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THERMAL PERFORMANCE OF A ROOM WITH AIR DISPLACEMENT VENTILATION SYSTEM

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ABSTRACT
The usual cooling load programs can only be used for rooms with a uniform temperature distribution. With a new program ACCURACY it is also possible to calculate situations with a vertical temperature stratification. With this program, the hour-by-hour cooling/heating loads have been calculated for a room with a displacement ventilation system (with temperature stratification) and a well-mixed system (without temperature stratification). With an energy calculation program, ENERK, the yearly energy consumption of both systems have been calculated and mutually compared. For the same inlet air temperature, the energy costs of the displacement ventilation system are about 16% lower in comparison with the well-mixed system in the situation considered.

INTRODUCTION.
A new cooling load program, ACCURACY, has been constructed for calculating the cooling load of a room with vertical temperature stratification [1]. In this program the air flow in the room or the temperature differences are considered. To show the possibilities for application in practise it is used for an evaluation of the energy consumption of different air supply systems. A more detailed description of this research project has been given in [2].

CALCULATION OF HEATING/COOLING LOAD WITH ACCURACY.
The hour-by-hour heating and cooling loads have been calculated with ACCURACY for a reference year for two systems i.e. a well-mixed system and a displacement ventilation system. The well-mixed system has been shown in Fig.1a (air inlet through two grills in the back wall near the ceiling and outlet through two grills in the back wall near the floor), and the displacement system in Fig.1b (air inlet through one grill in the back wall near the floor and outlet through two grills in the back wall near the ceiling). In the displacement system, cool air is supplied

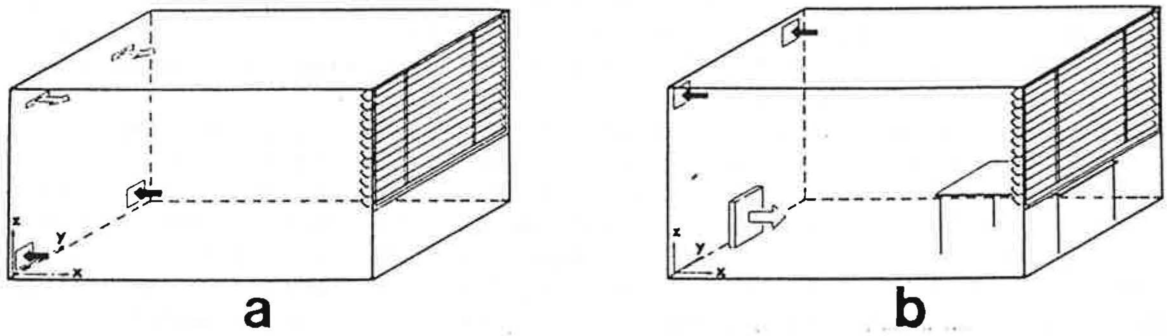

Figure 1. Air supply systems. (a) Well-mixed system; (b) Displacement ventilation system.

near the floor; then it is heated by heat sources and extracted near the ceiling. This results in a vertical temperature gradient in the room. Both systems have been examined in a climate room with dimensions 5.6 m x 3 m x 3.2 m (resp. length x width x height) and rather big heat capacity (concrete floor and ceiling). The calculations also have been based on the dimensions and physical data of the climate room.

As discussed in [1], the cooling load program ACCURACY can be used in different ways. In the most extended way (method 5, with air flow patterns), the calculation is very accurate but costs relatively much computer time. For the yearly calculations here, the simplified method (method 4) is used because this method costs less computer time. In this method the temperature differences in the room are expressed as functions of the cooling load, thus DT = f(Q). These functions have been derived from temperature distributions calculated with an air flow program.

Measurements and calculations on the well-mixed system showed that the temperature differences in the room were negligibly small (< 0.5 K). For the displacement ventilation system, the functions DT =f(Q) were derived from calculations during cooling situations. For heating situations both, calculations and experiments, showed a rather uniform temperature distribution, because under the window a radiator was installed.

Both systems were considered for variable air volume control (VAV) and constant air volume control (CAV). In the VAV control, the inlet temperature was kept at 16.0°C for the displacement system and 12.5°C and 16.0°C for the well-mixed system. In the CAV control, the inlet mass flow was 5-time air exchange rate per hour.

In this way, the hour-by-hour cooling and heating loads have been calculated for a so called Dutch reference year [3].

CALCULATION OF ENERGY CONSUMPTION WITH ENERK

In order to find the annual energy consumption, the energy required for cooling, drying, heating and air supply have been derived from the hourly heating and cooling loads by means of an energy calculation program ENERK [4]. In ENERK, the psychrometric chart has been divided into seven sections each with the same control strategy (see Fig.2). The outside conditions now are spread over the different sections and the occurrence of outside conditions in every section is counted. Also the average outside condition is calculated for every section together with the average heating and cooling load. In the same section, heating as well as cooling situations can occur. Therefore, they have to be handled separately. Next for every section, the most economic air handling method can be indicated in the psychrometric chart and the energy necessary for cooling, drying, heating and air supply is calculated. By multiplying these energies for every section with the amount of times, that the outside condition is in this section, and by summation of these data, the yearly heating and cooling energy can be calculated. With a certain COP for the chiller and efficiency for boiler and ventilator, these energy demands can be calculated into consumption of electricity and gas and also in energy costs.

During office hours, the air temperature in the occupied zone is maintained to be 22.0°C $\pm$ 2.0 K and the absolute humidity is controlled between 6.0 and 9.0 g/kg. If the air temperature is in the range between 20.0 to 24.0°C, there is no heat extraction in the room. However ventilation is always necessary for fresh air during office hours. It is supposed there is always 300 W convective heat released in the room during office hours from occupants, appliances etc.. During weekends and night hours, the air conditioning system is switched off. From April to

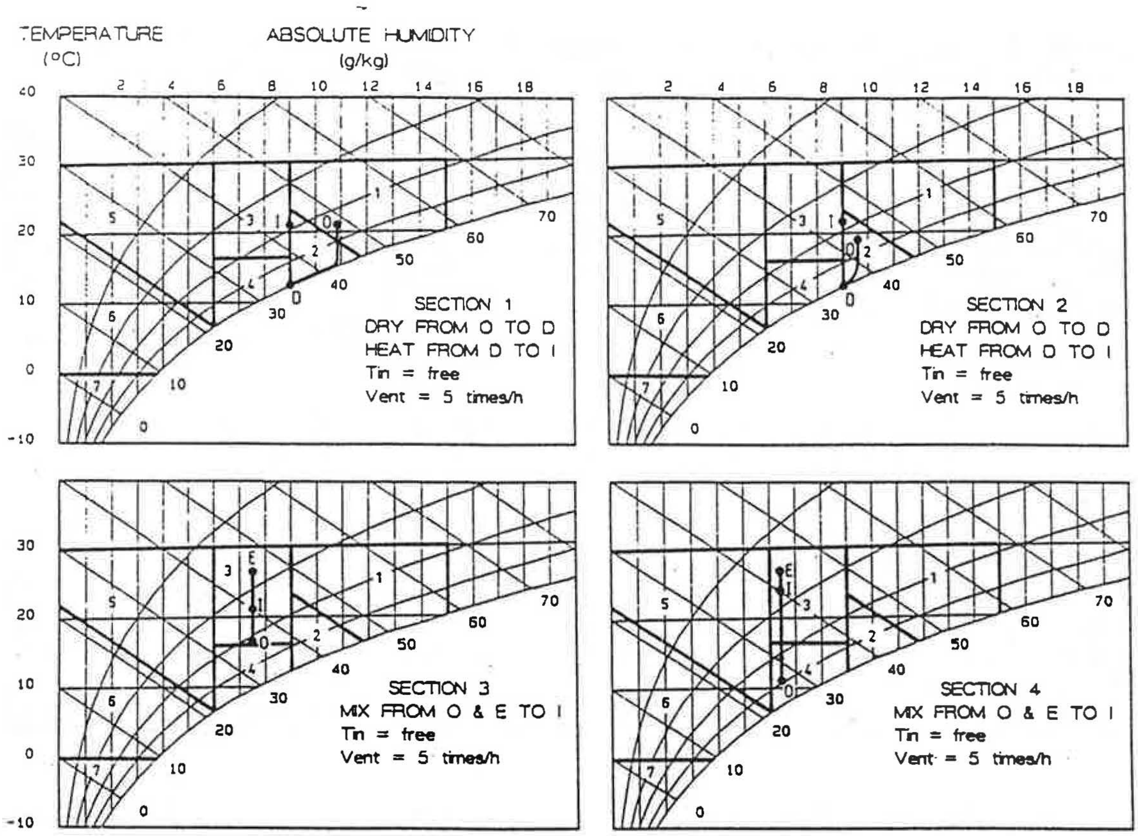

Figure 2. Control strategies for cooling in four sections of the psychrometric chart for VAV-control and displacement ventilation system.
(O - outdoor air, E - air extracted, D - dew point, I - inlet air, M - mixing point, H - heating point).

September an external venetian blind is used to reduce heat gain through the window.
The efficients of the primary equipment are assumed to be constant. The pressure of the ventilator is 1400 Pa and its efficiency is 0.6. The efficiency of the boiler is 0.75 and the COP value of the chiller is 3.5.

RESULTS

Fig.2 shows an example for four sections in the psychrometric chart. The most economic control strategies have been presented for cooling situations in the VAV system. In section 1, the air extracted (E) is mixed with outdoor air (O), then cooled and dried to point D (because the moisture content is restricted between 6 and 9 g/kg) and heated to point I. In section 2 the outdoor air has to be dried from O to D and then heated to I. In sections 3 and 4 the outdoor air can be used directly (section 3) or after mixing with outdoor air (section 4).
Table 1 presents the heat extraction of the room, the heat removed by cold water and the heat supplied by hot water in the different sections of the psychrometric chart for the displacement system. Table 2 shows the results for the well-mixed system.
From these tables, we can see that the heat extraction (cooling) for the displacement system is lower than that for the well-mixed system (in section 1 114.3 against 124.6 kWh). The heat supply for the two systems

Table 1. Heat extraction, heat removed by cold water and heat supplied by hot water with the displacement system. (VAV-control) (kWh)

Sections in psy. chart	1	2	3	4	5	6	7	Total
Heat extraction	114.3	121.7	239.2	17.9	69.8	2.8	-	565.7
Heat removed	154.0	104.7					-	258.7
Heat supplied	37.2	41.6				5.9	-	84.7
Heat supply	-	0.0	0.0	26.6	25.3	199.0	177.1	428.0
Heat removed	-	1.8						1.8
Heat supplied	-	5.0	6.2	51.6	51.8	347.2	244.5	706.3

Table 2. Heat extraction, heat removed by cold water and heat supplied by hot water with a well-mixed system. (VAV-control) (kWh)

Sections in psy. chart	1	2	3	4	5	6	7	Total
Heat extraction	124.6	132.4	254.2	18.4	76.6	2.9	-	609.1
Heat removed	182.7	139.3					-	322.0
Heat supplied	51.6	54.9				5.9	-	112.4
Heat supply	-	0.0	0.0	26.6	25.3	200.1	177.0	429.0
Heat removed	-	1.8						1.8
Heat supplied	-	5.6	9.4	51.6	51.8	347.2	244.5	710.1

is about the same. The reason is that in the displacement system (with a vertical air temperature difference for cooling) the average air temperature is higher than that of the well-mixed system. As a result the heat extraction of the displacement system during cooling is lower. However, the difference of the heat removed by cold water between the two systems is larger than that of the heat extraction (in section 1 154.0 against 182.7 kWh). The reason is that the temperatures of the air extracted are also higher in the displacement system and therefore the corresponding supply air flow is smaller. This of course influences the heat removed by cold water and also the energy consumption of the ventilator (see Table 3).

For heating situations, no vertical room air temperature differences existed for the displacement system and the well-mixed system. Therefore the heat supply for both systems is about the same.

From Tables 1 and 2, it is also clear that the relationship between the heat extraction and the heat removed by cold water and supplied by hot water is very complicated. In section 1 as shown in Fig.2, for example, the enthalpy difference between the outdoor air and the dewpoint is higher than that between the extracted air and the air supplied. However in section 3 free cooling can be used so that the heat removed by cold water is zero.

Table 3 presents the computational results of the energy consumption for the displacement system and Table 4 for the well-mixed system, both with VAV-control. The annual energy consumption of the chiller and the ventilator (electricity) for the displacement system is 26% smaller than that for the well-mixed system and the energy consumption of the boiler (gas) is 3% smaller.

According to the results computed by ACCURACY as shown in Table 1 the heat extraction for cooling is higher than the heat supply for heating. But the total energy consumption by the boiler seems to be ten times higher than that by the chiller (see Table 3). This is because the efficiency of the boiler is low (0.75) and the COP value of the chiller

Table 3. Energy consumption with displacement system. (VAV-control)*

Sections in psy. chart	1	2	3	4	5	6	7	Total
Chiller (kWh)	44.0	30.5					-	74.4
Ventilator (kWh)	21.0	24.4	54.0	8.6	17.6	14.3	4.1	144.0
							+	218.4
Boiler (kWh)	49.6	62.0	8.3	68.8	69.1	470.7	326.0	1054.

* The supply air temperature is 16.0°C.

Table 4. Energy consumption with well-mixed system. (VAV-control)*

Sections in psy. chart	1	2	3	4	5	6	7	Total
Chiller (kWh)	52.2	40.3					-	92.5
Ventilator (kWh)	29.2	32.0	72.6	9.1	22.0	14.3	4.1	183.3
							+	275.8
Boiler (kWh)	68.8	80.7	12.5	68.6	60.1	470.1	326.0	1095.

* The supply air temperature is 16.0°C.

Table 5. Annual cost of the room energy consumption (Dutch Guilders)

Air handling	Air supply	Inlet temp	Chiller	Ventilator	Boiler	Total
Variable air volume	displacement	16.0	20.27	39.22	48.51	108.0
	well-mixed	16.0	25.20	49.93	50.44	125.6
	well-mixed	12.5	17.57	42.52	43.67	103.8
Constant air volume	displacement	free	34.32	136.96	69.80	241.1
	well-mixed	free	31.41	132.05	58.94	222.4

Table 6. Energy consumption with well-mixed system. (VAV-control)*

Sections in psy. chart	1	2	3	4	5	6	7	Total
Chiller (kWh)	36.3	28.2					-	64.5
Ventilator (kWh)	20.3	22.6	72.6	6.4	16.1	14.0	4.1	156.1
							+	220.6
Boiler (kWh)		7.5	12.5	68.6	60.1	465.7	326.0	949.4

* The supply air temperature is 12.5°C.

is high (3.5) and a part of the energy is required for reheating during the cooling period. However, the prices for gas and for electricity are different. In the Netherlands at the moment one kWh electricity costs Dfl. 0.2724 (Dutch Guilders) and one kWh gas costs Dfl. 0.046. With these prices, the costs of annual energy consumption are shown in Table 5. The costs of the boiler show to be about two times those of the chiller and the ventilator costs are in between. The total costs of energy consumption for the displacement system are about 16% less than those for the well-mixed system (125.6 against 108.0).
Until now the displacement system and the well-mixed system have been compared both with an inlet air temperature of 16.0°C. To examine the influence of a lower inlet air temperature, the computations have been repeated for a well-mixed system with inlet air temperature 12.5°C. Because the supply air temperature is lower, the air mass flow to be supplied can be smaller in the sections 1, 2 and 4 for cooling (as shown in Fig.2). Moreover, reheating becomes unnecessary in sections 1 and 2

during cooling periods. Therefore, the energy consumption for cooling periods is smaller. The energy consumption for heating periods is the same as computed before. The annual energy consumption of the well-mixed system with inlet air temperature 12.5°C is given in Table 6. Compared with the results of the displacement system (supply air temperature 16.0°C) shown in Table 3, the energy consumption of the chiller and the ventilator of the well-mixed system with inlet temperature 12.5°C is the same and that of the boiler is 10% smaller. The costs of the annual energy consumption of this system are also given in Table 5. They are about 4% less than those for the displacement system with air supply temperature 16.0°C.

The displacement system with an air supply temperature of 12.5°C has not been calculated. In this case, the lowest energy consumption may be expected (due to the same reasons as discussed before).

Until now the energy consumptions have been calculated for a displacement system and a well-mixed system, both with VAV-control (variable air volume). In the same way as discussed before, the energy consumptions have been calculated for CAV-control (constant air volume) for both systems. The mass flow supplied was 0.09 kg/s, corresponding with a five-time air exchange rate of per hour. The calculations with ACCURACY and ENERK have been carried out as discussed before and here only the results of the annual costs are presented (see Table 5). It is clear that the costs of systems with CAV-control are much higher than those with VAV-control. The reason is that with CAV-control much more supply air has to be handled, which costs more energy and money. From Table 5, it is clear that the costs of CAV-control are about two times higher than of VAV-control.

CONCLUSIONS

The main results with respect to the annual costs of energy consumption have been presented in Table 5. It can be concluded for this particular case that the variable volume systems are about two times less expensive than the constant air volume systems. In the variable volume systems with an inlet temperature of 16.0°C, the displacement ventilation system is about 16% cheaper than the well-mixed system. If the well-mixed system is operated at an inlet temperature 12.5°C, this system is cheaper than the displacement system with inlet temperature 16.0°C. If the displacement system is also operated at an inlet air temperature of 12.5°C (which seems possible without causing discomfort) for this system the lowest energy costs may be expected.

REFERENCES

(1) Chen, Q. and Kooi, J. van der. Calculation of air-conditioning load in rooms with temperature stratification. 2nd World Congress of HVAC&R, CLIMA2000, Sarajevo. 1989.

(2) Chen, Q. Indoor Airflow, Air Quality and Energy Consumption of Buildings. Ph.D. Thesis, Delft University of Technology, Delft, 1988.

(3) Liem, S.H. and Paassen, A.H.C. van. Establishment of Short Reference Years for Calculation of Annual Solar Heat Gain or Energy Consumption in Residential and Commercial Buildings (Part 1), Final Report Contract No. ESF-010-80 B(B), Delft University of Technology, 1982.

(4) Paassen, A.H.C. van. Design of low energy HVAC-systems with a computerized psychrometric chart, The 2nd International Conference on System simulation in Buildings, Liége, Belgium, 1986.