerging fuel cell technologies the carbonate fuel cell (CFC) is specifically suited for stationary co-generation applications in small to medium power range (several hundred kilowatts up to several megawatts). At a temperature level of 650 °C the CFC incorporates all the advantages of high temperature fuel cells without having to cope with the problems of high temperature ceramic fuel cell manufacturing.

Triggered by good reasons MTU CFC Solutions GmbH has chosen the CFC technology in the form of the world-wide patented HotModule, which was developed for CHP, tri-generation and poly-generation in the stationary field of energy conversion. The present status is to reach maturity for a serial production of the HotModule units.

1.2 Basic Statements of Power Production and Combined Heat and Power Systems

The fuel cell technology of the HotModule is a technique for today. It does not depend on realisation of the high futuristic ideas of the so-called ‘hydrogen world’
or ‘hydrogen economy’. The HotModule uses both gaseous or gasified hydrocarbons and existing hydrogen- and/or carbon-monoxide-rich gas mixtures as fuel and as oxidant as well as for cooling medium simple air. This technology is most suitable for stationary and semi-stationary systems, which may also possibly include applications on board of ships or other big mobile systems (APU).

Putting our attention exclusively to the stationary field of power generation and neglecting for a while the requirements of mankind in the field of mobility and transportation, mankind needs only
- power,
- heat and
- cold

for basis and also for comfort of life. These energy forms we call ‘consumable energies’.

In fact, all these consumable energy forms can be produced from electrical power (‘all electric house’), but we should remember, that any conversion of any stored energy to electrical power is characterised by by-production of heat, which has – depending on the method – a different grade of possible utilization.

The mentioned consumable energy forms are all characterised by the fact not to be storable in necessary quantities in an economical manner. Therefore they have to be ‘produced’ just in time and just in right quantity. Basically, this is realised presently by the utilization of high value stored energy forms like coal, oil, natural gas and nuclear fuel. The conventional utilization of renewable energy sources (RES) is either mostly used (hydropower) or is presently emerging (wind power, biomass combustion (wood pellets), utilization of geothermal energy, etc.).

The possibilities of the applications of high temperature fuel cells, in particular of the carbonate fuel cell, to use directly gaseous or gasified hydrocarbons for conversion into power and heat are opening totally new ways for the production of consumable energy forms from energy sources till now used in small or medium quantities only.

1.3 Fuels for Fuel Cells

It is one of the most important advantages of high temperature fuel cells in general and of the carbonate fuel cell in particular to have a very broad fuel flexibility.

1.3.1 Fuels Containing Gaseous Hydrocarbons

The heating value of these gases is mostly based on their methane content. Further components are higher hydrocarbons, nitrogen, seldom small amounts of oxygen in fluctuating concentrations. Contaminants often are hydrogen sulphur (H₂S), organic sulphur (mercaptanes, thiophenes, COS), chlorine- and fluorine components, silanes and siloxanes, etc.
The most important gases of this group are:

- natural gas
- biogas from anaerobic fermentation (agricultural biogas, sewage gas, gas from industrial and municipal biogas plants)
- landfill gases
- industrial residual gases with a comparable high methane content.

1.3.2 Synthesis Gases

The heating value of synthesis gases is mostly characterised by fluctuating compositions of hydrogen and carbon monoxide. They often contain nitrogen, carbon dioxide, gaseous higher hydrocarbons and mainly the same contaminants as discussed under the methane-containing gases.

The most important gases of this group are:

- Coal gas from coal gasification (‘town gas’),
- Industrial residual gases with H₂ and CO components, e.g. furnace gases or purging gases,
- Gaseous products from thermal gasification systems of different (waste-) materials like wood, paper, cartoons, used rubber (tyres), slurry from sewage plants, organic waste material including waste from slaughter houses, hydrocarbon-containing fractions of waste, used plastics and so on.

The available techniques of gasification systems can be separated into autothermal and allothermal methods.

Autothermal gasifiers use a part of the heating value of the feed material producing the thermal energy, which is necessary for the gasification process. They need oxygen as gasification medium. As long as air is used for that, the resulting gases are characterised by a high amount of nitrogen (60% vol to 40% vol) and therefore by a low heating value. As the lower heating value of hydrogen as well as of carbon monoxide is in the range of 3 kWh/m³, such gases reach a LHV of 1.5 kWh/m³ or lower (for comparison only: Natural gas approximately 10 kWh/m³, biogases in the range of 5 to 7 kWh/m³). The alternative is to use oxygen enriched air or pure oxygen as gasification medium. Basically this is an economical decision, but technical problems should also be addressed.

Allothermal gasifiers mostly use water vapour as gasification medium, because they are heated from outside, which costs at least the same amount of fuel compared to autothermal heating. But the heating value of the produced gases is high (in the range of 3 kWh/m³) due to the avoided nitrogen component. The thermal energy supply from outside can be sourced on to different fuels, namely also to un-refined product gas. Generally speaking, gases from allothermal gasification processes are much more suitable for the utilization by high temperature fuel cells.
1.3.3
Group of Gasified Hydrocarbons

These include alcohols, gasoline, diesel, biodiesel, kerosene and glycerol. Within this group only alcohols, biodiesel and glycerol can be called renewable. Presently only methanol and ethanol are used for fuel cell operation.

1.3.4
Secondary Fuel

At this point the term ‘Secondary Fuel’ in contradiction to primary energy should be defined in a more exact way: ‘Secondary Fuel’ or ‘Secondary Energy Carrier’ describe a fuel based on any material, which is already used in any way. Following this definition, secondary fuels or secondary energy carriers mostly are waste materials from natural or artificial production processes converted to gaseous or liquid fuels. Secondary fuels mostly, but not exclusively, are biogases from anaerobic fermentation and synthesis gases from thermal gasification processes. Secondary fuels are not equal to regenerative fuels, because indeed they can be produced from materials, which are originally based on fossil sources. Synthesis gas produced from waste plastics or used tyres may be an example for that. Secondary fuels mostly are biogases from anaerobic digestion and gasification of used organic material (manure, harvest residuals, wood, paper, cartoons, etc.).

In fact it is understood that the utilization of secondary fuels for conversion to consumable energies not only saves fossil sources but also reduces the atmospheric load regarding greenhouse gases, pollution and emissions being set free at the alternative utilization of primary energy sources. The reduction of political and economical dependence from crude oil and natural gas imports should be mentioned positively.

1.4
Why Molten Carbonate Fuel Cells

Among all the fuel cell technologies, the molten carbonate fuel cell (CFC) is particularly suited for the stationary co-generation of electrical power and heat. This is due to its operating temperature: At approximately 650 °C, it is high enough for the electrochemical conversion processes to take place at the electrodes of the fuel cells without any precious metal catalysts. Nickel is sufficient to initiate the fuel cell reaction.

The most important reason for the utilization of high temperature fuel cells (CFC and SOFC) is their possibility to reform conventional fuel gases as well as gasified liquid or solid fuels (hydrocarbons) with the heat produced by the fuel cell itself. This internal reforming reaction, i.e. the reaction of hydrocarbons and water to form hydrogen and carbon dioxide, takes place at elevated temperatures in the presence of a catalyst inside the fuel cell block. Thanks to internal reform-
ing, the fuel cell system greatly can be simplified. The efficiency of the system significantly is increased, because the fuel gas energy needed for reforming is saved. Additionally, carbon monoxide (CO) is a welcome fuel for the CFC in contradiction to other fuel cells, where it acts as a catalyst poison.

Another reason for the high efficiency of the CFC system is the better utilization of the heat generated in the fuel cell. High temperature exhaust heat advantageously can not only be used in industrial processes of all kinds (e.g. as process steam) but also for further power generation in downstream turbine generators, especially in larger installations. The high temperature enables the supply of heat consumers with higher temperature requests, e.g. absorption refrigerators, steam injection cooling devices, pressurised hot water production, drying processes and sterilization.

On the other hand, the operating temperature is low enough for conventional metallic materials to be used in the construction of both the cell structure and the peripheral equipment. Thus large-area fuel cells can be manufactured simply, and the peripheral equipment can be constructed cost effectively from conventional materials.

1.5
The Carbonate Fuel Cell and its Function

The basic working principle of an MCFC is shown in Fig. 1.1. It basically consists of three layers, which are the porous anode and cathode electrodes and the electrolyte between these two. The metallic parts of the electrodes possess a certain electric conductivity, although they are far from being good conductors. Their thickness is only a few hundred micrometers. Nickel-based alloys are frequently used for the anode electrode, while nickel oxide is the preferred material for the cathode electrode. These materials serve as catalysts for the electrochemical reactions inside the electrode pores.

![Work principle of the MCFC with direct internal reforming (DIR).](image)
The electrolyte between these two is an eutectic carbonate salt mixture (e.g. Li$_2$CO$_3$/K$_2$CO$_3$), which is liquid at the operating temperature of about 600 °C. It is held in place by capillary forces in a porous matrix based on alloys with aluminium oxide, for example LiAlO$_2$. The layer is about as thick as the electrodes and is a fairly good conductor of carbonate ions. At the same time, this layer is a very good isolator against uncharged molecules like hydrogen or oxygen. The electrolyte is also present in the electrodes, where a part of the pores is flooded with it.

The chemical reactants of both electrodes are supplied by gas channels. The anode channel contains an additional porous catalyst for the reforming of the feed gas.

In Fig. 1.1, a mixture of methane and water is used as anode fuel gas. Upon entrance in the anode channel, these reactants undergo several reactions on the reforming catalyst, of which the methane steam reforming reaction and the water–gas shift reaction are the most important. The products of these reactions are primarily hydrogen, carbon monoxide and carbon dioxide. The concept of hydrogen production inside the anode channel is known as direct internal reforming (DIR). Although the water–gas shift reaction is slightly exothermic, the overall reforming process is endothermic:

$$\text{CH}_4 + \text{H}_2\text{O} \rightarrow 3\text{H}_2 + \text{CO}$$ Methane Steam Reforming

$$\text{CO} + \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{CO}_2$$ Water–Gas Shift Reaction

This endothermic process is heated by waste heat from the electrochemical reactions at the electrodes. This uptake of thermal energy leads to an increase of the heat value of the gas. In the case of a complete conversion of the reforming process, a portion of methane gas with a heating value of, say, 10 kWh will be transformed into hydrogen with a heating value of about 12 kWh. This is a significant increase in heating value using thermal waste energy. Furthermore, the endothermal character of this process possesses a kind of chemical cooling for the heat producing cell, which is important for thermal management of the system.

The reforming products, namely hydrogen and carbon monoxide, migrate into the anode electrode and react electrochemically, consuming carbonate ions from the electrolyte and producing free electrons on the electrode:

$$\text{H}_2 + \text{CO}_3^{2-} \rightarrow \text{H}_2\text{O} + \text{CO}_2 + 2\text{e}^-$$

$$\text{CO} + \text{CO}_3^{2-} \rightarrow 2\text{CO}_2 + 2\text{e}^-$$

The consumption of the reforming products hydrogen and carbon monoxide shifts the chemical equilibrium of the reforming process towards high conversions. Only with the direct internal reforming concept practically complete conversion of the reforming process can be obtained at a comparably low temperature of about 650 °C. Otherwise, this would require very much higher temperatures.
The anode exhaust gas consists of unreformed feed gas, reforming products and oxidation products. It is mixed with air and then fed into a catalytic combustion chamber, where all combustible species are completely oxidised. Intentionally air in stoichiometric excess is used here, so that some oxygen is left in the burner exhaust gas. This mixture is then fed into the cathode channel. Here carbon dioxide and oxygen react on the electrode producing new carbonate ions in the electrolyte and consuming electrons from the cathode electrode:

\[ \frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-} \]

The cathode exhaust gas leaves the system. The sum of the oxidation reactions with the reduction reaction corresponds to the combustion reaction of hydrogen to water or carbon monoxide to carbon dioxide, respectively. A part of their reaction enthalpy is transformed into electric energy, the rest is released as heat.

Driven by gradients in concentration and electric potential, the carbonate ions migrate through the electrolyte from the cathode towards the anode electrode. The surplus electrons on the anode are transferred to the cathode electrode, where electrons are missing, via an electric consumer, where they can perform useful electric work.

In the HotModule, the reforming process is split into three different steps, which are shown in Fig. 1.2. Outside the fuel cell, in an adiabatic external reformer (ER), short chained hydrocarbons are reformed to methane using heat from the fuel gas, which was earlier heated by the off-gas from the fuel cell, thus transforming its thermal energy into heating value. Its operating temperature is lower than the fuel cell temperature. The indirect internal reformer (IIR) is located between the cells in the cell stack. Due to the thermal coupling between the electrochemical processes in the cell and the IIR, waste heat from the cells is utilised and the reforming takes place at about cell temperature. However, no mass exchange occurs between the reforming in the IIR and the electrochemical

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**Fig. 1.2** Reforming steps in the HotModule system.
process. This reforming step significantly increases the hydrogen content of the gas before it enters the fuel cell's anode channels. There, the direct internal reforming (DIR) continuously produces new hydrogen from the remaining methane as the electrochemical consumption of hydrogen proceeds and thereby obtains a nearly complete conversion of the reforming process.

1.6 Optimisation by Integration: The HotModule Concept

The single cell is built up like a flat sandwich. Both porous nickel electrodes, the anode and the cathode wrap up the porous matrix, which is filled with electrolyte. The gas channels are supplied by corrugated current collectors, which build up the bipolar plate. The area of single cell is 0.8 m². The electrical power of one single cell is in the range of 0.8 kW. Approximately 300 cells of this kind are stacked and electrically connected serially. They are compressed by endplates and tension rods in order to ensure a good electrical and thermal contact from one to the other. Fuel gas and air form a cross flow through the stack.

The described method of the gas distribution- and gas collection facilities is called ‘external manifolding’. The ‘internal manifolding’ is not used by MTU.

The direct current is taken from the endplates of the stack and is connected to the grid via a DC/AC converter. The excess heat is taken out from the fuel cell by the cathode airflow and can be used after using it to heat up the fuel gas and the production of steam for the humidification of the fuel gas. The temperature level for the heat utilization is around 400 °C to 450 °C. This enables the production of a high-pressure steam, for example. According to the power requirements a number of fuel cell stacks will be connected (parallel in gas flow, serial or parallel in electric flow) and completed with a fuel gas treatment system, which is adapted to the used fuel type. The inverter converts the DC to AC. The control system works fully automatically.

The fuel cell structure leads to a completely new system design. The basics are shown below.

A fuel cell power and heat co-generation plant consists of (Fig. 1.3):

- Application independent subsystems including the HotModule or some of it in a HotModule periphery, the unit for conditioning and grid connection, and the control system. All these systems are application independent and can be produced in a serial manufacturing method. They have a substantial potential for cost reduction by serial manufacturing.

- Application specific subsystems including the fuel processing unit depending on the raw gas, which shall be used, and the heat utilization facilities depending on the requirements of the customer. For cost reasons these subsystems should be built in a standardized manner.
The Hot Module itself is a consequent translation of the fuel cell-function principle. The design of the Hot Module was awarded the prize for innovations and future applications of natural gas sponsored by the German gas business sector on September 29, 2000.

It combines all the components of a CFC system operating at similar temperatures and pressures into a common thermally insulated vessel. A typical configuration contains the CFC stack, a catalytic burner for the anode tail gas and a cathode recycle loop including mixing-in of fresh air and anode exhaust.

The cell stack is resting horizontally on the fuel-in manifold, thus providing excellent gas sealing by gravity forces. On the top of the stack the gases leaving the anodes are mixed into the cathode recycle loop together with fresh air supplied from outside. The mixture is transported through a bed of combustion catalyst located on top of the mixing area and blown back to the cathode input by the cathode recycle blowers on the top end of the vessel. No gas piping or sealed cathode manifolds are necessary. For startup, an electrical heater is placed at the cathode input face of the stack.

1.7 Manufacturing

As the mechanical components of the carbonate fuel cell consist of metallic materials they can be manufactured with conventional methods of metal sheet ma-

Fig. 1.3 Subsystems of a combined heat and power plant on the HotModule basis.
chining. Definition of material and application of adapted corrosion protecting layers need a lot of practical engineering and experience.

The porous electrodes and the matrix can be either produced in tape casting processes or spread to porous porter materials (Ni-foam material). The slurry for tape casting consists of metallic powder and ceramics for the electrodes and the matrix, mixed with some organic binders. A development is on the way to replace the organic binders by water soluble binders. After drying and sintering processes in drying tunnels or ovens the components will be integrated to ‘unitised packages’, which are roughly half cells. From these packages the fuel cell stack will be later formed.

The final conditioning of the cells will be done during the first heating up procedure in a fully integrated status. Presently, a new, different manufacturing method of producing the single cells is under development, qualification and testing. The mechanical properties of the so-called ‘EuroCell’ are better adapted to the horizontal position of the cell stack in the HotModule. This manufacturing process is based on new industrial available half-products. The potential of cost reduction is estimated much higher than that of the former cells. In a horizontal position every single cell is exposed to the same pressure at every position in the stack. In a vertical stack this pressure is superposed by gravity forces depending from the height of the stack. Additionally, the pressure requirements in a horizontal stack are lower, so the single cells can be defined for a lower pressurization, which saves material and costs.

1.8 Advantages of the MCFC and its Utilization in Power Plants

1.8.1 Electrical Efficiency

The most important advantage of the carbonate fuel cell and its application for power plants is the high electrical efficiency with all its positive impacts to economy and the reduction of pollutant emissions as well as production of the greenhouse gas carbon dioxide. Figure 1.4 shows that the high efficiency can be reached over a very wide range of power in contrast to other technologies, which can use their advantages in smaller ranges only.

1.8.2 Modularity

Fuel cell power plants comprise a number of individual modules. The performance of such a module will be within the range of 300 kW to 1 MW. These modules will be combined to a power plant of the performance desired and equipped with a media supply unit, the necessary units for heat utilization, the DC/AC-converter and installations for the power conditioning and last but not least the
control unit. The modular design of the fuel cell enables an industrial and serial production of the units; at users site they only have to be connected to the grid, the media supply and the utilization unit for thermal energy. This reduces construction time and cost at customer’s site. Co-generation plants in the power
range of 300 kW up to 30 MW can be built as well as power plants for electricity production only in the multi-MW-class using that modular design.

1.8.3
Inherent Safety

Another advantage of the fuel cell units is their inherent safety feature. This is in principle due to its low energy density. No sophisticated safety and control systems are required with the consequence that cost for operating and maintaining personnel can be kept low. Based on excellent efficiency, very low level of pollutant emissions, very low risk potential combined with high reliability and availability the Fuel Cell technology offers the possibility for applications in third world countries with increasing power requirements instead of conventional types of power plants with high risk potential (nuclear power) or low environmental compatibility.

Fig. 1.6 The first fuel cell HotModule during test at RuhrGas, Dorsten.
1.8.4 Environmentally Friendly – Pollution Free

The MCFC does not produce pollutant emissions; no NO\textsubscript{x}, no sulphur components, no higher hydrocarbons, no CO. The effluent of the MCFC is not an exhaust gas but only depleted air consisting of N\textsubscript{2} (in the case of air as oxygen carrier), small amounts of O\textsubscript{2} (residual O\textsubscript{2} from excess air), large amounts of CO\textsubscript{2} (less than the amount produced by a conventional engine due to the higher electrical efficiency of the fuel cell) and big amounts of water vapour.

1.8.5 Silent

Fuel cell systems are inherently silent, because they do not contain any moving parts and electrochemical reactions are – as far as they participate in fuel cells – noiseless. The only possible source of noise are blowers for gas transport, but these components can be capsuled and insulated for noise emission.

1.9 History

1.9.1 The European MCFC Development Consortium

The largest European program for the commercialisation of the molten carbonate fuel cell technology was carried out by the European Molten Carbonate Fuel Cell Development Consortium (ARGE MCFC). The consortium was founded in 1990 and comprised the following companies:

- MBB, Messerschmitt-Bölkow-Blohm GmbH, as predecessor of MTU Friedrichshafen GmbH (Germany), within the DaimlerChrysler Group in charge of off-road propulsion and decentralised energy systems,
- Energi E2, (Denmark), a Danish utility company, former Elkraft,
- Ruhrgas AG (Germany), a German gas company,
- RWE-Power AG (Germany), a German electrical utility company.

MBB and later MTU acted as consortium leaders. MTU shares a license and technology exchange agreement with Fuel Cell Energy Inc. (FCE), formerly known as Energy Research Corporation (ERC), Danbury, Connecticut, US.

The Consortium launched a three-phase program for the commercialisation of the MCFC technology in Europe. The overall program volume was approximately $100 million to be spent within 10 years from 1990 to 2000:
Within the first phase the basic development of the cell and stack technology was performed with the result, that an operational lifetime of a full size stack of minimum 20,000 h can be expected with a high probability. Other targets were the development of cost-effective production processes and the basic design of layouts for natural gas and coal gas fed plants. A certain number of different plant variants were investigated and high effective and innovative plant concepts were found.

Within the second phase cell improvement was continued in order to achieve an operational lifetime of 40,000 h. But the main issue of the second phase was the product development resulting in the concept of a highly integrated compact fuel cell power plant, the HotModule. The HotModule concept was triggered by a sustainable simplification of the MCFC power plant design and offered an important cost reduction potential.

The third phase of the program was dominated by the design, the construction and the tests of some field test units.

During the first and second phase of the program, the ARGE MCFC spent approximately $35 million for basic technology research and development succeeding in resolving fundamental materials, corrosion, and lifetime problems associated with the MCFC technology. During this period, essential breakthroughs in the development of corrosion resistant longlife cell components have been achieved and a highly innovative system design was developed.

1.9.2 Continuing of the HotModule Development at MTU CFC Solutions

The company MTU CFC Solutions GmbH was founded in early 2003 in order to collect all fuel cell development work carried out within MTU Friedrichshafen GmbH. Also in 2003 RWE Fuel Cells GmbH shared the company with a small participation. MTU CFC continued the work with the HotModule and with the EuroCell. By the end of 2004 MTU CFC together with their development and commercialisation partner FCE (Fuel Cell Energy Corp. Danbury, Connecticut, USA) had built and tested 25 plants of the HotModule type worldwide. Ten of them were erected in Europe to demonstrate their capability for combined heat and power production units. Some of them are tri-generation applications. Additionally, the ability for load-following operation as well as applications for uninterruptible power supply have been demonstrated (DeTeImmobilien, Munich). Other plants were installed at industrial environments (Michelin tyre works, Karlsruhe) or in hospitals (Bad Neustadt, Klinikum Grünstadt, Rhön-Klinikum Bad Berka).
Within 2005 and 2006 the worldwide first HotModules using biogenous gases were installed and started:

- A sewage treatment plant at Ahlen, Germany: The HotModule uses sewage gas for combined power and heat production. The heat is used partially for the sewage treatment process, the rest is fed to a district heating network. The electricity produced (230 kW) is fed to the grid.
- A municipal biological waste material treatment plant at Leonberg, Germany: Different biological waste materials collected from households, industry and public organizations is treated in a dry-fermentation process producing biogas, which is transferred to power and heat by two gas-engine modules with approximately 500 kWel each and a HotModule with 240 kWel. In this plant the heat produced is completely used for a thermophilic biogas production process and a subsequent fertilizer production, the electrical energy is fed to the grid.

Also in 2006, the lifetime threshold of 30,000 operational hours was exceeded by the plant at the Magdeburg hospital. This is presently the longest operational lifetime of any fuel cell worldwide. Additionally, this fuel cell plant was used over its complete operational period as the experimental counterpart of all the investi-
1.9 History

Fig. 1.8 HotModule CHP at Michelin Tire Works, Karlsruhe, Germany.

Fig. 1.9 Biogas HotModule CHP at Leonberg, Germany (small picture: biogas storage and fermenter).
1.10 Possible Applications of MCFC Systems

There are to be discussed at least two types of applications of MCFC systems in the field of decentralised stationary energy supply:

- Different applications at front end, i.e. utilization of different fuels.
- Different applications at rear end, i.e. different utilizations of the products of the fuel cell system.

Both types of applications can realise additional benefits by clever integration of the fuel cell system into an overall system, where some surplus over power, heat, cooling power can be gained (components of depleted air from fuel cell system, saving of deposition costs, by-products, etc.).

1.10.1 Different Applications Using Different Fuels

Biomass Utilization

Until now, regenerative and secondary gases are converted into electric energy in conventional CHPs with a relatively low electrical efficiency (approximately 36%) and a large quantity of low-temperature – low value – process heat production. Conventional CHPs in the performance class up to some 100 kW$_{el}$ are mostly based on gas-piston engines or diesel-injection-supported gas engines. Most of these CHP plants are operated according to the requirements of heat production with the result of short operational periods over the year (approximately 4000 h/year). Using the HotModule and its tri-generation-mode together with adapted absorption chillers, this situation can be improved to higher electrical efficiencies and better utilization of heat with the result of a full load operation all over the year. The pay back period of such an investment will decrease respectively.

The use of biomass for generation of consumable energy forms in the stationary field of power supply is one of the most important possibilities for at least a partial solution of our increasing energy problem. As biomass usable for consumable energy production is existing in two forms, namely as biomass, which is suitable to be digested within fermenters by bacteria and biomass with big amounts of ligno-cellulose, which is the main component of wood. This kind of biomass is only accessible for energy purposes by either burning or thermal gasification to synthesis gas (pyrolysis). This kind of biomass includes all sorts of wood, fresh wood, demolition wood, used wood, paper, cartoons, packing material, etc. This kind of biomass is a big component in municipal and industrial waste material. Estimations are given, that ligno-cellulose biomass represents approximately 70%
of total usable biomass. Therefore, we have to realise two different methods for utilizing biomass for consumable energy production:

- biogas utilization (biogas from digestion)
- syngas utilization (syngas from gasified biomass)

**Biogas Utilization**

By bringing the fields of biomass, (bio-)residues, anaerobic digestion and fuel cell technology together, several synergies make such applications attractive:

- **Utilization of renewable energy sources (RES) in fuel cell technology** – leading to a sustainable cycle by using a CO₂ neutral fuel. Such a fuel enhances the environmental advantage of fuel cell technology. Biogas and sewage gas is renewable energy with a very high potential for greenhouse gas reduction.
- **Efficient and clean energy conversion of valuable RES**: due to the nature of fuel cells, hardly any emissions are produced while converting biogas into electricity. And this is possible with high electrical efficiencies indicated above.
- **High user potential for utilizing the process heat which is released from the MCFC process**: due to the high temperature of the depleted air from the fuel cell system at approximately 400 °C, it is possible to use this heat in a broad variety.
- **Decentralisation of the energy production** is an approach for a more secure and stable energy supply. Decentralisation is one of the main advantages of RES, as these are in many cases locally available. Biogas plants are to be found usually in the decentralised agricultural sector.
- **Anaerobic digestion** enables a cost reduction of organic residue disposal and new income for the agricultural sector. Conventional organic waste treatment is usually strongly energy demanding, as in the case of composting. Anaerobic digestion has a higher investment cost as, e.g. composting facilities but provides the operator with energy which can be sold to the electrical grid. As organic wastes are usually co-digested in agricultural biogas plants, farmers are enabled to produce more electricity, giving them an additional income possibility.

By also involving the agricultural sector for the production of energy crops for the anaerobic digestion process it is possible to close the nutrient cycle, as the digested organic wastes are used as fertilizer on the farming land. By reducing the use of mineral fertilizers farmers contribute to the environment protection; as such fertilizers are produced with high amounts of mostly fossil energy. The digested substrate in biogas plants can substitute such fertilizers, solving in that way also the question of the disposal of these substrates.
The development of biomass digestion technology made a big step during the last decade and availability and reliability increased substantially in that period. The number of sewage treatment plants equipped with biological treatment steps also increased. The potential for biogas utilization is enormous.

**Syngas Utilization**

The development of gasification systems for wood, cartoon, paper, wooden harvest residues (e.g. nut shells and other residual material) and other waste material has not yet reached industrial standard. Many systems are under development, but no one is really ready and available for application. The adaptation of the Hot-Module to different synthesis gases is under progress. Much positive experience is made with that applications in lab scale. The MCFC has been tested in many lab scale projects with success for its operability with syngas, but till now no full size HotModule is tested in an operation with syngas. Here should be mentioned an EU-project, where the adaptation of the HotModule system to different wood and waste gasification systems is under investigation (EU-Project BigPower, Project leader VTT, Finland).

**Other Fuels – Methanol**

A HotModule combined heat and power production plant is under operation since September 2004 in Berlin, Germany at BEWAG facilities, which is a local
utility company in Berlin (Fig. 1.10). This modified HotModule is designed for operation with methanol and all possible methanol–natural gas mixtures. As the plant has been started with natural gas for practical reasons the operation with methanol started in January 2005. Its operability with pure methanol and continuously changed mixtures of methanol and natural gas is proven meanwhile. For methanol operation the electrical efficiency reached up to 47% (see Fig. 1.4).

The principle is that the methanol is evaporated in the preheater for the fuel together with water. This principle can be used for different liquid energy carriers, e.g. ethanol, glycols, etc. The methanol in the BEWAG project is produced from plastic waste material at the facilities of SVZ in Schwarze Pumpe near Bitterfeld, Germany.

1.10.2
Different Applications Using the Different Products of the MCFC System

The products of a MCFC system are:

- electrical power, originally generated in form of DC power,
- heat in form of a depleted air, originally leaving the fuel cell stack with a temperature near the operating temperature (600 °C to 650 °C),
- and the depleted air itself, containing the reaction products H₂O, CO₂ and N₂, O₂.

Due to the fact that most of the MCFC systems are equipped with an anode recycle, i.e. the use of the anode exhaust as part of the cathode input gas for feeding the cathode with necessary CO₂ and due to the implementation of a catalytic burner upstream the cathode input, the composition of the depleted air is only N₂, CO₂, and H₂O vapour. No CO, no higher hydrocarbons, no sulphur due to the desulphurization prior to entrance of feed gas to fuel cell system, no fluorines, no chlorines occur in the exhaust air.

The possible applications use these products:

- stationary electrical power supply,
- heat supply,
- use of the depleted air.

Stationary Electric Power Supply
The smallest commercial MCFC units are in the performance range of 200 to 250 kWₑₑ (MTU), the biggest known in the MW range (FCE). Most of these plants were installed for grid parallel operation, partially using their ability of load-following operation. But this only may be an economical solution in very particular situations, because a MCFC system is always a base load power supply unit seen from the economical point of view. This is correlated to the relatively high system cost (at least presently) combined with an excellent electrical efficiency, which only can lead under steady and full time operation conditions to a high ‘economic efficiency’ meaning a short pay back period of the investment costs.
Some of the realised plants were installed for a small stand-alone grid; but this is the exemption, because such grid shall be characterised by a permanent constant load, which normally cannot be granted.

Some of the realised plants were installed for DC supply in order to feed telecommunication and IT facilities via DC/DC converters.

An interesting application is the application as uninterrupted power supply (UPS), either DC or AC. Whereas a UPS normally uses three subsystems, namely the grid as base load, batteries for a short time power source and a piston engine generator for emergency power production, the fuel-cell-based UPS consists of only two subsystems, the fuel cell system for base load and the grid for emergency. Switching can be realised within microseconds.

**Heat Supply**

In most of the MCFC systems realised till now, the heat of the depleted air firstly is used for fuel treatment purposes. Fuel treatment are the functions:

- Gas clean-up (heat requirements depending on clean-up methods),
- Gas humidification. The necessary gas humidification has two reasons. One is to avoid soot formation (Boudouard-reactions), the other the availability of water vapour for the reforming step of hydrocarbons.
- Gas preheating to anode entrance temperature up to approximately 560°C.

The enthalpy calculations result in an exit temperature of the released depleted air between 350°C and 450°C depending on the utilization of different feed gases. In the case of the utilization of natural gas and methane containing biogases, the average temperature is in the range of 420°C minimum.

With such depleted air a cascade of different utilizations can be realised:

1. utilization as process heat wherever it is possible or production of high-pressure steam for any purpose,
2. production of saturated steam for any application,
3. feeding of a high temperature thermal cooling device (absorption chiller),
4. use for district heating,
5. use for low temperature heating purposes (swimming pool),
6. recondensing water from vapour and recycling as process water for humidification.

Obviously such cascade has to be adapted to customers requirements. With such heat utilization, the system becomes a CHP or a tri-generation system.

**Use of Depleted Air**

Besides the use of the enthalpy of the depleted air it can also be used as source of its chemical components. An example is the Integrated Greenhouse Supply:
Water vapour and CO₂ can be used in greenhouses for humidification in parallel to greenhouse heating and fertilizing. It is known that, e.g. tomatoes, cucumbers, salads and other vegetables like to have an atmosphere containing approximately 2 vol% of CO₂ for an accelerated growing and for increased building up of aroma compounds. The CO₂ fertilization is the present status of greenhouse operation; CO₂ normally is added from gas bottles to the greenhouse atmosphere or is produced by difficult and costly gas cleanup of exhaust of burners used for greenhouse heating or of motor based CHP systems.

A principle flow sheet of the ‘Integrated Greenhouse Supply’ is given in Fig. 1.11.

Due to the ‘poly-generation’, i.e. the utilization of the CO₂ additional to that of power and heat and the possibility to produce merchantable fertilizer from biogas-plant effluent, the pay-back period of the whole plant is in the range of some years only, even assumed today’s high fuel cell costs. Such applications with additional benefits are representing a niche market, where already today the threshold to an economical system can be reached.

1.11 Economical Impacts

High temperature CHP systems are economically suitable at investment costs of €3,000/kW, in particular, if revenues can be gained from otherwise unused waste material or by avoiding deposition costs. According coincident investigations a
big market opens at prices lower than €1,500/kW for sub-MW-plants (electrically). As distributed and decentralised installations for power production and CHP are the focus of fuel cell systems applications, the advantageous performance class is between 300 kW_{el} and some megawatts, see Fig. 1.12. The figure shows the specific costs of different stationary power plants in different typical power ranges. Because all of these systems are introduced to the market, they are all cost wise mutually compatible. The target area for the HotModule is marked with a green ellipse. Its specific price can be slightly higher due to its higher efficiency and the lower expected maintenance costs. Presently the manufacturing costs of MCFC systems are for economical applications too high due to their developments status and a missing market penetration, which do not allow a serial manufacturing. This ‘hen and egg’ problem only can be solved by financial market entry subsidizing, which allows to sell systems at an artificial ‘economic’ price, thus developing the market. Besides strong simplification of the system as it is already done by the implementation of the HotModule principle the next important step in order to bring down the manufacturing costs to economic values is to build up a serial manufacturing line for the big amounts of repeating parts of the fuel cell system, which are the single cells. A serial production line for cells and their components is already under construction in MTU CFC’s facilities near Munich, Germany. The startup of this production line is estimated for summer 2008, the planned capacity is between 20 MW and 50 MW plant performance per year.

Fig. 1.12 Comparison of specific investment costs of different stationary power plants in dependence to their typical performance class. The range of electrical efficiency is also mentioned.