MODELING AND SIMULATION OF COMPRESSORS IN MOBILE AIR-CONDITIONING SYSTEMS

Wilhelm Tegethoff[1], Tilmann Horst [1], Christoph Richter[2],
Roland Kossel[1], Michael Bodmann[1], Nicholas Lemke[2]

[1]TLK-Thermo GmbH,
38106 Braunschweig, Germany
[2]Technische Universität Braunschweig, Institut für Thermodynamik
38106 Braunschweig, Germany

w.tegethoff@tlk-thermo.de (Wilhelm Tegethoff)

Abstract

This paper presents a detailed mechanical and thermodynamic Modelica model for a CO_2 compressor used in prototype air-conditioning cycles for buses. The mechanical parts are modeled with Modelica's Multibody Library. The thermal part is modeled with basic thermodynamic conservation laws and uses the interface library TILFluids for refrigerant property data. The compressor is simulated as a component in a complete air-conditioning cycle. The Modelica library TIL is used for all remaining components in the complete air-conditioning cycle. Due to the very short timescale of the compressor physics in combination with the high effort for calculating fluid property data of the complete cycle, the total integration time is very high. Therefore, a simple multi-rate integration method was implemented by using co-simulation. The middleware TISC was used to couple the compressor model with the remaining air-conditioning cycle. Suction pressure, suction enthalpy and discharge pressure are the input variables for the compressor; suction mass flow rate, discharge mass flow rate and discharge enthalpy are the output variables. With this technique, the simulation speed of the complete air-conditioning cycle including the detailed compressor model could be increased by a factor of 40.

Keywords: Modelica, multi-rate integration, air-conditioning and refrigeration, thermal system, compressor, co-simulation

Wilhelm Tegethoff is engaged in modeling and simulation of thermal systems such as air-conditioning, refrigeration and heat pump systems for more than ten years. In 1995 he started working at Konvekta AG in R&D dealing with absorption systems and CO_2 as refrigerant. In 1999 he received his PhD from the TU Braunschweig. Afterwards he worked for one year as visiting lecturer in Brazil. Since seven years he is employed at the Institut für Thermodynamik at TU Braunschweig where he is responsible for the thermal science simulation group. He teaches Modelica and C++ for application in thermal science. In 2003 he founded the spin-off TLK-Thermo GmbH together with Nicholas Lemke and Jürgen Köhler. TLK offers engineering services and custom-made software for thermal systems.

1 Introduction

Nowadays most new cars and commercial vehicles are equipped with an air-conditioning system (AC system). The system has a significant environmental impact. The extra weight of the AC system as well as the power requirements during operation yield a higher fuel consumption of the vehicle. In addition refrigerant leakages have a direct impact on the global warming effect strongly depending on the GWP (Global Warming Potential) of the used refrigerant. Therefore many research facilities work on making mobile AC systems more energy-efficient and on using alternative refrigerants such as CO_2 with a lower environmental impact.

The compressor of the AC system influences the total energy consumption and is responsible for a significant part of the overall refrigerant leakage. The thermal and mechanical efficiency of the compressor determine the total energy that is needed to compress the refrigerant. The rotary seal of the shaft, influenced by vibration and other forces, determines the amount of refrigerant leakage.

Computer simulations can help to improve the compressor regarding an increase of its energy-efficiency and regarding the disadvantageous force distribution. An improved compressor design may lead to a lower environmental impact of the total AC system.

This paper deals with a detailed thermal and mechanical model for a CO_2 compressor that is used in prototype air-conditioning systems for busses. The model was developed in the modeling language Modelica using Modelica's Multi-Body library for the mechanical parts and thermodynamic conservation laws for the different volumes of the compressor containing refrigerant. The compressor model is tested on its own and assembled into a model for the complete AC system. All other components of the AC system are modeled using the Modelica library TIL. The paper presents two different approaches to a simultaneous simulation of the compressor and the total AC system. In the first approach, the compressor model is integrated as a sub-model into the complete model of the AC cycle. In the second approach, the compressor is coupled with the model of the remaining AC cycle using co-simulation.

2 Multi body simulation of the compressor with Modelica

Fig 1. presents the mechanical parts of the two cylinder CO_2 compressor [1]. The compressor is mounted in the engine bay of the bus. A pulley drives the clutch that is fixed on the compressor shaft. The connecting rod and the pistons are mounted on the crank shaft with corresponding bearings.

A multi-body model of the moving mechanical parts is built up using the standard Modelica library MultiBody [2,3]. The connection between the crank shaft and the connecting rod is modeled using a revolute joint that restricts the relative movement between the connected elements to a rotation around the desired axis. The crank shaft itself is modeled using a simple rigid-body model that contains the mass and inertia tensors. In order to allow for a dynamic visualization of the simulation results, graphical surface information of the mechanical objects is linked to the physical models using visualize-objects and the corresponding vector translations to achieve the correct positions.

Fig. 1 Mechanical parts of the CO_2 compressor used in prototype AC systems for busses

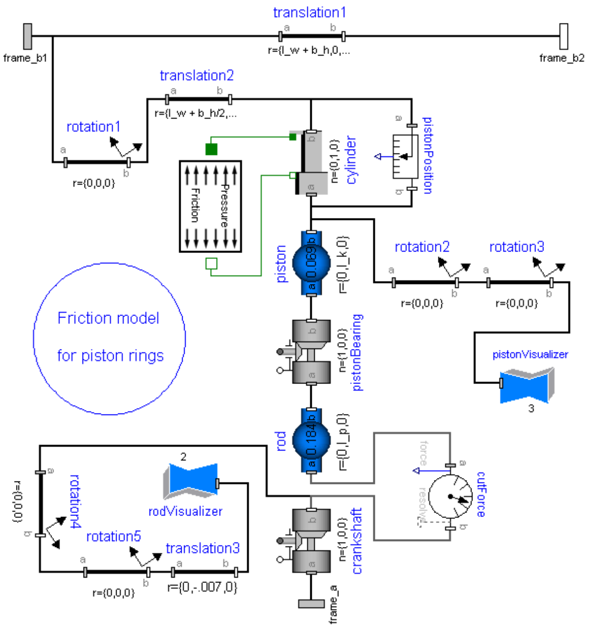

Fig. 2 Multi-body model of the crank and the piston

The piston bearing is a revolute joint that is connected to the connecting rod on one side and to the piston on the other side. The used connector objects of type frame contain the basic definition of the coordinate system that is fixed to the mechanical component. Further on, it contains the cut-force and the cut-torque corresponding to the origin of the coordinate system

The cylinder leads to a linear movement of the piston. This degree of freedom is enforced by a prismatic joint. The forces resulting from friction and pressure inside the cylinder are calculated in a separate model.

The thermodynamic model yielding the pressure information is discussed in the next section. The simple friction model considers the Stribeck curve.

Fig. 3. demonstrates the assembly of the complete compressor. The signal for determining the speed of the compressor is transferred to the crank shaft bearing. Two objects of the cylinder assembly, containing the cylinder itself, the piston and the connecting rod, are connected to the crank shaft. The world object describes the inertial system and defines the direction and type of the gravity and the gravitational constant.

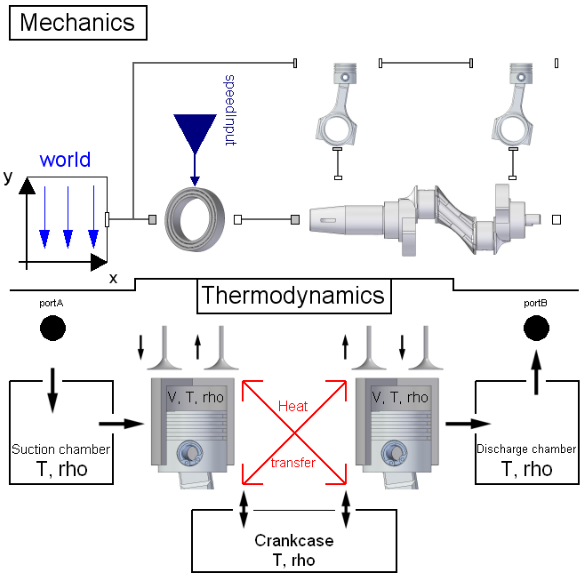

Fig. 3 Complete compressor assembly combining the mechanical and the thermodynamic part

The mechanical model delivers kinematic and dynamic results. The kinematic information is used for the compression and expansion process of the refrigerant gas in the cylinder chamber. Further on, the kinematic information is used for the visualization (see Fig. 4). The dynamic information results in calculating the torque at the clutch.

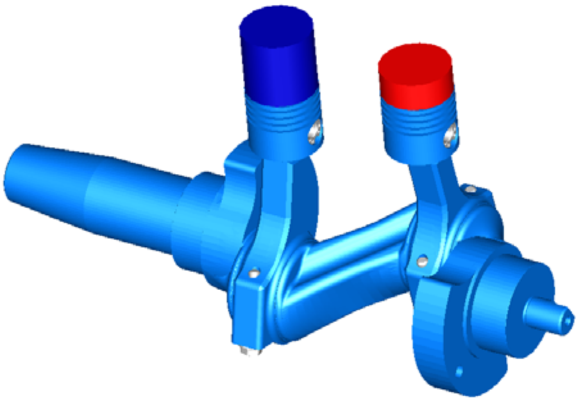

Fig. 4 Multi-body animation of the mechanical parts of the compressor including two pressure-dependent colored visualizers for the actual cylinder volumes

Details of the models and the corresponding validation of the model with experimental data will be given in future publications. The focus of this paper is to show a methodology for combined detailed modeling of the mechanics and the thermodynamics of the compressor assembled in a complete AC system. Further on, the numerical aspects of combining detailed compressor models with models of the entire refrigeration cycle are discussed.

3 Thermal model of the compressor

The compressor consists of different volumes containing refrigerant namely the suction chamber, the discharge chamber, the crank case and the cylinders. The conservation laws for energy and mass can be formulated for each of these volumes:

$$\frac{dU}{dt} = \sum_i \dot{H}_i + \dot{Q} - p\frac{dV}{dt}$$

$$\frac{dM}{dt} = \sum_i \dot{m}_i$$

where U is the inner energy, $\dot{H}_i$ are the enthalpy flows, $\dot{Q}$ is the heat flow, p the pressure, V the Volume, m the mass, and $\dot{m}_i$ are the mass flow rates.

Modern refrigerant models are described using a fundamental equation in the independent variables T and ρ [4]:

$$z = F(T, \rho)$$

In the next section, the equation of state and the calculation of the thermo physical data are discussed regarding the numerical efforts.

Obviously, the thermodynamic states (T and ρ) and the originally formulated numerical states (U and M) are not the same. Hence, a transformation of the algebraic differential equation system is required.

The differential equations are transformed corresponding (U,M)→(T, ρ):

$$\rho V c_v \frac{dT}{dt} = \sum_i \dot{H}_i + \dot{Q} - p\frac{dV}{dt} +$$

$$\frac{V}{\rho}\frac{d\rho}{dt}\left(\frac{\beta T}{\kappa} - p\right) + V\left(h - \frac{p}{\rho}\right)\sum_i \dot{m}_i$$

$$V\frac{d\rho}{dt} = \sum_i \dot{m}_i - \rho\frac{dV}{dt}$$

where ρ is the density, c_v the specific heat capacity at constant volume, T the temperature, β the isobaric expansion coefficient, κ the isothermal compressibility, and h the specific enthalpy.

The models for the calculation of the mass and heat flows are given in [5]. The calculation of the mass flow is based on pressure drop correlations for the corresponding flow areas, especially for the valve. The leakage between the cylinder chamber and crankcase is modeled in this way, too. The convective heat flow in the considered chambers is modeled by adequate heat transfer correlations. Heat conduction is considered using simple heat resistance models. The volume V and the corresponding time derivative are given by the multi-body model described in the previous section.

4 Simulation of compressor and complete air-conditioning system

The compressor is simulated as a part of a complete CO_2 air-conditioning system for a bus. The other component models of the systems like gas cooler, expansion valve, evaporator and suction line receiver are taken from the Modelica library TIL [6,7]. TIL is a library for steady-state and transient simulation of fluid systems such as heat pump, air-conditioning, refrigeration or cooling systems including the models described in [12,13]. TIL uses the object-based Modelica library TILFluids [6,15] to access the fluid property data computation routines of REFPROP [8] or other fluid databases. Further on, TIL contains a comprehensive library for models for detailed heat transfer and pressure drop correlations. TIL also provides an interface to the AirConditioning library developed by Modelon [9].

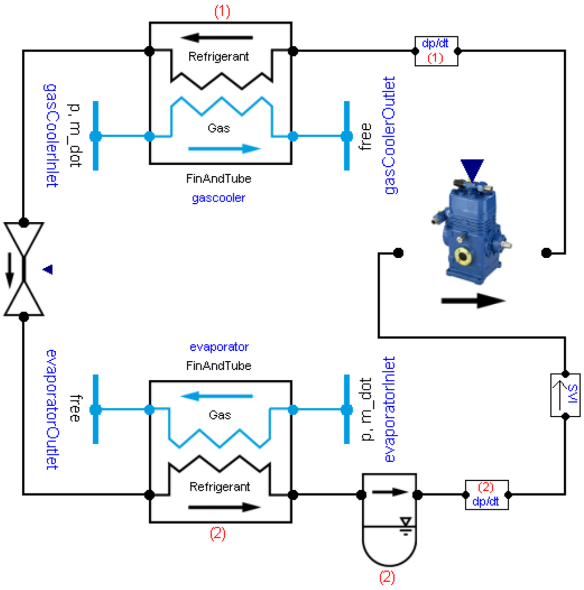

Fig. 5 Model of the complete CO_2 AC system in one single thread

Fig 5 shows the complete model of the AC cycle including the detailed compressor model as described in section 2 and 3. A result of this model at an arbitrary time t is shown in Fig. 6. The pressure-enthalpy diagram shows various refrigerant states. Each refrigerant state is modeled by a refrigerant object containing all property data and corresponding equations as described in [4]. The evaluation of the equations for calculating the thermophysical fluid properties of CO_2 requires a significant amount of the total computation time. Therefore the number of refrigerant objects determines the relative calculation effort of each component. Tab. 1 lists the total number of refrigerant objects for each component in the simulated AC system. This number is used to estimate the relative calculation effort for each component. It can be seen that the compressor model requires about 16% of the total computational effort.

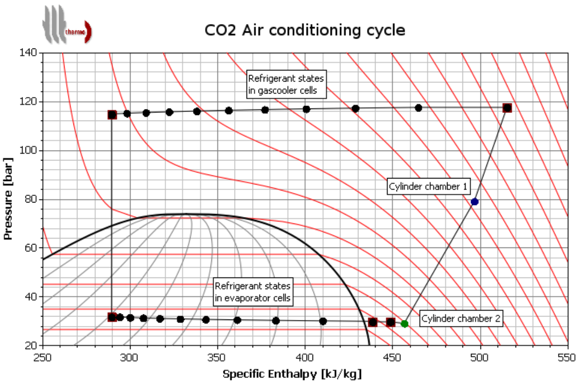

Fig. 6 Thermodynamic states of the complete cycle in the pressure enthalpy diagram at an arbitrary time t

Tab. 1 Estimation of the calculation effort due to the number of refrigerant objects

Component	**Refrigerant objects**	**Estimation of rel. calculation effort**
Compressor	5	16%
Gas cooler	12	36%
Valve	2	6%
Evaporator	12	36%
Receiver	2	6%
System w/o compressor	28	84%
Total system	33	100%

The complete integration time is proportional to the integration step size. The integration step size is determined by the shortest timescale of the system. This is obviously given by the rotation frequency of the compressor. The integration step size is about two orders lower than the time T for one revolution. This leads to an estimation of 0.5 ms, assuming 1150rpm. The typical timescale for the complete AC cycle is around 100 times larger.

In order to approve this estimation, the complete cycle was calculated with a very simple compressor model based on constant isentropic, volumetric and energetic efficiencies. When using this model, the calculation speed of the complete AC cycle could be accelerated by a factor of 300 (64 seconds compared to 5.2 hours calculation time for simulating 15 seconds of the transient CO_2 AC cycle).

These considerations demonstrate the need for multi-rate time integration methods [10,11]. While the compressor should be integrated with a timescale around 0.5ms the rest of the system can be integrated with a timescale about 0.5s. Unfortunately, the used simulator Dymola does not yet support multi-rate integration. In the following chapter a simple multi-rate method, realized by using a co-simulation technique, is presented.

5 Decoupling of time constants with the middleware TISC

In order to decouple the time constants of the compressor from the rest of the system, two instances of Dymola were used. In one instance the detailed compressor is integrated with a step size controlled DASSL solver algorithm (Fig. 9). In the other Dymola instance, the rest of the system is integrated with the same numerical method (Fig. 8). The middleware TISC [6,14] is used to couple the two instances. TISC is a middleware for exchanging data between different simulation applications. The exchanged data can consist of scalars, vectors or matrices which are uniquely identified by their name and type (Fig. 7). The data is transferred asynchronously between the client applications and the TISC-server using TCP-sockets. Beside the distribution of data among the clients the server also synchronizes the data at each time step.

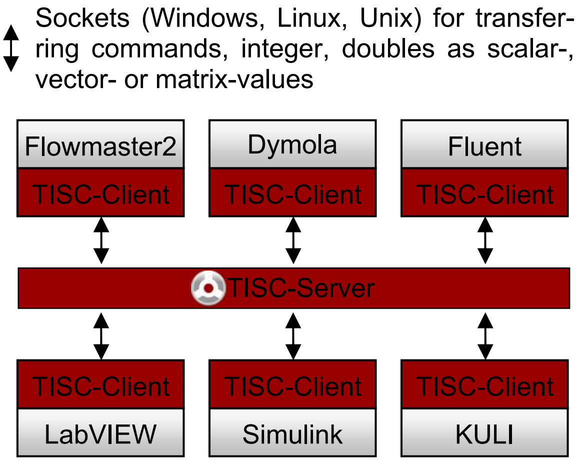

Fig. 7 Coupling of simulation tools and data acquisition software through Middleware

The used coupling variables are shown in Fig. 8 and 9. The compressor uses the refrigerant state at the suction inlet and the discharge pressure as given variables. For defining the suction state, the pressure p and the specific enthalpy h are selected. The mass flow rates through the suction and discharge ports and the specific enthalpy at the discharge port are calculated by the compressor model and therefore used as outputs.

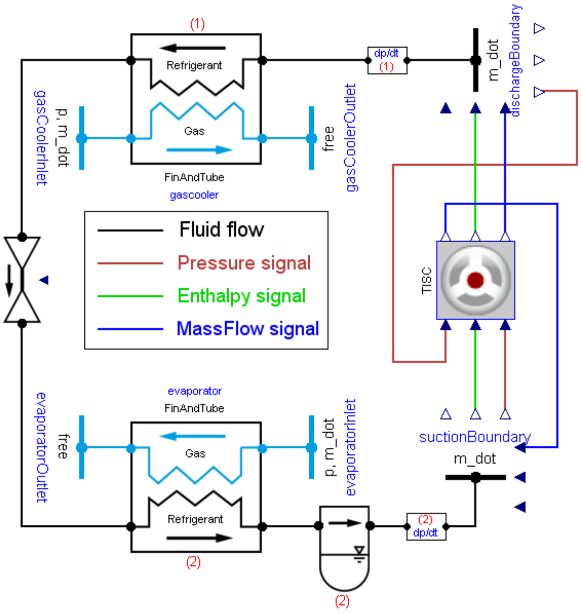

Fig. 8 AC cycle with external compressor model, coupled with the co-simulation platform TISC

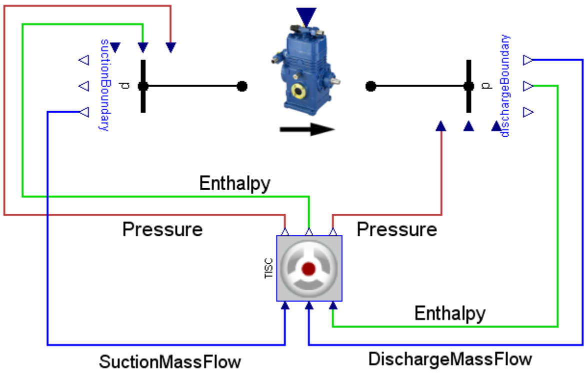

Fig. 9 Detailed compressor model with external AC cycle coupled with the co-simulation platform TISC

When applying this simple multi-rate integration method exchanging data via TISC every 0.1s, the calculation speed was accelerated by a factor of 40 in comparison to the simulation of the complete system without co-simulation (7.53min compared to 5.2h calculation time for simulating 15 seconds of the transient CO_2 AC cycle). When considering the estimated calculation efforts presented in Tab 1., an acceleration by a factor about 6 could be expected, due to the fact that the calculation effort for the cycle can be neglected because of the comparatively large integration step size. In this case, the significantly higher integration speed can be explained by the piecewise constant pressure conditions for the compressor. When the compressor is simulated in one instance with the entire AC cycle, the suction and discharge pressures vary continuously yielding a much smaller integration step size for the compressor.

6 Conclusion and outlook

The object-oriented modeling language Modelica was designed to allow component-oriented modeling of complex physical systems covering various engineering domains. This paper demonstrates the possibility of connecting mechanical and thermodynamic systems in a convenient way. The resulting hybrid system of differential algebraic equations could be solved in a consistent way. The solving method can be accelerated by using a multi-rate integration method and typical time scales for the two subsystems.

It seems to be a promising approach to combine Modelica compilers with an efficient method for detecting subsystems with different time scales for automatic detection of multi-rate integration methods. This might not be possible for all cases. In the presented system, the short time scale is determined by the compressor speed as a dynamic boundary condition. The compressor speed might not be known at compilation time. Therefore, Modelica should allow to define subsystems for multi-rate integration manually. The same method could be used for the parallelization of the problem which might yield significantly shorter computation times.

7 References

[1] H. Kaiser. Auswirkungen auf die Konstruktion von Kältemittelverdichtern bei Einsatz sogenannter Hochdruckkältemittel R404A/CO2. DKV-Tagungsbericht, Band II.2. Berlin. 1999.

[2] http://www.modelica.org.

[3] M. Otter, H. Elmqvist and S.E. Mattsson. The New Modelica MultiBody Library. *Proceedings of the 3rd International Modelica Conference*, pp. 311-330, Linköping, November 3-4 , 2003.

[4] R. Span, W. Wagner. A New Equation of State for Carbon Dioxide Covering the Fluid Region from the Triple-Point Temperature to 1100 K at Pressures up to 800 MPa. Journal of Physical and Chemical Reference Data, 25/6: 1509-1596, 1996.

[5] S. Försterling. Vergleichende Untersuchung von CO2-Verdichtern in Hinblick auf den Einsatz in mobilen Anwendungen. Dissertation. Technische Universität Braunschweig. 2004.

[6] http://www.tlk-thermo.de.

[7] C. Richter. PhD-Thesis (to be published 2008).

[8] E.W. Lemmon, M.L. Huber and M.O. McLinden. Reference fluid thermodynamic and transport properties. *REFPROP Version 8.0.* National Institute of Standards and Technology. Gaithersburg, USA. 2007.

[9] http://www.modelon.de.

[10] M. Arnold. Numerically stable modular time integration of multiphysical systems. In K. J. Bathe, editor, Proceedings of the First MIT Conference on Computational Fluid and Solid Mechanics, Elsevier, pp. 1062-1064, Cambridge, MA, USA, June 12-15 2001.

[11] R.M. Howe. Real-time multirate synchronous simulation with single and multiple processors. *Enabling technology for simulation science, ISSN 0277-786X*, pp. 331-342, [3369-38]. 1998.

[12] N. Lemke. Untersuchung zweistufiger Flüssigkeitskühler mit dem Kältemittel CO2. Dissertation. Technische Universität Braunschweig. 2004.

[13] W. Tegethoff. Eine objektorientierte Simulationsplattform für Kälte-, Klima- und Wärmepumpensysteme. Dissertation. *Fortschritts-Berichte VDI Reihe 19, Wärmetechnik/Kältetechnik, Nr. 118.* Düsseldorf. 1999.

[14] R. Kossel, W. Tegethoff, M. Bodmann, N. Lemke. Simulation of complex systems using

Modelica and tool coupling. *Proceedings of the 5th International Modelica Conference*, pp.485-490. Vienna. 2006.

[15] J. Köhler, C. Richter, W. Tegethoff, C. Tischendorf. Experimental and Theoretical Study of a CO2 Ejector Refrigeration Cycle. VDA Winter Meeting. Saalfelden. February 14-15. 2007.