Development of an interactive virtual reality simulation environment with a thermal feedback for the user

Christoph Nytsch-Geusen[1], Werner Kaul[1], Kushagra Mathur[1], Lucas Westermann[1], Martin Kriegel[2]
[1]Berlin University of the Arts, Berlin, Germany
[2]Technische Universität Berlin, Berlin, Germany

Abstract

This contribution describes the first experimental results of the development of a virtual reality (VR) simulation environment, in which the users are immersively embedded in a 3D visualization of the building model and experiences the simulated indoor climate of the associated thermal simulation model physically as thermal feedback. The users can interact with the room model in the VR environment (e.g. open a window) and thus influence the room energy and moisture balance. To implement this approach, a Modelica-based building model was coupled with the game engine Unity in real time. These interactions cause a change in the physical state of the building model. The calculated current indoor climate is generated in the VR simulation environment for the users by several air conditioning devices and made physically experienceable for them.

Key Innovations

- Immersive visual and physiological experience of indoor climate simulation experiments
- Direct thermal feedback to the user dependent on his or her interaction with the room model

Practical Implications

Use the future possibilities to experience your own thermal building model immersively in virtual reality and to communicate with it interactively. Experience the difference between a rising and falling temperature value in a diagram of a simulation program and your own physical reaction due to the same temperature changes caused by a real thermal feedback.

Introduction

In 2018 the buildings and construction sector in the world was responsible for 36 percent of final energy use and 39 percent of energy and process-related CO_2 emissions (IEA, 2019). Regulators and the building industry are in the process to reduce the energy demand of buildings by applying energy saving solutions. If focused only on the reduction of the energy footprint of the building, these energy saving solutions often are applied at the expense of the occupant's wellbeing, specifically the **I**ndoor **E**nvironmental **Q**uality (IEQ) of the building. The main purpose of a building is to provide a pleasant, healthy and productive environment for its occupants with a preferably high standard for the IEQ. This results in a need for a high quality in thermal, acoustic, visual, olfactory, hygienic and psychological comfort, in which most factors require energy to perform to a high standard. The classic definition of an efficiency is use per effort. For a buildings efficiency this translates to a relation of IEQ per energy use. As it stands, there is no known approach to assess the efficiency of a building with this definition, in part because there is no single approach to assess the IEQ of a building.

In the joint project EnOB: GEnEff of TU Berlin and UdK Berlin an immersive and interactive VR simulation environment is developed that can artificially generate the IEQ as a combined visual and indoor climate experience by physically simulating radiation, heating and air flow of an occupied space in the building. For this purpose, a climate chamber is coupled with a building model that simulates the energy use of a building operating with the indoor climate of the VR chamber. The factors that influence the perceived IEQ (use) can be put in relation to the simulated energy usage (effort) of the building to provide a basis for developing a new building efficiency assessment index called GEnEff index.

In order to determine the IEQ for a room or building in a VR simulation environment, several fundamental questions will be investigated in the GEnEff project: How real can a simulated indoor climate be reproduced in a VR climate chamber? How fast can the VR climate chamber react to dynamic changes of a simulated indoor climate?

This paper describes the conception and evaluation of a first, still highly simplified, research prototype of a VR climate chamber developed in the GEnEff project. In this prototype, the generation of specific flow patterns as well as differentiated radiation temperatures on the room enclosure surfaces are still omitted. A hemispherical room with the shape of a dome is filled with warm and cold air via air conditioning units to create different room climates, whereby the room humidity can also be increased and decreased. The air conditioning units are controlled by a control logic which reproduces the room climate in the dome calculated in the simulation model. The user perceives the simulated 3D room model in the VR environment and can influence the indoor climate of it by interactions, e.g., by opening a window.

Related work

VR and interactive simulation: Various interactive VR environments have been developed in recent years, integrating programs for thermal room and building energy simulation (Bahar et al., 2013; Fukuda et al., 2018)

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or for daylight and artificial light simulation (Natephra et al., 2017; Keshavarzi et al., 2021).

VR and sensory stimuli: Other research investigated the impact of physical feedback on individual sensory stimuli of users in VR, such as the sense of smell (Nakamoto et al., 2020), or the sense of hearing (Kim et al., 2019). Other work has explored the effects of simultaneous stimulation of two (Tagliabue et al., 2020) or more sensory stimuli (Martin et al., 2021) on VR users such as visual, thermal, and tactile sensation.

VR and thermal displays: Another group of papers important to our research approach have focused on the development and evaluation of thermal displays, which are devices with direct body contact, such as thermally adjustable gloves (Cai et al., 2020), earmuffs (Narumi et al., 2009), and devices for the arm and the abdomen (Günther et al., 2020). Likewise, the VR gaming and industrial industry has developed devices and interfaces to perceive heat and cold by the user, such as the climate mask FealReal (https://feelreal.com), the Teslasuit (https://teslasuit.io), or the gloves and sleeves of ThermoRealPlus (http://tegway.co).

However, during the literature review, the authors did not come across any research approach in which an interactive VR environment was integrated with a computational core for thermal room simulation and a climate chamber with a physical thermal feedback to form an overall approach to virtual room climate generation.

For the conception of the first prototype, we were able to build on our own preliminary research on the real-time coupling of VR environments with models for thermal room simulation based on Modelica (Nytsch-Geusen et al., 2017; Nytsch-Geusen and Mathur, 2020).

Research approach

Previous simulation tools used in the design and planning process for indoor climate analysis and building energy efficiency are not immersive in use. The user considers the room and the building as objects to be analyzed or optimized with a certain distance in the simulation tool. However, the perception of the indoor climate is inherently an immersive sensual process. A VR simulation environment in which the user perceives the 3D space visually on the one hand, but also receives thermal feedback on the other and can also significantly influence the room energy balance through interaction, opens up the potential to convey realistic experiences about the dynamics of the indoor climate of rooms and buildings.

System design of the VR simulation environment

The entire VR simulation environment consists of several software and hardware components which are interconnected with interfaces for the necessary data transmission (compare with Figure 1). The user is immersively embedded in an interactive virtual reality environment based on the game engine Unity (Unity, 2020) in which he or she can perceive the inner space of a building. There, they can show different types of user interactions which changes the energy and moisture balances of a coupled dynamic room model in real-time. The possible interactions include the opening process of the window, changes of the set point temperatures for heating and cooling, switching events for the room lighting, and takes into account also the presence or absence of the users with the associated waste heat and moisture output of their bodies (more details see in Nytsch-Geusen et al., 2017). The physical room model is based on Modelica and considers the room geometry as well as aspects of the building physics. Beside the outside climate boundary conditions, the heat transfer processes within the opaque and transparent constructions and the energy and moisture balance of the enclosed air of the inner space are also taken into account (Nytsch-Geusen et al., 2016). The values of the simulated indoor climate (air temperature, air humidity etc.) and the outdoor climate are transmitted to a control algorithm, which is responsible to reproduce the indoor climate in an "experienceable climate space" in a sufficient approximation.

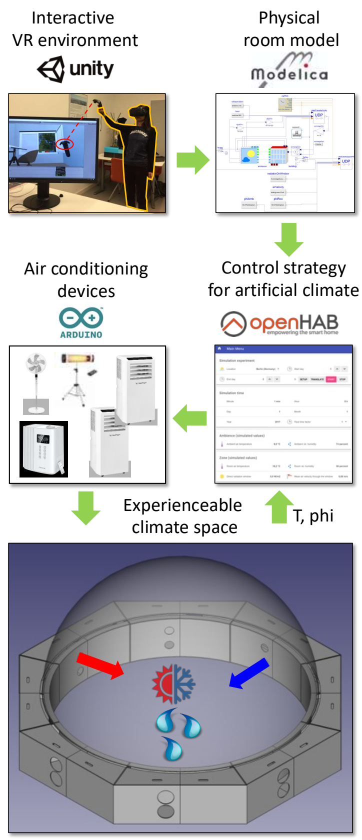

Figure 1: Structure of the VR simulation environment

For this purpose, the rule-based building automation software framework openHAB (openHAB, 2020) is used. It takes control over a set of air conditioning devices which are able together increasing and decreasing the air temperature and moisture in a certain range. These devices, two air conditioners with heating, cooling and dehumidification function, a humidifier and two heating columns, supply a dome in which the user is present with hot and cold air, and optional internally with heat and moisture. Further, an infrared heater, simulates the incoming solar radiation through the windows and two fans the air movement through openings (open windows

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or doors) of the analysed spaces. The mean values of the air temperature and air moisture in the dome are constantly measured and transmitted to the control algorithm, which adapts the operation of the mentioned devices in a manner that the sensible experiential climate becomes similar to the simulated model condition.

Interactive VR environment

The interactive VR environment is realised in Unity, version 2019.4.9 LTS. For the beginning of the experiments, a simple one-room model was imported into Unity and equipped with models of a working desk, a chair, a light and a room thermostat. The space has the inner dimension of 3 m x 3 m x 3 m, one window with a size of 1 m x 1 m and a door with a height of 2 m and a width of 1 m (compare with Figure 2). The VR room model allows user interactions with the door (opened or closed), the light (off or on with 10 W), the window (closed, tilted, totally open) and the room thermostat for the air conditioning (set point temperatures for heating and cooling between 16 and 32 °C, max. capacity for heating and cooling respectively 2,000 W). If the user is present inside of the space, his or her body emits 70 W heat and 45 g/h water vapour. All mentioned internal heat gains are fed into the room model half by convection and half by radiation.

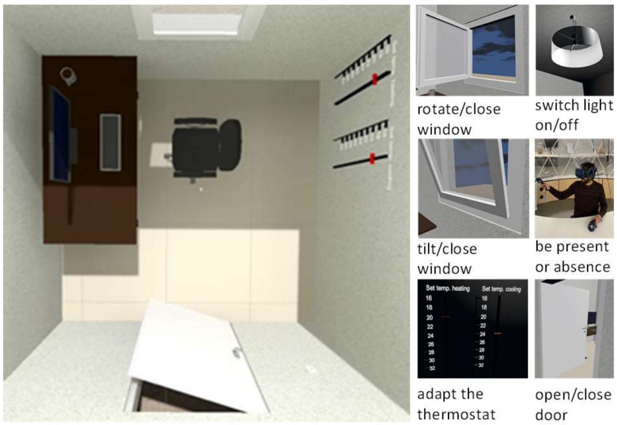

Figure 2: Virtual room model with possible interactions

Physical room model

The physical room model is based on component models of the Modelica libraries BuildingSystems (Nytsch-Geusen et al., 2016) and Modelica_DeviceDrivers (Thiele et al., 2017). At this, the core of this Modelica system model (see Figure 3) is the thermal building model which calculates the ideal-mixed energy and moisture balance of the inner space. This space is surrounded by wall models from concrete with a thickness of 20 cm plus inner (1.5 cm) and outer (2 cm) plaster, a door model from wood with a thickness of 3 cm, a window model with a U-value of 3.0 W/m^{2}K and g-value of 0.8 respectively and as well as a ground plate model and a roof model from concrete, both with a thickness of 30 cm.

A climate model delivers exchangeable weather boundary conditions of different climate zones (Berlin/Germany, Moscow/Russia, Manaus/Brazil or El Gouna/Egypt) for the building model and for the animation of the clouds (wind speed and direction in 1000 m height) in the VR. The weather data files of the climate data model were generated by Meteonorm version 8.0 (Meteonorm, 2021).

The Modelica model is bi-directionally coupled with the Unity VR environment via the UDP protocol: information about the model state (a selection of model variables for visualisation) is sent to Unity, and outside information from Unity (all user triggered events) is received by the Modelica model (the data exchange mechanism is described in detail in Nytsch-Geusen and Mathur, 2020).

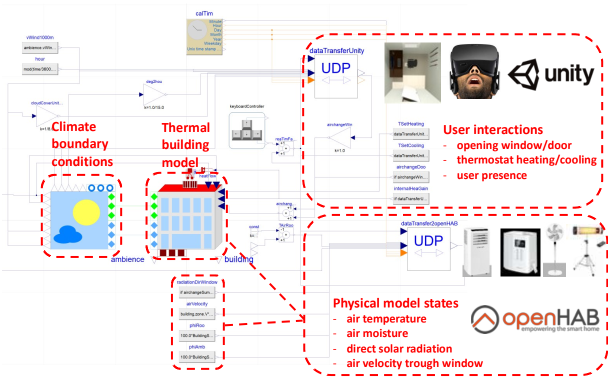

Figure 3: Physical room model and its interfaces to the VR room model and to the control algorithm for the devices of the experimental testbed

In contrast, the data exchange between the Modelica model and the openHAB software system is unidirectional: the physical model sends the calculated indoor and outdoor values of the air temperature, the air moisture, the solar radiation and the air velocity also via the UDP protocol to openHAB as the physical set point values, which shall be reproduced inside the dome with the help of the devices of the experimental testbed.

Experimental testbed

The experimental testbed consists of a combination of an igloo shaped tent and a wooden base level construction, which increases the maximum available inner height of the dome to 2.8 m. It has an inner diameter of 3.6 m. Two separate ring tubes are embedded in the base level construction to transport warm and cold air through 16 circular openings from the two air conditioning devices into the dome (see Figure 4).

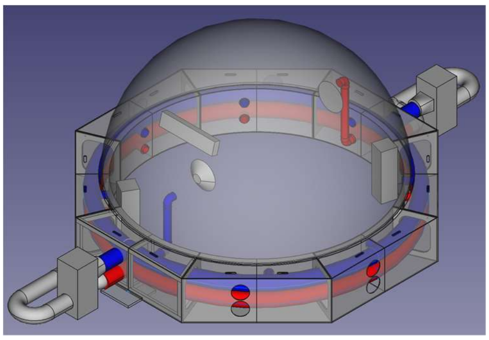

Figure 4: Air supply of the dome with cold and warm air by two air distribution ring tubes

The experimental testbed is equipped with following devices:

- two air conditioners with heating, cooling, and, dehumidification function for supplying the two tube

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rings (each with a cooling capacity of 2,050 W, a heating capacity of 1,800 W and a max. air volume flow rate of 320 m³/h),

- two humidifiers for increasing the air moisture level in the dome (each with a max. dust rate of 700 ml/h),
- two convective tower heaters for a fast increasing of the air temperature level in the dome (each tower with two stages of 1,200 W and 2,200 W),
- two fans with 26 stages for simulating the felt air movement through windows and doors (max. air speed 2.7 m/s) and
- one electric heating radiator for simulating the felt solar radiation through closed or opened windows (three stages with 850 W, 1,650 W and 2,500 W).

All mentioned devices are consumer products which are originally operated with an IR remote control. In the present application, the IR signal sequences of the individual remote controls were first decoded. An IR transmitter generates exactly the same signal sequences and replaces the original remote controls. In this way, the different functions of the devices can be activated, deactivated and controlled via Arduino microprocessors (e.g., the volume flow rate, the heating, cooling or ventilation mode of the air conditioners), which themselves are controlled via the serial bus interface of openHAB.

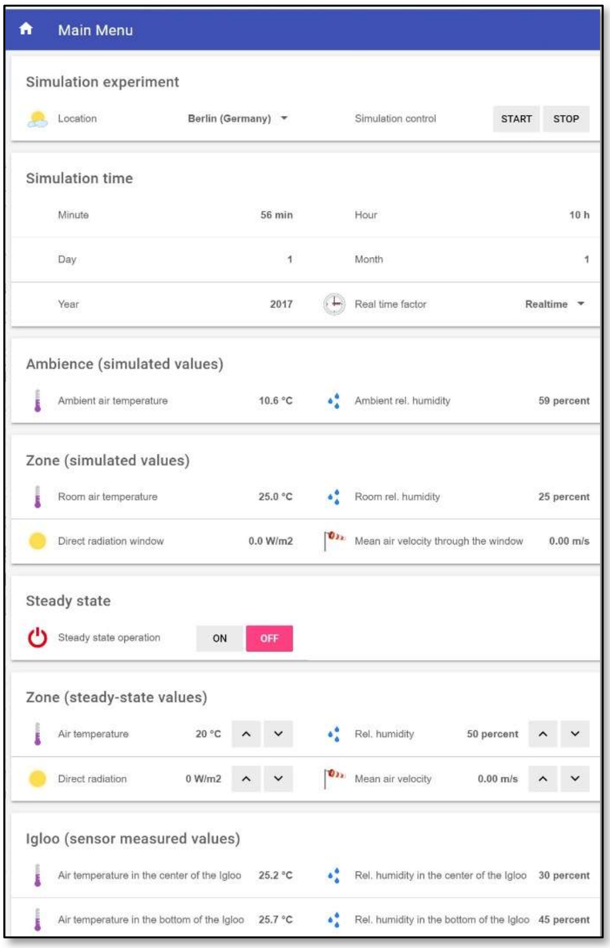

Figure 5: openHAB web interface for controlling and observing VR simulation experiments

Further, the software system offers an openHAB based web interface which can be used to control and observe the VR simulation experiments (see Figure 5). This user interface supports the selection of the climate location, the definition of the simulation time period or the type of simulation experiment (physical based dynamic simulation or steady state of an indoor climate). Furthermore, the real time factor of the simulation experiment can be adjusted in a wide range, so that time periods in which user interactions appear are performed in real time and longer time periods in which only few system dynamics is present are calculated considerably faster than real time.

Results

Different simulation studies were performed to determine the thermal characteristics and the system dynamics for the technical equipment of the experimental plant. This includes, firstly, the investigation of the achievable maximum speed for the adjustment of the room air temperature and humidity in the dome. Furthermore, it was analysed how the heated and cooled air is distributed in the dome when it is fed in through the openings of the base level construction. After these theoretical preliminary investigations, a real test scenario was carried out with the VR simulation environment.

Dynamic of the air conditioning devices

Figure 6 shows the Modelica model which was used to simulate the dynamic of the heating-up and cooling-down process and of the half dome with different combinations of the air conditioning devices (two air conditioners AC1 and AC2, two tower heaters TH1 and TH2, two humidifiers).

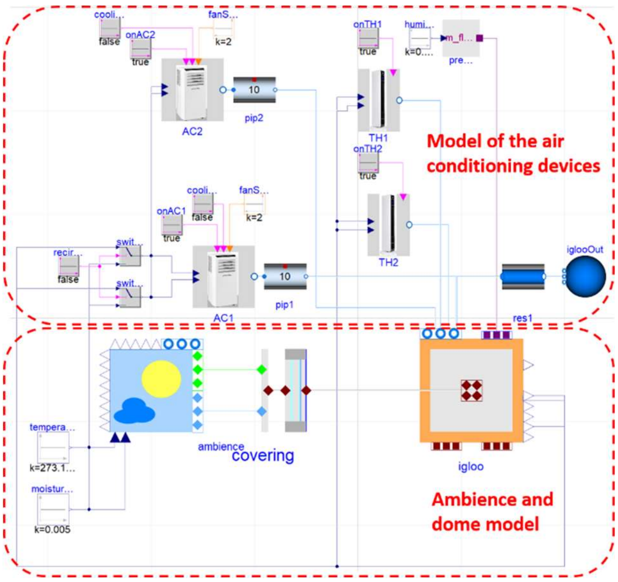

Figure 6: Modelica model for analysing the dynamic of the heating up and cooling down process of the dome

Following variants were analysed for a heating up process over 60 seconds:

1. Blowing heated air from one of the AC devices (1.8 kW heating rate) into the dome with an air flow rate of 320 m³/h. The entire air leaves the dome through the two small openings on top of the dome.

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2. As 1., but two AC devices are in heating mode.
3. As 2., but the entire heated air of two AC devices is re-circulated to the AC device.
4. Two internal tower heaters inject in total 4.4 kW convective heat into to dome.
5. Both AC devices and both tower heaters are operating, and re-circulation is active.

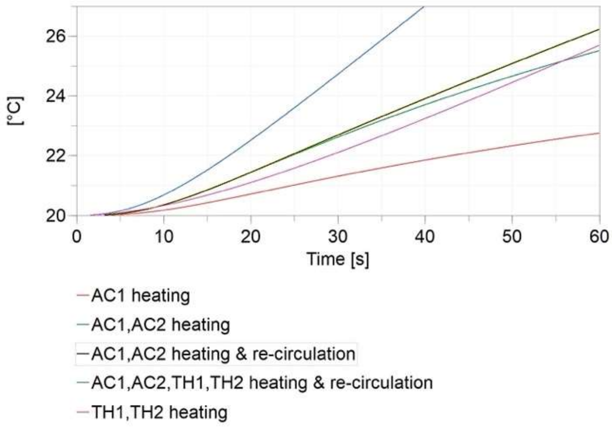

Figure 7: Heating up process of the dome

Figure 7 shows that the air temperature in the dome can be heated up from 20 °C by a minimum of 1.3 K to a maximum of 4.7 K within 30 s, depending on the selected operating mode. This corresponds to an average heating up rate of 0.043 K/s to 0.156 K/s.

Following variants were analysed for a cooling down process over 60 seconds:

1. Blowing cooled air from one of the AC devices (2.05 kW cooling rate) into the dome with an air flow rate of 320 m^3/h. The entire air leaves the dome through the two small openings on top of the dome.
2. As 1., but two AC devices are operating in the cooling mode.
3. As 2., but the entire cooled air of two AC devices is re-circulated to the AC device.

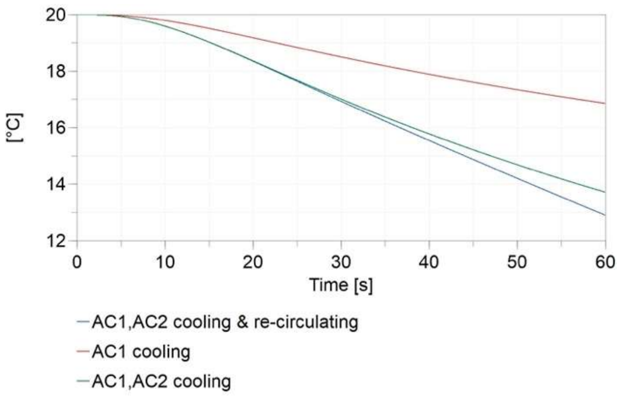

Figure 8: Cooling down process of the dome

Figure 8 shows that the air temperature in the dome can be cooled down from 20 °C by a minimum of 2.2 K to a maximum of 7.1 K within 60 s, depending on the selected operating mode. This corresponds to an average cooling down rate of 0.036 K/s to 0.118 K/s.

The following variants were analysed for the humidification process over 60 seconds:

1. Humidification with a dust rate of 1.400 ml/h and no heating.
2. Humidification with a dust rate of 1.400 ml/h and a heating rate of two internal tower heaters (4,400 W convective heat).

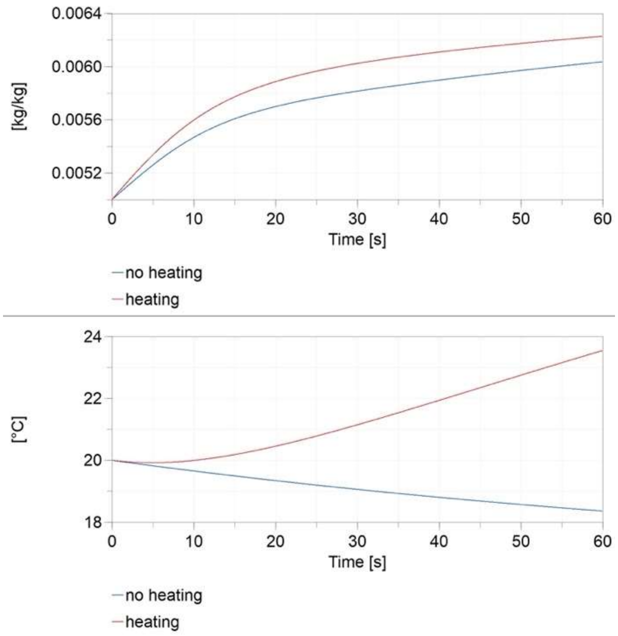

Figure 9: Humidification process of the dome

Figure 9 shows that the humidity can be increased by 1.0 g/kg without heating and by 1.2 g/kg with heating from 5 g/kg within 60 s. The temperature decreases by about 1.6 K due to the evaporative cooling phenomenon if the tower heater is switched off and increases by 3.6 K when the tower heater is in operation. This corresponds to an average humidification rate of 0.017 kg/kg·s without heating and 0.02 g/kg·s with heating.

Temperature and velocity distribution in the dome

A CFD analysis based on IDA ICE (IDA ICE, 2020) and the OpenFOAM plugin was performed to gain insight into the typical vertical temperature gradients and flow patterns that occur when heated or cooled air is injected through 8 circular openings of 20 cm diameter into the dome.

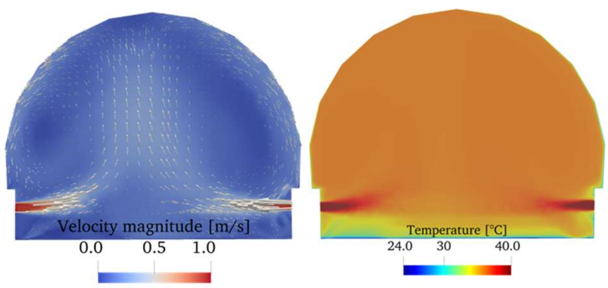

Figure 10: CFD analysis for the heating case of the dome

Figure 10 shows the case that one of the air conditioners supplies the dome with an air flow rate of 320 m^3/h and an air temperature of 39.5 °C. The ambient air temperature of the dome is 22 °C. Close to the openings the magnitude of the air velocity is about 1 m/s, but in the

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middle of the dome where the users mainly spends their time, the air velocity is clearly below 0.5 m/s, so that at most only a slight breeze can be felt. The supply of warm air in the floor area results in a largely uniform vertical temperature distribution within the dome except in the immediate floor area.

Test scenario with the entire VR environment

Based on the knowledge gained from the preliminary theoretical investigations, a first interactive test scenario with the entire virtual reality simulation environment was defined, appropriately configured with the corresponding devices and performed.

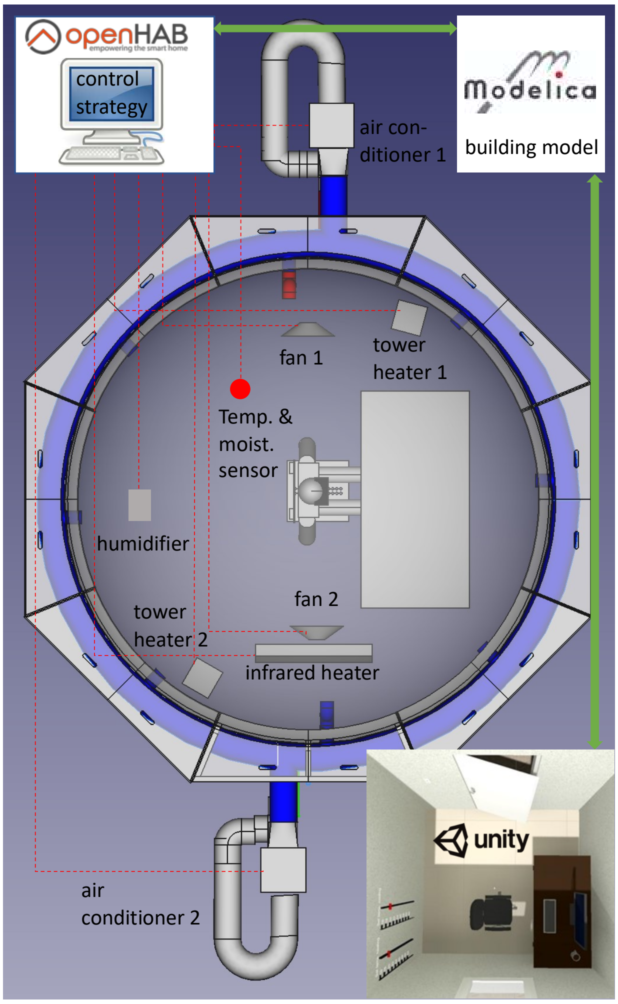

Figure 11: configuration in the test scenario

In Figure 11, the configuration of the test scenario is illustrated. The image shows that the experimental setup is adapted to the interactive Unity based VR model experienced by the user through the HMD device. To obtain haptic feedback, the user sits on a real chair in front of a real desk during the experiment, although both are also present as visual objects in the virtual world (compare Figure 11 with Figure 12). Both fans (fan 1 and fan 2) are responsible to generate an airflow in a different intensity depending on whether the user tilts or rotates the window and/or opens the door. The two air conditioners are supplying the dome with heated or cooled air to adapt the indoor air temperature to the simulated indoor climate, whereby the heating up process can be accelerated by two tower heaters. On the back of the fans, heated or cooled air can be supplied via air ducts to allow the experience of a differently tempered outdoor air caused by natural or cross ventilation through the window and the door.

Figure 12: Inner and outer view on the test scenario

The indoor moisture may be increased by a humidifier, and a special mode of the air conditioning devices allows the dehumidification of the fed in air as well. Finally, an infrared heater, placed behind and in top of fan 2 simulates the felt solar radiation of the sun if her position leads to a direct radiation gain through the window. The devices of the test bed are switched on and off by a control strategy, implemented in openHAB, which compares the measured air temperature and moisture in the dome by two sensors in a height of 0.3 m and 1.35 m and the physical values provided by the Modelica building model and tries to match them as best as possible.

The scenario includes following assumptions, boundary conditions and user interactions (see also Figure 13):

- It takes place during a winter day (January 1) over 24 hours. Two different climate locations are considered; Berlin (Germany) and El Gouna (Egypt, Red Sea).
- The window of the room is oriented to the south.
- The maximum heating rate of the building model is set to 2,000 W.
- At the beginning (midnight), the indoor air and the building construction is initialized with a temperature of 20 °C and the window and door are closed. The set temperature for heating $T_{set,heating}$ is set to 18 °C (lowering of the set temperatre during the night).
- At 9 am the user enters the room, switches on the light and adapts $T_{set,heating}$ to 22 °C.
- At 11 am the user switches the heating off ($T_{set,heating}$ =
- 12 °C) and tilts the window for 15 min that cold and fresh outside air enters the room with an air change of 2 h^{-1}. Afterwards he or she closes the window and adapts $T_{set,heating}$ to 20 °C.

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- At 3 pm the indoor air quality has to be renewed again after 4 hours of intensive work. The user does cross ventilation for 10 minutes by rotating the window and open the door with an air change of 8 h^{-1}. During the ventilation period he or she adapts $T_{set,heating}$ again to 12 °C to save heating energy, closes afterwards the window and sets $T_{set,heating}$ to 22 °C.
- At 4 pm he or she switches off the light, adapts $T_{set,heating}$ to 18 °C and leaves the room.

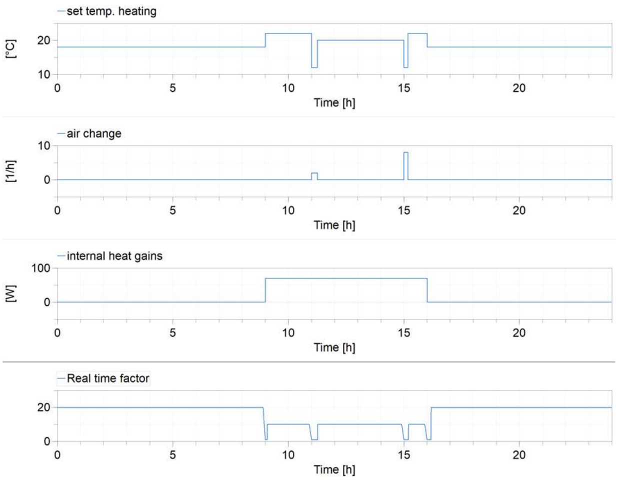

Figure 13: User interactions and used real time factor

To be able to carry out the simulation over a whole day in the VR experiment in a reasonably practicable time, the real time factor was adjusted from 1 to 10 or 20 for the periods in which no user interaction (changing the set point heating temperature, opening, and closing the window and the door) takes place and no large changes in the room air temperature are to be expected as a result (last diagram in Figure 13). In this way, the simulation time of a VR experiment could be reduced from 24 hours to about 2 hours of real time.

The simulated and measured values that resulted from the performance of the test scenario described above are illustrated in Figure 14 for the location Berlin (Germany) and in Figure 15 for the location El Gouna (Egypt).

Discussion

The upper graph in Figure 14 and Figure 15 shows the air temperatures simulated in the building model (blue lines) and the measured mean air temperatures in the dome (green lines). Further, the outdoor air temperature of the building model (red dotted lines) and the measured air temperature in the lab (black dotted lines) in which the dome is located is depicted.

Qualitatively, the experimental setup can reproduce the simulated air temperature for both climate locations. If the air temperature in the simulation model changes only slowly, it can be reproduced in the dome with comparatively small deviations of 0.5 to 1.5 °C. If the indoor air temperature drops very quickly in the building model, e.g., due to ventilation at the cold location Berlin at 11 am and 3 pm, the realizable dynamic of the cooling proves to be too weak. Dynamic heating up processes, however, can be better reproduced in the dome.

The lower graph in Figure 14 and Figure 15 indicates the three possible valves states of the hydraulic air distribution system, whereas 0 means “no air”, 1 “warm air” and 3 “cooled air” enters the dome. It can be stated that the currently used simplified on/off control strategy to operate the heating and cooling mode of the dome works according to the implementation in openHAB.

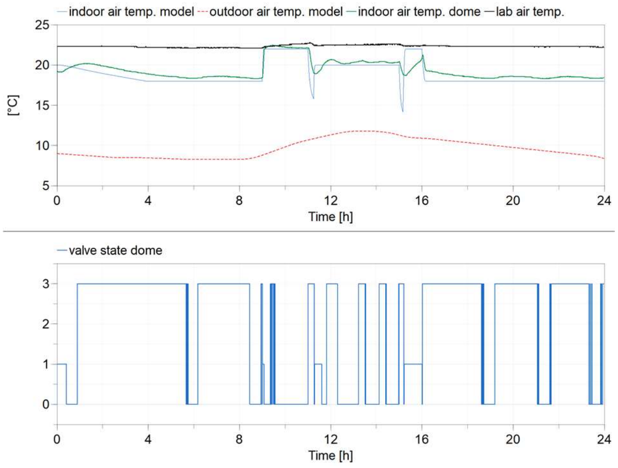

Figure 14: Simulated and reproduced indoor climate for the colder location Berlin (Germany)

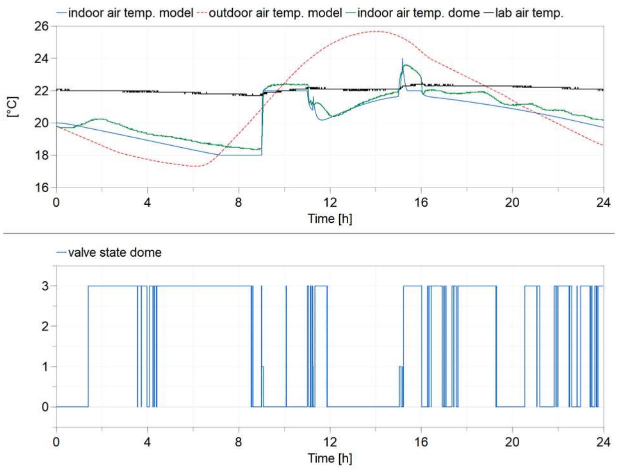

Figure 15: Simulated and reproduced indoor climate for the warmer location El Gouna (Egypt)

The results show that the capacity of the refrigeration devices must be significantly increased, and the control strategy must also be refined that also the faster system dynamics of the simulation model can be sufficiently reproduced. For this purpose, the control logic for the actuators should be extended so that instead of the still simplified states “100 percent warm air”, “100 percent cold air” and “no air” a continuously controllable supply of warm air and cold air to the dome is made possible.

Conclusion

A first prototype of an interactive VR simulation environment with thermal feedback for the user was designed, structurally realized in the form of a climate dome and tested in its basic functions. For this purpose, theoretical Modelica system simulations were first performed to investigate the achievable dynamics for the heating, cooling and humidification processes. Finally, a

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first application scenario was defined for a simple one-room example for a winter day and executed as a real-time experiment for a colder and a warmer climate location.

Outlook

Based on the first prototype, individual tests will be carried out in the further phase of the project to generate air flow patterns and radiation temperature distributions on boundary surfaces to be able to realize more complex patterns of the indoor climate in the VR simulation environment. Furthermore, an improvement of the system dynamics of the dome is intended, to be able to represent also short-term user interactions on the simulation model even more realistically with thermal feedback.

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