INTELLIGENT COMBINATION OF SIMULATION TOOLS AND EXPERIMENTAL INVESTIGATIONS BY MEANS OF THE V APPROACH

Wolfgang Puntigam[1], Klaus Martin[1]

[1]The Virtual Vehicle Research Center GmbH (vif),
8010 Graz, Inffeldgasse 21a/I, Austria

wolfgang.puntigam@v2c2.at (Wolfgang Puntigam)

Abstract

With the V-approach full vehicle prototype testing can be reduced by increasing numerical simulation and components tests. Full vehicle prototype testing is necessary to prove different functionalities of the vehicle and to prove the interaction of the different sub-systems under real vehicle conditions. To reduce full vehicle prototype testing the methodology behind the simulation must be able to simulate interdependencies within the entire vehicle simulation model. This paper presents a methodology for intelligent combination of simulation tools and experimental investigations by means of the so called V-approach. Within this approach the entire system is divided into several sub-systems which are stripped to component level and verified by means of experimental investigations. Afterwards the models are re- assemble to a comprehensive simulation model of the entire vehicle. For this purpose a platform for coupling of several simulation tools and co-simulation is required, which is presented in this paper. The Coupling process is done with an independent Co-Simulation environment (ICOS). With this tool it is possible to build up a validated entire vehicle simulation model which is based on the coupling of validated simulation sub-models. Furthermore in the presented paper comparisons between the entire vehicle simulations and measurements of an entire vehicle are shown. With this approach it is possible to prove different functionalities of the vehicle and to understand the interactions of the different sub-systems with an entire vehicle simulation model by coupled simulation.

Keywords: Combination simulation and tests, Coupled Simulation, Co-Simulation, V-approach, full vehicle simulation,

Presenting Author's biography

Wolfgang Puntigam received his master degree from the university of applied science in Graz, department automotive engineering in 2001. He finished his PhD at the technical university in Graz, department mechanical engineering in 2007. Since 2003 he is employed at the Virtual Vehicle Research Center GmbH (vif). Since 2005 he is divisional director of the department Thermo- and Fluid Dynamics at the vif. His interests are comprehensive vehicle simulation, coupled simulation and co-simulation, as well as the thermal management, hybrid systems, alternative modelling techniques and robust optimization.

ISBN 978-3-901608-32-2

1 General

Shortening of development times in the automotive industry with simultaneous rise of complexity, efficiency and product variety encourages the application of numerical simulation tools to meet present and future demands in the development process. Therefore comprehensive models are required to represent complex car designs with all sub-systems, including all parts of the powertrain and passenger compartment. However an optimization of the entire system can only be reached with a consideration of the interactions of the different systems.

In the last years great progress has been achieved in the field of the development of numerical simulation tools. Nevertheless a reliable simulation result can only be obtained with the assistance of experimental investigations. This paper presents a methodology for intelligent combination of simulation tools and experimental investigations by means of the so called V-approach.

Within this approach the entire system is divided into several sub-systems which are stripped to component level and verified by means of experimental investigations. Afterwards the models are re-assembled to a comprehensive simulation model of the entire vehicle. For this purpose a platform for coupling of several simulation tools and co-simulation is required, which is presented in this paper. One of the key points for a successful application of this independent co-simulation platform (ICOS) is the time management and the data transfer between the different tools.

The presented approach is illustrated with the example of the thermal management of a car. A basic requirement of the thermal management is to cool all components of the engine under all driving conditions. Temperatures of components and of the engine itself must not exceed threshold values in all extreme driving conditions (steady state and transient).

Additionally the system must control the exhaust temperature to guarantee reliable after treatment. Another important part of the thermal management is the air conditioning system, since the compressor is directly driven by the engine and therefore has a direct impact on the other circuits of the cooling system.

Moreover the compressor is the auxiliary unit with the greatest power consumption, which offers a big potential for a reduction of fuel consumption. Additionally the air conditioning assures a comfort climate which is an important fact for the customer.

2 Methodology

The aim of the V-approach (Figure 1) from VIF is to reduce full vehicle prototype testing by increasing numerical simulation. Full car prototype testing is necessary to prove different functionalities of the vehicle and to prove the interaction of the different subsystems under real vehicle conditions (engine, powertrain, cooling system, HVAC system …). Increasing numerical simulation to reduce full vehicle testing is possible if the simulation methodology is able to concern interdependencies between these different sub-systems. These different sub-systems consist of individual components (e.g. cooling system: pipes, tubes, bends, heat exchangers…). The components of the sub-systems must be adjusted with experimental data from test benches.

The first step of the V-approach (Figure 1) is to divide the vehicle into different hardware sub-systems. The breakdown process of the entire vehicle into hardware sub-systems depends on the company structure. A functional oriented breakdown process should be used. Each department is responsible for the development of its own hardware sub-system (e.g. engine development, HVAC development …).

For this development process of the hardware sub-systems, numerical simulation is a standard tool. For this purpose the hardware sub-systems are modelled within different simulation tools, which results in the so called simulation sub-models. These simulation sub-models consist of several individual simulation components. These individual simulation components must be validated by means of experimental investigations on the test bench with hardware components. To ensure a high quality and reliability of the simulation sub-models, the simulation sub-models themselves also have to be validated with the hardware sub-model on a test bench.

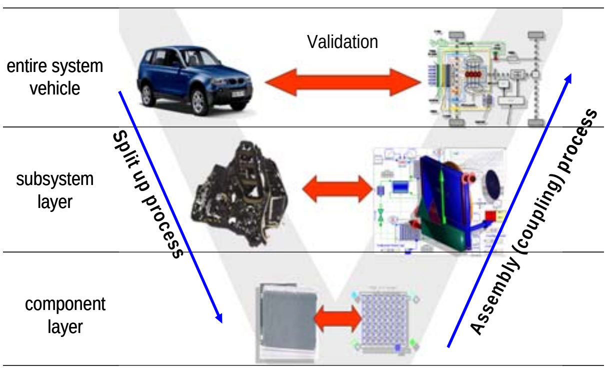

Fig. 1 The v-approach in an entire vehicle system approach

As a result of this process, validated simulation sub-models are available which can be used for the simulation of the functionality of the hardware sub-models. For the simulation of the entire vehicle, these different simulation sub-models can be coupled to concern interdependencies between the different simulation sub-models. For the coupled simulation of the different simulation sub-models the independent Co-Simulation environment ICOS from VIF is used. Further information about an independent coupling approach can be found in Puntigam et al. (2006a). With this approach it is possible to build up a simulation model of the entire vehicle and as a result avoid vehicle prototype testing. The reliability of the simulation model is ensured by means of test bench measurements.

3 V-Approach in detail

In this section the V-approach will be described for the thermal management as an example.

3.1 Split Up process

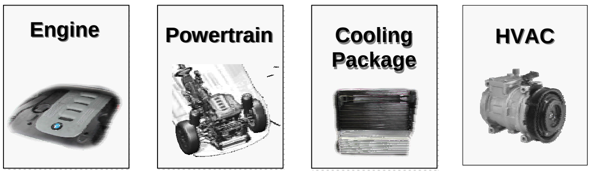

Fig. 2 Split up of the entire vehicle into different hardware sub-systems. The split up process depends on the company structure. A functional oriented split up process should be used

Sub-system Engine

The main heat source of a vehicle is the engine. The engine also produces a torque for the vehicle propulsion. The heat which is produced by the engine will be transferred in the solid parts of the engine and via the solid to the lubrication circuit and cooling circuit. Another heat source, which is not directly released in the coolant circuit, is the heat caused by friction.

Sub-system Powertrain

The power train consists of different components (gear box, differential, tyres...). Depending on different driving cycles, the powertrain is responsible for the driving behaviour and in combination with the engine for the fuel consumption.

Sub-system Cooling Package and Sub-system HVAC

The coolant circuit is responsible for cooling the engine and also for providing heat to the passenger cabin. The heat release to the water and oil circuit will be transferred from the flow network. These circuits consist of different components (pump, heat exchanger, tubes, and pipes…). The HVAC (Heating, Ventilating and Air Conditioning) system is responsible for a comfort climate within the passenger cabin, independent from the ambient conditions. The refrigerant cycle is driven by the compressor which usually is the most powerful auxiliary aggregate of the car and therefore has a notably impact on the entire vehicle thermal management system.

3.2 Components – simulation models

Once the hardware sub-systems and components which have to be modelled have been determined, an approach for modelling the components has to be chosen. Therefore two different methods exist: The first one is to create a simulation model on the basis of measured data and the second is to base your simulation model on geometry data. Of course the latter one has to be verified by means of experiments. The advantage of the first method is the simplicity of the model which results in shorter calculation times compared to a more complex geometry based model. The advantage of the geometry based modelling is that you can already conduct initial calculations without experimental data, e. g. in an early phase of the development process where no hardware is available.

Within the presented study for the modelling of the components of the coolant circuit (especially the heat exchangers) an approach has been chosen that requires several experimental data. For this purpose a component wind tunnel has been built up. The schematic of this test bench is shown in Figure 3. It can be used for the determination of the relevant parameters of a cooling package, e. g. the transferred heat and the pressure drop. Further information on this test bench can be found in Hörmann et al. (2005).

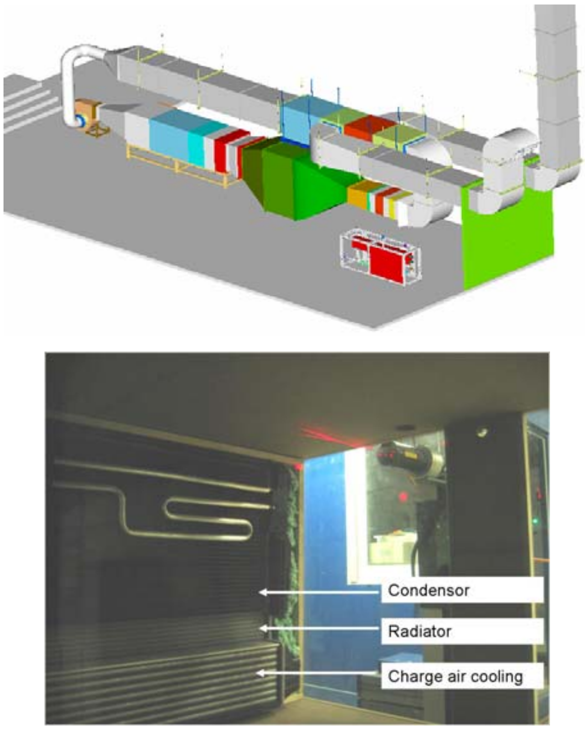

Fig. 3 Test bench for investigations of cooling packages: top picture – 3D schematic overview, bottom picture – cooling package test chamber

The cooling circuit is modelled using the simulation tool Kuli (2006). The used model of the heat exchangers requires a map for the transferred heat. Figure 4 (top) shows some typical results which have to be determined by experimental investigations. Furthermore the pressure drop over the cooling package is needed for the air path modelling and has to be measured. An exemplary result of the pressure drop is shown in Figure 4 (bottom).

With these results a simulation model which delivers reliable results can be provided.

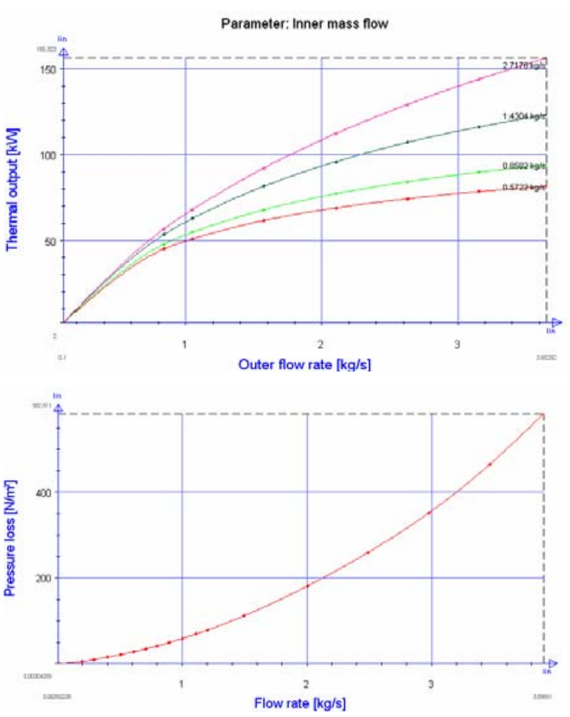

Fig. 4 Map of transferred heat in radiator (top) and pressure drop (bottom), which is needed for the simulation of the cooling circuit

For the modelling of the components of the refrigerant cycle the geometry based modelling method was chosen. Therefore the simulation tool Dymola with the AirConditioning Library (Dymola/AC Lib, 2006) has been utilised. An overview of the input parameters for the air/refrigerant heat exchangers is shown in Figure 5.

Even though the quality and depth of simulation models has increased in the last years the simulation results should be verified by means of experiments. Therefore a test bench for the refrigerant cycle has been built up (see Figure 6-top). This allows the investigation of the single components as the heat exchangers as well as the determination of the performance of the entire refrigerant cycle, e. g. for system optimization purposes.

Within the current research activities a focus is set on the alternate refrigerant R744 which seems to be a promising candidate as substitute for R134a which will be stepwise prohibited in the European Union with beginning of 2011 (EU 2006).

Figure 6 (bottom) also shows a comparison of measured data and simulation results. It can be seen that the calculated results deviate to the measurements no more than ± 10 %. Therefore it can be concluded that the simulation model can be used for further investigations by means of simulation.

A detailed description of the test rig with further information on verification of simulation models can be found in Martin et al. (2005).

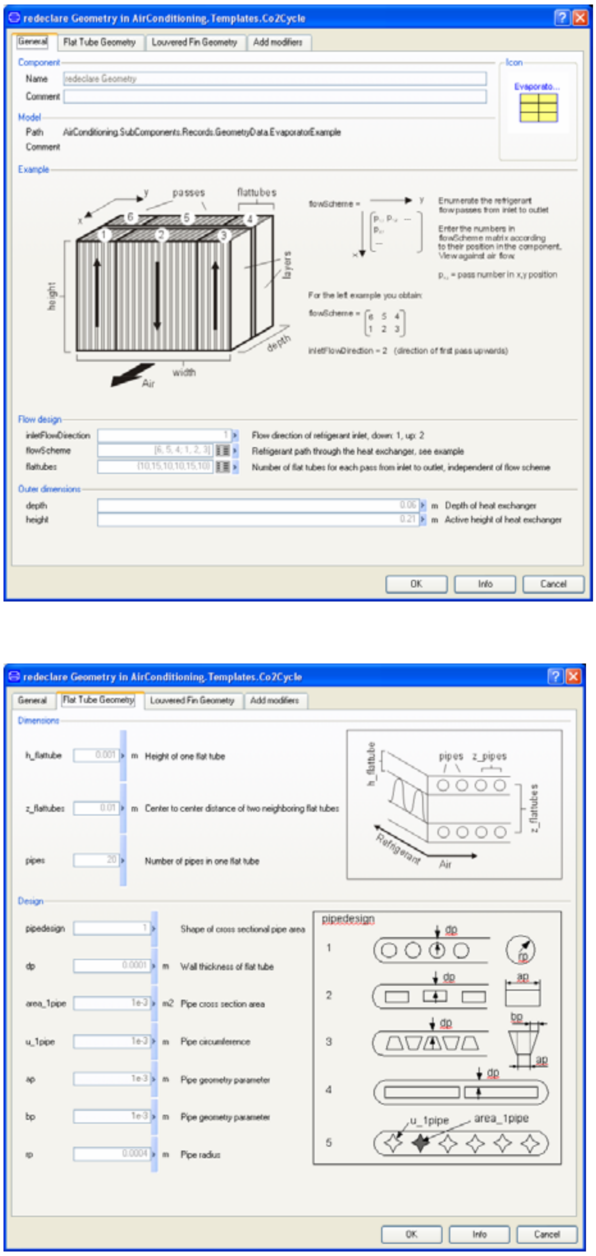

Fig. 5 Modeling of a refrigerant/air heat exchanger based on geometry data (Dymola/AC Lib, 2006)

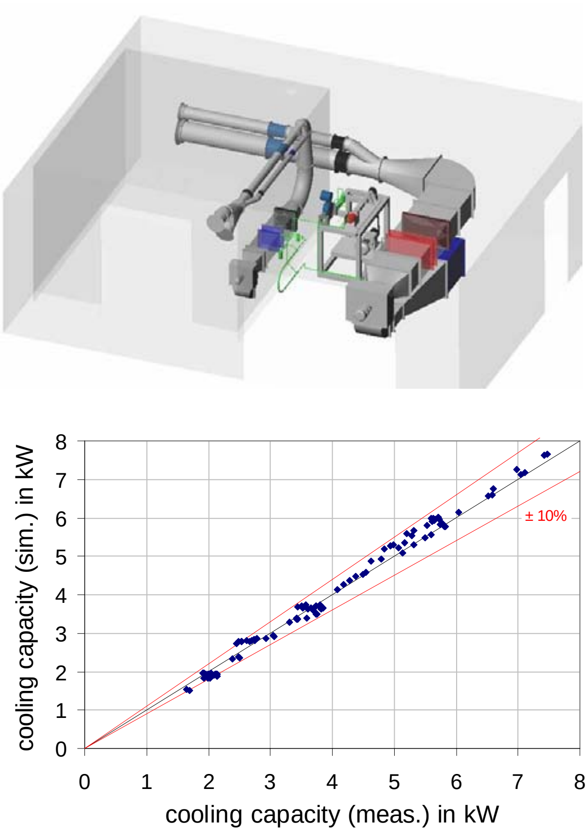

Fig. 6 Test bench for investigation of refrigerant circuit, top: 3D schematic, bottom: comparison of simulation results and measurements

3.3 Assembly Process

Consequently the vehicle simulation model of the thermal management of a car consists of different simulation sub-models, each of which covers a specific simulation aspect of the thermodynamic behaviour.

Each simulation sub-model uses the appropriate information structure related to its behaviour. In order to compute the behaviour we have chosen different programs with different modelling depths, starting from 0D simulations for the drive train, thermal network and 1D models for the cooling system, HVAC system and for the engine simulation

With this strategy calculation time can be reduced dramatically, compared to straightforward vehicle simulation model. In this example the thermal management system is divided into five simulation sub-models (Compare to Figure 2).

The hardware sub-system engine is divided into 2 simulation sub-models, one simulation sub-model engine and into a simulation sub-model thermal network. With this additional break down, the engine warm up can be investigated in more detail.

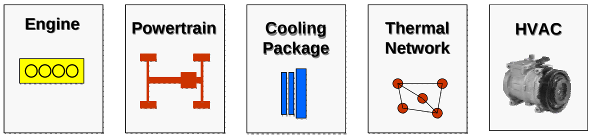

Fig. 7 Different simulation sub-models of the entire vehicle model. This breakdown process is derived from the hardware breakdown process. The hardware sub-system engine is divided into two simulation sub-models.

In Figure 7 the different simulation sub-models are displayed. Each of the sub-system is modelled within a different simulation tool:

- Powertrain simulation sub-model – AVL CRUISE
- Thermal Network simulation sub-model – Matlab/ Simulink
- Engine simulation sub-model – AVL CRUISE
- Cooling system simulation sub-model – KULI
- HVAC simulation sub-model – Modelica/ Dymola

In Figure 8 the different simulation sub-models are displayed. For a more detailed documentation of the different simulation sub-models compare Lang et al. (2006) and Puntigam et al. (2006b).

Each of the simulation sub models is adjusted with test bench measurements. So validated simulation sub models are ensured which are showing the same behaviour as the hardware subsystems.

In the following the sub-systems of the cooling circuit and the refrigerant circuit will be described in detail, since this two systems can be seen as example for simulation models which base on experimental data (the cooling circuit including the air path) and as example for simulation models which base on geometry data and are verified by means of experiments (the refrigerant circuit). Further information on the simulation models, its validation and the other circuits can be found in Petutschnig and Puntigam (2006), Kitanoski et al. (2006) and Puntigam et al. (2005).

SUB-System Coolant cycle

For the modelling of the coolant and the lubrication circuit the software package KULI (2006) has been used. As shown in Figure 8 the coolant and the oil circuit are rebuilt by means of a hydraulic network. The coolant circuit resolves all its branches in detail (by-pass and radiator circuit, cabin heater, etc.), including control functions for the thermostat opening characteristic and the fan speed, which are required for reproducing real-life engine warm-up cycles. The flow of the inner medium and the heat transfer in the heat exchangers are calculated based on measured component maps (compare chapter 3.2).

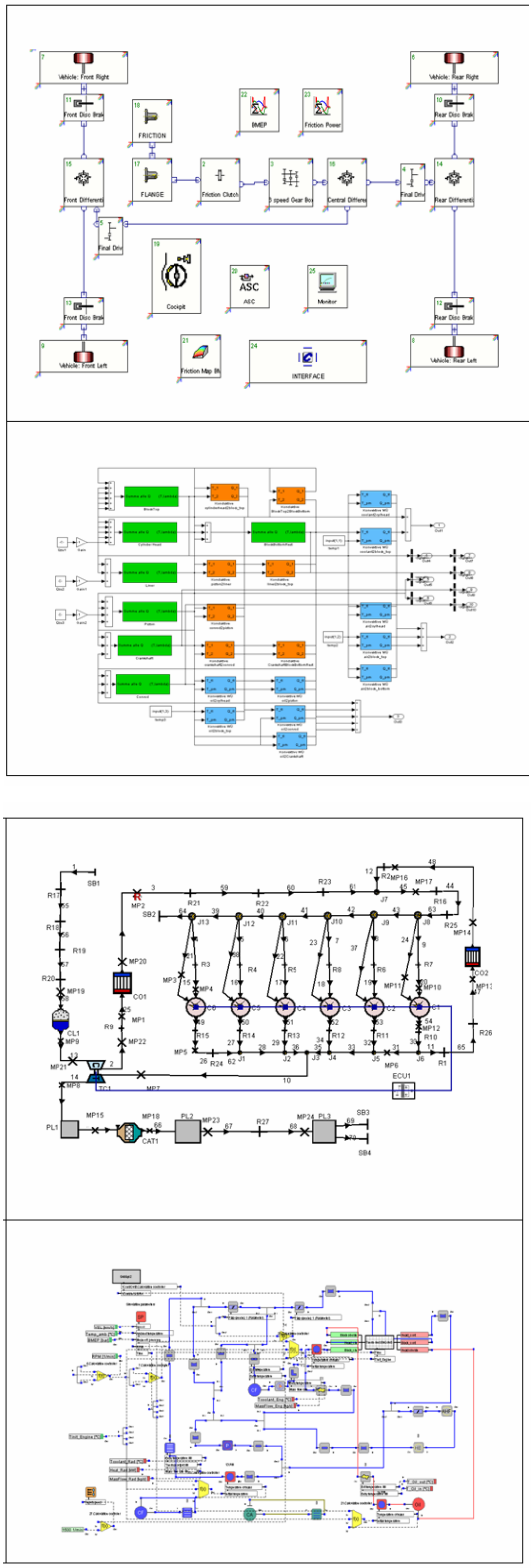

Fig. 8 Each of the sub-models will be calculated in a specialized simulation tool. These different simulation sub models must be connected to an entire vehicle simulation model.

Additionally the cooling air path through the radiator package in the under hood (charge air cooler, climate condenser, coolant radiator, fan, etc.) is included in this model and has been calibrated according to measurement data (compare chapter 3.2).

SUB-System HVAC

For the model of the refrigerant cycle the software tool Dymola with the AirConditioning Library (Dymola/AC Lib, 2006) has been used (see Figure 9).

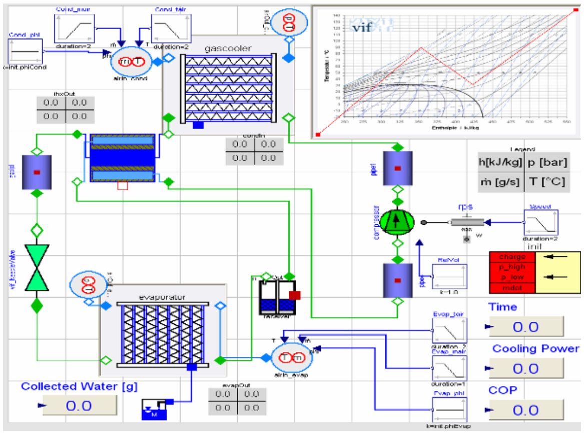

Fig. 9 Model of refrigerant cycle in Dymola with AC Library

The refrigerant cycle stands in strong interaction with the other cycles of the thermal network since the compressor is directly driven by the engine. Therefore the compressor shaft power has to be calculated within the simulation model and transferred to the simulation models of the diverse sub-systems of the thermal managements system. Another important parameter of the model is the air outlet temperature from the evaporator since this is the air which is fed into the passenger compartment and therefore directly impacts the cabin temperature.

Coupling Process

For the entire vehicle simulation model, the different validated simulation sub-models must be coupled to a comprehensive system. For the coupling process, the parameter exchange between the simulation sub-models, also called the physical interface for the entire vehicle simulation model must be determined (see Figure 10).

After the description of a physical interface within the entire vehicle model, the parameters are linked together. Every simulation sub-model will be solved by a separate simulation tool. The challenge here is to find a way for coupling these different simulation tools in a time depended way.

As an additional challenge, these different simulation tools can be placed on different computer platforms with different operating systems on it. Therefore we regard the different simulation sub-models as objects with specific features. Each object has specific input and output parameters defined by its physical interface. The linking process of the input and output parameters and the time depended coupling process is ensured with ICOS (see Figure 11).

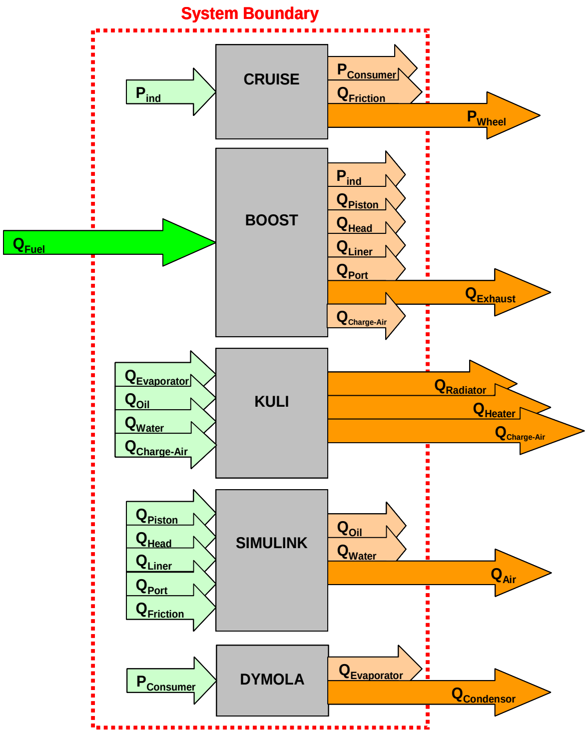

Fig. 10 Physical Interface between the different simulation sub-models. Each sub-model provides output information to the other sub-models and needs input information from the other sub-models.

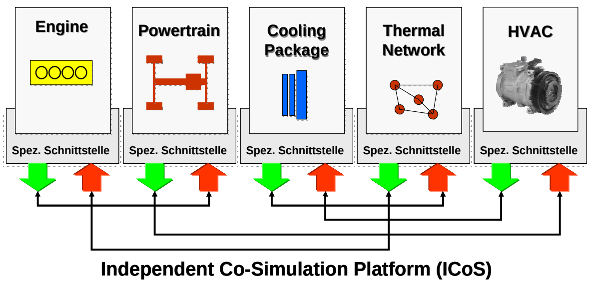

Fig. 11 Coupling of different simulation sub-systems with the independent Co- Simulation Platform ICOS. A conservative and time synchronized coupling process is ensured.

The Co-Simulation provides the possibility to investigate the energy flows and the interdependencies between the different simulation sub models. With this possibility, energy management can be done, depending on different driving and ambient conditions. In Figure 12 the entire vehicle simulation model is displayed to investigate the energy flows within the entire vehicle.

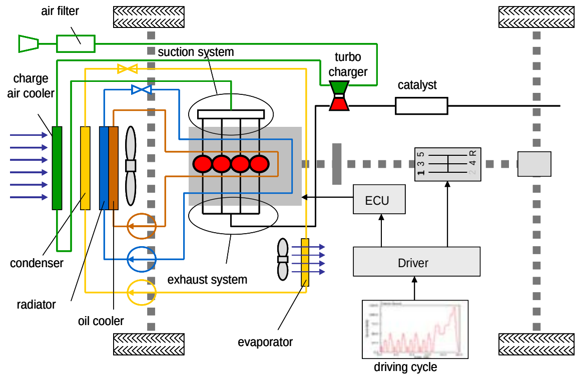

Fig. 12 Entire vehicle simulation model which consists of different simulation sub models. The entire vehicle simulation model covers all relevant thermodynamic energy flows.

4 Results

Results of the coupled Co-Simulation are discussed in this section. For the investigation of the thermal behaviour a heat up process of an engine will be regarded under the NEDC (New European Driving Cycle).

The velocity profile is an input map for the Co-Simulation. In Figure 13 the behaviour of coolant temperature during des NEDC is displayed. A comparison between measurements of an entire vehicle with the coupled simulation of validated simulation sub-models is done.

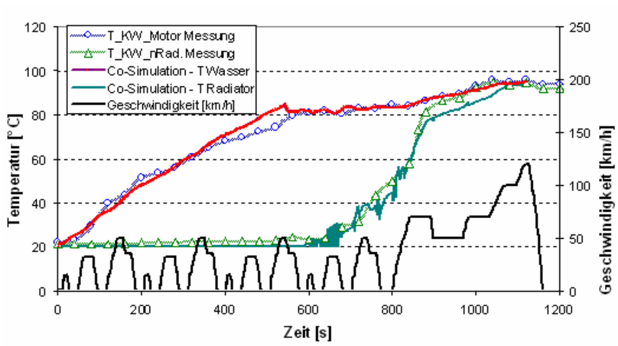

Fig. 13 Behaviour of water temperatures during the engine warm up. In this illustration a comparison between the coupled simulation of validated sub-models and measurement of an entire vehicle is shown.

The simulation results in Figure 13 are out of the Co-Simulation of different validated sub simulation models. The results of the Co-Simulation are well correlated to the measurements of the entire vehicle tests.

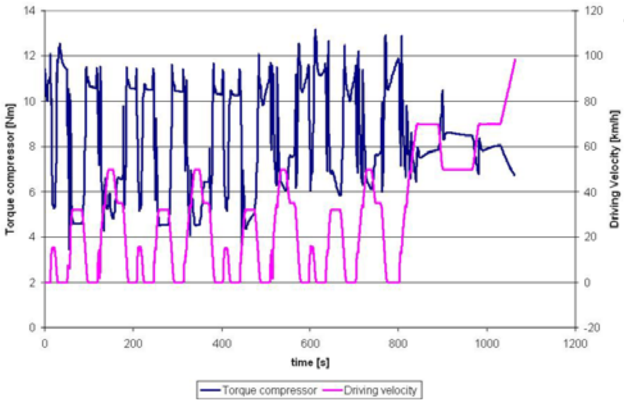

Fig. 14 Compressor torque characteristic over the NEDC.

Figure 14 shows the characteristic of the compressor torque over the NEDC. In this example the simulation sub-model of the AC system was linked via ICOS to the entire vehicle simulation model. So it is possible to make predictions about the increase of the fuel consumption, depending on the compressor power.

5 Conclusion

With the V-approach it is possible to build up entire vehicle simulations models which consist of validated sub simulation models. It is possible to reduce full vehicle prototype testing, because the entire vehicle simulation model is also able to prove different functionalities of the vehicle and to prove the interaction of the different subsystems. Full vehicle prototype testing could not be avoided but reduced. The vehicle prototype test is the last validation of the entire vehicle simulation model.

With the presented linking possibility of different sub simulation models by the independent Co-Simulation environment ICOS it is possible to consider interdependencies between different sub-systems and it is possible to establish energy management. With the consideration of the energy management within an entire vehicle, it is possible to optimize energy flows during the operation of the car and to minimize energy loses by an intelligent combination of energy between different subsystems.

In this article also an entire vehicle simulation model is presented, which consist of five different sub simulation models. There are simulations performed with the focus on the warm up behaviour of different coolant cycles and the power consumption of the AC-compressor.

The presented methodology in combination with an independent Co-Simulation environment is possible to reduce full vehicle prototype testing by increasing coupled simulation and by increasing component testing. This is possible by an intelligent combination of simulation tools and experimental investigations.

6 References

[1] Dymola/AC Lib, 2006, Dymola Version 6.0b, Dynasim AB Sweden and AC Library Version 1.4.1, Modelon AB Sweden

[2] EU 2006, Official Journal of the European Union, L162/12, 14.6.2006

[3] Hörmann T., Lechner B., Puntigam W., Moshammer T., Almbauer R., 2005, Numerical and Experimental Investigation of Flow and Temperature Fields around Automotive Cooling Systems, Proc. VTMS7, Toronto, SAE Technical paper No. 2005-01-2006

[4] Kitanoski F., Puntigam W., Kozek M., Hager J. (2006): An SI Engine Heat Transfer Model for Comprehensive Thermal Simulations, SAE World Congress 2006, Detroit, SAE Technical Paper 2006-01-0882

[5] KULI, 2006, Version 7.0, MAGNA STEYR Engineering Center Steyr GmbH & Co KG, St.Valentin

[6] Lang G., Petutschnig H., Puntigam W., Kitanoski F., Hager J. (2006): Simulation des Aufwärmverhaltens von Verbrennungsmotor und Fahrzeug mittels Kopplung von Teilmodellen , Wärmemanagement am Kraftfahrzeug, Haus der Technik, Expert Verlag, Berlin 01-02 Juni, 2006

[7] Martin K., Lang G., Rieberer R. 2005, Mobile HVAC-System with CO2 as refrigerant – Simulations and Measurements, Proc. VTMS7, Toronto, SAE Technical paper 2005-01-2023

[8] Petutschnig H., Puntigam W. (2006): Numerical Thermal Vehicle Analyses Using a Comprehensive Simulation Model and its Experimental Validation, JSAE World Congress 2006, JSAE Technical Paper 2006-05-26, Yokohama, Japan, May 2006

[9] Puntigam W., Hörmann T., Hager J., Schierl K., Wiesler B. (2005): Thermal Management Simulation by Coupling of Different Software Packages to a Comprehensive System – Proc. VTMS7, Toronto, SAE Technical Paper 2005-01-2061

[10] Puntigam W., Balic J., Almbauer R., Hager J. (2006a): Transient Co-Simulation of Comprehensive Vehicle Models by Time Dependent Coupling , SAE World Congress 2006, Detroit, MI, SAE Technical Paper 2006-01-1604

[11] Puntigam W., Petutschnig H., Lang G., Almbauer R. (2006b): Instationäre Simulation des Thermischen Verhaltens von Fahrzeugen durch Kopplung von Teilmodellen am Beispiel des Motoraufwärmverhaltens, Konferenz für Simulation am Kraftfahrzeug, VDI Tagung Würzburg, VDI Berichte 1967.2

7 Acknowledgement

The Authors wish to thank the "Kplus Kompetenzzentren-Programm" of the Austrian Federal Ministry for Transport, Innovation, and Technology (BMVIT), Österreichische Forschungsförderungsgesellschaft mbH (FFG), Das Land Steiermark, Stadt Graz, and die steirische Wirtschaftsförderung (SFG) for their financial support. Additionally we like to thank the supporting companies and project partners AVL List GmbH, MAGNA STEYR Fahrzeugtechnik AG & CO KG, MAGNA POWERTRAIN - Engineering Center Steyr GmbH & Co KG, Obrist Engineering GmbH, OMV and Graz University of Technology.

Contact:

Dr. techn. Wolfgang Puntigam
Divisional Director Thermo- and Fluid Dynamics
The Virtual Vehicle Research Center GmbH (vif)
Inffeldgasse 21a/I
8010 Graz
Austria
Wolfgang.Puntigam@v2c2.at
www.v2c2.at

