Proceedings
of the 4th International Modelica Conference,
Hamburg, March 7-8, 2005,
Gerhard Schmitz (editor)

D. Limperich, M. Braun, G. Schmitz, K. Prölß
DaimlerChrysler AG; TUHH, Germany
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System Simulation of Automotive Refrigeration Cycles

Dirk Limperich, Marco Braun, DaimlerChrysler AG

Katrin Prölß, Gerhard Schmitz, Hamburg University of Technology, Dept. of Thermodynamics

Dirk.Limperich@DaimlerChrysler.com, k.proelss@tu-harburg.de

1 Introduction

Numerical simulation in the automotive design process is gaining increasing significance. This also applies for thermodynamic and thermohydraulic systems i.e. also for the air conditioning system (HVAC) of an automotive vehicle. In order to optimize the efficiency of HVAC-systems and to obtain a better understanding of the complex transient system behaviour of automotive refrigeration cycles a Modelica library named ACLib was developed in a joint research project by DaimlerChrysler AG, Airbus Deutschland GmbH and TUHH. It was based on the thermohydraulic models of the free ThermoFluid library [2] and was applied to automotive refrigeration cycles running on the refrigerants R134a and carbon dioxide in an early development stage, when only limited experimental data was available [1, 5].

In order to share development costs and to combine the system knowledge and expertise on vehicle boundary conditions on one hand and the detailed component knowledge of the supplier on the other hand, a standardization process for a refrigeration cycle simulation tool was initiated by DaimlerChrysler. Modelica/Dymola was chosen by a pool of several OEM's and suppliers for this task, after several tools had been extensively investigated.

A new Modelica library, named AirConditioning Library, which meets the requirements of industrial application, and partly based on the former ACLib is currently developed by Modelon AB. Due to its user's group as mentioned above, special emphasis is placed on decoupling of physical equations and possibly confidential and encrypted component data as well as on high model flexibility.

2 Automotive Refrigeration Cycle

A Heating Ventilation and Cooling system (HVAC) is the primary element in controlling environmental temperatures of an enclosed automotive cabin. The HVAC systems also provide fresh outdoor air and adjust the temperatures and humidity to improve comfort and increase efficiency (e.g. increase cabin air circulation). Figure 2.1 shows the design of a common automotive HVAC system. The design of the AC-System (e.g. R134a refrigeration cycle) is important for the cooling performance and demands a high attention. A common R134a refrigeration cycle consists of a compressor, condenser, high pressure receiver, expansion device evaporator and several hoses and tubes.

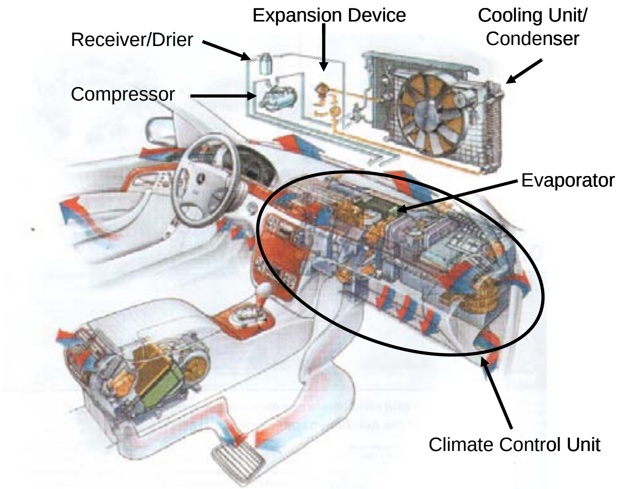

Fig. 2.1: Design of an automotive HVAC-Unit

As shown in figure 2.2, the R134a refrigeration cycle is a subcritical vapor process. The process path in the ph-Diagram is represented by the numbers 1-2-3-4 and shows the compression (1-2), isobaric heat rejection at the condenser (2-3), adiabatic expansion (3-4) and the isobaric evaporation (4-1). In steady state the high pressure receiver is also represented by number 3. In most cases the receiver is totally filled with liquid R134a, assumed the refrigeration plant is sufficiently charged.

The refrigerant mass is an important factor of a vapor cycle and is one motivation for a complete transient simulation. During different boundary conditions (e.g. changing air temperature, air massflow through heat exchanger) conditions the refrigerant mass is moving to different parts of the system and must be observed. The task is to find out the optimal charge of the system and the changing process behavior during any variation of the compressor speed, air massflow and temperature.

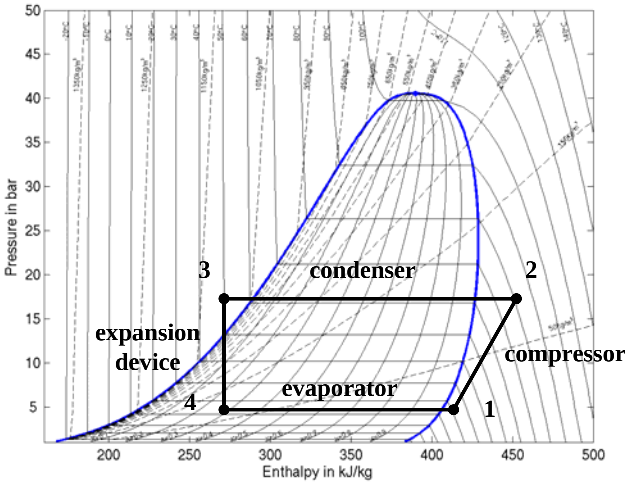

Fig. 2.2: Ideal case of R134a vapor cycle

Due to the additional fuel consumption which is about 100 liter gasoline [7] per year an exact and realistic simulation is necessary for efficiency optimization.

3 Heat Exchangers

In order to capture the transient as well as the steady-state behaviour of the complete automotive refrigeration cycle, detailed models of both main heat exchangers, condenser/gas cooler and evaporator, are required. They need to reproduce correctly the heat transfer between refrigerant and air flow and their respective property changes under given boundary conditions. Commonly used in automotive applications are compact cross flow heat exchangers that use finned flat tubes with internal microchannels as shown in Figure 3.1. Cross-co as well as cross-counter flow versions are also widely used for evaporators.

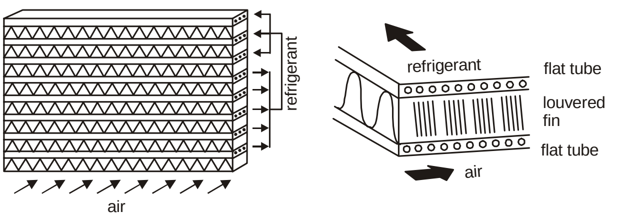

Fig. 3.1: Schematic of fluid flow in compact cross flow air-refrigerant heat exchangers

Based on physical parameters and heat transfer correlations from the literature, the heat exchanger model from the AirConditioning library is suitable for a wide range of applications without requiring experimental input data. It can be used for the evaporator on the low pressure as well as for the condenser / gas cooler in the high pressure side. Due to the object oriented approach of the used Modelica language and a standardized interface the heat exchanger component can be used in variable cycle positions and also as multiple instances with different parameterization, i.e. as two evaporators operated in parallel.

The component specific parameterization, geometry data, heat transfer and pressure drop correlations, is decoupled from the physical equations and therefore allows storage of confidential and encrypted component data in a separate location.

3.1 Modelling approach

The fluid component models in the AirConditioning library are based on fluid flow models realized in the free Modelica library ThermoFluid [2][3]. This approach applies a finite volume method (FVM) allowing a numerically robust simulation of thermo-hydraulic systems including flow reversal. Mass and energy balances on one and the momentum balance on the other hand are solved on a staggered grid with upwind property propagation.

The dynamic formulation of energy and mass balances allows a representation of the transient system behaviour. However, the major contribution to transient component response rather originates from heat capacities of the solid wall material.

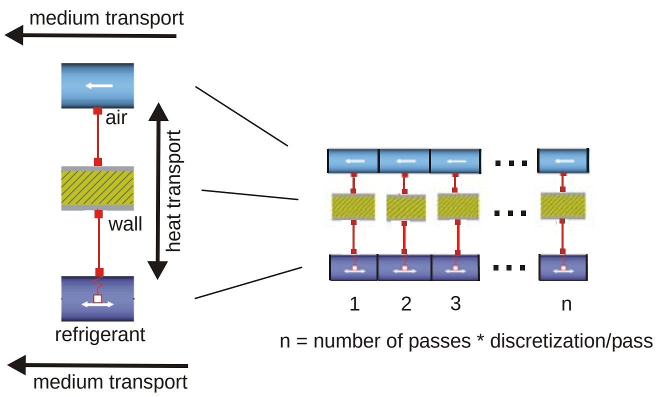

Fig. 3.2: Object diagram of heat exchanger composition from air, wall and refrigerant submodels.

The heat exchanger model is composed from two fluid objects (air and refrigerant) and one wall element. The wall mass is determined from detailed geometry input data and therefore reflects distributed capacities. Heat conduction in the solid material is modelled one-dimensional and perpendicular to both fluids, longitudinal conduction is neglected for efficiency reasons and because no significant loss in accuracy is expected [4]. Heat is transferred between wall and fluid using a heat connector class (Fig. 3.2). Further information on the heat exchanger composition approach can also be found in [5].

Heat transfer correlations for both fluids from the literature, e.g. by Chang et. al. [6] for airflow through louvered fins, are part of the library and used as replaceable classes in the component. They are easily replaced by correlations determined from experimental data. In the same way pressure drop correlations, geometry data or model switches as e.g. air humidity condensation can be set by the user in a top level dialog.

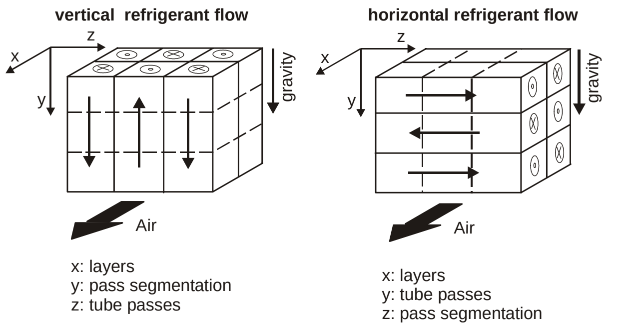

Fig. 3.3: Orientation of component triple in 3D-space

A single pipe approach combines all parallel refrigerant flows through the component in a single flow with variable cross section, resulting in an array of cross flow elements. They have to be formed into a 3D structure to support different flow schemes. Using a defined coordinate system with respect to air flow and gravity (fig. 3.3), the generic heat exchanger model can handle arbitrary flow patterns. It also allows a defined interface for inhomogeneous air inlet, which can be coupled with external 2D data. However, resulting from the one-dimensional flow approach in favour for numerical efficiency, the air inlet (and outlet) resolution is restricted by flow discretization (separated by dotted lines in figure 3.3) and the number of refrigerant passes (separated by solid lines in figure 3) in the component.

3.2 Validation of evaporator model

Simulations in a test configuration have been run with the described models. The test configuration (fig. 3.5) consisted of a source providing mass flow and enthalpy at the heat exchanger inlet and a sink generating a defined pressure at the outlet. The source and sink were used to set the boundary conditions resulting from data measured at the component. The following comparison was made for a cross-counterflow evaporator from an automotive R134a-system built at Chrysler (Michigan, USA). The heat exchanger is shown in Figure 3.4. The geometric parameters of the component are all known. In Table 3.1 the measured data and the results of the simulations at steady state are shown. The comparison of experimental data and simulation results show very good correspondence in transferred heat. The calculation of the refrigerant side pressure drop and the air side water condensing (drainage) has to be revised.

Fig.3.4: R134a-Evaporator, cross counter flow

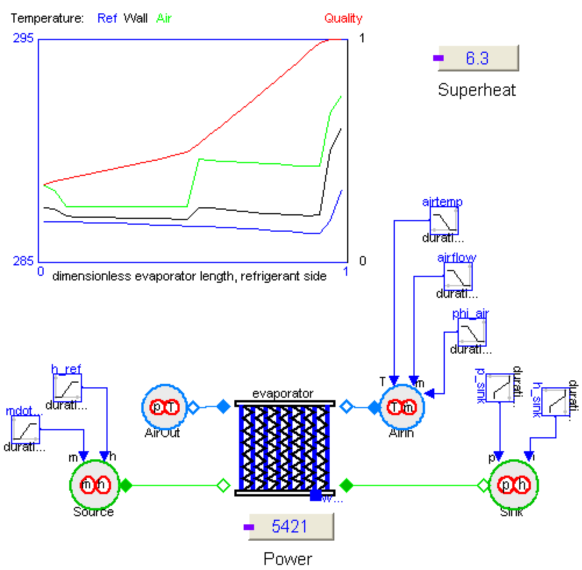

Fig. 3.5: Object diagram of test configuration

Boundary conditions for the evaporator from measured data						
$\dot{m}_{Air}$	$\dot{m}_R$	p_R	$T_{R,in}$	$h_{R,in}$	$T_{Air,in}$	$r.H._{Air\_in}$
[kg/s]	[kg/s]	[MPa]	[K]	[kJ/kg]	[K]	[%]
0.132	0.043	0.633	296.5	289.6	330.3	19.2
0.132	0.048	0.434	281.8	271.2	316.5	18.9
0.132	0.054	0.439	281.3	272.7	316.5	19.1

Measured data				Simulation			
$h_{R,out}$	$T_{Air,out}$	$\dot{Q}_R$	$r.H._{Air\_in}$	$h_{R,out}$	$T_{Air,out}$	$\dot{Q}_R$	$r.H._{Air\_in}$
[kJ/kg]	[K]	[kW]	[%]	[kJ/kg]	[kJ/kg]	[kW]	[%]
410.7	296.7	5.19	82.5	411.3	298.6	5.2	89.9
401.4	283.7	6.25	79.7	385.6	283.6	5.5	89.8
400.2	282.7	6.84	70.8	380.3	282.8	5.78	89.1

Table 3.1: Comparison of measured data at the evaporator with the simulation results in steady state

4 New European Driving Cycle

The New European Driving Cycle (NEDC) consists of defined vehicle speeds in an urban as well as an extra-urban section (fig 4.1). The NEDC is part of the emission test EURO 4 and is also widely used as a standard for fuel and energy consumption experiments and evaluation.

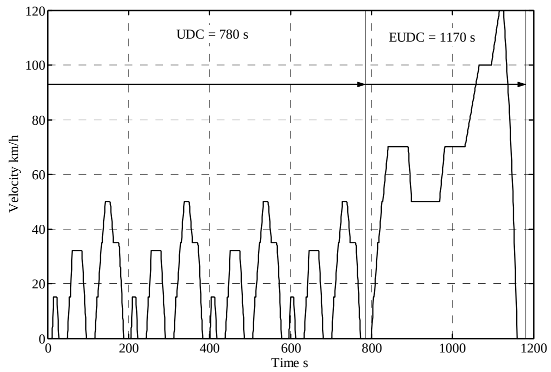

Fig. 4.1: Driving speed during NEDC

The resulting compressor speed and air velocity are in the following used as boundary conditions in a complete cycle simulation of a defined passenger car (fig 4.2). The air inlet temperature for the evaporator is constant at 310 K and the air massflow is constant 0.166 kg/s. The boundary condition for the condenser is also shown in figure 4.2, the air temperature is constant at 320 K and the air massflow depends on driving speed.

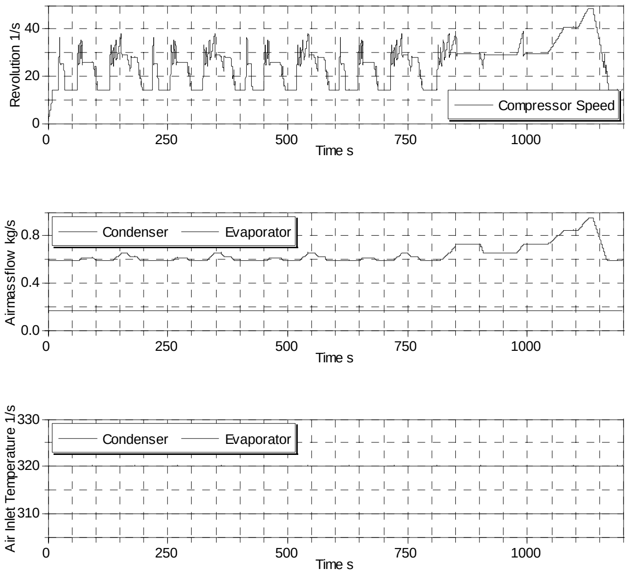

Fig. 4.2: Boundary conditions for the refrigeration cycle during the NEDC

The Modelica object diagram of the model used for the NEDC-cycle simulation is shown in figure 4.3. The refrigeration cycle consists of an external controlled compressor, a condenser, a receiver (with integrated drier), thermostatic expansion valve, evaporator and several pipes. The total volume and the ratio of the high pressure side and suction side volume are equal to the real refrigeration cycle. Also the refrigerant charge of the simulation model is equal to the real system.

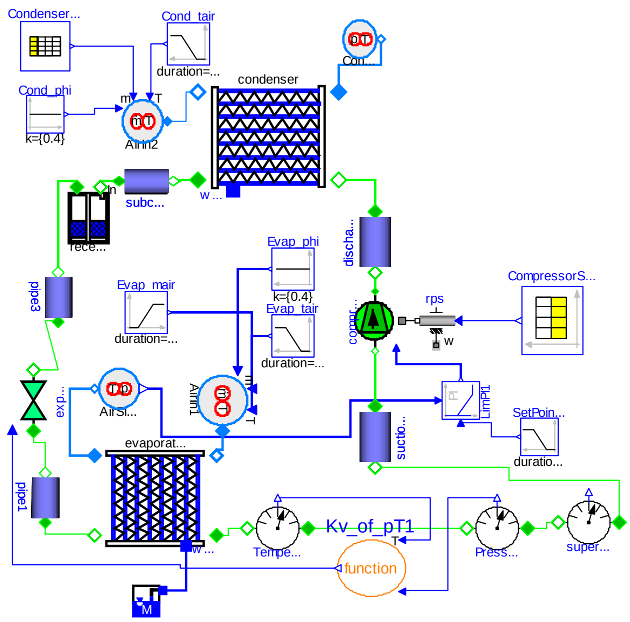

Fig. 4.3: Object diagram of complete R134a refrigeration cycle

In the following part, two simulation runs will be discussed. The refrigeration cycle shown in figure 4.3 provides a basis for the two experiments. For both experiment the described NEDC boundary conditions were used. Only two different compressors were used during the simulation runs. They are referred to as compressor A and B in the following. Compressor A has a 6 percent higher displacement and one more cylinder, so that the characteristic diagrams of both compressors are also different.

The results of the simulation runs are shown in the figures 4.4 -4.6. Three characteristic values of the refrigeration cycles are shown and compared: the air temperature behind the evaporator, the cooling capacity and the required compressor power.

When using compressor B in the cycle the air temperature behind the evaporator during UDC part is mostly 1K higher than using the compressor A. Only during the EUDC part there is nearly no difference between the temperatures (fig. 4.4).

The comparison of the cooling capacity and the compressor power shows the same behavior (fig. 4.5 and fig. 4.6). The total energy consumption for type A is 733 Wh and for type B 720 Wh. Interesting is, that during the EUDC the smaller compressor needs less power for equal cooling capacity.

The solution of that experiment is that a 6% smaller compressor could perform nearly the same cooling capacity.

It is concluded, that the simulation tool is able to predict the change of cycle behavior when the accuracy of the component models is high enough.

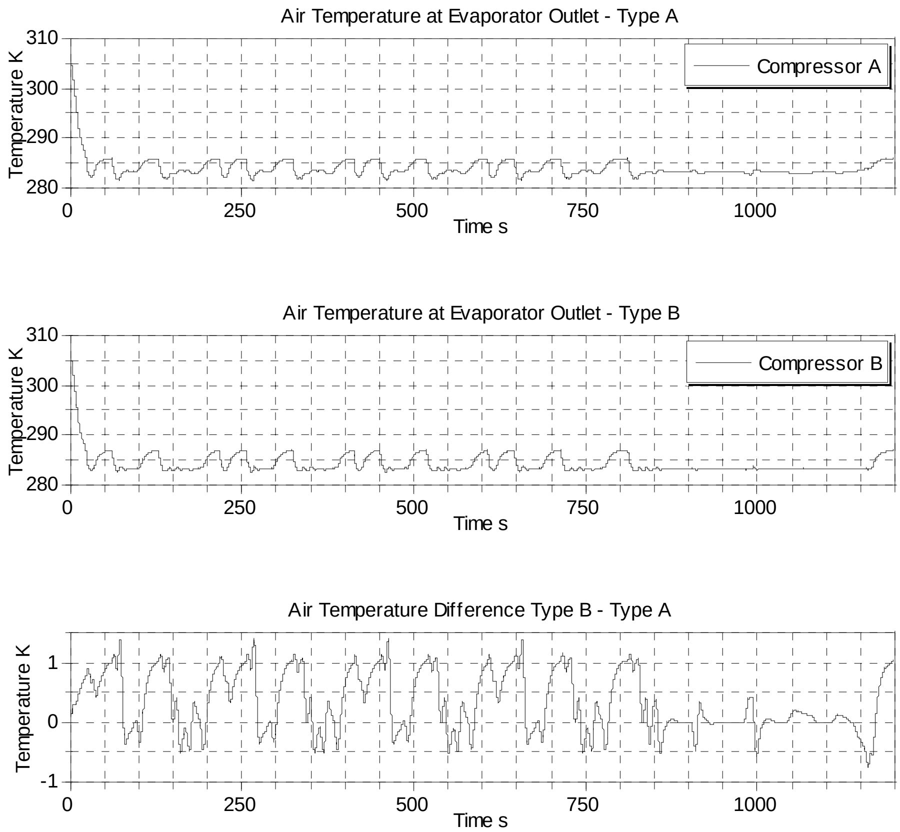

Fig. 4.4: Air Temperature behind evaporator - reference temperature for controlling T=283.15K

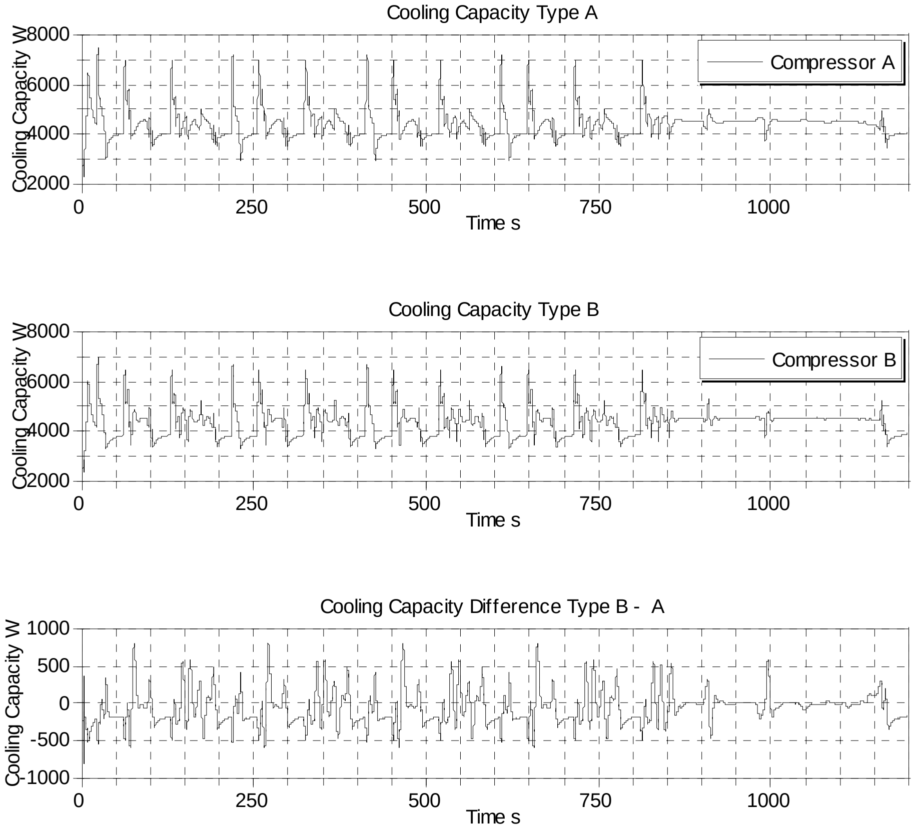

Fig. 4.5: Comparison of cooling capacity using compressor A and B

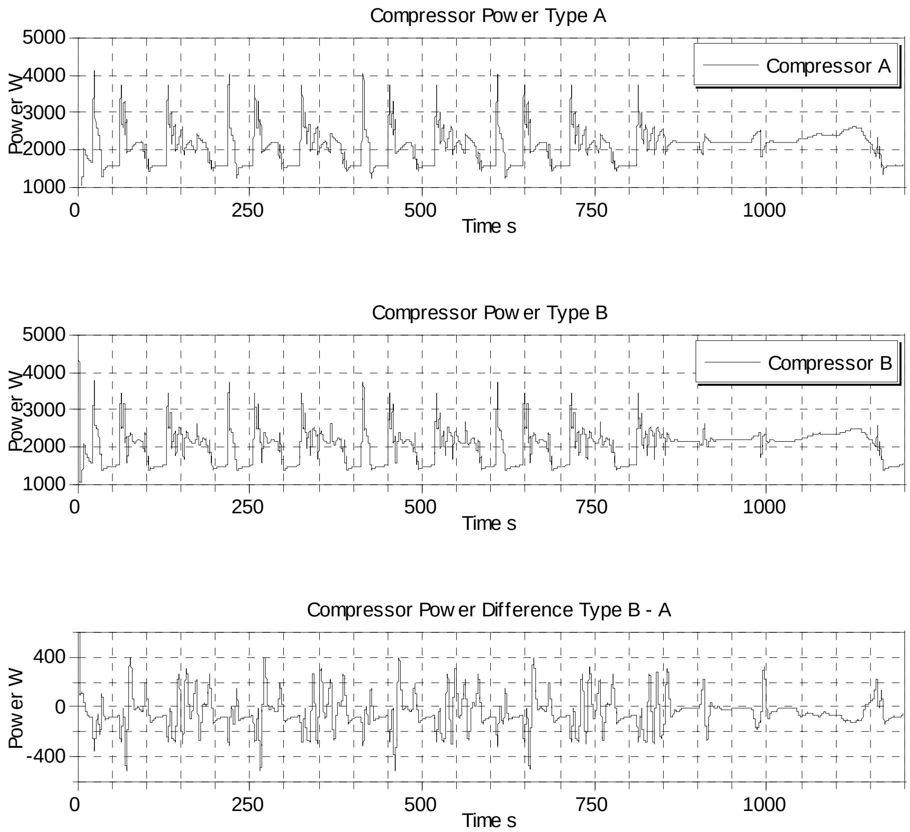

Fig 4.6: Comparison of Compressor power for compressor A and B

5 Common Simulation Tool in German Automotive Industry

In Germany, a working group with members of Audi, BMW, DaimlerChrysler and Volkswagen have compared different simulation tools in order to standardize the simulation of refrigeration cycles. The advantages of standardization are mainly the ability to integrate the supplier into the simulation process. This makes it possible to simulate components of different suppliers on one simulation platform. After a benchmark test the group decided to use Dymola Modelica for simulating refrigeration cycles.

In the future models of refrigeration cycle components are needed during the development process. If the supplier is not able to create such a model, detailed information of the geometry in combination with measured data has to be provided during the offer phase.

6 Conclusions

The dynamic simulation of an automotive refrigeration cycle with Dymola/Modelica as part of the design process is described in the paper. In a cooperative effort between Hamburg University of Technology (TUHH) and DaimlerChrysler AG, a model library for modeling refrigeration cycles has been developed based on the AirConditioning library. Based on geometrical data, the single components can be modeled and composed to an entire cycle.

The validation of the evaporator is one example for the component simulation and the results are in good accordance with the experimental data.

The simulation of the NEDC has shown that a prediction of the process behavior is possible, so that the simulation is able to support the design of refrigeration cycles for automotive applications.

At last the standardization has the advantage or the chance that the component supplier's expertise as well as the automotive manufacturer's knowledge of vehicle parameters can be combined in a reliable simulation.

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