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Energy Simulation of Displacement Ventilation in Offices

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ABSTRACT Modelling and simulation of heating, ventilating, and air-conditioning systems in the context of building performance evaluation, is rapidly gaining more and more interest (see eg [1]). The objective of the case study described in this paper is to evaluate the performance of displacement systems in offices (ie an environment with a low air pollution load) in terms of thermal energy.
The paper describes the modelling, how the model is verified, and summarizes the simulation results. The main conclusion of this case study is that - from an thermal energy point of view - application of a displacement system in typical offices is only recommended when the casual gains are relatively low (ie up to 30 W/m^2).

1. INTRODUCTION

In recent years there has been a considerable interest in displacement ventilation systems. In literature there are several texts discussing the principles and application of these systems (eg [2]).
In general, displacement ventilation has a higher ventilation efficiency than mixing ventilation. In case cooling is needed, heat dissipation can be regarded as an indoor air "contaminant". Thus, due to its higher ventilation efficiency, displacement ventilation is said to result in cooling energy savings when compared to a mixing ventilation system.

In regions like Scandinavia, displacement ventilation has been applied for already a few decades in both industrial and commercial buildings. Because of its relatively high ventilation efficiency, displacement ventilation is used in countries like for instance the UK and The Netherlands in factories and workshops where there is a high degree of heat dissipation or air contamination. For such applications displacement ventilation is a proven technology.

In recent years there seems to be a trend towards using displacement ventilation also for office type environments. The work underlying this paper concerns the applicability of displacement systems in offices. The current work focused on possible energy savings of displacement ventilation relative to a mixing system. In this case only thermal energy is considered; ie. electricity consumption for fans is not taken into account. The primary investigation technique is computer modelling and simulation (employing the ESP-r building and plant energy simulation environment [3].

The remainder of this paper gives an overview of the modelling and verification, followed by a summary of the main simulation results.

2. MODELLING

The simulations are based on a "standard office module" located in The Netherlands (temperate sea climate). This module is an office (5.4 *m* deep x 3.6 *m* wide x 2.7 *m* high) with only one external wall (3.6 *m* wide x 2.7 *m* high). The South facing facade has a window area of 40% (double glazing). Solar shading is "activated" whenever the incident solar radiation on the window is above 300 W/m^2.

When a room with displacement ventilation is cooled, there will be a vertical air temperature gradient due to the upward air flow. Modelling of such conditions is still very difficult. Like most other building energy simulation systems, the current ESP-r version assumes complete mixing of the zone's air. Predictions regarding local air flow patterns within a zone are therefore not yet possible (however this is the subject of ongoing research which involves incorporation of Computational Fluid Dynamic techniques in ESP-r [4]).

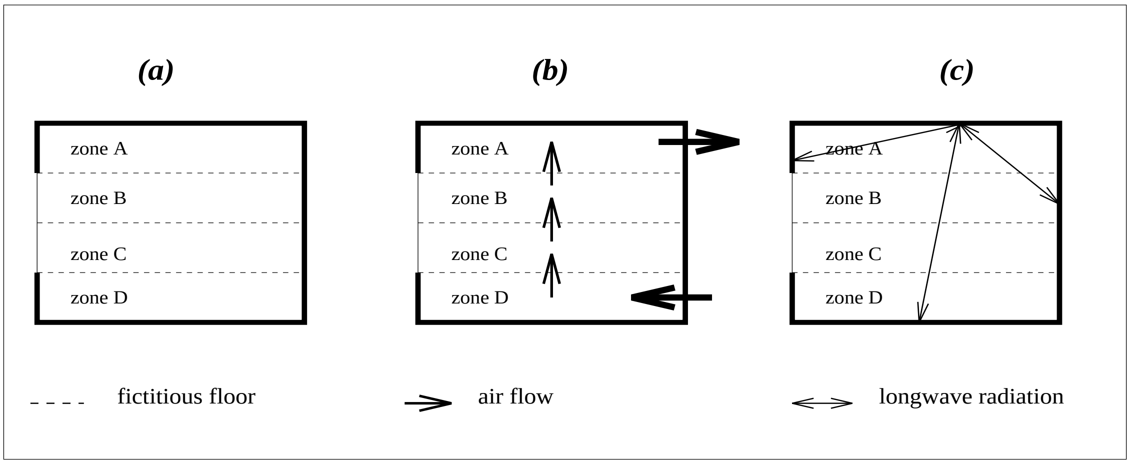

Figure 1 Dividing a zone in stacked sub-zones separated by fictitious floors

For the current work thermal stratification is approximated by sub-dividing the office in stacked sub-zones separated by "fictitious" floors (Figure 1a). In the case of displacement ventilation (in cooling mode) the dominating flow in the room can be approximated as shown in Figure 1b. In each sub-zone, completely mixed conditions are assumed.
From an "analytical" validation study it is concluded that for displacement systems it is necessary to take inter-zonal longwave radiation exchange (eg from the floor to the ceiling) into account. Therefore some modifications had to be made to the current ESP-r version which effectively made the fictitious floors transparent for longwave radiation (Figure 1c).

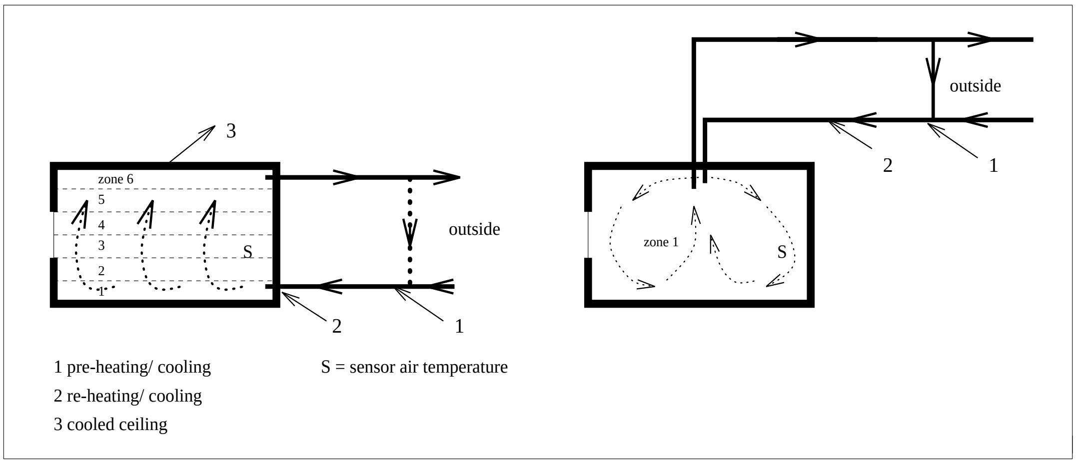

Figure 2 Modelling displacement ventilation and mixing system

Heating or cooling of the room is controlled on the basis of the air temperature sensed at a height of 1.2 m. The supply air consists of fresh air which might be mixed with recirculated air (for energy conservation reasons). This air is pre-heated or pre-cooled in a separate zone which represents the air handling unit, and re-heated or re-cooled before entering the room. The resulting model is schematically indicated in Figure 2.

3. MODEL VERIFICATION

The model is verified with experimental results [5] from a displacement system in an office very similar to the standard office module described above.

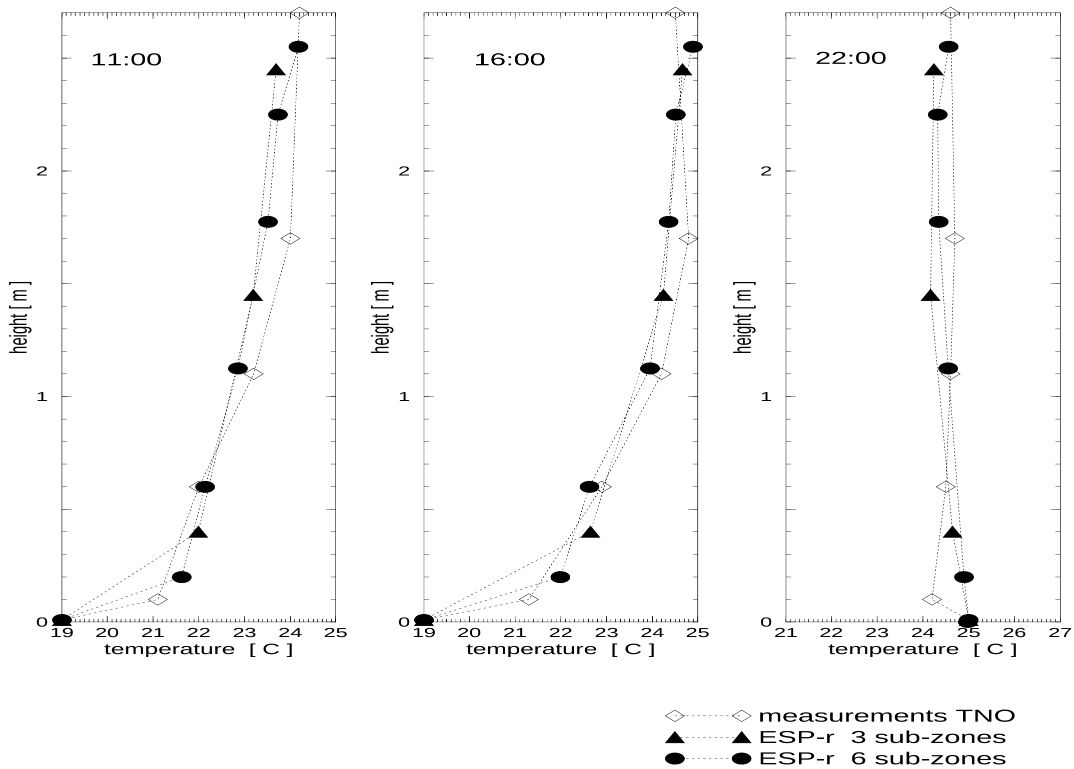

Figure 3 Vertical air temperature gradients for different times during 8 August 1989

In order to verify the model, a number of simulations were carried out with models incorporating respectively three and six stacked sub-zones. Figure 3 illustrates both measurements and "predictions" for vertical air temperature gradients during 8 August 1988.

From Figure 3 it can be seen that the predicted vertical air temperature gradients during office hours (due to the relatively cold incoming air) quite well represent the measured values. The maximum error in the predicted air temperatures is approximately 1 K.

From the verification it is concluded that ESP-r is capable of generating quite accurate predictions of air and surface temperatures in a room being cooled with a displacement ventilation system. However since there were no experimental results available for a displacement ventilation system combined with a cooled ceiling, it is not yet possible to verify the model for that case.

4. SIMULATIONS

Simulations were carried out in order to compare a displacement system with a mixing system in terms of annual energy consumption. As implied in Figure 3, the basis of comparison is the same air temperature at 1.2 m above the floor. During office hours (8:00 - 18:00) the set points (air temperature) were 20°C for heating and 22°C for cooling. In the period 6:00 - 8:00 the set point for heating increases (linear) from 15°C to 20°C. Outside these hours and during weekends the set point for heating is 15°C. In the case of a cooled ceiling the cooling set point for the air temperature is 1.5°C higher in order to achieve a comparable operative temperature.

For energy conservation reasons, part of the extracted air is recirculated. The recirculation ratio depends both on the amount of fresh air needed for indoor air quality and on the outdoor temperature T_e; in the current case: no recirculation when $16°C \leq T_e \leq 22°C$, 60% recirculation when $T_e > 22°C$ or $T_e < 10°C$, and a linear varying ratio (from 60% to 0%) when $10°C \leq T_e < 16°C$.
If necessary, the air is pre-heated or pre-cooled (with a proportional controller) to achieve a temperature between 16°C and 22°C when leaving the mixing-box. Depending on the load of the room, the air is then re-heated or re-cooled (using on-off control) before entering the room. In the current case the simulation (and thus on-off control) time-step is 3 minutes.

Although several more parameters were investigated, this paper outlines only the effects of casual gains, recirculation of extracted air, and location of the temperature sensor.

4.1. Casual Gains

Simulations were performed for casual gains of 30, 35, 40 and 50 W/m^2. In the two latter cases an additional cooled ceiling is assumed due to the limited capacity of a displacement system; the maximum load which can be handled while ensuring thermal comfort is about 30...35 W/m^2 [6, 7].
Table 1 holds the results for casual gains of 30 W/m^2. The quoted energy consumption is the net supply to the air; ie electricity for the fans is not included. The energy consumption for heating incorporates both pre-heating and re-heating of the supply air.

Table 1 Energy consumption (in kWh) for the standard office module and assuming casual gains of 30 W/m^2

	mixing system		displacement system	
period	heating	cooling	heating	cooling
January	172	0	167	0
February	130	0	128	0
March	95	1	95	1
April	40	18	41	17
May	6	41	7	39
June	3	76	4	68
July	1	79	1	70
August	3	92	3	81
September	8	53	9	46
October	17	12	20	13
November	106	0	106	0
December	166	0	164	0
Annual	746	372	744	333

The annual energy consumption for cooling is about 10% lower in the case of the displacement system. In absolute values this is a saving of about 40 kWh per year for the standard office module. The savings occur mainly in the summer from June to September. Both relative and absolute savings are biggest for that period. In the spring and autumn the savings are smaller: about 2 ... 6% per month.

The savings are due to the fact that, although the control temperature is the same, in case of the displacement system in cooling mode the average air temperature in the zone is higher than in case of the mixing system. Furthermore, in case of the displacement system the temperature of the extracted air is about 1 ... 2 K higher than for a mixing system. For identical supply air temperature and flow rate, this implies a larger cooling capacity. This is illustrated in Figure 4. The upper part of Figure 4 shows the

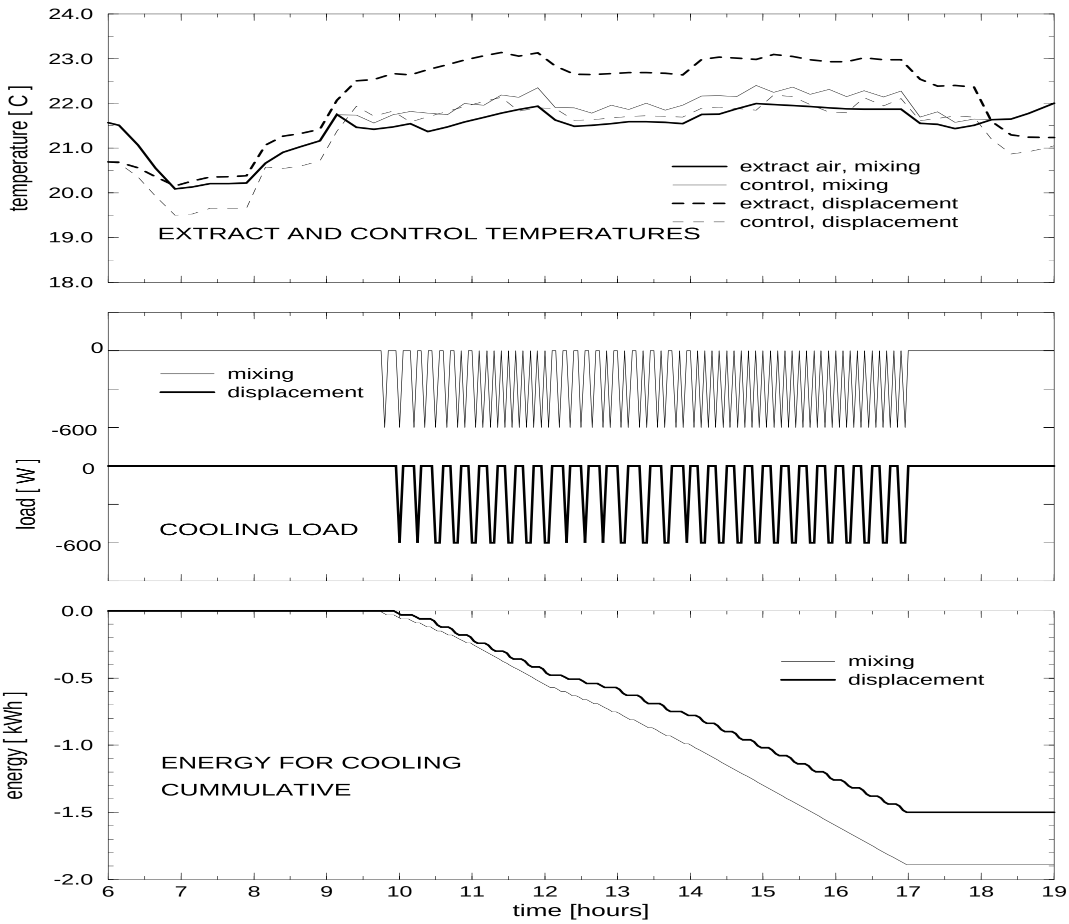

Figure 4 Temperatures, loads and energy consumption in case of cooling mode (for 25 August of a reference year)

control and extracted air temperatures (averaged over 15 minute periods) for 25 August.
As indicated before, the simulation (and control) time-step is 3 minutes in the current case. Each time-step, the cooling is either on or off depending on the initially sensed control temperature. If the cooling is off, control and air temperature will be identical. However, when the cooling is on, the initial control temperature and final air temperature will differ for that particular time-step. This effect plus the averaging over 15 minute periods result in a difference between extract air and control temperature for the mixing system.

The middle part of Figure 4 shows the cooling loads, and the lower part holds the cumulative energy consumption for cooling. The energy consumption for cooling is lowest in case of the displacement system.

It should be noted that on the basis of the energy consumption in Table 1 one should not conclude that there is no cooling load in the winter months, since during those periods cooling is achieved by adjusting the amount of outdoor air in the supply air. Additional cooling is then not necessary.

The energy consumption for heating is approximately the same for both systems. As can be seen from Table 1, this is not only so on an annual basis but also for the individual months.

The same standard office module but now oriented towards North, also has a lower energy consumption with the displacement system when compared to a mixing system. The annual energy consumption for heating and cooling is in case of a displacement system 897 and 280 *kWh* respectively. In case of a mixing system these numbers are 898 and 308 *kWh* respectively. This implies an annual 9% saving of

energy for cooling.
In case the standard office module is part of a single-story building, a 7% annual energy saving for cooling is predicted for a displacement system (252 kWh/a) when compared to a mixing system (281 kWh/a).
In all cases (North and South orientation, and single- or multi-story buildings) the savings are biggest (up to 14% per month) during the summer months.

Table 2 Energy consumption for cooling as a function of casual gains, and maximum monthly saving for displacement system relative to mixing system; + cc denotes combination with cooled ceiling.

casual gains W/m^2	energy for cooling		maximum monthly saving
	displacement kWh/a	mixing system kWh/a	
35	359	356	6% (July)
40	559 + cc	446	-43% (September)
50	751 + cc	642	-29% (May)

The results for the simulations assuming higher casual gains are summarized in Table 2. From the results follows that in case of casual gains of approximately 35 W/m^2 the energy consumption for cooling is about the same for a displacement and a mixing system. As evidenced in Table 2, the energy consumption for cooling in case of a displacement system combined with a cooled ceiling is markedly higher than in case of a mixing system. The main reason for this is that the efficiency of a cooled ceiling is relatively low. Due to the low surface temperature of the ceiling part of the cooling capacity is actually cooling the room above. A higher thermal resistance of the floor immediately above the cooled ceiling will decrease this effect.
The low ceiling temperature also influences the vertical air temperature gradient. The air in the uppermost part of the room is overcooled. Thus the air temperature decreases near the ceiling which has a negative effect on the efficiency of the displacement system.

Although the studies differ on a number of points, the conclusions of the current study in terms of thermal energy consumption are very similar to those reported by Haendel et al [8] and by Niu [9] who also compare a mixing system (VAV system) with a displacement system combined with a cooled ceiling. However these authors also include electrical energy consumption and found that for the cases they considered there is almost no difference in total energy consumption between the different systems. This is mainly due to the larger required fan power for the VAV system relative to the displacement system combined with a cooled ceiling.
As indicated by Niu [9] the comparison results will depend on which climate is taken into account; for example in a hot, humid climate the cooled ceiling might be more favourable.

4.2. Recirculation of Extracted Air

In all the considered cases it is assumed that part of the extracted air will be recirculated. Because the temperature of the extracted air in case of a displacement system is up to 2 K higher when compared to a mixing system, this part of the make-up air needs to be cooled deeper. However, even when in summer conditions 25% of the extracted air would be recirculated, the absolute differences between displacement and mixing appear to be relatively small. Recirculation therefore has only a small effect on the total energy consumption for cooling. Obviously the effect on ventilation efficiency and indoor air quality is much higher; therefore recirculation seems not advisable.

4.3. Vertical Location of Temperature Sensor

In a space with a displacement system there will usually be a vertical air temperature gradient. For that reason the vertical location of the air temperature sensor is important. This is particularly so in situations where the occupants have no direct control over the set point for the indoor climate. The vertical location of the temperature sensor does in a case like that not only affect the temperature distribution in the space but obviously also the energy consumption.

Placing the sensor 10 *cm* higher (cooling energy = 341 *kWh*) or 10 *cm* lower (cooling energy = 300 *kWh*) than the "standard" height of 1.2 *m* (cooling energy = 332 *kWh*) results in an annual energy consumption for cooling which is about 2% higher or 10% lower respectively, assuming that the actual set point is the same. The energy consumption for heating is in both cases approximately 2% higher.
Since the vertical air temperature gradients are neither linear nor constant over the height of the room (as can be seen in Figure 3) it is important in terms of thermal comfort to carefully consider both the vertical location of the air temperature sensor and the actual set points. Obviously it is also important to take the location and actual set point into account in comparison studies of displacement and mixing systems.

5. CONCLUSIONS

From a literature review (not described in this paper) followed that the most important design constraint for application of displacement ventilation in offices will be the magnitude of casual gains. In a space with a ceiling height of 3 ... 3.5 *m* the casual gains should be less than about 35 W/m^2 if a displacement system is to be considered. However if the displacement system is combined with a cooled ceiling, up to 80 W/m^2 of casual gains can be handled.

Simulations were carried out using a computer model of a typical office module located in The Netherlands (temperate sea climate). From the results it can be concluded that application of displacement ventilation in case of relative low casual gains (30 W/m^2) results in energy savings of up to 14% for cooling during the summer months. During the rest of the year - because of the relatively low outdoor temperatures - there is hardly any saving to be expected from application of displacement instead of a mixing system. The overall annual energy consumption for cooling can be up to 10% lower in case of a displacement system when the casual gains are relatively low.

However, at casual gains higher than 30 W/m^2 the advantage, in terms of cooling energy consumption, of a displacement system disappears. At casual gains above about 35 W/m^2, and a ceiling height of 3 ... 3.5 *m*, a displacement system needs an additional cooled ceiling. In that case, the energy consumption for cooling will be considerably higher than in case of a mixing system only.
In the current study, electricity consumption was not taken into account. As evidenced by other authors ([8, 9]) the difference between the systems decreases when electricity consumption is included.

So the main conclusion of this case study is that application of a displacement system in typical offices is only recommended - from a thermal energy point of view - when the casual gains are relatively low.

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