Chapter 58

System design for vehicle applications: Daimler Chrysler

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1 INTRODUCTION

Fuel cell systems are able to deliver electrical power with high efficiency, without or with very low emissions and at low noise levels, from hydrogen or hydrogen-rich reformer gases and air. By-products are exhaust gases, water and waste heat. The electrical power generated can be used in vehicles for propulsion as well as for the operation of electrically driven components.

PEM fuel cell systems require on-board stored hydrogen or hydrogen-rich gases which can be generated from liquid fuels such as methanol or the conventional hydrocarbons gasoline and diesel. The advantages and disadvantages of the different fuels are as follows (Figure 1):

- Fuel cell systems using pure hydrogen have the highest efficiency because the generation of a hydrogen-rich gas from methanol or gasoline consumes some of the fuel energy. Hydrogen-based fuel cell systems are emission-free and very compact. However, this size and weight advantage is, at least partly, reduced by the low energy density of the compressed or liquefied hydrogen, requiring large and heavy storage tanks.
- Methanol can be fueled in the same way as conventional fuels and can be reformed more easily and with higher efficiency than gasoline. The biggest drawback of a methanol-based fuel cell vehicle is the current absence of a methanol infrastructure.
- Gasoline and diesel have the highest energy density and are available worldwide. The energy efficiency of a vehicle with a fuel cell propulsion system based on gasoline is lower than the efficiency of systems based on hydrogen but higher than the efficiency of a car with an internal combustion engine, especially at low power.

The use of gasoline and diesel as fuels for PEM fuel cell propulsion systems would simplify the installation of a fuel cell-based vehicle market. The concurrent use of the fuel infrastructure by internal combustion engines and fuel cell propulsion systems can work alongside the use of synthetic fuels for the long term.

The question of which fuel will succeed cannot be answered now. In looking for that answer, DaimlerChrysler is developing fuel cell propulsion systems based on both hydrogen and methanol. Fuel cell systems based on hydrocarbon reforming are in the research stage.

2 TARGET SPECIFICATIONS FOR VEHICLES

Fuel cell systems for vehicle propulsion have to meet very strict technical and economic requirements to exceed the properties of the future internal combustion engine.

Handbook of Fuel Cells – Fundamentals, Technology and Applications, Edited by Wolf Vielstich, Hubert A. Gasteiger, Arnold Lamm. Volume 3: *Fuel Cell Technology and Applications*.

	H_2	Methanol	Hydrocarbons gasoline/diesel
Infrastructure	-- -- --	-- --	+ + +
Energy density	-- -- --	+ +	+ + +
Toxicity	0	--	-- --
Simple system	+ + +	--	--
Efficiency	+ + +	+ +	+

Figure 1. Advantages and disadvantages of different fuels for fuel cell systems.

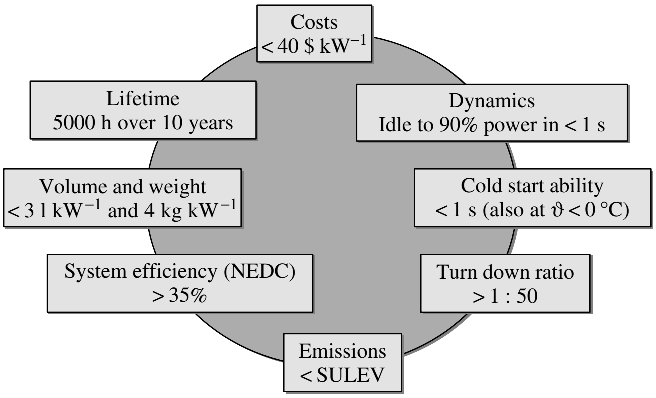

Figure 2. Requirements for fuel cell propelled passenger cars.

Figure 2 shows the most important requirements derived from the features of today's cars.

Additional specifications can be found by comparison with propulsion systems based on internal combustion engines regarding acceleration, top speed, climbing abilities and, last but not least, operation range on one tank volume. Most customers will not be willing to accept restrictions regarding these items and also regarding comfort, especially as long as there is an alternative propulsion concept available. Higher initial costs are only acceptable if the fuel economy and therefore operation costs are much lower.

2.1 Vehicle concept

The concept of a fuel cell vehicle is fundamentally oriented towards the individual vehicle to be realized, the envisaged field of application and the overall resulting operating conditions, especially regarding the fuel cell itself. The decision in favor of a particular vehicle is determined first and foremost by the purpose of application. First, a fundamental distinction can be made between passenger cars and commercial vehicles. This consideration rigidly determines many physical parameters, such as the required power output of the fuel cell and the electric motor, or space considerations. A further important factor is concerned with the field of application and the conditions under which the fuel cell vehicle is to be operated. A specifications book for a fuel-cell drive train can be drawn up on the basis of these clearly defined outline conditions; this allows the necessary or desired (driving) characteristics of the vehicle to be determined. A major challenge relates to the driving requirements of a fuel cell vehicle, independently of operating conditions.

In order to define the requirements placed on a fuel cell system and its application on board the vehicle, it is appropriate to determine the typical parameters of the basic vehicle as a basis of comparison. The parameters of a Mercedes-Benz A 160 CDi (W168 series) are as follows. This car typically weighs 1155 kg. Its CDi engine delivers 45 kW power output. This gives the vehicle an acceleration from 0 to 100 km h^{-1} in 15.1 s; it has an operating range of 1100 km on a single tank filling. A basis of comparison between various vehicles can be obtained by expressing the mechanical drive power as a function of a vehicle's mass. This generates specific power outputs (power-to-mass ratios). Table 1 shows typical values for various categories of vehicles.[1]

These values indicate that top-category vehicles typically have the highest power-to-mass ratios, whilst trucks have a relatively low specific power output of 10 kW (1000 kg)$^{-1}$ vehicle mass. The development of fuel cell systems for mobile application in passenger cars determines the long-term objective of a power-to-mass ratio in the order of 75 kW (1000 kg)$^{-1}$ overall vehicle mass. These fundamental observations regarding the power outputs of road vehicles yield target values for fuel cell vehicles and thus for the fuel cell systems themselves.

A distinction is to be made between fuel cell vehicles which allow energy recuperation and those which do not. Fuel cell vehicles with this facility are hybrid vehicles featuring two energy reservoirs, e.g., battery and hydrogen tank, and two energy converters, e.g., fuel cell and battery.

Table 1. Typical values of specific power of different categories of vehicle.

Vehicle	Mass (kg)	Power output (kW)	Specific power output (kW (1000 kg^{-1}))
Car	1000	75	75
Car	2000	350	175
Van	3000	100	30
Bus	16 000	320	20
Truck	40 000	400	10

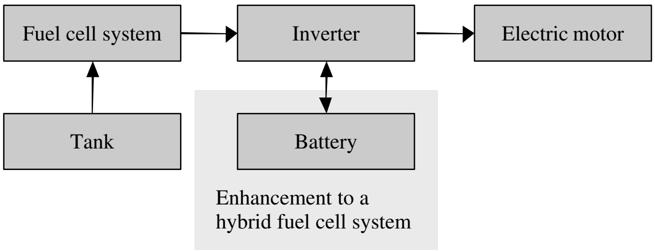

Figure 3. Possible hybrid configuration of a fuel cell system.

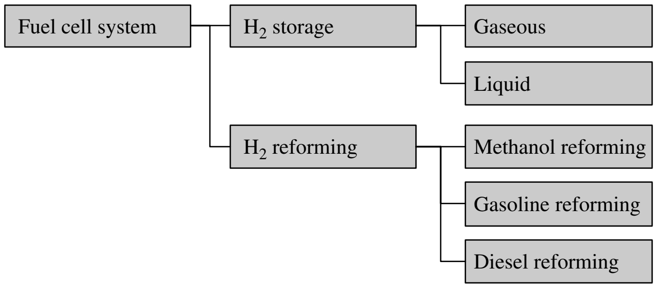

Figure 4. Storage of primary energy source.

Vehicles powered by a fuel cell alone can be categorized into those whose fuel cell is directly powered by hydrogen, and those in which the fuel is prepared in the fuel cell system (Figure 3).

The conventional variant generally defines the overall requirements for the design of a fuel cell vehicle. Driving performance and comfort are the overriding objectives. Like a conventional A-Class car, a fuel cell vehicle – even a fuel cell hybrid vehicle – must provide space for four to five occupants. The vehicle's mass, especially the additional mass of the hybrid version, must be taken into account when designing the drive unit. The top speed is to be in the order of 140 km h^{-1}. A fuel cell system typically has an output of 75 kW, of which 45 kW are available as mechanical power at the drive shaft. In this configuration, such a vehicle has an operation range of 300 km. The drive energy is stored, e.g., in the form of methanol or gasoline; these primary energy media are easier to handle than hydrogen and can be reformed into hydrogen. Moreover, in the hybrid version energy can be stored in chemical form in a NiMH battery.

As already mentioned, fuel cell systems fundamentally fall into two categories: systems which operate directly with hydrogen supplied from a tank, and systems which generate hydrogen from another primary energy medium. The former are further categorized according to energy storage method, and the latter in the choice and preparation of the primary energy medium. In most cases, the hydrogen is stored in the form of either a compressed gas or a liquid at low temperature. Systems which use a primary energy medium rich in hydrogen (hydrocarbons such as methanol, gasoline or diesel) as their hydrogen source reform these substances in order to release the bound hydrogen in molecular form. In order to even further increase the efficiency of a fuel cell system or of a vehicle, kinetic energy can be recovered partly and stored in the battery (Figure 4).

2.2 Driving requirements

All road vehicles must fulfill the basic requirements shown in Figure 5 which lists the conditions under which a vehicle can be operated. The vehicle's practical value is reduced if one or more of these possibilities are not provided; fuel cell vehicles must also satisfy these demands.

In this section, we will focus on the major technological challenges of the fuel cell developers. These are:

- start-up (with cold start and stop-start ability);
- driving operation (including maximum driving speed, and mountain driving with inclines); and
- driving cycles (described in detail in the following section).

Cold-start ability is the requirement for a vehicle to be started at a temperature of $-25\,^{\circ}C$. This represents a particular challenge, since fuel cells take a few minutes to reach operating temperature. In the following, on the basis of some fundamental assumptions, the necessary power output is determined for cold-starting a fuel cell system. Heating

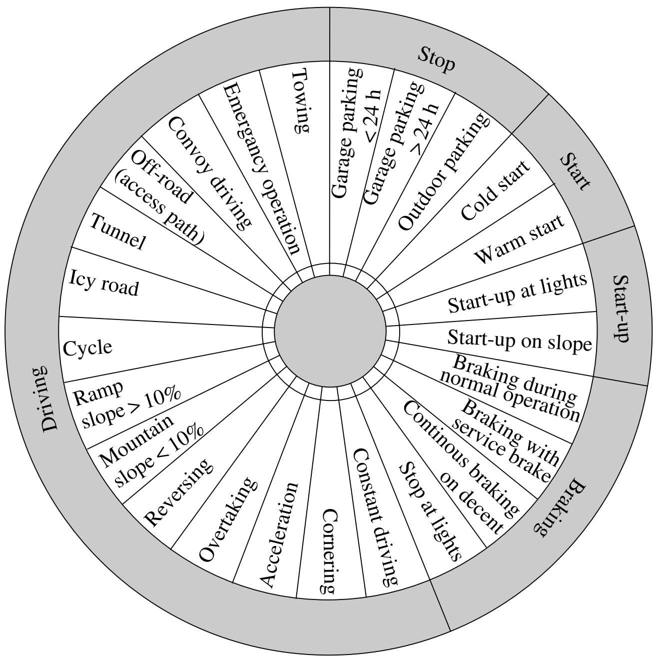

Figure 5. Possible vehicle conditions.

a fuel cell stack weighing 100 kg from −25 °C to 0 °C, for example, requires 1200 kJ of energy. In comparison the stack produces heat at a rate of 5 kW; this yields a warm-up time of 4 min if there is no other heat source, e.g., a burner.

A system needs to become standard over the next few years which will allow the drive system to be stopped and conveniently restarted. This is termed stop-start functionality. A vehicle's fuel consumption on one of the various standard consumption cycles can be reduced by 3–5%, assuming the drive system does not consume fuel while the vehicle is stationary.

In fuel cell vehicles with stop-start functionality, no mechanical power or electrical power (including parasitic electrical power) and thus no chemical power, is released – in other words, there is no transfer of matter or of energy, e.g., as heat. An acceptable system must be able to be restarted in well under one second, with only negligible noise development.

Considering the increased vehicle mass and limited cooling power, maximum speed is a critical driving requirement. At a comparable mechanical power output of 45 kW, 125 kW of primary energy must be provided under full load by a conventional drive train and 120 kW by a fuel cell drive train, by reason of system-imminent losses. With a conventional drive train, 34 kW is required to cool the system, but the corresponding figure for the fuel cell system is 60 kW. As this comparison indicates, cooling of a fuel cell system is a challenge. In the system under consideration, the heat dissipated by a fuel cell system and the maximum cooling power are in equilibrium under full load at 150 km h^{-1}. The maximum coolant power thus represents a limiting factor for the fuel cell's maximum overall power. This is due to the limitations on the inlet temperature of the fuel cell's coolant water. On upgrade or in high ambient temperatures, power output requirements are increased, or conversely, the power that can be delivered is reduced. In a compact-class vehicle, at an ambient temperature of 35 °C and an upgrade of ≥6%, for example, a state of equilibrium is reached at 100 km h^{-1} – assuming the coolant power remains unchanged compared to the previous case. However, the maximum cooling power is reduced as a result of the slower coolant air stream. Equilibrium is reached at 75 km h^{-1}. A target for future development is further improvement of the fuel cell's efficiency factor, in order to reduce the quantity of heat that needs to be dissipated. Moreover, the temperature level is to be increased at which the fuel cell discharges its thermal energy, in order to produce a more efficient coolant system. This can be attained for example by dispensing with moist process gases.[2]

2.3 Power demand and fuel economy

A vehicle's fuel consumption per distance covered (g m^{-1}) can be calculated according to the following formula:[3]

Driving resistances

Drive train: Motor | Drive train | Rolling resistance | Air drag | Gradient resistance: Acceleration resistance | Gradient resistance | Braking resistance

$$B_e = \frac{\int be \cdot \frac{1}{\eta_{DT}} \left[\left(m \cdot f \cdot g \cdot \cos\beta + \frac{\rho}{2} \cdot c_w \cdot A \cdot v^2 \right) + m \cdot (a + g \cdot \sin\beta) + B_r \right] \cdot v \cdot dt}{\int v \cdot dt} \quad (1)$$

The three principal factors influencing a vehicle's fuel consumption can be determined on the basis of this definition of consumption per distance. They can be categorized as contributing factors relating to the motor, the drive train and exterior resistance. In the internal combustion engine, the only major influencing parameter is specific fuel consumption B_e (g kWh^{-1}). At its most favorable point of operation, gasoline engines have a specific fuel consumption of approx. 240 g kWh^{-1}. Diesel engines have a considerably higher efficiency and thus a lower specific fuel consumption at their best mark of under 200 g kWh^{-1}. In the case of fuel cell vehicles, this parameter corresponds to the overall efficiency factor comprising the fuel cell system and the electric motor, expressed as g kWh^{-1}.

With regard to the drive train, only the transmission efficiency needs to be taken into account. Transmission losses amount to about 1–2% per gear stage. However, fuel cell vehicles can often dispense with a transmission by reason of the characteristic curve of the electric motor.

Driving resistance has a strong influence on fuel consumption. The contributing factors are rolling resistance, air drag, acceleration resistance, uphill gradient resistance and braking resistance.

The following measures can reduce fuel consumption:

- 10% reduction in rolling resistance: average fuel savings approx. 2%;
- 10% improvement in aerodynamics: average fuel savings approx. 3%; and
- 10% mass reduction: average fuel savings approx. 6%.

The overall driving resistance is calculated as the sum of rolling, air and uphill gradient resistance in accordance with Figure 6. Rolling resistance results from the flexing work loss between the tire and the road and is defined as follows:

$$F_{Ro} = f \cdot m \cdot g \quad (2)$$

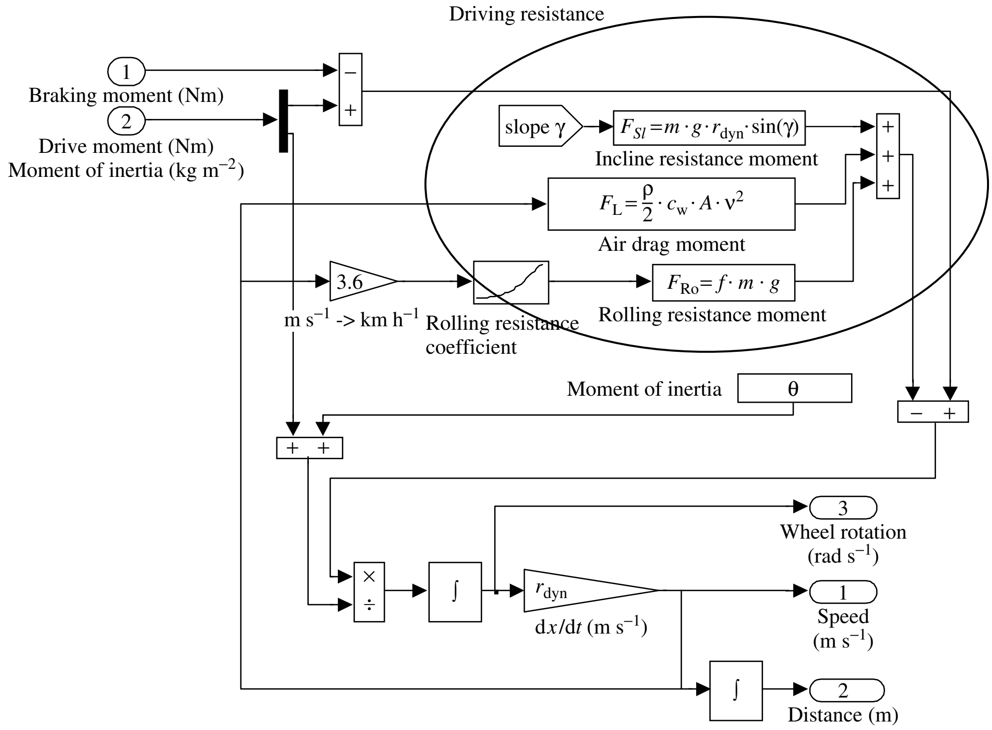

Figure 6. Schematics for vehicle model.

The rolling resistance coefficient f is inversely proportional to tire radius and directly proportional to tire distortion. It increases with increasing load, increasing speed and a reduction in tire pressure. At low speeds, new low-resistance tires have a rolling resistance coefficient of 0.008.

Air drag is a function of air density ρ, flow speed v, frontal area A and drag coefficient c_w as follows:

$$F_L = \frac{\rho}{2} \cdot c_w \cdot A \cdot v^2 \tag{3}$$

Drag coefficients for passenger cars range from 0.25 to 0.4, and for trucks from 0.4 to 0.9. These days, frontal areas are typically 1.5–2.5 m^2 for cars and 4–9 m^2 for trucks. Intensive development work in the optimization of vehicle contours has brought about a considerable reduction in drag coefficients over the past few years. Since air drag increases with the square of a vehicle's speed, it is the major contributing factor to driving resistance especially at high speeds and is thus the dominant factor in determining fuel consumption.[4]

In order to make meaningful statements regarding fuel consumption, a basis of comparison must be defined. Numerous standardized driving cycles currently exist in various countries. To determine the masses of emitted pollutants and fuel consumption levels, these driving cycles make use of a precisely standardized speed sequence. With defined gear shifts, acceleration, braking and idling phases as well as stationary periods, a driving cycle emulates typical operation of a car in normal traffic conditions; this provides a basis of comparison for fuel consumption measurements. The New European Driving Cycle (NEDC), Federal Test Procedure (FTP75) and 10•15-Mode are the most well known of these test methods.[5]

The NEDC (Figure 7), used throughout the European Union, is valid for vehicles with a permissible gross mass of $<$3.5 tonnes. The speed sequence is as follows: The cycle has a duration of 1220 s and an overall length of 11 km. The mean vehicle speed is approx. 34 km h^{-1} and the maximum speed 120 km h^{-1}. The mean drive power output for a vehicle with a mass of approx. 1.1 tonnes, a frontal area of approx. 2.3 m^2 and a drag coefficient of 0.32 (data for the Mercedes-Benz A-Class) amounts to 5 kW, and the maximum drive power output for this vehicle on the NEDC is approx. 31 kW. The NEDC is a cold-start test: prior to the test run, the vehicle must be left to stand for 12–36 h until the engine has assumed ambient temperature. Shift times and gears are specified for manual transmission vehicles. Since the speed of a vehicle must not deviate from specifications by any more than 2 km h^{-1}, these test runs call for extreme precision.

FTP75 (Figure 8) is mainly used in the United States and is valid for all vehicles from model year 1994 onwards. It is based on the following sequence.

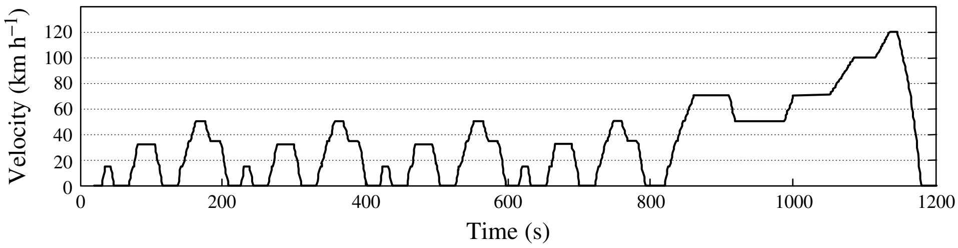

Figure 7. New European Driving cycle (NEDC).

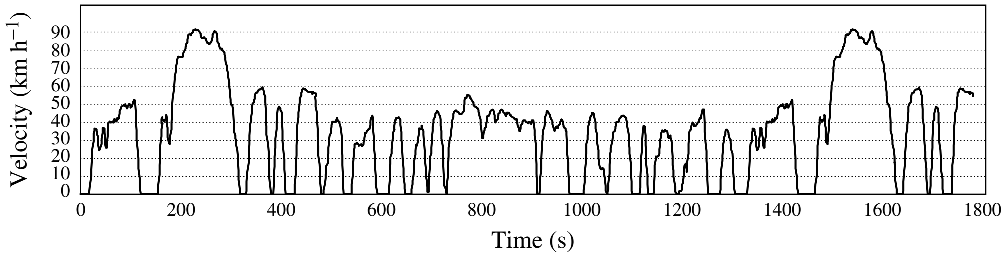

Figure 8. FTP 75 cycle.

The cycle has a duration of 1372 s + 505 s = 1877 s. The first 505 s are the cold start or cold transition phase. The next test stage, the stabilization phase, extends from seconds 506 to 1372. This phase is followed by a 10-min stationary period with the engine turned off. The warm transition phase (seconds 1373 to 1877) then follows; this hot test follows the same speed sequence as the cold transition phase. The overall cycle emulates a distance covered of 11 miles or 17.6 km. The mean speed amounts to approx. 32 km h^{-1} and the maximum speed is 91 km h^{-1}. The mean drive train power output for a vehicle mass of approx. 1.1 tonnes, a frontal area of approx. 2.3 m^2 and a drag coefficient of 0.32 (data for the Mercedes-Benz A-Class) amounts to 5 kW, and the maximum drive train power output for this vehicle on the FTP75 cycle is approx. 33 kW.

Finally, the 10•15 Mode (Figure 9) is a standardized driving cycle used in Japan as a test method for determining fuel consumption.

The cycle has a duration of 660 s and an overall length of 4 km. The mean vehicle speed amounts to approx. 23 km h^{-1}, with a maximum speed of 70 km h^{-1}. As the speed sequence already indicates, the required drive powers are very low; high-performance engines in particular are thus largely operated under part load, i.e., in a condition of unfavorable efficiency.

The mean drive train power output for a vehicle mentioned above (Mercedes-Benz A-Class) amounts to 3 kW, and the maximum drive train power output for this is only 14 kW.

Standardized driving cycles are intended to ensure a good basis of comparison for measurements by emulating the driving behavior of a passenger car under normal traffic conditions. The selected driving profiles, however, are artificial and only provide an approximate representation of genuine fuel consumption conditions. So-called customer cycles, on the other hand, are said to give a realistic picture of driving conditions "out on the road". They are therefore measured directly in real traffic. The disadvantages of this method, however, are its limited basis of comparison and its lack of acceptance – after all, what stretch of road is

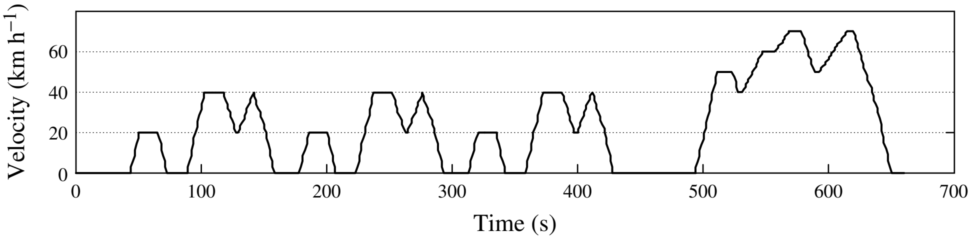

Figure 9. 10•15 cycle.

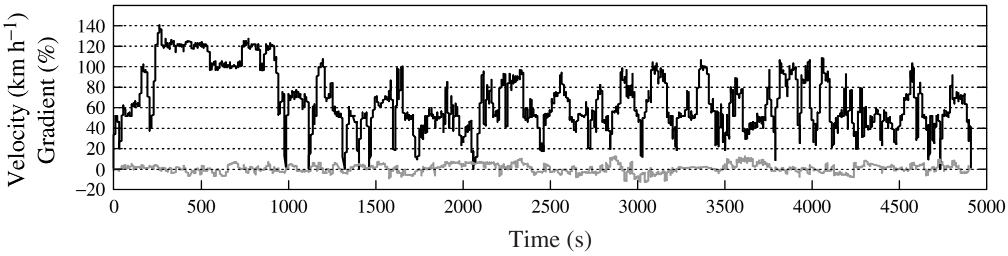

Figure 10. AMS cycle.

genuinely "typical"? A customer cycle used in Germany is the *Auto Motor Sport* cycle (Figure 10). In order to compare diverse vehicles, the German motoring journal *Auto Motor Sport* makes use of a particular test stretch 91 km in length. Speed profiles can vary depending on the vehicle and driver.

This customer cycle lasts approx. 1.5 h. As a result, it is not eligible for certification on the roller dynamometer. In addition to the speed profile, it also has a gradient profile. The mean speed is approx. 67 km h^{-1}, with a maximum of 140 km h^{-1}. The mean power train output for a vehicle mass of approx. 1.1 tonnes, a frontal area of approx. 2.3 m^2 and a drag coefficient of 0.32 (data for the Mercedes-Benz A-Class) is 7 kW, and the maximum drive output for this vehicle is approx. 59 kW. As these figures indicate, this is a much more dynamic cycle, since the engines operate under full load to a greater extent.

In view of equation (1) for fuel consumption per distance covered, the drag coefficient and the mass of the vehicle are highly significant. Figure 11 shows the connection between these parameters. There are diverse ways of reducing this vehicle's consumption, for example from the original figure of 3.1 l (100 km)$^{-1}$ to 3.0 l (100 km)$^{-1}$. This can be attained by reducing the vehicle's weight by 80 kg, but also by reducing the drag coefficient by a factor of 0.03. On the other hand, a reduction in drag coefficient of this order is considerable and requires enormous effort in terms of development and finance.

Further information about influence of aerodynamics on NEDC fuel consumption can be derived from Figure 12. It shows the power at the wheels of an A-Class car as measured on the New European Driving Cycle. The urban cycle is depicted only once; it is carried out four times, after which the extra-urban cycle is driven through once. In other words, the urban cycle is dominant in the NEDC. The overall wheel power comprises the following elements:

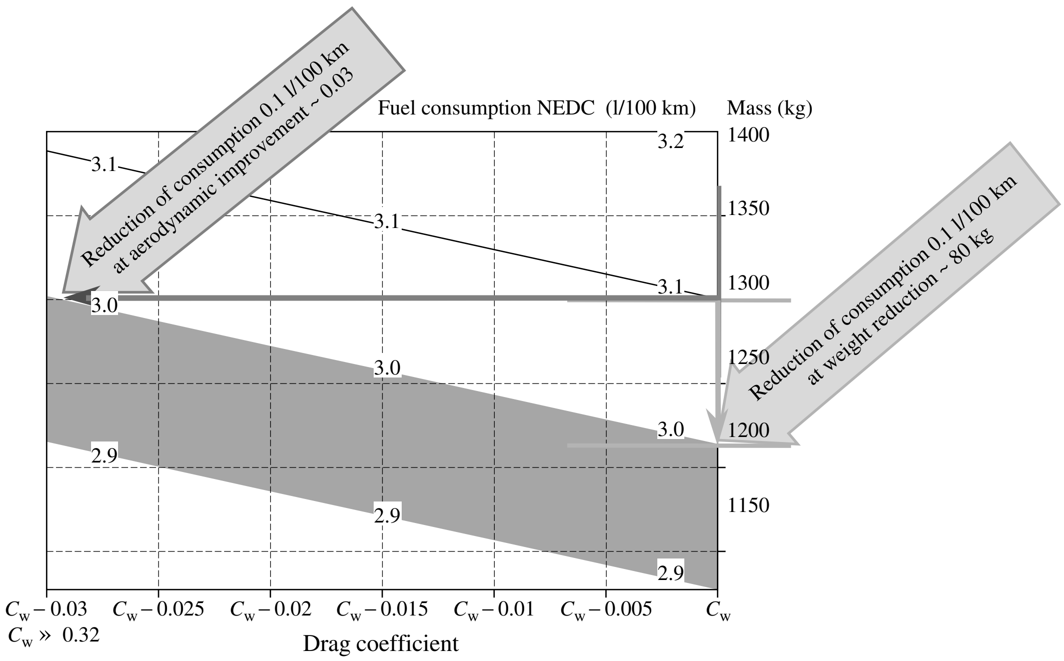

Figure 11. Fuel consumption in relation to vehicle mass and drag coefficient.

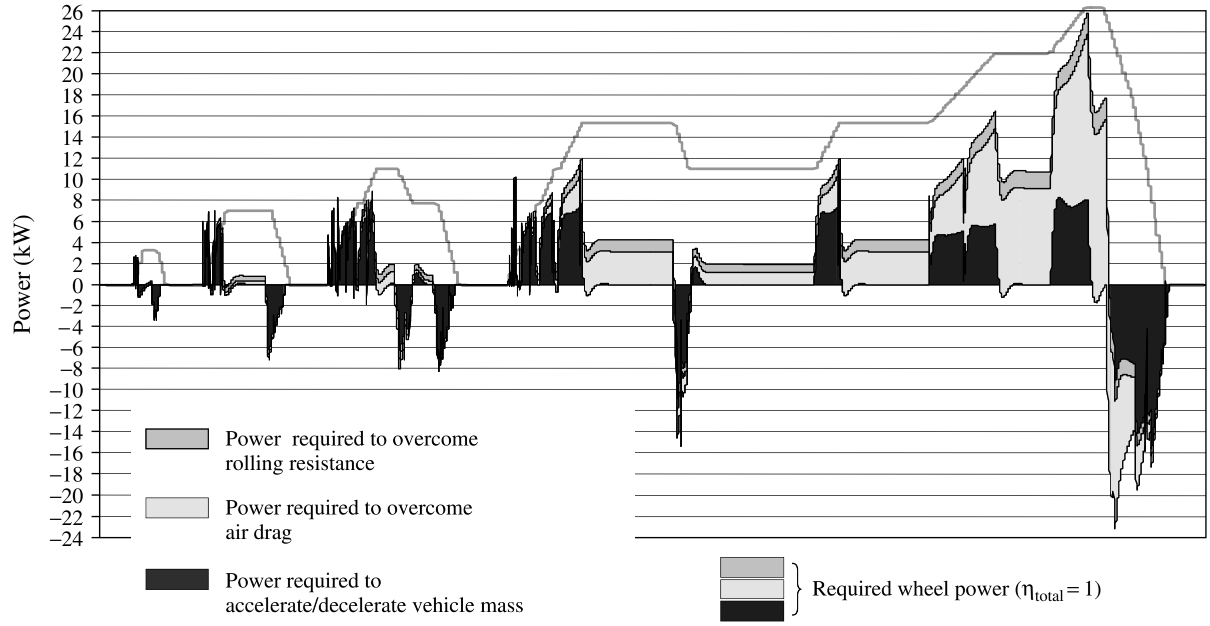

Figure 12. Required power ratios for the NEDC.

- power required to overcome rolling resistance;
- power required to overcome air resistance; and
- power required for accelerating and braking the mass of the vehicle.

The following conclusions can be drawn:

1. On stretches covered at speeds $<70\,\mathrm{km\,h^{-1}}$ while accelerating or decelerating, inertia is the dominant factor in terms of wheel power requirements.
2. On stretches covered at a constant low speed $<30\,\mathrm{km\,h^{-1}}$, rolling resistance is dominant.
3. On high-speed stretches above $70\,\mathrm{km\,h^{-1}}$ aerodynamics is the dominant factor in terms of wheel power requirements.

In view of these considerations, it is mainly weight reduction and tire improvement measures that bring about fuel savings on driving cycles with a major urban component (e.g., NEDC). In the case of cycles with a significant highway component, on the other hand, reduction in fuel consumption is brought about largely by aerodynamic improvements.

In terms of energy considerations, too, important conclusions can be drawn with regard to measures for reduced fuel consumption. All energy losses in the drive train can be shown by means of Sankey diagrams (Figure 13). This is illustrated by the following example. In 1996, Daimler-Benz built Necar II (New Electric Car), an electric fuel cell vehicle on the basis of the V-Class. The fuel cell system has an output of 50 kW and an electric potential of 250 V. The hydrogen pressure tanks have a combined volume of 280 l at a pressure of 250 bar and are located on the roof of the vehicle. In addition to the power losses in the fuel cell, the other main drive train losses in this vehicle occur in the auxiliaries (compressor, etc.), direct current (d.c.)/d.c. converter, power electronics and motor and in the transmission. The extent of these power losses on the NEDC is shown in Figure 13.

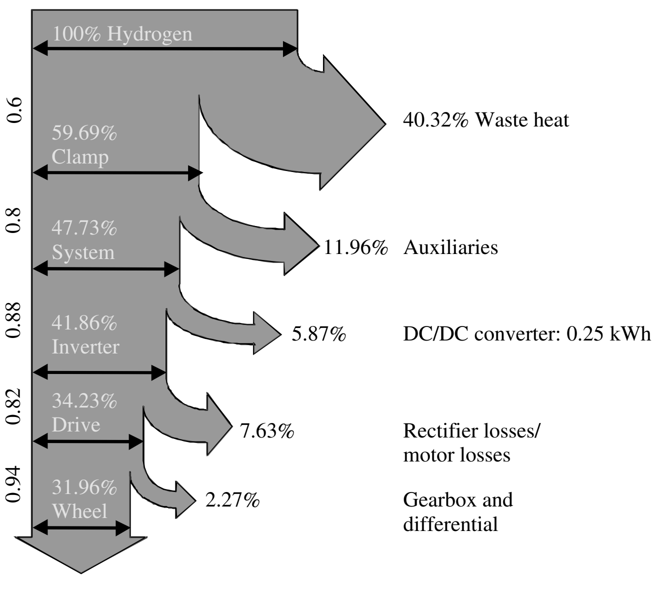

Figure 13. Energy flow diagram for Necar II.

3 FUEL CELL SYSTEMS FOR ALTERNATIVE PROPULSION CONCEPTS

3.1 Basic specifications

For propulsion applications PEM fuel cell systems are mostly in use because of the low operation temperature, the short start-up time and the good dynamic and transient behavior.[6, 7] Therefore only PEM fuel cell powered vehicle concepts are subject of this article.

A fuel cell propulsion system can be seen in a first step to be a black-box with the inlet streams fuel and oxidant and the outlets electrical power and exhaust gas (see Figure 14). In addition the system produces waste heat and therefore it needs to be cooled.[3]

The second step is the definition of the kind of these inlet and outlet streams (Figure 15). For propulsion applications the fuel can be hydrogen, methanol or a hydrocarbon like gasoline, diesel, compressed natural gas (CNG), or liquefied natural gas (LNG) and for practical reasons the oxidant

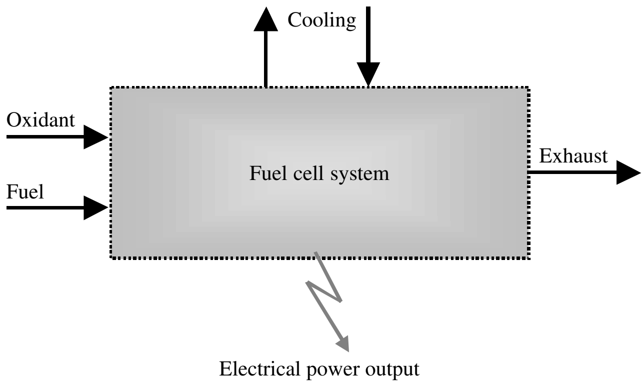

Figure 14. Schematic diagram of a fuel cell system.

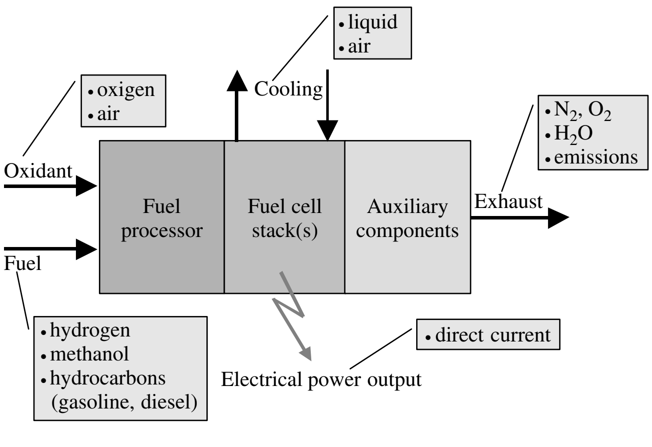

Figure 15. Inlet and outlet flow streams of a fuel cell systems.

will always be air. The electrical power delivered is direct current. Voltage and current depend on the layout of the fuel cell stacks. The cooling of the system – the stack and the system components – can be done with liquid cooling (water or water glycol mixture) or by air cooling.

The decision of the kind of fuel for the FC system has the greatest consequences: a hydrogen fuel cell system is relatively simple and has the highest efficiency. On the other hand, in this case the largest and most heavy storage tanks must be assigned based-on the very low volumetric power density of pressurized or liquefied hydrogen. If methanol or hydrocarbons are used, the hydrogen for the fuel cells has to be generated in a reforming and gas cleaning device (exception: direct methanol fuel cell), including exhaust gas cleaning.

In addition, the composition of the exhaust gases depends on the fuel. Hydrogen fuel cell systems only emit nitrogen, oxygen and water steam, whereas the exhaust gases of fuel cell systems with reformer also contain at least carbon dioxide and some ppm carbon monoxide. The choice of the applied fuel also influences other properties of the system and most of the boundary conditions, especially the storage tank type, volume and weight, and therefore also the free volume that can be used for the fuel cell system including the propulsion components electrical motor and transmission itself. Also, this decision defines the essential system design and architecture of the fuel cell propulsion system.

The third step is the definition of the properties and specifications of the fuel cell system based on the demands that should be fulfilled by the vehicle including driving requirements like operation range, top speed, acceleration, dynamics, climbing ability and comfort and usage aspects, e.g., durability, reliability, cold start time and energy consumption, costs, fuel consumption, weight and volume of the system.

Some of these specifications, especially weight and volume of the system including storage tank and E-drive can only be calculated as one of the results of the complete layout process. These properties are also input data for the calculation of fuel consumption, operation range, speed and acceleration and influence the propulsion power. Therefore the complete layout process for a vehicle with a fuel cell propulsion system is an iterative process and the properties have to be estimated in the first step. After definition of the main components of the propulsion system the weight of the complete vehicle including fuel cell system, E-drive, storage tanks and other components can be estimated more accurately, starting with the required driving characteristics to the required power for propulsion at the wheel that now can be calculated using top speed, acceleration and climbing ability. With the efficiency of the propulsion components the net power output of the fuel cell system can be defined.

3.2 Basic system layout, variables and properties

Fuel cell systems can be characterized by their main components and the substantial specifications. For the following discussion it is presupposed that the fuel cell system examined works on the basis of conventional fuels (gasoline or diesel). In this case the main sub-systems or components of the system are (Figures 16 and 17):

1. Fuel cell stack(s)
2. Fuel processor system with the components
   - reformer
     - partial oxidation (POX) or
     - steam reforming (SR) or
     - autothermal reforming (ATR)
   - shift reactor
     - high and/or low temperature shift reaction (HTS/LTS)
   - gas cleaning
     - preferential oxidation (PROX) or
     - methanation or
     - membrane separation
3. Dosing
4. Auxiliary components, such as
   - air supply with pressure and flow control as well as silencers and pipework system

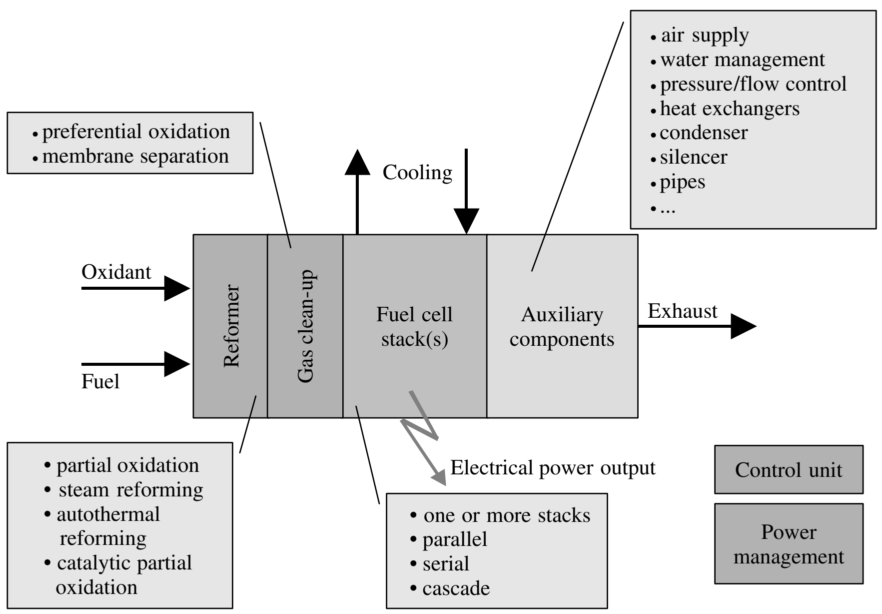

Figure 16. System components.

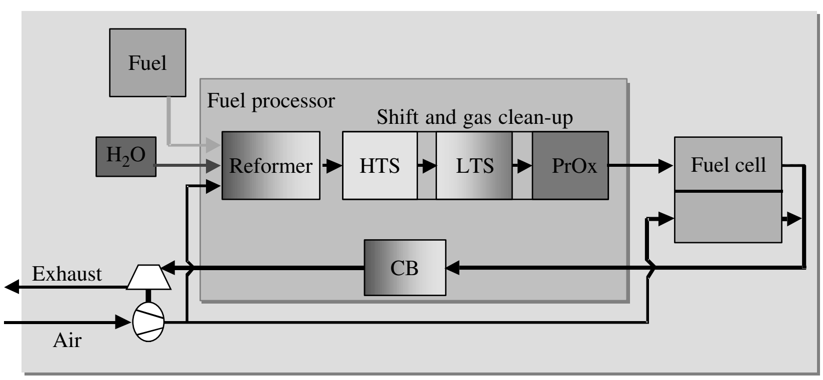

Figure 17. System components of a fuel cell system based on fuel reforming.[8, 9]

- water management including condensers and water separators, feed pump, regulating valves, storage tank and pipework
- cooling fans
- gas heat exchangers
- sensors for pressure, temperature, and other data
- control units
- power adjustment, e.g., d.c./d.c. converter.

The substantial electrical specifications of the system result from the definition of

- maximum net power
- turn-down ratio and part-load behavior
- duty cycle and
- voltage range.

Beyond that further specifications are to be considered and specified for the fuel cell system, whereby some of the data can only be estimated initially, because they are results of detailed system layout and simulation:

- system efficiency at maximum power
- efficiency within the driving cycle
- dynamic behavior
- cold start-up: minimum starting temperature, cold start-up time and energy
- life time
- emissions
- volumes and weight
- packaging and installation
- costs.

Most of these data affect each other: for instance a high system efficiency and a high life time can be achieved by a small loading related to the fuel cell area, according to a small current density; on the other hand this leads to larger volume, weight and rising costs.

For the mode of operation of the stack still the variables

- operating pressure
  - high pressure, $p \geq 2\,\mathrm{bar_a}$
  - low pressure, $p < 2\,\mathrm{bar_a}$
  - ambient air, $p \approx 1\,\mathrm{bar_a}$, as well as
- stack humidification
  - externally
  - internally
  - humidification-free

have to be specified. “Stack humidification” means only the humidification of the inlet gas flow streams of the stack. Beyond that the water balance for the reforming process must be guaranteed in the system. This means that the water needed for the reforming of the fuel must be recovered by usually complex measures within the system from the outlet flow streams cathode exhaust, anode exhaust or reformer outlet or it must already be present in the refueled fuel (so-called “Premix”), because for reasons of acceptance for the fuel cell powered propulsion system by the customer, an additional refueling with water should be avoided.

The result of the fixing of the components and the operating parameters is the definition of the fundamental system architecture and the system structure, respectively. The layout of the sub-systems and individual components can be accomplished afterwards as described in the following.

3.3 Proceeding during the layout of a fuel cell propulsion system

Based on the requirements of the driving profile of the vehicle described in Section 2, the actual layout of the system and sub-system components can now take place (Figure 18). First the required propulsion power necessary at the wheel has to be specified for different driving

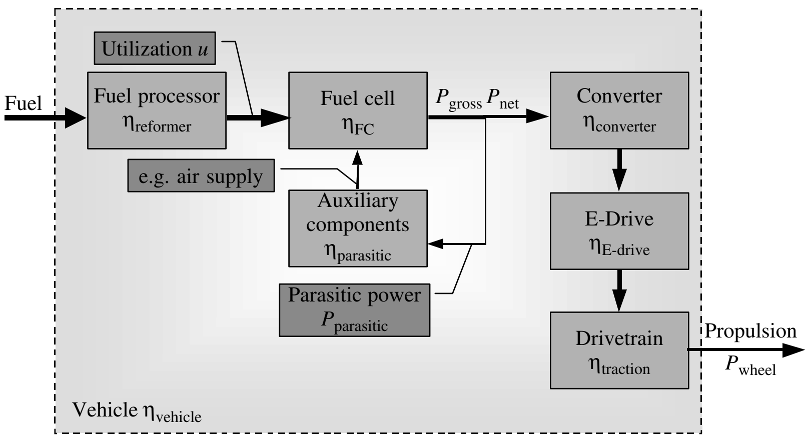

Figure 18. Efficiencies of a fuel cell propelled vehicle and the system components.

conditions (e.g., maximum speed in the plane, climbing). Taking into account the effective efficiency for each of these conditions for the drive train η_{traction}, electric engine $\eta_{\text{E-drive}}$ as well as voltage converter $\eta_{\text{converter}}$ the electrical net power, which must be supplied by the fuel cell system, results:

$$P_{\text{net}} = \frac{P_{\text{wheel}}}{\eta_{\text{traction}} \cdot \eta_{\text{E-drive}} \cdot \eta_{\text{converter}}} \quad (4)$$

Beyond the drive power the fuel cell system must also be able to supply the auxiliary components with electricity, which are necessary to cover its own demand. Here, the air supply unit, represents the main usage, as well as pumps, electrical valves, cooling fans. The portion of electricity consumed by these auxiliary components and thus not available for the drive power, can be defined by a parasitic efficiency $\eta_{\text{parasitic}}$ and/or the parasitic consumption $P_{\text{parasitic}}$. Thus the electrical gross power that has to be supplied by the fuel cell stack results in

$$P_{\text{gross}} = P_{\text{net}} + P_{\text{parasitic}} = \frac{P_{\text{net}}}{\eta_{\text{parasitic}}} \quad (5)$$

or

$$\eta_{\text{parasitic}} = \frac{P_{\text{net}}}{P_{\text{gross}}} \quad (6)$$

respectively. For high performance fuel cell systems the efficiency $\eta_{\text{parasitic}}$ is in the order of magnitude of 80–95%.

The next step is the calculation and definition of the efficiency of the fuel cell stack or fuel cell stacks, respectively. From the U/j characteristic of the fuel for the analyzed application as a function of the previously specified data operating pressure, fuel composition, hydrogen and air stoichiometry and humidification, the correlation between current density in the stack and the voltage per cell results (schematic diagram see Figure 19). By this the efficiency of the hydrogen conversion in the fuel cell η_{FC} and consequently the efficiency of the gross power generation of the fuel cell system are also specified.

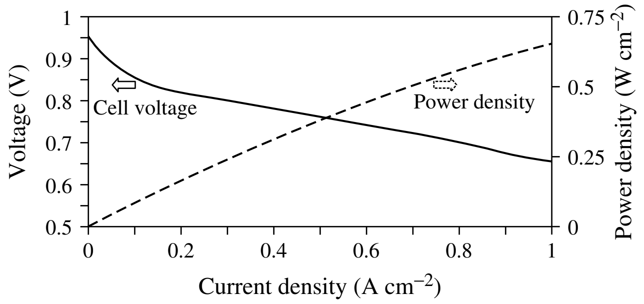

Figure 19. Schematic diagram of the fuel cell U/j characteristic.

The supply of hydrogen by the fuel processor system is subject likewise to an efficiency η_{reformer}, which can be defined by the energy content of the hydrogen produced, related to the energy content of the fuel input:

$$\eta_{\text{reformer}} = \frac{h_{H_2} \cdot \dot{m}_{H_2,\text{reformer}}}{h_{\text{fuel}} \cdot \dot{m}_{\text{fuel}}} \quad (7)$$

As overall efficiency results for the fuel cell system

$$\eta_{\text{system}} = \eta_{\text{reformer}} \cdot u \cdot \eta_{\text{FC}} \cdot \eta_{\text{parasitic}} \quad (8)$$

whereby u represents the utilization, i.e., the ratio of the hydrogen used in the fuel cell to the hydrogen generated in the fuel processor.

The overall efficiency of the conversion from fuel energy to the driving power within the complete propulsion system of the vehicle results as

$$\begin{aligned}\eta_{\text{vehicle}} &= \eta_{\text{traction}} \cdot \eta_{\text{E-drive}} \cdot \eta_{\text{converter}} \cdot \eta_{\text{system}} \\ &= \eta_{\text{traction}} \cdot \eta_{\text{E-drive}} \cdot \eta_{\text{converter}} \cdot \eta_{\text{reformer}} \\ &\quad \cdot u \cdot \eta_{\text{FC}} \cdot \eta_{\text{parasitic}} \end{aligned} \quad (9)$$

For the realization of a low fuel consumption the total vehicle efficiency η_{vehicle} and thus also the individual terms of the efficiency equation (9) should be as high as possible. However, some fundamentals have to be considered:

- the efficiencies of the different steps of the process are not independent but partly affect each other mutually (e.g., the parasitic energy consumption and thus $\eta_{\text{parasitic}}$ is usually smaller with a low-pressure system than with a high-pressure system, on the other hand the efficiency of the fuel cell η_{FC} decreases with decreasing operation pressure and otherwise the same parameters).
- e.g., in the case of electric motor and voltage converter components with higher efficiency are mostly heavier, which affects negatively the drive power needed for a certain drive performance.

In addition, for the function of the fuel cell system as high an efficiency as possible is still indispensable for other reasons: the water balance can be solved more easily with a high efficiency of the overall system, i.e., at higher condensation temperatures, and the fraction of the input fuel energy, which is not converted into traction power, results unavoidably as waste heat and must be exhausted with the help of a cooling system, which becomes larger the lower the efficiency of the overall system.

3.4 Layout of the sub-system components

After the fundamental definition of the system structure and the first definition and estimation of the most important operating parameters, the layout of the various sub-systems and components takes place. This is demonstrated in the following using the example of the fuel cell stack.

An essential component of the fuel cell system is the fuel cell stack or the fuel cell stacks, respectively. As is well known, the U/j characteristic for given operating parameters such as composition and stoichiometry of the anode gas represents the relationship between the voltage of the fuel cell and current load, related to the active cell area. Additionally, a fixed relationship between cell voltage and fuel cell efficiency exists (Figure 20). Therefore two cases for the layout of the fuel cell stack must be differentiated in practice (Figure 21):

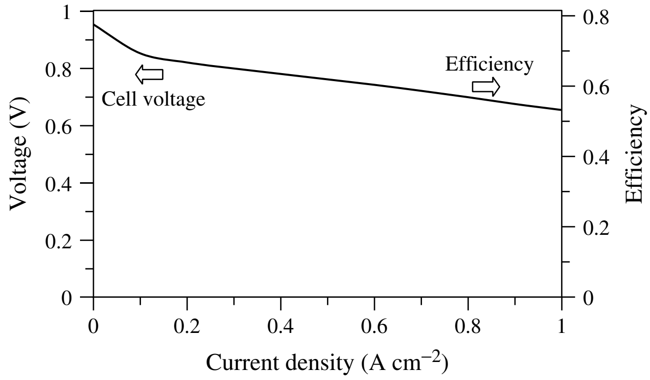

Figure 20. Relation between cell voltage and efficiency.

If highly efficient hydrogen conversion in the fuel cell is required, the cell voltage chosen should be relatively high with corresponding low current density. In this case the necessary cell area and also volume, weight and costs of the stack becomes larger, since material costs are directly proportional to the cell area.

The stack should be as compact, light-weight and cheap as possible, and therefore a large current density has to be chosen, whereby the cell voltage and thus the efficiency of the fuel cell decreases. At the same time it must be taken into account that the higher cell load reduces the lifetime of the stack or individual cells.

Further, the fuel cell stack must also be able to supply the auxiliary components of the fuel cell system with the necessary electrical energy. This is expressed, as shown above, by the parasitic efficiency $\eta_{parasitic}$. Based on a demanded net power P_{net} of the fuel cell system, therefore the stack must be able to produce the electrical gross power

$$P_{gross} = \frac{P_{net}}{\eta_{parasitic}} \tag{10}$$

From the chosen point of cell voltage/current density of the U/j characteristic, the further data can be calculated:

$$P_{gross} = U_{cell} \cdot I \cdot n_{cells} = U_{cell} \cdot n_{stack} \cdot n_{cells/stack} \cdot j \cdot A_{active} \tag{11}$$

where P_{gross} is the electrical gross power of the fuel cell stack (W), U_{cell} is the voltage per cell (from U/i characteristic) (V), I is the current (A), n_{cells} is the total number of the cells (–), n_{stack} is the number of the stacks (–), $n_{cells/stack}$ is the number of cells per stack (–), j is the current density

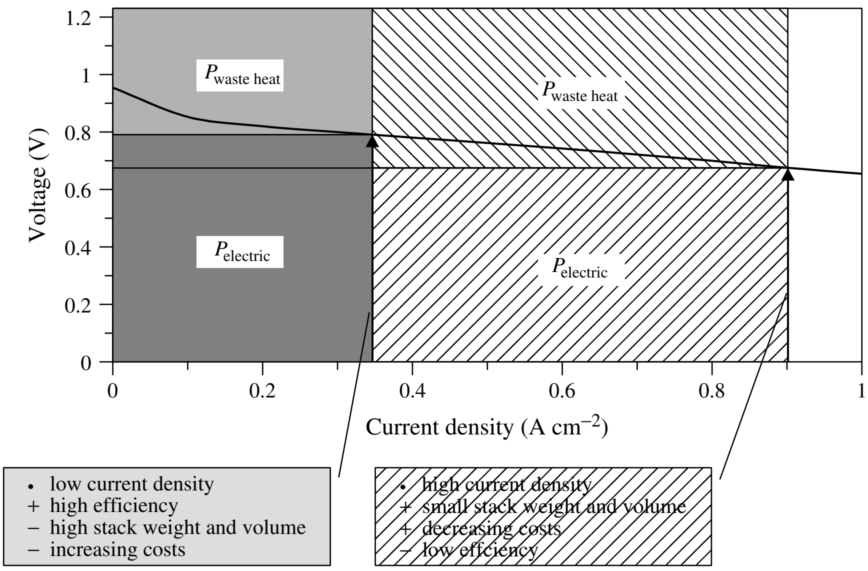

Figure 21. Power and waste heat for low and high current density.

(from U/i characteristic) ($\mathrm{A\,cm^{-2}}$), and A_{active} is the active cell area ($\mathrm{cm^2}$).

If, for example, the total number of cells is divided into two stacks, then the stacks can be connected electrically either in parallel to increase the current or serially for high voltage. Typically for drive systems the total voltage should be in the range of 250–400 V, because on one hand a high voltage is necessary for small and effective propulsion components, but on the other hand the difference between the lowest voltage during maximum power and the highest voltage during idle mode should be as small as possible. From these considerations typical cell voltage values in the range of 700 mV result. With the calculated data the size of the stacks can be determined:

Active cell area:

$$A_{\mathrm{active}} = \frac{P_{\mathrm{gross}}}{U_{\mathrm{cell}} \cdot n_{\mathrm{stack}} \cdot n_{\mathrm{cells/stack}} \cdot j} \tag{12}$$

and the required cell/stack area

$$A_{\mathrm{cell}} = \frac{A_{\mathrm{active}}}{\alpha_{\mathrm{active}}} \tag{13}$$

where α_{active} represents the ratio of active area to bipolar plate area, according to the active cell area related to the total area of the cell (not active ranges of the cell area are, e.g., inlets and seal areas). Typical α_{active} values are in the range of 80–86%.

The distribution of the total area into the height and width dimensions of the stack can be specified within limits to a large extent freely, based on, e.g., the installation conditions into the vehicle

$$A_{\mathrm{cell}} = h_{\mathrm{stack}} \cdot w_{\mathrm{stack}} \tag{14}$$

The stack length results from the number of the cells, the cell thickness as well as the thickness of the two end plates of the stack

$$l_{\mathrm{stack}} = n_{\mathrm{cells/stack}} \cdot d_{\mathrm{cell}} + 2 \cdot d_{\mathrm{end\ plate}} \tag{15}$$

So the total volume of the stack becomes

$$V_{\mathrm{stack}} = (n_{\mathrm{cells/stack}} \cdot d_{\mathrm{cell}} + 2 \cdot d_{\mathrm{end\ plate}}) \cdot h_{\mathrm{stack}} \cdot w_{\mathrm{stack}} \tag{16}$$

Thus the main component of the fuel cell system is fixed. In a similar way the determination of the size of the other system and sub-system components like fuel processor, air supply, water recovery including storage and dosing up to pipework system, control units with measuring components and electrical connection, can all be carried out. For these components the required performances are to be specified first, in order to derive the necessary data from them.

Determining data for the different components are:

- Fuel processor: kind and mass flow of fuel, water and air, pressure level, catalyst, reforming process, gas cleanup, component arrangement, heat integration, quantity and composition of recirculation, quantity and composition of the feed gas for the fuel cell, hydrogen stoichiometry;
- Air supply: air stoichiometry, air mass flow, inlet pressure, outlet pressure, efficiency, electrical power consumption, part-load behavior;
- Water recovery: quantity of the water, temperature level of condensers, storage volume, dosing quantity, pressure level;
- Control unit: type and number of the sensors, signal processing, control algorithm;
- Electrical connection: power, fuel cell voltage level, voltage level intermediate circuit, voltage e-drive, turn-down ratio, part-load behavior, efficiency;
- Cooling: temperature of cooling fluid and ambient air, temperature difference between inlet and outlet, mass flow cooling fluid and air, electrical power consumption;
- Other equipment: pipework, valves, sensors, support structure, framework, insulation.

The calculated data and dimensions of the components and the system has to be compared with the free space available for the propulsion system in the vehicle. Therefore after designing the different components, the arrangement and packaging of the components usually has to be analyzed with the target to arrange the components in a functional and suitable way in the vehicle. Further volume is needed for the driving motor and drive train as well as for fuel tanks. From the fuel tank volume the driving range of the vehicle results in the reversal conclusion with consideration of the vehicle weight.

As already mentioned, all data for the system including weight, size, dimensions, available fuel tank volume, cooling fan layout, but also in addition, drive performance and fuel consumption of the vehicle, affect each other mutually. Hence it follows that, in the first step of the layout usually no satisfying solution can be found, because some of the data needed at the beginning are only result of the complete layout process for fuel cell system including power supply units, electric motor and fuel storage. The layout of a fuel cell system for propulsion is therefore always an iterative process, until an optimized solution for the respective application can finally be found.

4 FUEL CONSUMPTION OF A FUEL CELL CAR BASED ON GASOLINE

In this section the steps necessary for fuel consumption calculations are described. The fuel consumption of a fuel cell car with a gasoline reformer in a special driving cycle is calculated as an example. For that purpose a conventional car is taken as the basis for the calculations, the weight of that car with a fuel cell system based on gasoline is estimated and classified. The average power demand in a certain driving cycle is calculated, estimations for the efficiencies of the propulsion system are given and the fuel consumption is calculated.

4.1 Description of the procedure

In order to calculate the fuel consumption of a fuel cell car based on gasoline, one has to proceed as follows. The first step is to specify the aerodynamic properties (c_w, A) and the weight of the car including the fuel cell system and the propulsion system, because these are the decisive factors for the calculation of the power demand in the driving cycle. The next step is to look into the frequency distribution curve of the power demand in a certain driving cycle and to determine the average power demand. Then it is necessary to specify ranges of the efficiencies which are linked to vehicle efficiency at average power demand. In this way a range for the vehicle efficiency is defined. Finally it is possible to calculate the fuel consumption if the weight of the car, the power demand of the specified driving cycle and the vehicle efficiency are available. An example of a calculation of the fuel consumption of a fuel cell car with a gasoline reformer system is shown in the following steps.

4.2 Properties and weight of the car, weight classification

In order to calculate the fuel consumption of a fuel cell car with gasoline reformer, it is necessary to specify the type of car used in the calculations. The specification of the car fixes its aerodynamic properties which are of increasing importance for the power demand with increasing velocities. In contrast to that the weight of the car is of main importance at low velocities e.g., in urban traffic (see Section 2).

In this example the fuel consumption of a Mercedes A-class with 60 kW fuel cell system (net system power output) is calculated, for which the aerodynamic properties are well known.

Table 2. Estimation of the weight of a fuel cell-powered vehicle.

	Conventional		Fuel cell
Vehicle weight (A 160 CDi)	1155 kg		
ICE	−69 kg		
Gear	−20 kg		
Exhaust	−10 kg		
⇒ Body	1056 kg	⇒	1056 kg
Fuel cell system (power density = 300 W kg^{-})			200 kg
Inverter			20 kg
E-Drive			60 kg
Gear			10 kg
Total vehicle weight	**1155 kg**		**1346 kg**

For the specification of the car weight a conventional Mercedes A-class with internal combustion engine is taken as the basis and the weight of the fuel cell system and the gasoline reformer is estimated (Table 2).

The assumption of a power density of 300 W kg^{-1} is not yet achieved by today's fuel cell systems with gasoline reformer, but it is the target for 2004 for the fuel cell system being developed in the DOE program.[10]

The fuel cell vehicle with a fuel cell system including a gasoline reformer is approximately 200 kg heavier than a conventional car with ICE which leads to the conclusion that the power density of future fuel cell systems has to be in the range of 1000 W kg^{-1}, which is the power density of internal combustion engines.

For fuel consumption calculations 100 kg additional load and fuel to fill up 90% of the tank volume are added to the total vehicle weight:

$$\text{Calculation weight} = \text{Total vehicle weight} + 100\,\text{kg load} + 40\,\text{kg fuel} \quad (17)$$

This leads to a calculation weight of approximately 1500 kg which fits in the weight classification of "1470 kg". This weight classification considers all vehicle weights between 1470 kg and 1590 kg as the same. Weight classifications were introduced for standardization reasons in order to simplify vehicle comparisons.

4.3 Power demand and distribution of power demand in the NEDC

Figure 22 shows the power demand at the wheel during the NEDC of which the temporal velocity development is shown in Section 2 with the specified vehicle.

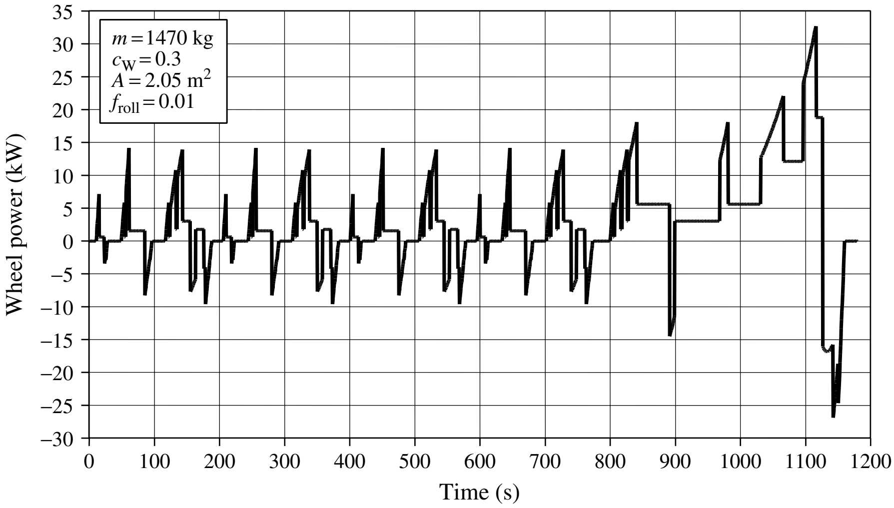

Figure 22. Temporal development of wheel power during NEDC.

The absolute power demand at the wheel is below 15 kW in the first four phases which represent urban traffic driving. The phases with the highest power demands occur during the last 400 s where high velocities and high accelerations are required (highway driving). The maximum power demand is 33 kW.

Figure 23 shows the frequency distribution of the power demand. It is possible to drive 53% of the NEDC with 5 kW wheel power, and 77% with 10 kW wheel power. The frequency of wheel power demands higher than 20 kW is below 2%. The average power demand is 5 kW. Consequently the fuel consumption of a car in the NEDC is mainly dependent on its performance at low wheel power demands.

4.4 Ranges for the efficiencies of a fuel cell system's components

As mentioned in Section 3.3, vehicle efficiency is composed of the efficiencies of traction, the converter, the electric motor, the gasoline reformer, the fuel cell, the hydrogen utilization in the fuel cell and the parasitic efficiency. The efficiencies of traction, the converter, the electric motor and the hydrogen utilization can generally be estimated as follows:

$$\eta_{\text{traction}} = 0.93$$

$$\eta_{\text{converter}} = 0.95$$

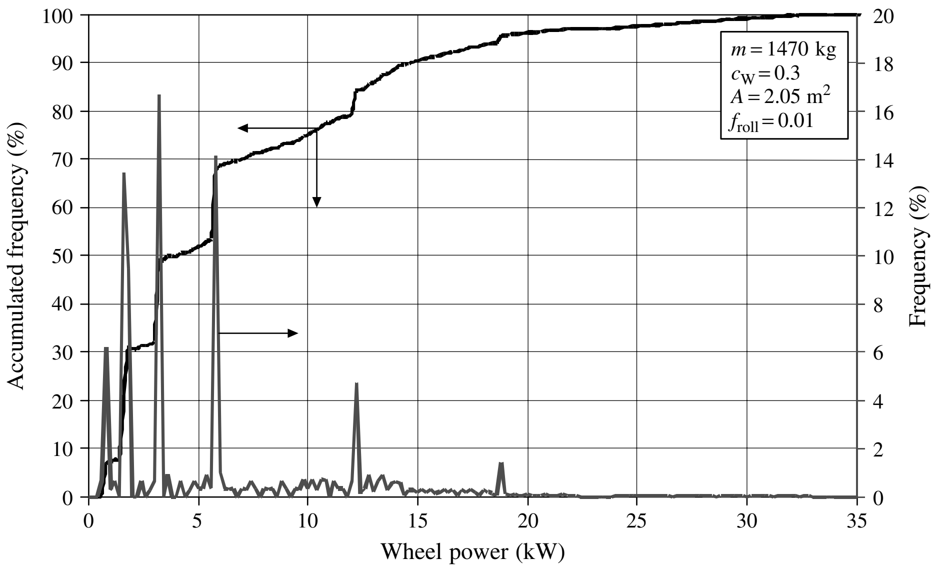

Figure 23. Frequency and accumulated frequency of wheel power during NEDC.

$$\eta_{E-drive} = 0.9$$
$$u = 0.8$$

The efficiencies for the fuel cell, the gasoline reformer and the parasitic losses have to be estimated at the average power demand of 5 kW:

$$\eta_{FC} = 0.65\text{–}0.75$$
$$\eta_{reformer} = 0.75\text{–}0.82$$
$$\eta_{parasitic} = 0.8\text{–}0.9$$

This leads to an overall vehicle efficiency of $\eta_{vehicle} = 0.25 - 0.35$.

4.5 Fuel consumption

Figure 24 shows how the fuel consumption (diesel) depends on the vehicle weight and the vehicle efficiency.

It is obvious from the diagram that a vehicle weight reduction of 100 kg reduces the fuel consumption by a constant amount which strongly depends on the vehicle efficiency. So the amount of reduction is about 0.4 l/100 km at a vehicle efficiency of 15% 0.15/100 km at a vehicle efficiency of 40%.

For the considered vehicle (weight classification "1470") with its efficiency range between 25 and 35% it can easily be shown that the diesel consumption in the NEDC lies between 4.6 and 3.41 100 km^{-1}.

5 DYNAMIC CONSIDERATIONS OF FUEL CELL SYSTEMS BASED ON GASOLINE

The aim of this section is to describe the dynamic behavior of a gasoline fuel cell system. This is necessary for the evaluation if a fuel cell system is able to follow the given load changes during a driving cycle without any battery support and for the calculation of the battery characteristics if battery support is inevitable. The procedure to reach a dynamic description of a fuel cell system is explained and an example for component modeling is shown. The implementation of the component models in a simulation program is described and examples given.

5.1 Motivation and description of the procedure

One of the most important requirements in the development of a fuel cell system with gasoline reformer is its dynamic behavior, which should be similar to conventional engines. Therefore it is necessary to consider concepts for fuel cell systems, not only from the aspect of "efficiency", but also from the aspect of "dynamic". Theoretical considerations by dynamic simulation can be a very helpful tool.

- The first step is to write mathematical models of all components of a fuel cell system. One has to decide about the complexity of the models, erect mass and energy balances and implement or assume geometric parameters. Because the power generation in the fuel cell and the reformer is the critical step, it is advisable

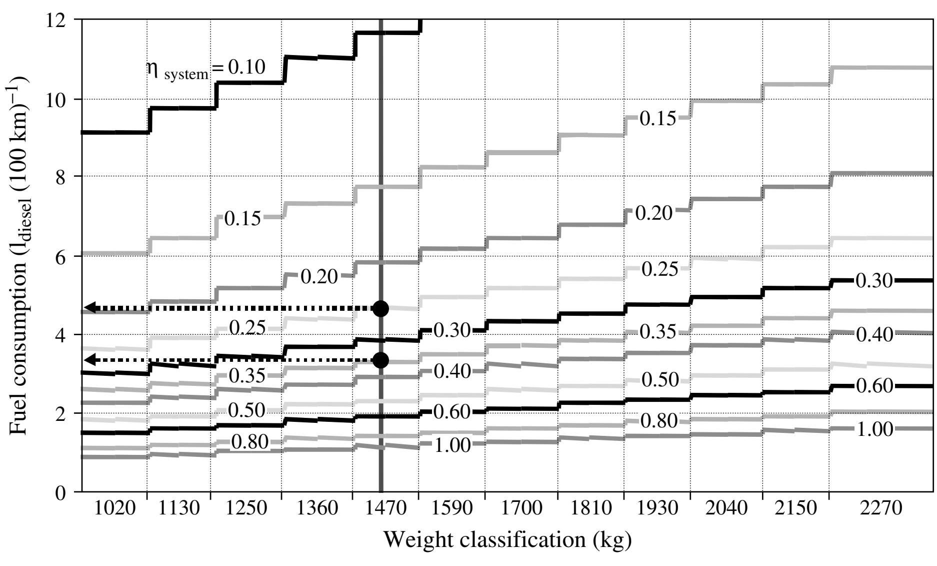

Figure 24. Dependency of fuel consumption in NEDC on weight classification and vehicle efficiency.

to reduce the "system" to the fuel cell system and the reformer.

- The next step is to implement these models in a simulation program which is able to solve the (partial) differential equations reliably in order to illustrate the fuel cell system.
- The final step is the generation of results for, e.g., the dynamic behavior of a fuel cell system during a load change or during a driving cycle.

In the following example, the model of a component in a fuel cell system, the implementation in a simulation program and the presentation of dynamic results, which give a good impression of the dynamic behavior of a gasoline fuel cell system, are described.

5.2 Modeling of the components

Mathematical models of chemical reactors can be written in the following ways.[11]

- Homogeneous models do not distinguish between a solid (catalysator) and a gaseous phase and are therefore not very suitable to describe precisely the interaction of the two phases. The advantage of these models is the low numerical cost.
- In comparison, heterogeneous models distinguish between a solid and a gaseous phase so the interactions between the catalyst and the gaseous phase can be described precisely but with a high numerical expense.
- The number of dimensions considered in the models also has an important influence on the model precision and the numerical cost. For most reactor models considered here, one-dimensional dynamic models are precise enough to describe the processes in a chemical reactor with a justifiable expense.

In the following a description is given of the procedures in component modeling for a fuel cell system by an example model of a reactor for a gasoline reformer.

First one has to list the assumptions and simplifications. For example, it is common to consider an adiabatic reactor, to consider the gaseous phase as ideal, to neglect the influence of heat radiation and to consider the catalyst properties as constant. Beyond that one has to decide whether more simplifications can be made or not.

Figure 25 shows a balance element in a reactor where the catalyst is a solid phase and fixed on a monolithic carrier with many channels parallel to each other. This model considered is a dynamic, one-dimensional model.

The following equations can be derived from the balances for energy and mass which are similar to those known from other authors:[12]

Energy balance for the gaseous phase:

$$\varepsilon\rho_{\mathrm{g}}c_{\mathrm{p,g}}\frac{\partial T_{\mathrm{g}}}{\partial t} = -\frac{1}{A_{\mathrm{ch}}}\frac{\partial}{\partial x}(\dot{n}_{\mathrm{g}}c_{\mathrm{p,g}}T_{\mathrm{g}}) + \varepsilon\lambda_{\mathrm{g}}\frac{\partial^2 T_{\mathrm{g}}}{\partial x^2} + \alpha_{\mathrm{s,g}}a_{\mathrm{v}}(T_{\mathrm{s}} - T_{\mathrm{g}}) \tag{18}$$

Energy balance for the catalyst phase:

$$(1-\varepsilon)\rho_{\mathrm{s}}c_{\mathrm{s}}\frac{\partial T_{\mathrm{s}}}{\partial t} = (1-\varepsilon)\lambda_{\mathrm{s}}\frac{\partial^2 T_{\mathrm{s}}}{\partial x^2} - \alpha_{\mathrm{s,g}}a_{\mathrm{v}}(T_{\mathrm{s}} - T_{\mathrm{g}}) + (1-\varepsilon)\sum_j R_j\Delta H_j \tag{19}$$

Mass balances for the gaseous phase:

$$\varepsilon\rho_{\mathrm{g}}\frac{\partial y_{i,\mathrm{g}}}{\partial t} = -\frac{1}{A_{\mathrm{ch}}}\frac{\partial}{\partial x}(\dot{n}_{\mathrm{g}}y_{i,\mathrm{g}}) + \varepsilon D_{i,\mathrm{g}}\frac{\partial^2 y_{i,\mathrm{g}}}{\partial x^2} - \beta_i\rho_{\mathrm{g}}a_{\mathrm{v}}(y_{i,\mathrm{g}} - y_{i,\mathrm{s}}) \tag{20}$$

$$\varepsilon\frac{\partial \dot{n}_{\mathrm{g}}}{\partial t} = -u\frac{\partial \dot{n}_{\mathrm{g}}}{\partial x} + a_{\mathrm{v}}\sum_j\left(\sum_i \nu_{i,j}\right)R_j \tag{21}$$

Mass balance for the catalyst phase:

$$(1-\varepsilon)\rho_{\mathrm{g}}\frac{\partial y_{i,\mathrm{s}}}{\partial t} = \beta_i\rho_{\mathrm{g}}a_{\mathrm{v}}(y_{i,\mathrm{g}} - y_{i,\mathrm{s}}) - (1-\varepsilon)\sum_j(\nu_{i,j}R_j) \tag{22}$$

It is obvious from the equations that the geometric parameters of the reactor and the kinetic formulations of the occurring reactions have to be known.

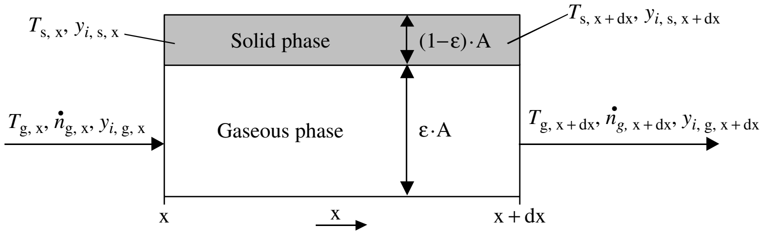

Figure 25. Balance element for modeling of a reactor with a catalyst carrier.

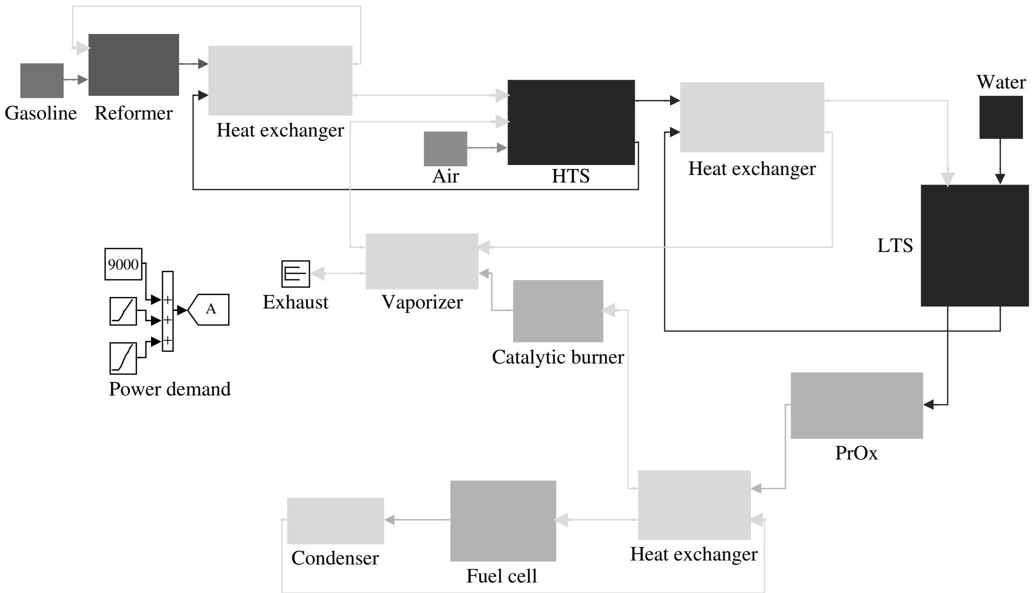

Figure 26. Simulation model for transient response calculations of a fuel cell system with gasoline reformer.

5.3 Implementation in a simulation program

In order to make calculations and obtain results with the above described component models they have to be implemented in an appropriate simulation program which is able to solve partial or ordinary differential equations. Simulation tools which are common for these applications are, e.g., Matlab Simulink™ or ASPEN Dynamics™ and have different methods which create the solutions for the differential equations. If there is a method for ordinary differential equations available, discrimination of the models is necessary. Normally, the discrimination of the models is done in the variable of space. For this purpose there are many methods in use of which that of finite differences is the most popular. To simplify the partial differential equations the reactor volume is divided into a certain number of elements. The method is easily implemented, reliable and stable. If the reactor volume is large and the required precision is very high, the number of equations is also very high and subsequently the calculation takes a long time.[12]

The method of orthogonal collocation is a method which offers a high precision with a low number of equations because of variable approximation by the help of orthogonal polynoms which are exact solutions of the partial differential equations at the collocation points.[13]

5.4 Example results

In this section example results regarding the dynamic behavior of a fuel cell system with gasoline reformer are shown. The system's transient response on a jump in power requirement from 1 kW to 9 kW is calculated. The system was modeled with Matlab Simulink™, the component models described above were implemented as "S-functions", and a solver for ordinary differential equations was chosen. The system model is shown in Figure 26.

Figure 27 shows the transient response of the gas mole flow at the reformer inlet, the reformer outlet and the fuel cell outlet. After the load change ($t = 100\,\mathrm{s}$) the mole flow at the reformer inlet does not rise on its stationary value directly because of the differences in residence time for air and vapor which also affects the reformer stoichiometry. The mole flow at the reformer outlet and the fuel cell outlet

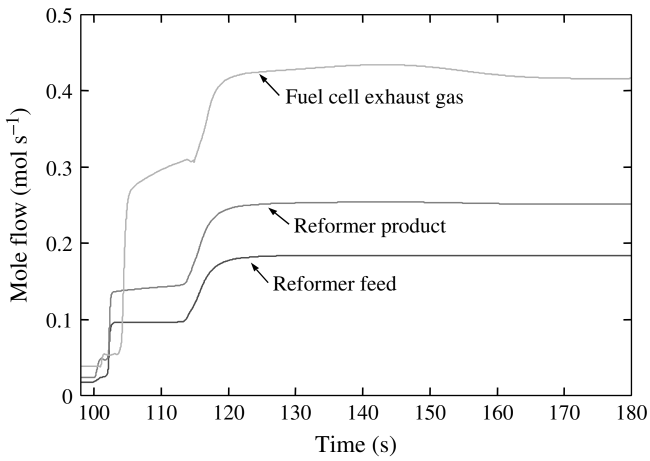

Figure 27. Transient response of mole flow at reformer inlet, reformer outlet and fuel cell outlet.

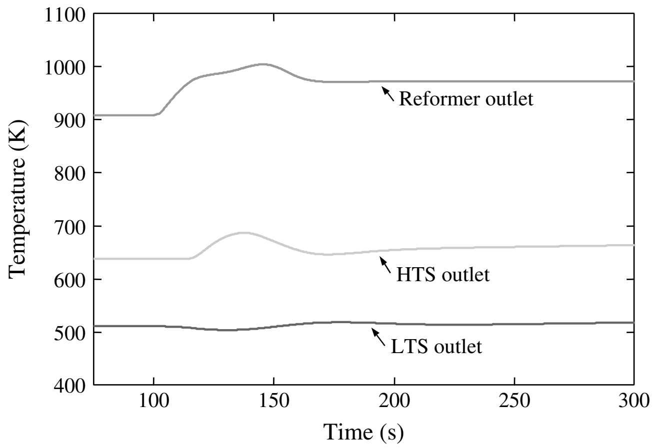

Figure 28. Transient response of gas temperature at reformer outlet, HTS and LTS outlet.

shows a similar behavior but is shifted to later times because of the residence times.

In comparison to the mole flows the transient responses of the gas temperature at certain places in the system are much slower (Figure 28). As the gas mole flows reach their new steady states after approximately 25–30 s, it takes 80 s for the gas temperature to reach its new steady state. The reason for this behavior is the catalyst carrier, of which the heat capacity interacts thermally with the gas and therefore delays the transient response of the gas temperature. The reformer temperature shows a super-oscillation because there is a temporal lack of vapor caused by the residence time for the vapor which is generated by heat exchange with the reformate in a few heat exchangers.

Gas temperatures in the HTS and LTS reactors also show an oscillation because these temperatures are influenced by the behavior of heat exchangers the performance of which depends on the mole flows (→ residence times) and temperatures of the fluids on both sides of the heat exchanger.

5.5 Conclusion

According to these results the dynamic behavior of the reformer is mainly influenced by the volume of the different components which influence the residence times. The calculations also show that the dynamic behavior is also influenced by the mass of each component of which the high heat capacity on the one hand functions as energy storage and on the other hand absorbs changes in temperature with the result that it takes much longer for the temperature to reach the new steady state but also prevents the component from reaching temperature peaks as it works like a buffer.

In order to make the reformer as dynamic as possible has to be constructed a compact and light-weight reactor system which enables short residence times of the gases in the different sections and short times for the temperature to reach its new steady state.

The calculated response times also show that even with regard to the action items described in order to construct a dynamic reformer, the dynamic behavior of the system will be too slow to work as a propulsion system without any energy storage. The required dynamic system for mobile applications is a response time of 1 s for a load change from 10% to 90% of full load.[10] Therefore, it can be easily estimated that the required dynamic of such a system will only be achieved with the help of a battery which is electrically loaded by the fuel cell system. Nevertheless it is absolutely necessary to build a fuel cell system which is as dynamic as possible because, with increasing dynamics of the fuel cell system, the required capacity and power of the battery becomes lower and the battery itself becomes cheaper and lighter.

6 SUMMARY

This chapter describes the fundamental procedures for the lay-out of fuel cell systems for vehicle applications, especially propulsion systems. In particular, specifications derived from the customer's requests have to be considered in this process. For example, the main requirements are top speed, dynamics, fuel consumption, operation range, climbing ability as well as durability, reliability, cold start-up behavior and, last but not least, costs.

On the basis of these requirements, the fundamental procedure is described for the lay-out of fuel cell systems by the example of a system based on gasoline reforming. Initially the choice of the fuel is important for the subsequent design process. Next, the lay-out of the basic architecture of the system and the individual components takes place in an iterative process.

Modeling and simulation of the overall system offers the possibility of estimating the fuel consumption in different operating cycles at the start of the design process.

SYMBOLS AND ABBREVIATIONS

a	acceleration ($m\,s^{-2}$)
A	cross-section of vehicle (m^2)
A_{ch}	cross-section area of one channel (m^2)
A_{active}	active cell area (cm^2)
A_{cell}	complete cell area (cm^2)
a_v	specific catalyst surface area ($m^2\,m^{-3}$)
be	specific fuel consumption ($g\,kWh^{-1}$)
B_e	fuel consumption per distance ($g\,m^{-1}$)

B_r	braking resistance (N)
$c_{p,g}$	heat capacity gas (J (mol K)$^{-1}$)
c_s	heat capacity solid (J (kg K)$^{-1}$)
c_w	air drag coefficient (–)
d_{cell}	thickness of one cell (cm)
$d_{end\ plate}$	thickness of end plate (cm)
$D_{i,g}$	diffusion coefficient of component i in the gas phase (mol (m s)$^{-1}$)
f	rolling resistance coefficient (–)
F_L	air drag (N)
F_{Ro}	rolling resistance (N)
g	gravitation coefficient (–)
h_{fuel}	heating value fuel (kJ (kg K)$^{-1}$)
h_{H_2}	heating value hydrogen (kJ (kg K)$^{-1}$)
h_{stack}	height of stack (cm)
ΔH_j	enthalpy of reaction j (J mol^{-1})
I	current (A)
j	current density (A cm^{-2})
l_{stack}	length of stack (cm)
m	vehicle mass (kg)
$\dot{m}_{fuel}$	mass flow fuel (g s^{-1})
$\dot{m}_{H_2}$	mass flow hydrogen (g s^{-1})
n_{cells}	total number of fuel cells (–)
$n_{cells/stack}$	number of fuel cells per stack (–)
n_{stack}	number of stacks (–)
$\dot{n}_g$	gas mole stream (mol s^{-1})
P_{gross}	electrical power output stack = gross power (kW)
P_{net}	electrical net power of the fuel cell system (kW)
$P_{parasitic}$	parasitic power = consumption of the auxiliary components (kW)
P_{wheel}	mechanical power at the wheel (kW)
R_j	reaction rate of reaction j (mol (m^2 s)$^{-1}$)
T_g	gas temperature (K)
T_s	solid temperature (K)
u	utilization (–)
u	velocity (m s^{-1})
U_{cell}	cell voltage (V)
v	velocity (m s^{-1})
$\dot{V}_g$	gas flow rate (m^3 s^{-1})
w_{stack}	width of stack (cm)
$y_{i,g}$	mole fraction of component i in the gas phase (–)
$y_{i,s}$	mole fraction of component i at the catalyst surface area (–)
α_{active}	active area ratio (–)
$\alpha_{s,g}$	heat transfer coefficient gas → solid (W (m^2 K)$^{-1}$)
β	gradient angle (°)
β_i	mass transfer coefficient of component i (m s^{-1})
ε	porosity of catalyst structure (–)
$\eta_{converter}$	efficiency converter (–)
η_{DT}	efficiency drive train (–)
$\eta_{E-drive}$	efficiency E-drive (–)
η_{FC}	efficiency fuel cell (–)
$\eta_{parasitic}$	parasitic efficiency (–)
$\eta_{reformer}$	efficiency reformer (–)
η_{system}	efficiency fuel cell system (–)
$\eta_{traction}$	efficiency drive train (–)
$\eta_{vehicle}$	efficiency vehicle (–)
λ_g	heat conductivity gas (W (m K)$^{-1}$)
λ_s	heat conductivity solid (W (m K)$^{-1}$)
υ_{ij}	stoichiometry coefficient of component i, reaction j (–)
ρ	air density (kg m^{-3})
ρ_g	gas density (mol m^{-3})
ρ_s	solid density (kg m^{-3})

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