Dynamic performance of displacement ventilation in a lecture hall

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ABSTRACT

An accurate temperature gradient calculation is essential for displacement ventilation (DV) system design, since it directly relates to the calculation of the required supply air flow rate. Inaccurate temperature prediction can cause the poor thermal comfort and w sizing of the ventilation and cooling systems. Several simplified nodal models were developed and implemented in the various building simulation software to estimate the temperature stratification in rooms with DV. Recent studies reveal that the multi-nodal models provide the most accurate temperature gradient prediction. However, the most building simulation software uses the air models with only one air node. The present study introduces the dynamic temperature gradient model for DV and investigates the effect of thermal mass on the temperature stratification. The model was validated with the experimental results of the lecture room with displacement ventilation. The room air temperature measurements were conducted during three weeks at 20 different heights. The supply air temperature and occupancy rate were recorded during each scheduled lecture. The developed dynamic nodal model is able to accurately calculate the air temperatures in occupied zone. The effect of the thermal mass and varied heat loads on the indoor air temperature stratification is analysed for the lecture room with DV.

KEYWORDS

Displacement ventilation, RC-model, building simulation, thermal mass, thermal comfort

1 INTRODUCTION

In displacement ventilation (DV) systems, cool air is supplied into the occupied zone of the room near the floor at low velocity and then entrained by buoyant plumes over any warm objects. As a result, a two layer profile of room air temperature, stratified and mixed, is developed. Ideally, the air movements induced by thermal plumes transport heat and pollutants up to the occupied zone, promoting a vertical temperature and contaminants stratification. The transition level between a mixed upper layer and stratified layer is called mixing height, which is related to the height where the inflow rate matches the airflow induced by the thermal plumes in the occupied zone. Controlling the mixing height position is one of the most challenging tasks in DV system design, since it directly related to the calculation of supply air flow rate.
The temperature gradient in DV systems is usually calculated with the nodal approach. (Griffith and Chen, 2004). The multi-nodal models provide a promising method for the temperature gradient prediction (Kosonen et al, 2016). Some of the simple and multi-nodal models are applied in DV design and available in thermal energy simulation tools, such as IDA-ICE (Mundt, 1995) and EnergyPlus (Mundt, 1995 and Mateus, 2015, Mateus and da Graça, 2017)..

Nowadays, building energy simulation methods are applied to study the dynamic behaviour of heat and mass balance. They have been developed starting from engineering steady-state analytical models through simplified dynamic balance methods to the modern validated energy modelling programmes (Wang and Zhai 2016). The programs could use simplified dynamic method, for instance response function methods, or numerical finite difference method. Having been driven by the increase of computational power, the use of building simulation software is getting widespread in the design and consulting communities. However, simplified models are still applied in building energy analysis due to their user-friendliness, straight forward calculation and suitability for optimisation and demand control calculations (Kramer et al., 2012). The simplified models are classified to physical and mathematical data-driven models (Foucquier et at., 2013; Ji et al, 2016). Among the simplified model RC models are the most popular, since their parameters have obvious physical meanings and the models require less data than data-driven models. Based on circuit principles and Kirchhoff electric current theory, constructing building models with RC-networks implies representing every element of the building with resistors and capacitors. The simplest one-capacity models are not able to represent accurately the indoor air temperature dynamics, since the real physical process behaves like a two- or higher order system. In addition, several studies show that higher order models are more accurate than the first order RC models in capturing thermal behaviour of a building (Fraisse et al., 2002; Tindale, 1993). The RC models can be focused mainly on the dynamic thermal behaviour in building envelope or in the whole building. The building envelope RC models usually consist of at least three wall resistances and two (Gouda et al, 2002) or four (Fraisse et al., 2002) capacitances. These models are usually suitable to predict dynamic indoor and outdoor heat pulses and working insufficiently with lasting thermal loads (Antonopoulos & Koronaki, 2001).

Lumped parameter methods can also be applied for modelling the whole zone instead of individual construction elements (Crabb, 1987; Dewson, 1993; Neilsen, 2005 Kämpf, 2007). In this approach, all the thermal capacities of the different construction elements that the zone is composed of are concentrated in a single equivalent capacitance, and another additional capacitance is added for the air of the zone. The accuracy of these methods highly depends on the value of their characteristic capacities, so they need to be adjusted using different methods. Values of the characteristic parameters of the model be obtained with simple configurations (Seem et al., 1989) or analytically by comparing the response with a high-order reference model using optimization with single objective (Wang and Xu, 2006; Gouda et al, 2002; Fraisse et al., 2002) or multi-objective (Underwood, 2014) function.

This study introduces simplified 2-capacity R2C2 model, where the capacities and conductances are calibrated against the results taken from the advanced building simulation model IDA-ICE. The 2-capacity model structure and the calibration methodology was initially created by Kai Sirén (Sirén, 2016) and implemented for the space heating using model predictive control in an office building (Mäki, 2018) for one air node. The initial model was modified with calculate the temperature gradient in rooms with DV with the use of the multi-nodal model (Lastovets et al., 2018). The presented calibrated two-capacity model was validated with the measurements in the lecture hall.

2. METODS

2.1 Simplified 2-capacity model

The structure of the proposed model is shown in Fig.1. The initial model was modified to calculate the indoor air temperature gradient in rooms with displacement ventilation to calculate three air temperatures: along the floor at the height 0.1 m $t_{0.1}$, at the level of mixing height t_{mx} and the exhaust temperature tex. The first two temperatures were counted with following

assumptions: the supply air temperature reflects the temperature along the floor; there is a load division between the mixing height level and the height of exhaust air.
The inputs of the models are the outdoor air temperature T_{out} and the supply air temperature T_s. T_{mx} is the air temperature at the mixing height that is calculated using the plume theory (Lastovets et. al, 2018).
In the model, there is two capacities: conductances of room air C_a and building thermal mass C_m. The mass capacity C_m is related to the thermal mass in the walls, ceiling and floor. The model includes the heat capacity flow through ventilation H_{as}, heat conductances of window H_{ae}; between mass node and outdoor air node point H_{ms} and between mass node and indoor air node point Ham.

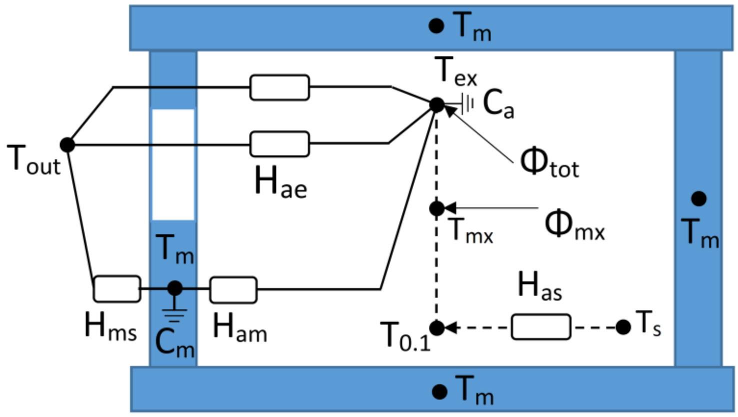
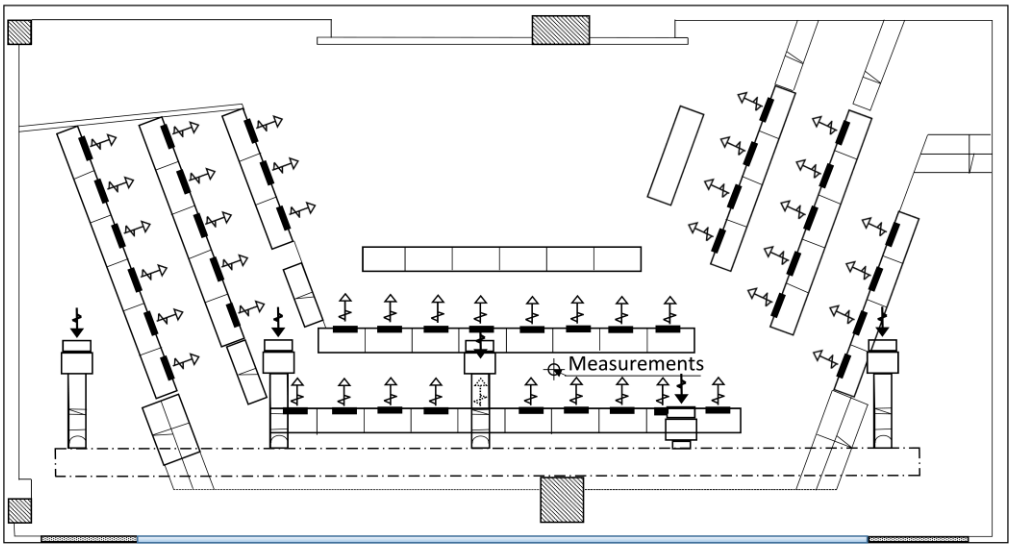


Figure 1: Structure of the simplified 2-capacity

Both conductances H_{ms} and H_{am} contain heat conduction in the solid wall material as well as convection on the surfaces. The mass node point is located in an undefined depth inside the building structure and represents a kind of mean temperature of the active building mass.
The total heat load in the zone heat balance in the model Φ_{tot} consists of low Φ_{mx} and high Φ_{high} heat loads.
Low heat loads are related the ones that occur in the occupied zone of the room, whereas high heat loads are located near the ceiling. The examples of low heat loads are the ones from people and office equipment. The high heat loads in practice could be from lighting units or solar gains through high-located windows. When heat load occurs in the middle of the room, it depends on the mixing height whether consider them high or low heat loads. If the mixing height is located within the occupied zone, it refers to low heat loads, and vice versa (Lastovets et al., 2018).

2.2 Experimental study of the lecture room

Measurements were carried out between 27th of October and 1st of December 2017 in the lecture room of Aalto University. A sketch of the layouts are provided in Figure 1. The exhaust grilles are near the ceiling height and located along the back walls. The supply air flow rate has maximum value when occupancy sensors detect any presence though ventilation rate does not change with number of students present.



a) b)

Figure 2: The layout of the classroom and the location of the measurement mast a) and the image of it b).

For measuring temperature at different heights, floor to ceiling, the measuring mast was assembled with 20 TinyTag Plus 2 Dual Channel loggers. Seventeen TinyTags were located at 10 cm separation, starting from 0.1 to 1.7 m, followed by three more at 2, 2.5, and 3 m respectively. A Swema 3000md manometer was used for measuring flow rates from individual diffusers

Table 1: Table Caption

Column Title	Column Title	Column Title	Column Title	Column Title
Table content				

2.3 IDA-ICE building simulation as a source of the reference data

The building model was formed using IDA indoor Climate and Energy 4.0 (IDA-ICE) building simulation software. This software allows modelling of the building, HVAC-systems, internal loads, outdoor climate, etc. and provides simultaneous dynamic simulation of heat transfer and mass flows. It is a suitable tool for the simulation of thermal comfort, indoor air quality, and energy consumption in complex buildings. A modular simulation environment, IDA-ICE, has been developed by the Division of Building Services Engineering, KTH, and the Swedish Institute of Applied Mathematics, ITM (Shalin et al. 1996, Björsell et al. 1999). The mathematical models are described in terms of equations in a formal language using non-negative matrix factorization. The IDA-ICE simulation software was validated both empirically (Bjorsell at al., 1999; Moinard and Guyon, 1999; Jokisalo at al., 2007; Travesi et al, 2001) and via several independent inter-model comparisons (Achermann and Zweifel, 2003; Loutzenhiser et al, 2009). In addition, IDA-ICE was validated according to the European Standard prEN 13791 by Kropf and Zweifel (2001). The standard defines the test cases: heat conduction through opaque walls, internal long wave radiation exchange, shading of windows by external constructions, and a test case for the whole calculation method, for which the IDA-ICE simulations gave the results as demanded by the standard. The robustness and reliability of IDA-ICE building simulating program to perform building energy calculations allows using it as a reference for the calibration of the 2-capacity model.

Since the software does allows building only "show box" rooms, the sizes of the model was adjusted from the volume of the room (Table 1). The internal staircase massive was also shrimped to equal floor thickness (Figure 3).

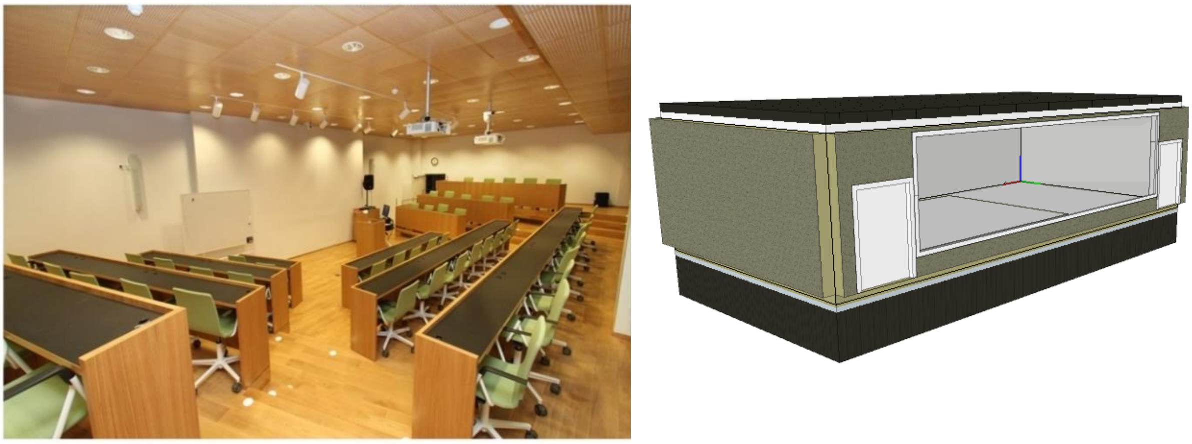


Figure 3: The photo of the studies lecture room and the IDA-ICE model of it

Table 1: Constructional and system parameters of the study case

Parameter	Value	Dimension
Net floor area	A_f	86.4
Total internal surface area	A_{int}	289.2
Internal volume	V_{int}	256.5
Internal heat loads	Φ_t	0.0
Window conductance	H_{ae}	45.4
Leakage air flow	q_{inf}	0.0
Supply air flow	q_s	0.6
Supply air temperature	t_s	18.0
Room air temperature	t_a	21.0

3. CALIBRATION METHOD OF THE TWO-CAPACITY MODEL

In the RC model , the heat conductances and heat capacitances are needed to determine. The characteristic parameters of the presented R2C2 model are calibrated against IDA-ICE simulation results. In the method, the thermal behaviour in RC-model matched with the results of the detailed model of IDA ICE. The methodology of the model calibration was performed for one air node ta by using the methodology developed by Kai Sirén (Sirén, 2006). The calibration consists of steady-state and dynamic set response parameter identification (Figure 4).

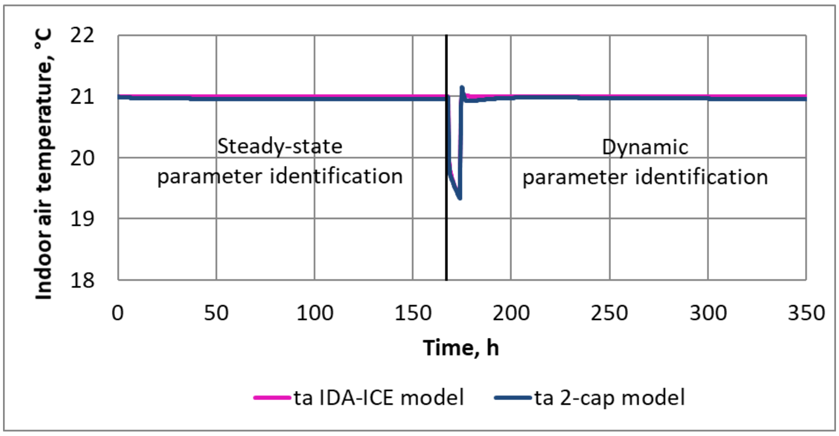


Figure 4: Steady-state and dynamic parameter identification in RC-model calibration with constant T_{out} = 18 °C.

3.1 Steady-state parameter identification

In steady state parameter identification, the steady state energy balance was matched with the indoor air node point to fix the conductance values of the 2-capacity model. The internal heat loads were not applied in the models since they are not needed in the calibration. The IDA-ICE simulation program generates the reference data for the steady state conditions. Conductance values were calculated by running the IDA ICE model with artificial weather file were all the parameters, such as outdoor air temperatures, wind speed, had constant values. Three different values of outdoor temperatures (+18 °C, +19 °C, +20 °C) were used to get an average performance that are outdoor temperature dependent such as heat transfer coefficients and window U-values.
The simulation with the IDA ICE model with constant outdoor parameters has to carry out long enough, so that the building reached steady-state condition, from which the conductance values and the heat capacity flows could be determined. In order to keep the indoor air set point temperature 21 °C, the ideal heater is applied with the maximum power 5 kW.
The conductance values of window H_{ae} and room constructions H_{ams} and as are inserted directly from the IDA-ICE model. The conductance H_{ams} in steady-state parameter identification is combined from the conductances on both side of the mass node point (H_{am} and H_{ms}), which are determined in the dynamic identification stage.
The correct value for H_{ams} was searched so that the error in heating powers resulting from air node energy balance between the IDA ICE and the RC-model at the three different outdoor temperatures was at the minimum with the use of nonlinear optimization using the generalized reduced gradient method.
Parameters from the steady-state identification together with the calibration parameters are presented in Table 2.

Table 2: 2-capacity model parameter values from steady-stare identification

t_{out} , °C	Φ_{hc}, W	H_{as}, W/K	H_{ae}, W/K	H_{ams}, W/K
18	2714			
19	2573	726	45	146
20	2439			

3.2 Dynamic parameter identification

The dynamic parameter identification was performed after the steady-state one. The purpose of the dynamic parameter identification was to determine the air and mass heat capacities Ca and Cm and the conductance between mass node and indoor air node point Ham. The conductance between mass node and outdoor air node point H_{ms} is determined from the Eq 9.
Three model parameters H_{am}, C_m and C_a were searched in a dynamic state by applying an excitation influence the system based on the IDA reference simulations. The excitation can be achieved by a sudden change in the external temperature, solar intensity, internal loads or heating power. Since the 2-capacity model was intended to forecast the indoor heat gains and temperature stratification, the heating power was chosen as a variable when the time-dependent change was made.
In the presented calibration, the simulated identification sequence had first a 167-hour one-week period for stabilizing the temperatures, a 6 hours interruption in the heating power and a second one-week period to check the final temperature level and the heating power will reach steady-state values. The IDA-ICE reference simulations were again performed in three different

outdoor air temperatures (18 °C, 19 °C, 20 °C) with the correspondent recording of the air temperatures and heating powers.

Indoor air temperature was chosen as identification criterion the difference between simulated reference and model produced values of a chosen quantity in the system is used. The room air temperatures calculated in the 2-capacity model and IDA model were compared for parameter identification. The dynamic calibration was defined as a minimization problem, where the average absolute differences between air temperatures in IDA model and 2-capacity model from the simulations with three different outdoor temperatures were minimized. The minimization problem was solved by using a sequential search algorithm supplemented with a local refinement procedure. Table 2 shows the calibrated parameter values.

Table 3: The parameters of the calibrated 2-capacity

H_{am}, W/K	H_{ms}, W/K	C_a, kJ/K	C_m, kJ/K	$\lvert t_a - t_{ar} \rvert$, °C
1453	162	1581	48158	0.04

The indoor air temperatures in the IDA model and in the 2-capacity model after the calibration with three constant outdoor air temperatures are showed at the Figure 5.

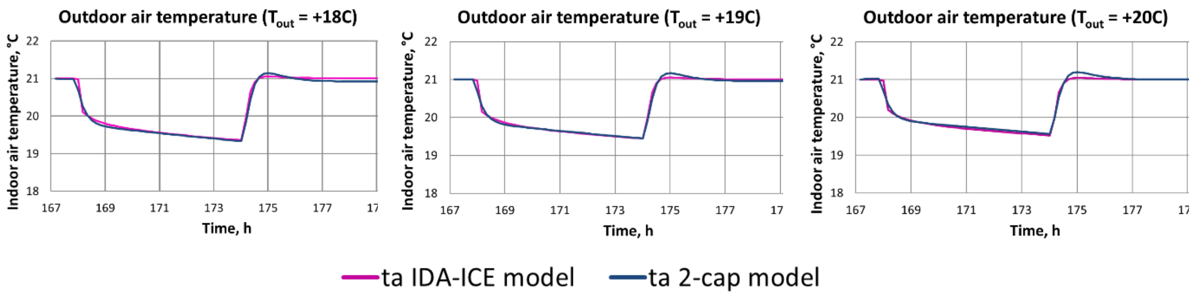


Figure 5: Comparison of the two-capacity model and IDA-ICE simulation indoor air temperature with tree different outdoor temperatures

The decay curves depict first a rapid change when the air is cooling down and then after that a more slow decay when the building mass thermal mass is activating. The indoor air temperatures calculated with the IDA-ICE model and 2-capacity model demonstrate a reasonable fit to describe the thermal mass effect of the room air and structures. That makes possible to use the celebrated parameters (Tables 2 and 3) to calculate indoor air temperatures in 2-capacity model.

4. VALIDATION OF 2-CAPACITY MODEL

This section presents the validation of the 2-capacity model based on the air temperature measurements in the lecture hall for two conditions (Table 4). The heat gains of people were estimated to be 100 W per person. The high-levelled heat gains consisted of the lighting units. Figure 5 presents the measured indoor temperature gradients and the comparison between two-capacity model simulations and indoor temperature measurements for the cases with different heat loads and load profiles.

Table 4: The parameters of the two validation cases

	Φ_{tot}, W	Φ_{mx}, W	Φ_{high}, W	$\lvert t_s \rvert$, °C
Case 1	8000	5000	3000	19

Case 2	5000	3000	2000	21

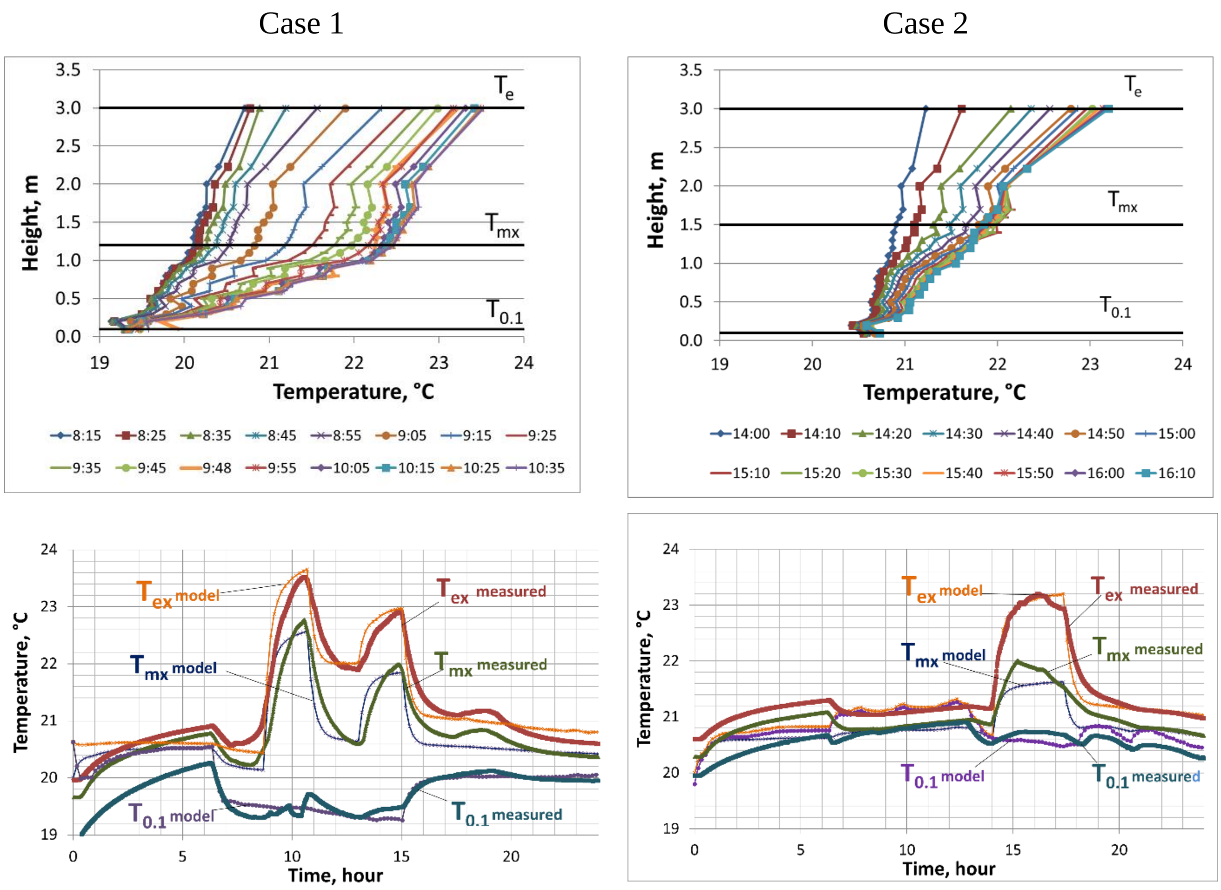


Figure 5: The measured indoor temperature profiles (upper) and the comparison of the two-capacity model three temperatures with measurements (lower).

In both cases, the 2-capacity DV model predicted well the trends of the indoor air temperatures in all three studied heights. The model was able to account the changing supply temperatures and heat loads. Thus, the calibrated capacities are applicable to the presented R2C2 model. The important temperatures for displacement ventilation, such as a mixing height temperature tmx and a temperature along the floor $t_{0.1}$, were calculated with the high average level of accuracy. In the Case 2, the mixing height temperatures were slightly underestimated. However, in this case it could be related to the uneven internal load distribution.

5. CONCLUSIONS

The accurate dynamic model to calculate the temperature gradient in rooms with DV is crucial in the design process, since it reflects the close to the reality conditions. The introduced calibration procedure allows accounting the thermal mass effect on the internal air temperatures. The presented model is able to take into account time schedules of heat loads and thermal mass of building. The results show that the trained two-capacity model can predict the indoor air temperature gradient in dynamic conditions. The model has good robustness to predict the thermal performance under different operation conditions by capturing the dynamic characteristics of the building system correctly. The good robustness of the model is due to the parameters of the building internal mass model and the model structure, which not only describes the behaviour or performance of the building internal mass but also represents the building thermal mass physically. The procedure to estimate the lumped thermal parameters of the building internal mass model is presented in the study can be effectively used to identify the parameters using short-term operation data. The model can be applied in design DV in various dynamic conditions.

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