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CONTROLLED NATURAL VENTILATION FOR COMMERCIAL AND INDUSTRIAL BUILDINGS

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Controlled Natural Ventilation for Commercial and Industrial Buildings

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Abstract

The Dutch organization for applied scientific research TNO in Delft developed a system of Controlled Natural Ventilation (CNV). It is produced by the Dutch ventilation firm Brakel in Uden. The system controls ventilation grills and windows. Its purpose is:

- to compensate for fluctuating buoyancy forces (wind and temperature) so that natural ventilation flows are kept on set point value, independent of weather changes and changes in internal heat production;
- to optimize the air flow distribution over the building to get the highest possible ventilation efficiency;
- to restrict ventilation openings when draught risks occur.

The CNV system is based on a computer program that simulates ventilation. A special inverse version is derived that calculates the optimal ventilation openings for a specific building on each weather condition and for each ventilation set point.

The program needs input on local wind effects on the building. They are predicted with another new developed simulation tool, called the 'Cp-Generator'. This special computer program for prediction of wind pressure coefficients (Cp's) is build in as a module in the main program.

Extra features of the CNV system are:

- rain protection without decrease in flow rate,
- improved noise reduction,
- collaboration with mechanical ventilation,
- anticipation on opening doors,
- building leakage compensation,
- adjustment of both flow rate and direction to varying pollution or heat sources,
- smoother temperature control,
- special control for smoke ventilation.

Introduction

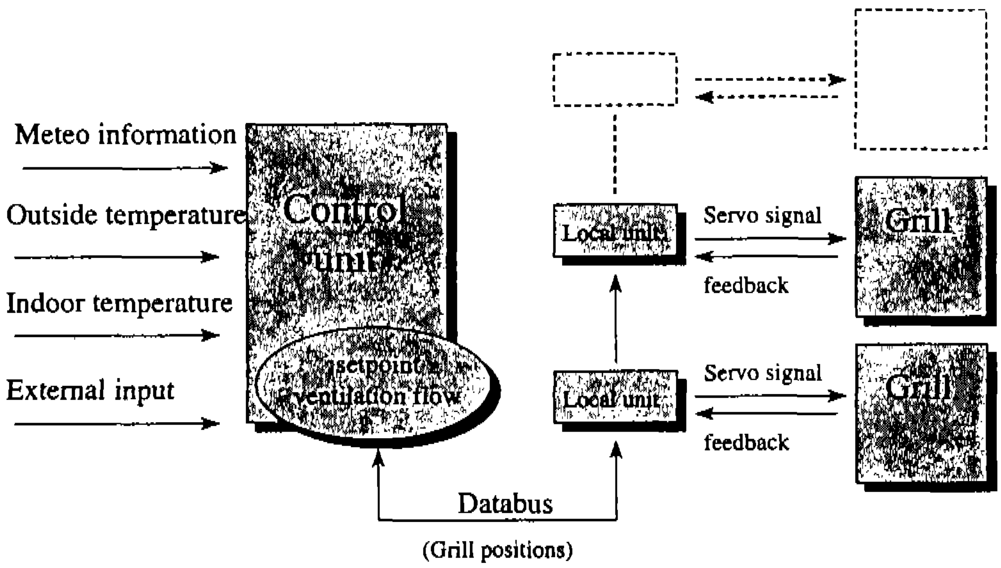
Natural ventilation is known as a cheap but poorly controlled system. In practice, a large variation of ventilation flows and directions occurs. As a consequence, users have to accept varying indoor air quality and draught.
To mitigate poor indoor air quality, in general natural ventilation shows an overshoot. Therefore, improving control also has an energy saving potential.
The main factor to be controlled is the wind. Combined with thermal buoyancy forces it causes the large 'unpredictable' fluctuations in ventilation.
To enable improved control, one large manufacturer recently came up with individual control per grill. However, this is just one of the necessary steps. The major steps are:

- to decide which position of each grill is the best in the present situation, depending on the users ventilation need;
- to automatically set each grill in its best position, however leaving the user in control over the ventilation set point.

The Dutch organization of Applied Scientific Research (TNO) in cooperation with the Dutch ventilation firm Brakel in Uden and its partner Helder engineering in Heeze developed this Controlled Natural Ventilation (CNV) system. Since late 1996 it is applied on a rapidly growing scale. The CNV system is described in this publication.

System Principle

The principle controller of the CNV system is a computerized ventilation simulation model, named 'TNO Regel'. It is a special version of the TNO ventilation model [1]. For a matrix of occurring situations the model 'TNO Regel' produces an output table with optimal grill positions. A control unit is fed with this data.



A local weather station measures the actual weather conditions (figure 1). Also the indoor temperature is measured. Together with the users ventilation set-point, it forms the input for a programmable logic controller (PLC). The input for this central control unit can also be generated by an external source.

The PLC looks up the occurring condition in the output table and calculates from the ventilation set point the optimal grill positions. The grill positions are send as an output signal to local grill controllers.
Each local controller recognizes its signal and uses it to set the correct grill position.

The ventilation model 'TNO Regel'

Basic calculation model

The calculation of ventilation is based on a number of equations. The physics behind them is explained using figure 2.
The wind causes an outdoor pressure distribution over openings in facades and the roof. The pressures over the height are influenced by thermal buoyancy. This will result in pressures P1, P2, P3, etc. compared to the indoor building pressure Pb. Each pressure difference over an opening causes a ventilation flow (q_v). The flow through an opening depends on its conductance (C) and the type of flow (n).
The flow per opening is described by:

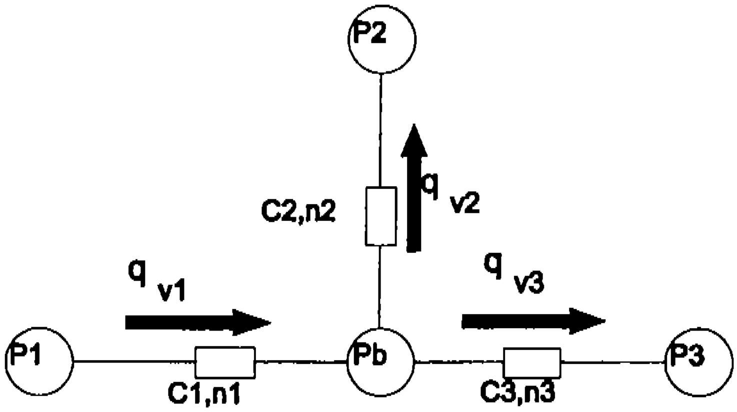


Figure 2 *Basic calculation model*

$$q_{vx} = C_x \times (p_x - p_b)^n \quad \text{.......} \quad (1)$$

Also the sum of the incoming flows must equal the outgoing flows:

$$\Sigma\, q_v = 0 \quad \text{.......} \quad (2)$$

This means there are as many equations as unknown variables. Therefore, a solution can be found. The solver for this type of ventilation models often uses iterative calculation techniques.

Inverse calculation

Unlike the basic model, 'TNO Regel' is not a straight forward ventilation model that calculates ventilation flows from known openings. Its purpose is to calculate opening positions from a ventilation flow, set by the user.
One has to realize that this inverse calculation needs a calculation strategy. That is because there are numerous solutions to set the different ventilation openings, which all result in one and the same ventilation flow.
The basis of the calculation strategy is an optimization of the flow distribution over the building. The default is an evenly distributed flow, because this will minimize the occurrence of draught. However, the user may give his own preferences for the flow

distribution. If, for instance, a certain area of the building has a high contamination level, one defines nearby grills as exhaust openings and the other ones as supply openings, thus preventing the contamination to spread through the building.
This may rise the question whether and how it is possible to control ventilation flow directions in case of natural ventilation. It appears to be one of the benefits of CNV. To prevent cross flow according to the incidental wind direction, the windward openings are restricted and the roof openings where the lowest pressures (--) occur are enlarged (figure 3). This will lower the internal building pressure (-) below the leeward pressure (0), thus allowing supply at leeward side.

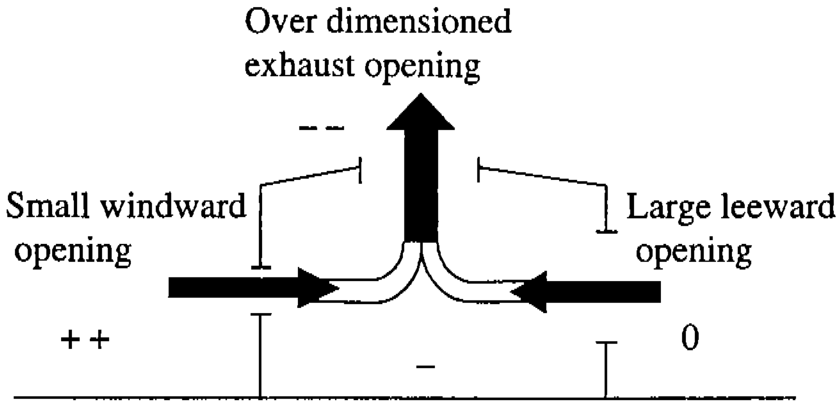


Figure 3 *Good ventilation design and control allows supply at leeward side*

The control of flow directions also needs a good design. The design is checked in the process of generating the output table. Apart from the optimal opening positions, a ventilation score is calculated. The score represents both whether the desired flow and flow distribution is met. In case of low ventilation scores the maximum grill openings and the grill locations have to be adjusted. A special add-on has been developed to guard the designer through this optimization process [2].

Input

The input for 'TNO Regel' is simple. For both the building and nearby obstacles the coordinates and wind orientations have to be given (figure 4). Also the locations of grills, doors, windows, leaks and other openings per facade and roof are transferred in a comparable manner. Each opening type is defined by its C and n-value. For some characteristic grill and window types

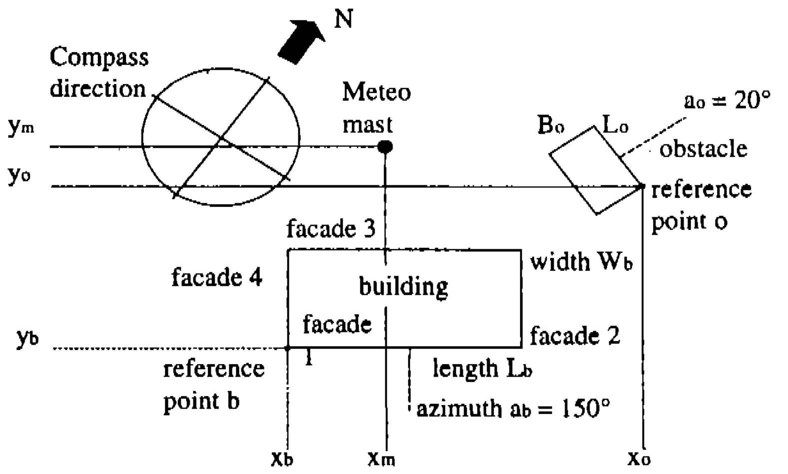


Figure 4 *The basic input consists of the main coordinates and measures of the building and surrounding obstacles*

the C and n-values are determined by measurements. Others are calculated from these measurement results and their geometry with an inaccuracy of about 10%.

Output table

For a matrix of weather conditions and flow settings the ventilation program 'TNO Regel' produces an output table with optimal grill positions and the ventilation score. Each output table is unique for a specific building with its surroundings and its grill positions and sizes.

The wind model 'Cp Generator'

A major input variable for the ventilation model is the wind pressure distribution over the building. The locally occurring wind pressure is presented as a factor to the dynamic pressure of the undisturbed wind, called Cp. In this way, the wind pressure is dimensionless.
Normally expensive wind tunnel measurement are necessary to accurately define the wind pressure coefficients (Cp's) for each opening at each wind direction. However, in this case a new computer program, called 'Cp Generator' is used [3].
The 'Cp Generator' is based on data of wind tunnel tests that were carried out systematically. The relationships derived from these data were programmed to calculate Cp's out of the simple input data mentioned before.
The process of Cp calculation is a fully background task of the program 'TNO Regel'.

Draught correction

A major disadvantage of traditional natural ventilation is the occurrence of draught. Draught problems can be highly reduced or even eliminated by:
1) preventing ventilation overflow;
2) optimizing flow distribution over the building (prevention of high local flows);
3) upward directing the incoming air by adjusting the positions of the grill strips;
4) decreasing incoming air flows at draught sensitive spots;
5) a higher positioning of ventilation openings in facades (increasing the mixing zone);
6) positioning air entrances in unoccupied zones;
7) preheating incoming air.
The CNV system takes care of a major draught reduction by performing the first four tasks. Tasks 1 and 2 are implicit tasks of the ventilation control system. Tasks 3 and 4 are extra. To perform these tasks, for each air entrance the curve of the incoming air is calculated. Using descriptive relations of air jets, the temperature and velocity at the upper limit of the occupied zone is calculated. The outcome is compared to draught criteria, to decide whether an additional draught correction is necessary. If so, the grill opening areas in case are decreased till the draught criteria are met. To compensate its effect on the ventilation flow, if possible, other grill opening areas where no draught risk occurs, are increased.

Known draught criteria are only valid for non-moving persons with rather low metabolic rates. Especially in industrial buildings, these conditions are exceeded. Hence, much higher draught limits are allowed. Therefore, the draught criteria used, are derived especially for this purpose (figure 5).

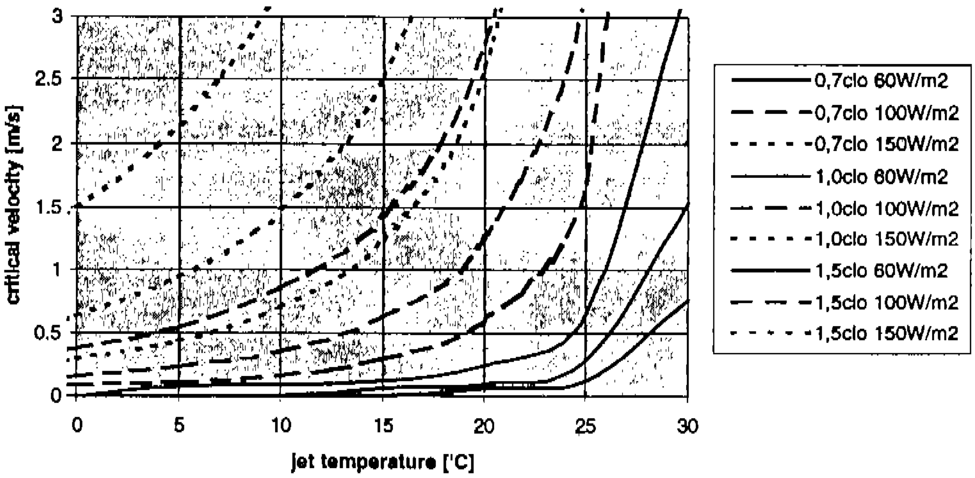


Figure 5 *Draught criteria for 30% dissatisfied*

The basis of the corrected draught criteria is a simple thermal exchange model of the skin, because skin sensors are responsible for the primary draught reaction. The velocity and temperature of the skins convective boundary layer of the neck is predicted from the metabolic rate and the clothing isolation on the one hand and the thermal environment (air temperature, air velocity and radiant temperature) on the other hand. Draught will occur when a critical skin temperature is descended.

Terrain roughness correction

A local weather station measures the actual weather conditions. The local wind pressures (p_{wind}) are calculated from the Cp-values, the wind velocity (v_{meteo}) measured on the local weather station and the specific mass of air (ρ), according to the formula:

$$p_{wind} = Cp \times \tfrac{1}{2} \rho \, v_{meteo}^2 \qquad \text{(3)}$$

The local wind velocity (v_{meteo}) will increase when the position of the local weather station is higher above the building and its surroundings. However, the wind pressure on a ventilation opening (p_{wind}) may not increase when a higher meteo mast is used. Therefore, 'TNO Regel' will compensate for this. It relates the calculated Cp-values to the position and height of the meteo mast.
The meteo correction on Cp's is based on a description of the velocity profile in the lower part of the boundary layer. Common expressions like the power law and Davenport's logarithmic relation (z_0 description) are not valid here. The descriptions are derived from velocity measurements in different terrain roughness' in the wind tunnel.

Description of major components

Local weather station

The local weather station has the following components:

- a cup anemometer to measure the local wind velocity, starting at 0.8 m/s;
- a rotating vane to measure the wind direction;
- a PT100 temperature meter, shielded for direct radiation;
- a conductive rain sensor.

The sensor signals are read electronically.

Indoor temperature sensors

The indoor temperature is measured at four spots in the room, using PT100 elements. Two spots are at 1 m above ground level, two spots are 1 m beneath the ceiling. The average value is used as indoor temperature in ventilation calculations. Also the temperature gradient over the height is used as a measure for the internal heat production.

The programmable logic controller AVC2080

A simple programmable logic controller (PLC) deals with the input of the weather station, the temperature sensors, the users input and any alternative external input, e.g. from a production capacity indicator, a rain detector, door position sensors, a smoke or fire detector and a fan use indicator.

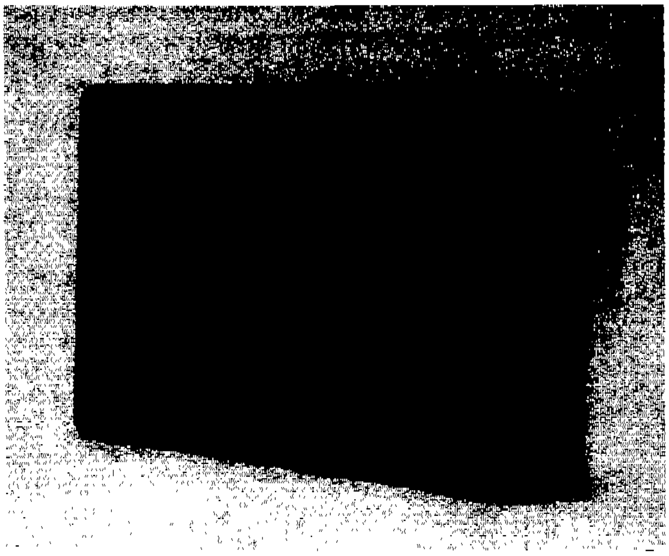


Figure 6 *The central control unit*

The user sets his ventilation requirement by turning a large knob on the central control unit (figure 6).
The user may also set his draught sensitivity, using small button tips. This will adjust the draught limit, used to restrict the grill openings in case of a draught risk.
The users settings are read on a display. Scrolling a menu with the button tips, the user is also able to show measured values on the display.

The PLC has some memory modules (E-proms), containing the output data from the 'TNO Regel' program. The data is specific for the case. There are no on-line ventilation calculations performed by the PLC. Major reasons for using this low intelligence local controller are cost reduction and software copy protection.
The PLC searches the memory for data nearest to the input information. For major variables interpolation is used. The grill positions for the occurring situation are the output.
The control speed is about once a minute.

The local grill controllers LU40

Each grill or group of grills is regulated by a local controller. Each local controller has its own code to recognize his information on the data bus. If the given grill position differs from the set position, a three-way pneumatic valve is activated to pressurize a two-way cylinder, allowing a positive or negative correction.
A potentiometer on the grill gives feedback over the actual position. If the desired position is reached, the pneumatic valve is set in its neutral position.
The local controllers make it possible to proportionally regulate the grills, still using cheap and fail-safe pneumatic adjusting devices.

System performance

Results of on-site measurements

To check the CNV system, an evaluation project is carried out [4]. The major actions are to measure ventilation flows and to deduce Cp-values from on-site measured pressure differences. This evaluation is still going on. Nevertheless, some first results can be shown already.
In general the ventilation flow ($q_{v\,real}$) still shows a considerable overshoot, compared to the set values (figure 7). The major cause is in the fast pressure fluctuations. This is shown by the continuous line in figure 7, showing the ventilation flow derived from the quarterly averaged measured pressure differences. If the ventilation model accounts for the fast fluctuations, a much better agreement with the set ventilation flow will occur.

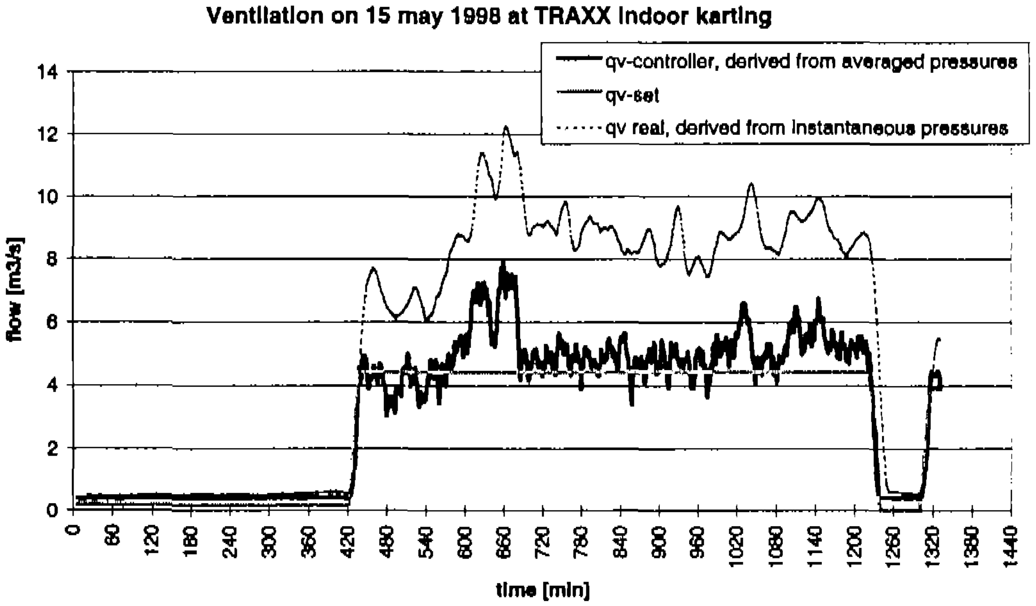


Figure 7 *Example of a typical evaluation result*

The large flow error due to pressure fluctuations is more or less caused by the control strategy, resulting in numerous large openings with pressure differences nearby zero. Figure 8 explains what happens if in this case the average pressure difference is taken in stead off the instantaneous one.

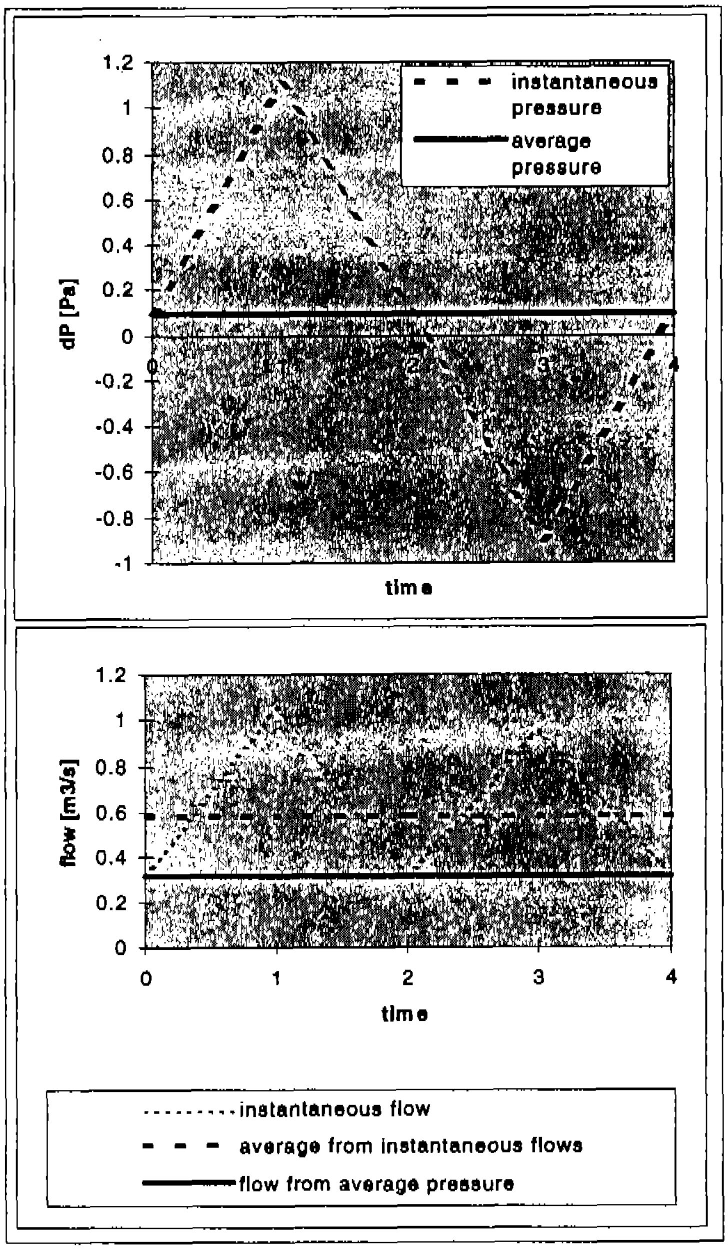


Figure 8 *Effect of pressure fluctuations on ventilation*

Accounting for a correction for the pressure fluctuations and some other minor errors, we consider the results as promising. The major goals, preventing large flow fluctuations and provide reproducible ventilation, appear to be fulfilled. The system, once fully developed, has the potential to keep ventilation flows constant within a 20% range.

Further analyses indicate that pre-calculated Cp-values, using the computer program 'Cp Generator' show a fairly good agreement with measured values (figure 9). Average Cp-values and global Cp-patterns do match reasonably. Only details are not predicted well.

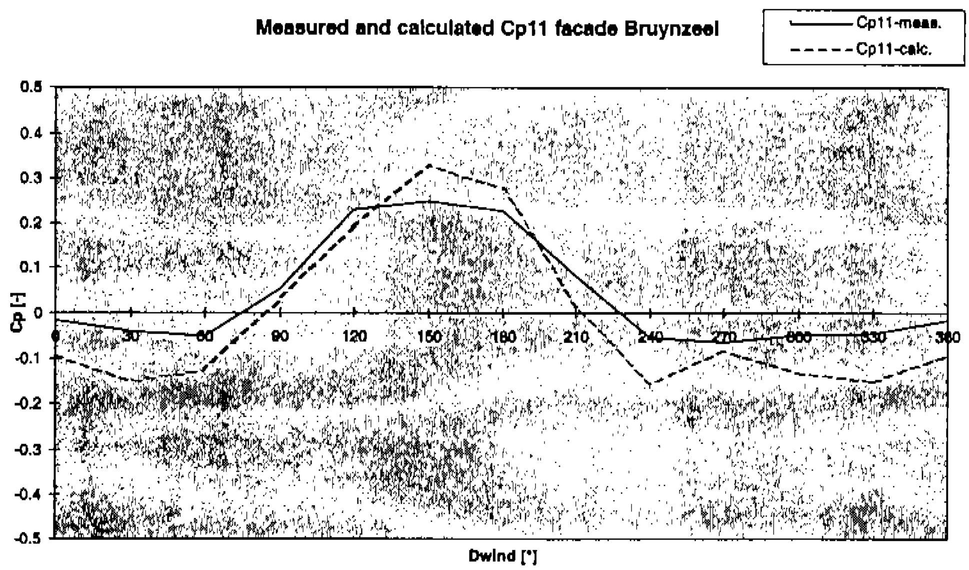


Figure 9 *Example of a comparison of measured and calculated Cp's*

User experiences

The users of CNV systems experience:

- better indoor air quality (IAQ);
- less draught;
- improved optimization between IAQ on the one hand and draught and energy losses on the other hand;
- mitigation of overheating problems.

An illustration of the improved optimization between IAQ and draught show the findings at an indoor cart track with a CNV system. This type of building is known as draughty or contaminated, but never ventilated well. CFD calculations for this case revealed that the mixing of ventilation air is improved significantly by application of a CNV system [5]. This is accomplished by the uniform distribution of ventilation air over the building exterior.
A further improvement of mixing is possible by the use of additional mixing fans, which are situated inside the building. User experiences confirmed these findings.

System costs

An important reason for the application of a natural ventilation system is its cost benefit compared to a simple mechanical ventilation system. One may wonder whether this still goes for the CNV system with its extras. To check this, the manufacturer did a cost analyses on actual project data. Figure 10 illustrates there is still an important saving on equipment costs of about 25%. The saving depends on the ventilation need (horizontal axis).
The cost comparison includes the provisions for heating the ventilation air and the room itself.
Costs are expressed in Dutch florins, which are about half a US dollar.

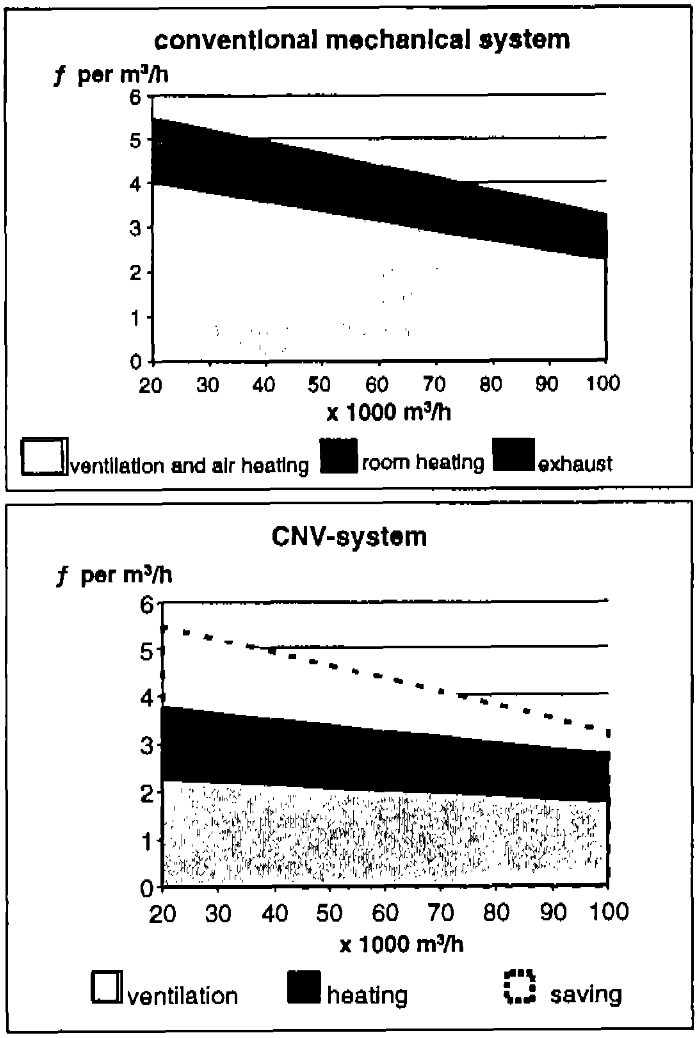


Figure 10 *Comparison of equipment costs for a simple conventional mechanical ventilation system and CNV*

Special applications

rain protection

One of the numerous special applications of CNV concerns rain protection. To prevent rain pouring in, grill openings are restricted. The restriction itself is not unique for CNV. However, compensating for the effect of the restriction on the ventilation flow is.
In case of rain especially roof openings will close. CNV will try and compensate this by increasing facade openings. The compensation is possible because natural ventilation systems are designed to function at minimal buoyancy forces. Often more advantageous conditions occur, so the ventilation goals can be realized even with a restricted number of openings.

noise reductive measures

Noise, whether coming in or going out, nowadays is a major problem. Additional dampers on the ventilation provisions may mitigate this problem. However standard dampers do highly restrict the air passage of the grills, so the number of (expensive) ventilation provisions increases to meet the ventilation need.
For this case the manufacturer of CNV offers a two way solution:

1. special developed low resistance dampers can be added on the grills;
2. CNV can be programmed with a special control regime, that squeezes grill openings at the noisy side as much as possible.

interaction with mechanical ventilation

In many cases some kind of (local) mechanical ventilation system may be present. The use of these fans will interfere with the CNV system. However, 'TNO Regel' is able to program CNV to work with these fans. In that case the fan use is given to the central control unit as external input.

anticipating on opening doors

Just as CNV may anticipate on fan use it may on the use of doors, if it is programmed for it. The door positions are send to the control unit.

building leakage compensation

Especially at low flow rates, interference by building leaks may cause CNV not to function properly. If building leaks are estimated in the design stage, CNV can be programmed to account for it.
Advantages of the leakage compensation are:

- minimizing uncontrollable infiltration, therefore minimizing energy loss;
- optimizing flow control, due to minimized cross flow.

automatic set-point adjustment

In the basic version of CNV the ventilation set point is adjusted manually. In many cases this will do, due to the reproducibility of the ventilation setting. This makes it possible to learn which ventilation set point is adequate in which situation.
In more complex situations however, an automatic adjustment of the ventilation set point may be preferred. Any external signal is suitable. Examples are temperature control, production dependent control or signals from a building control system.
The automatic setting can be overruled manually by the user.

local preheating

In case of temperature critical or draught sensitive situations, local preheating of the incoming air is advisable. The CNV system recognizes whether air intake or air exhaust will occur and at what rate. Therefore it is able to define how much preheating at which grill has to take place. The information is also used to close down at exhaust, thus preventing unnecessary energy loss.

area venting

Sources of contamination or heat may vary not only in size, but also in time and per spot. Depending on this, not only the ventilation flow set point of CNV may be adjusted dynamically, but also the major flow direction and flow distribution.
To accomplish this, first each grills contribution to the total exhaust and supply is redefined. Next, the output table for this alternative is calculated and loaded too in the central control unit. The output of different sensors over the place determine whether the basic flow regime or the alternative one has to be used.
A special type of area venting concerns smoke exhaust in case of fire. Depending on where the fire is, smoke may be directed different, better enabling people to evacuate. The advantage of CNV over a mechanical system in such cases is clear. It needs no extra distribution system, nor expensive extra components.

Conclusions

Controlled Natural Ventilation (CNV) is a system with all the benefits of natural ventilation, but without its major disadvantages. Moreover, the CNV system clearly shows some extra advantages, like a higher ventilation efficiency due to a more uniform distribution of ventilation air.

CNV prevents large flow fluctuations and provides reproducible ventilation. Once fully developed, it is expected that ventilation flows may be kept on set values within a 20% range.

The CNV system positions between conventional natural ventilation and mechanical ventilation. Due to its interesting possibilities, in a number of special cases it even may be qualified better than mechanical ventilation.
Nevertheless, CNV is about 25% cheaper than a simple mechanical ventilation system. Hence, it is expected that the application of natural ventilation may be widened by CNV.

The information that is produced standard in the design stage, allows a guaranteed performance of CNV systems.

Acknowledgement

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References

[1] Phaff, J.C.
The computer program 'VENCON' for industrial and commercial buildings. A simulation model for ventilation of buildings and dispersion of indoor air contamination.
Delft, TNO, internal report B-92-1217-I (confidential) (in Dutch), 1992.

[2] Knoll, B. and J.C. Phaff
Two unique new tools for the prediction of wind effects on ventilation, building construction and indoor climate.
Delft, TNO publication, 1996.

[3] Knoll, B., J.C. Phaff and W.F. de Gids
Pressure simulation program.
Delft, update of a TNO publication for the 16th AIVC conference, 1997.

[4] Knoll, B.
Evaluation of a CNV system.
Delft, TNO report 98-BBI-R0391 (in Dutch), 1998.

[5] Knoll, B. and A.D. Lemaire
A study of the mixing of car exhaust gasses at the TRAXX Indoor Cart Center at Uden.
Delft, TNO report 96-BBI-R0978 (in Dutch), 1996.