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Development of Fuel Cell Powered Drive Trains With Modelica

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Abstract

The DLR Institute of Vehicle Concepts uses MODELICA in the area of fuel cell powered vehicles, where multidisciplinary simulation is required. The paper gives an overview of the existing libraries of DLR Institute of Vehicle Concepts and discusses our approach writing models in MODELICA.

An investigation of hybrid concepts of fuel cell powered vehicles is presented using the so called hyzem cycle as reference cycle. The results show that hybridisation of the energy supply, i.e. combining fuel cell and battery, yields to lower fuel consumption compared to vehicles only powered by fuel cells.

Introduction

The DLR Institute of Vehicle Concepts is investigating the potential and design of fuel cell powered vehicles.

One of the main issues is the simulation of the operational behavior in order to find suitable designs and operational strategies. Basis of the vehicle modeling is an appropriate block diagram, where the vehicle is separated in several sub systems. Figure 1 shows a block diagram representing a fuel cell hybrid vehicle.

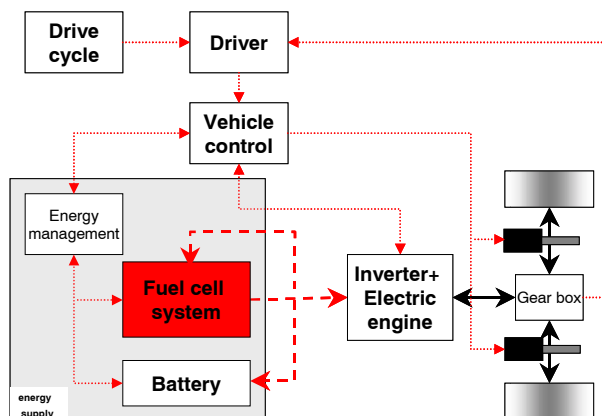


Figure 1: Block diagram of a fuel cell hybrid vehicle

It consists of the following sub systems: drive cycle, driver, vehicle control, energy management, fuel cell system, battery, inverter + electric engine, gear box and driving resistance. The thin lines represent the flow of data, the thick lines the flow of energy. The drive cycle gives the requested velocity as function of time. The driver model compares the actual velocity of the vehicle with the requested velocity and determines a request for acceleration or deceleration, which is given to the vehicle control. For safety reasons a direct mechanical or hydraulic connection between brake pedal and mechanical brake is mandatory. Therefore the vehicle control gives priority to the mechanical brakes above a certain level of deceleration. This approach should be sufficient to evaluate the potential of regenerative braking. However, our analysis does not cover the final realization of the braking system.

Finally, the vehicle control determines the signal for the inverter of the electric engine with respect to the state of the energy supply system (i.e. battery and fuel cell system). This state is determined by the energy management module, which receives the signals of the sensors installed in the battery and fuel cell system. The state of the energy supply system is also transferred to the vehicle control. For example, regenerative braking is not possible with fully charged battery. The state of the fuel cell system depends on the state of the fuel cell itself and also the state of several supply systems; e.g. air supply, fuel supply and heat and water management. Details to the fuel cell system are given below.

The short introduction should make clear that modeling of fuel cell powered vehicles is a multidisciplinary task, requiring electric, mechanical, electrochemical (fuel cell, battery), control, thermo-hydraulic models.

Libraries

Table 1 gives an overview of the existing libraries.

Library	Content
Property	Thermal and caloric properties of fluids (air, water, hydrogen, glycol-water, ..)
Piping	Ducts, fans, compressors, blowers, valves
Heatex	Heat exchanger
Accu	Battery models
Carmechnic	Mechanical components of cars
Control	Control units
Power_electronics	Inverters, DCDC-converters
Fuel cell	Fuel cells
Tank	Models of fuel tanks compressed gas, metal hydride

Table 1: Listing of libraries

Additionally, standard MODELICA libraries as electric library and block library were used. As simulation results were needed for ongoing projects, the libraries were designed under a very limited time scale. We felt that the hierarchical layout of the libraries should not be too complex. We therefore decided to limit the usage of base models creating a usable model to only one base model. Our general approach is outlined by two examples of the property and piping library.

The following listing shows a property model for wet air. Wet air describes a mixture of ideal gases (O_2 and N_2) with one condensable component (H_2O). As we are working at moderate pressures and temperatures, the ideal gas assumption lead to sufficiently accurate results. General equations for such a mixture have been put into the base class `base_prop_01` (extend statement) setting the modifier `n` to three, which means the mixture is composed of three components: `water[1]`, `nitrogen[2]` and `oxygen[3]`. The specific properties of the components are given by functions.

```

bzvt.property.air01.wet_air

see bzvt.property.bass_classes.base_prop_01

Modelica definition

model wet_air "siehe bzvt.property.bass_classes.base_prop_01"
  extends bzvt.property.bass_classes.base_prop_01(n=3);
  equation
  //-----properties-----
  ps = bzvt.property.h2o.satproperties.ps03(t);
  rhom_1_tp*mm_i[1] = bzvt.property.h2o.propfunctions.rho_1_of(t);

  mm_i[1] = bzvt.property.h2o.constants.mm;
  mm_i[2] = bzvt.property.n2.constants.mm;
  mm_i[3] = bzvt.property.o2.constants.mm;

  hm_g_i[1]=xm_g_tp*bzvt.property.h2o.janaf.h_g(t+ 273.15)*mm_i[1];
  hm_g_i[2] = xm_i[2]*bzvt.property.n2.janaf.h(t + 273.15)*mm_i[2];
  hm_g_i[3] = xm_i[3]*bzvt.property.o2.janaf.h(t + 273.15)*mm_i[3];
  hm_1_tp=xm_1_tp*
    bzvt.property.h2o.janaf.h_1_ofp(t+273.15,p)*mm_i[1];
  sm_g_i[1]=xm_g_tp*
    bzvt.property.h2o.janaf.s_g(t+273.15,p)*mm_i[1];
  sm_g_i[2] = xm_i[2]*bzvt.property.n2.janaf.s(t + 273.15, p)*mm_i[2];
  sm_g_i[3] = xm_i[3]*bzvt.property.o2.janaf.s(t + 273.15, p)*mm_i[3];

  sm_1_tp = xm_1_tp*bzvt.property.h2o.janaf.s_l(t + 273.15)*mm_i[1];
  //-----
end wet_air;

```

We use the same base model for other mixtures of gases with one condensable component. The thermodynamic state of such a mixture is determined by two state variables and $n-1$ compositions. After a period of refinement, we achieved a very good robustness even with several sets of input variables:

- Composition, p, T
- Composition, p, h .
- Composition, p, s
- Relative humidity, p, T

Key points to get this good performance have been the appropriate formulation of the general equations, i.e. structure of the equations. Molar or mass specific state variable can be used, which underlines the general formulation of this routine.

Figure 2 shows the icon and object diagram of a compressor. The fluid connectors inlet and outlet contain the potential variables pressure p , enthalpy h , composition x_i and the flow variable mass flow rate \dot{m} . The compressor is described by an efficiency model with the isentropic efficiency as a parameter. The calculation scheme is indicated in the object diagram by means of an enthalpy, entropy diagram. Three similar property models are embedded into the model: prop1, prop2, isentrop. Prop1 and prop2 are used to calculate the inlet and outlet state. Isentrop calculates the state for an isentropic compression.

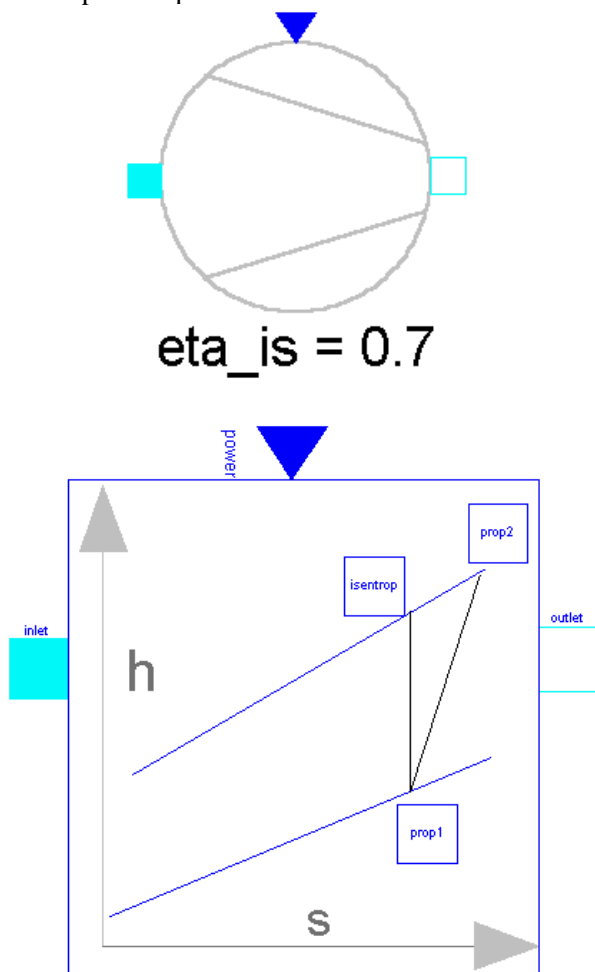


Figure 2: Above: icon diagram of compressor; below: object diagram of compressor.

Formulating our models we have taken special care to handle cases like mass flow rates getting very small values down to zero and to get a robust and stable formulation. Therefore we tried several formulations of heat exchangers: description by piecewise discretisation, log mean temperature and efficiencies.

In the beginning we had problems with robustness of our models, e.g. the convergence of the simulation run depended on the parameter values used. Also the appropriate initialisation of the model was difficult. To overcome the initialisation problems we have written special initialisation routines, which allow us to formulate the equations with numerically appropriate state variables and use common variables for parameterisation. For example inside a volume the internal energy u is used as state variable. However, by means of the initialisation function temperature t is used to parameterise the model.

As mentioned above we have restricted ourselves primarily to alternative drive trains and fuel cell systems due to time limitations. To simplify the usage of models for people working in DLR Stuttgart e.g. on solar thermal engineering our colleague Wolf-Dieter Steinmann has generalized a property and a thermohydraulic library [2].

In the following we will give some examples how we are using the libraries.

Modeling of Fuel Cell cars

Figure 3 shows the object diagram of a fuel cell powered car composed from models of the libraries listed in table 1. The object diagram represents the layout of the scheme given in figure 1, whereby the object dcsupply corresponds to the gray lighted (energy supply) in figure 1.

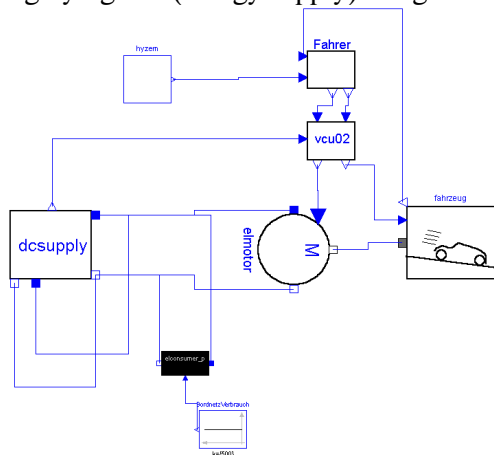


Figure 3: Vehicle model as MODELICA object diagram.

The object diagram consists of four main parts:

1. **the overall control of the vehicle**, which includes the representation of the drive cycle (object hyzem), which has specially been derived for hybrid vehicles [1], the driver model (object Fahrer) and the control unit (object vcu02).
2. **the supply of electrical energy** (object dcsupply), which includes the fuel cell system.
3. **the inverter and electrical engine** (object elmotor), which convert the DC current to mechanical energy.
4. **the mechanical parts and driving resistance of the car** (object fahrzeug)

Our special interest is the energy supply, which provides energy for elmotor, auxiliaries and for to energy supply system itself (indicated by the two additional electrical connectors of the object dcsupply).

Figure 4 shows the object diagram of the object dcsupply in detail.

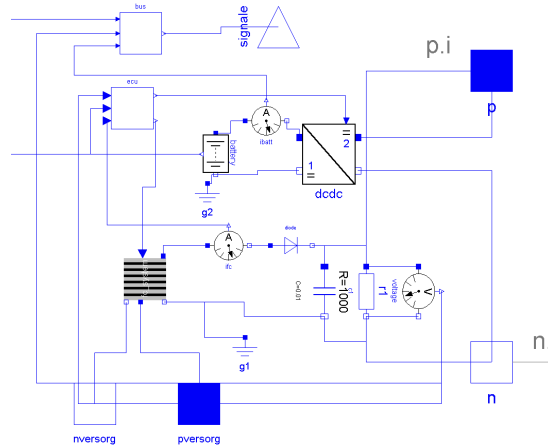


Figure 4: Object diagram of energy supply

Fuel cell system and battery are combined to a hybrid energy supply system. A bi-directional DCDC-converter adjusts the battery voltage to the fuel cell voltage. The DCDC-converter is controlled by the energy control unit (object ecu), which gets input from sensors installed in the battery and fuel cell system.

DC power is supplied to the electrical engine by the two electrical connectors p and n (right). Compressors and pumps of the fuel cell system are supplied with electrical energy by the two additional electrical connectors (nversorg and pversorg).

The dcsupply object can be parameterized in order to generate three different hybrid fuel cell vehicle designs.

1. **Fuel Cell Vehicle:** vehicle with a fuel cell solely to supply energy
2. **Fuel Cell Vehicle + Booster** battery: a vehicle with high power fuel cell and relatively low power battery to recover brake energy and provide additional peak power
3. **Fuel cell as battery loader:** high power battery and low power battery. The fuel cell is mainly used as a battery loader.

For the following examples we used a reference vehicle with the following parameters: vehicle mass 1240 to 1280 kg depending on option, drag resistance times front area 0.6m^2 and rolling resistance 0.01. The total installed power in all designs is 60 kW.

first design “**Fuel Cell Vehicle**” the fuel cell power is 60 kW.

second design “**Fuel Cell Vehicle + Booster**” the fuel cell power is 40 kW

third design “**Fuel cell as battery loader**” the fuel cell power is 20 kW

Figure 5 compares the requested velocity of the hyzem cycle and the achieved velocity of the fuel cell car for the third design “Fuel cell as battery loader”. The first 500 s of the hyzem cycle represent the urban part of the drive cycle, then up to approximately 1500 s the extra urban part follows. The last part is the motorway part.

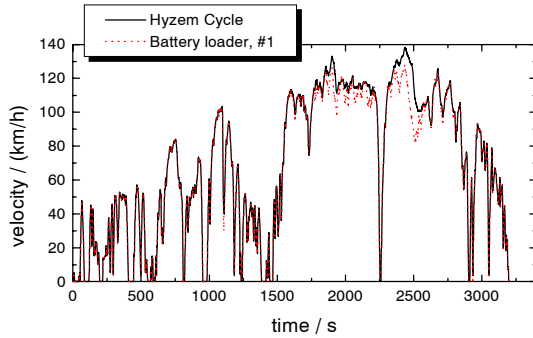


Figure 5: Results of drive cycle simulation; velocity as function of time

The battery loader can not follow the drive cycle at higher velocities in contrast to the other designs. Due to the relatively weaker voltage curve compared to the other designs, which yields to lower maximum torques of the electric engine.

Figure 6 compares the state of the battery for the booster design and battery loader design. Over the urban (first 500 s) and the extra urban part (to 1500 s) of the drive cycle the degree of discharge decreases, which means the battery is loaded. During the motorway part of the drive cycle, the battery loader design needs a significant amount of energy from the battery, whereas the state of the battery for the booster design keeps almost stable.

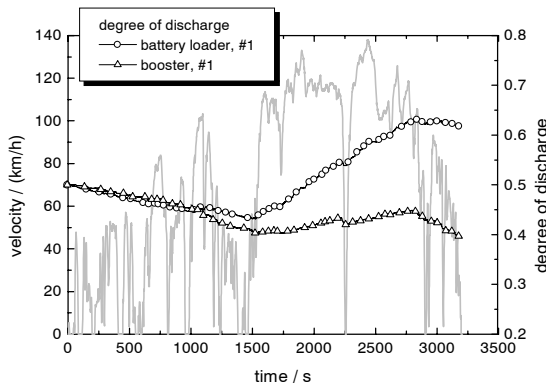


Figure 6: Results of vehicle simulation; degree of discharge as function of time.

Table 2 summarizes the results of the investigation. It shows the energy consumption per km obtained for the simulation of the three vehicle designs. The energy content of hydrogen is approximately 120 MJ/kg. Thus the vehicles would consume around 1 kg hydrogen per 100 km.

The operation strategy reflects the control strategy of the fuel cell system. Operation strategy #1 minimizes the auxiliary energy consumed to operate the fuel cell system. The results show that from the point of energy efficiency the second design “Fuel Cell Vehicle + Booster” battery combined with operation strategy #1 is the most energy efficient. The results clearly show that the energy consumption of the vehicle without battery suffers from the lack of energy recovery.

Degree of hybridisation	Operation Strategy	Cons. Energy (MJ/km)
Fuel Cell Vehicle	#1	1.57
	#2	1.65
	#3	1.75
Fuel Cell Vehicle + Booster Battery	#1	1.09
	#2	1.15
	#3	1.21
Fuel Cell as a battery loader	#1	1.17
	#2	1.20
	#3	1.23

Table 2: Energy efficiency for Hybrid fuel cell vehicles

Modeling of Fuel Cell Systems

Figure 7 shows the object diagram of a fuel cell system where two stacks are electrically connected in series. The stacks have to be cooled and supplied with fuel and oxygen. In this example hydrogen is used as the fuel. The complete hydrogen supply containing tank and pressure reducer etc. is hidden in the object H2 (left in figure 7).

Oxygen is taken from air. As hydrogen H2 the components of air supply (compressor, pressure control, mass flow control etc.) are hidden in the air object (right in figure 7).

The fuel cell stacks (each with 120 cells) are

directly cooled with water. Each stack has separate inlets for air and water. Inside the stacks air and water are combined and dragged out at one single outlet. Therefore a separator is needed to separate air and water.

The water(dark blue) and glycol(green) modules includes pumps, heat exchangers, ducts and control valves. The glycol module additionally contains a fan and an air – glycol heat exchanger to cool the glycol.

An electric load, which is connected to the anode and cathode of the fuel cells, is used to examine the fuel cell system with different load profiles.

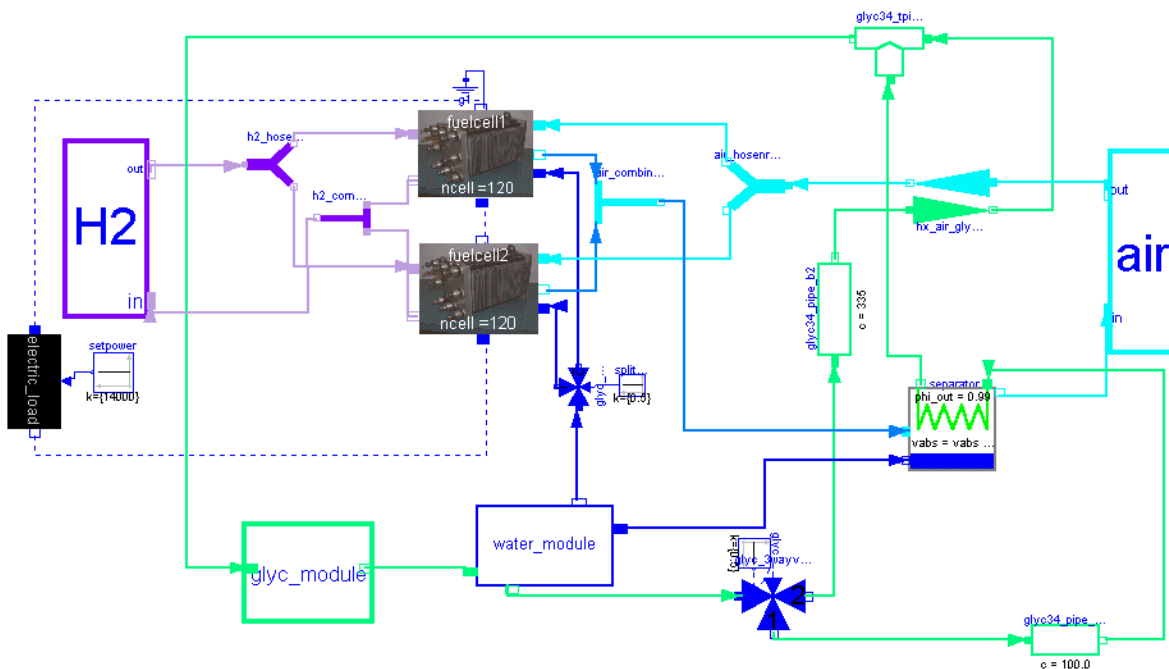


Figure 7: Object diagram of a fuel cell system

The description of the fuel cell systems shows that,

- thermo-hydraulic components are important
- the system has several closed loops
- advanced property routines are needed e.g. covering phase change

One main problem of fuel cell systems is that water is dragged with the exhaust stream. Despite of the production of water in the fuel cell a negative water balance could occur. In such a situation an additional water tank would be needed. The water balance is influenced by a number of parameters which influence each other, e.g. air supply strategy, cooling strategy, pressure drops, load profile. Beyond the task of layout and design of the components of fuel cell system, we use our simulation models to adjust the system in order to achieve water neutrality.

Summary

The DLR Institute of Vehicle Concepts uses MODELICA in projects, where components of fuel cell powered cars are developed. During last year a number of libraries for several disciplines have been created. We find MODELICA a very promising tool to analyse the complex interaction in such systems. Our models have brought us a lot of insight on how the design of fuel cell powered cars should be. They are especially useful for the design of the components of the fuel cell system and for the definition of operation strategies. The work with MODELICA will be continued in the future.

Literature

- [1] Gossen, F., Grahl, M.: Vergleich von Brennstoffzellen- und weiteren zukünftigen Antrieben hinsichtlich Wirkungsgrad und Wirtschaftlichkeit. 8. Aachener Kolloquium Fahrzeug- und Motorentechnik, Aachen, October 1999
- [2] Steinmann, W-D.: 2nd MODELICA Conference, Munich 2002