

INTEGRATED HEAT, AIR AND MOISTURE MODELING TOOLKIT IN MATLAB

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ABSTRACT

This paper gives an overview of recent developments and results of a new integrated heat, air and moisture (HAM) modeling toolkit in Matlab named HAMLab. The recent developments include integration of a whole building model with building systems and controllers, 2D/3D HAM transport in constructions and 2D airflow respectively. The results include a short review on HAM models, a motivation of the selected simulation environment Matlab and extensive verification/ validation results. Furthermore, the integration capabilities are demonstrated by applications. It is concluded that the simulation environment HAMLab is capable of solving a large scale of integrated HAM models. Limitations, benefits and drawbacks are discussed.

1. INTRODUCTION

It is widely accepted that simulation can have a major impact on the design and evaluation of building and systems performances. Also, the modeling and simulation of whole building heat, air and moisture (further-on called HAM) responses in relation to human comfort, energy and durability are relevant. IEA Annex 41 will focus on a holistic approach of HAM transfer between the outside, the enclosure, the indoor air and the heating, ventilation and air-conditioning (HVAC) systems. Therefore integrated HAM models capable of covering all these issues are sought-after. There is no single simulation tool that covers all of the issues [Augenbroe 2002]. One option is the external coupling of tools [Hensen et al. 2004; Djunaedy 2005]. Recent developments in general modeling and simulation tools give rise to another option: the use of a single computational environment. What are the limitations if we use state-of-art computational software? What are the benefits and drawbacks?

The aim of this paper is to answer these key questions. The outline is as follows: Section 2 presents the methodology. Section 3 presents the review results. Sections 4 through 6 present all modeling and simulation results. First, Section 4 discusses the selection of the computation simulation environment. Second, Section 5 gives verification

and validation results of the developed HAM models. Third, Section 6 presents applications of integrated HAM models. Finally, in Section 7, the key questions will be revisited and answered.

2. RESEARCH METHODS

The research consisted of four parts. First, a review of integrated HAM models was carried out. The aim of this review was to obtain a group of recent simulation tools, based on the criteria provided in Section 3. The goal of the review is to specify common modeling problems that are to be solved and to have some reference tools for the discussion of the benefits and drawbacks. Second, a single computational environment was selected, based on a criterion presented in Section 3. Third, a range of HAM models were modeled simulated and validated using the selected software. Fourth, case studies were performed concerning integrated HAM models for possible solutions of the above mentioned common modeling problems.

3. REVIEW

The first Section summarizes recent single simulation environment HAM models. The second Section summarizes common modeling problems to be solved within a single simulation environment.

3.1 HAM models

In 2005, 14 different tools were used in an Annex 41 common exercise about simulating the dynamic interaction between the indoor climate of a room and the HAM response of the enclosure. All tools model the indoor air and the enclosure. Six HAM models are stand-alone simulation tools and have promising capabilities for simulating HVAC systems: Bsim, IBPT, IDA-ICE, TRNSYS, EnergyPlus, and HAMLab. The latter is presented in this paper. A complete overview will be published with the final reports, expected in 2008. In [Schwab et al. 2004] 265 different energy related software tools at the Energy Tools website [U.S. Department of Energy U.S, 2005] are reviewed. In this study a search was performed in order to determine what kind of simulations each tool could perform. After this, the list was narrowed down to 11 programs that might

simulate whole building HAM transfer and energy consumption. From this group three tools met all criteria: moisture storage in building materials, calculate indoor climate, moisture exchange in HVAC system, access to source code. The three tools are Bsim, TRNSYS and EnergyPlus. These tools are already mentioned. In [Gough 1999] tools were reviewed with the focus on new techniques for building and HVAC system modeling. In this study four new simulation techniques were investigated. The equation-based method is most relevant for this work. The other three techniques: modal, stochastic and neural networks are not based on physical parameters and are therefore less suitable for solving design problems. The next three equation based method techniques are already included in one or more tools of the previous Section: Neutral Model Format and IDA solver are included in IDA-ICE and TRNSYS. The other 11 mentioned equation based method techniques are simulation environments with limited HAM models for building simulation. [Clarke 2001] describes the approach to domain coupling as implemented with within the ESP-r system. Some recent Matlab based tools are: SIMBAD provides HVAC models and related utilities to perform dynamic simulation of HVAC plants. Although moisture transport capabilities are limited, this toolbox is useful as a starting point for the development of HAM-HVAC models. IBPT is a tool that focuses on 1D HAM transport in building constructions. It originates from the HAMSTAD project [Hagentoft et al. 2002].

3.2 Common modeling problems

Note that the aim of review is not to obtain an exhaustive list of HAM models, but to obtain a representative group of HAM models that will be used in this Section for identifying common modeling problems and in Section 5 for comparison purposes. All HAM tools mentioned in previous Sections, face at least one limitation that cannot be solved by the tool itself. Either a problem occurs at the integration of HVAC systems models into whole building models, or a problem occurs at the integration of 2D and 3D geometry based models (for example airflow and HAM response of constructions) into whole building models. The first problem is caused by the difference in time constants between HVAC components and controllers (order of seconds) and building response (order of hours). This can cause inaccurate results and long simulation duration times; see also [Gouda et al. 2003, Felsman et al. 2002]. The second problem is caused by the lack of lumped parameter tools that include internal 2D, 3D finite element method (FEM) capabilities; see also [Sahlin et al. 2004]. In order to be able to solve all above-mentioned problems in a single simulation environment, the toolkit should be able to integrate:

- (1) a whole building model for the simulation of the indoor climate and energy amounts;
- (2) a high spatial resolution tool, for the simulation of HAM responses of building constructions and internal/external airflow, for example a 2D and 3D FEM PDE solver;
- (3) a high time resolution tool, for the accurate simulation of HVAC systems and controllers, for example an ODE solver.

These three items will be presented in the following Sections, including already published and new preliminary verification and validation data.

4. MODEL IMPLEMENTATION

MatLab/SimuLink including FemLab has been selected as the simulation environment. Justification of this crucial choice is explained below.

4.1 Whole building model

The model is based on ELAN, a computer model for building energy design. [Wit et al. 1988]. The ELAN model, together with an analog hygric model has been implemented in a Building Physics Toolbox in MatLab (WaVo) [Schijndel and de Wit 1999]. A major recent improvement is the development of a model in SimuLink (HAMBBase) [Wit 2004; HAMLab 2005]. The implemented numerical model consists of a continuous part, solved with a variable time step and a discrete part, solved with a time step of one hour. For the HVAC system and the room response of indoor climatic variations, a continuous model is used. For the external climate a discrete model is used. The main advantages of this numeric hybrid approach are: (1) the dynamics of the building systems where small time scales play an important role (for example on/off switching) are accurately simulated; (2) the model becomes time efficient as the discrete part uses 1-hour time steps; (3) the moisture (vapor) transport model of WaVo is also included. With this feature, the (de-) humidification of HVAC systems can also be simulated.

Already published verification and validation data

In [Schijndel 2003c], the heat transport part of HAMBBase is verified with a standard test method [ASHRAE 2001].

In [Schellen 2002], the HAMBBase model has been subjected to a validation study. The measured and simulated air temperature and Rh, during one month in a church, are compared.

New preliminary verification data

[Schijndel 2004] presents preliminary results for the Annex 41 exercise on the dynamic interaction of the indoor climate of a room and the HAM response of

the enclosure. As mentioned before, the final results of this Annex will be published in 2008.

The geometry is identical to the one in the ASHRAE standard test [ASHRAE 2001]. Further test conditions are as follows: (1) there is only one 1D construction type with linear properties; (2) the exposure is completely isothermal; (3) the outside relative humidity (Rh) is 30%; (4) there are no windows; (5) the internal gains equal 500g/hour; (6) the ventilation rate is 0.5 ach. The exercise seeks to provide the analytical solution as well as the simulation results of the model. The model solution is obtained by applying HAMBase. The analytical solution is obtained by integration of a FemLab model of the construction into a first order model of the room modeled in SimuLink. In figure 1 the corresponding SimuLink model is shown. All blocks are standard blocks from the library. The FemLab model block of figure 1 is based on the following PDE:

$$\frac{\partial w}{\partial t} = \nabla \cdot (D_w(w) \nabla w) \quad (1)$$

where w is moisture content, t is time and D_w is diffusivity. In figure 2 the analytical solution and the model solution are shown. Preliminary results of all models attending the exercise show that both the analytical solution obtained using FemLab and the HAMBase solution are satisfactory.

4.2 High spatial resolution tool

HAM responses of building constructions and internal/external airflow are modeled and simulated with FemLab. This is an environment for modeling scientific and engineering applications based on partial differential equations (PDE).

Already published verification and validation data

Two FemLab models are developed as part of the benchmark study, concerning 1D HAM transport in constructions: HAMSTAD [Hagentoft 2002]. One FemLab model shows an excellent agreement with the solution of the analytical case. A second FemLab model, simulating the insulated roof case, shows a good consensus with the other solutions.

In [Schijndel 2003a] a validation of the simulated water absorption in an initially dry brick cylinder (length 24 mm) is presented. All sides except the bottom are sealed. One side is submerged in water at $t=0$ sec. The measured 1D water absorption process of several brick materials based on [Brocken 1998] are successfully simulated.

In [Schijndel 2003a] a validation of a combined heat and moisture transport for a 2D geometry is presented. The problem is based on a 2D-problem presented in [Kunzel et al. 1996]: a brick specimen, initially dry and with two of the flanks sealed, is

placed with its lower surface about 1 cm under water. The simulated moisture uptake profiles agree well with the measurements of [Kunzel et al. 1996].

In [Schijndel 2003a] a CFD model in FemLab for indoor airflow is verified with the results of [Sinha 2000]. The problem is modeled by 2D incompressible flow using the Boussinesq approximation with constant properties for the Reynolds (Re) and Grasshof (Gr) numbers. In [Sinha 2000] the problem is solved and validated with measurements for several combinations of Re and Gr.

New preliminary verification data

In [Schijndel 2005a] a k-epsilon model in FemLab concerning outdoor airflow (wind) is verified by another exercise of the mentioned IEA Annex 41 exercise, on boundary conditions. The exercise seeks to provide for several building geometries: (1) simulated wind velocity profiles around buildings. They are calculated using the standard k-epsilon turbulence model of FemLab. The turbulence parameters are presented in Table I

Table I. The k-epsilon turbulence parameters

<u>Name</u>	<u>Variable</u>	<u>Value</u>
Cmu	Cmu_ke	0.09
Cd1	Cd1_ke	0.1256
Cd2	Cd2_ke	1.92
sigmak	sigmak_ke	0.9
sigmad	sigmad_ke	1.3

Figure 3 shows the simulated wind profile around the lower building.

(2) simulated raindrop trajectories. They are obtained from the equation of motion of a raindrop, moving in a wind-flow field characterized by a velocity vector v is:

$$g + f(Cd, Re) \cdot (v - \frac{dr}{dt}) = \frac{d^2 r}{dt^2} \quad (2)$$

where g is gravity, f is a function dependent on Re (Reynolds number) and Cd (drag coefficient), v is wind velocity, t is time and r is the position of raindrop. Equation 2 is solved with the ODE solver of Matlab providing raindrop trajectories for the low building case. The result is shown in figure 4.

(3) simulated wind-driving-rain coefficients on the building facades are obtained from the locations of raindrops hitting the building façade.

The preliminary results are in good agreement with the results obtained by other models (Fluent)

4.3 High time resolution tool

HVAC systems and controllers are modeled and simulated using SimuLink. This is a platform for the simulation of dynamic systems.

Already published verification and validation data

In [Schijndel 2003c], results of ODE based models of a heat pump, an energy roof and a thermal energy storage (TES) are compared with measurements.

New preliminary verification data

In [Schijndel 2005b], a room of a famous museum in the Netherlands is simulated, using HAMBBase. The HVAC system and controller are modeled by standard blocks in SimuLink. This model is presented in figure 5. After completing the models with the necessary input data, the integrated HAM model in SimuLink, consisting of the room, HVAC system and controller was validated by measurements, see figure 6. The model was successfully used to design a new HVAC controller strategy.

5. APPLICATIONS

Already published applications

[Schijndel 2003d] shows the integration of an airflow model, using FemLab, into a controller model of SimuLink. In [Schijndel 2003b] the set point operation of the HVAC system of a church is optimized by the use of MatLab, FemLab and SimuLink models. The goal was the preservation of the monumental church organ. Evaluation after a year showed that the operation strategy functioned satisfactory.

New application

[Schijndel 2004] demonstrates the integration of a 3D HAM model of a roof/wall construction into a whole building model. The geometry of the building is identical to one in [ASHRAE 2001]. HAMBBase is used as whole building model. Figure 7 shows the input/output structure of the integrated model. The output (air temperature and Rh) of this model and climate data are used as input for the FemLab model of a 3D roof/wall construction. The output of the FemLab model (heat and moisture flow) is connected to the input of the building model. The FemLab models solves the following PDE:

$$\begin{aligned} \frac{\partial w}{\partial t} &= \nabla \cdot (D_w(w)\nabla w + D_F(T, w)\nabla T) \\ \frac{\partial T}{\partial t} &= \nabla \cdot (D_T(w)\nabla T) \end{aligned} \quad (3)$$

where T is temperature, D_w , D_F , D_T are diffusivities. Figures 8 and 9 demonstrate the 3D temperature and vapor distributions at a specific time. The integrated model is capable of simulating the indoor climate and

construction details within reasonable simulation time: 1 year simulation, takes 12 hours of computation time.

6. CONCLUSIONS

6.1 Limitations, drawbacks and benefits

It may be concluded that the simulation environment HAMLab is capable of solving a large range of integrated HAM problems. Furthermore, it is promising in solving common modeling problems of other HAM models such as problems caused by the difference in time constants between HVAC components and building response and problems caused by the lack of lumped parameter tools that include internal 2D, 3D FEM capabilities. However, there are some limitations: (1) some specific solvers such as time-dependent k-epsilon turbulence solvers are not available yet. This means that, for example, time dependent 3D airflow around buildings cannot be solved; (2) although it is possible to construct a full 3D integrated HAM model of the indoor air and all constructions in FemLab, the simulation duration time would probably be far too long to be of any practical use; (3) the modeling of radiation is just recently available in FemLab and is not included in this research.

Possible drawbacks are: (1) the software package MatLab itself and basic knowledge of Matlab are required to use the models; (2) at this moment HAMLab is research tool. Therefore it lacks facilities for design-oriented users such as user-friendly interfaces and user guides. (3) although state-of-art solvers are present, the simulation of FEM based integrated models can easily become very computation time consuming.

The main benefits of HAMLab are: (1) it takes advantage of the facilities of the well maintained Matlab/SimuLink and FemLab simulation environment such as the state-of-art ODE/PDE solvers, controllers library, graphical capabilities etc; (2) all presented HAMLab models in this paper are public domain; (3) although not explicitly shown in this paper, compared to other HAM models, it is relative easy to integrate new models that are based on ODEs and/or PDEs. (4) the simulation facilitates open source modeling and if desired, models can be compiled into stand-alone applications.

6.2 Current research projects

At this moment we are working on: (1) implementation of web based models for designers using the Matlab web server Toolbox to meet drawbacks 1 and 2; (2) speed up of computation duration times by the use of system identification modeling approximations of complex models to meet drawback 3. (3) development of a full 2D integrated HAM model for indoor air, building constructions

and outdoor wind profiles & rain distributions. This project is a pilot study for a full 3D model and fits into the IEA Annex 41.

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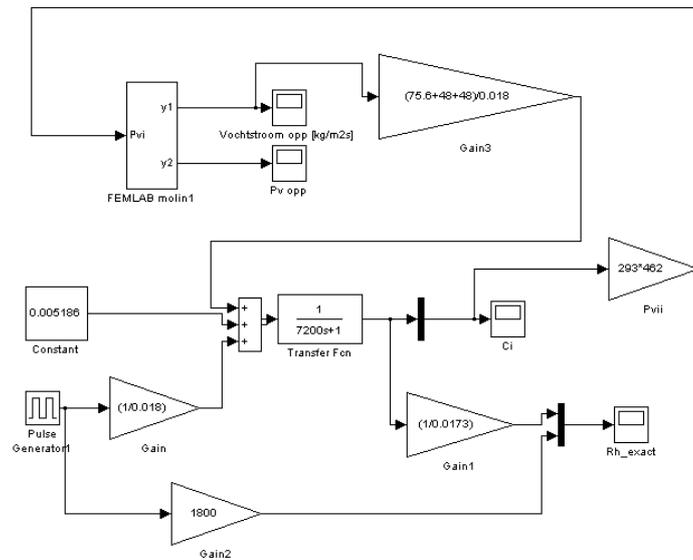


Figure 1. The SimuLink model of the analytical solution

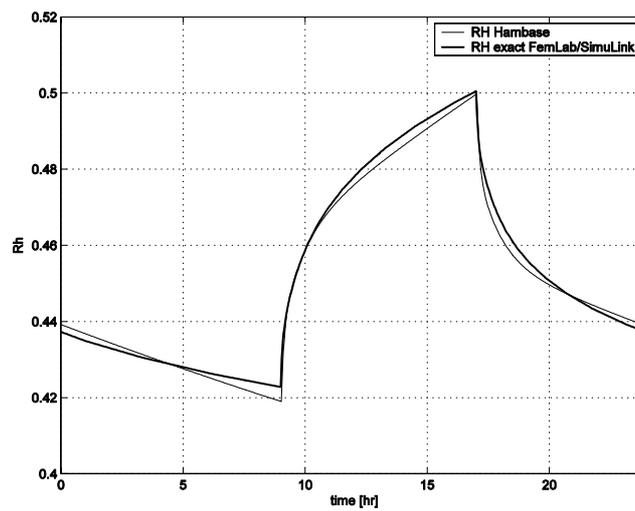


Figure 2. Simulated Rh of the indoor climate of HAMBBase and the analytical solution using FemLab/SimuLink

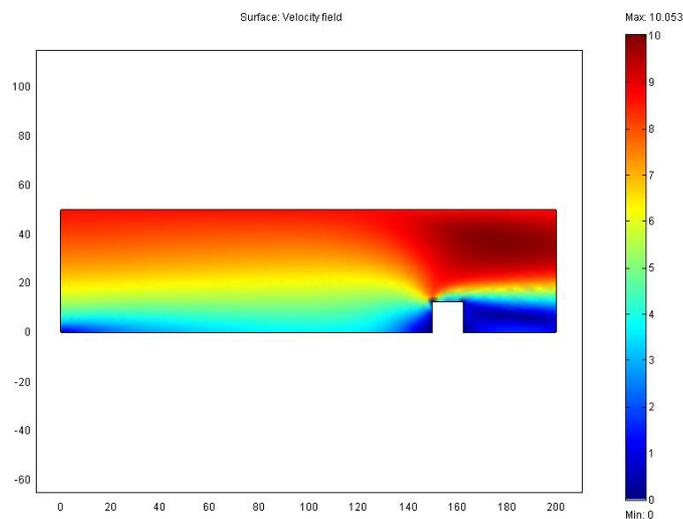


Figure 3. The wind velocity profile: absolute value of the velocity [m/s] for each coordinate x, y [m].

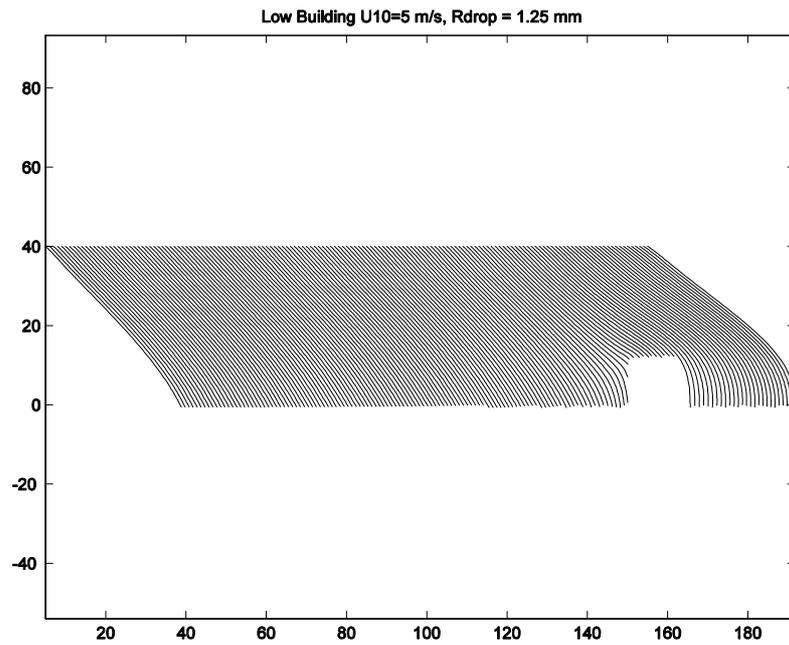


Figure 4. The raindrop trajectories

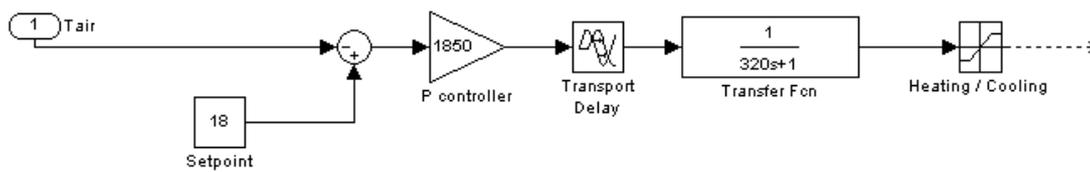


Figure 5. The HVAC and controller model in SimuLink

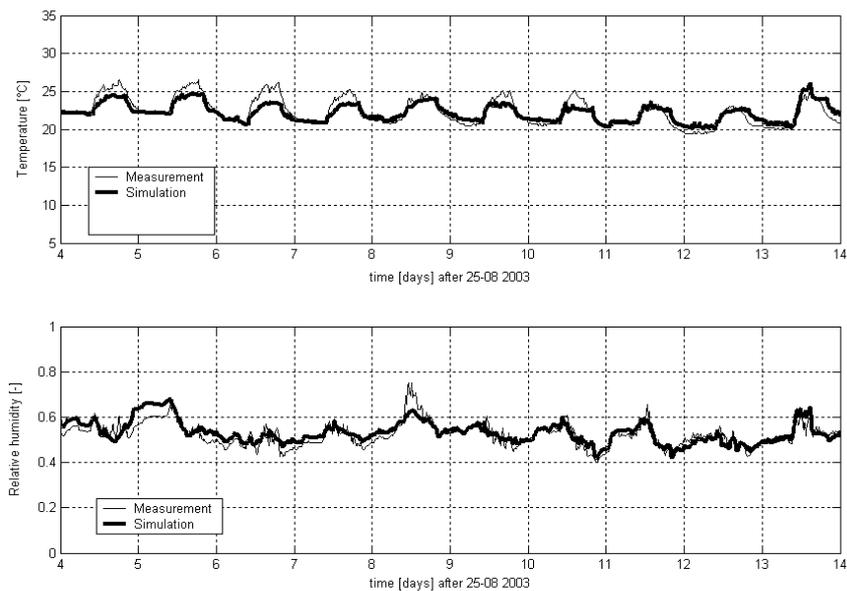


Figure 6 Simulated and measured room air temperatures (top) and Rh (bottom) for a week

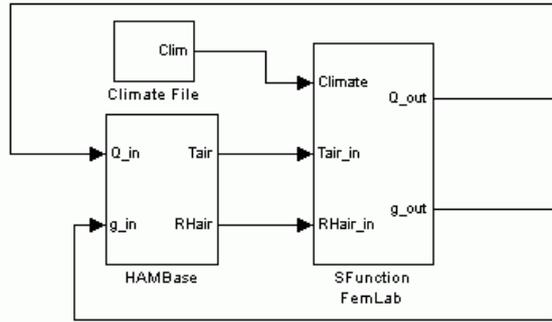


Figure 7 Input/output structure of the SimLink model.

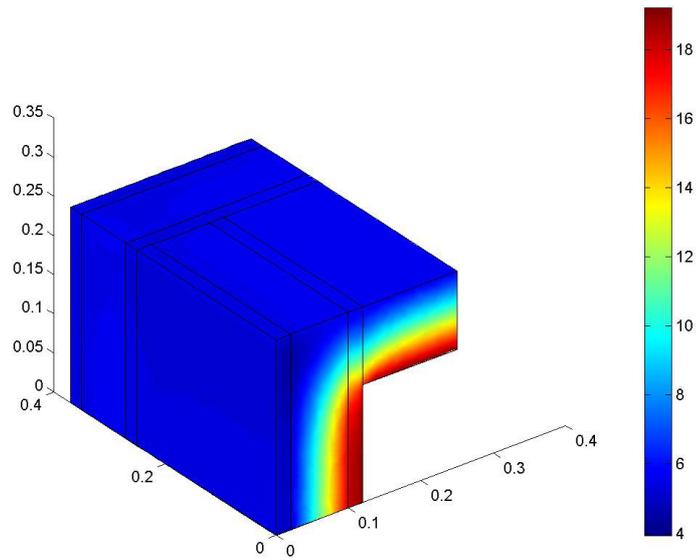


Figure 8. The temperature distribution: temperature [$^{\circ}\text{C}$] for each coordinate x, y, z [m].

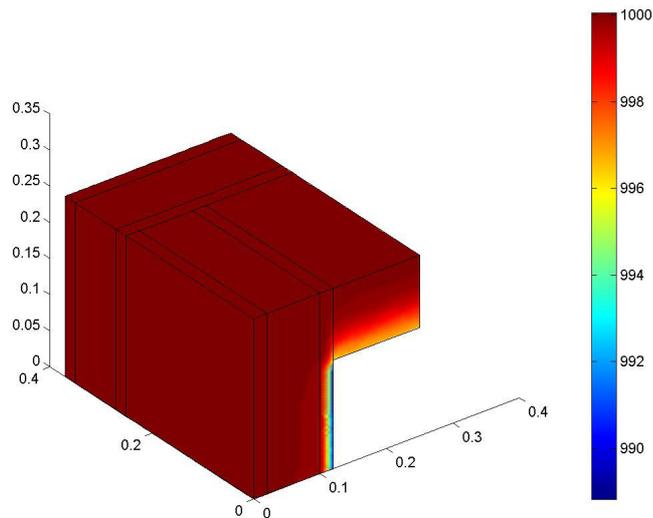


Figure 9. The vapor pressure distribution: vapor pressure [Pa] for each coordinate x, y, z [m].