

# SIMULATION WITH MODELICA FOR A DYNAMIC REPRESENTATION OF AN AIRCRAFT CABIN CLIMATE FOR COMFORT-IMPROVED CLIMATE CONTROL

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## Abstract

*In cooperation with the Airbus Deutschland GmbH the Hamburg University of Technology (TUHH) participates in the German national funded project KATO (TP07 "Komfortverbesserte Klimaregelung"). One of the goals of this project is to model the inside of an Airbus A340 fuselage using dynamic system simulation in such a way that it can serve as a control path for advanced controller design. A model library is currently under development using the modeling language Modelica™. This library can be used for the setup of simulation models, that describe the thermo-pneumatic conditions in the pressurized fuselage. An adequate simulation model including heat flux, mass flow and momentum balance will be provided, which will serve as a control path, both for the computer-assisted controller development and for "hardware in the loop" applications. The Modelica™ simulation environment (Dymola™ [3]) used for this task offers the possibility, to export models through an interface to the software Matlab/Simulink™ [7]. Here they can provide a basis for controller optimization tools, e.g. MOPS [4], or can be integrated into control loops. By using this method, new control techniques and control concepts can be tested quickly and economically.*

## 1 General Introduction

In the past of aircraft construction engineering activities focused especially on the solution of numerous technical problems, which mainly had the goal to optimize the flight performance, e.g. by improving of the airplane aerodynamics and engine performance. Other activities concentrated on the enhancement of the mechanical structure and on other security relevant factors for the passengers and cabin crew. These days also the investigation of possible improvements of the passengers' comfort plays an important role. Apart from the seat comfort and the kind of available entertainment system, the health aspect due to air quality and cabin climate particularly on long-range flights is of great interest [1], [2], [9]. Besides the layout of the air conditioning facility, the choice of suitable temperature sensors and their positioning in the aircraft, it is decisive, with regard to the required thermal comfort specifications for a changing cabin layout, to achieve an optimum design of the temperature controllers.

While the question of positioning the sensors can be determined best by means of a CFD-program due to its higher spatial resolution, the application of a 3D-model, as a control path for the controller design, is hardly realizable considering the limited technical possibilities that we still have today. Here the limits are set in particular by the immense expenditure of time for model setup and simulation and the needed amount of computing

power to perform this task.

For those reasons a high performance system simulation tool and the modeling language Modelica™ were chosen to handle the TUHH part of the KATO project.

## 2 The Simulation Environment

### 2.1 The Modelica™ Language

The object-oriented modeling language Modelica™ is designed for modeling dynamic heterogeneous physical and technical systems. The language is a product of the Modelica Association [8], a non-profit organisation that was founded in February 2000. The basic idea behind this language was to set up a standard for the exchange of models and model libraries for physical and technical systems. The key features of this language are:

- Non-causal use of algebraic mathematical equations (differential, algebraic and discrete equations)
- Modeling of complex systems of heterogeneous physical areas with continuous and discrete behavior
- Facile reusability of models due to inheritance, instantiation and replaceability
- Flexible combination of models via connectors

### 2.2 The Simulation Environment Dymola™

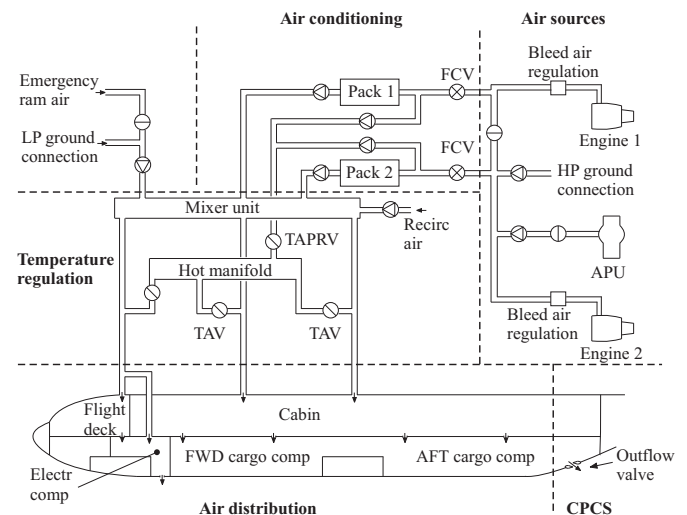
The simulation environment Dymola™, **D**ynamic **M**odeling **L**aboratory, is suitable for modeling various kinds of physical systems and objects [3]. Dymola™ supports the composition of hierarchical models, libraries of truly reusable components, connectors and composite acasual connections. The new modeling methodology used in Dymola™ is based on object orientation and equations. The simulation environment supports automatic formula manipulation that removes the usual need for manual conversion of equations to

a block diagram. Other key features of Dymola™ are:

- Handling of large, complex multi-domain models
- Support of Graphical model composition
- Symbolic pre-processing
- Open for user defined model components
- Open interface to other programs
- 3D Animation capability
- Possibility for Real-time simulation

## 3 The Environmental Control System

The environmental control system (ECS) is of great importance in order to keep the cabin pressure at a constant level and to provide air conditioning to the passengers and crew during the flight. In this chapter the function of the ECS during normal mode of operation is explained. With the exception of the new bleed-less ECS concepts a standard ECS works as shown in Figure 1.



**Fig. 1** Scheme of a standard ECS with its sub-systems [12]

The bleed air (high pressure, high temperature) is taken from one of the compressor stages

of the aircraft engines (*Air sources*). It then passes the flow control valves (*FCV*) and enters the air conditioning packs. One part of this air is led through air cycle machines (*Pack 1* and *Pack 2*), where it is expanded and cooled down. The other part is stored in the *Hot manifold*. In the *Mixer unit* the cooled air from the packs is mixed with filtered recirculation air coming from the cabin. The temperature in the *Mixer unit* is adjusted in such a way that it meets the lowest required zonal cabin temperature. Subsequently the mixed air is further distributed through the ducting to the cabin zones. Depending on the demand in the different temperature zones the fine adjustment of the air temperature is accomplished shortly after the *Mixer unit* by blowing in hot air through the trim air valves (*TAV*). The part of the supply air that is not reused as recirculation air leaves the aircraft through the (*Outflow valve*), which is responsible for the adjustment of the cabin pressure.

## 4 Modeling Approach

Thermodynamic systems in general consist of single units, e.g. fans, heater, cooler and volumes, that are connected by each other and are flown through by a working agent, such as water or air. Depending on the required level of detail the single components can be described through sets of algebraic, differential and/or partial differential equations.

The most important elements for the modeling of a thermodynamic system are the control volume (CV) and the flow model.

A control volume can be regarded as a continuously stirred tank. This means that there exists only one thermodynamic state in the CV and that every outgoing mass flow corresponds to this state. To connect adjacent CVs, a flow model is necessary that calculates the mass flow between the two due to a driving force, e.g. the pressure difference.

### 4.1 The Control Volume

The control volume approach used for this work is based on the staggered grid finite volume method described in [10]. It is commonly used for system modeling and one-dimensional discretisation. The thermodynamic model inside the CV contains the equations for mass and energy conservation for a system of constant volume:

$$\frac{dM}{dt} = \sum_{i=1}^n \dot{m}_{in,i} - \sum_{j=1}^o \dot{m}_{out,j} \quad (1)$$

$$\frac{dU}{dt} = \sum_{i=1}^n \dot{H}_{in,i} - \sum_{j=1}^o \dot{H}_{out,j} + \dot{Q} + \dot{W}_s \quad (2)$$

The calculation of thermodynamic states in the CV is realized by a coefficient database and a collection of functions for the thermodynamic behavior of air, which is already part of the *Modelica Standard Library* [8].

The fluxes on the border of the control volume are calculated by the half grid staggered flow model, which contains either a stationary pressure drop model or in case of a discretized control volume (pipe model) a dynamic momentum balance [11], [6]:

### 4.2 The Flow Model

The flow models used for this task are simplified pressure loss models. Right now there are three different variants possible: A constant laminar, a constant turbulent and a detailed friction pressure loss model.

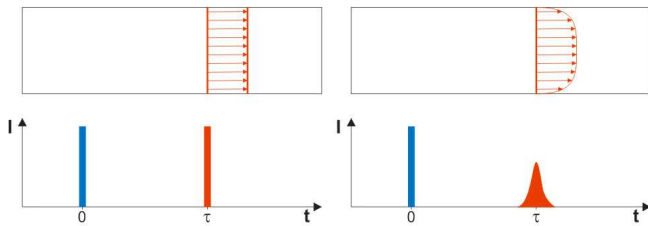
While the first two models calculate the pressure loss by a constant linear or a constant quadratic dependency between pressure loss and mass flow rate, the detailed friction model is basically based on the equations that provide the basis for the *Moody Chart*. In order to avoid a division by zero in the laminar region at zero mass flow rate and to allow a flow reversal the equations of the detailed friction model have become mathematically rearranged [5].

## 5 The Simulation Model

The simulation model basically consists of two major parts, for which experiments have shown that they have a significant influence on the cabin temperature behavior: the supply air distribution system (ducting) and the cabin itself.

### 5.1 The Ducting Model

The ducting system has a significant influence on the thermal behavior due to its large heat transfer area and its heat accumulation capacity. It mainly consists of insulated pipes made of glass-fiber reinforced plastic (*GRP*). The ducting is represented in the simulation model by a network of pipe models. Those models, in order to meet the behavior of real pipes (see Figures 2), where diffusion and friction effects lead to axial dispersion, are programmed as cascades of connected CVs.

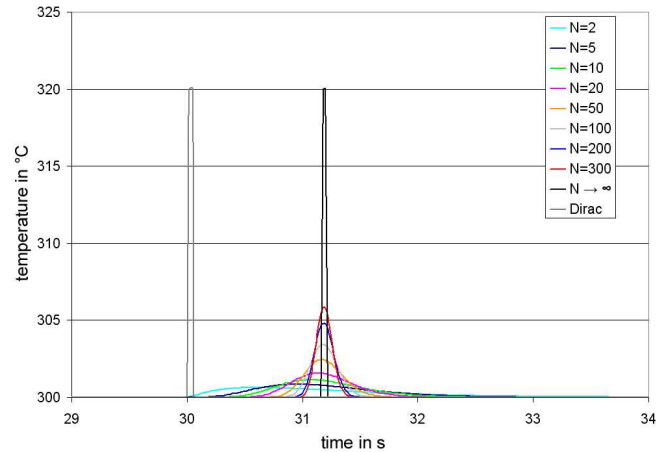


**Fig. 2** Dirac response of an ideal pipe vs. a real pipe

The number of CVs of the pipe models is defined by the discretisation ( $N$ ). Its influence on the behavior of the model can be seen in Figure 3.

This technique derives from the domain of chemical engineering, where pipe reactors are modeled in a similar way.

Each of the CVs in the pipe model contains a dynamic heat transfer model [13], that enables the CV to calculate the heat transfer coefficient automatically, depending on the geometric pipe data, the media properties and the flow velocity. Additionally the CVs contain two wall models, that calculate the heat conduction and the heat accumulation in the pipe wall and the insulation,



**Fig. 3** Dirac response of the pipe model in dependence of the discretisation  $N$

and finally another heat transfer model to the surrounding ambient air.

### 5.2 The Cabin Model

Depending on the selected discretisation, the cabin model is represented by a more or less complex network of control volumes, that are connected via flow models. Contingent upon the arrangement of the volumes in the cabin, the CVs can contain heat sources (passengers, crew, electrical systems etc.) and heat accumulators (e.g. hat racks or seats).

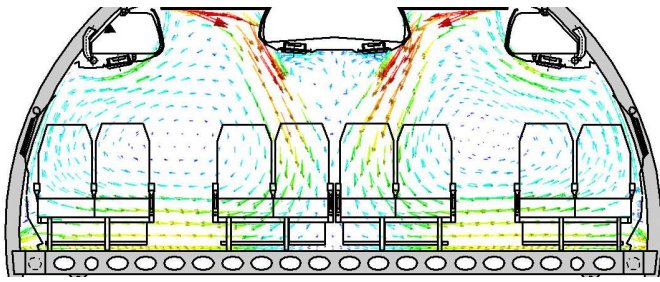
As the used flow models are currently not designed for calculating the mass flow rate in a different way to standard pressure loss models, it is unfortunately not possible to cover the mass transport due to the momentum driven vortices that develop in the real cabin (see Figure 4).

In the simulation model this effect has to be covered by inserting an additional heat transfer between adjacent control volumes.

## 6 Validation/Simulation Results

First simulations of the cabin model, which neglected the influence of the ducting, showed that the results were not meeting the expected behavior measured in flight tests (see Figure 10). Therefore in addition to the comparison of the

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**Fig. 4** Generic scheme of the air flow pattern in a cabin

complex cabin models with the few available sets of flight test data an Airbus test rig was constructed (see Figure 5) for the validation and tuning of the simulation models.

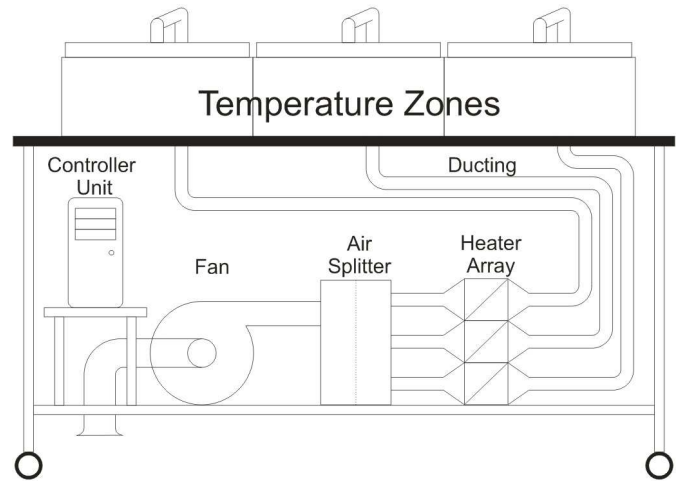


**Fig. 5** KATO test rig

With this test rig the acquisition of the necessary transient temperature data for the improvement of the system models could be obtained much more flexible and comfortable.

The test rig comprises of three cabin temperature zones, including the ducting. A scheme of this test rig is shown in Figure 6.

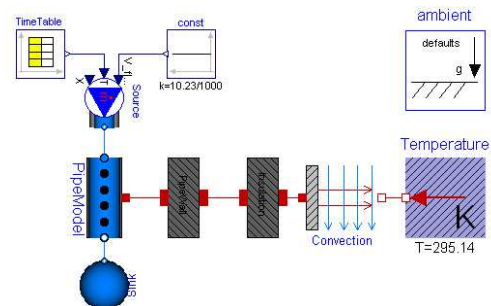
When compared to the scheme of the ECS (Figure 1) some analogies can be noticed. The mixer unit is represented by the air splitter. The task of the trim air valve is performed by an array of fast working heater units and the behavior of the ducting is replicated by insulated polypropylene pipes. The pipes in the test rig disemogue into six air inlets that are connected to the three independent temperature zones. The box shaped



**Fig. 6** Scheme of KATO test rig

temperature zones are equipped with numerous electric bulbs that represent the additional heat load due to passengers, crew and electronic devices.

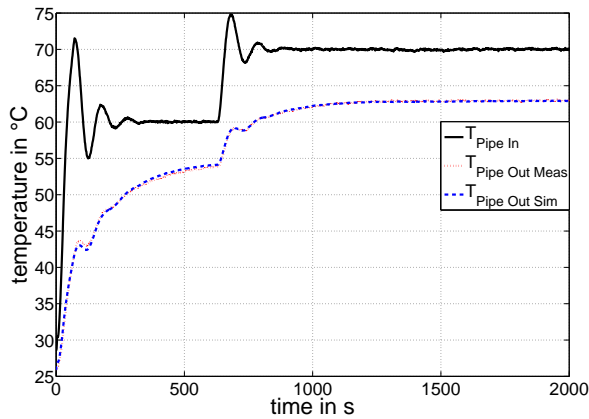
The experimental data from the test rigs ducting system showed a good correspondence with the simulation results obtained with the ducting model (see Figure 7).



**Fig. 7** Test rig ducting model

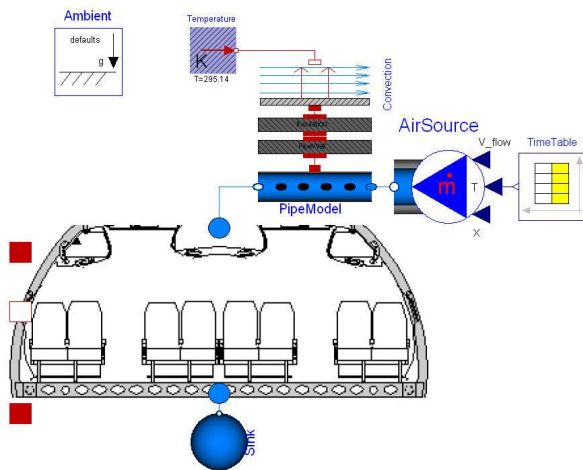
Figure 7 shows the measured input temperature, the measured output temperature and the simulated output temperature of the test rig ducting model. The demand of the test rigs controller unit for this experiment was for a double input temperature step from 28 to 60 and from 60 to 70 degree Centigrade. The overshoot on the input temperature was caused by the controller unit triggering the heater units.

After the validation of the pipe model it was



**Fig. 8** Simulation result of test rig ducting model

integrated into the cabin model (see Figure 9). Afterwards a comparison of the simulation results with available flight test data showed a more realistic behavior of the cabin model temperature (see Figure 10).

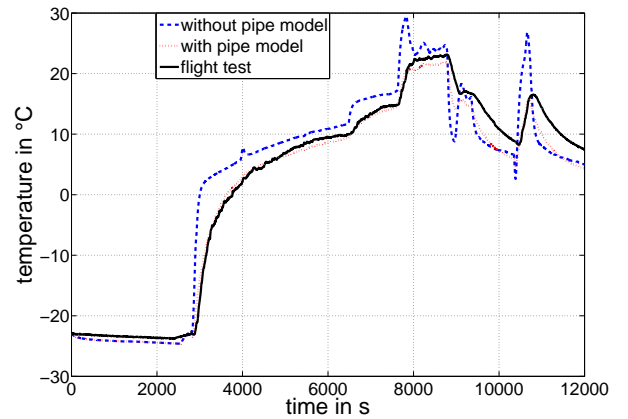


**Fig. 9** Modelica™ cabin zone model with ducting

Currently the test rig is further upgraded by the installation of a hot manifold, to better meet the behavior of the trim air system, and a cabin contour, to better converge the cabin air flow pattern.

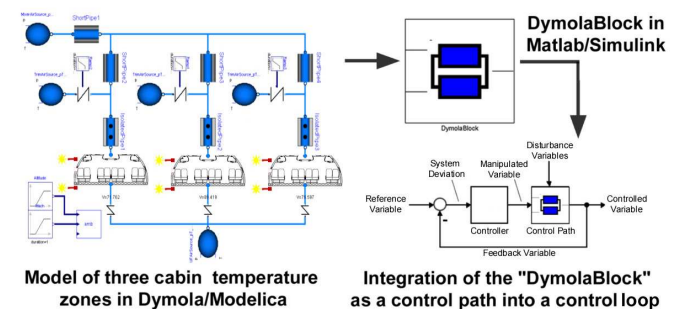
## 7 Using the Cabin Model as a Control Path

For the export of the Modelica™ simulation model Dymola™ offers an interface to



**Fig. 10** Simulation results for cabin zone model with ducting

Simulink™, the so called *Dymola Block*. Within this block the Modelica™ model can be chosen, compiled and edited. For a successful export to Simulink™ a simulation model has to be prepared in Dymola™ by dragging the necessary input and output values as signal connectors to main model layer. This procedure is required because otherwise the in- and output connectors won't be accessible in Simulink. Figure 11 schematically shows the export procedure.



**Fig. 11** Schema of the export to Simulink™ and the integration of the *Dymola Block* into a control loop

## 8 Outlook

Although first simulation results look already quite promising, the simulation models intro-

duced in this paper do not describe the temperature behavior of a cabin in a satisfactory way. Therefore TUHH's further contribution to the project KATO will be to identify factors of influence that have not been considered yet and to integrate those factors into the models. This covers in particular a further refinement of the cabin model discretisation. The time-frame for the project KATO ends in June 2007.

## References

- [1] ASHRAE. *Standard 161-2000 - "Air quality within commercial aircraft", Draft*, May 2000.
- [2] CABINAIR. *Improving air quality in aircraft cabins using 'measurements in the sky' and innovative designs and technologies*. 5th European Framework Programme, 2001 - 2004.
- [3] Dynasim AB. *Dymola - User's Manual*, 4.2b edition, 2006. <http://www.dynasim.se/>.
- [4] G.Looye K.Schnepper H.-D.Joos, J.Bals and A.Varga. A multi-objective optimisation-based software environment for control systems design. In *CACSD '02*, pages 7–14, September 2002.
- [5] H.Tummescheit H.Elmqvist and M.Otter. Object-oriented modeling of thermo-fluid systems. In *Proceedings of Modelica 2003*, pages 269–286, November 2003.
- [6] J.Eborn H.Tummescheit and F.J.Wagner. Development of a modelica base library for modeling of thermohydraulic systems. In *Modelica Workshop 2000 Proceedings*, pages 41–51, October 2000.
- [7] The MathWorks, Inc. *Getting Started with Matlab™*, 7th edition, 2006. <http://www.mathworks.com>.
- [8] MODELICA Association. *Modelica - A Unified Object-Oriented Language for Physical Systems Modeling*, 2.2 edition, February 2005. [www.modelica.org](http://www.modelica.org).
- [9] N.Nagda and H.E.Rector. *Report No. A20048 - "Ventilation Rates for the Aircraft Cabin Environment"*. Energen, May 2000.
- [10] S.V.Patankar. *Numerical Transfer and Fluid Flow*. Hemisphere Publ. Corp., Washington, 1980.
- [11] T.Pfafferott and G.Schmitz. Implementation of a modelica library for simulation of refrigeration systems. In *Proceedings of Modelica 2003*, pages 197–206, October 2003.
- [12] U.Carl. *Aircraft systems III*. Lecture Notes, Hamburg, 1995.
- [13] VDI-Wärmeatlas. *Berechnungsblätter für den Wärmeübergang (in German)*. VDI-Verlag, Düsseldorf, 7. edition, 1994.