# Influence of office layout and ceiling height on vertical temperature gradient in office rooms with displacement ventilation

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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 supply air flow rate. Several simplified nodal models were developed and implemented in the various building simulation programmes in order to estimate the temperature stratification in rooms with displacement ventilation. However, the most commonly used models do not count the types and locations of the typical heat loads in rooms with displacement ventilation. As a result, the calculated air temperature in the occupied zone can defer from the real one, which causes poor thermal comfort and inadequate sizing of the ventilation system.

In the present study, five simplified nodal models are analysed and validated with the experimental results in two measurement setups. In addition, the effect of the room heights and locations of the indoor heat sources were studied for the typical office environment. The experiments demonstrate that displacement ventilation provides even temperature gradient throughout the simulated office room spaces. The influence of the room height on the vertical temperature gradient is significant in the cases with high-level heat loads. The novel nodal model demonstrates an accurate calculation of the temperature gradient for the typical heat loads office layouts.

## KEYWORDS

Displacement ventilation, thermal plume, mixing height, nodal model, temperature gradient

## 1 INTRODUCTION

Displacement ventilation (DV) was first implemented in industrial buildings in order to take its benefit of creating acceptable condition in occupied zone of industrial premises. Recently this air-distribution strategy has gained extensive use in commercial buildings. Depending on the space requirements two types of design methods are being used. Temperature based design method is used when indoor heat sources are the main source of contaminants and cooling requirements are important. In industrial applications air quality based design is typically applied, where the design criteria is air quality and contaminant is let to stratify over the occupied zone (Kosonen et al, 2017). In this paper, the focus on commercial buildings and thermal comfort is the main concern.

Nodal models are the analytical energy balance models with lumped parameters that treat the building room air as an idealized network of nodes connected with flow paths. They are widely applied in building design because of their simplicity, flexibility and applicability (Griffith, 2002). They differ in the number of nodes, flow and heat load configuration and mixing height consideration. The models with two air nodes (Mundt, 1996; Li, 1992; Arens, 2000) predict the linear slope between the air nodes near the floor and exhaust one.

The multi-nodal models introduce the temperature profile composed by variable slopes between the nodes. These models can use precalculated air flow rates (Rees, 2001) or empirical coefficients (Mateus et al, 2015; Chen, 1999) to predict the air-temperature distribution and the division of the heat loads. The stratification or mixing height calculation is essential for all the multi-nodal models. It can be found from the plume theory (Hunt, 2011) as a height where the air flow rate of the plume is equal to the room air flow rate. The mixing height calculation is applied in the simplified three-nodal model proposed by Mateus and da Graca (Mateus et. al., 2015) and novel nodal model (Lastovets et al., 2018). Several nodal models are currently available in thermal energy simulation tools. The Mundt and the Mateus and da Graça models are implemented in EnergyPlus and the Mundt model is also available in IDA ICE.

The most of the experimental studies of DV in commercial buildings were conducted for limited amount of internal heat loads in laboratories with room height up to 3 m (Arens et al., 2000). Whereas, the typical application of DV systems are high-ceiling room with various heat load sources. Moreover, current simplified models for DV design, including 50%-rule for the vertical temperature distribution, were developed and validated with the use of these limited experimental results. The results for low-ceiling rooms were applied in dimensionless form. However, measurements depict that modelled non-dimensional temperature profile with low ceiling height is not valid with high ceiling applications (Kosonen et al., 2015). Therefore, there is a need to check the effect of different ceiling height on the temperature gradient in rooms with different heights.

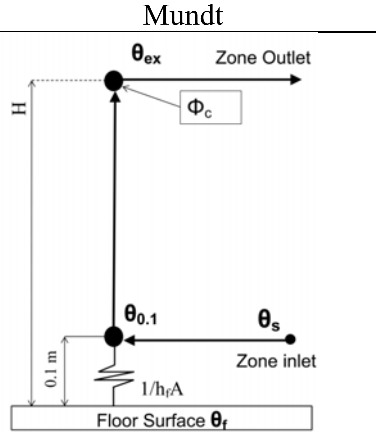
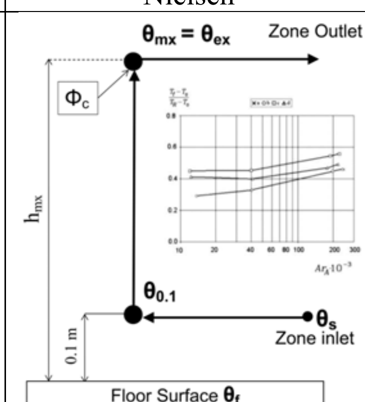
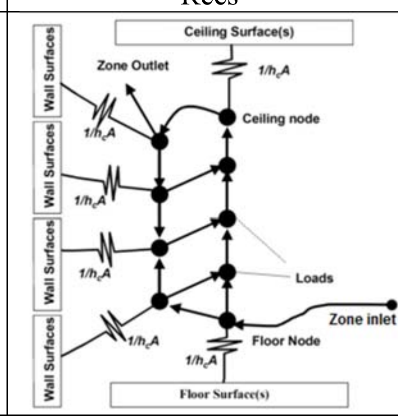
In addition, all the current nodal models have been validated only for the simple heat load configurations and room layout. Therefore, considering the limitation of simplified models to predict temperatures in space, the model needs to be validated with temperature measurements in different part of the room with DV.

## 2 METHODS

The study utilises experimental and analytical methods. The simplified nodal models are analysed and validated with the experimental results in two measurement setups in order to evaluate the effect of different types and locations of heat loads, room height and office layout on the temperature gradient calculation in rooms with displacement ventilation.

### 2.1 Simplified nodal models

Five nodal models with different approaches were chosen to be analysed and compared with the proposed one: the Mundt, the Nielsen, the Rees, the Mateus and Novel nodal model (Fig. 1).

| Mundt | Nielsen | Rees |
|---|---|---|
|  |  |  |
| Mateus | Novel nodal model | |

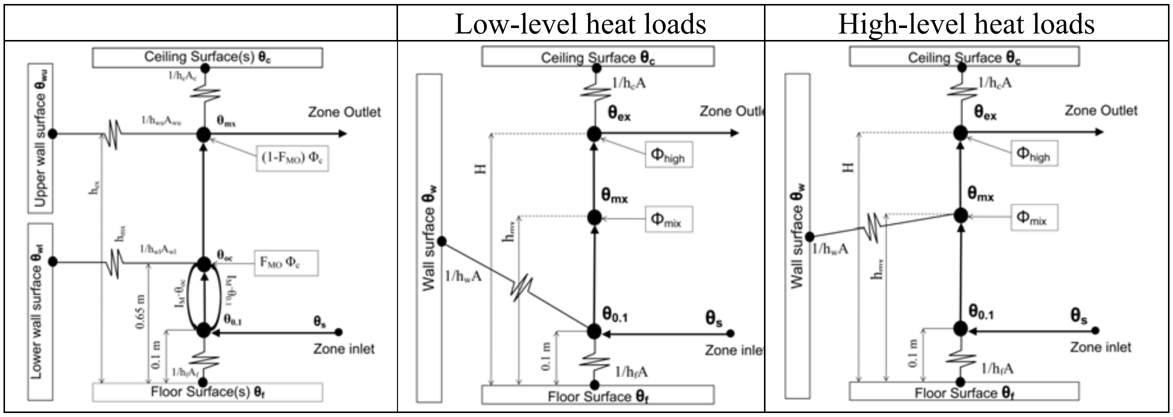



Figure 1. Simplified nodal models to calculate a temperature gradient in rooms with DV

Mundt (Mundt, 1996) proposed the 2-nodal model where temperature gradient is calculated to be linear over the room height. In this model the radiative energy flux from the floor is balanced by convective heat transfer from the floor surface to the air.

In the Nielsen model (Nielsen 2003) the linear vertical temperature gradient between floor and the height of mixing layer is predicted with Archimedes number and the type of heat load. The mixing height is calculated for a point source in stratified environment.

The alternative approach to consider the flow patterns between nodes was developed by Rees and Haves (Rees at al., 2001). The model includes 11 interrelated nodes: 4 room air nodes out of the thermal plume, 4 nodes of the air flow within the plume and 3 surface nodes representing floor, ceiling and wall temperatures. In addition, this model uses 14 flow paths between the nodes with flow rate parameters that are predetermined by experimental and numerical studies.

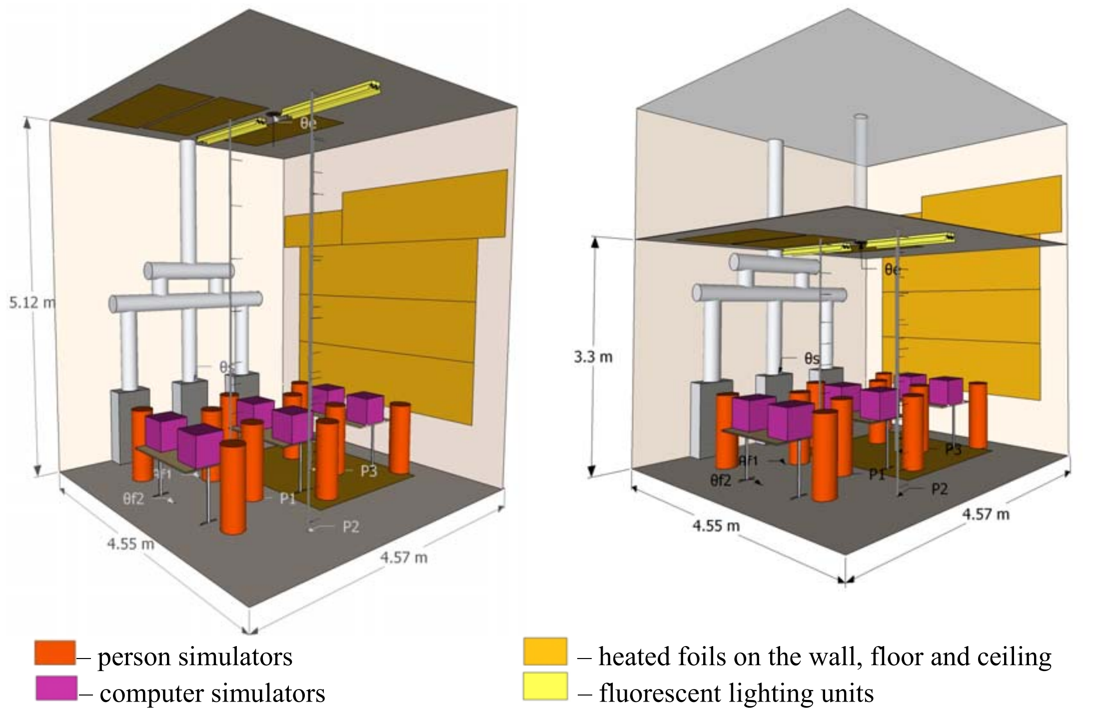
A simplified three-nodal model was proposed by Mateus and da Graca (Mateus et. al., 2015) with the use of load separation and low zone mixing factor. In addition, this model calculates the temperatures of wall surfaces: floor, ceiling, high and low levels of the walls.

Novel nodal model (Lastovets et al., 2018) predicts room air temperature at three heights: 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. Heat load distribution determines the convection heat transfer connection between the wall and air nodes. Low heat loads are considered to be the ones that occur in the occupied zone of the room. The mixing height calculation in this model depends on the type of the main flow element. The model consists of the set of 3 convection and 3 radiation heat balance equations assuming 50% split between the convective and radiative heat loads.

Thus, five analytical methods that use different semi-empirical correlation to estimate the temperature gradient for the displacement ventilation design are chosen to be validated with the experimental results introduced below.

## 2.2 Experimental setup

The test setup to check the novel model calculation in rooms with different flow elements consists of displacement diffusers with perforated front face and ceiling exhaust in well-insulated room with 20.8 $m^2$ floor area and room heights of 5.12 m and 3.33 m. The case with lower height was organized so that whole ceiling was moved down together with the exhaust diffuser, heated foils and light units (Fig. 2).




Measurement points: P1, P2, P3 – room air temperatures; θf1, θf2 – floor surface temperatures; θs – supply air temperature; θe – exhaust air temperature

Figure 2. Measurement setup to study the effect of different room heights and heat loads

The internal heat loads (Table 1) consist of heated cylinders representing persons, heated cube-shaped boxes representing computers, heated foils in one wall and ceiling representing solar load on window at different levels and fluorescent lighting units.

Table 1. Measured cases with different heat load combinations

| Case | | Heat loads, W | | | | | | Total heat loadsW | Supply temperature, room height 5.12/3.3 m °C | Supply air flow rate $m^3/s$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Heated Cylinders | Heated Boxes | Foils on the wall | Foils on the floor | Foils on the ceiling | Lighting units | | | |
| h) | 10 people, window* and floor heat loads, lighting | 750 | – | 520 | 260 | – | 232 | 1762 | 15.9 | 0.1 |
| | | | | | | | | | 18.1 | |
| j) | 10 people, ceiling heat loads, lighting | 750 | – | – | – | 466 | 232 | 1448 | 16.7 | 0.1 |
| | | | | | | | | | 17.7 | |

* Window height 3.6 m at initial level of 0.8 m over the floor

The temperature profiles are measured from four locations (P1-P4 in Fig.2) at ten heights with calibrated PT100 sensors (accuracy ± 0.2 °C). Surface temperatures were measured with Testo 830-TI-infrared thermometer (accuracy ± 0.1 °C). Supply and exhaust air flows were measured with air flow rate measurement device MSD 100, that was calibrated with an orifice plate to reach the accuracy ±3%.

In addition, the model was validated with the experimental results published by Arens (Arens, 2000) for open-plan and cubicle-style office arrangements.

The test room layout is shown in the Figure 3. The open-plan office case was measured with the partitions dividing the workplace, whereas the cubicle-style office includes them. The supply air is delivered from two opposing air distributors, whereas the exhaust grille is located overhead to the right at height of 5 m. The internal heat loads were modelled by rectangular person and computer simulators and 3 rows of lighting units. The room height is 6.5 m, whereas the fluorescent lighting fixtures were located 3.8 m above the floor. Air temperature measurements were conducted with 0.6 mm diameter copper-constantan thermocouples with a ± 0.2 °C accuracy at each of the ten positions indicated during each test.

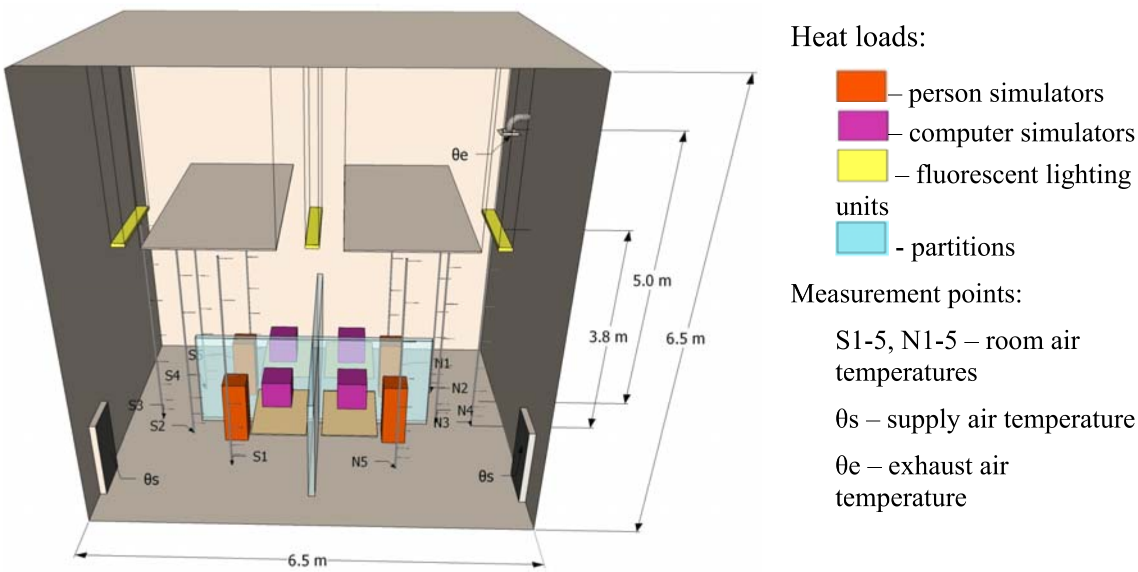



Figure 3. Measurement setup to study the effect of different room heights and heat loads

Table 2. Measured buoyant flow elements and heat load combinations

| Case | Heat loads, W | | | Total heat loads | Averaged supply temperature | Supply air flow rate |
|---|---|---|---|---|---|---|
| | Heated rectangular-shaped boxes | Heated square-shaped boxes | Lighting units | W | °C | $m^3/s$ |
| Open-plane office, Cubicle-style office<br>4 people, 4 computers, lighting units | 360 | 300 | 732 | 1392 | 15.5 | 0.18 |

Thus, the validation of the model was conducted for rooms with different layout and typical heat loads in commercial building.

## 3 RESULTS

The measured data of the temperature gradient for the typical indoor heat loads (Table 1, 2) were compared with the calculation results of the selected simplified nodal models: the Mundt, the Nielsen, the Mateus, the Rees and Novel nodal model. The results of the corresponding measurements and calculations are presented at the Figure 4.

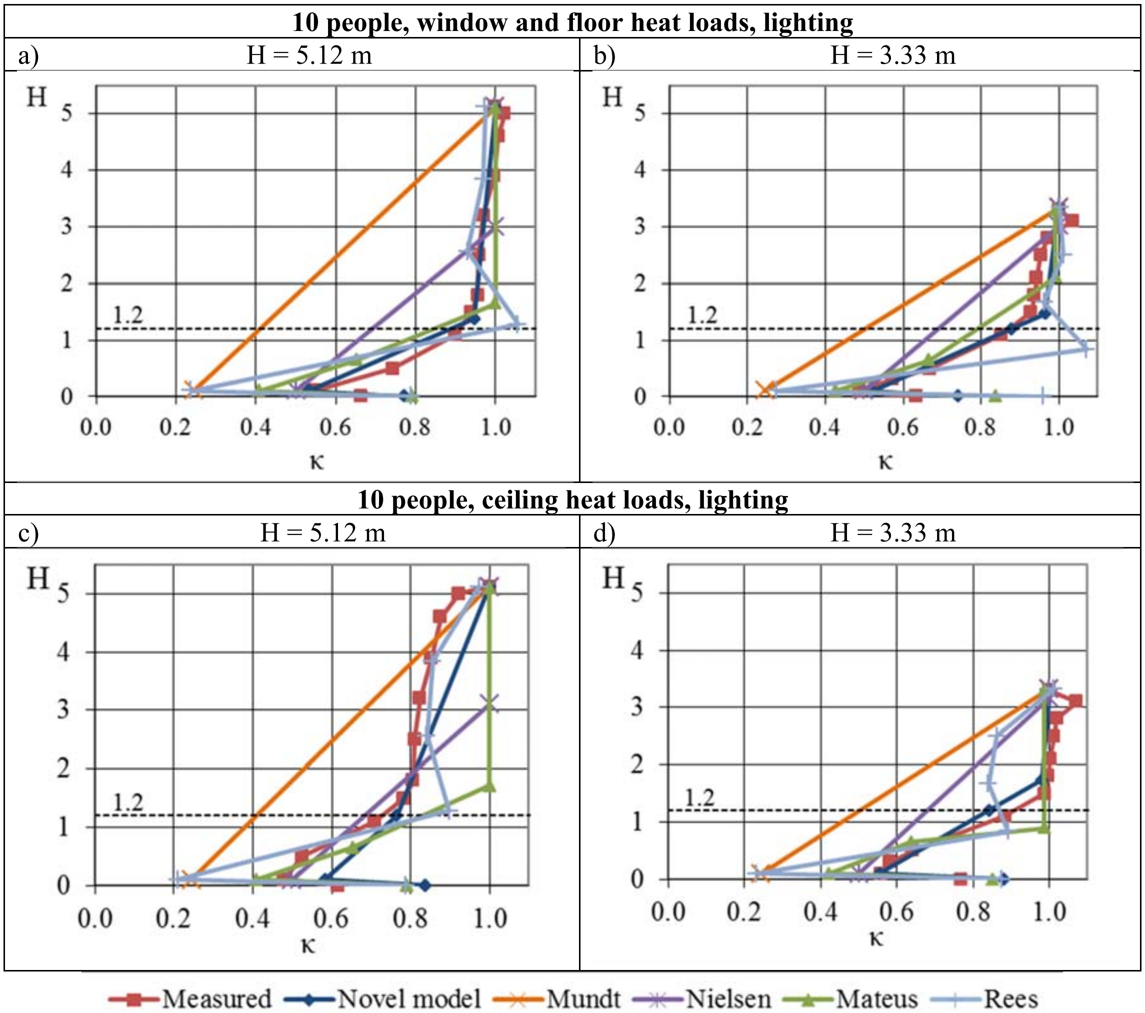



Figure 4. Measured and modelled temperature gradients for the rooms with different heights and heat loads

In the cases with low level heat sources the major part the gradient exists in the occupied zone regardless of the room height (Fig.4 a,b). The influence of the room height on the vertical temperature gradient is essential in the cases with high-level heat loads, when the temperature tends to stratify over the mixing level due to the increased air mixing in this level (Fig.4 c,d).
An arrangement of office layout affects the thermal stratification in rooms with DV only in low zones of the room. Despite the fact that the vertical temperature gradients tend to be similar throughout the room, the office furniture that prevents even air distribution slightlyincreases unevenness of temperature stratification (Fig.5). However, these temperature differences are negligible for the DV design calculations. Therefore, the average temperature gradients are relevant for all the treated cases.

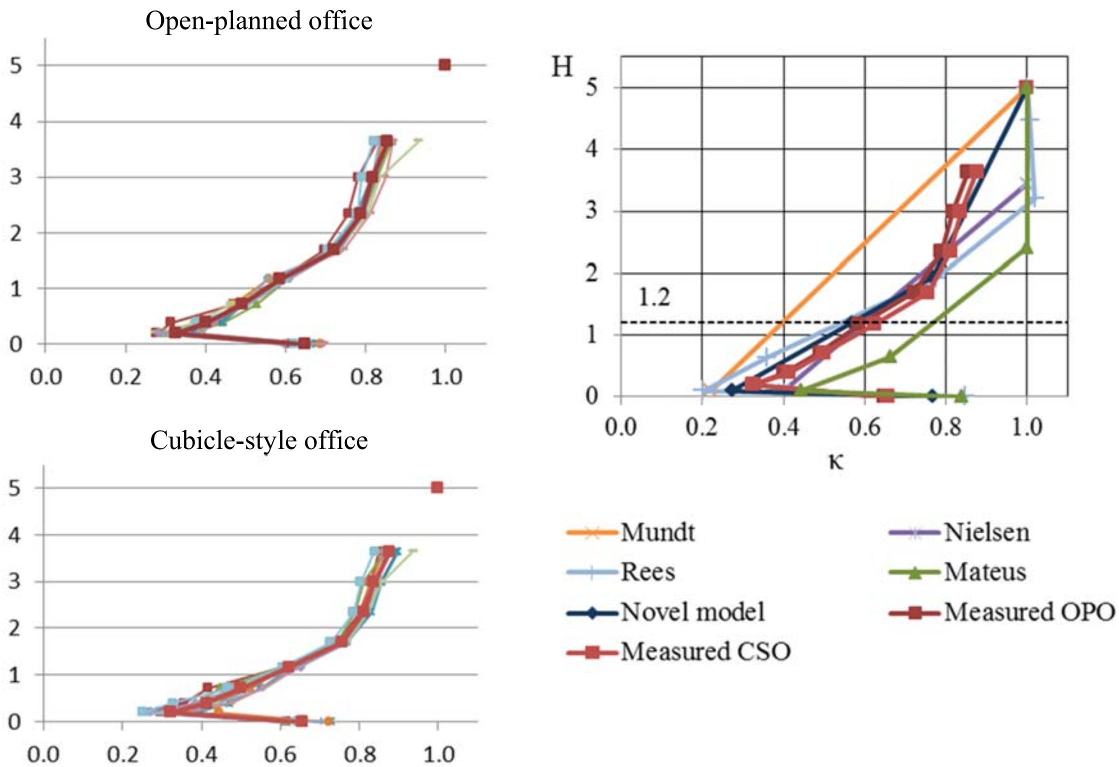



Figure 5. Measured and modelled temperature gradients in different place of the room

The two-nodal Mundt model is not able to calculate the temperature gradient for all the cases. The occupied zone temperature at the height 1.2 m calculates by the Mundt model was roughly 3°C lower than the measured one. The Nielsen model is able to predict the temperature near the floor; however it overestimates the mixing height level.
The Rees model in some cases (a, c) demonstrates the ability to follow the curve of the gradient. However, the recommended (Rees et al, 2001) air capasities do not suit in all the combinations of internal heat loads. Thus, it requires precalculation of air capasities in every complicated case.
The Mateus and the novel nodal models demonstrate accurate temperature gradient prediction in the cases with low level heat loads (Fig. 4 a,b). However, in the cases with high level heat gains, such as heated ceiling, high window and computers, the Mateus model overestimates the temperature in the occupied zone of the room, since it does not assume the gradient upper the mixing height (Fig. 4 c, Fig, 5).
Heat load distribution in Novel nodal model conduces to a better temperature prediction in the cases of high-level heat loads (Fig. 4 c, Fig, 5) loads.

## 4 CONCLUSIONS

The simplified nodal models are analysed and validated with the experimental results in two measurement setups in order to evaluate the effect of different types and locations of heat loads, room height and office layout on the temperature gradient calculation in rooms with displacement ventilation. In all the treated cases displacement ventilation provides even temperature gradient throughout the simulated office room spaces. Heat load distribution and accurate mixing height calculation are the most essential factors to predict the temperature stratification for the DV design conditions. Two-nodal model is not able to count these factors. Among the multi-nodal models Mateus and Novel nodal model demonstrate the closest temperature gradient prediction. Novel nodal model is able to accurately calculate the all temperatures for all the typical room heights and indoor loads.

## 5 ACKNOWLEDGEMENTS

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