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Modelica Workshop 2000 Proceedings, pp. 89-92.

Numeric simulation of an integrated CO_2 cooling system

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October 13, 2000

Abstract

In a research project of EADS Airbus and the TUHH a system simulation of a cooling system is to be realized, using the refrigerant carbondioxid (CO_2). The simulation models of the cooling cycle are created using Modelica and the thermohydraulic model library ThermoFlow. Modelica and the model library operate since spring 2000. The project will be finished untill the end of 2002.
For the structure of the CO_2 models so far a FORTRAN program was introduced in Modelica that calculates the state variables of CO_2 using an equation of state. Furthermore the heat transfer and pressure loss relations were implemented of CO_2 for one- and two-phase and the supercritical status area. Literature reviews of currently measured results were used to check the models. Therefore, the modelling of pipes, evaporators and gascooler/condenser is possible.
First results of an uncomplex CO_2 -refrigertion cycle are presented and a preview of future work is given.

1 Introduction

In a research project of European Aeronautic Defence and Space Company (EADS) Airbus and the Department of Technical Thermodynamics of the Technical University Hamburg–Harburg (TUHH) a system simulation of a cooling system is to be realized, using the refrigerant carbondioxid (CO_2). The aim of the project is to prove the feasibility of an integrated cooling system on board of future airliners. The idea of an integrated cooling system is to get more flexibility by the design of the cabin layout. Until now, every galley is cooled by a single airchiller system. In future airliners the galleys and other cooling points will be cooled by evaporators, which are supplied by the piping of the integrated cooling system. Such a system consists of central components like compressor, gas coller (condenser), receiver and control unit and the distributed components like evaporators and expansion valves at the cooling points. The piping connects the components.
The thermal and hydraulic system properties has to be modelled in combination with the control of the system. With the verificated models the operating efficiency of the cooling systems should be verified for extreme climates at the ground and at the flight. Also different concepts of system design und control strategies could be simulated and compared.
Since the object oriented programming tool SMILE is used for several years for the simulation of energy systems at the Department of Technical Thermodynamics, now Modelica is used for the simulation of CO_2 -systems. In several research projects like, *Energy requirements and comfort of gas- and electric-powered hot-water systems* and *Modelling and simulation of power plant components* the object oriented modelling was used and reasonanble results have been achieved. The models of the CO_2 -system are built-up mainly on base of own models and the thermohydraulic model library ThermoFlow [4].

2 Carbondioxid as refrigerant

In the 19th century CO_2 (R744) was a widespread refrigerant. The synthetical refrigerants (HCFCs) displaced CO_2 in the 1930s because lower system pressures and a simpler technique could be realized. Due to the ozone depleting potential (ODP) of the HCFCs new refrigerants (HFCs) were introduced. Although the HFCs like R134a have no ODP, the global warming potential (GWP) is much higher than that of natural refrigerants like CO_2 or ammonia (NH3).

2.1 The CO_2 -refrigeration cycle

Due to the critical point of CO_2 (73,77 bar and 30,98 °C) the refrigeration cycle has to be operated transcritically when the ambient temperature is near or higher than the critical temperature. In this case the evaporation takes place at subcritical pressure and temperatur and the heat rejection at supercritical state.

As seen in figure 1, the main components of a CO_2 -refrigeration cycle are compressor, gas cooler (instead of a condenser because of the supercritical heat rejection, that occurs sometimes), internal heat exchanger, expansion valve, evaporator and low-pressure receiver. At the transcritical cycle the compressor sucks refrigerant as superheated vapour and compresses to high pressure. At the supercritical pressure, the CO_2 is cooled in the gas cooler by transferring a heat flux to the ambient climate. The CO_2 is cooled down near to the ambient temperature. In the internal heat exchanger the high-pressure CO_2 is cooled and the low-pressure CO_2 , as saturated vapour from the receiver, is superheated. Then the refrigerant is throttled to low pressure. In the evaporator the CO_2 evaporates incomplete by constant pressure and temperature and removes a heat flux from the air at the cooling point. The low-pressure receiver seperates the two phase; only saturated CO_2 is sucked through the internal heat exchanger to the compressor. If the ambient temperature is well below the critical temperature of CO_2 , the refrigeration cycle operates like a typical refrigerant compression cycle with heat rejection by condensation.

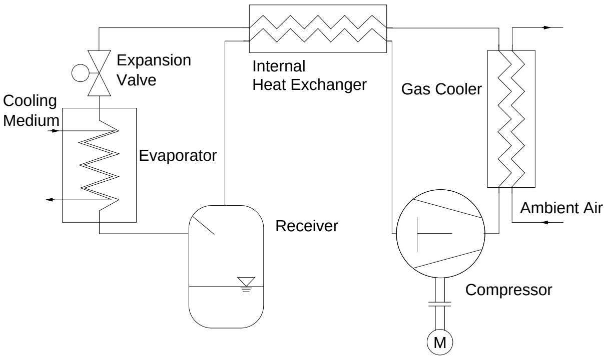

Figure 1: Schematic diagram of a CO_2 -refrigeration cycle

3 Builtup of numerical models with Modelica

The basic structure of the modelling of CO_2 -cycle-components is given by the decision to use the thermohydraulic library ThermoFlow. ThermoFlow is based on a thermodynamic model which is suited to model systems like a CO_2 -refrigerant cycle. Especially the base models of the library and parts of the partial components can be used to programm own models.

3.1 Base classes for the CO_2 -models

For the beginning of modelling components a FORTRAN programm [1] was introduced in Modelica that calculates the state variables of CO_2 using an equation of state. Additionally other CO_2 medium properties were implemented. After checking the medium models, the heat transfer and pressure loss relations were implemented of CO_2 for one- and two-phase region and the supercritical status area.

The one-phase region and the supercritical status area are modelled with the same common correlations for heat transfer and pressure drop according to [2]. The verification of the heat transfer correlation, with experimental data from the SINTEF [3], shows a good correspondence (see figure 2). The comparsion of the measured pressure drop data with calculation models shows good accordance. At the two phase region the heat transfer relations are differentiated between evaporation and condensation. The heat transfer coefficent by evaporation

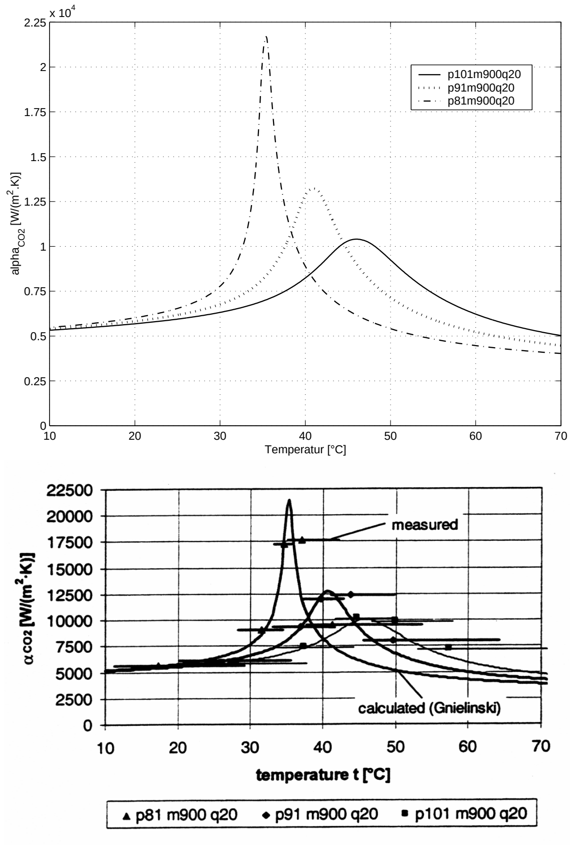

Figure 2: Simulation results of supercritical heat transfer (top) and measured data from SINTEF (bottom)

is calculated by an equation considering convective boiling and nucleate boiling. From a critical vapour fraction, the dry-out effect is also considered in the model. For the calculation of heat transfer coefficent of condensation the relation of turbulent film condensation is implemented [2]. Checks of the calculation with results the measured results yields good correspondence.

The frictional pressure gradient in two-phase region is calculated with a two-phase multiplier according to the Friedel correlation. In general the calculated pressure drop results in values that are too low compared with the measured data. However for a first estimation the implemented correlations can be taken.

3.2 Pipe and heat exchanger models

On base of the implemented base classes the modelling of pipes, evaporators and gas cooler is realized. The pipe model as base for the piping and for of all types of heat exchangers is built up from base models of ThermoFlow and own models for medium properties, heat transfer and pressure drop. First, the static momentum balance equation is used for the pipe model instead of the dynamic one, because the simulation of thermal system charateristics is the priority objective. The use of class parameters in base models of ThermoFlow enable the use of own models for medium properties and pressure drop. The heat exchangers can be simulated with different models for the wall and the boundary conditions, depending on the certain context of investigation.

3.3 Modelling of compressor and expansion valve

The compressor is modelled in a simple way, basing on the possible separation of control volume and flow model in ThermoFlow. Therefore, the general equation for mass flow of a reciprocating compressor is implemented and the enthalpy change is calculated according to the isentropic efficiency. Future work contains improved equations of the isentropic and volumetric efficiency, which are based on measured charateristic diagramms of a CO_2 compressor.

The throttling process is treated as isenthalpic and the pressure drop is calculated with a general mass flow charateristic of expansion valves including geometric and hydraulic coefficents, which are specified by construction of valves.

4 Simulation of a CO_2 -refrigeration cycle

As seen in figure 3, a simple CO_2 -refrigeration cycle consisting of compressor, expansion valve, evaporator and gas cooler is simulated in Dymola. The heat exchangers are composed of a discretized pipe, a linear wall model and an air flow as boundary condition. The boundary condition of the evaporator is modelled as a volume filled with air (ideal gas) and a constant heat transfer coefficent. This model represents conditions like in a refrigerator.

The geometric parameters of heat exchangers, compressor and valve are similary set as real components of a CO_2 -cycle. The isentropic and volumetric efficiency are set as parameter of the compressor. The revolution of the compressor and the mass flow coefficent of the expansion valve are constant input signals. First simulation results will be presented at the workshop.

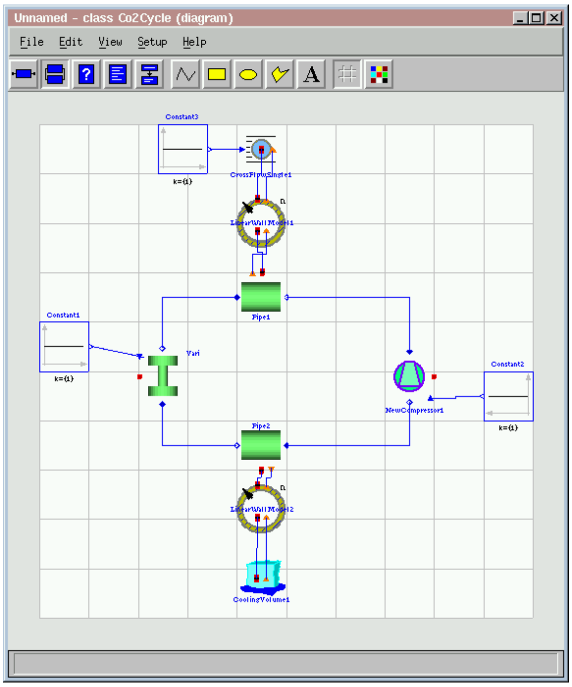

Figure 3: Diagram of simulated CO_2 -cycle

5 Conclusion

So far, basic work for the simulation of CO_2 -refrigeration cycles has been done implementing a CO_2 medium model, heat transfer, pressure drop correlations, modelling of simple components and simulating a simple refrigeration cycle. Future work in the research project *Numeric simulation of an integrated CO_2 cooling system* consists in the implementation of a controller for the compressor and the expansion valve and of the results of characteristic compressor data. Furthermore, the simulation of a ramified piping with two or more evaporators and controlled expansion valves has to be done. The use of the CO_2 medium model in the ThermoFlow library and the provided formulation of balance equations in density (d) and temperature (T), instead of the actual used formulation in pressure (p) and enthalpy (h), should be realized to speed up the simulations.
The simulation results of the CO_2 -cycle will be verified, using measured data from an experimental CO_2 -refrigeration cycle, where measurements will be undertaken next year. Right now, this experimental system is built up at the Department of Aircraft Systems Engineering of the TUHH in context of the research project *Integrated CO_2 cooling system*.

5.1 Acknowledgement

The presented results and efforts would not have been possible without the help and the work of some people apart from the authors. Thanks to Hubertus Tummescheit for providing ThermoFlow before publishing the library. Thanks to Stefan Wischhusen for the implementation of various models in his master thesis. Thanks to Guido Ströhlein for the implementation and testing of the CO_2 -FORTRAN code.

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