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MODELLING AND SIMULATION OF REFRIGERATION SYSTEMS WITH THE NATURAL REFRIGERANT CO2

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ABSTRACT

This paper presents the current results of the development of a Modelica library for CO2-Refrigeration systems based on the free Modelica library ThermoFluid. The development of the library is carried out in a research project of EADS Airbus and the TUHH and is focused on the aim of getting a library for detailed numerical investigations of refrigeration systems with the rediscovered refrigerant carbon dioxide (CO2). A survey of the concept of an integrated cooling system on-board of airliners, the used modelling language Modelica™ and the developed CO2-Library is given and the modelling of CO2-Heat exchangers is described. A comparison with steady state results of heat exchangers is presented showing a very good agreement. The presented transient simulation results show the expected trends, but the models have not yet been validated with transient experimental data.

NOMENCLATURE

A: Cross-section of flow [m²]  
I: Momentum flow [kg*m/s]  
M: Total Mass [kg]  
U: Total internal energy [J]  
V: Volume [m³]  
g: Constant of gravitation [kg/(m*s²)]  
h: Enthalpy [J/kg]  
p: Pressure [Pa]  
u: Specific internal energy [J/kg]  
Δx: Length of control volume [m]  
Δp: Pressure loss due to friction [Pa]  
P: Power [W]  
•m: Mass flow [kg/s]  
•Q: Heat flow [W]

INTRODUCTION

In a research project of European Aeronautic Defence and Space Company (EADS) Airbus, Hamburg (Germany) and the Department of Technical Thermodynamics of the Technical University Hamburg-Harburg (TUHH), Hamburg (Germany) a system simulation of a cooling system is to be realised, using the refrigerant carbon dioxide (CO2). The main objective of the project is a proof of concept of a CO2 based integrated cooling system on-board of future airliners. For this purpose numerical and experimental investigations are in progress.

The fact of climate changes due to ozone depletion and global warming has been directed to significant research activities on the field of refrigeration and air-conditioning since the 1990s [10]. The objective of the investigations may result in a long-term solution, which is especially important for the aerospace application due to the long life cycle of airliners. Therefore so called natural, resp. alternative refrigerants with no Ozone Depleting Potential (ODP) and no or a very low Global Warming Potential (GWP) are investigated and new technical developments are driven. Carbon dioxide (CO2, R 744) as a natural refrigerant was rediscovered and has achieved a very high potential to substitute currently used refrigerants in the area of mobile/automotive air-conditioning and refrigeration. This development is caused by the excellent thermodynamic, transport and environmental properties of CO2. In order to obtain a better understanding of the complex thermodynamic and hydraulic behaviour of CO2-Refrigeration processes under the specific boundary conditions of aeroplanes the modelling of components of a CO2-System has been realised. For the modelling the object-oriented modelling language Modelica™ is used [20],
The scope of the CO2-Library is the modelling of the system behaviour by consideration of the most important physical effects like compressible flow, heat transfer, pressure drop, large capacities and time delays.

**CO2-REFRIGERATION SYSTEM**

Carbon dioxide was used as a refrigerant until the 1930s, but was then replaced by the synthetical refrigerants (HCFCs) that offered lower absolute pressures, simpler techniques and higher efficiencies in conventional vapour compression cycle. Due to the ODP and the GWP of the synthetical refrigerants the substitution of these by more environment friendly refrigerants is aspired. Recent research on carbon dioxide is pushed for mobile, resp. automotive air-conditioning and refrigeration and has focused on the development of a transcritical cycle [3]. The temperature and pressure at the critical point of CO2 are 304,13 K and 73,77 bar. Therefore, the refrigerant cycle has to be operated transcritically when the ambient temperature is near or higher than the critical temperature. In this case the heat rejection takes place at supercritical state. However, in the aerospace application the system operates in flight in the condensation mode but at ground a transcritical process has to be realised.

As shown in figure 1 the on-board cooling system is designed as a direct expansion cycle. The remote components, expansion valve and evaporator are placed at the cooling points inside the cabin. They are supplied by the piping, which connects remote and centralised components. The centralised components consist of compressor, gas cooler, internal heat exchanger, low-pressure receiver and control unit, which are placed outside the cabin. So the heat rejection at the gas cooler is to the ambient (ambient temperatures in flight can be -30 °C). The idea of such a concept is to get more flexibility by the design of the cabin layout since only the remote components and the piping are inside the cabin.

**MODELICA**

Modelica is an object-oriented modelling language to model large, complex and heterogeneous physical systems. The language is designed for convenient, component-orient modelling of physical multi-domain systems. A basic design idea of modelling with Modelica is, that it can be utilised in a similar way as an engineer builds a real system: First trying to find standard components like compressor and heat exchange from manufacturers' catalogues with appropriate specifications and interfaces. Only if there does not exist a particular subsystem, a component model would be newly constructed based on standardised interfaces [12]. The manufacturers catalogues, as a collection of components, are represented in Modelica by libraries. The models in Modelica are mathematically described by differential, algebraic and discrete equations. This means that no particular variable needs to be solved for manually. A Modelica tool will have enough information to decide that automatically by the causality between components in a complete physical system. Therefore, the particular models are modelled in Modelica non-causal. This leads to reusability of the developed models because they contain fewer assumptions about the context of their use [20]. To determine the causality between components the sum-to-zero equations of the conservation laws are used, which are formulated in all physical domains, e.g. Kirchhoff's law, Newton's law. In Modelica connectors are used to specify the interaction between components. The connector variables can be differed between across and through (resp. flow) variables; through variables sum to zero at a node (resp. connector) and are declared by the prefix `flow`. As mentioned above the reuse of models is possible as well as a hierarchical structure of models due to the fact that Modelica is an object-oriented language. The ability of reuse (by inheritance and instancing), hierarchical decomposition and model exchange enables the handling of complexity in a very good way. Furthermore Modelica supports arrays, the handling of time and state events and the use of external C- and FORTRAN-functions.

For the utilisation of the Modelica language a Modelica translator is needed to transform a Modelica model with regard to the causality to a DAE\(^1\). Therefore symbolic transformation algorithms have to be applied to transform the equations into a form, which can be integrated with standard methods. These transformation algorithms and solvers are available in two commercial Modelica modelling and simulation environments, Dymola™ [2] and MathModelica™ [9]. Both simulation environments include a graphical user interface (GUI) for model editing and browsing, Modelica translator, simulation engine and visualisation of results. We are using

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\(^1\) DAE stands for Differential Algebraic Equation system
Dymola, which provides some more features like a convenient interfaces to Matlab/SIMULINK™ allowing the combination of both and hardware-in-the-loop simulation.

**CO2-LIBRARY**

The aim of the modelling is to create a library with physical based models of the components mentioned in the section CO2-Refrigeration system. Such a library with models of these components and of additional components for testing, like sinks and sources, can be used for investigations of both, single components and complete refrigeration cycles. Furthermore it is of great interest to make dynamic simulation as well as steady state simulation of CO2-Systems and single components, especially heat exchanger. The numerical investigation of heat exchanger components is of particular interest to find optimised heat exchangers for limited space. On the other hand the concept of connectors in Modelica provides the opportunity using the same heat exchanger models for single component simulation as well as for a complex cycle simulation. There are different backgrounds for modelling and simulation of complex, closed CO2-Refrigeration cycles. The first aim is a better understanding of the complex, coupled thermodynamic, fluid-mechanic and heat transfer effects in a CO2-System by the typical aerospace boundary conditions. Furthermore aspects of the control of the system should be investigated. Finally, the library can be used for simulation and evaluating of different system design in various applications.

**ThermoFluid Library**

The CO2-Library is based on free Modelica library ThermoFluid [21], [22], [23]. The ThermoFluid library, especially the base classes and partial components, is in regard to the implementation of the three balance equations and the method of discretisation very well suited for modelling of CO2-Systems. The basic design principles of the library are:

- models are designed for system level simulation,
- one-dimensional one- and two-phase flow is considered,
- one unified library both for lumped and distributed parameter models,
- both bi- and unidirectional flows are supported,
- conservation laws are implemented separate from the medium models, so the reusability is given.

The use of distributed parameter models requires the finite volume method as discretisation method. The finite volume method is very common for system modelling and one-dimensional discretisation [13]. By the implementation of the conservation laws of energy, mass and momentum by the finite volume method the thermodynamic model and the flow model can be separated, since the storage of momentum is calculated in a control volume, which usually is staggered by a half grid length versus the grid of the control volume of mass and energy. The thermodynamic model holds the equations for total mass and internal energy for a fixed control volume:

\[
\frac{dU}{dt} = \frac{d(u\cdot M)}{dt} = m\dot{v}\cdot h_u - m\dot{v}\cdot h_{sat} + Q + P, \tag{1}
\]

\[
\frac{dM}{dt} = m - m_{sat}, \tag{2}
\]

with \( P = -\frac{dV}{dt} + P_{atm} \)

The fluxes on the border of the control volume are calculated by the half grid staggered flow model, which holds either a stationary pressure drop model or the dynamic momentum balance:

\[
\Delta z \cdot \frac{dM}{dt} = \frac{dL_{sat}}{dt} - \frac{dL_u}{dt} + (p_u - p_{sat})A - \Delta p_{sat}A - M \cdot g \cdot sin(\beta) \tag{3}
\]

The state variables of \( \{M,U\} \) for the thermodynamic model are numerical not efficient. Therefore, the equations (2) and (1) are transformed into a form with \( \{p,h\} \) or \( \{d,T\} \) as state variables. The constitutive equations needed for the calculation of pressure drop and heat flow in the equations (1) and (3) are not implemented in the ThermoFluid
library yet. However, in cooperation with the developers of ThermoFluid we have implemented a high accuracy medium model for CO2 based on an equation of state for the whole fluid region [14].

**Survey Of The CO2-Library**

So far, the following models and classes have been implemented:

- **Heat transfer and pressure loss relations for the whole fluid region:** This constitutive equations are used for the calculation of heat flux and pressure drop due to friction, which are added to the balance equations of energy and momentum [15], [16], [17].
- **Models for the air side of heat exchangers:** The balance equation of energy is implemented by the finite volume method [13]; heat transfer correlations for the air side have been implemented [5] as well as medium properties of air by polynomial fitting.
- **Pipes and heat exchangers:** Based on the medium model, classes of ThermoFluid, the heat transfer and pressure drop correlations and the air side models pipes and heat exchangers have been modelled.
- **Compressor:** The model is made for a reciprocating compressor. Therefore, the mass flow is calculated by the general equation of a reciprocating compressor and enthalpy change is calculated according to the isentropic efficiency.
- **Expansion valve:** The throttling process is treated as isenthalpic and the pressure drop is calculated according to the flow coefficient of the valve [1]. Since the flow coefficient results by specific valve data and the opening ratio the model has to be parameterised with corresponding data.
- **Receiver:** Up to now, a simple receiver model is implemented. The model separates the incoming two phase flow into its vapour and liquid phase. As long as the liquid level of the receiver is lower than the outlet height saturated vapour leaves; if the liquid level reaches the outlet height a two phase flow leaves up to a height only liquid leaves. However, the modelling is in progress.
- **Flow splits and junctions:** For this models classes of ThermoFluid are used; for the pressure drop in the momentum equation special correlations for splits and junctions have been implemented taking the ratio of mass flow into account [4]. The change of mass flow direction is also taken into account in the implementation.

**MODELLING OF HEAT EXCHANGERS**

So far, available heat exchangers for CO2-Refrigeration systems are compact prototype components from the automotive application. The heat exchangers are built up as follows: The CO2-Flow is splitted in different streams through so called Flat-Tubes (or Multiport-Micro-Tubes), see figure 2. The Flat-Tubes consist of a number of parallel bores in which the CO2 flows. The refrigerant is splitted and collected at the feeder and manifold of the heat exchangers. Outside the heat exchanger air passes over multi-louvered fins enhancing the air side heat transfer area and heat transfer coefficient, see figure 3. In a heat exchanger different flow paths for the CO2 are possible; usually gas coolers are constructed as crossflow and evaporators are built up as cross-counterflow heat exchangers.

For the modelling of the CO2-Flow a homogenous distribution of the flow is supposed. By this assumption the flow is modelled by one single pipe. The heat transfer area and the flow cross section are determined by the geometry and the number of all concurrent flowed pipes; whereas the heat transfer coefficient and the pressure loss is calculated with the mass flow rate and the geometry of a single bore. The assumption of homogenous mass flow and temperature distribution is also made for the air side. Therefore, it is possible to model the air flow through one air channel. The wall is modelled as a capacitive, cylindrical wall. For more detailed explanation of the modelling see [19]. These specific models of CO2-Pipe, wall and air have to be connected in the right way to get a reasonable model of a heat exchanger. For the connection the heat connectors of ThermoFluid can be used; the connecting variables are temperature (across variable) and heat flux (through variable). In figure 4 the graphical representation of the heat exchanger model in Dymola is shown. This is the top level of the model consisting of the connected instances of the models for the air side, the wall and the pipe. Furthermore, the interfaces for the CO2 (symbolised by filled and hollow rhombus) can be seen as well as the imports for the air side boundary conditions (symbolised by triangles). The extensive parameterisation of the heat exchanger is realised with a so called record, symbolised by the rectangle geoHX.
Comparison Of Steady State Simulation And Measurement

With these models simulations in a test configuration have been run. The test configuration consists of a source providing pressure and enthalpy at the heat exchanger inlet and a mass flow sink generating a defined mass flow at the outlet. The source and sink are used to set the boundary conditions resulting from the measured data at the component. The following comparison is made for a crossflow gas cooler and cross-counterflow evaporator from the CO2-Experimental system built up at the Department of Aircraft Systems Engineering of the TUHH. The geometry parameters of the components are known. In the tables 1 and 2 the measured data and the results of the simulations at the point of steady state are shown. The comparison of experimental data and simulation results show a very good correspondence.

Table 1: Comparison of measured data at a gas cooler with simulation results in steady state

<table>
<thead>
<tr>
<th>Boundary conditions from measured data</th>
<th>Measured data</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{m}_{\text{air}}$ [kg/s]</td>
<td>$\dot{m}_{\text{CO}_2}$ [kg/s]</td>
<td>$p_{\text{CO}_2}$ [bar]</td>
</tr>
<tr>
<td>---------------------------------------</td>
<td>---------------</td>
<td>-------------</td>
</tr>
<tr>
<td>0.605</td>
<td>0.013</td>
<td>96.0</td>
</tr>
<tr>
<td>0.593</td>
<td>0.032</td>
<td>87.5</td>
</tr>
<tr>
<td>0.598</td>
<td>0.036</td>
<td>88.3</td>
</tr>
</tbody>
</table>

Table 2: Comparison of measured data at an evaporator with simulation results in steady state

<table>
<thead>
<tr>
<th>Boundary conditions from measured data</th>
<th>Measured data</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{m}_{\text{air}}$ [kg/s]</td>
<td>$\dot{m}_{\text{CO}_2}$ [kg/s]</td>
<td>$p_{\text{CO}_2}$ [bar]</td>
</tr>
<tr>
<td>---------------------------------------</td>
<td>---------------</td>
<td>-------------</td>
</tr>
<tr>
<td>0.21</td>
<td>0.032</td>
<td>49.1</td>
</tr>
<tr>
<td>0.21</td>
<td>0.036</td>
<td>40.3</td>
</tr>
<tr>
<td>0.21</td>
<td>0.013</td>
<td>34.6</td>
</tr>
</tbody>
</table>

SIMULATION RESULTS OF A CO2-SYSTEM

In the following simulation results of the start up of a CO2-System are presented. The results are discussed with respect to plausibility since reliable data of transient processes from a test rig are only available for a few weeks. The simulated model is shown in object diagram in figure 5. This configuration does not consists a receiver since the receiver model is not implemented in the right way. In table 3 the boundary conditions and initial values are listed. The following boundary conditions are changed during the simulation run:

- Start up of compressor speed $n$ from 120 to 1000 rpm in 2 seconds;
- Step change of flow coefficient $K_V$ from 0.03 to 0.02 m³/h at 60 seconds.

Table 3: Boundary conditions and initial values of the simulation run

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor</td>
<td>$\lambda$</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>$\eta_{\text{ls}}$</td>
<td>0.75</td>
</tr>
<tr>
<td>Gas cooler</td>
<td>$\dot{m}_{\text{air}}$</td>
<td>3200 kg/h</td>
</tr>
<tr>
<td></td>
<td>$T_{\text{air,\text{in}}}$</td>
<td>305 K</td>
</tr>
<tr>
<td>Evaporator</td>
<td>$\dot{m}_{\text{air}}$</td>
<td>580 kg/h</td>
</tr>
<tr>
<td></td>
<td>$T_{\text{air,\text{in}}}$</td>
<td>305 K</td>
</tr>
<tr>
<td>System volume</td>
<td>$V_{\text{tot}}$</td>
<td>1.13 l</td>
</tr>
<tr>
<td>Refrigerant filling</td>
<td>$200$ kg/m³</td>
<td></td>
</tr>
<tr>
<td>Initial value</td>
<td>$p_0$</td>
<td>66 bar</td>
</tr>
<tr>
<td></td>
<td>$h_0$</td>
<td>420 kJ/kg</td>
</tr>
</tbody>
</table>

Results

In figure 6 the pressure at compressor inlet and outlet is plotted versus time. What can be seen from the results is the divergent run of the pressures and a typical overshoot, resp. undershoot at the beginning. This system behaviour is plausible as well as the divergent run of pressure after the step change of the flow coefficient. This can
be made clear by looking at the mass flow rates at the compressor and the expansion valve in figure 7. At the beginning the compressor mass flow rate is much higher than the mass flow at the valve. The compressor mass flow increases proportional with the compressor speed, whereas the flow rate at the valve just increases with the increasing pressure difference at the valve. The difference between both mass flows effects a shifting of refrigerant mass from the low pressure section to the high pressure section of the system. The decreasing density of the sucked refrigerant at the compressor causes the strong decreasing of the compressor mass flow after 2 seconds. The valve mass flow rate is mostly affected by the pressure difference, so the mass flow does not decrease; the system time delay causes a higher valve flow rate for a few seconds resulting in the shown over- and undershooting of pressures. The same effect of displaced mass explains the divergent run of the pressures after the step change. Finally you can illustrate the steady states of the process in a p,h-Diagram of CO2, see figure 8. The simulating of the start up and the changing of flow coefficient was performed on a PC with a Pentium 1000 MHz and 256 MB of main memory and took 5 minutes.

CONCLUSION

A developed CO2-Library based on free Modelica library ThermoFluid was presented, which contains models for all important components of a CO2-Refrigeration system. The intention is to create a library for the simulation of single components and complete cycles. Such a library can be used to make fundamental investigations of a CO2-System. Furthermore, it can be used for the optimisation of specific heat exchangers, for the evaluating of optimal system configuration and for the layout and optimisation of the system control. The presented simulation results for the steady state of two different types of CO2-Heat exchangers show a very good correspondence with measured data. The results of transient simulation show the expected trends of the state variables and a plausible system behaviour due to the thermodynamic and hydraulic effects but the model has not yet been validated with experimental data. Furthermore the simulation results show that Modelica, the free Modelica library ThermoFluid and the CO2-Library are very well qualified for the simulation of the complex processes in a CO2-Refrigeration cycle.

Future work contains the validation of the models and the improvement of the initialisation and the receiver model. If the models are verified the control of the system will implemented. For further investigations of the system control and the exploration of the dominant system dynamics it is possible to use a moving boundary model for evaporators, which is implemented in Modelica and is an extension of ThermoFluid [7]. This model will give the possibility for a reduced-order model for more control-oriented investigations.

REFERENCES


**FIGURES**

**Figure 1:** Schematic diagram of a CO2-Refrigeration cycle for an on-board cooling system [18]

**Figure 2:** Cross section of a Flat-Tube

**Figure 3:** Multi-louvered fins
Figure 4: Graphical representation of the heat exchanger model in Dymola

Figure 5: Object diagram of simulated CO2-Cycle in Dymola

Figure 6: Pressure run at compressor in- and outlet

Figure 7: Mass flow rate at valve and compressor

Figure 8: Steady states of simulated process in a $p,h$-Diagram of CO2