A SIMPLIFIED MODEL FOR HUMAN INDUCED CONVECTIVE AIR FLOWS - MODEL PREDICTONS COMPARED TO EXPERIMENTAL DATA

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Abstract
Displacement ventilation is often used in occupant dense rooms like meeting rooms, classrooms and theatres. This is due to its potential to provide cool and clean air to the breathing zone of the occupants in a room. The air quality and thermal comfort in the occupation zone, is a function of the convective air flows induced by heat sources in the lower part of the room. In occupant dense room like those mentioned above, the dominant heat source are people.
To design such displacement ventilated rooms, it is essential to estimate the human induced convective air flows.
This paper proposes a simple mathematical model for calculation of the convective air flow rate induced by humans.
This model has been compared to a more complex model (intermodel comparison) and to experimental data (empirical validation) with satisfactory results.

Introduction
Displacement ventilation is often used in occupant dense rooms like meeting rooms, classrooms and theatres. This is due to its ability to provide cool and clean air to the breathing- and occupation zone (see fig. 1), compared to conventional mixing ventilation (with the same air flow rate).
The height of the clean and cool zone (fig. 1), and hence the air quality and thermal comfort in the occupation zone, is a function of the convective air flows induced by heat sources in the lower part of the room. In occupant dense room like those mentioned above, the dominant heat source are persons.
To design such displacement ventilated rooms, it is vital to estimate the human induced convective air flows.

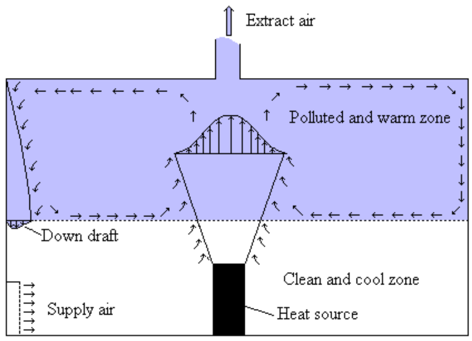

Figure 1 The working principles in displacement ventilation

This paper proposes a simple mathematical model for calculation of the convective air flow rate induced by humans. The model is compared to the linear temperature gradient model of Mundt (Mundt, 1996). These two models are also compared to experimental data found in the literature.

A model for human induced convective air flows
A model for convective air flow around and above a person has been developed, based on the following assumptions:

- A person can be modelled as a cylinder (with height h_{per} and diameter d_{per}). The diameter of the person is derived from the given surface area and the height of the person.
- In displacement ventilated rooms the air flow of main interest is the air flow entering from the lower clean zone into the polluted zone.
- When the height of the lower clean zone is below the height of the person, the convective air flow is mainly governed by boundary layer air flow around the person.
- When the height of the lower clean zone (fig.1) is above the height of the person, the

convective air flow is mainly governed by plume air flow.

- The transition region between boundary layer flow and plume flow around the top of the person is taken as the larger of the two calculated air flows.

Boundary layer flow
The rising air flow along a vertical heated surface can be calculated as (Skåret, 1986):

$$\dot{V} = 2.9 \cdot w \cdot \Delta T^{0.4} z^{1.2} \qquad (1)$$

ΔT is the difference between the room air temperature (T_a) and the surface temperature (T_f) of the hot surface, w and z is the height and width of the hot surface respectively.
The surface temperature of the person is most often unknown, but the convective heat output of the person (P_{per}) can often be estimated. The convective heat transfer coefficient (α_c) gives a relationship between the temperature difference (ΔT) and the convective heat output (P_{per}). The convective heat transfer coefficient for a vertical plate (for air at 20 °C) can be calculated by the following expression (Cengel, 1998):

$$\alpha_c = 1.21 \cdot \Delta T^{1/3} \qquad (2)$$

The convective heat output from the person can be calculated as:

$$P_{per} = A_{per} \alpha_c \Delta T \qquad (3)$$

Inserting (2) and (3) into (1) gives the following expressions for the boundary air flow rate along a person:

$$\dot{V}_{per} = 8.61 \cdot \left(\frac{P_{per}}{A_{per}} \right)^{0.3} z^{1.2} d_{per} \qquad (4)$$

Plume air flow
The plume air flow above a point source can be calculated as (Popiolek, 1998)

$$\dot{V}_{point} = 6.0 \cdot P_{point}^{1/3} \left(z + z_p \right)^{5/3} \qquad (5)$$

This model is derived assuming undisturbed air and uniform temperature in the room.
For extended sources, like our "human cylinder", the distance to the virtual origin point (Z_p) must be estimated. In most cases Z_p is given as a linear function of the cross sectional dimension, which in this case is equal to the diameter of the cylinder (d_{per}) :

$$z_p = a \cdot d_{per} \qquad (6)$$

Practical values for the coefficient *a* is in the range from 1.7 to 2.5 (Dokka, 2000).

Taken into accont the height of the "human cylinder" (h_{per}) the plume air flow above the cylinder can then be calculated as:

$$\dot{V}_{plume} = 6.0 \cdot \left(P_{per} \right)^{1/3} \left(z - h_{per} + a \cdot d_{per} \right)^{5/3} \qquad (7)$$

Based on the above stated assumption, the human induced convective air flow can be taken as the larger of the boundary layer flow and the plume air flow:

$$\dot{V}_{pers} = \max \begin{cases} 8.61 \left(\frac{P_{per}}{A_{per}} \right)^{0.3} z^{1.2} d_{per} \\ 6.0 \cdot \left(P_{per} \right)^{1/3} \left(z - h_{per} + a \cdot d_{per} \right)^{5/3} \end{cases} \qquad (8)$$

where the diameter of the "human cylinder" can be derived from the height (h_{per}) and surface area (A_{per}) of the person:

$$d_{per} = 2 \cdot \left(-h_{per} + \sqrt{h_{per}^2 + A_{per} / \pi} \right) \qquad (9)$$

The surface area of an average adult person (A_{per}) can be set to 1.8 m² (Fanger, 1992). The height of an average adult seated and standing can respectively be set to: $h_{p,sit}$ = 1.2 m, and $h_{p,stan}$ = 1.75 m. The distance z in equation (18) is the distance from the floor level. At normal room temperature conditions and with normal indoor clothing and activity, the convective part of the sensible heat output of a person can be estimated to 50 % (50 % radiation). Under other circumstances the convective heat output from a person can be estimated by the heat balance algorithms of Fanger (1992).

Results

Prediction from the above proposed model has been compared to prediction from the model developed by Mundt (1996) and to experimental data published by Mundt (1996) and Kofoed (1991). The model of Mundt also takes into account linear temperature gradients often encountered in displacement ventilated rooms, and is based on the work of Morton (1956)

Experimental data
The convective air flow above a vertical circular cylinder used as a simulator for a person, has

been investigated. Experiments are reported by Mundt (1996) and Kofoed (1991). The human simulator used is 1 meter high and has a diameter of 0.4 meters, which gives a surface area of 1.38 m².

In figure 2-5, calculated air flows with equation (8) and the temperature gradient models of Mundt (1996), are compared to the experimental results reported by Mundt and Kofoed. Air flows for different heights above the floor and different temperature gradients are compared. The heat output for the human simulator is 100 W, where 50 W is estimated to be convection (Mundt, 1996). In equation (8) both the upper and lower limit values of *a*, respectively *2.5* and *1.7*, are calculated.

Discussion

The gradient model of Mundt and the proposed human model, expression (8), with the lower limit value (a = 1.7) predict very similar air flow rates. The human model with the upper limit value (a = 2.5) predicts considerably higher air flows.

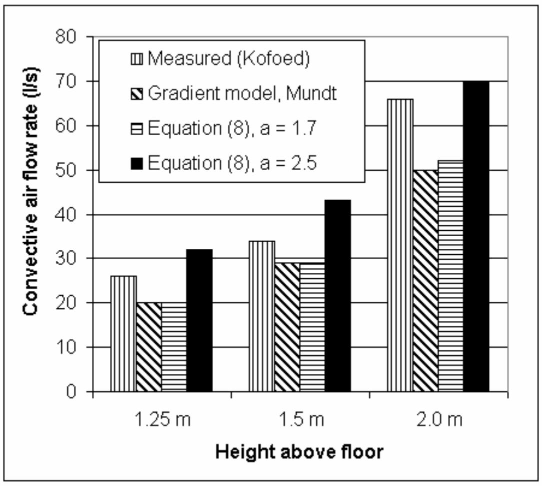

Figure 2: Comparison between model prediction and experimental data reported by Kofoed (1991), with a temperature gradient of 0-0.1 K/m.

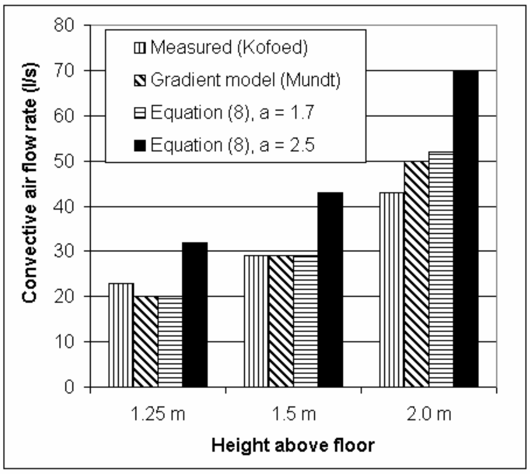

Figure 3: Comparison between prediction and experimental data reported by Kofoed (1991), with a temperature gradient of 0.3 K/m.

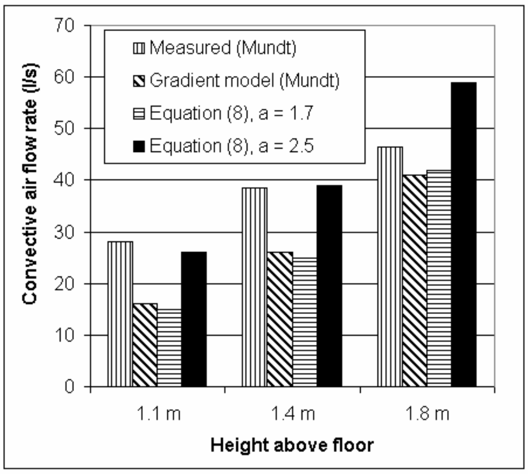

Figure 4: Comparison between model prediction and measurements, with a temperature gradient of 0.6 K/m.

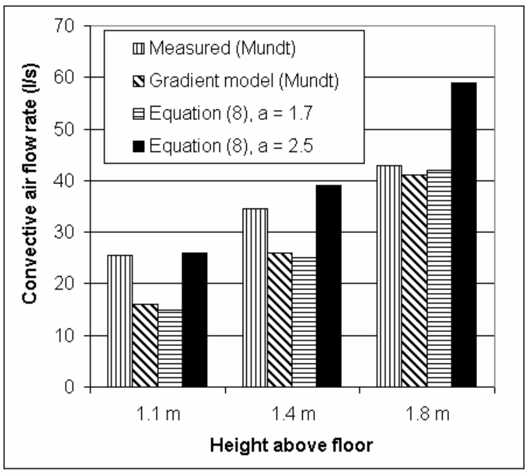

Figure 5: Comparison between model prediction and measurements, with a temperature gradient of 1.2-1.5 K/m.

For the experiments with small temperature gradients (fig. 2 and 3), the gradient model or the ‘lower limit’ model give the best predictions.
For the experiments with higher temperature gradient (fig. 4 and 5) the “human cylinder” model with the upper limit value gives the best predictions up to 1.4 m, but for 1.8 and 2.0 m above the floor it over-predicts the air flows.
In comfort ventilation with normal ventilation rates (1 - 4 ACH) the intersection between the clean and polluted zone is approximately in the range 0.8 – 1.4 meters above the floor. In this height range there is small difference between the two models, and the simplest model can be used (the human model based on uniform room temperature). A compromise for the value of *a* in equation (8) seems to be: $a \approx 1.9$.
Mierzwinski (1980) have measured air flow rates 0.75 meter above a seated person, and reports the air flows to be between 28 l/s and 56 l/s. Assuming the height of the seated person to be 1.2 m and the convective heat output to be 40 W, the prediction of the model is: 40 l/s and 55 l/s, for the lower ($a = 1.7$) and upper ($a = 2.5$) limits respectively, i.e. the proposed model seems to give a reasonable prediction also for real persons.

Conclusions

A simplified model for human induced convective air flows has been developed.

Comparison (inter model comparison) with the more complex temperature gradient model of Mundt (1996), reveals that there is little differences between the two models (with the value $a = 1.7$ in eq. (8)).

Compared to experimental data the gradient model and the "human cylinder" model (8) with $a = 1.7$ give good predictions for cases with small temperature gradients (0-0.3 K/m).

Compared to experimental data for cases with high temperature gradient (0.6-1.5 K/m), the “human cylinder” model with $a = 2.5$ gives the best prediction.

Based on the results, a compromise for the coeffisient *a* in eq. (8) seems to be 1.9

Nomenclature

A	Area (m²)
a	Coefficient for the virtual point
d	Diameter (m)
h	Height (m)
P	Convective heat output (W)
Z	vertical distance from floor
V	Air flow rate (l/s)
w	Width (m)
ΔT	Temperature difference between the surface and the air (K)
α_c	Convective heat transfer coefficient

Subscript

per	Person
p	Virtual pole point
point	Point source

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