Combined heat, moisture and CFD modelling to assess the impact of climate control on local climates near cultural objects in a museum exhibition room

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Abstract

In this study Comsol Multiphysics is applied to simulate an indoor climate in a museum exhibition room by means of the Computational Fluid Dynamics (CFD) and Heat, Air and Moisture (HAM) transport modules. A museum exhibition room is often located in a historic building and the indoor environment is mainly controlled by a heating, ventilation and air-conditioning (HVAC) system. Though heat and moisture transfer through the walls are present, the main disturbances in the indoor climate stem from the fast control of the HVAC system to keep the indoor climate as constant as possible. The purpose of the use of a Comsol Multiphysics model is to investigate the effect of different HVAC control strategies.

The results of the study will give an indication to what extent indoor climate control in museum buildings influences the behavior of local climates near objects based on a case study. In this paper a first step is made in coupling the CFD and HAM modules for the before mentioned purpose.

1. Introduction

The historic Regentenkamer in the Amsterdam Museum was chosen as a case study. This exhibition room is located in the midst of the historic center of Amsterdam and the location dates back to the middle ages when it housed a women's convent. The Regentenkamer locates unique heritage composed of interior pieces such as a 17th century ceiling painting and fireplace. It also exhibits 17th and 18th century paintings of the governing regents and 19th century furniture that is still used for special occasions. Since the mid-16th century the building was used as an orphanage until the 1960s. In 1975 the Amsterdam Museum moved to the old orphanage and now exhibits the history of Amsterdam and the building they are housed in (see Figure 1).

The Regentenkamer has one south facing façade, the remaining walls are internal walls (see Figure 1). Since 2007 an air handling unit (AHU) was installed to provide indoor climate control to this exhibition room.

Figure 1. Interior of Regentenkamer in the Amsterdam Museum.

Figure 2. Exterior south-facing facade of the Regentenkamer, Amsterdam Museum.

An experimental and numerical study have been performed on the indoor climate of the Regentenkamer [1]. From July 2015 until now continuous measurements on indoor climate conditions have been carried out.

During a typical winter and summer day infrared thermographs were made of the room. Figure 3 shows the effect of conditioned air being supplied to the exhibition room in the vicinity of cultural objects. During summer, cooling is needed to maintain a suitable climate for object preservation. This leads to supply temperatures of 16 ˚C. During winter, heated air will be supplied when the indoor climate is influenced by colder outdoor temperatures. Though temperatures in the thermogram show surface temperatures of around 20 ˚C, the gradient created by the inlet air and the air near the cool external wall might cause serious deterioration to the object or the building itself.

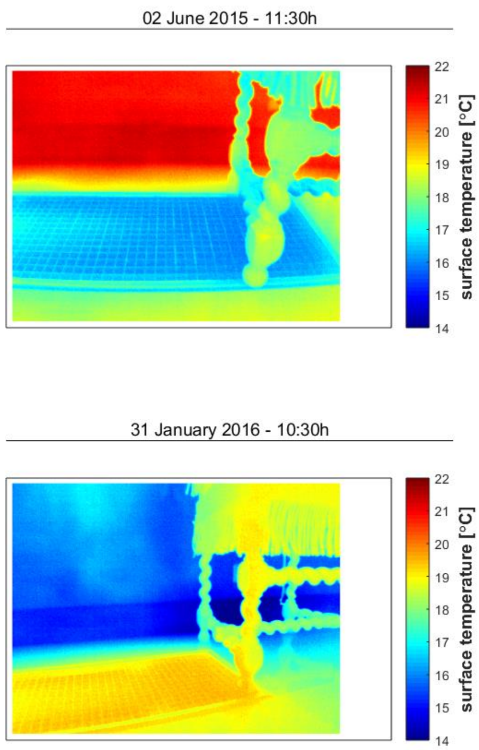

Figure 3. Infrared thermograms showing surface temperatures of the HVAC supply and a furniture object near the inlet.

In general, indoor climate measurements are made based on an average of an exhibition room. These measurements will not detect locally deviating climates. Since the infrared thermograph is an instantaneous snapshot it is important to understand the impact of short-term temperature and relative humidity changes in indoor air supply on the indoor climate near objects. Comsol Multiphysics is used to research the effect of fluctuating conditioned supply air on the indoor climate near objects in an exhibition room.

Section 2 describes the geometry and boundary conditions used in the Comsol Multiphysics model. The results are described in section 3 where a first validation of the model is explained based on on-site measurements. Conclusions are drawn in section 4 together with recommendations for further research.

2. Numerical modeling and simulation

The model represents the Regentenkamer in a simplified form. The length, width and height are kept equal to the room itself. The furniture such as the unused fireplace and table which inhabit quite a large part of the room are not modelled due to simplification. The inlets of the HVAC system are placed in the floor near the external wall. The outlets are located in the west wall above closed doors. To reduce computational resources in the first step of this study, only the air volume is considered and conduction and radiation processes are excluded.

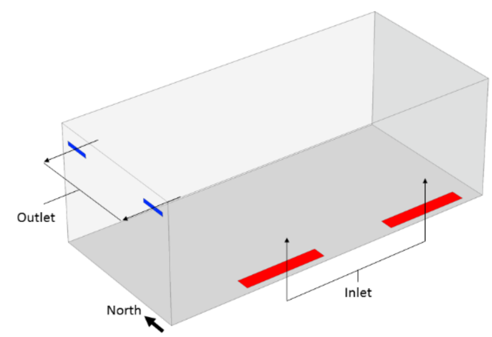

Figure 4. Model setup of the Regentenkamer.

The Comsol Multiphysics model is built with the heat transfer module and k-ε turbulent flow module. The multiphysics node non-isothermal flow was used to couple the two modules. Moisture transport was modelled by the eponymous module and coupled through heat and moisture coupling with the heat transfer module.

A user-controlled mesh was applied. Free tetrahedral cells were applied with normal element size on the 2D surfaces. The volumes are calibrated for fluid dynamics with coarse element size. The inlet and outlet boundaries are restricted with a maximum element size of 0.1 m. In total this mesh consists of 23.678 cells (Figure 5). The simulated period for the study is 2 hours. Though measurements have been ongoing since summer 2015, the validation was performed within a 2 hours frame to include short-term measurements and keep computational effort within reason. To validate the COMSOL model, the minimum and maximum measured inlet conditions of October 1st between 9 and 11 o'clock have been used as inlet conditions in the model. To reduce computational effort and aim for convergence a smoothened step function was used representing inlet conditions (see dotted red line in Figure 6). The boundary condition on the walls were set as a constant temperature of 20 ˚C based on a surface temperature measurement at the north wall during that period.

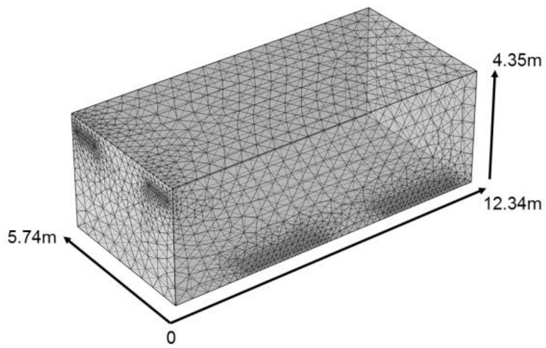

Figure 5. Geometry and mesh setup for normal sized mesh elements.

The simulation was divided in two time-dependent studies. The first study solves the turbulent flow and heat transfer nodes. The second study is used to simulate the relative humidity with help of the moisture transport in air module as presented in COMSOL version 5.3 [2]. In order to improve convergence in non-linear time-dependent models, the solver settings were changed. The steps taken by the time-dependent solver were changed from freely chosen time steps to strict in order for the solver to converge. This was done in combination with the time-steps of 20 seconds imposed in the second study.

3. Results

Part of the results of the indoor climate measurement campaign can be seen in Figure 6. This figure shows the inlet air conditions (blue) and the air conditions considered to be representative of the Regentenkamer (orange). The transmitter measuring the indoor temperature and indoor relative humidity is positioned on top of a cabinet located at the center of the north wall. The black line represents northwest corner and shows significant deviating conditions compared to the orange line. In certain periods the difference can be up to 20% RH. The northwest corner is situated near the return duct in which the new inlet conditions are calculated. The image shows relatively steady temperature and relative humidity

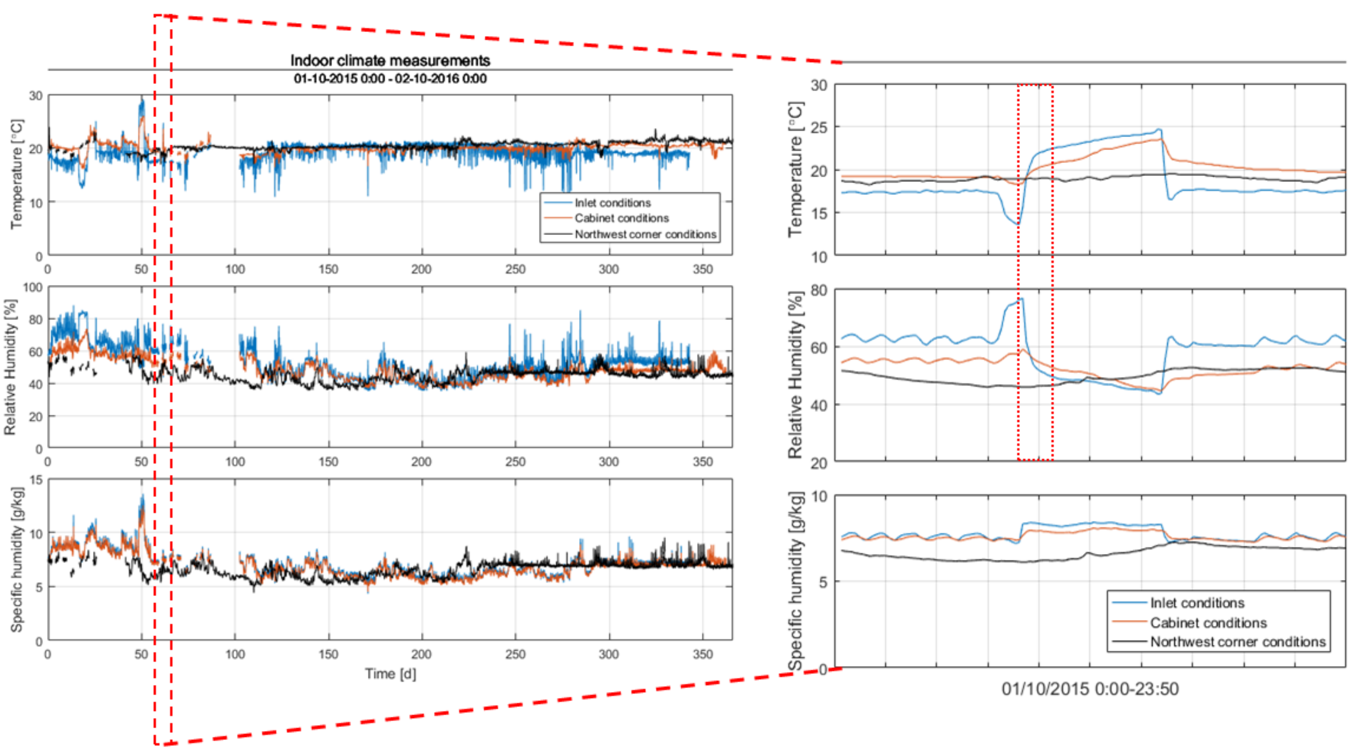

Figure 6. Indoor climate measurements collected over a year of measurements.

values measured on the cabinet, while the inlet conditions show spikes of deviating temperatures and relative humilities. During summertime the capacity of the HVAC system seems limited to maintain a strict indoor climate.

The positions of the measurement equipment used in the comparison of experimental data and simulation data are shown in Figure 7 (red dots) and the red line represents the horizontal cross-section to determine temperature distribution near the wall and the room.

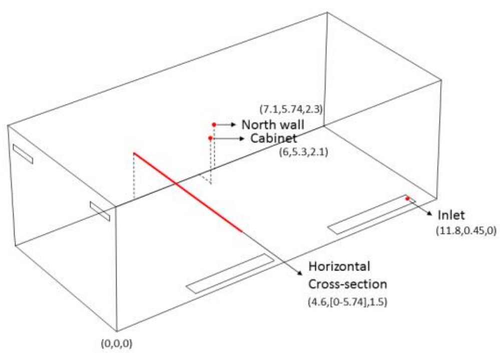

Figure 7. Measurement set-up positions used in the comparison between experimental data and simulation.

Figure 8 shows the results of the simulation compared to the measurements. The Building Management System (BMS) calculated inlet temperature has been applied as boundary condition. Measured inlet conditions deviate quite significantly compared to the BMS system.

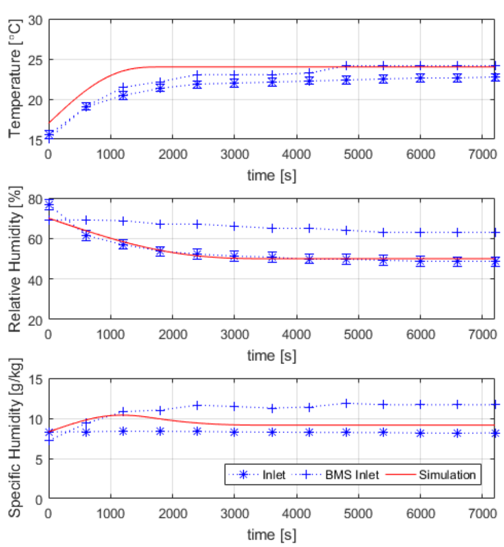

Figure 8. Comparison between the measured inlet conditions, building management inlet conditions and the COMSOL simulation inlet conditions for temperature (upper), relative humidity (middle) and specific humidity (lower).

Figure 9 shows the results of the first study step (upper) and the second study step (lower) at t = 7200s. Inlet conditions at that time are 24 ˚C and 60% RH at a constant inlet air speed of 0.12 m/s. Near the walls some condensation might occur according to the simulation, this could be ascribed to the imposed wall temperature of 20 ˚C and the coarse mesh used to reduce simulation time.

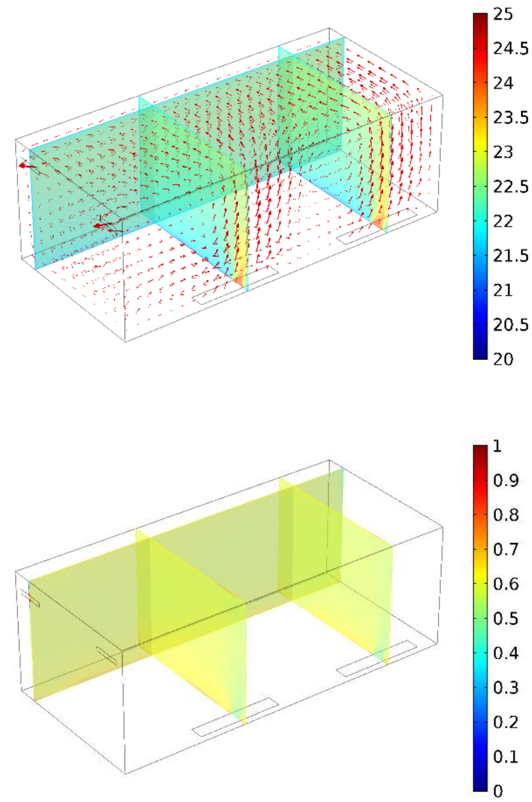

Figure 9. Results of COMSOL simulation with temperature distribution and flow field (upper) and relative humidity distribution (lower) at t = 7200 s.

The temperature distribution in the horizontal cross-section has been plotted to see whether the constant temperature of the walls – based on the surface temperature experimental data – influences the near wall region. Figure 10 shows a peak just above the inlet area where a temperature of 24 ˚C is imposed as boundary condition. No significant deviations are present near the walls.

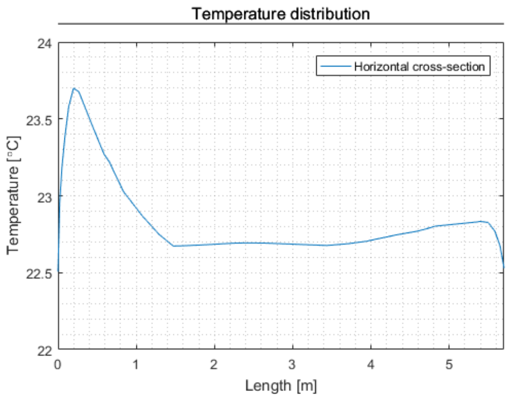

Figure 10. Temperature distribution at t = 7200 s in horizontal plane with south wall (x = 0 m) and north wall (x = 5.74 m).

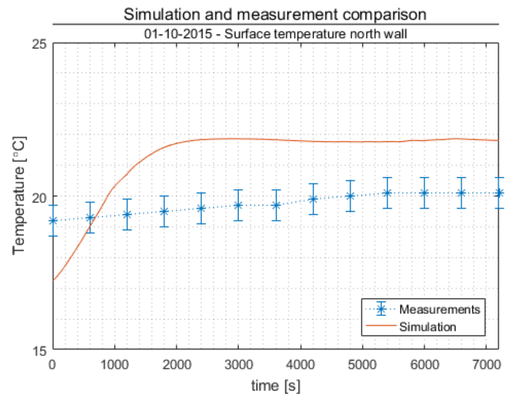

Figure 12. Comparison of the boundary conditions measured near painting on north wall and the COMSOL simulation.

To determine whether the model is representative for the real situation, comparisons between indoor climate and surface temperature measurements and simulations are shown in Figure 11 and Figure 12.

The air volume shows a quick response of the imposed step function boundary condition in the center of the room and near the north oriented wall. The surface temperature on the wall does not show a good agreement with the simulation results. This could be caused by the lack of modelled airflow blocking furniture such as the cabinet, or the choice in boundary mesh conditions.

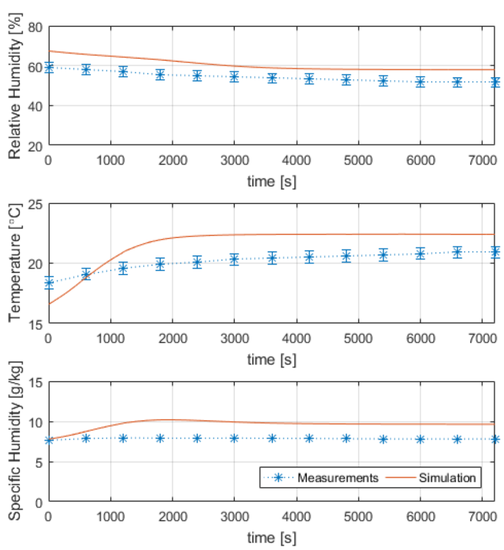

Figure 11. Comparison of temperature (orange) and relative humidity (blue) of measurements located above cabinet and COMSOL simulation.

4. Discussion and conclusions

This exploratory study resulted in a model that gives insight in the effect of forced indoor temperature and indoor relative humidity control on the ambient indoor climate. It is still work in progress which resulted in not being able to perform a comprehensive grid sensitivity analysis. Oversimplification resulted in a working model, however, it also resulted in an indoor climate outcome that should be used cautiously. To draw conclusions for accurate results such a grid sensitivity analysis is needed for proper validation to exclude grid dependency of the model's results. This also applies for the current exclusion of conduction and radiation principles during this study.

To enhance the accuracy of the model it is important to perform some additional experiments. Gaining insight on the influence of the inlet conditions is necessary. Not only transient temperature and relative humidity conditions are important, in-situ volumetric flow rate data of the present inlet system provides a more accurate inlet profile than is currently used.

The main conclusions of this study are:

- It is possible to use COMSOL Multiphysics as computational tool for indoor environment modeling influenced by HVAC climate control.
- It takes quite some computational effort to model coupled Heat, Air and Moisture transport, even in a simplified situation.
- The simulation results are sensitive to the imposed boundary conditions and solver settings.

- The outcome is valuable for locating critical areas in an exhibition rooms and could be of help while staging a museum exhibition, or evaluating novel climate control strategies.

Future steps in this study will include performing a grid-sensitivity analysis and re-evaluate the validation of the model based on extensive experimental data.

In a further model it is interesting to include radiation and conduction to create a comprehensive model for risk evaluation for museum objects. A next step could then be to use a stress-strain model to evaluate possible damage to objects [3].

A next step could be altering HVAC control strategies to energy conserving strategies as has been suggested in [4] and see the effect on the distribution of indoor temperature and relative humidity of these more tolerant strategies compared to the current strict environmental specifications used in climate control.

References

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