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Detlef Stolten, Thomas Grube (Eds.):
18th World Hydrogen Energy Conference 2010 - WHEC 2010
Parallel Sessions Book 3: Hydrogen Production Technologies - Part 2
Proceedings of the WHEC, May 16.-21. 2010, Essen
Schriften des Forschungszentrums Jülich / Energy & Environment, Vol. 78-3
Institute of Energy Research - Fuel Cells (IEF-3)
Forschungszentrum Jülich GmbH, Zentralbibliothek, Verlag, 2010
ISBN: 978-3-89336-653-8

Development of Fuel Cell Systems for Aircraft Applications Based on Synthetic Fuels

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Abstract

At present, in the aviation sector considerable scientific project work deals with the development of fuel cell systems based on synthetic fuels to be integrated in future aircraft. The benefits of fuel cell systems in aircraft are various. They offer the possibility to simplify the aircraft layout. Important systems, i.e. the gas turbine powered auxiliary power unit (APU) for electricity supply, the fuel tank inerting system and the water tank, can be substituted by one single system, the fuel cell system. Additionally, the energy demand for ice protection can be covered assisted by fuel cell systems. These measures reduce the consumption of jet fuel, increase aircraft efficiency and allow the operation at low emissions. Additionally, the costs for aircraft related investments, for aircraft maintenance and operation can be reduced. On the background of regular discussions about environmental concerns (global warming) of kerosene Jet A-1 and its availability, which might be restricted in a few years, the aircraft industry is keen to employ synthetic, sulfur-free fuels such as Fischer-Tropsch fuels. These comprise Bio-To-Liquid and Gas-To-Liquid fuels. Within this field of research the Institute of Energy Research (IEF-3) in Jülich develops complete and compact fuel cell systems based on the autothermal reforming of these kinds of fuels in cooperation with industry. This paper reports about this work.

1 Synthetic Fuels

XtL (“Anything to Liquid”) is the general term for high value liquid hydrocarbon fuels synthesized from synthesis gas. Furthermore the abbreviations CtL (“Coal to Liquid”), GtL (“Gas to Liquid”) and BtL (“Biomass to Liquid”) are commonly used to refer to the feedstock materials applied for the production of the synthesis gas. The conversion of synthesis gas to hydrocarbon fuel with similar properties as petroleum diesel, gasoline or jet fuel can be realized with different processing routes: the Fischer-Tropsch (FT) process consists of a catalytic polymerization step which forms straight chain hydrocarbons that are converted to the desired final products during the following upgrade processing. Another process route called MtSynfuel produces methanol as a multi-purpose and storable intermediate product which can be chemically converted to XtL fuel. In contrast to conventional petroleum fuels XtL products are almost free of sulfur and aromatic compounds. Nevertheless it can be necessary to blend XtL with conventional fuel to meet the existing transportation fuel specifications [1-3].

In Jülich recently, four different synthetic fuels were ordered, which were produced via the “Gas to Liquid” technology. Their physical and chemical properties are summarized in Table 1. The fuel in the fifth line in Table 1 is produced by the “Bio to Liquid” process and is based on palm oil. All synthetic fuels have in common that they reveal a very low aromatics and sulfur content. Only Shell MDS Kerosene from Table 1 can be classified as jet fuel with a quite narrow boiling range between 150 °C and 200 °C. All other synthetic fuels are so-called diesel fuels. Former experiments in Jülich compared the boiling ranges of conventional diesel fuels with those of synthetic fuels. They showed that the boiling range of synthetic fuels proceeds on a plainly lower level. That means that the critical step within each reforming unit, i.e. the complete evaporation of the fuel, is expected to be significantly easier when employing synthetic fuels.

Table 1: Different synthetic fuels to be used for autothermal reforming.

	Lower heating Value		**Density**	**Sulfur content**	**Aromatics**	**Boiling Range**
	MJ/kg	MJ/l	kg/m^3	ppm	vol.%	
Shell MDS Kerosene	-	-	737	< 3	< 0,1	150 °C - 200 °C
Shell GTL Fuel (Winter Grade)	-	-	778	< 3	< 0,1	210 °C - 318 °C
Shell GTL Fuel (Summer Grade)	-	-	781	< 3	< 0,1	204 °C - 356 °C
EcoPar Diesel			798	< 1	< 0,5	268 °C - 378 °C
NExBTL	44	43	775 – 785	≈ 0	≈ 0	260 °C (10%) – 300 °C (95%)

2 System Layout

As can be seen in Figure 1, a compact system design is possible by integrating heat exchangers in the reactors in order to recover reaction heat for educt conditioning. The reformer is operated with cold air and fuel. The heat input for fuel evaporation comes from superheated steam which is fed into the reformer with a temperature of 480 °C. A part of the required water for reforming is evaporated and slightly superheated in the integrated heat exchanger of the catalytic burner. The residual cold water flow is then mixed with this slightly superheated steam resulting in saturated steam. The integrated heat exchanger of the reformer is designed in such a way, that the saturated steam is superheated to the required temperature level. At the same time the reformate is cooled down to the temperature level, which is required at the entrance of the high temperature shift stage. The cooling between the shift stages is carried out using water quench. This strategy eliminates the necessity of a further heat exchanger and at the same time shifts the equilibrium towards CO reduction in the low temperature shift stage. After the shift reactor the reformate is cooled down to the inlet temperature of the fuel cell anode. At the same time, air for the cathode is heated up. After the electrochemical conversion in the fuel cell stack, the anode tail gas is directly fed into the catalytic burner. The catalytic burner enables a low emission operation of the system and supplies heat for educt conditioning as discussed above. Water autonomy is provided using the exhaust gas coolers and condensers after the cathode and the catalytic burner.

According to the outside and design conditions, additional water can be produced to be used in aircraft.

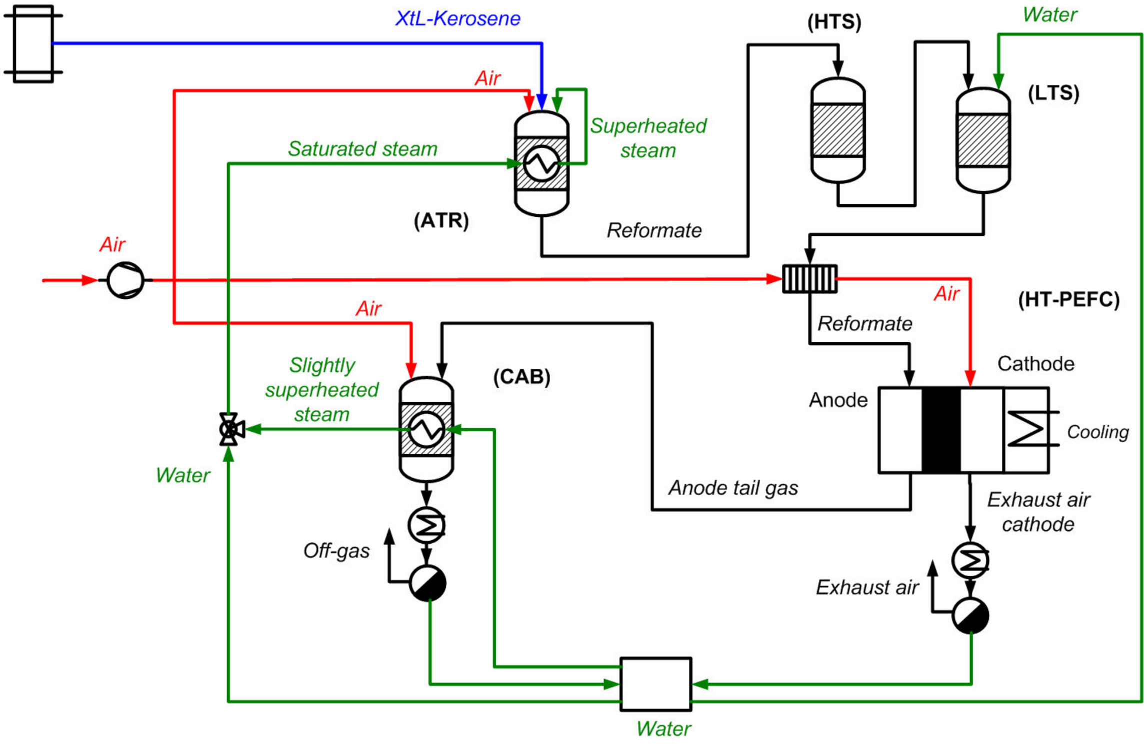

Figure 1: **Flow sheet of the high temperature Polymer Electrolyte Fuel Cell (HT-PEFC) system based on autothermal reforming of synthetic fuels. ATR: Autothermal reformer, HTS: High temperature water-gas-shift reactor, LTS: Low temperature water-gas-shift reactor, CAB: Catalytic burner.**

3 Component Development and Design

3.1 Autothermal reformer

The actual autothermal reformer of the Forschungszentrum Jülich of the ninth generation (ATR 9.2) is shown in Figure 2. Experimental results with former ATR generations (ATR 7 and ATR 8) are given in [4,5]. ATR 9.2 is specifically designed for the conversion of synthetic fuels and can produce a molar hydrogen flow with a thermal power of 28 kW. CFD simulations of ATR 9.2 aimed at a special design of the air injection device of the reformer. Figure 3 shows the results of these simulations. The mass fraction of oxygen in a mixture of steam, vaporized fuel and air is displayed. The red spots in Figure 3 indicate those positions, at which air is injected in the mixing chamber of the reformer. It becomes obvious from Figure 3 that due to the geometry of the air injection device strong turbulences occur very close to the air injection point. Thereby, the majority of oxygen molecules flow in direction of the catalyst of the reformer on the right hand side of Figure 3. The concentration of oxygen in the catalyst is very homogeneous. Simultaneously however, a low mass fraction of oxygen also flows in that part of the reformer, in which already a mixture of steam and vaporized fuel prevails being injected via the fuel nozzle on the left hand side of the reformer. By this means, a homogeneous, slightly exothermic pre-reaction between oxygen and fuel in the mixing chamber is favored, which eases the complete evaporation of the fuel. This pre-reaction is supported by employing synthetic fuels, which consist of more lower boiling, aliphatic components in comparison to conventional fuels.

Moreover, ATR 9.2 in Figure 2 shows the following characteristics, which partly represent advancements in comparison to former ATR generations:

- An integrated heat exchanger device for producing steam by using the reaction enthalpy from the reforming reaction
- A one-fluid-nozzle (diameter of the drilling: 0.2 mm) for fuel injection. The nozzle is cooled and replaceable.
- For the first time, the mixing chamber of ATR 9.2 was made from sheet metal. In former ATR generations ceramics were used. This shift offers the potential to manufacture the mixing chamber more easily.
- In former ATR generations a cyclone was integrated into the mixing chamber, in which carbonaceous deposits being produced during the ATR process were collected. This cyclone was omitted in the case of ATR 9.2 since synthetic fuels consist of more lower boiling, aliphatic components in comparison to conventional fuels, which have a clearly weaker tendency towards the formation of carbonaceous deposits.
- The reaction chamber, in which the catalytic reforming reaction takes place at temperatures between 800 °C and 1000 °C, was also made from metal sheet. In former ATR generations turned tubes were used for that means. This shift offers the chance to reduce costs to a large extent during manufacturing if huge numbers of the reformer are considered.

Figure 2: Autothermal reformer of the ninth generation (ATR 9.2) of Forschungszentrum Jülich

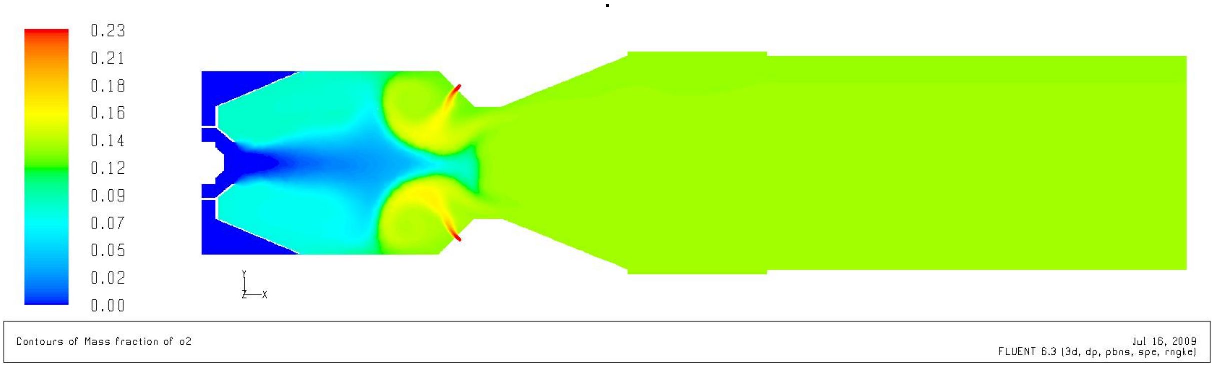

Figure 3: **Simulation of air injection into the mixing chamber of ATR 9.2, mass fraction of oxygen in the mixing chamber (left) and the catalyst of the reformer (right).**

3.2 Water-Gas-Shift reactor

The actual water-gas-shift reactor of the Forschungszentrum Jülich of the fourth generation (WGS 4) is shown as a model in Figure 4 on the left hand side. It well fits to the thermal power class of ATR 9.2 of 28 kW.

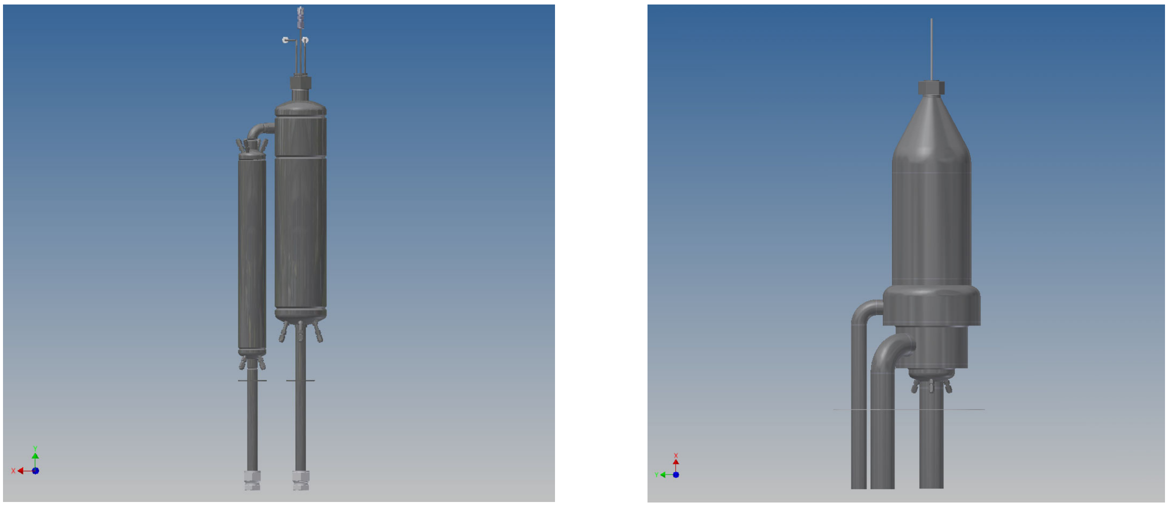

Figure 4: **Models of the water-gas-shift reactor of the fourth generation (WGS 4, left) and of the catalytic burner of the third generation (CAB 3, right) of the Forschungszentrum Jülich, each with a thermal power of 28 kW.**

The function of a water-gas-shift reactor within a fuel cell system is to reduce the concentration of carbon monoxide in the product gas of the autothermal reforming from approx. 8 vol.% to 1 vol.%. WGS 4 is a two-stage reactor. In the high temperature shift stage (HTS) the reaction runs in the temperature range between 400 °C and 450 °C. Carbon monoxide reacts with water giving carbon dioxide and hydrogen. In the HTS carbon monoxide conversion is thermodynamically controlled with a maximum of about 60 %. After the HTS the reformate is cooled down to 300 °C by injecting water at ambient temperature. In the low temperature shift stage (LTS) the residual carbon monoxide molecules again react with water into hydrogen and carbon monoxide with a maximum conversion of approx. 85 %. In the LTS the reaction is kinetically controlled and proceeds in the temperature range between 300 °C and 330 °C. By these means, the carbon monoxide concentration in the reformate is reduced to approx. 1 vol.%. So, the reformate can be fed to the anode of a high temperature Polymer Electrolyte Fuel Cell (HT-PEFC).

3.3 Catalytic burner

The function of a catalytic burner in a fuel cell system is to catalytically convert the flammable components of the off-gas of a fuel cell anode (H_2, CO, CH_4) into H_2O and CO_2. Thereby, reaction enthalpy is released, which is used for the production of steam. Figure 4 on the right hand side shows the model of the catalytic burner of the third generation (CAB 3) of the Forschungszentrum Jülich. It again well fits to the power class of ATR 9.2.

During the design of CAB 3 it became obvious that CFD simulations have to be performed to optimize the process of water evaporation. In Jülich´s catalytic burner the stream of water to be vaporized is injected at ambient temperature via a one-fluid nozzle onto a so-called deflecting surface. The deflecting surface itself is heated by the enthalpy flow of the off-gas of the catalytic combustion, which proceeds in a cylindrical reaction zone underneath the deflecting surface. Thereby, a minor part of the water stream directly vaporizes, while the majority forms a water film on the deflecting surface. Then, this water films drains off into an annular gap, which is also heated by the enthalpy flow from the catalytic combustion. In the annular gap the residual water stream should completely vaporize. Figure 5 shows CFD simulations, which illustrate the way, in which the water film drains off a plane, a Klöpper head and a hemispherical head at 30 ° inclination of the catalytic burner. Such inclination most probably occurs during operation of a catalytic burner on-board aircraft. It becomes obvious from Figure 5 that in the case of a plane the water film drains off into only one third of the annular gap, while using a Klöpper head more than one half of the perimeter was exploited. In the case of a hemispherical head however, the simulation shows that almost the whole perimeter of the annular gap is available for the water film to drain off. Based on these results, the deflecting surface inside the catalytic burner CAB 3 was constructed as a hemispherical head.

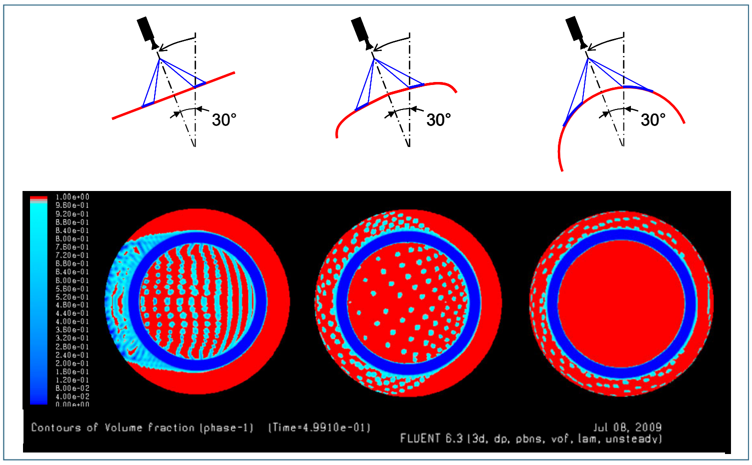

Figure 5: **CFD simulations showing in which way the water film drains off a plane, a Klöpper head and a hemispherical head at 30 ° inclination.**

Acknowledgements

The work was partly financed by the German Federal Ministry of Economics and Technology within the National Aerospace Research Programme (LuFo IV-2).

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