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Published in:
Proceedings Roomvent & Ventilation 2018

Published: 01/06/2018

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
COMPARISON OF SIMPLIFIED MODELS TO ESTIMATE VERTICAL TEMPERATURE GRADIENT IN ROOMS WITH DISPLACEMENT VENTILATION

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SUMMARY

Vertical temperature gradient prediction is essential for displacement ventilation 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 error between the calculated with the commonly used models and measured temperature in the occupied zone can reach 2-3°C. It results in poor thermal comfort and inadequate sizing of the displacement ventilation system.

The aim of the study is to compare four commonly used simplified models and a novel nodal model to calculate the temperature gradient in a room with various single flow elements and combinations of them. The measurement data were compared with the existing nodal models and the proposed novel nodal model in terms of predicting the occupied zone temperatures. The proposed nodal model provides a simplified and accurate technique to predict the temperature gradient for typical indoor heat loads.

Keywords: displacement ventilation, thermal plume, mixing height, nodal model, temperature gradient

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 room air temperature profile, stratified and mixed, is developed. Ideally, the air movements induced by thermal plumes transport heat and pollutants to the layer above 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.

Two different approaches are applied to control the supply airflow rate: a temperature based design where the design criterion is the room air temperature in the occupied zone; and an air quality based design where the design criterion is contaminant level over the occupied zone. An air quality based approach is typically used in industrial applications where the contaminant stratification is significant for DV design. In commercial buildings where the thermal comfort is the main issue, the temperature based design is the most common method. The present research focuses on commercial buildings where the temperature gradient calculation is applied to calculate an air flow rate of DV systems.

Nodal models treat the thermal stratification of the indoor air as an idealised network of nodes connected with flow paths. Such models vary according to the application, number of nodes, flow and
heat load configuration and mixing height consideration. The most common linear temperature modelling with two room air nodes has been proposed by Mundt (Mundt, 1996). The multi nodal models that introduced the temperature profile composed by variable slopes between three nodes were proposed by Nielsen (Nielsen, 2003) and Mateus and da Graça (Mateus at al.,2015). Several nodal models are currently available in thermal energy simulation tools. Mundt and Mateus and da Graça models are implemented in EnergyPlus and Mundt model is also available in IDA ICE.

The multi-node models usually provide the accurate temperature gradient prediction. However, for cases with high level flow elements, which are typical for commercial spaces, all the current models provide the incorrect results. In addition, the distribution of heat loads between the nodes still needs a deeper comprehension for better gradient prediction. The new model, proposed in the present study, is developed and validated as a result of comparison and reconsideration of current nodal models.

2 METHODS

Two-nodal models are not able to predict the temperature gradient, which is logical considering two-layer structure of the room with DV. The layer that divides is called a mixing height. It can be found from the plume theory as a height where the air flow rate of the plume is equal to the room air flow rate.

2.1 Plume theory methods to calculate the mixing height

Since fluid flow in displacement ventilation is driven by convective flows from the heat sources, plume theory is widely applied in the temperature gradient calculation. The sources of indoor heat loads normally differ in geometrical shape, heat loss and location. Plumes in rooms are most commonly have a circular cross-section, since heat sources are three-dimensional. Therefore, point source method can be applied to the heat sources close to cylindrical and rectangular shape:

\[
h_{mx}^{ver} = 23.5 \cdot \left(\frac{q_v}{n}\right)^{\frac{3}{5}} \cdot \Phi_c^{-\frac{1}{5}} + h_{0}^{ver}
\]

where: \(q_v\) – volume flux (m\(^3\)/s), \(\Phi_c\) – convective heat (W), \(n\) – amount of plumes, \(h_{0}^{ver}\) – virtual origin height (m).

The location of the virtual point source is dependent on geometrical parameters of the source and model of virtual origin correction. In the case of vertical heat source conical correction with the opening angle 25\(^\circ\) and 80\% of the source diameter (Skistad, 1994) is applied:

\[
h_{0}^{ver} = H_s - 1.47 \cdot D_s
\]

where: \(H_s\) and \(D_s\) are correspondently the height and the diameter of the source (m).

To calculate the thermal plume from the rectangular source, the diameter is replaced by hydraulic diameter of the top of the source.

The plume height in the case horizontal heated surfaces is dependent on the shape of this source. The point source formulae better works with round shape sources or the rectangular ones with the aspect ratio greater than 2 (Devienne et al., 2012):

\[
h_{mx}^{hor} = 23.5 \cdot \left(\frac{q_v}{n}\right)^{\frac{3}{5}} \cdot \Phi_c^{-\frac{1}{5}} + h_{0}^{hor}
\]

In the case when the aspect ratio in less than 2, the formulae corresponding to a linear source must be considered:

\[
h_{mx}^{hor} = 85.5 \cdot q_v \cdot (l)^{-\frac{2}{3}} \cdot \Phi_c^{-\frac{1}{3}} + h_{0}^{hor}
\]

where: \(l\) – length of the source (m).
The virtual origin for the horizontal area source of buoyancy still is a subject of the various studies, the most of which agree with the following correlation:

$$h_{mx}^{hor} = 2.2 \cdot D_s/2$$  \hspace{1cm} (5)

The mixing height from the convection vertical surface usually happens in a high zone of a room. However, first temperature near the heated vertical surface happens due to the flow transition from laminar to turbulent regime (Cooper et al., 2001). The transition level can be estimated considering the condition for changing the flow regime: $Gr \cdot Pr = 7 \cdot 10^8$:

$$h_{tr}^{surf} = \left( \frac{7 \cdot 10^8 \cdot \nu \cdot k}{g \cdot \beta \cdot (\theta_w - \theta_{sur}) \cdot c_p \cdot \rho} \right)^{1/3} + H_w$$  \hspace{1cm} (6)

where: $\nu$ - kinematic viscosity (m$^2$/s); $k$ – thermal conductivity (W/(m·K)); $g$ – gravity acceleration (m/c$^2$); $\theta_w$ – temperature of the window surface (°C); $\theta_{sur}$ – surrounding temperature (°C); $c_p$ – heat capacity (W/(m²·°C)); $H_w$ – height of the bottom of the window (m).

When several types of heat sources are located in the room with DV, the mixing height is obtained using the weight factors of the corresponding heat loads:

$$h_{mx} = h_{mx}^{hor} \cdot \frac{\Phi_{c}}{\Phi_{c}} + h_{mx}^{ver} \cdot \frac{\Phi_{c}}{\Phi_{c}} + h_{tr}^{surf} \cdot \frac{\Phi_{c}}{\Phi_{c}}$$  \hspace{1cm} (7)

Thus, the mixing height of the room can be found for all the typical heat sources.

### 2.2 Nodal models to predict the temperature gradient

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. They differ in the number of nodes, flow and heat load configuration and mixing height consideration. Three nodal models with different approaches were chosen to be analysed and compared with the proposed one: Mundt, Nilsen and Mateus 3-nodal model.

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 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 gain. The mixing height is calculated for a point source in stratified environment. A simplified three-nodal modal 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.

The novel nodal model (Fig.1) predicts room air temperature at four heights: at the height of 0.1 m, at the height of the mixed layer (hmx) 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. The model consists of the set of 3 convection and 3 radiation heat balance equations assuming 50% split between convective and radiative heat loads.
Figure 1. Novel modal model scheme. a) The most of heat loads located in the lower zone of the room; b) The most of heat loads located in the upper zone of the room.

Therefore, the proposed novel nodal model increases modelling accuracy by reconsidering mixing height calculation and high level heat loads.

2.3 Validation of the nodal models

The test setup consists of displacement diffusers with perforated front face and ceiling exhaust in well-insulated room with 20.8 m² floor area and room height of 5.12 m. 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. Simulated heat loads for the presented cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Heat loads from the simulators, W</th>
<th>Total heat loads, W</th>
<th>Supply temperature, °C</th>
<th>Supply air flow rate, m³/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinders</td>
<td>Boxes</td>
<td>Foils on the wall</td>
<td>Foils on the floor</td>
<td>Foils on the ceiling</td>
</tr>
<tr>
<td>Single loads</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 people</td>
<td>450</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>6 computers</td>
<td>–</td>
<td>720</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Floor heat loads</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>466</td>
</tr>
<tr>
<td>Combinations of heat loads</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 people, window* and floor heat loads</td>
<td>750</td>
<td>–</td>
<td>520</td>
<td>466</td>
</tr>
<tr>
<td>6 people, 6 computers</td>
<td>450</td>
<td>720</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>10 people, ceiling heat loads, light</td>
<td>750</td>
<td>–</td>
<td>–</td>
<td>466</td>
</tr>
</tbody>
</table>

* Height 3.6 m at initial level of 0.8 m over the floor.

In the present cases vertical temperature profiles are measured from four locations 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%.
3 RESULTS

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

![Figure 2](image)

*Figure 2. Comparison of the different nodal model with the measurement data for single (a – c) heat loads and combinations of heat loads (d – f)*

The two-nodal Mundt model is not able to calculate the temperature gradient for all the cases. Nielsen model is able to predict the temperature near the floor, however overestimates the mixing height level. Unlike the cases with high level heat gains, such as heated ceiling, high window computers, Mateus model accurately calculates the temperature gradient in the occupied zone of the room. The proposed novel nodal model demonstrates the most accurate prediction for all the types of indoor heat loads.

4 DISCUSSION

The results represent typical temperature stratification in rooms with displacement ventilation, when the main gradient happens in low zone. Two-nodal models that do not count the level of stratification are not able to predict the temperature gradient. For the accurate temperature gradient prediction in displacement ventilation the minimum number of nodes is 3: the temperature along the floor, mixing height and exhaust temperatures.
Despite their simplicity and applicability, nodal models are not universal in predicting the temperature gradient, since they are not able to count all the variety of factors affecting the indoor air flows. In the case of complicated unconventional heat load sources, uneven distribution of heat and momentum fluxes, CFD methods are more applicable. In addition, since the model is steady-state, it is not able to count the effect of dynamic loads and thermal mass on the temperature gradient. The novel model should be validated in dynamic mode. Due to the increase of computational power, the attention for simplified models has decreased. However, through the years it became clear that simplified models have benefits over complex models user friendliness, straight forward and fast calculation.

5 CONCLUSIONS

The study compares and validates four nodal models in terms of their ability to calculate vertical temperature gradient in room with displacement ventilation and different heat sources. Heat load distribution and accurate mixing height calculation are the most essential factors to predict the temperature stratification for the DV design conditions. Even though the main temperature gradient happens in low zone of the room with DV, the high level heat loads in high-ceiling premises decrease the mixing height temperature. The proposed method of weight-averaged mixing height calculation allows counting the heat gains of typical indoor heat sources. The proposed nodal model with heat load division and weight-averaged mixing height calculation provides an accurate prediction for all types and combinations of heat loads.

ACKNOWLEDGEMENTS

The study was financially supported by K.V. Lindholm grant and Finnish government scholarship.

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