VENTILATION TECHNOLOGIES IN URBAN AREAS

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Practical Guidelines for Integrated Natural Ventilation Design

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Synopsis

Natural ventilation in office buildings can sometimes offer other advantages than traditional mechanical ventilation systems. Often natural ventilation systems are promoted at an early stage by an architect, but perceived difficulties, e.g. to pre-determine the function of a natural ventilation system, can serve as a barrier and a mechanical system is often chosen instead. In this paper the difficulty to determine the indoor climate achieved by a natural ventilation system is addressed, both by presenting a computer simulation tool coupling a thermal model with an air flow model and by a statistical analysis of test runs made with the simulation tool to determine the most important parameters for a natural ventilation system. Results from the statistical analyses for evaluating the expected indoor climate determine the influence of different parameters as well as their interactions. It can generally be concluded that natural ventilation design is enhanced by a number of factors, the most important ones being large facade vent areas, limited internal heat loads, possibility for night ventilation and window use during daytime and use of well designed solar shading devices.

Introduction

In many countries, there is a turn towards natural ventilation as an alternative to what many consider energy and cost demanding mechanical ventilation systems. The objective is to save money and energy while maintaining an acceptable indoor air quality and thermal climate, or even to improve the indoor environment by reducing noise levels, giving the user more control over the indoor climate etc.

Often this process is promoted by architects while engineers have a more restricted view of natural ventilation. In an in-depth study (Aggerholm 1998, Svensson & Kronvall 1998) the perceived barriers to natural ventilation held by e.g. architects, consultants, contractors and developers, are identified and one of the major perceived barriers to natural ventilation is the lack of means to predict the indoor climate that can be achieved with a natural ventilation system. Furthermore, in the same study, it was found that pre-design tools for determining the performance of natural ventilation systems were desired.

In this piece of work the need for abilities to determine the indoor air temperature and the ventilation rate have been addressed, with the development of a computer simulation tool and with statistical analysis of systematical simulations of the performance of naturally ventilated office buildings. From this study conclusions of the suitability of natural ventilation in office buildings with different prerequisites can be drawn.

Methods

One of the main objectives of this work is to identify the parameters that have the largest influence, as well as what significance interaction between different parameters have, on the performance of natural ventilation. To achieve this, a large number of prerequisites had to be studied. Thus a computer simulation tool was developed and by changing input parameters in a systematic way, different conditions were studied. These test runs were then statistically analysed and from the statistical analysis, conclusions were drawn on the importance and influence of different parameters. In this chapter, the different steps in the work are described.

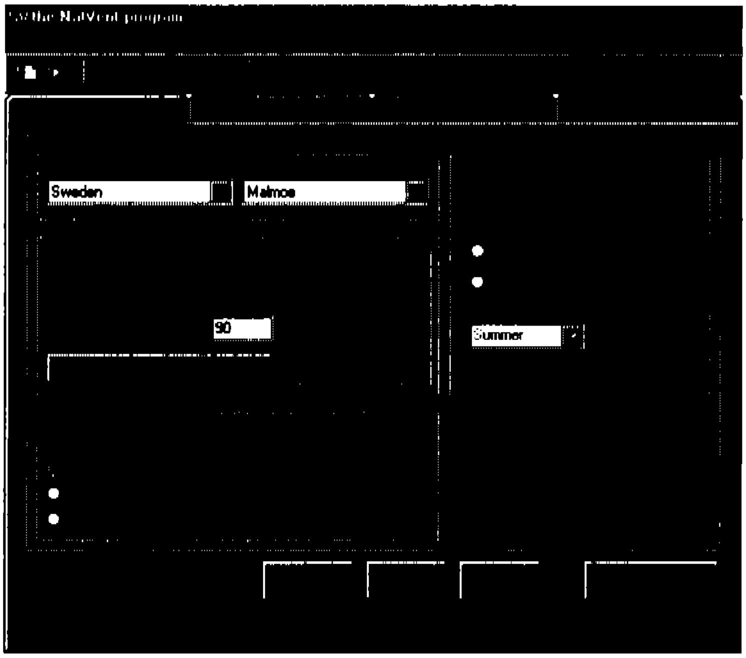
Computer Simulation Tool - The *NatVent*^{TM} program

In order to be able to predict natural ventilation air flow rates and indoor air temperatures at the design stage, a computer model has been developed within the *NatVent*^{TM} -project. The program is an integrated model with a thermal and an air flow model coupled together. It can be used early in the design process to determine possibilities and restrictions in the use of natural ventilation in an office building.

Features

The *NatVent*^{TM} program is set in a typical Windows environment. As a platform, a main window is created. Within this main window, input and output forms may be opened and adjusted to fit the specific building.
The aim for the user interface is to facilitate the use of the program by any building designer, architect or engineer at an early stage. Therefore the interface uses input that are simple to quantify, even at an early stage in the design process.
The input is given by the user step-by-step in four forms describing the building. Under these headings, the relevant input for the different topics are found.

The Location
describes the surroundings and the climate.
The Building
describes the geometry of the building as well as the construction.
The Ventilation Strategy
describes the vents and other ventilation devices, if any.
The Windows
section describes input about the windows.
As the input is given, it is easy to go back to review and to change the input. When the user is satisfied with the input given, the calculation is started with the "Run project" button. For every hour in the studied period values for temperature and ventilation rate are calculated.



Sweden
Malmoe
90
Summer

Figure 1 One of the input forms

The Results

A number of different results are extracted and shown in an illustrative way. Depending on the period chosen for the calculations, temperature and air flow rates are presented as duration diagrams or as graphs with hourly values. If the results indicate e.g. an air flow rate too low, it is easy to go back to the input form to change some input to give a higher air flow rate.
In the User's guide criteria for acceptable indoor air temperatures and air flow rates and CO_2 levels are found, as well as suggestions of parameters to change to affect the temperature or ventilation rate in the desired way.

Theory

The program uses a single-zone model. Thus, the entire building or a selected part is represented by only one single zone. The selected part can be either one of the floors or a part of a single floor. The single zone has one temperature and one internal pressure at floor level. The zone is influenced in many ways by the weather, the occupants and maybe by a mechanical ventilation system. To visually illustrate these factors, Figure 2 shows a picture of the thermal paths and the air flow paths that create the temperature and ventilation flows in the zone.

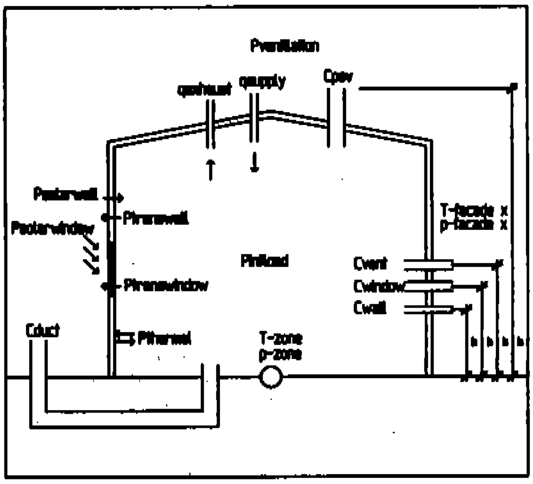


Figure 2: Factors effecting the air flow

To calculate the temperature and the air flow pattern a temperature model, coupled to an air flow, model is needed. To simplify the calculations the indoor temperature of the previous time step is used in the air flow model. Below those two models are introduced.

Thermal model

The solar radiation on external walls and the roof and the insolation through windows and skylight are calculated either from actual weather data e.g. with a test or design reference year or from summer design weather data generated for a stationary hot, calm, clear sky period. The thermal model is a single zone, one time constant model. In the model, it is assumed that all internal structures and surfaces have the same temperature and that the internal air temperature can be averaged to one air temperature representing the hole building or zone. The thermal model is not applied during winter periods and instead a constant temperature is used.

Air flow model

Due to wind, thermal buoyancy and fans, if any, a pressure difference over the building envelope will be created. As a pressure difference occurs over the building envelope, the air is bound to flow from higher pressure to lower pressure and thus an air flow to and from the building will arise.

Air flow to and from the building can take many paths. Air flow through small cracks and imperfections in walls and ceiling, through vents in the façade, through window airing, through ducts for supply air or passive stacks and through a forced flow from fans - if any. The equations for each one of these links between the outside and the building are determined and by an iteration process, the internal pressure is found when the mass flow rates to and from the building are equal. These flows are then used in the thermal model.

Parametric study

The Test Runs

The significance of different parameters and the different parameters' interaction, with respect to the indoor climate, was studied. In order to study the influence of different parameters on the performance of natural ventilation, systematic test runs were made. A "typical" office building was chosen and then different input parameters were systematically altered.

The Building

The building is chosen to be a typical office building, with a general layout of the building as in Figure 3. It is symmetric with a length of 21 meters and a width of 10 meters. The room height is 2.5 meters and the height of the intermediate floor is 0.3 meters. The offices are cellular offices along the two parallel longer façades. Each office room is 3 meters wide and 4 meters deep and the building is divided by a two meters wide corridor. There are a total of 14 office rooms on each floor. Each office room has a window and a vent (if vents are used). With this basic design, different parameters e.g. thermal mass, window area etc. can be changed. Half of the office rooms are south facing and half of them are north facing.

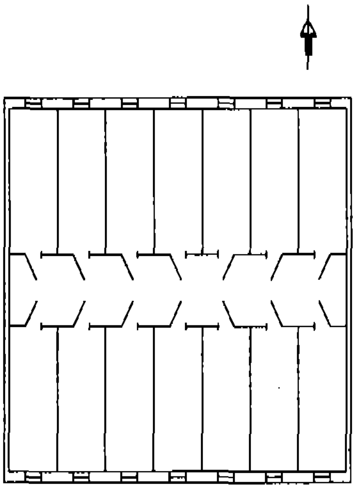


Figure 3 A general lay-out of the studied building.

Climate

The computer simulation tool contains test or design reference years for seven locations in six different countries in Europe. The climates used for the test runs were from Switzerland, the Netherlands and Norway.

Ventilation Strategies

For the building, five different ventilation strategies were studied, see Table 1. These five cases represent ventilation with passive stacks and ducted air supply; with passive stacks; with ducted air supply and skylight; with skylight and with cross ventilation, i.e. ventilation with windows and vents. All five cases are being addressed in the same way as described.

Table 1 Five different ventilation strategies.

Case	1	2	3	4	5 *)
Passive Stacks	x	x	-	-	-

Ducted Air Supply	x	-	x	-	-
Skylight	-	-	x	x	-

*) For case 5 cross ventilation, i.e. ventilation by means of vents and windows, was used.

Important Parameters

For the test runs, a number of important parameters were studied. By doing some initial test runs in a simplified scheme a number of parameters were determined to have a high significance on the indoor temperature and/or the ventilation rate. Some of the parameters were then grouped, i.e. as it is likely to have the same degree of insulation in the roof as in the walls those two parameters were treated as one. The final parameters were climate (i.e. temperature, wind conditions and solar radiation); number of storeys; air tightness of the building envelope; U-value (average value of walls and roof); thermal mass; vent size; internal heat loads; if there was night ventilation or not; fenestration; window opening; solar shading (i.e. external or internal solar shading and overhang over the window); and the type of windows (i.e. the U-value and transmittance of the glazing). The values of the parameters can be found in Table 2.

Table 2 Parameters for the test runs. There are three levels for all parameters except for night ventilation, which either is applied or not.

Parameter	**-1**	**0**	**1**	
Climate	Norway	The Netherlands	Switzerland	
Number of Storeys	2	6	12	-
Air Leakage	1	5.5	10	l/sm^{2}at 50Pa
U-Value	0.2	0.4	0.8	W/m^2/K
Thermal Mass	40	100	160	Wh/K/m^2
Equiv. Vent Size Facade 1 & 3	0	420	840	cm^2
Internal Heat Loads	15	27.5	40	W/m^2
Night ventilation	None	■	2	l/s/m^2
Fenestration	1	3	5	m^2 per office room
Windows open	0	0.25	0.50	m^2 per office room
Solar Shading ***Solar shading*** ***Overhang***	 None (100) None (0)	 Internal (60) Medium (40)	 External (20) Large (60)	 (% of radiation through) Angle of overhang (°)
Type of windows ***U-Value*** ***Transmittance***	1 pane 5 0.85	2 panes 2.7 0.75	Energy glazing 1.6 0.65	 W/m^2/K

Criteria of critical performance

The criteria of critical performance that were studied were the outdoor air ventilation rate below 0.7 l/s/m^2 , the indoor air temperature exceeding 25°C and the indoor air temperature exceeding 28°C. The number of hours the ventilation rate was below the limit during work hours were registered as well as the numbers of work hours the temperature did exceed the lower and/or the higher of the two temperature limits. The number of work hours were calculated from a year that holds approximately 261 weekdays of 8 work hours + a lunch hour. This gives 2349 work hours per year.

Statistical Analysis

With twelve parameters and with three levels ("low", "medium" and "high") for each parameter, except for the night ventilation with only two levels ("applied" and "not applied") the number of test runs should be 3^{11}x2 (= 354 294) in order to try all combinations. Instead of this time consuming work fractional factorial design of the experiment has been used. The test runs were planned, and the outputs from them were analysed statistically. By using this method, the number of simulations has been reduced to 90. As totally five ventilation strategies are studied, the total number of simulations has been reduced from 1 771 470 to 450.

The Statistical Analysis Tool

The results have been examined statistically by using a PC-Windows program called MODDE (Umetri, 1997). This is a program for the generation and evaluation of statistical experimental designs. A simulation plan has been made in an attempt for extracting the maximum amount of information from the fewest number of simulations. In this study screening design has been used, using fractional factorial design method and partial least square model (Fisher, 1990). In a set of test runs the parameters are varied simultaneously and with a mathematical model the results are combined.

The output from the statistical analysis tool is in the form of normalised coefficients for the different parameters. At the same time parameters, having significant interactions, can be found. By selecting the parameters and interactions that have significant value, as well as erasing the parameters where the coefficients are not statistically verified, a regression equation can be created.

Output from the statistical analysis

From the statistical analyses, normalised coefficients showing the different parameters' influence on the number of hours with the outdoor air ventilation (vent < 0.7 l/s per m^2), or the indoor air temperatures (temp > 25 and temp > 28 degC) exceeding the limits. The input parameters are as in Table 2.

For both the ventilation criteria and the two temperature criteria, constants ($a_1 - a_n$) are determined by erasing the parameters where the standard errors are too large compared to the actual value of the coefficient. With these constants, three different equations, one for each criterion, can be determined. The equation is written on the form e.g.:

Work hours with limit exceeded = $10^{(a0\ + a1*parameter1 + a2*parameter2 + \ldots an*parametern)}$

where the parameters ($parameter_1$ to $parameter_n$) are presented as -1, 0 or 1, representing "low", "medium" and "high". The actual values of the parameters are found in Table 2, while the resulting coefficients from the statistical analyses are shown in table 3.

Table 3 *Results of the statistical analyses*

	Case 1 **Passive stacks** **Ducted air supply**			**Case 2** **Passive stacks**			**Case 3** **Ducted air supply** **Skylight**			**Case 4** **Skylight**			**Case 5** **No vent devices**		
	VENT	**T25**	**T28**	**VENT**	**T25**	**T28**	**VENT**	**T25**	**T28**	**VENT**	**T25**	**T28**	**VENT**	**T25**	**T28**
Parameter	**Coeff.**	**Coeff.**	**Coeff.**	**Coeff.**	**Coeff.**	**Coeff.**	**Coeff.**	**Coeff.**	**Coeff.**	**Coeff.**	**Coeff.**	**Coeff.**	**Coeff.**	**Coeff.**	**Coeff.**
Climate Netherlands chosen	-0.81	+0.03		-0.66	-0.10		-0.82			-0.31	-0.06		-0.28		
Number of storeys Two chosen		-0.15	-0.22	-0.78		-0.14		-0.07	-0.12	-0.79		-0.11	-0.80	-0.07	-0.11
Air leakage Low chosen				-0.78	-0.07	-0.12	-1.10	-0.06	-0.08	-0.66	-0.06		-0.61	-0.06	
U-value		+0.05	+0.08					+0.03	+0.07						
Thermal mass		-0.10	-0.17		-0.06	-0.12		-0.07	-0.14		-0.04	-0.10		-0.04	-0.10
Eq. Vent size	-0.88			-1.13	-0.05	-0.07	-0.71		-0.06	-0.50			-0.55		
Int. heat loads	-1.54	+0.16	+0.22	-1.05	+0.17	+0.26	-0.90	+0.16	+0.24	-0.49	+0.17	+0.25		+0.17	+0.25
Night ventilation					-0.07	-0.10		-0.07	-0.11		-0.10	-0.15		-0.10	-0.16
Fenestration		+0.07	+0.12		+0.04	+0.10		+0.05	+0.11			+0.08			+0.07
Windows open	-1.04	-0.06	-0.10	-0.67	-0.09	-0.15	-0.39	-0.66	-0.10		-0.09	-0.15	-0.55	-0.09	-0.15
Solar shading	+1.52	-0.19	-0.29	+0.82	-0.17	-0.27	+0.97	-0.18	-0.28	+0.61	-0.16	-0.27	+0.61	-0.17	-0.28
Type of windows															
Unit	h	h	H	h	h	h	h	h	h	h	h	h	h	h	H
Base case	0	339	160	3	644	382	19	516	272	1 294	706	366	1 552	762	397
Optimise VENT	0	661	412	0	885	670	0	845	526	190	1 197	993	336	912	467
Optimise T25	1	86	28	15	158	20	665	83	19	541	99	21	1 622	124	19
Optimise total	0	86	28	15	158	20	46	83	17	173	99	21	24	93	19
Measure(s) taken for total optimisation	Increased vent size			None			Increased vent size			Increased vent size			Increased vent size Increased leakage		

Optimisation

Different parameters influences on indoor climate performance – ventilation rates and indoor temperatures – are shown in table 4.

Table 4 Generalised influences of different parameters on indoor climate performance.

	Influence on ventilation rate		**Influence on indoor temperatures**	
Parameter	**In-fluence**	**Comments**	**In-fluence**	**Comments**
CLIMATE				
- cold	+	Cool / windy summer conditions beneficial	+	Cool / windy summer conditions beneficial
- warm	-	Less thermal forces for natural ventilation	--	High thermal impact on indoor temperatures
NUMBER OF STORIES				
- low rise	--	Decreases flow rates	0	
- high rise	++	Increases flow rates	0	
AIR LEAKAGE OF ENVELOPE *)				
- low leakage	(--)	Decreases flow rates, but necessary for flow control!	(-)	Increases peak temperatures.
- high leakage	(++)	Increases flow rates But energy wasting etc. To be avoided!	(+)	Decreases peak temperatures. But energy wasting etc. To be avoided!
U-VALUE				
- low	0		+	Decreases peak temperatures
- high	0		-	Increases peak temperatures
THERMAL MASS				
- light building	0		-	Increases peak temperatures
- heavy building	0		++	Beneficial
FACADE VENTS				
- no vents	--	Decreases flow rates substantially	-	Increases peak temperatures
- large vent area	++	Increases flow rates substantially.	+	Decreases peak temperatures
INTERNAL HEAT LOADS				
- low	(--)	Decreases flow rates	++	Decreases peak temperatures substantially
- high	(++)	Increases flow rates	--	Increases peak temperatures substantially
NIGHT VENTILATION				
- no night ventilation	0	(Only working hours ventilation considered)	--	Increases peak temperatures substantially
- night vent. in use	0		++	Decreases peak temperatures substantially
FENESTRATION				
- few / small windows	0		+	Decreases peak temperatures
- many / large windows	0		-	Increases peak temperatures
WINDOWS OPEN				
- never	--	Decreases flow rates substantially	-	Increases peak temperatures
- a lot	++	Increases flow rates substantially	+	Decreases peak temperatures
SOLAR SHADING				
- no solar shading	(++)	Increases flow rates substantially	--	Increases peak temperatures substantially
- large external	(--)	Decreases flow rates substantially	++	Decreases peak temperatures substantially
WINDOW TYPE				
- simple single glazing	0	No apparent effect	0	No apparent effect
- advanced triple energy glazing	0	No apparent effect	0	No apparent effect

Conclusions

Some general conclusions regarding natural ventilation design are:

- It is important to carefully study the conditions for a building before deciding on the ventilation system.
- It is essential that some key parameters are kept under adequate control if natural ventilation should be an alternative.
- Under certain circumstances e.g. high thermal loads, natural ventilation is not an acceptable system.

From this specific study, it can be concluded that these factors are beneficial for natural ventilation performance

- Higher buildings
- Airtight buildings *)
- Well insulated envelopes
- High thermal mass
- Large area of (adjustable) facade vents
- Limited internal heat loads
- Night ventilation
- Minimised window area
- Active use of windows
- Effective solar shading

*) The leakage of the envelope is a parameter that must be handled with care. Although the results of the parameter study indicates more favourable performance regarding both ventilation rate and indoor temperatures with increasing leakage, it must be kept in mind that the leakier the envelope is the more difficult it is to control the ventilation air flow rates and more energy is wasted during the heating season. Thus, the optimum strategy must be to build tight and ventilate right – i.e. to give opportunities to control the airflow rates by means of facade vents and window opening.

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