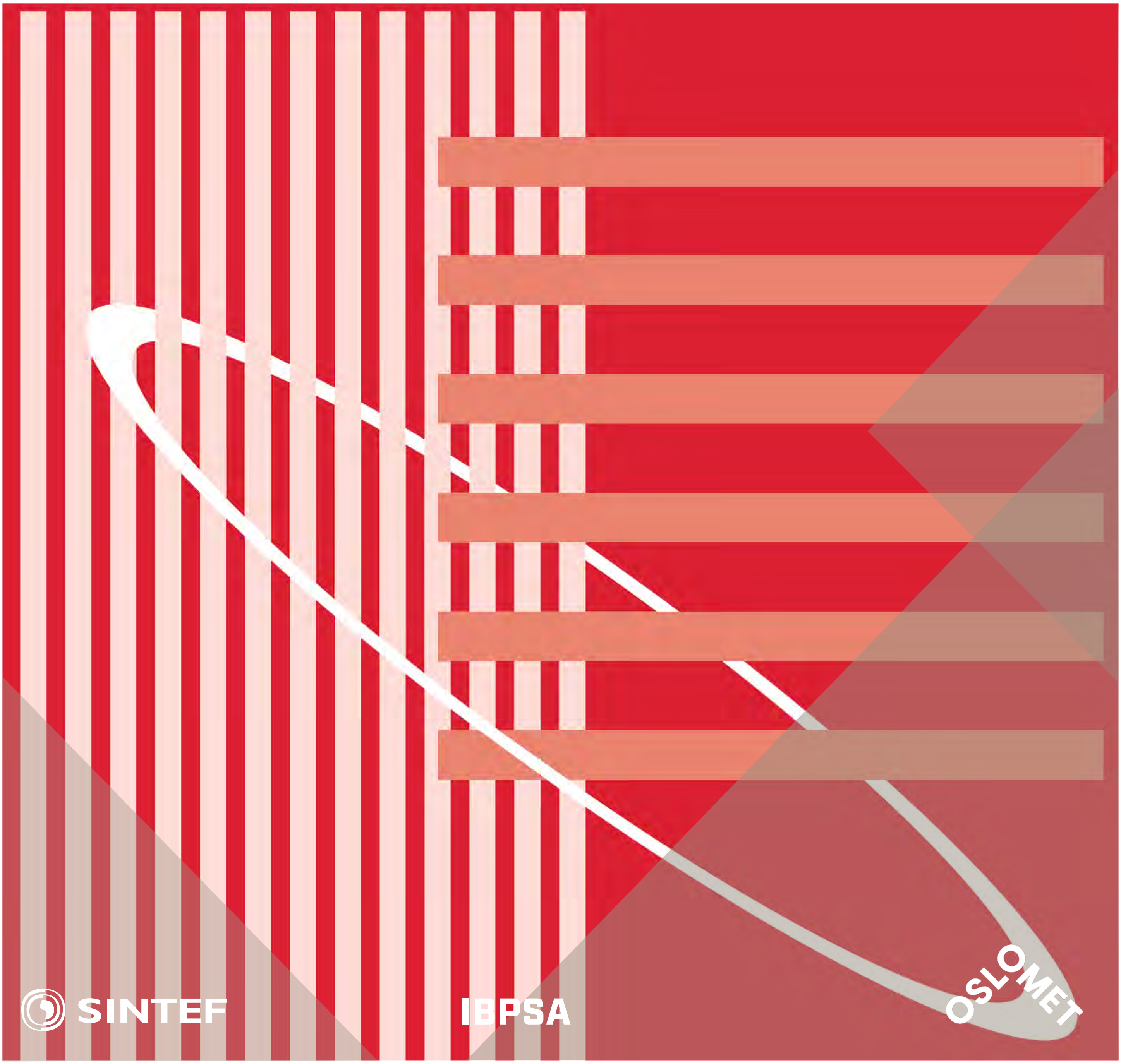
SINTEF
PROCEEDINGS
5

International Conference Organised by
IBPSA-Nordic, 13th–14th October 2020,
OsloMet

BuildSIM-Nordic 2020

Selected papers



SINTEF Proceedings

Editors:
Laurent Georges, Matthias Haase, Vojislav Novakovic and Peter G. Schild

BuildSIM-Nordic 2020

Selected papers

International Conference Organised by IBPSA-Nordic,
13th–14th October 2020, OsloMet

SINTEF Academic Press

SINTEF Proceedings no 5
Editors:
Laurent Georges, Matthias Haase, Vojislav Novakovic and Peter G. Schild
BuildSIM-Nordic 2020
Selected papers
International Conference Organised by IBPSA-Nordic,
13th–14th October 2020, OsloMet

Keywords:
Building acoustics, Building Information Modelling (BIM), Building physics, CFD and air flow, Commissioning and control, Daylighting and lighting, Developments in simulation, Education in building performance simulation, Energy storage, Heating, Ventilation and Air Conditioning (HVAC), Human behavior in simulation, Indoor Environmental Quality (IEQ), New software developments, Optimization, Simulation at urban scale, Simulation to support regulations, Simulation vs reality, Solar energy systems, Validation, calibration and uncertainty, Weather data & Climate adaptation, Fenestration (windows & shading), Zero Energy Buildings (ZEB), Emissions and Life Cycle Analysis

Cover illustration: IBPSA-logo

ISSN 2387-4295 (online)
ISBN 978-82-536-1679-7 (pdf)

SINTEF Academic Press
Address: Børrestuveien 3
PO Box 124 Blindern
N-0314 OSLO
Tel: +47 40 00 51 00

www.sintef.no/community
www.sintefbok.no

SINTEF Proceedings
SINTEF Proceedings is a serial publication for peer-reviewed conference proceedings on a variety of scientific topics.
The processes of peer-reviewing of papers published in SINTEF Proceedings are administered by the conference organizers and proceedings editors. Detailed procedures will vary according to custom and practice in each scientific community.

Calculation of airflow rate with displacement ventilation in dynamic conditions

Natalia Lastovets[1*], Risto Kosonen[1,2], Juha Jokisalo[1]
[1] Aalto University, Espoo, Finland
[2] Nanjing Tech University, Nanjing, China
* *corresponding author: natalia.lastovets@aalto.fi*

Abstract

Design of displacement ventilation (DV) is usually based on a heat balance method when overheating is the primary indoor climate concern. Various models for calculating airflow rate have been developed for several decades. Commonly used models are based only on steady-state models. However, in practical applications, the performance of DV depends on potentially dynamic parameters, such as strength, type and location of heat gains and changing heat gain schedule. Besides, thermal mass affects dynamically changing room air temperature. The paper presents case studies of dynamic DV design in a lecture room. The difference in the designed airflow rate was studied with various models in both dynamic and steady-state conditions. The presented dynamic DV model demonstrated a capability to take into account the combination of dynamic parameters in typical applications of DV. In the case analysed, the airflow rate calculated with the dynamic model is significantly lower than the one calculated with the steady-state models.

Keywords: Displacement ventilation design, airflow rate, temperature gradient, dynamic model.

Introduction

Displacement ventilation (DV) has been first applied in industrial buildings and since the 1980s in non-industrial applications. The basic principle of displacement ventilation is that the cool air is supplied into the occupied zone of the room at low velocity and then rises upwards from the heat sources by the vertical convection currents. As a result, room air with DV has both stratified and mixed zone with different temperature profiles. The design of displacement ventilation is usually based on controlling the desired air temperature in the occupant zone. Thus, the estimation of the vertical temperature gradient is essential in displacement ventilation design.

The temperature gradient in DV systems is usually calculated with the nodal approach, which is suitable for design and system sizing since it provides a rapid solution. Nodal models apply the electrical analogy to represent a heat balance of the room air as an idealised network of nodes connected with airflow paths. Unlike zonal models, nodal models do not predict mass transfer in a room, so that prior knowledge of the airflow patterns is needed in order to specify mass flow in the thermal network (Griffith 2004). Until recently design guidelines from various researchers for displacement ventilation have applied two-nodal models (Mundt 1996, Li et al. 1992, Arens 2000) that predict the linear slope between the air nodes above the floor and exhaust terminal, which is assumed to be always at the ceiling.

Other design guidelines assume a constant vertical air temperature gradient between the head and feet (2°C/m) from the temperature above the floor (Skistad 1994). Since only the heat entering the occupied zone needs to be considered in displacement ventilation systems, later studies proposed fractional coefficient methods to calculate the reduced heat gains in the occupied zone (Yuan et al. 1999, Cheng et al. 2012, Liang et al. 2018, Zhang et al. 2019). In this method, total room space heat gains are artificially divided into occupied and unoccupied fractions. The part of the heat gains in the occupied zone is calculated from the total heat gains with fraction coefficients. These coefficients are estimated empirically or derived from statistical methods based on a database of CFD simulation cases (Lau and Niu 2003).

The multi-nodal models introduce a temperature profile composed by variable slopes between the nodes. The models with a different number of nodes, heat gain configuration and mixing height consideration can be found in the literature (Nielsen 2003, Mateus and da Graça 2015, Lastovets et al. 2020). These models calculate mixing height with plume theory depending on types and number of convective heat sources. The multi-nodal models provide a promising method for the temperature gradient prediction (Kosonen et al., 2016).

However, all models mentioned above have been developed for steady conditions. At the same time, air stratification created by plumes depends on the potentially dynamic parameters, such as strength, type and location of heat gains, ventilation airflow rate and supply air temperature. Besides, since DV is usually applied in non-residential buildings that are not occupied continuously, the thermal mass effect, varied internal and solar heat gains significantly reflect the room air temperatures. It means that in practical applications, current steady-state models cannot accurately predict the room air temperature gradient in dynamic conditions. Thus, an accurate calculation of the vertical temperature gradient in dynamic conditions is required for DV design.

Nodal models implemented in building energy simulation software is an accessible option for design. Some of the two- and multi-nodal models are applied in DV design and available in thermal energy simulation tools. The most frequently used Mundt's model (Mundt 1996) is implemented in IDA-ICE (Shalin 2003) and EnergyPlus (Crawley et al., 2004). The multi-nodal DV model implemented in Energy Plus (Mateus and da Graça 2015), together with the calculation methods of mixing height was validated in dynamic conditions with the measurements in classrooms (Mateus et al. 2016) and large rooms (Mateus and da Graça 2017).

Simplified building energy models are still practical for pre-design and system sizing in typical applications due to their user-friendliness and straightforward calculation (Kramer 2012). Among the simplified models, the most common are the resistance-capacitance (RC) models of a building zone that imply thermal-electrical analogy based on the similarity between electric current and heat flux. In this approach, an RC-network of a building zone represent every element of the building construction elements and room air with thermal capacities and conductances (Parnis 2012).

The present study applies a simplified dynamic DV model to calculate the vertical temperature gradient (Lastovets et al., 2019) that integrates with the multi-nodal DV model (Lastovets et al., 2020) and two-capacity building energy model (Sirén 2016, ISO 13790: 2008). The thermal capacities and conductances of the dynamic multi-nodal model are calibrated against the results taken from the dynamic building simulation model IDA-ICE (Shalin 2003) and validated in a lecture room. The validated dynamic is further used in to calculate design airflow rates of the steady-state and dynamic models are compared. The novelty of his paper is to study the difference between the selected state-state and dynamic displacement model in dynamic conditions. The paper gives an insight into the investment savings potential when dynamic displacement model is introduced.

Methods

This section introduces the methods to evaluate the feasibility of different models in displacement ventilation (DV) design. This section presents steady-state and dynamic design models of DV. The models are first validated with measurements in a lecture hall. Then design airflow rate is analysed in the validated case room with steady-state and dynamic models.

Design models of DV

The studied design DV methods represent the analytical energy balance approach with lumped parameters. These models threat the building room air as an idealised network of air temperature nodes connected with airflow convection conductances (Griffith 2004). In these nodal models, the room surface temperatures are coupled convectively to air temperatures and long-wave radiatively to each other. The transmission heat transfer through the room structures is calculated with RC (Resistance-Capacitance) method (Parnis 2012).

Two steady-state nodal models with different numbers of nodes and heat gain configuration were chosen for the present analysis. The Mundt (Mundt 1996) model estimates linear vertical temperature gradient over the room height (H) between the air temperature along the floor at the height 0.1m ($T_{0.1}$) and the exhaust temperature (T_{ex}) (Figure 1a).

The multi-nodal DV model (Lastovets et al. 2020) calculates the temperature profile composed by variable slopes between the nodes (Figure 1b). This model calculates the height of air temperature stratification (h_{mx}) with the vertical heat gain breakdown. The mixing height is the transition level between a mixed upper layer and stratified layer, which is related to the height where the supply airflow rate matches the airflow induced by the thermal plumes in the occupied zone.

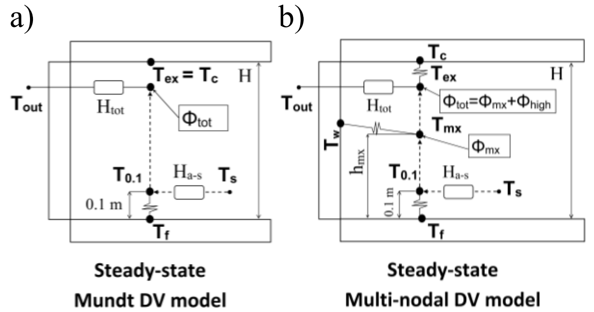


Figure 1: Steady-state displacement ventilation design models.

In the Mundt model, the convective heat flux at the floor is the same as the air temperature increase near the floor from the supply air temperature (T_{sup}) to air temperature at 0.1 height ($T_{0.1}$) (Eq.1). The model assumes that all radiant heat transfer happens only between the floor surface temperature (T_f) and the ceiling surface (T_c). The exhaust air temperature (T_{ex}) is assumed to be the same than ceiling temperature (Eq. 2)

$$H_{a\text{-}s}\cdot(T_{0.1} - T_s) = \alpha_{c,f}\cdot A_f\cdot(T_f - T_{0.1}) \quad (1)$$

$$\alpha_{r,f}\cdot A_f\cdot(T_{ex} - T_f) = \alpha_{c,f}\cdot A_f\cdot(T_f - T_{0.1}) \quad (2)$$

where: $H_{a\text{-}s}$ is the heat conductance of ventilation (W/K); $\alpha_{c,f}$ is the convective heat transfer coefficient at the floor surface ($\alpha_{c,f} = 3$ W/(m^{2}K)); $\alpha_{r,f}$ is the radiative heat transfer coefficient at the floor surface ($\alpha_{r,f} = 5.5$ W/(m^{2}K)); A_f is the floor area (m^2).

The heat conductance of ventilation ($H_{a\text{-}s}$) is calculated from the room air properties and supply airflow rate:

$$H_{a\text{-}s} = \rho\cdot c_p\cdot q_v \quad (3)$$

where ρ is the air density (kg/m^3), q_v is the supply airflow rate, (m^3/s) and c_p is the specific heat of the air (W/(kg·K)).

The exhaust air temperature is calculated from the room air heat balance:

$$H_{a\text{-}s}\cdot(T_{ex} - T_s) + H_{tot}\cdot(T_{ex} - T_{out}) = \Phi_{tot} \quad (4)$$

where Φ_{tot} is the total heat gains (W); H_{tot} is the total conductance of building structures (W/K); T_{out} is the outside air temperature (°C).

The total heat conductance (H_{tot}) determines transmission heat transfer through room structures as follows:

$$H_{tot} = U_{tot} \cdot A_{tot} \quad (5)$$

where U_{tot} is the total U-value of the room structures ($W/(m^2 \cdot K)$) and A_{tot} is the total area of room surfaces (m^2).

The steady-state multi-nodal model calculates three air temperatures at the height of 0.1 m, at the height of the mixed layer (h_{mx}) and the height of the exhaust air temperature that is equal to the room height. The mixing height is calculated with the point source model of plume theory (Kosonen et al. 2017):

$$h_{mx} = \left(k_q^p\right)^{-\frac{3}{5}} \cdot \left(\frac{q_v}{n}\right)^{\frac{3}{5}} \cdot \Phi_c^{-\frac{1}{5}} + h_0^{ver} \qquad (6)$$

where: h_{mx} is the mixing height (m); q_v is a supply airflow rate (m^3/s), Φ_c is a convective heat gain of the vertical buoyancy source (W), n is the number of thermal plumes, h_0^{ver} is a virtual origin height (m), k_q^p is an entrainment coefficient for a point source plume ($k_q^p = 0.005$).

The present study applies the conical correlation with the "minimum" approach (Kosonen et al. 2017) to calculate the virtual origin height above the vertical heat source:

$$h_0^{ver} = H_s - 1.47 \cdot D \qquad (7)$$

where H_s is the height of the heat source (1.1 m) and D is the diameter of the heat source (0.4 m).

Heat gain distribution determines the convection heat transfer connection between the wall surfaces and air nodes. The model consists of the set of three convection and three radiation heat balance equations assuming 50% split between the convective and radiative heat gains. The energy conservation equations for the three model air temperatures are the following (Lastovets et al. 2020):

$$H_{a\text{-}s} \cdot (T_{0.1} - T_s) = \alpha_{c,f} \cdot A_f \cdot (T_f - T_{0.1}) \qquad (8)$$

$$H_{a\text{-}s} \cdot (T_{mx} - T_{0.1}) = \alpha_{c,w} \cdot A_w \cdot (T_w - T_{mx}) + \Phi_{mx} \qquad (9)$$

$$H_{a\text{-}s} \cdot (T_{ex} - T_{mx}) = \alpha_{c,c} \cdot A_c \cdot (T_c - T_{ex}) + \Phi_{high} \qquad (10)$$

where $\alpha_{c,c}$, $\alpha_{c,f}$ and $\alpha_{c,w}$ ($W/(m^2 \cdot °C)$) are the convective heat transfer coefficients of the room surfaces: ceiling, floor and wall surfaces; Φ_{mx} are the convective heat gains under in the occupied zone (W), Φ_{high} are the convective heat gains over the occupied zone (W); T_w is the average temperature of the walls (°C).

The total heat gain (Φ_{tot}) calculated consists of gains located in the occupied zone of the room (Φ_{mx}) and near the ceiling (Φ_{high}):

$$\Phi_{tot} = \Phi_{mx} + \Phi_{high} \qquad (11)$$

The occupied zone heat gains (Φ_{mx}) are usually caused by solar radiation through low or high located windows on the floor, people and office equipment. The gains near the ceiling (Φ_{high}) could be from light fittings, warm high-located windows or solar radiation through windows.

Heat transfer from internal surfaces influences the temperatures of air nodes which are in direct contact with the surfaces. The long-wave radiation between the surfaces is calculated with the mean radiation temperature method (Davies 1990).

The dynamic DV model (Lastovets et al. 2019) represents a hybrid of the room air multi-nodal DV model (Lastovets et al. 2020) and 2-capacity model of building structures (Sirén 2016).

The model calculates dynamic energy balance where the thermal mass of building structures and air capacities are taken into account. The structure of the dynamic DV model (Figure 2) includes thermal capacities of room air (C_a) and building thermal mass (C_m). C_a considers the room air and furniture, while C_m is related to the thermal mass of the building structures (walls, floor and ceiling). In this model, the transmission heat transfer includes the window heat conductance ($H_{a\text{-}out}$) with negligible thermal mass and the total conductance of remaining opaque surfaces (H_{tot}) that is divided into the conductances at both sides of the thermal mass node ($H_{a\text{-}m}$ and $H_{m\text{-}out}$). Both thermal conductances include heat conduction in the solid wall material as well as convection on the surfaces.

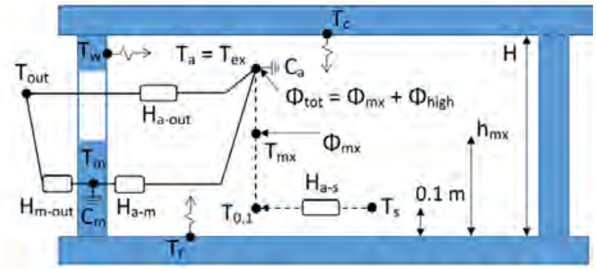


Figure 2: Dynamic design model for displacement ventilation.

The dynamic DV model represents six first-order differential equations to calculate three air and three mass temperatures for the vertical temperature profile (Lastovets et al., 2020). The differential equations can be solved numerically with the explicit Euler method since there is no tendency for numerical oscillations.

Measurements for validation of design DV models

The lecture hall (Lastovets et al. 2020) with the floor area 108 m^2 is located at Aalto University (Espoo, Finland). The room does not have any outdoor walls since it is located in the central part of the second floor of the building. The air is supplied through 50 diffusers located under the seats and extracted from five exhaust grilles. The exhaust grilles are located near the ceiling height (3 m) along the corridor walls (Figure 3).

For measuring air temperatures at different heights from floor to ceiling, the measuring mast was assembled with 20 TinyTag loggers (Gemini Data Loggers 2018). Seventeen TinyTags were located at ten centimetres distance, starting from 0.1 m to 1.7 m, followed by three more loggers at 2 m, 2.5 m and 3 m, respectively.

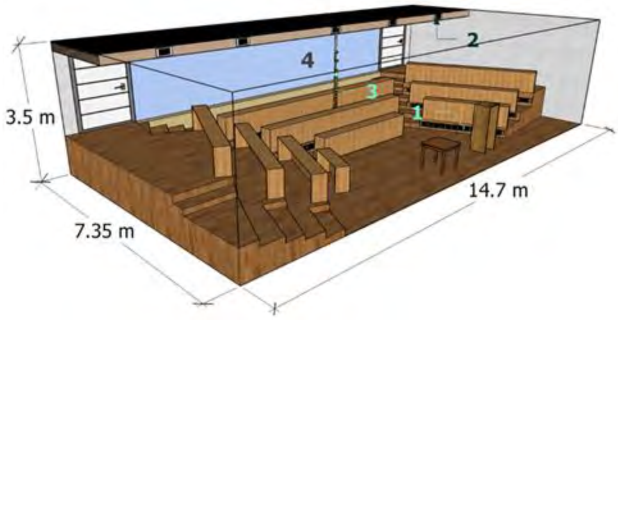


Figure 3: The layout of the lecture hall and the location of the measurement.

Notations: 1 stands for DV diffusers; 2 – exhaust air grilles; 3 – location of the air temperature measurements; 4 – internal glazing.

The lecture hall construction includes internal glazing and remaining heavy concrete opaque surfaces. The internal thermal mass takes into account the furniture in the studied room.

Results

Validation of design DV models

This section presents the validation of the DV design models (Figures 1 and 2) with measurements in the lecture hall (Figure 3) to estimate the capability of the DV models to calculate the occupied zone temperature. The simulation models of both validation spaces were modelled in the building simulation software IDA-ICE to calibrate the thermal capacities C_a and C_m and conductances $H_{m\text{-}out}$ and $H_{a\text{-}m}$ of the dynamic multi-nodal DV model. The calibration method is presented in detail in (Lastovets et al. 2020) publication. The calibration is conducted for fully-mixed conditions, and thus, the air temperature is the same as the exhaust air temperature. The calibration method consists of two phases where steady-state and dynamic set response parameters are separately calibrated. In the calibration, the total conductance H_{tot} is defined in the steady-state parameter identification. The division of this conductance to $H_{m\text{-}out}$ and $H_{a\text{-}m}$ and two capacities C_a and C_m are determined in the dynamic parameter identification.

In the studied cases, the internal heat gains, supply air temperatures, outdoor air temperatures and airflow rates were constant. The total heat gains in both validation cases consisted of the heat gains from occupants and lighting.

The lecture hall had heavyweight concrete building structures and relatively high internal thermal mass (Table 1). The heat gains of sitting people were estimated to be 100 W per person, and the lighting heat gains were 2.5 kW. During the measurements in all cases, the air temperature of neighbouring rooms was constant 21 °C. In all cases, the operation schedule of fans with the design airflow rate was as follows: mechanical cooling with constant supply airflow rate 0.6 m^3/s between 07:30 – 00:50 and the fans were off between 00:50 – 07:30. Table 1 presents the validation cases in the lecture hall.

Table 1: The description of the validation cases in the lecture hall.

Case	Occ. period		№ of occ.	Internal heat gains, kW			T_s °C
	№	time		occ.	light.	tot.	
1	1	1 h 50 min	65	6.5	2.5	9.0	18
	2	1 h 50 min	32	3.2	2.5	5.7	18
2	1	1h 50 min	65	6.5	2.5	9.0	18
	2	50 min	65	6.5	2.5	9.0	18
	3	1h 10 min	58	5.8	2.5	8.3	20

Table 2 presents the calibrated total conductance H_{tot}, conductances $H_{a\text{-}out}$, $H_{a\text{-}m}$ and $H_{m\text{-}out}$ and thermal capacities C_a and C_m of the multi-nodal DV model for the lecture hall.

Table 2: The calibrated parameters of the dynamic DV model in the lecture hall.

H_{tot} (W/K)	$H_{a\text{-}m}$ (W/K)	$H_{m\text{-}out}$ (W/K)	$H_{a\text{-}out}$ (W/K)	C_a (kJ/K)	C_m (kJ/K)
102	1431	110	45	1636	48701

Figure 4 shows the measured and simulated vertical temperature gradients during the validation period. In Figure 4, the heights of the temperatures modelled at $T_{0.1}$, T_{mx} and T_{ex} are marked with dotted lines. Even though multi-nodal modal is more accurate than the linearised Mundt's model in steady-state conditions (Kosonen et al. 2016), in dynamic conditions, both models overestimate the predicted temperature gradient in rooms with DV. It reveals the importance to take into account the dynamic behaviour of the thermal mass in the modelling.

The temperature gradient below 1m height calculated with the Mundt's model was closer to the measurements than the gradient calculated with the steady-state multi-nodal model. However, the dynamic multi-nodal model provided an accurate prediction of the evolution of the vertical air temperature profile at all heights (T_{ex}; T_{mx} and $T_{0.1}$). Also, the room air temperature modelling as a function of time was close to the measured values.

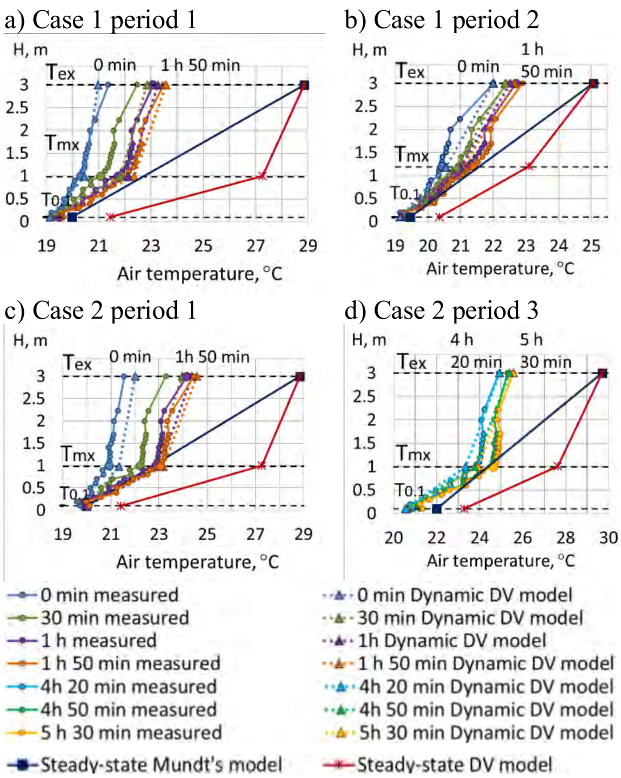


Figure 4: Vertical air temperature gradients measured and calculated with the design DV models

Calculation of the airflow rate with different design DV models

The design airflow rates are calculated with the selected DV models (Figures 1 and 2) for the validated case (Figure 3). In the dynamic DV model, the airflow rate was obtained to fulfil the set of the maximum target room air temperature (25 °C) during the occupied hours (Figure 5).

Since Mundt's model does not take into account the usage profile and thermal mass, it led the same airflow rate of 0.45 m^3/s in the case analysed (Table 3). The steady-state multi-nodal DV model taking into account the heat gain breakdown calculates the airflow rate of 0.77 m^3/s. Thus, the linear Mundt's model provided a 41% lower design airflow rate than a more detailed steady-state multi-nodal model. However, it should be emphasised that the Mundt's model underestimates the airflow rate required in steady-state conditions, and the target room air temperature cannot be achieved at the occupied zone. In those steady-state conditions, the multi-nodal model is more accurate than Mundt's model (Kosonen et al., 2016). In addition to considering the heat gain breakdown, the dynamic multi-nodal DV model provided different values of airflow rates depending on the effects of thermal mass and varied heat loads during operation time. The dynamic multi-nodal DV model calculated the lowest airflow rate of 0.34 m^3/s, quarter lower than with Mundt's model and almost twice lower than the steady-state multi-nodal model calculated (Table 3). It indicates that the thermal mass and dynamic usage profile are playing a significant role in the determination of the design airflow rate.

Table 3: Design airflow rates of three different calculation models.

Case	Airflow rate with different DV design models, m^3/s		
	Steady-state Mundt's model	**Steady-state multi-nodal model**	**Dynamic DV model**
Case 1 period 1	0.45	0.77	0.34
Case 2 period 3	0.57	0.95	0.43

Figure 5 presents the dynamic changes in air temperature in the occupied zone in the calculation of the designed airflow rate. In the steady-state models, the design occupied zone temperature remains the same. In Case 1 (Figure 5a), the first occupied period with higher heat gains is determining in the airflow rate calculations. In Case 2 with more extended occupancy period, the highest temperature is at the end of the occupied period.

a)

b)

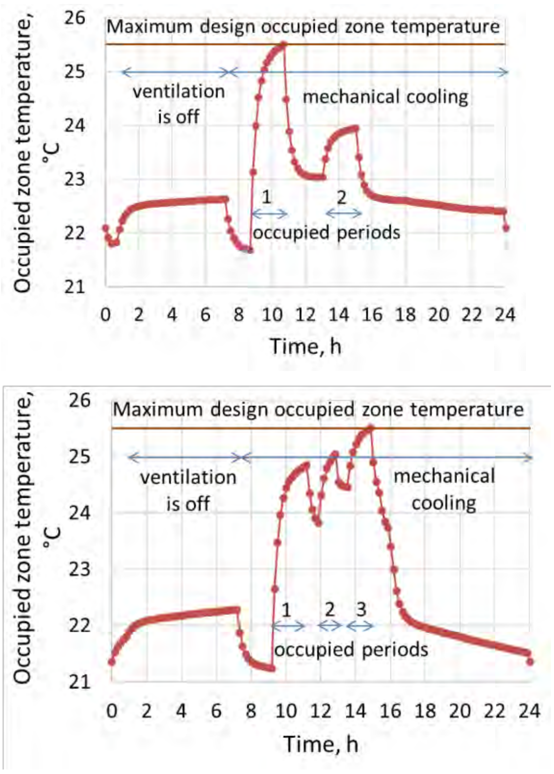


Figure 5: Room air temperatures at the occupied zone with the dynamic DV multi-nodal model for Case 1 (a) and Case 2 (b).

Discussion

In the existing DV design practice, the supply airflow rate is calculated with either the heat balance method or air quality-based methods (Kosonen et al. 2017). The air quality-based design by applying thermal plume theory is only used in industrial types of applications where high exit contaminant loads. In non-industrial premises, e.g. in theatres, design practice it is based on the minimum airflow rate per person of local building codes (e.g. 6 l/s). Heat balance method as the most method in DV design is applied in rooms where room air temperature in the occupied zone is the primary design criterion. In this case, the airflow rate is usually calculated with steady-state models. In some cases, the steady-state heat balance method overestimates the design airflow rate (Lastovets et al., 2020).

Even though some building energy simulation software (e.g., EnergyPlus and IDA ICE) include the model of the thermal environment with displacement ventilation, they are limited to the specific system configuration (Citherlet et al. 2001). In addition, the utilisation of those models requires prior knowledge of both the indoor thermal environment simulation and building energy simulation, which could be a challenge to a building energy engineer.

The commonly used models to design displacement ventilation are based on steady-state temperature gradient calculation with simplified nodal models, among which the multi-nodal models are the most accurate (Kosonen et al. 2016 and Lastovets et al. 2019). However, for accurate design, these models are insufficient in the estimation of room air temperatures due to the missing effect of thermal mass and varied heat loads during operation time. Steady-state approach and neglecting the dynamic behaviour of heat loads and thermal mass could lead to significant overestimation of the required airflow rate. Thus, the dynamic approach is appreciated in the DV system design.

The presented dynamic DV model predicts the dynamic behaviour of the thermal mass and room air vertical temperature gradient with a proper level of accuracy. However, this model has certain limitations. Since all internal mass, such as floors, walls and furniture, are presented in the model as one entity, it is not able to take into account different thermal properties of individual structures. On the other hand, it could be assumed that in a typical application, it would not significantly affect the thermal behaviour. The dynamic DV model is able to predict within reasonable accuracy the thermal behaviour of typical buildings where the only relatively small active thickness of the structure interacts with the regularly varied heat gains.

In steady-state conditions, Mundt's linearised model underestimates occupied zone air temperature by up to 3 °C and provides unrealistic vertical air temperature profile (Kosonen et al. 2016). However, in the cases with significant lighting heat loads and short occupied period, Mundt's model calculates close airflow rate to the dynamic DV model.

Since the premises with DV are usually not occupied continuously, the dynamic model of room air vertical temperature gradient is appreciated in DV design. The possible application of the presented dynamic DV model is in the rooms where different dynamic factors, such as heat gain variation, location and type of heat gains and building thermal mass have a different effect on indoor thermal conditions. Typical applications are in concert halls that are occupied for a short time and in lobbies that are influenced by highly varied internal heat loads and solar radiation.

Conclusion

The estimation of the vertical temperature gradient reflects airflow rate calculation and thermal comfort estimation in rooms with displacement ventilation (DV). At the moment, it is common to use a steady-state model that is not taken into account occupancy profiles and thermal mass. In this study, two steady-state and one dynamic DV model were validated with measurements in terms of accuracy and dynamics of room air temperature changes in different vertical levels in the lecture hall. Besides, the design airflow rate was calculated with different models in both dynamic and steady-state conditions in the validated case. In the case analysed, the airflow rate calculated with the dynamic DV model is significantly lower than the airflow rate calculated with the steady-state DV models.

The dynamic model can significantly decrease the design airflow rate of DV, which can result in a reduction of investment costs and electrical consumption of fans. The presented calibrated multi-nodal dynamic DV model is able to take into account varied heat loads and the effect of building thermal mass within good accuracy. The dynamic DV model can be applied in DV design with various applications where heat gains varied, and thermal mass is playing a significant role. The model has good robustness to predict thermal performance under different operation conditions.

Acknowledgement

The authors are grateful for the funding provided by the School of Engineering of Aalto University. Special thanks to Aalto University Properties (ACRE) and Fidelix Oy for the assistance with the measurements and the arrangement of the measurement setup.

References

Arens, A.D. (2000). Evaluation of displacement ventilation for use in high-ceiling facilities. Master thesis, Massachusetts Institute of Technology (USA) Available at https://dspace.mit.edu/handle/1721.1/9305. Accessed 05 May 2020.

Cheng, Y., Niu, J., Gao, N. (2012). Stratified air distribution systems in a large lecture theatre: A numerical method to optimise thermal comfort and maximise energy saving. *Energy and Buildings 55*, 515–525.

Citherlet, S., Clarke, J.A., Hand, J. (2001). Integration in building physics simulation. *Energy and Buildings, 33*, 445-461.

da Graça, G.C.C. (2003). *Simplified models for heat transfer in rooms*. Doctoral dissertation, University of California, San Diego.

Davies, M.G. (1990). Room heat needs in relation to comfort temperature: Simplified calculation methods. *Building Services Engineering Research and Technology 11*, 129–139.

Griffith, B., Chen, Q.Y. (2004). Framework for coupling room air models to heat balance model load and energy calculations (RP-1222). *Hvac&R Research 10*, 91–111.

Kosonen, R., Lastovets, N., Mustakallio, P., da Graça, G. C., Mateus, N. M., Rosenqvist, M. (2016). The effect of typical buoyant flow elements and heat load combinations on room air temperature profile with displacement ventilation. *Building and Environment 108*, 207–219.

Kosonen, R., Melikov, A., Mundt, E., Mustakallio, P., Nielsen PV (2017). *Displacement Ventilation, REHVA Guidebook No 23*. Forssa: Federation of European Heating and Air-Conditioning Associations.

Lastovets N, Kosonen R, Jokisalo J, Kilpeläinen S (2019). Dynamic design model of displacement ventilation. Proceedings from *CLIMA 2019*. Bucharest (Romania), 26-29 May.

Lastovets N, Kosonen R, Mustakallio P, Jokisalo J, Li A (2020). Modelling of room air temperature profile with displacement ventilation. *International Journal of Ventilation 19*, 112–126.

Lau, J. and Niu, J.L. (2003). Measurement and CFD simulation of the temperature stratification in an atrium using a floor level air supply method. *Indoor and Built Environment 12*, 265–280.

Li, Y., Sandberg, M., Fuchs, L. (1992). Vertical temperature profiles in rooms ventilated by displacement: Full-scale measurement and nodal modelling. *Indoor Air 2*, 225–243.

Liang. C., Shao, X., Melikov, A.K., Li, X. (2018). Cooling load for the design of air terminals in a general non-uniform indoor environment oriented to local requirements. *Energy and Buildings 174*, 603–618.

Mateus, N.M. and da Graça, G.C. (2015). A validated three-node model for displacement ventilation. *Building and Environment 84*, 50–59.

Mateus, N.M. and da Graça, G.C. (2017). Simulated and measured performance of displacement ventilation systems in large rooms. *Building and Environment 114*, 470–482.

Mateus, N.M., Simoes, G.N., Lúcio, C., da Graca, G.C. (2016). Comparison of measured and simulated performance of natural displacement ventilation systems for classrooms. *Energy and Buildings 133*, 185–196.

Mundt, E. (1995). Displacement ventilation systems – Convection flows and temperature gradients. *Building and Environment 22*, 129–133.

Nielsen, P.V. (2003). Temperature and air velocity distribution in rooms ventilated by Displacement ventilation. *Proceedings from the 7th International Symposium on Ventilation for Contaminant Control (Ventilation 2003)*. Sapporo (Japan), 5 – 8 August.

Parnis, G. (2012). *Building Thermal Modelling Using Electric Circuit Simulation*. Ph.D thesis, University of New South Wales. Sydney (Australia).

Shalin, P. (2003). On the effects of decoupling air flow and heat balance in building simulation models. *ASHRAE Transactions 109*, 788–800.

Sirén, K. (2016). *Course material: A simple model for the dynamic computation of building heating and cooling demand*. Espoo (Finland): Aalto University (2016) Available at: https://mycourses.aalto.fi/pluginfile.php/317972/mod_resource/content/1/Building%20energy%20calculation_Sep_2016.pdf. Assessed 30.03.2020.

Skistad, H. (1994). *Displacement Ventilation*. Somerset, England: Research Studies Press Ltd.

International Organisation for Standardisation (2008). *Energy Performance of Buildings-Calculation of Energy Use for Space Heating and Cooling* (ISO 13790: 2008). ISO Central Secretariat: Geneva, Switzerland.

Yuan, X., Chen, Q., Glicksman, L.R. (1999). Models for prediction of temperature difference and ventilation effectiveness with displacement ventilation. *ASHRAE Transactions* 105, 353–367.

Yang L. and Li, Y. (2008). Cooling load reduction by using thermal mass and night ventilation. *Energy and buildings 40*, 2052–2058.

Zhai, Z., Chen, Q.Y. (2003). Solution characters of iterative coupling between energy simulation and CFD programs. *Energy and buildings 35*, 493–505.

Zhang S., Cheng, Y., Huan, C., Lin Z. (2018). Heat removal efficiency based multi-node model for both stratum ventilation and displacement ventilation. *Building and Environment 143*, 24–35.

Zhang, S., Cheng, Y., Huan, C., Lin Z. (2019). Equivalent room air temperature based cooling load estimation method for stratum ventilation and displacement ventilation. *Building and Environment 148*, 67–81.