Relative influence of boundary conditions on the indoor air quality of a displacement ventilated room

Henrik Brohus*

Aalborg University, Denmark

ABSTRACT
In the indoor air quality (IAQ) assessment of ventilated enclosures it is useful to know the relative influence of key boundary conditions on the personal exposure and ventilation effectiveness, for instance as a source of information on where to allocate the greatest effort in the design phase. CFD is used to predict ventilation effectiveness and personal exposure to contaminant sources in a displacement ventilated room subject to variation of several key boundary conditions. The influence is studied regarding the relative influence of room height, wall heat flux, air change rate and Archimedes number for two different contaminant source types. The results show how IAQ may be significantly influenced by changes of the key parameters although with differences in the relative influence. Tendency information provides rough guidance on parameter sensitivity to changes.

INDEX TERMS
IAQ assessment; Ventilation effectiveness; CFD; Displacement ventilation; Personal exposure

INTRODUCTION
In general, building design and, more specifically, indoor climate design, a large number of parameters may influence the result. In the design process it is, in practice, obviously not possible to investigate thoroughly all parameters of interest and possible influence. Thus, it is deemed necessary to strictly limit the number of parameters and cases investigated in detail. Most often experience, fingertip knowledge and project budget determine what parameters to choose and what parameters to disregard. This paper suggests a simple methodology to investigate the relative influence of boundary conditions on the indoor air quality (IAQ) in ventilated rooms.

This kind of information can be beneficial for the architect in the pre-design phase of building design as a source of information on where to allocate the greatest effort. At the same time, modellers can benefit from knowing which of the boundary conditions are most crucial to focus on when IAQ assessment is performed.

A displacement ventilated room is applied as a test case to show the principle. Several boundary conditions are varied to get a rough idea of the relative impact. In this way it is fairly easy to get an idea of the influence, whether it is significant and/or in what direction regarding the indoor climate.

METHOD
The steady-state, three-dimensional, non-isothermal flow field is simulated by means of a numerical solution of the continuity equation, the Navier–Stokes equations and the energy equation. Turbulence is modelled by means of the k–ε turbulence model. Contaminant transport is simulated by means of a concentration equation. Standard wall functions are applied on all surfaces. The CFD conditions are given in Table 1.

* E-mail: hb@civil.auc.dk

In order to include the local influence of inhabitants, a computer simulated person (CSP) is located in the ventilated room. Numerous measurements demonstrate that erroneous results may be obtained if the local effect of the person is neglected when the personal exposure is assessed (Rodes *et al.*, 1991; Brohus and Nielsen, 1996a). The CSP applied in the simulations is a simple model of an average sized woman where the clothing has an insulation value of 0.8 clo. The CSP is modelled as a heated cuboid with a height of 1.7 m, an aspect ratio of the width and the depth of approximately 2, and a surface area of 1.62 m^2. The heat transfer boundary condition is a convective heat flux of 25 W/m^2, which corresponds to an activity level of a person standing relaxed, i.e. approximately 1 met (Brohus and Nielsen, 1996b). In the present simulations the personal exposure, c_e, corresponds to the contaminant concentration in the nearest cell along the CSP at a height of 1.5 m.

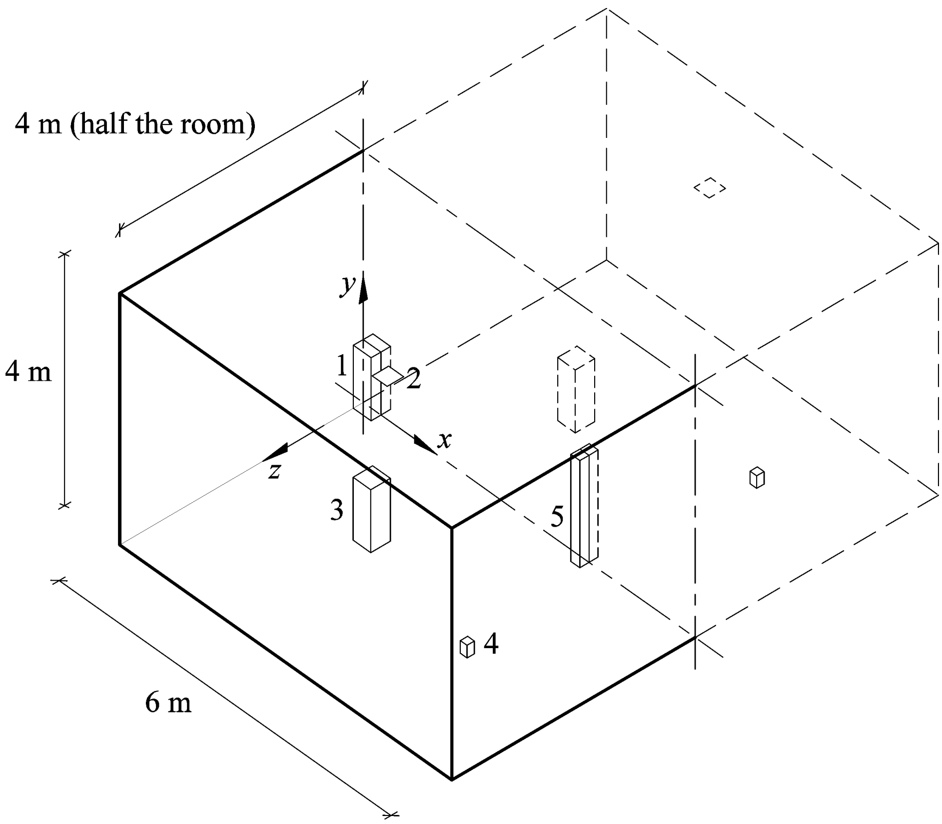

Figure 1 Geometry of displacement ventilated room. Only one symmetry plane is simulated.

The air is supplied through the inlet device (1) and exhausted through openings in the ceiling (2). The heat load is generated by person simulators (3), a point heat source (4), and the CSP (5). The end wall (x = 6 m) supplies or removes convective heat, whereas the other walls are assumed to be adiabatic. The room height of 4.0 m is changed to 2.5 and 6.0 m, respectively, in Case B (see Table 2).

The geometry is shown in Figure 1 for the displacement ventilated room. The test cases are set up according to the matrix in Table 2. In order to obtain a method of practical use, a rather coarse computational grid is chosen (approximately 50 000 grid points) to obtain fast results that will form the basis of judgement of whether to investigate certain boundary conditions in more detail.

Table 1 CFD boundary conditions. Average room air temperature $T_a \cong 22°C$

Parameter		Value
Air flow rate		373.13 m^3/h
Supply air temperature, Cases A and B		18°C ($Ar < 0$)
Supply air temperature, Case C		22°C ($Ar = 0$) and 26°C ($Ar > 0$)
Heat sources	Convective heat output	Implementation in CFD simulation
Person simulator	50 W	Obstacle with prescribed surface heat flux
Point heat source	Varies	Transparent volume source
CSP	25 W/m^2	Obstacle with prescribed surface heat flux
End wall	From –30 to 30 W/m^2	Surface with prescribed heat flux

Two different contaminant sources are applied. *Contaminant Source 1*: A 'warm' point contaminant source simulated by a small transparent volume source (0.1 m × 0.1 m × 0.1 m) located above the point heat source at a height of 2 m above the floor (see Figure 1). The combination of the point heat source generating an ascending plume of warm air and the contaminant source located above causes a transport of the contamination to the upper part of the room. *Contaminant Source 2*: A 'neutral' source is simulated by means of a passive constantly emitting planar contaminant source in the shape of the entire floor.

The ventilation effectiveness is investigated by means of the personal exposure index (Brohus and Nielsen, 1996a) $\varepsilon_e = c_R / c_e$, where c_R is the concentration in the return opening and c_e is the concentration of inhaled contaminant. The personal exposure index expresses the effectiveness actually experienced by a person in the ventilated room. A high personal exposure index reveals a low personal exposure. A personal exposure index close to 1 indicates a case close to fully mixed conditions.

In order to investigate the influence of supply air temperature and inlet velocity, the Archimedes number, *Ar*, is applied. *Ar* expresses the relative influence of buoyancy forces versus inertial forces within the fluid. $Ar = [g \cdot H \cdot (T_s - T_a)]/(u^2 \cdot T_a)$, where g is the gravitational acceleration (m/s^2), H is the height of the inlet device (m), T_s is the supply air temperature (°C) and T_a is the ambient air temperature (°C).

RESULTS

The main results are summarized in Table 2. Figure 2 shows the relative influence of the air change rate on the ventilation effectiveness for the two contaminant sources. Figure 3 visualizes the impact of the Archimedes number on the flow field.

DISCUSSION AND CONCLUSIONS

It is found that the results depend highly on the kind of contaminant source. It is a well-known fact that warm or light contaminant sources lead to high ventilation effectiveness in displacement ventilated rooms, whereas cold or 'neutral' sources behave more like they would in mixing ventilated rooms (Etheridge and Sandberg, 1996). Close to the CSP, the concentration field is significantly modified due to the convective transport in the boundary layer. In case of the 'warm' contaminant source (1) the ventilation effectiveness, i.e. the personal exposure index, is on average above 2. In case of the 'neutral' contaminant source (2) the ventilation effectiveness approaches on average 1.

The influence of the wall heat flux (Case A) may, in practice, arise from badly insulated surfaces like glazing giving rise to cold down draught. Solar radiation or influence of heat storage in the daytime may create ascending convection currents. In this test case, the influence of the heat flux is found to be of minor importance regarding the personal exposure index even though the influence on the concentration field is quite significant.

Table 2 Summary of main results. ε_e is the personal exposure index; n.s. = not significant

Case	Value	ε_e (n.d.)		Gradient tendency	
		C. Source 1	C. Source 2	C. Source 1	C. Source 2
Case A: Wall heat flux	–30 W/m^2	1.7	1.2	None (n.s.)	None
	0 W/m^2	2.5	1.1		
	+30 W/m^2	2.0	1.0		
Case B: Room height	2.5 m	3.5	1.1	Negative	None
	4.0 m	2.5	1.1		
	6.0 m	2.1	1.1		
Case C: Archimedes number	–3.7 (cold supply)	2.5	1.1	Negative (n.s.)	None (n.s.)
	0.0 (isothermal)	3.1	2.1		
	3.7 (warm supply)	1.1	1.0		
Case D: Air change rate	2.6 h^{-1}	2.1	1.1	Positive	None
	3.9 h^{-1}	2.5	1.1		
	6.2 h^{-1}	3.5	1.1		

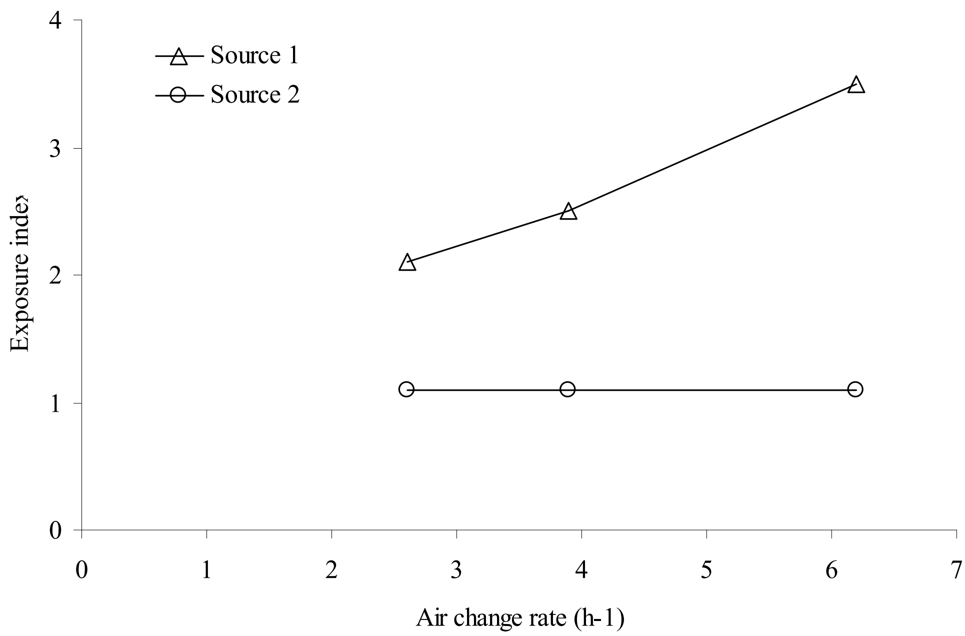

Figure 2 The relative influence of the air change rate on the personal exposure index (ventilation effectiveness) for the two different contaminant sources.

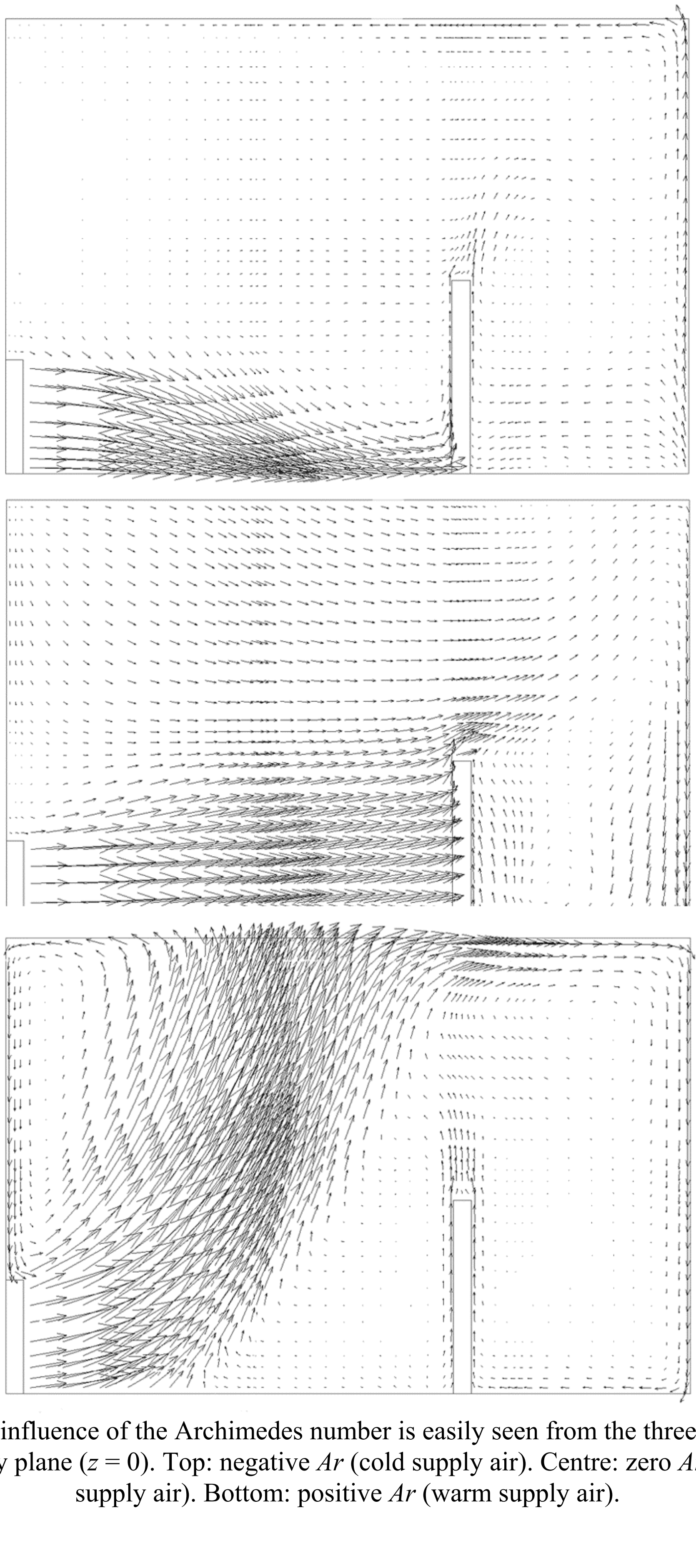

Figure 3 The influence of the Archimedes number is easily seen from the three flow fields in the symmetry plane ($z = 0$). Top: negative Ar (cold supply air). Centre: zero Ar (isothermal supply air). Bottom: positive Ar (warm supply air).

The room height (Case B) is found to influence the ventilation effectiveness significantly in case of the warm contaminant source, however, in a rather unexpected direction. The results show that the effectiveness decreases when the room height increases. The reason for this result may be sought in the confounding factor that the air change rate varies at the same time, see Table 2. All other things being equal, it is expected that increased room height will increase or maintain the ventilation effectiveness. This factor should be further investigated for maintained air change rates when the room height is changed.

Figure 3 shows the significant influence of the Archimedes number (Case C), which is quite expected. Supply of warm air to a displacement ventilated room ($Ar > 0$) is decidedly a design error. The influence on the effectiveness, however, is not significant in this case and is furthermore substantially influenced by the location of the inlet device relative to the person. A slight decreasing tendency of the effectiveness in case of warm air supply is seen, which may also be expected.

Increased air change rate (Case D) is found to increase the indoor air quality in the displacement ventilated room significantly in case of the warm contaminant source, see Figure 2. The increase in air change rate is caused by a reduced room volume (room height) while maintaining the air flow rate. If the air flow rate is increased while the room height is maintained even more pronounced increase in effectiveness may be expected.

For all cases it is important to note that specific and local phenomena may affect the results that cannot be generalized on the basis of a single test case. For instance, the location of the person relative to the inlet device may highly influence the results. The aim of this paper is to exemplify the idea rather than give specific guidance regarding the influence of boundary conditions.

In order to manage the investigation of a sufficiently high number of parameters, it will most likely be necessary to use a rather coarse computational grid to evaluate the relative influence as the first step. If the influence is found to be significant, a denser grid should be applied to make sure that the solution is grid independent. Similarly, if general guidance with regard to boundary conditions is provided, grid dependence must always be ensured.

ACKNOWLEDGEMENTS

This article is produced within the research project IDEEB, Intelligently Designed Energy Efficient Buildings. IDEEB is partly financed by the European Commission within the 5th Framework Programme, ENERGIE.

REFERENCES

Brohus, H. and Nielsen, P.V. (1996a). Personal exposure in displacement ventilated rooms. *Indoor Air* **6** (3), 157–167.

Brohus, H. and Nielsen, P.V. (1996b). CFD models of persons evaluated by full-scale wind channel experiments. *Proceedings of Roomvent ´96, 5th International Conference on Air Distribution in Rooms*, July 17–19, Yokohama, Japan,Vol. 2, pp.137–144.

Etheridge, D.W. and Sandberg, M. (1996). *Building Ventilation: Theory and Measurement*. New York: John Wiley & Sons Ltd. ISBN 0 471 96087 X.

Rodes, C.E., Kamens, R.M. and Wiener, R.W. (1991). The significance and characteristics of the personal activity cloud on exposure assessment measurement for indoor contaminants. *Indoor Air* **2** (1) pp. 123–145.