Demand Controlled Ventilation in a Bathroom

D. K. Mortensen, T. R. Nielsen, S. Svendsen
Technical University of Denmark, Department of Civil Engineering

C. Topp
ALECTIA A/S

ABSTRACT

In residential buildings moisture is a dominant pollution source removed by the ventilation system. The Danish building code requires a minimum air change rate of $0.5h^{-1}$ in residential buildings to avoid moisture related problems. However a constant ventilation rate results in unnecessary energy consumption during periods where the demand for ventilation is low and poor indoor climate during periods where the demand for ventilation is high. Controlling the ventilation rate by demand can improve the energy performance of the ventilation system and the indoor climate.

This paper compares the indoor climate and energy consumption of a Constant Air Volume (CAV) system and a Demand Controlled Ventilation (DCV) system for two different bathroom designs. The air change rate of the CAV system corresponded to $0.5h^{-1}$. The ventilation rate of the DCV system was controlled by occupancy and by the relative humidity in the bathroom. The two designs differed by the construction of the shower cubicle which in one case was sealed and in the other case unsealed. The construction influenced the relative humidity within the bathroom during a shower, i.e. the pollution source the ventilation rate was controlled by. The indoor climate and the energy consumption were estimated based on a simplified calculation of the variation of the water content within the bathroom during a day.

The results showed that the DCV system controlled by occupancy and relative humidity had an improved energy performance and an improved indoor climate compared to the ventilation system with a constant air change rate of $0.5h^{-1}$. Moreover it was found that the bathroom with a sealed shower cubicle reduced the period where the relative humidity exceeded 70% by approximately half and in both the CAV and DCV system. Moreover the energy performance of the DCV system was slightly improved in the case with the sealed shower cubicle compared to the unsealed cubicle. The study indicated that indoor climate and energy optimizations of DCV systems should not be limited to considerations of the control system, but should also include considerations of the design of the ventilated rooms.

1 INTRODUCTION

Moisture is a dominant pollution source in residential buildings and in dry climates it is mainly removed by the ventilation system. Moisture is removed to prevent periods where the indoor relative humidity exceeds 70% because these periods provide optimal conditions for microbial growth and can result in deterioration of building materials over time (EN15251, 2007). The Danish building code requires a minimum air change rate of $0.5h^{-1}$ during all hours in residential buildings (EBST, 2008) as this air change rate empirically has proven to keep the relative humidity at a level where most moisture related problems are avoided. However maintaining the ventilation rate at a constant level results in unnecessary energy consumption during periods where the demand for ventilation is low, and poor indoor climate during periods where the demand for ventilation is high. Controlling the ventilation rate by demand remedies these problems. In a Demand Controlled Ventilation system (DCV) the ventilation rate is controlled by a sensor detecting a pollutant in order to keep the concentration of the pollutant below a preset value.

In a dwelling where the ventilation rate was controlled by relative humidity an energy saving of 40% was reported for heating and operation of the fan, (Månsson, 1995). In a study where the ventilation rate was increased during periods with high moisture load it was found that the basic ventilation rate could be reduced by 20% to 30% without negative impact on the indoor climate (Bergsøe, 2000).

The indoor climate and the energy consumed by a DCV system depend on the ventilation rate which is controlled by the preset value of the pollution source. Thus, the magnitude of the pollution load influences the performance of the system. If the pollution load could be reduced, the performance of the DCV system would improve.

This paper compared the indoor climate and energy consumption of a Constant Air Volume (CAV) system and a Demand Controlled Ventilation (DCV) system for two different bathroom designs. The ventilation rate of the DCV system was controlled by occupancy and by the relative humidity in the bathroom. In one case the bathroom had an unsealed shower cubicle and in the other case the shower cubicle was sealed. The design of the cubicle influenced the relative humidity within the bathroom during a shower, i.e. the pollution source that controlled the ventilation rate.

2 THE CONCEPT

A bathroom is equipped with a shower cubicle. Two designs of the shower cubicle are proposed, see Figure 1. In one case the door of the cubicle has an opening to the remaining volume of the bathroom, and air is exchanged between the bathroom and the cubicle at all times. In the other case the door of the cubicle is sealed and air cannot be exchanged between the cubicle and the bathroom when the door is closed.

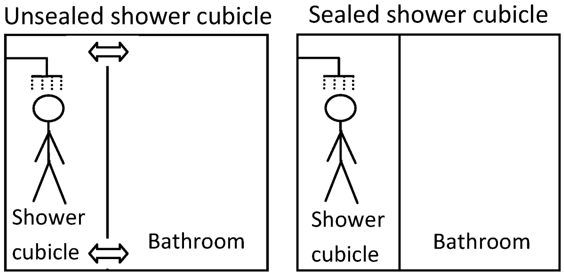

Figure 1: Left figure: Air is exchanged between the bathroom and the cubicle at all times in the unsealed cubicle. Right figure: Air cannot be exchanged between the bathroom and the cubicle when the door to the cubicle is closed.

The variation of the moisture content within the bathroom during a shower is described in the following for the two cases.

2.1.1 The unsealed shower cubicle

The water vapour content within the bathroom and the shower cubicle is the same before the shower starts. At the beginning of the shower the water vapour content in the entire bathroom increases due to the openings in the cubicle. After some time the air in the bathroom is saturated and water begins to condense on the walls of the bathroom. The condensation process proceeds until the end of the shower. During the shower the walls of the cubicle are splashed with water and at the end of the shower an amount of water will remain on the surfaces. Once the shower ends the water vapour content in the air starts to decay and the condensed water and the water which remains on the walls of the cubicle evaporates. When all liquid water has evaporated the water vapour content decays till the initial condition is reached.

2.1.2 The sealed shower cubicle

The water vapour content within the bathroom and the shower cubicle is the same before the shower starts. At the beginning of the shower the door o the cubicle is closed and the water vapour content within the cubicle increases. The water vapour content within the remaining part of the bathroom remains unchanged throughout the shower as no air is exchanged between the volume of the cubicle and the remaining volume of the bathroom. Shortly after the shower has begun the air within the cubicle is saturated and water begins to condense on the walls of the cubicle. During the shower water is splashed on the walls of the cubicle and at the end of the shower an amount of water remains left on the surfaces. Once the shower ends the door to the cubicle is opened. The saturated air within the cubicle is dissipated to the entire volume of the bathroom and the water vapour content adjusts to the new volume. The water which remains on the walls of the cubicle evaporates. When all liquid water has evaporated the water vapour content decays till the initial condition is reached.

3 METHOD OF INVESTIGATION

The investigation of the two bathroom designs was based on a dormitory room with an area of 30m^2 and a room height of 2.5m. The dormitory room included a bathroom of 5m^2 which was equipped with a shower cubicle of 90cmX90cm. The investigation was made on a day where the outdoor temperature and relative humidity constantly was assumed to be 10°C and 80%. One person occupied the room. The daily user profile and the associated moisture production are given Table 1 (Månsson, 1995), (Dorer et al., 2005).

Table 1: Daily user profile in the dormitory room and the associated moisture production.

	Human activity		Other activity	
Time	-	g/h	-	g/h
00:00-07:00	Sleeping	30	None	0
07:00-07:10	Awake	55	Shower	2640
07:10-08:00	Awake	55	None	0
08:00-18:00	Away	0	None	0
18:00-23:00	Awake	55	None	0
23:00-24:00	Sleeping	30	None	0

In the dormitory room air was supplied to living room and extracted through the bathroom. No extract efficiency was assumed for the air terminal device in the bathroom. The air change rate of the CAV system corresponded to 0.5h^{-1} in the entire dormitory room all day in accordance with the requirement in the Danish building code. The ventilation rate of the DCV system was determined by the occupancy of the room and the relative humidity in the bathroom. The sensor detecting the relative humidity in the bathroom was placed outside the shower cubicle. In Table 2 the ventilation rates of the CAV and DCV systems are given.

Table 2: Ventilation rates of the CAV and DCV systems determined by occupancy and the relative humidity in the bathroom.

	CAV	DCV
	l/s	l/s
Unoccupied hours	10.4	3.0[1]
Occupied hours	10.4	10.4
RH$_{bathroom}$>70%	10.4	20.8[2]

[1] Equivalent to 0.1 l/sm^2. (EN15251, 2007)

[2] The maximum ventilation rate equalled a doubling of the ventilation rate during occupied hours

3.1 Calculation of the relative humidity

The relative humidity within the bathroom was calculated by setting up a mass balance for the room. The indoor air and wall temperature was 24°C, with the exception that the temperature of the saturated air within the sealed shower cubicle reached 30°C during a shower.

The mass balance of the bathroom was given by: the content of water in the supply air, the moisture production within the dormitory room, the moisture transport from the walls of the bathroom and the water content of the extract air.

$$V\frac{dc}{dt}=nVc_e + G + \beta(p_s\text{-}p_i)A - nVc_i \qquad (1)$$

Where:

A: Surface area of evaporation, m^2.

β: Wall surface film coefficient, $1.85\cdot10^{-5}$g/sm^{2}Pa (Hens, 2007)

c$_e$: Water content of the supply air, g/m^3

c$_i$: Water content of the bathroom air, g/m^3

G: Moisture production in the bathroom, g/h
n: Air change rate in the bathroom, h^{-1}
p_s: Partial pressure at the surface of the wall, Pa
p_i : Partial pressure in the bathroom, Pa.
t: Time, s
V: Volume of the bathroom, m^3

During periods with evaporation of water β equalled $1.85\cdot10^{-5}$ g/sm^{2}Pa, at all other times beta equalled zero.

During periods when condensation occurred, the water content of the air remained constant at 100% relative humidity and a simplified estimation of the build-up of condensate was made. It was assumed that the difference in moisture content released by the pollution source (G) and the moisture content of the saturated air within the bathroom (c_i) times the ventilation rate was deposited as liquid water on the surfaces of the walls of the bathroom.

The amount of water deposited on the walls of the shower cubicle due to splashing during the shower was estimated based on an experiment. The experiment was made by weighing a tissue before and after wiping off the water that remained on a given area of bathroom tiles after a shower. It was found that 20g of water remained pr. m^2 wall.

3.2 Calculation of energy consumption

The energy consumption for heating the air and for operation of the fan was calculated for one day.

The energy consumed by the fan, E_{fan}, is the product of time the fan is operated multiplied by the power consumption during that time. The power consumption of the fan is given by:

$$P_{fan}=\frac{q\cdot\Delta p}{\eta} \qquad (2)$$

Where:
Δp: Pressure drop, Pa.
P_{fan}: Power consumption of the fan, W.
q: Ventilation rate, m^3/s.
η: Efficiency of the air handling unit, %.

It was assumed that one air handling unit supplied air to16 dormitory rooms and that the efficiency of the complete air handling unit was 10%. A static pressure of 100Pa was maintained at a reference point in the system to ensure even distribution of the air. At an air change rate corresponding to 0.5h^{-1} in the 16 similar dormitory rooms the pressure drop in the system was assumed to be 150Pa. A fan performance curve was created based on these assumptions and the following equation (Hansen, -):

$$\Delta p=p_{ref}+ r\cdot q^{1.4} \qquad (3)$$

Where:
p_{ref}: Pressure maintained in the reference point, Pa
r: Specific resistance of the system, -

The energy consumption for heating the air was calculated assuming that a heat exchanger with an efficiency of 80% was applied to the ventilation system. The energy used for heating the air, E_{heat}, is the product of the time with a given ventilation rate multiplied by the power consumption during that time. The power consumption is given by:

$$P_{heat}=q\rho c_a(1-\varepsilon)(T_{in}-T_{out}) \qquad (4)$$

Where:
c_a: Specific heat capacity of air, J/kgK
ε: Efficiency of heat exchanger, %
P_{heat}: Power consumption for heating, W
q: Ventilation rate, m^3/s
ρ: Density of air, kg/m^3
T_{in}: Temperature in the bathroom, K
T_{out}: Temperature outdoor, K

4 RESULTS

The quantity of air passing through the room and the energy consumed for heating the air and operating the fan are given in Table 3 on a daily basis.

Table 3: Quantity of air passing through the room and energy consumption for heating the air and operation of the fan on a daily basis.

	q	E_{fan}	E_{heat}
	m^3/day	kWh/day	kWh/day

Unsealed cubicle	CAV	900	0.375	0.846
	DCV	656	0.271	0.616
Sealed cubicle	CAV	900	0.375	0.846
	DCV	645	0.262	0.606

The number of minutes where the relative humidity exceeded 70% in the bathroom is given in Figure 2 on a daily basis.

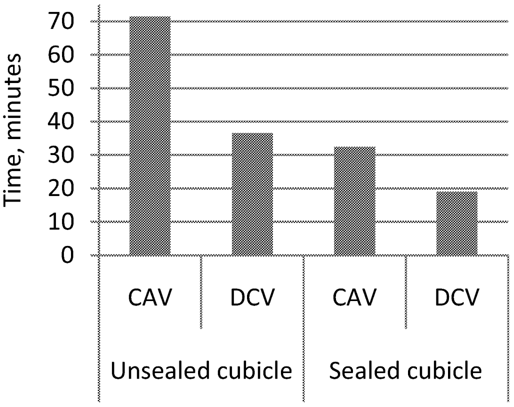

Figure 2: Number of minutes with a relative humidity above 70% in the bathroom on a daily basis.

5 DISCUSSION

The energy consumed for heating the air and operating the fan of the DCV system was reduced by respectively 28% and 27% compared to the CAV system in the case with an unsealed cubicle. In the case with a sealed shower cubicle the reductions were respectively 30% and 28%. The improved energy performance of the DCV systems compared to the CAV systems were due to the lower quantity of air passing through the room on a daily basis. I.e. less air was moved by the fan and less air needed to be heated. The energy performance of the DCV system was slightly improved in the case with the sealed cubicle compared to the case with the unsealed cubicle. This was because the maximum ventilation rate in the bathroom with the sealed cubicle was not activated until the end of the shower, whereas it was activated during the shower in the bathroom with the unsealed shower; i.e. the quantity of air that needed to be moved and heated was slightly reduced.

The number of minutes where the relative humidity on a daily basis exceeded 70% was reduced in the DCV system compared to the CAV system for both bathroom designs. In the case with the unsealed shower cubicle the number of minutes was reduced by 48% and in the case with the sealed shower cubicle the number of minutes was reduced by 41%. The improved performance of the DCV systems was due to the increased ventilation rate during periods with a relative humidity above 70%. Considering the two ventilation systems individually the results showed that there were fewer minutes with a relative humidity above 70% in the case with a sealed cubicle compared to the case with an unsealed cubicle. For both the CAV and DCV system it was found that the time where the relative humidity exceeded 70% was reduced by approximately half in the case with a sealed shower cubicle. The sealed cubicle prevented dispersion of water vapour to the entire bathroom during the shower and thereby no water condensed on the walls of the bathroom during the shower.

The use of a sealed shower cubicle will change the atmosphere in the shower. To ensure that a person would accept such a change further investigations should be made. However the results of this study indicate that optimization of a DCV system should not be limited to the control of the system but should also include considerations of the design of the ventilated rooms.

6 CONCLUSION

This paper compared the indoor climate and energy consumption of a Constant Air Volume (CAV) system and a Demand Controlled Ventilation (DCV) system for two different bathroom designs. In one case the bathroom had an unsealed shower cubicle and in the other case the shower cubicle was sealed.

The DCV system controlled by occupancy and relative humidity had an improved energy performance and an improved indoor climate compared to the ventilation system with a constant air change rate of $0.5h^{-1}$. In the bathroom equipped with a sealed shower cubicle the period where the relative humidity exceeded 70% was reduced by approximately half and in both the CAV and DCV system. Moreover the energy performance of the DCV system was slightly improved in the case with the sealed shower cubicle.

The study indicates that indoor climate and energy optimizations of DCV systems should not be limited to considerations of the control system, but should also include considerations of the design of the ventilated rooms.

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