Key findings of four years of research on Ventilative Cooling and how it is done

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1 ABSTRACT

Over the course of the four-year research project of the IEA EBC Annex 62, Ventilative Cooling (VC) has been proven a robust and highly energy efficient solution to support summer comfort in both residential and commercial buildings. Furthermore our findings show that VC can be successfully applied in both cool and warm temperate climates.

This paper concludes on how the application of Ventilative Cooling will become successful. It offers detailed insights on VC elements, their application and control strategies most commonly linked to well-operating VC systems. Beyond that hands-on information on algorithms for early stage air-flow estimation as well as key performance indicators, which should be considered, are stated.

These key findings are of interest especially for researchers, architects, HVAC designers and facility managers striving after designing and operating energy efficient buildings making use of Ventilative Cooling to achieve indoor thermal comfort.

2 KEYWORDS

Ventilative Cooling implementation, Ventilative Cooling performance indicators, Ventilative Cooling challenges

3 INTRODUCTION

Over the course of the IEA EBC Annex 62 in depth research on Ventilative Cooling (VC) such as short time performance measurements, user surveys, involvements in VC-building-design, long-term case studies and expert interviews has been carried out. This paper presents a list of key performance-indicators derived from successful VC solutions as well as a list of major challenges and examples of successful practical solutions. The focus of this paper is solution-oriented and supports hands on approaches rather than background analysis.

4 KEY-PERFORMANCE INDICATORS

- Airflow
- Temperature
- Usability and Reliability

In addition to these three main topics, we collected associated findings for successful VC implementation. Such as:

- Favour airflow through architectural apertures
- Enhance airflow by powerless ventilators
- Design for very low pressure drop in the VC-system
- Make the most of available temperature differences, limit VC to periods which physically make sense
- Strictly emphasise Operability and Reliability of VC components

5 AIRFLOW

Sufficient airflow, whether naturally or mechanically induced is crucial for Ventilative Cooling systems. Design for significant air change rates is necessary in order to get a VC-system working.
An air change rate (ACH) of greater 3 h^{-1} is mandatory, whereas an ACH greater 5 h^{-1} is recommended to achieve substantial heat removal and justify noteworthy investments.[1] The analysis of case studies showed, that the percentage opening area to floor area ratio (POF) has to be around 2-8%, whereas in temperate climates with dry hot summers ratios at the higher end have been recorded. The analysed case studies show no correlation of building category concerning POFs. These values do not take into account the flow effects of the opening, but may be used as rule of thumb in early design stages.[2]

The following example shows the balance of temperature and energy flow in a standardized room within a characteristic Central European summer.

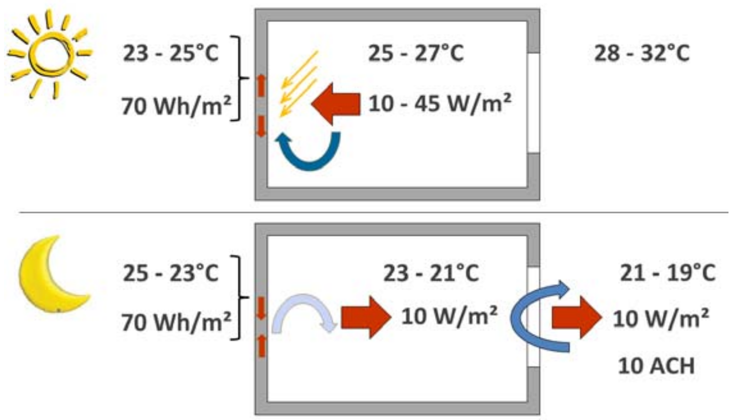

Figure 1: Scheme of typical VC temperatures, loads and air change rates

A massive wall, ceiling or floor may store up to 70 Wh/m² within one day. To release this heat by night ventilation, seven hour duration of specific heat flow of 10 W/m² is necessary. In a 24 m² room, under realistic circumstances this leads to the need of at least ACH 8,0 h^{-1}, better ACH 10,0 h^{-1}. ACH 5 is five to ten times more than needed for hygienic aspects only. Therefore it is recommended to unlink the function of Night Ventilation from the function of hygienic ventilation. It is more promising to use window ventilation to achieve higher ACH. In the worst case of single sided ventilation in still air at only 3 K temperature difference a fully opened window of 2 m height and 0,5 m width will already provide an air exchange of approx. ≈300 m³/h. [3] This would represent approx. ACH 4,2 h^{-1} for the 24 m² and 3 m high room.[1]

There are several options to induce the necessary airflow and as a result high enough air change rates.

[1] Holzer, P. et al. (2017), p.3
[2] O'Sullivan, P. O'Donovan, A. (2018), p.24

[3] According to formula I.14 from ISO 13791:2012 $m_{a,T} = c_d \ \rho \frac{A_T}{3} \left(\frac{\Delta\theta \, g \, H}{T_m} \right)^{0,5}$

5.1 Favour airflow through architectural apertures

Airflow through architectural apertures is mostly common and a very cost-effective manner to achieve increased air volume flow. The magnitude through an architectural aperture is a function of the openable geometric cross-sectional area, the aerodynamic property of the aperture and the pressure drop on it (caused by temperature differences, wind magnitude and orientation). Scientific literature offers numerous algorithms to calculate the airflow efficiency provided through an architectural aperture.
A robust algorithm for single sided ventilation (one opening) is that proposed by de Gids & Pfaff including airflow driving forces of temperature (buoyancy) and wind (1):

$$U_m = \sqrt{C_1 U_{10}^2 + C_2 h \Delta T + C_3} \quad (1)$$

$$Q = \frac{1}{2} A U_m \quad (2)$$

A Opening area [m^2]
C_1 Wind constant (0.001)
C_2 Buoyancy constant (0.0035)
C_3 Turbulence constant (0.01)
h Window height [m]
Q Volume flow rate [m^3/s]
U_{10} Reference wind speed measured at the height of 10 m [m/s]
U_m Mean velocity [m/s]

Airflow might as well be enhanced by certain components which are not solely restricted to ventilative cooling applications. If applied in ventilative cooling applications though, they have to be selected and applied knowing the air volume flows that may result (typically high).

5.2 Enhance airflow by powerless ventilators

Powerless ventilators generally make use of wind pressure to generate either additional pressure driving supply air flow or - more often - generate a negative pressure driving extract air. The most widely used are Venturi ventilators, powerless rotating ventilators and wind scoops. Powerless ventilators are generally robust, inexpensive and very effective. Again, their effects depend inevitably on the presence of wind.

The Venturi effect may be utilized for providing a negative pressure at extract vents and thus enhancing ventilation. Venturi elements for ventilative cooling may be shaped as Venturi roofs or Venturi roof ventilators. The driving ventilation force can be significant, depending on the square of the air velocity.

$$p_{wind} = C_p \, {}^{\rho}/_{2} \, v^2 \quad (3)$$

C_p Pressure coefficient (negative value)
p_{wind} Wind pressure, additive to static pressure of the free stream [Pa]
v Flow speed of the free stream [m/s]
ρ Air density at sea level (1.204 kg/m^3)

Industrial Venturi ventilators reach pressure coefficients up to (– 1), leading to remarkable negative pressures of:

- 4 Pa at an undisturbed wind speed of 2.5 m/s;
- up to 60 Pa at an undisturbed wind speed of 10 m/s.

Venturi roofs ventilators and Venturi chimney caps are offered throughout the world as robust and effective air flow enhancing devices for exhaust air (Figure 2: Prefabricated ventilators which utilize the Venturi effect.Figure 2).

Figure 2: Prefabricated ventilators which utilize the Venturi effect.[4]

5.3 Design for very low pressure drop in the VC systems

A very low pressure drop is mandatory for successful VC application. Driving forces of buoyancy, as for instance for stack ventilation, are typically low[5] as also expressed in equation (6). If the air driving force is buoyancy, typically design for less than 5 Pa. If the air driving force is mechanical ventilation, design for less than 100 Pa.

With a given pressure drop the airflow through an architectural aperture can be calculated with the analytical algorithm based upon mass and spin balance [4]:

$$\dot{V} = C_d \sqrt{\frac{2}{\rho}} \sqrt{\Delta p} A = C_F \sqrt{\Delta p} \quad (4)$$

$$(C_d)^2 = \frac{1}{k} \quad (5)$$

A Opening area [m²]
C_d Discharge coefficient of aperture (C_d for windows = 0.6-0.7; 0.67 (EN 16798-7:2017))
C_F Flow coefficient of the aperture [$m^3/sPa^{0.5}$]
k Flow resistance (k typical for windows = 2.1)
$\dot{V}$ Volumetric airflow from aperture [m^3/s]
Δp Pressure difference across the perimeter [Pa]
ρ Air density (1.21 kg/m^3 at 20°C and standard pressure)

Driving force by buoyancy equals: [6]

$$\Delta p = (\frac{1}{30}) \times \Delta T \times h \quad (6)$$

Δp pressure difference [Pa]
ΔT temperature difference [K]
h height [m]

[4] Passivent Airstract roof ventilation terminals, https://specificationonline.co.uk/directory/passivent/products/airstract-roof-ventilation-terminals (05/06/2018)
[5] Heiselberg, P. (2018) p.76
[6] Kolokotroni, M., Heiselberg, P. (2015).

This leads to driving forces in the range of 5 Pa, rarely more. Wind pressure might help with another 5 Pa, equalling the dynamic pressure at a wind speed of ≈3 m/s.

Driving force by mechanical ventilation technically can be raised to some hundred Pa, but economically and ecologically is limited by the call for high power efficiency (COP), given by the ratio of $P_{thermal}$ / $P_{elecrtical}$. A total pressure drop of 100 Pa will lead to a power efficiency (COP) of ≈20, which is a reasonable benchmark, compared to a mechanical chiller. EN 13779 defines the best category of Specific Fan Power (SFP) lower than 500 W/(m³.s), equalling a pressure drop of 250 Pa. In Ventilative Cooling this is still too much. VC applications have to be designed within the non-existing category “SFP 1+” with a specific fan power of lower than 200 W/(m³.s), equalling a pressure drop of 100 Pa. [7]

A well performing example of VC exhaust ventilation has been monitored in a Viennese social housing project. The air is drawn in via automated staircase windows, guided through the central aisles, drawn out via <10 m duct length by a central exhaust ventilator on the roof of the building. The monitoring proofed a Specific Fan Power (SFP) lower than 170 W/(m³.s), equalling a total pressure drop of 85 Pa, resulting in COP = 24 at an extract air flow of 22.000 m³/h. [8]

Figure 3: Air inlet window with chain actuator (left) Exhaust ventilator on roof (right)

6 TEMPERATURE

The efficient operation of VC is highly dependent on outdoor air temperatures. As shown in chapter 5 natural airflow rates are strongly linked to temperature differences (ΔT) of indoor and outdoor air temperatures. Especially in dense urban areas day night swings might not be sufficient for effective night ventilation. Site specific circumstances however can make a big difference. Green outdoor spaces, like parks with trees and unsealed surfaces, may provide adequate reduction of night temperatures. Orientation of air inlet openings should consider such circumstances.

6.1 Exploit available temperature differences, limit VC to periods which physically make sense

VC system should only operate at a sufficient temperature difference potential of indoor to outdoor temperature. A recommendable threshold seems a ΔT of 2 K or higher. Automated

[7] Calculations based on an average ventilator efficiency ratio of 50% and air temperature rising by 3 K.
[8] Holzer, P. et al. (2017), p.2

VC systems always consume resources such as energy or attrition of components. In the case of a long term monitored building of the University of Innsbruck even higher temperature differences proofed practical. It has been reported, that windows opened and closed several times during the course of one night with a set temperature difference of only 2 K, as outdoor air temperature fluctuated within such amplitude. In that specific case a ΔT of 3 K proofed more suitable and efficient.

Note that 1.000 m³/h carry the thermal load of 340 W at a temperature rise of 1 K. If driven mechanically at "SFP 1" at 500 $W_{el}/(m^3.s)$ this will cause an electrical load of 140 W. Thus, running automated VC at low indoor-outdoor temperature differences is only effective in naturally driven systems. Even there, 2 K or more seem to be a recommendable threshold.

The following figure shows short time monitoring results from mechanical ventilative cooling in a Viennese office during a mild summer period. Mechanical ventilation runs from 22:00 to 06:00. Outdoor Air Temperature (green) undergoes the extract air temperature (yellow) at 22:00. The monitoring results show that the start point is well set. As ΔT has its peak in the early morning hours the operation of the operation time should be extended to fully benefit from low outdoor temperatures.[9]

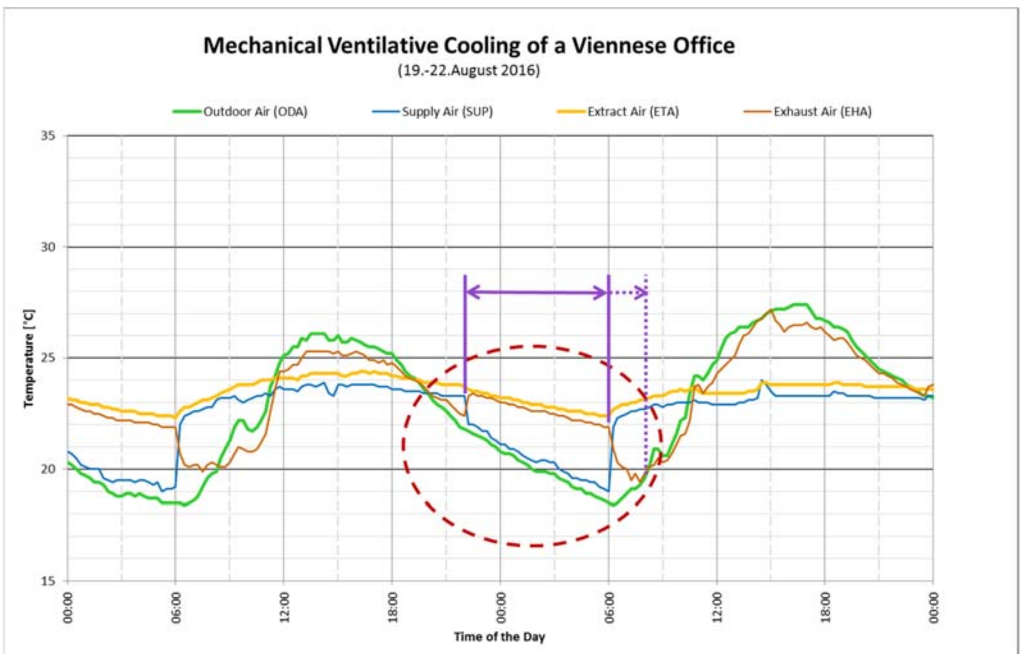

Figure 4: Temperature profile of mechanical Ventilative Cooling system in an office

6.2 Design the VC system for summer comfort at increased air temperatures

The ability of thermal mass to absorb thermal energy is highly dependent on the prevailing indoor air temperature. Utilisation of this ability can be increased by allowing higher indoor temperatures during the day. If the space is mechanically cooled to indoor air temperatures below 26°C, activation of thermal mass is less effective. Ventilative Cooling in the sense of increased indoor air velocity can also provide summer comfort in such cases.

[9] Holzer, P. et al. (2017), p.4

Air movement is the most effective mean of extracting heat from the human body, both by convection and evaporation in and ordinary indoor environment. Thus, air movement, hereby addressed as comfort ventilation, is not a measure for extracting heat from houses but of extracting heat from human bodies.

The effect of raising the personal neutral temperature by moving air is quantitatively described in many comfort Standards (i.e. ISO 7730:2005, Appendix G). The graph indicates the air speed needed to offset an elevated temperature. It is valid for light sedentary work of 1.2 met and for summer clothing of 0.5 clo. The set of curves indicates the correlation for specific temperature differences between the air temperature and the mean radiant temperature (Figure 5Figure 5 Thermal effectivity of comfort ventilation.).

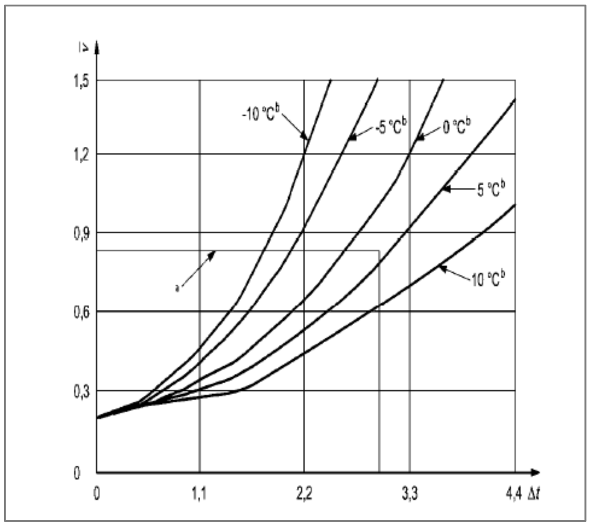

Figure 5 Thermal effectivity of comfort ventilation[10].

Air movement may be provided both by natural airflow, whereas heat transfer has to be prevented, and by mechanical fans. Box fans, oscillating fans or ceiling fans are well known and proven for increasing the interior air speed and improving thermal comfort. Higher air speeds permit the buildings to be operated at a higher set-point temperature and thus to reduce its cooling needs. Air circulation fans allow the thermostat to increase by >2°K. Thus, fans can meet up to 40% of the cooling need of buildings under the assumption that the occupants are always affected by increased air movement.

Regarding personal acceptability it is necessary to enable people to personally control comfort ventilation. Air movement at a velocity of 1 m/s, which is the same speed as normal walking, may be regarded as a nice breeze, or as a nasty draft, all depending on the degree of personal adaptive options and preferences.

7 USABILITY AND RELIABILITY

User integration is crucial for a functioning VC system and a well excepted indoor environment. There might be discrepancies concerning the desired operation of VC components (e.g. the scheduled opening and closing of windows) and user preferences, which have to be taken into account. Case study documentations show best results when automated

[10] International Organization for Standards. ISO 7730: 2005. Ergonomics of the thermal environment.

components also allow for manual control. Such implementations prove to be the most adaptable and reliable solutions, where VC systems work well and users are satisfied.[11]
One example of such a combination from a Viennese primary school has been documented, where windows (shown in Figure 6) are used for night ventilation. They allow users to manually open the window which increases user acceptance, but still are controlled automatically for night ventilation which ensures high efficiency of VC.

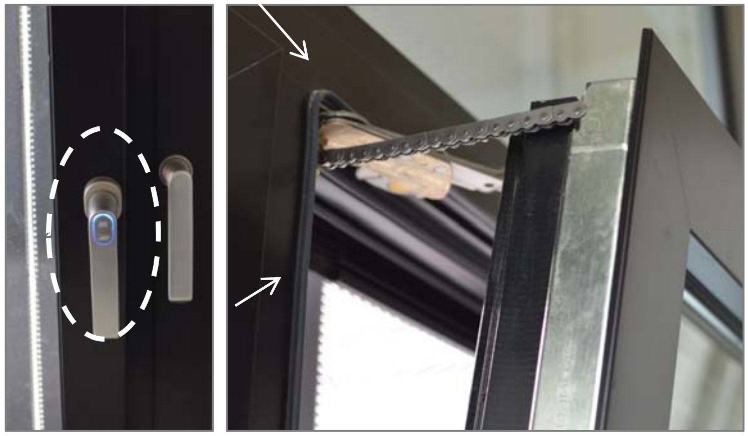

Figure 6 Automated window, with optional manual operation and resistance sensitive gasket

VC systems with natural ventilation give the chance of reducing energy consumption significantly and represent the most cost-effective option for VC[12]. Their design and operation however implies greater insecurities in terms of reliability than those with mechanical ventilation. Case study research shows that computer simulations can reduce uncertainties which occur with the implementation of natural ventilation, although design should be conservative when estimating cooling potential.[13]

7.1 Strictly emphasise Operability and Reliability of VC components

The operability of VC components, especially of the airflow guiding and airflow enhancing components, is key to success of the whole VC system. The following aspects are related to previous chapters and offer close links to practical VC application.

Within Annex 62 we identified the following aspects as challenges of VC in an operational context:

- Safety & security aspects dealing with injury, burglary and vandalism
- Operational aspects dealing with wrong settings in the control systems
- Economic aspects dealing with investment and maintenance

Safety and security measures have to be taken into account from early design stages on. They play an important role especially in public buildings where users and visitors might not be that well informed about the building’s technical equipment. For automated components, like windows, flaps or louvres, entrapment prevention is mandatory. The best solution comes by making moveable parts of VC components inaccessible for users (Figure 7). If placed at heights above 2 m they are usually save. Another option is to use pressure sensitive sealing as shown in Figure 6. This measure needs additional installation care and raises maintenance costs, but allows for placement of VC components in positions reachable by users.

[11] O’Sullivan, P. O’Donovan, A. (2018), p.30
[12] O’Sullivan, P. O’Donovan, A. (2018), p.27
[13] O’Sullivan, P. O’Donovan, A. (2018), p.29

Figure 7 Automated window in an Austrian kindergarten

Problems within the control systems manifest themselves only during the operation of a VC system. Case study research also showed that post occupancy optimisation is very important, especially for VC systems of high technology levels. Problems of the control system are often only revealed over the course of a whole year.
It has also been reported, that occupants take less responsibility for maintaining indoor climatic conditions and engage less with the building use over the course of the first months after occupation of the building, which makes well configured automated systems even more vital.[12]

Economic aspects should always consider both investment and maintenance costs. Case study research show, that over long periods of operation, VC systems are more cost effective than conventional cooling systems[14]. Naturally driven VC systems may cause higher investment costs, but are less expensive in running costs. One case study showed that after 15 years of operation of the naturally driven VC system, 10% of the actuators had to be replaced. It has been reported that during that time good thermal summer comfort had been maintained and that the system is still in use today.[15]

Reliability of VC operation is higher for automated systems than for manually controlled ones. Users tend to open windows during warm periods and usually keep windows shut during cold and windy weather which can compromise VC control strategies.[16] In case of singular automated ventilation openings in small and medium residential buildings, local controllers of automated ventilation openings usually are an appropriate option. There are wireless solutions together with smart home controllers which minimize installation costs. Input variables may be temperature, humidity, CO_2 and time.[17]

The next figure illustrates an example of a window, meant for manually operated night ventilation in an Austrian school, which was analysed within Annex 62: Protection against

[14] O'Sullivan, P. O'Donovan, A. (2018), p.83
[15] O'Sullivan, P. O'Donovan, A. (2018), p.104
[16] Heiselberg, P. (2018) p.98
[17] Holzer, P. Psomas, T. (2018), p.76

rain, burglary and fall is secured by a fixed metal grill in front of the window. Usage of the window is compromised by the exceptional deep windowsill, which invites users to use it as a shelf board, blocking its opening.

Figure 8 Window for manual night ventilation secured against rain fall and burglary but blocked by books

In most cases of large residential as well as commercial ventilative cooling applications central control will be the best option. Ventilative cooling may be integrated in the building's central Direct Digital Control (DDC). Input parameters may be again indoor temperature, humidity, CO2 and time (outdoor temperature, wind, solar radiation). It is important to clarify the control needs of ventilative cooling components already at the early design stage. Though, DDC in principle is open to all kinds of algorithms. Professional DDC solutions are predefined and limited in many aspects. Alterations of systems once installed may turn out impossible or expensive.[17]

8 CONCLUSIONS

Ventilative Cooling proofs to be a robust, cost and highly energy efficient solution to ensure climatic indoor comfort in buildings in both cool and warm temperate climate. Taking on the findings and results from this paper and the Annex 62 will help to make its implementation successful and promote its application on a broad scale. For further results and in depth reading please refer to the official Annex 62 deliverables cited in the references below.

9 ACKNOWLEDGEMENTS

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