# Contaminant stratification in displacement ventilated spaces - a two zone model approach. Model prediction compared to experimental data.

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## ABSTRACT

Displacement ventilation (DV) is an alternative to conventional mixing ventilation in various types of rooms. DV is superior to mixing ventilation when it comes to removing contaminants and surplus heat in a room if designed and applied correctly. In the design process of a space with DV it is necessary to have design methods and simulation tools that can predict the vertical contaminant stratification that arise.

In this paper, both steady state and transient models for prediction of contaminant stratification are proposed. The models are based on a two-zone approach, where also a model for the entrainment of clean air in the human boundary layer is included. Sub-models for convective air flow rates and boundary layer air flow in the rooms are also included. The proposed models can be used for design of displacement ventilation and for evaluation of different ventilation efficiency indices.

Predictions from the model have been compared to measurements in fourteen empirical cases found in the literature. The evaluation of the two contaminant models (steady state and transient) is promising for most of the variables compared. However, experimental results for indices measuring air quality in the inhalation zone is better than the predicted values. This under-prediction is conservative if the models are to be used for design of DV and determining necessary ventilation air flow rates.

## KEYWORDS

Displacement ventilation, mathematical models, contaminants, inhalation zone, entrainment.

## 1 INTRODUCTION

The main objective of ventilation is to provide sufficiently clean air for the occupants, i.e. without any harmful or unpleasant contaminants. Secondary objectives can be the removal or supply of heat, or controlling the humidity level. With regard to air quality, this can be done by diluting contaminants and/or by supplying clean air to the inhalation or occupation zone. Conventional dilution ventilation is primarily based on the first principle (dilution/mixing) and so called displacement ventilation is mainly based on the second principle (supplying clean air and displacing polluted air). The fact that cool air is denser than warm air, leads to a buoyancy effect of warm air raising. Above monitors, lamps, people, radiators, etc. warm air will raise towards the ceiling. Such vertical currents of warm air are often called plumes. If there is no air supply near the ceiling, and no other “disturbing” air currents/movements, a layer of warm air will accumulate below the ceiling. The thickness of this layer is mainly dependent of the plume air flow rates and the ventilation air flow rates. This accumulation will lead to a vertical temperature gradient in the room, with low temperature at floor level and a higher temperature at ceiling level. If the pollution sources in the room are associated with the heat sources, and therefore the plumes, the pollution is also accumulated in a layer near the ceiling, causing a vertical contaminant gradient. This principle is used in displacement ventilation where clean and cool air is supplied to the lower part of the room while the polluted and warm air generated in the occupation zone is transported by the plumes to the upper zone. The height of the clean zone and the polluted zone are dependent of the magnitude of the supplied ventilation air flow and the convective air flows in the room. Displacement ventilation should ideally, given the same air flow rates, give much cleaner and cooler air in the inhalation and occupation zone, compared to conventional mixing ventilation. Chemical and physical measurements in laboratories and in real rooms show that the air quality in the occupation zone and the inhalation zone is substantially better than standard mixing ventilation, see e.g. Mundt (Mundt, 1996), Mattson (Mattson, 1999), Brohus&Nielsen (Brohus, 1996a), Holmberg et.al. (Holmberg, 1990) and Hatton&Awbi (Hatton, 1998). In addition, laboratory and field experiments show that people perceive the air as more pleasant in displacement ventilated rooms compared to rooms with dilution ventilation, see e.g. Ørhede et.al. (Ørhede, 1996) and Brohus et.al. (Brohus, 1996b). Displacement ventilation has successfully been used in industrial premises, where large concentrated heat and pollution sources often are present at floor level. Displacement ventilation has also grown popular in comfort ventilation, especially in northern Europe.

In the design process of a building or room it is of interest to predict the thermal comfort, indoor air quality, the heating and cooling load and energy use during various seasons. Good simulation tools make it possible to design optimal ventilation solutions. Most existing models and simulation tools for IAQ and energy use are based on the assumption of full mixing, and are unable to predict the advantages of displacement ventilation. However, various alternative methods and models have been proposed to predict the effect of displacement ventilation. Skåret (Skåret, 2000) has proposed a transient two-zone model to predict vertical contaminant stratification in a room. Flow element models are used to calculate the air exchange between the two zones. Koganei et.al.(Koganei, 1993) has proposed a two-zone model for vertical contaminant distribution, assuming piston flow in the lower clean zone. The most advanced models for prediction of vertical contaminant and temperature stratification are CFD models (CFD: Computational Fluid Dynamics). CFD models are based on the governing equations for fluid flow and heat transfer, i.e. conservation of mass, energy and momentum, and different rate laws (e.g. Fourier's law and Fick's law), together with turbulence models, and can also be used to model displacement ventilation. However, the modelling of thermal plumes and boundary layer flow, which is important in displacement ventilated rooms, is difficult in CFD models, as shown by Jacobsen & Nielsen (Jacobsen, 1993).

The aim of this work has been to develop both simplified hand calculation methods and more refined models for implementation in building simulation tools. Models for vertical contaminant stratification in displacement ventilated rooms are proposed, covering both stationary and transient conditions. All models are based on a two-zone model approach, assuming a lower clean and cool zone and an upper polluted and warm zone.

# 2 THEORY AND MODELS

## 2.1 The two zone approach

The model is based on a two-zone model approach as illustrated in figure 1, with a lower clean zone (zone 1) and a upper polluted zone (zone 2). Air exchange between the two zones is calculated with sub-models for plumes and the boundary layer flow, se e.g. Dokka (Dokka, 2000) and Dokka & Tjelflaat (Dokka, 2001).

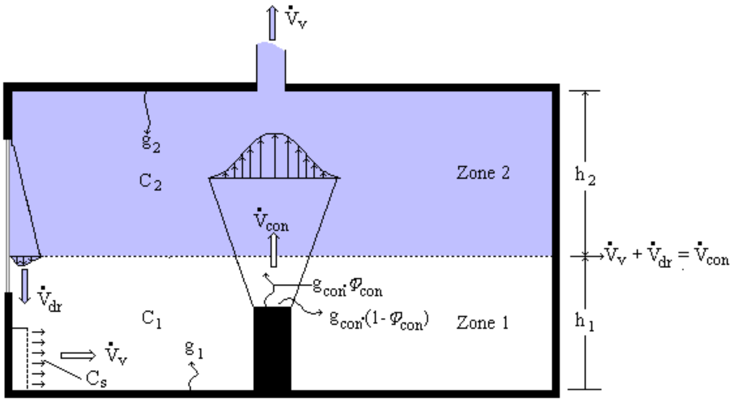

Figure 1: Principles and variables in the two-zone model.

Referring to figure 1, if we assume that the density of air is constant, an air mass balance of zone 1 (clean zone) can be written as (see figure 2):

$$\overbrace{\dot{V}_v + \dot{V}_{dr}(h_1)}^{\text{Air flow to zone1}} = \overbrace{\dot{V}_{con}(h_1)}^{\text{Air flow from zone1}} \qquad (\mathrm{m^3/h}) \qquad (1)$$

The air mass balance for zone 2 gives the same result. In practice, only the ventilation air flow ($\dot{V}_v$) is known, and the down draft air flow ($\dot{V}_{dr}$) and the convective air flow ($\dot{V}_{con}$) are dependent on the height of the clean zone ($h_1$), i.e. the height of zone 1 has to be iterated until equation (1) is satisfied.

Referring to figure 1, the transient contaminant mass balances for the two zones become:

$$g_1 + (1-\varphi_{con})g_{con} + \dot{V}_V C_s + \dot{V}_{dr} C_2 - \dot{V}_{con} C_1 = V_1 \frac{dC_1}{dt} \qquad (\mathrm{g/h}) \qquad (2)$$

$$g_2 + \varphi_{con} g_{con} + \dot{V}_{con} C_1 - \dot{V}_{dr} C_2 - \dot{V}_V C_2 = V_2 \frac{dC_2}{dt} \qquad (\mathrm{g/h}) \qquad (3)$$

where $V_1$ and $V_2$ are the air volumes of zones 1 and 2 respectively, and $t$ is time. $g_1$ and $g_2$ are the “cold” contaminant generation in zone 1 and 2 respectively, while $C_1$, $C_2$ and $C_S$ are the contaminant concentration in zone 1, zone 2 and the supply air. $g_{con}$ is the “hot” contaminant generation associated with the heat sources, and $\varphi_{con}$ are the part of the hot contaminants that follow the plume air flow to zone 2. Equations (2) and (3) are two coupled ordinary linear differential equations, which for example can be solved by the eigenvalue/eigenvector method (Dokka, 2000):

$$C_1(t) = d_1 \exp(\lambda_1 t) + d_2 \exp(\lambda_2 t) + C_{1\infty} \qquad (\mathrm{g/m^3}) \qquad (4)$$

$$C_2(t) = d_1 k_1 \exp(\lambda_1 t) + d_2 k_2 \exp(\lambda_2 t) + C_{2\infty} \qquad (\mathrm{g/m^3}) \qquad (5)$$

where the steady state concentrations are given by:

$$C_{1,\infty} = \frac{b_1 \cdot a_{22} - b_2 \cdot a_{12}}{\det(\vec{A})} \qquad \text{(g/m}^3\text{)} \tag{6}$$

$$C_{2,\infty} = \frac{b_2 \cdot a_{11} - b_1 \cdot a_{21}}{\det(\vec{A})} \qquad \text{(g/m}^3\text{)} \tag{7}$$

The entries in the coefficient matrix and the source vector is:

$$\begin{aligned} a_{11} &= -\frac{\dot{V}_{con}}{V_1} \quad ; \quad a_{12} = \frac{\dot{V}_{dr}}{V_1} \\ a_{21} &= \frac{\dot{V}_{con}}{V_2} \quad ; \quad a_{22} = -\frac{\dot{V}_{dr} + \dot{V}_v}{V_2} \end{aligned} \qquad \text{(1/h)} \tag{8}$$

$$b_1 = \frac{g_1 + g_{con}(1 - \varphi_{con}) + \dot{V}_v C_s}{V_1} \; ; \; b_2 = \frac{g_2 + g_{con}\varphi_{con}}{V_2} \qquad \text{(g/h m}^3\text{)} \tag{9}$$

The constants $d_1$ and $d_2$ can be calculated as:

$$d_1 = \frac{[C_1(0) - C_{1\infty}]k_2 - C_2(0) + C_{2\infty}}{k_2 - k_1} \qquad \text{(g/m}^3\text{)} \tag{10}$$

$$d_2 = \frac{C_2(0) - C_{2\infty} - [C_1(0) - C_{1\infty}]k_1}{k_2 - k_1} \qquad \text{(g/m}^3\text{)} \tag{11}$$

The eigenvalues ($\lambda$) and the entries in the eigenvectors ($k$) are given as:

$$\lambda_{1/2} = \frac{a_{11} + a_{22} \pm \sqrt{(a_{11} + a_{22})^2 - 4 \cdot (a_{11} \cdot a_{22} - a_{12} \cdot a_{21})}}{2} \qquad \text{(1/h)} \tag{12}$$

$$k_1 = \frac{\lambda_1 - a_{11}}{a_{12}} \quad ; \quad k_2 = \frac{\lambda_2 - a_{11}}{a_{12}} \qquad \text{(-)} \tag{13}$$

## 2.2 Contaminant removal efficiencies

From the derived expressions in the preceding section, the mean concentration in the complete room and in the occupation zone can be calculated as:

$$< C > = \frac{C_{1\infty} h_1 + C_{2\infty}(h_{ceil} - h_1)}{h_{ceil}} \qquad \text{(g/m}^3\text{)} \tag{14}$$

$$C_{occ} = \begin{cases} C_{1\infty} & ;\text{if } \mathrm{h_1 \geq h_{occ}} \\ \dfrac{C_{1\infty} h_1 + C_{2\infty}(h_{occ} - h_1)}{h_{occ}} & ;\text{if } \mathrm{h_{occ} > h_1} \end{cases} \qquad \text{(g/m}^3\text{)} \tag{15}$$

where $h_{occ}$ is the height of the occupation zone. The contaminant removal efficiency in the complete room and in the occupation zone can now be calculated:

$$\varepsilon^{C} = \frac{C_{2\infty} - C_s}{<C> - C_s} \qquad (-) \qquad (16)$$

$$\varepsilon^{C}_{occ} = \frac{C_{2\infty} - C_s}{C_{occ} - C_s} \qquad (-) \qquad (17)$$

If we assume that air in the human boundary layer is entrained evenly from floor level to the height of the inhalation zone ($h_{exp}$), the mean concentration entrained in the human boundary layer is given by the expression:

$$C_{\exp} = \begin{cases} C_{1\infty} & ;\text{if } \mathrm{h}_1 \geq \mathrm{h}_{\exp} \\ \dfrac{C_{1\infty} h_1 + C_{2\infty}\left(h_{\exp} - h_1\right)}{h_{\exp}} & ;\text{if } \mathrm{h}_{\exp} > \mathrm{h}_1 \end{cases} \qquad (\mathrm{g/m^3}) \qquad (18)$$

where we have assumed that the entrained concentration is the same as the concentration in the inhalation zone, which has been experimental verified by Brohus&Nielsen (Brohus, 1996a). $h_{exp}$ is the height to the inhalation zone (exposure). The contaminant removal efficiency in the inhalation zone can now be calculated as:

$$\varepsilon^{C}_{\exp} = \frac{C_{2\infty} - C_s}{C_{\exp} - C_s} \qquad (-) \qquad (19)$$

## 3 COMPARISON WITH EXPERIMENTAL DATA

### 3.1 Experimental test cases

Data form 14 experimental cases (14) have been taken from the literature to evaluate the contaminant models. Data sets for evaluation of the contaminant model have been taken from Mattson (Mattson, 1999): three office cases and two classroom cases; Heiselberg & Sandberg (Heiselberg, 1990): five office cases; and from Brohus & Nielsen (Brohus, 1996a): four meeting room cases. The different cases are shortly descrbied in table 1.

Table 1: Description of the test cases used in the evaluation of the contaminant model.

| **Case** | **First author** | **Type of room** | **Heat sources** | **Heat load** | **Flow rate** | **Floor area/ ceil.height** |
|---|---|---|---|---|---|---|
| 1 | Mattson | Office | Thermal manikin, PC, ceiling light | 295 W | 20,9 l/s | 15,1 m$^2$/2,5 m |
| 2 | Mattson | Office | Thermal manikin, PC, ceiling light | 395 W | 20,9 l/s | 15,1 m$^2$/2,5 m |
| 3 | Mattson | Office | Thermal manikin, PC, ceiling light | 395 W | 36,6 l/s | 15,1 m$^2$/2,5 m |
| 4 | Heiselberg | Office | Heated slender cylinder | 600 W | 10,6 l/s | 15,1 m$^2$/2,5 m |
| 5 | Heiselberg | Office | Heated slender cylinder | 600 W | 21,1 l/s | 15,1 m$^2$/2,5 m |
| 6 | Heiselberg | Office | Heated slender cylinder | 600 W | 31,4 l/s | 15,1 m$^2$/2,5 m |
| 7 | Heiselberg | Office | Heated slender cylinder | 600 W | 41,9 l/s | 15,1 m$^2$/2,5 m |
| 8 | Heiselberg | Office | Heated slender cylinder | 600 W | 52,5 l/s | 15,1 m$^2$/2,5 m |
| 9 | Brohus | Meet.room | Thermal manikins, point source | 771 W | 40,3 l/s | 48 m$^2$/4,0 m |
| 10 | Brohus | Meet.room | Thermal manikins, point source | 771 W | 40,3 l/s | 48 m$^2$/4,0 m |
| 11 | Brohus | Meet.room | Thermal manikins, point source | 381 W | 80,6 l/s | 48 m$^2$/4,0 m |
| 12 | Brohus | Meet.room | Thermal manikins, point source | 381 W | 80,6 l/s | 48 m$^2$/4,0 m |
| 13 | Mattson | Classroom | Person simulators, ceiling light | 2900 W | 191 l/s | 60,5 m$^2$/3,0 m |
| 14 | Mattson | Classroom | Person simulators, ceiling light | 2900 W | 117 l/s | 60,5 m$^2$/3,0 m |

COMMENT: In the cases of Heiselberg & Sandberg (cases 4-8), the convective air flow rates around the heated cylinder are measured and not calculated values. For all other cases the convective air flow induced by heat sources are calculated.

## 3.2 Results and discussion

Fig. 2 shows the height of zone 1 (the clean zone), also called the stratification height or the height of the stationary front. The predicted height of zone 1 is calculated after equation (1) Higher ventilation air flow or down draught air flow raises the height of zone 1, while higher convective air flows induced by heat sources lower the height of zone 1. The measured height of zone 1 is defined as the height where the concentration is 50% of the concentration in the extract, as proposed by Heiselberg & Sandberg (Heiselberg, 1990). The predicted and measured heights of zone 1 seem to follow each other for the different cases quite well. Only in case 2 (the office case of Mattson) is there a significant under-prediction. But in this case the measured height of zone 1 is uncertain due to few measuring points for the concentration (based on a linear interpolation), and could in reality be much closer to the predicted value.

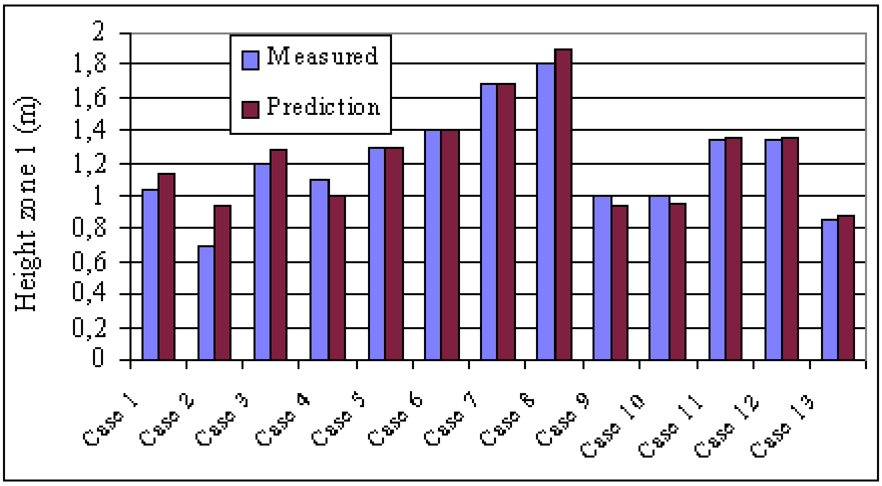

Figure 2: Comparison of predicted and measured height of zone 1.

Fig. 3 shows the contaminant removal efficiency for the complete room. The predicted values calculated after equation (16). This index shows the ability of the ventilation systems to remove contaminants from all points in the room under steady state conditions. The measurements and predictions are close for all the compared cases.

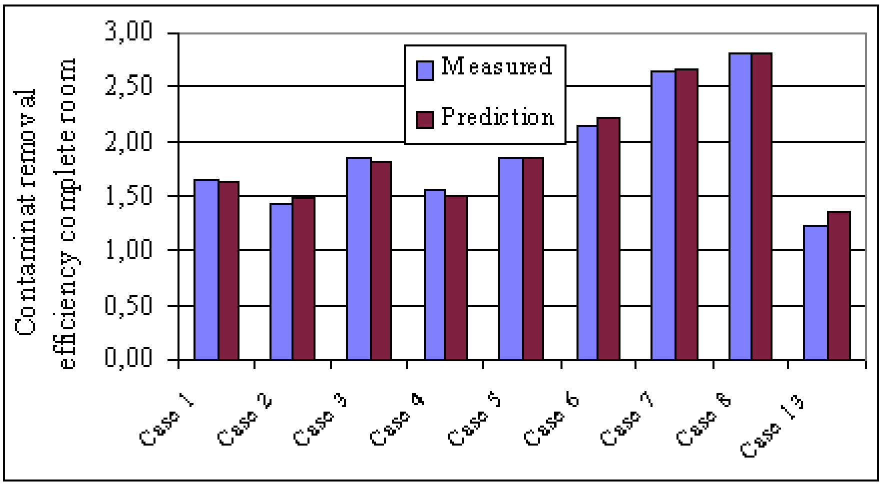

Figure 3: Comparison of predicted and measured contaminated removal efficiency for the complete room

Fig. 4 shows the contaminant removal efficiency for the occupation zone. The predicted values calculated after equation (17).This index shows the ability of the ventilation systems to remove contaminants from the occupation zone. The predicted efficiency is very close to the measured value in all cases.

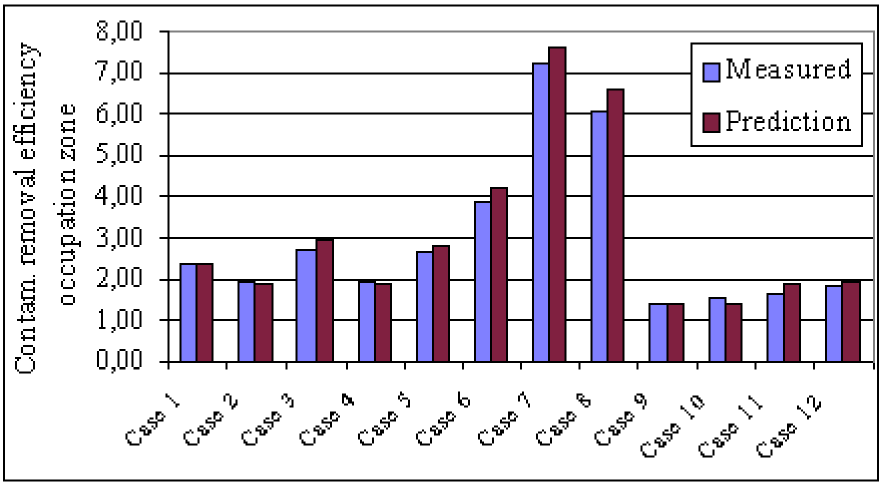

Figure 4: Comparison of predicted and measured contaminant removal efficiency in the occupation zone.

Fig. 5 shows the contaminant removal efficiency in the inhalation zone for the cases with seated persons (person simulators). This efficiency shows the ventilation systems ability to provide clean air to the occupants. A high efficiency value means that the concentration to which the occupant is exposed is low compared to the concentration in the extract. The comparison shows that the model under-predicts the measured efficiency, especially for case 3 (office case). In case 3 the air in the inhalation zone is almost as clean as the supply air, which implies that the air in the boundary layer around the person is entrained from the clean air layer at floor level. In our model (eq.18), which on this point is similar to the model proposed by Brohus & Nielsen (Brohus, 1996a), it is assumed that the air in the human boundary layer is entrained evenly from all heights up to the height of the inhalation zone. Cases 9, 11 and 13 in Fig. 5, seems to correspond well to this assumption, but also in case 2 (office case) the air in the inhalation zone is substantially better than predicted by the model. However, the model gives in all cases a conservative estimate of the air quality in the inhalation zone. If the contaminant removal efficiency in the inhalation zone is to be used for design of DV-systems and determining the necessary air flow rates it is preferable that the model under-predicts the efficiency to be on the safe side (conservative).

Fig. 6 shows the contaminant removal efficiency in the inhalation zone for standing persons. Compared to seated persons, the inhalation zone for standing persons is often located high into the polluted zone (zone 2), and one would expect that the efficiency was lower in these cases. This holds true for cases 2 and 3, where both the efficiency for seated and standing persons are measured. The efficiency for the seated persons are much higher than for the standing persons. The model under-predicts the efficiency substantially for cases 1 and 3, but predicts quite closely for the other cases (2, 10, 12). The reason for under-prediction in cases 1 and 3, could be due to the fact that zone 1 is relatively high in these cases, and that the human boundary layer is therefore entraining air to the inhalation zone mostly from the clean zone (zone 1).

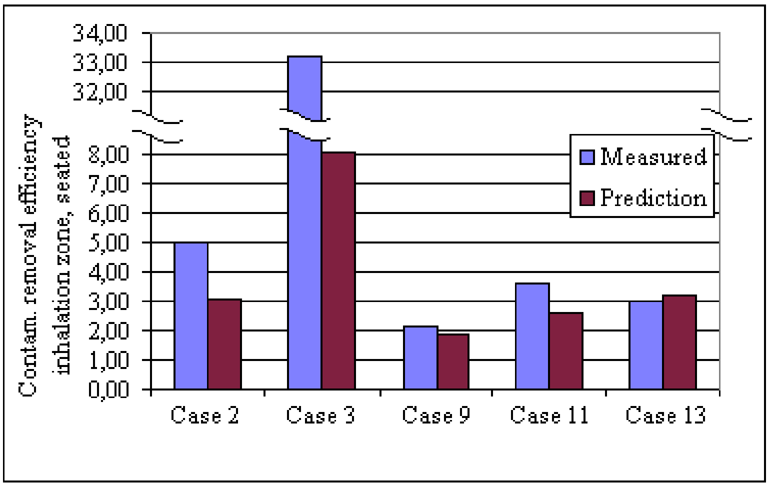

Figure 5: Comparison of predicted and measured contaminant removal efficiency in the inhalation zone, seated persons

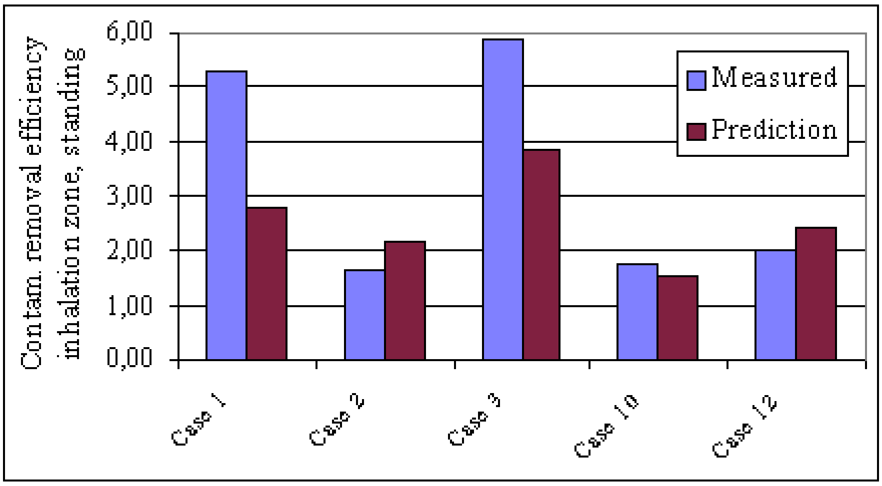

Figure 6: Comparison of predicted and measured contaminant removal efficiency in the inhalation zone, standing persons

## 4 CONCLUSIONS AND FURTHER WORK

The evaluation of the proposed contaminant model is very promising for most of the variables compared, where model prediction is close to the measured values. However, experimental results for indices measuring air quality in the inhalation zone is better than the predicted values. This under-prediction is conservative if the models are to be used for design of DV and determining necessary ventilation air flow rates.

If the models is to be used for design, it should also be compared to results from more “real life” experiments with e.g. moving people and different “non-ideal” settings, like furniture placed in front of DV-supply vents. Such experiments has currently been undertaken and will be reported in the future.

## 5 ACKNOWLEDGEMENTS

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