SIMULATION AND VALIDATION OF THERMAL AIR STRATIFICATION IN LIVING SPACES

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INTRODUCTION

Use of building simulation tools

The use of building energy simulation tools for analysis and optimization of the building energy efficiency and the indoor climate has a lot of advantages: this approach is more detailed, precise and faster than an analysis by hand and can lead to a better understanding of the energy balance of the building envelope, especially in the early phase of a building design process.

In some cases, the widely used building simulation tools have still some disadvantages, because they cannot consider all necessary building physics phenomena of building design, e.g. a strong horizontal thermal stratification within a thermal zone. A thermal zone model with an ideal mixed air volume would be not accurate enough for this special case. An alternative model would be a simulation tool based on a spatial resolved CFD approach. This would lead to very detailed analysis and results (e.g. local air temperature distribution and air velocity fields), but it would also address a huge amount of computation time. With present standard computer hardware only stationary simulation experiments or transient analysis over some minutes or hours can be realized based on a CFD approach.

Limits of building simulation tools

Previous research indicated a discrepancy between real cooling demand simulated cooling demand in an apartment with a vaulted ceiling (Banhardt et al., 2015).

First analysis showed that assuming one heterogeneous temperature over a relatively high zone produces errors. As measures have shown, a vault, with an apoapsis of 4.415m, the temperature between ground and ceiling can vary up to 10K in summer times. The air layer within the dome structure is almost unaffected by the air condition system. 0D models of simulated building zones cannot reproduce these effects. Hence, the calculated energy balance is not reliable.
Methodology

A new algorithm for IDA-ICE which includes a layering of a single zone and certain parameters for internal heat sources like occupants is introduced in the upcoming version 5.0 of IDA-ICE.

There, the setup of a reference system, according to real boundary conditions, is done. It is simulated as single zone and compared with different approaches to simulate thermal stratification. The results are compared with the reference system.

The performance of the new algorithm is compared to real measurements in the existing room.

The result is a relatively fast (compared to CFD) but much more accurate simulation for cases with not negligible thermal stratification.

SIMULATION METHOD

Simulation tool

IDA-ICE is chosen as simulation environment. IDA-ICE is a comprehensive building energy simulation platform for modular systems (Drury et al, 2008). The new approach was implemented and presented by Eriksson et al (2012).

Standard zone model

A central part of the simulation is the so-called zone model, which computes the indoor climate in a single room of a building, and hence the comfort and satisfaction of the occupants. The climate zone model in IDA-ICE keeps track of all the essential parameters that affect the indoor climate, including but not limited to: air temperature, heat radiation, lighting conditions and air quality in the room.

Every model is a simplification of the physical reality. It is valid only subject to a number of restrictions. The climate zone model in IDA-ICE has been developed for a typical shoe-box shaped room. Some serious simplifications are made, including constant temperature everywhere in the zone, simple view-factor calculation and objects without positions. On one hand, these assumptions are not very wrong for most zones, and they result in a relatively fast computation time. On the other hand, they make the model less reliable for some relatively rare but non-negligible real-world cases, such as big atriums or rooms with vaulted ceilings. In order to take these cases into account, a new IDA-ICE climate zone model is under development.

New advanced zone model

The main differences from the previous zone models are these three main features:

1. View factors between the surfaces are correctly and accurately calculated. This makes the radiation exchange calculations very accurate for zones of arbitrary geometry.
2. Vertical temperature gradient is modeled by dividing the zone into several horizontal layers.
3. Special air flows are introduced from hot objects, such as occupants, and surfaces, as well as from mechanical ventilation nozzles and openings.

The new climate zone model uses a not-CFD approach and has not been done before for arbitrary zones and flow elements. Though the resulting field might look like CFD, a completely different calculating mechanism lies behind it. The temperatures in the layers are calculated using the equations presented below. Flow elements and wall currents are calculated algorithmically. The equations and the algorithms are described in detail by Eriksson et al (2012).

The zone is divided into horizontal air layers. The layer at the floor has number 1, the layer at the ceiling has number nLay. Each layer is assumed to have uniform temperature. The air in the layers interacts with air in other layers through heat, mass and vapor transport. Flows are defined as positive in the upward direction and from flow elements to layers.

Mass balance – transmission

The mass balance in layer i is given by the following equation (1):

\[ \dot{m}_{trans,i} = \dot{m}_{term,i} + \dot{m}_{wall,i} + \dot{m}_{fe,i} + \begin{cases} \dot{m}_{trans,i-1} & \text{for } 1 < i \leq nLay \\ 0 & \text{for } i = 1 \end{cases} \]  

\[ \dot{m}_{trans} = \text{mass flow to or from layer } i; \dot{m}_{term} = \text{air mass flow due to mixing by flow elements}; \dot{m}_{wall} = \text{air mass flow due to mixing by wall currents}; \dot{m}_{fe} = \text{air mass flow from terminals to layer}. \]

Since the total amount of mass in the zone is constant, it must in addition hold that the sum over all layers is \( \sum \dot{m}_{trans,i} = \dot{m}_{trans,1} = 0 \).

Mass balance – turbulences

Due to turbulence in the air, there is a mass exchange between neighboring layers, calculated by the following equation:

\[ \dot{m}_{turb,i} = \begin{cases} c_{turb} A_{top,i} & \text{for } 1 < i \leq nLay \\ 0 & \text{for } i = 1 \end{cases} \]  

\[ c_{turb} = \text{empirical parameter}; A_{top,i} = \text{area of the top of layer } i. \]

The coefficient \( c_{turb} \) depends on many factors and conditions in the zone, such as number and movement of occupants or air stream through ventilation openings. It is beyond the scope of this paper to present the calculation of it. Currently the value is set
to 0. Further investigations on the empirical quantity of the value for different boundary conditions will be done in the future.

**Mass balance – inversion**

An inversion of the mass flow can occur, if layer \( i+1 \) has a lower temperature than layer \( i \). Then, there will be an exchange of air between the layers due to inversion. The mass inversion is calculated through the method presented in StorageStandard (2002). The derived formulation for the inverse mass flow \( \dot{m}_{inv,i} \) is given by the following equation:

\[
\dot{m}_{inv,i} = \begin{cases} 
1 & \text{for } 1 < i \leq nLay \\
0 & \text{for } i = 1
\end{cases}
\]

For the simulation of the annual energy balance, the weather data of Hurghada is imported through the software integrated download interface, connecting to the EnergyPlus weather database. For later comparison with real measurements the months of March and July are exchanged through weather data of the meteorological weather station within El Gouna. A full annual data set is not available so far and the room is simulated as a single zone. Only a cooling set point of 26°C is introduced. Furthermore, a constant air volume, CAV, is implemented on the westward facing wall as it is done in the real existing apartment. The operation parameters are typical for a split-unit A/C systems in the MENA region (Carrier 2013).

**Variant systems**

The reference system is tested against three different simulation variants. The three variants are designed to achieve a thermal stratification within the zone. At first, a rectangular model is created. It consists of six horizontal layers, each with a height of 0.736m. Horizontally, they are connected with a surface which only consists (due to modeling reasons) of an air gap. Vertical transfers are neglected. The architectural boundaries and the simulation model in IDA-ICE are presented in the following Figure. The air conditioning system is placed in layer 4. This layer is set to \( \theta_{sp,cooling} = 26 \)°C. The window is present in layer 3 and the properties match those of the reference system, except its rotated position to fit into one layer only. An illustration as well as the simulation model in IDA-ICE are given in Figure 2.

**CASE STUDY**

**Reference system**

A real existing apartment room of the Red Sea Town El Gouna is modeled within the environment of IDA-ICE 5.0 alpha. It is a room with a vaulted ceiling (\( \text{h}_{\text{total}} = 4.415 \) m), a floor area of 15.95 m² and a zone volume of 65 m³. The dimensions of the room are shown in the following figure on the left side. The right side shows the appearance in IDA-ICE. The building physics of the construction material as well as the occupant behavior are adapted to local conditions (Banhardt et al. 2013). The heat transfers to neighboring rooms (below, northwards, and southwards) is neglected. Furthermore, a constant air exchange rate of ACR = 0.5 m³/h is set. With the given zone volume, this accounts for \( \dot{V}_{\text{old}} = 33 \) m³/h.
zone volume. All other boundary conditions are kept the same.

The other two simulation variants are exactly the same set up within IDA-ICE as the reference system. The only difference is the chosen model fidelity. Both variants use the fidelity “climate” and a layered set-up. The height of each layer is set to be 0.736m. This set-up will initialize the use of the new simulation algorithm of IDA-ICE which is currently only available in a pre-released alpha version. Within the second simulation variant, the “air flow elements” are deactivated while they are activated in the third variant.

**Results of simulation**

The following graph in Figure 3 compares the annual sensible cooling energy demand of the simulated variants. They are drawn in blue and indicated on the left y-axis. Furthermore, the simulation time is highlighted as red bar on the right y-axis. The reference system calculates an annual cooling demand of $Q_{\text{ref}} = 4,220$ kWh/a and takes only 30 seconds to simulate.

The first variant, the rectangular construction, takes around three minutes to simulate and evaluates an energy demand of $Q_{\text{rect}} = 2,645$ kWh/a which is 37% lower than the reference calculation. On the other side, the vaulted zone model, without flow elements, simulates 30 seconds and concludes a total of $Q_{\text{vault,Nf}} = 3,357$ kWh/a. This is 20% less than the reference. The longest time, with more than one hour, takes the simulation with flow elements. The result is, with $Q_{\text{vault,Wf}} = 4,636$ kWh/a, about 10% higher than $Q_{\text{ref}}$ of the reference simulation.

**Comparison of simulation results**

Due to the high variation in the simulation results, the different results are compared with a focus on a single day in July. There the temperature profiles are compared with each other.

Figure 4 Shows a graph with the operative (blue) and mean air (red) temperature profile of the reference simulation. As the room is set to a constant temperature, the mean air temperature is constant at $\vartheta_{\text{air,mean}} = 26^\circ\text{C}$ over the whole day. Only the operative temperature varies. During afternoon it reaches its maximum. This is due to the higher temperature of the ceiling which is caused by the incoming solar radiation.

The next graph in Figure 5 shows the temperatures of each layer in the rectangular, layered model. Highlighted in solid red with squares is the mean Temperature in Layer 4. This layer is set to $\vartheta_{\text{sp,cooling}} = 26^\circ\text{C}$. The top layer 7 is drawn in dashed grey with a rotated square. The bottom layer 1 is indicated by a solid blue line with straight marks.

The layers 5, 6, and 7 are connected to the dome and are mainly influenced by the solar radiation onto the vault and reach much higher temperatures than the others. The mean air temperature in layer 4 is kept constant at 26°C and hereby the lowest overall temperature. The air exchange to other layers happens through the openings to the upper and lower layer. This happens only due to pressure differences. Hence, the cooling effect of layer 4 to layer 1, 2, and 3 is relatively low. They are mainly heated by their small fractions of the outer walls and the relatively low air exchange.

Compared to this is the graph in Figure 6. It shows the temperature in each layer in a simulation with the new algorithm. The layering is done there automatically, according to the entered layer height. Within a first
simulation, the “flow-elements” are not activated. The temperature $T[4]$ within layer 4 (drawn in purple, marked with crosses) is constant at 26°C. This layer contains the intake of the split-unit. The temperature of the inlet air is the reference for the cooling set point of the room. Hereby, it is kept constant. The air outlet of the A/C unit is as well in this layer. Layer 5 and 6 are above and connected to the dome. They are mainly influenced by the solar gains of the vaulted ceilings and almost behave like free floating temperatures. They reach temperatures up to 35°C. The temperatures in the lower layers, 1, 2, and 3, is highly influenced by the A/C system as the air exchange between the layers is not only influenced by pressure differences. The empirically gained equations for mass exchange cause the temperature to drop to 2K below the set-point temperature of 26°C.

The maximum temperature difference between ground and the upper layers in the dome is more than 10K around 8pm.

The upcoming graph in Figure 7 shows the temperature profile with activated flow elements. The curves behave less smooth than compared to the other simulations. All layers are influenced by the airstream of A/C outlet. The purple line, marked with crosses, indicates the temperature profile of layer 4. It is almost constant as this layer is the reference for the cooling set-point. The values in the top layer reach their maximum around 2pm with almost 30°C. The influence of the thermal mass can be seen in the lower levels. In the morning hours, the air in all lower layer has the same temperature. After the heat has dissipated through the walls, around 2 pm, the temperatures start to vary in different layers. The maximum temperature difference between floor and ceiling is around 8K at 5pm.

**DISCUSSION OF RESULTS**

**Comparison of simulation models**

The common simulation approach with a homogenous zone delivers a higher simulation result in case of cooling energy demand than all other simulation approaches. The results show that a homogenous temperature is not realistic. Especially, the temperature within the dome is highly affected by solar gains but not by the air conditioning system. This results in unnecessary cooled air space within the vault. Hence, the simulated cooling demand is too high. This is shown as well in the layered simulation model within the conventional simulation environment. There, only layer 4 is kept at 26°C. A much lower air volume needs to be cooled which reduces the cooling load tremendously. Nevertheless, this results in unrealistic temperature stratification as also lower layers get hotter than layer 4.

The new simulation model, without activated flow elements show the occurring thermal stratification well. Without the activated flow elements, the impact of the room air cooling system on the air mixing is close to none, which results in an almost daily constant temperature profile with only small influences due to the outer wall. This results in a lower cooling demand as for the reference system as the vault is not cooled. Still, the cooling demand is higher than in the rectangular self-constructed layered model, as also the lower layers are now below 26°C. This result is much more realistic than the two mentioned cases with only slightly more calculation time (half a minute) than compared to the self-constructed layer model.

More realistic results, in terms of thermal behavior, are achieved with activated flow elements. A mixing of the air is now happening and a mass exchange with all layers is achieved. As the cold airstream is blown in horizontally and “falling” to the ground, the lower layers cool down much more than in the previous case without flow-elements. This causes an increased cooling demand which is almost the same as in the reference case.
Comparison with real consumption
The high variation of this simulation results is compared with the real electric consumption of the apartment. The existing room is equipped with a smart meter and the data is available for the period from March 2015 to March 2016. The daily electricity demand is shown in orange in the following graph in Figure 8. The data is assembled to an annual overview of the electric consumption.

The overall annual electricity demand is \( Q_{\text{elec}} = 6,379 \text{ kWh/a} \) while the demand during the cooling season (May to November) is \( Q_{\text{elec,cs}} = 5,265 \text{ kWh} \).

![Figure 8 - Real electricity consumption of the apartment from March 2015 to March 2016](image)

The living room of the apartment was always set to 26°C and the fan for the recirculation of the air was always activated. The peak in February is caused by the use of the heating mode of the split-unit.

Clearly visible is the increased demand during the summer months. During the time from mid-May to mid-July, the apartment was occupied. Within the months to end of September only the A/C system and the fridge were activated. In beginning of August and end of September, the A/C system was deactivated for maintenance for about a week. The maintenance week and the base load of the cooling season were used to estimate the overall electricity demand for cooling. It is calculated to be \( Q_{\text{elec,AC,cs,SPL}} = 3,440 \text{ kWh} \).

This surprisingly high difference is analyzed through a detailed look to the temperature distribution within the following section.

Comparison of air temperatures
For the comparison the same day in July is chosen. As all simulations have been done with real weather data for July 2015. The thermal stratification within the real existing apartment is shown in the following Figure 10. There, the top blue line indicates the measured temperature in the apoapsis of the dome while the brownish bottom line indicates the temperature on floor level. The yellow line highlights the outdoor temperature. It is clearly visible that the temperature within the dome exceeds the outer temperature by up to 2K around 5pm. During the night, the radiation exchange with the night sky cools down the vault to 4K below the outer temperature shortly after sunrise at around 7am.

The top layers are not influenced by the A/C system at all. This is shown in the simulation without flow-elements as well, indicating that the simulated impact of mass exchange with activated flow elements might be too high.

The impact of the air condition system is clearly visible within the lower layers, which was previously shown within the simulation with flow elements.

The maximum temperature difference between vault and ground is more than 10K and happens at 6pm. This result was also produced by the simulation without flow elements.
CONCLUSION

The reference “standard” simulation calculates with relatively low computational efforts good cooling load results. The error to real room behavior of special cases, like the presented vaulted ceiling, couldn’t yet be determined. The wide range of simulation results indicates the need for further research.

Nevertheless, the new model approach can produce CFD-like results with acceptable computational effort as the following Figure 11 shows. There, the simulated temperature profile on June 24 is visualized. Highlighted, as green surface is the isentropic temperature of 23.2°C, showing the incoming air from the air conditioning system. This picture clearly shows the advantages of the new simulation algorithm that air flow analyzes are possible without detailed CFD simulations.

LITERATURE

Banhardt, C & Nytsch-Geusen, C June 2013, ‘Simulation Based Design of a Test Rig for Developing Solar Cooling Concepts for the MENA Region’, Building Simulation Conference Proceedings, p. 165-174, Cairo, Egypt. Figure 3, p. 167


