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CONTROL OF NIGHT COOLING WITH NATURAL VENTILATION

Sensitivity Analysis of Control Strategies and Vent Openings

A H C van Paassen, S H Liem and B P Gröninger

Laboratory of Refrigeration Engineering and Indoor Climate Technology
Faculty of Design, Engineering and Production
Delft University of Technology

The inverse of C, 1/C, denotes the resistance as shown in figure 3. The driving pressure sources 1 to 9 are calculated with a Cp-generator [3] according $P_i = \frac{C_p \cdot \rho \cdot v^2}{2}$.

The thermal model calculates the air and mean wall temperatures in the rooms and the air temperature in the corridor or hall, see figure 4. The inputs are the outdoor weather data, the ventilation flows from the ventilation model and the window and louvre angles from the controller. During office hours there is an internal heat source in the rooms but not in the corridor. Moreover there are the ventilation heat flows caused by the airflow's calculated by the ventilation model in all spaces. The window and sun-shading device have no heat storage. The solar gain that enters the room is splitted into a convective and radiant part and is determined by respectively:

$Q_{s\_conv} = Q_s \cdot ZTA \cdot CF$ and $Q_{s\_rad} = Q_s \cdot ZTA \cdot (1 - CF)$

With:

CF = convection factor
Q_s = solar radiation on the façade [W/m^2]
Q_{s_conv} = convective heat flow from the window to the room air [W/m^2]
Q_{s_rad} = radiant heat flow falling through the window [W/m^2]
ZTA: = solar atmittance factor

The radiant part is assumed to be equally divided across the entire inner area of the room. In figure 4 the broken arrows represent these solar gains. For a double pane window with the outside sun shades down, ZTA=0.13 and CF=0.07; with the sunshades up, ZTA=0.7 and CF=0.03. The sun shades goes down when $Q_s > 250$ W/m^2. In [1] the ventilation and thermal models are described in more detail.

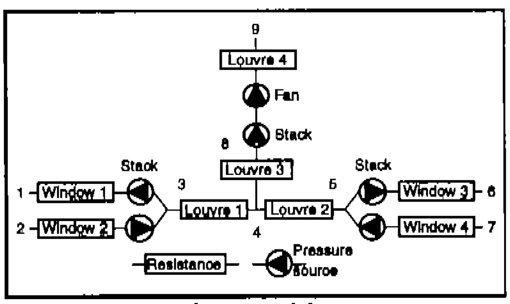


Figure 3. The ventilation model

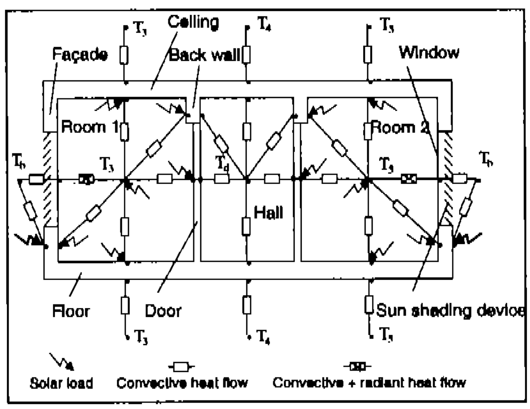


Figure 4. The thermal model

3. THE CONTROL STRATEGIES

In [1,2,4,5,6] various predictive control strategies for cooling are described. Five are compared:

- 'Cooling day' control strategy [1,2]
- 'Degree hour' control strategy [4]
- 'Setpoint' control strategy [4]
- 'Slab temp' control strategy [4]
- 'Manual control'

All control systems use the same control strategy during office hours (08:00-18:00) (PI-feedback algorithm that tries to keep the resultant temperature at the cooling setpoint (22 ^{0}C);

when $T_0 > T_{in}$, or when $T_0 < 12\ ^0C$, the vent openings and louvres are closed), but in off hours (18:00-08:00 and weekends), each system uses its own control strategy to precool the room.

The 'Cooling Day' control strategy uses the same PI-algorithm as during office time, only the precooling setpoint is variable. It is set according a rule based prediction between 18-22 ^0C: after a day with demand for cooling, the setpoint is decreased with 2K until 18 ^0C. No cooling day set the opposite in operation. So it anticipates on a coming warm period [2].
Precooling mode with 'Degree Hour' control strategy. At the end of the office time the degree hours are determined (number of hours $T_{in} > 21\ ^0C$). A positive number means heat has been absorbed in the slab. Night cooling is only permitted, when the air temperature during that day exceeds 24 °C for more than 1 hour.
Precooling mode with 'Set Point' control strategy. Night cooling is enabled if the average outside air temperature between 12:00 and 17:00 hours exceeds 18 °C.
Precooling mode with 'Slab Temperature' control strategy. The 'Slab Temperature' control strategy is the same as the 'Cooling Day' control strategy, only now the controlled variable is the floor slab temperature in the room at a depth of about 4 [cm].
Precooling mode with Manual Control. The vent openings or louvres are set manually based on the indoor temperature at the end of the office time and the maximum outside temperature as forecast by the weather station for the next day. For the weekend this means that no corrections will be made at changing weather.

4. THE INPUT VARIABLES

Weather data: The Bilt, May, 1ste - September, 30th, 1964:

- Outdoor temperature [°C]
- Wind velocity [m/s]
- Wind direction [degrees]
- Global radiation [W/m²]

  The total solar radiation on the 4 vertical orientations (North, South, West and East) are calculated values based on the splitting procedure of Orgill and Hollands [7]. Linear interpolation is used to determine the values per time step.

Building orientation

- NS-orientation (room 1 north, room 2 south)
- WE-orientation (room 1 west, room 2 east).

Building inertia

Simulations were made with 3 different building (room) inertia, M:= 55 (low inertia), 75 (medium inertia) and 100 (high inertia) [kg/m²]. The inertia, M [kg/m²] of a room is defined as half of the mass of the four walls, the ceiling and the floor divided by the enclosing area.

Internal heat gain

The internal heat gain represents the body heat of people, the heat from printers, computers, lights and other electrical devices in the room during office hours. The unit is Watts per square meter of net floor area. It is varied from 20 to 40, with steps of 5 [W/m²].

Comfort criterion

The resultant temperature is allowed to exceed 25.5 ^0C for a maximum of 100 hours; of this only 15 hours may exceed 28 ^0C in office hours in one year.

Windows and effective vent openings

The total transparent window area is 40 [%] of the façade area. Four types of vent openings or louvres are used. The specifications are given in table 1.

If vertical or fan assisted ventilation is used, the fan is switched on if one of the windows are full open, the wind velocity is less than 2 m/s and T_0>20 °C. The fan is dimensioned for 4ach.

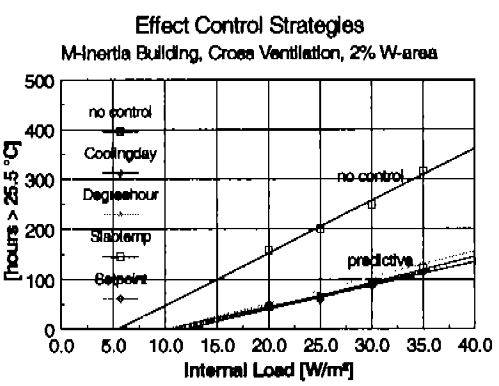
Table 1 Specifications of $A_{eff.max}$

Type	Dimension	Maximum effective vent opening area $A_{eff,max}$	
	w*h [m]	[m²]	% of net floor area
1	3.2*0.091	0.18	1
2	3.2*0.20	0.41	2
3	3.2*0.31	0.64	3
3/2	2*3.2*0.155	0.64	3

The dimensions of type 1 [6,8] and 3 [7] are chosen based on directives found in literature. Type 3/2 is a split window, one half above and one half below the fixed transparent window (more stack). The type 2 window is a compromise between type 1 and 3. The louvres above the doors, in the back walls of both rooms, have the same dimensions as the windows. The louvres in the air duct have twice the dimensions of the louvres above the doors.

5. SIMULATION RESULTS AND DISCUSSIONS

Here only the results of the control strategies are discussed. The simulation results of a South oriented, cross ventilated, medium inertia office building room, with effective vent opening type 2, using the different control strategies mentioned above, is shown in figure 5.



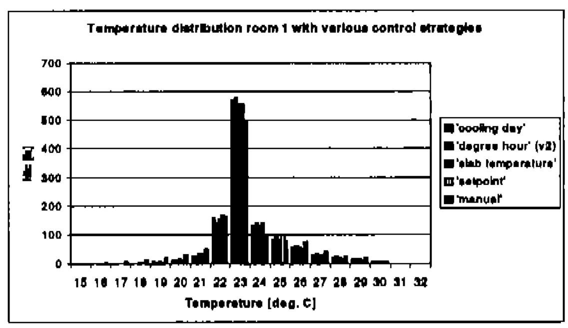


Figure 6. Temperature distribution in a South room with cross ventilation with various control strategies.
← Figure 5. Effect of the control strategies

As reference situation is taken a natural ventilated building with the windows closed after office hours and in the weekend. This is shown in the upper curve (no control) in the plot in figure 5. It clearly demonstrates the merits of night cooling.

Surprisingly, only by using night cooling, whether it be manually (not shown in the graph), or automatically controlled, the overheating hours drop dramatically. Through night cooling with manual control there are hours with too low as well as too high temperatures, see figure 6. Moreover, the overheating hours (Ti > 25 °C) are also higher than with the other control strategies. It seems, that the differences between the considered control strategies are very small, what really matters, is to cool the building at night and in particular in the weekends. Also the setting of the control parameters shows to be more important than the strategy itself.

Allowable internal heat gain with the three ventilation types

As has been shown in the previous paragraphs, the various control strategies produce nearly the same results (see figures 5 and 6). So only one control strategy, the 'Cooling Day' control strategy, will be used to investigate the influence of the three ventilation types, single sided, cross and fan assisted ventilation (designed for 4 ach) in more detail. The following parameters has been used:

Building inertia: low (55), medium (75) and high inertia (100 kg/m^2)
Building orientation: North-South (NS) and West-East (WE)
Window type: Type 1, 2, 3 and 3/2 (Table 2)

The results are shown in Table 2.

Single sided ventilation depends very much on the wind direction. The north and west rooms (first values) allows higher internal loads than the south and east rooms. A split window with the same effective vent opening gives better results than an undivided window. This is shown with the results of window types 3 and 3/2. This is caused by the extra stack effect that occurs by two vent openings. Light buildings are unsuitable. Medium inertia building can be used, but only with 3% vent openings. High inertia buildings perform best with window type 2 and up. Window type 1 is too small.
With cross ventilation light buildings can only be used with 3% windows; window type 2 is sufficient for medium inertia buildings. Window type 1 can only be used with high inertia buildings.

Table 2 Simulation results

Building inertia [kg/m^2]	Orien tation	Window type	Allowable internal heat gain [W/m^2] for		
			Single sided vent.	Cross vent.	Fan assisted vent. (2 ach)
Low [55]	NS	1	<20/<20	<20	<20
Low [55]	NS	2	<20/<20	<20	20
Low [55]	NS	3	<20/<20	23	22
Low [55]	NS	3/2	21/<20	26	23
Low [55]	WE	1	<20/<20	<20	<20
Low [55]	WE	2	20/<20	<20	<20
Low [55]	WE	3	<20/<20	<20	21
Low [55]	WE	3/2	<20/<20	23	22
Medium [75]	NS	1	<20/<20	<20	24
Medium [75]	NS	2	<20/<20	26	28
Medium [75]	NS	3	23/22	32	32
Medium [75]	NS	3/2	30/27	33	33
Medium [75]	WE	1	<20/<20	<20	22
Medium [75]	WE	2	<20/<20	22	28
Medium [75]	WE	3	22/<20	26	31
Medium [75]	WE	3/2	29/26	28	32
High [100]	NS	1	<20/<20	24	27
High [100]	NS	2	26/22	33	36
High [100]	NS	3	29/27	42	47
High [100]	NS	3/2	38/36	43	40
High [100]	WE	1	<20/<20	21	28
High [100]	WE	2	24/20	27	34
High [100]	WE	3	29/24	32	44
High [100]	WE	3/2	37/32	36	40

Vertical fan assisted ventilation is only slightly better than cross ventilation.
In practice requirements about flexibility do not allow interior sidewalls to be build of stone. Therefore medium inertia buildings are more often built then high inertia buildings.
Although vent windows type 3 is better than type 2, preference should be given to type 2, for safety reasons (burglary). All this taken into consideration leads to the following conclusions:

Cross ventilation with 2% effective vent opening can be applied in medium and high inertia buildings. Smaller effective vent openings should not be applied. Light buildings are not suitable for natural ventilation. The allowable internal heat gain for a medium inertia building with orientation north-south is 26 [W/m^2] and east-west 22 [W/m^2]. For a heavy inertia building these are respectively 33 [W/m^2] and 27 [W/m^2].

6. CALCULATION EFFECTIVE VENT OPENING AREA A_{eff}

A great number of simulation runs have been performed. For each simulation run, only one parameter is varied. By analyzing the outputs of all these simulation runs, it is possible to identify two design methods to determine the effective vent opening area:

a. Method based on a selection chart
b. Method based on simplified equations

Method based on a selection chart

Based on the same simulation outputs a graph is designed in which the effective ventilation opening can be found without any knowledge about building physics. First the internal heat gain should be fixed. Then the type of window with its solar shading system, the accumulation factor M and the control strategy lead to the ventilation systems and effective openings that can be applied. The procedure is shown in figure 7

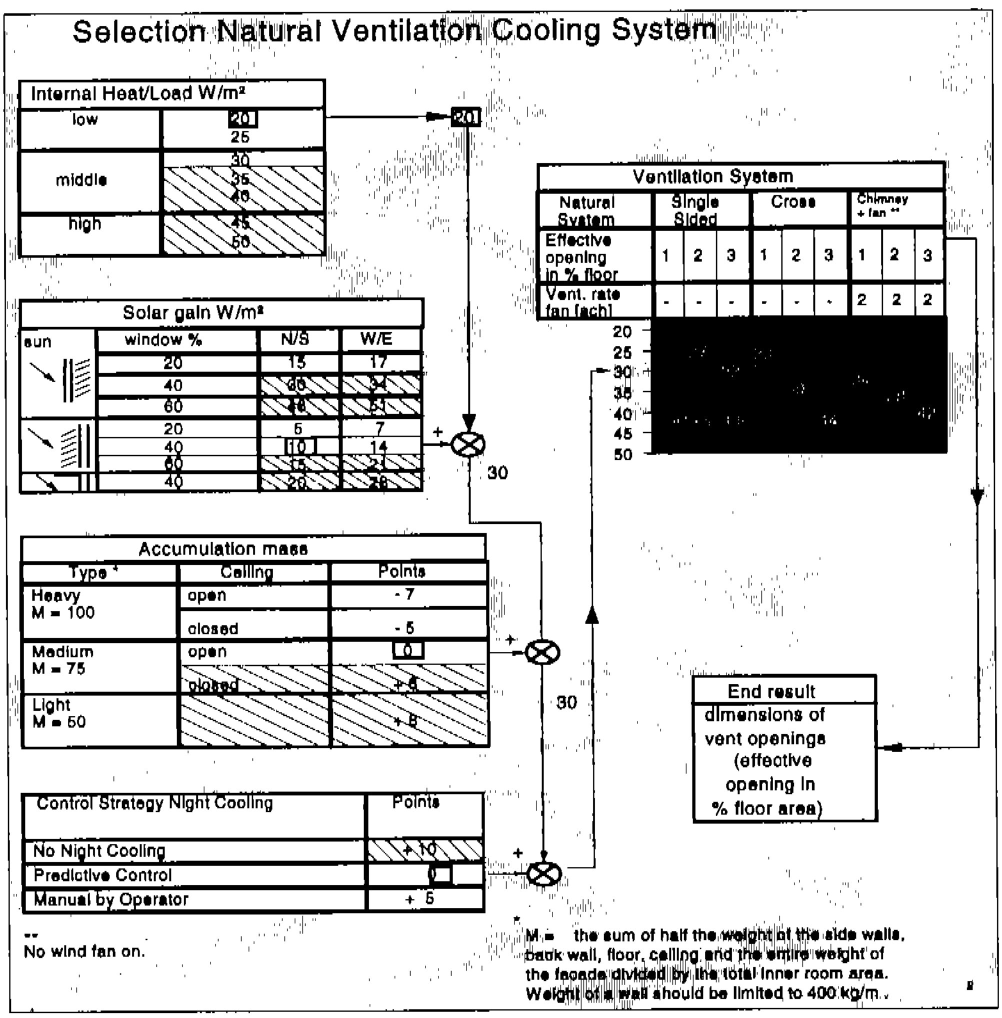


Figure 7. Graphical design tool for night cooling

Method based on simplified equations

The dimensions of the effective opening can be expressed as function of internal heat gain, solar protection system, mass of the building, control strategy and type of ventilation (single sided, cross, and fan assisted systems). The reference situation chosen is: cross ventilation, 40% glass area, outside shading, medium inertia building (M=75 kg/m^2).

Based on the simulation results for this particular situation, the required effective opening area, $A_{eff,ref}$, is determined as function of the heat gain (internal and solar), the comfort criterion, and the building inertia. These parameter values are the central point for further calculations. The coefficients are found by fitting the equations on the simulation output data.

The total heat gain, Q_{im}, consists of two heat flows: the internal heat flow, Q_i, that consists of heat of people and electrical appliances and lights, and the transmitted solar heat that depends on the glazing type internal and external sun shades, denoted by the solar atmittance factor ZTA, and the window area, A_{window}. Q_{im} [W/m^2] is denoted by:

$$Q_{im} = Q_i + 10 \cdot \left(\frac{ZTA \cdot A_{window}}{0.585} - 1\right) \quad \text{with} \quad ZTA = \frac{\textit{nett solar heat entering the room}}{\textit{solar radiation falling on the window}}$$

The effective vent opening for the reference situation, $A_{eff,ref}$ (cross) [%], can be denoted by:

$$A_{eff,ref}(cross) = -0.172 + 0.124 \cdot Q_{im}$$

When the building inertia is different from: 75 [kg/m^3], this becomes

$$A_{eff}(cross) = \frac{75 - 0.41 \cdot (M - 75)}{M} \cdot A_{eff,ref}(cross)$$ with M [kg/m^2] is the building inertia.

The effective vent opening for single sided ventilation can be derived from:

$$A_{eff}(single\ sided) = 2 \cdot A_{eff}(cross)$$

Cross ventilation can be improved by using a duct system with exhaust fan. The power of the fan is designed to realise a ventilation rate of n ach (air changes per hour). It is only switched on when the wind speed is less than 2 m/s. The effective vent opening becomes:

$$A_{eff}(fan\ assisted, ventilation\ rate\ n) = (-0.1875 \cdot n + 1.375) \cdot A_{eff}(cross)$$

The equations derived above are found for a comfort criterion $N_{hour} = (N_{>25.5} \leq 100)$ (maximum 100 overheating hours above 25.5 [^{0}C] are allowed) with an internal heat gain Q_{im} of 20 [W/m^2]. In case more than 100 overheating hours are allowed $N_{hour} = (N_{>25.5} > 100)$, the reference effective vent opening, $A_{eff,ref}$, is given by

$$A_{eff,ref}(cross) = -0.172 + [0.124 + a_2 \cdot (100 - N_{hour})] \cdot Q_{im}$$

Where

$$a_2 = [3.8 + 0.09 \cdot (Q_{im} - 20)] \cdot \frac{N_{hour} - 50}{100} \cdot 10^{-4} + [1.24 + 0.009 \cdot (Q_{im} - 20)] \cdot \left(1 - \frac{N_{hour} - 50}{100}\right) \cdot 10^{-3}$$

Warning: Accuracy of the equations can be quaranteed for: $20 < Q_i < 30$; $50 < M < 100$; $0 < ZTA < 0.3$ and $50 < N_{hour} < 150$.

7. CONCLUSIONS

The optimal solution for a natural ventilated office building with night cooling would be a system with cross ventilation and an effective vent opening area of 2% net floor area. The allowable internal heat gain for a medium inertia building is 22-26 [W/m^2] and for a high inertia building 27-32 [W/m^2]. It performs better than single sided ventilation that works only in a high inertia building and is a lot cheaper than vertical ventilation (air duct). Windows with 1% vent opening are too small and with 3% effective opening too large (burglars). Although the split window of 3% is burglar free, its better performance does not match the higher costs.

All predictive control strategies mentioned in this paper show more or less the same performance. What really matters is the tuning of the night cooling strategy and the application of night cooling.

Vertical fan assisted ventilation with 2% effective vent openings improves the performance of cross ventilation provided a ventilation rate of at least 4 air changes per hour is applied

Based on the outputs of a large series of simulation runs, two user friendly design tools are developed. The first design tool is a graphical tool in the form of a chart. The second design tool consist of simplified equations and can be used in a spreadsheet. With these design tools it is easy to determine the required ventilation opening and control strategy at an early stage of the building design.

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