Design and performance of ventilative cooling: a review of principals, strategies and components from International case studies

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ABSTRACT

Overheating is an unwanted consequence of modern building designs and internal gains that will be aggravated by the effects of climate change on local climates within urban and suburban areas. To minimise the energy cost of limiting overheating several different approaches exist for passive cooling dissipation techniques. Free cooling by ventilation, or Ventilative Cooling, (VC), is a generally accepted effective, energy efficient, mitigation strategy to building overheating. There are many factors that influence the design and selection of suitable VC strategies. Obtaining quantitative data about the spectrum of solutions employed across the range of suitable VC applications can be difficult and high in collaborative effort. A recent International Energy Agency project gathered information about well documented case studies of buildings with VC and investigated the existence of synergies in design, selection and simulation of solutions as well as any heterogeneous patterns in the adoption of VC principles and VC system component characteristics. This paper presents the aggregated data for 14 international case studies, provides a review of the VC systems adopted and design methods applied to ensure successful performance for different building types and climates. Various methods for VC system sizing at each stage of the design process are discussed along with the design criteria adopted in each case. Values for the percentage opening area to floor area ratio, a key metric for benchmarking the sizing of ventilation openings are presented and discussed. Further, a recommended range for this fundamental design parameter is suggested. Demonstrated implementation of control strategies for different types of VC solutions is also reviewed and discussed. Similarities in lessons learned were found to exist across multiple case studies. Finally, a synopsis of the key lessons learned during the design and operation phases of the case studies is also presented and reviewed.

KEYWORDS

Natural ventilation, ventilative cooling, case studies, thermal simulation

1 INTRODUCTION AND BACKGROUND

With 1983-2012 likely the warmest 30 year period of the last 1400 years in the Northern Hemisphere, Europe's human and managed systems, which include the built environment and urban infrastructure, are providing a major contribution to accelerating global climate change (IPCC 2014). Along with factors such as urban densification, a warming world is leading to increasingly hostile internal thermal environments in buildings. Evidence exists that current ambitious envelope and fabric oriented heating demand reduction strategies might result in an increased risk of extended periods of overheating in new buildings as well as in building retrofits (McLeod, Hopfe, and Kwan 2013; Psomas et al. 2016). A number of studies, both residential and non-residential have investigated the occurrence of overheating in buildings and found that a range of factors contribute to unacceptable levels of overheating (Beizaee, Lomas, and Firth 2013; Lomas and Kane 2013; Mavrogianni et al. 2012). Passive and hybrid cooling through the integration of natural and mechanical ventilation principles with the building morphology and materials has long been championed as a viable alternative to mechanical cooling. However, the basic premises under which mechanical and natural approaches operate are fundamentally different and this has led to a scepticism from building owners regarding the ability of a natural ventilation system to adequately deliver acceptable internal conditions in buildings during the warmer months of the year. The criteria by which natural ventilation is assessed is often one suited only to mechanically controlled environments and this is diametrically opposed to the basic principles of the concept. However, there are still many barriers to the effective adoption of natural ventilation for cooling (Carrilho da Graça and Linden 2016). Passive cooling techniques can be organised into a three-step framework: 1. prevention of heat gains, 2. modulation of heat gains and 3. heat dissipation (Santamouris and Kolokotsa 2013). When implemented correctly in this way, ventilative cooling (VC) solutions, properly integrated with the building design, are generally accepted as effective, energy efficient, mitigation strategies to building overheating. The ongoing international project IEA-EBC Annex 62 on VC deals with improving the suitability of VC for buildings. This project addresses the existing challenges for VC application and devises recommendations through development of design methods and compliance tools related to predicting, evaluating and eliminating the cooling need and the risk of overheating in buildings and through the development of new attractive energy efficient VC solutions (Kolokotroni et al. 2015). IEA-EBC annex 62 State of the Art Review report recently defined VC as, '*The application of ventilation flow rates to reduce the cooling loads in buildings. VC utilizes the cooling and thermal perception potential of outdoor air. The air driving force can be natural, mechanical or a combination*'(Kolokotroni et al. 2015). This project included a subtask to analyse and evaluate the performance of real VC solutions and of used design methods and tools using similar criteria and methods. In doing this the objective was to identify lessons learned and develop recommendations for design and operation of VC as well as identifying barriers for application and functioning of ventilative cooling. To achieve this, well-documented case studies in their operational phase at various international locations were studied. The benefit of real buildings and field study measurements is the realistic nature of the boundary conditions and thermal gains. In total 19 case studies are proposed for the project, with the results of their performance evaluations due to be published in an IEA report in January 2018. This paper gives an initial overview of the characteristics and lessons learned of investigated case studies in Annex 62. It summarises the features of the various case studies including the building characteristics, VC strategies and systems, design criteria and approach and lessons learned. It presents results from performance evaluations for selected case studies.

2 OVERVIEW OF CASE STUDIES

The 14 case studies of Annex 62 that will be analysed in this paper are located in 10 participant countries. Of the 14 case studies, three were completed in 2014, three in 2013, two in 2012, four in 2011 with the two remaining case studies in 2003 and 2007. Over 85% of case studies were built after 2010. There are three office buildings, five educational buildings, four residential, one mixed use and one kindergarten. Eight of the case studies have rural surroundings and six have urban surroundings. Four case studies were refurbishment projects. Table 1 shows the range of climate regions represented within the case studies while Table 2 summarises key categorical information about the case study buildings.

3 BUILDING DESIGN

What are the typical characteristics of buildings that utilise ventilative cooling? Some of these characteristics are developed in response to the decision to use VC while others are the reason VC was adopted.

Table 1: Variation in climate regions for all case study buildings. (Please refer to the Koppen-Geiger climate classification system for details on KG abbreviations in column 1)

KG	General Description	Qty	Locations
Cfb	Temperate with warm summers and no dry season	6	Cork, IE; Ernstbrunn,AT; WaregemandGhent, BE;Verrieres-le-Buisson, FR; Bristol, UK
Cfa	Temperate, hot summers and no dry season	2	Changsha, CN; Hayama, JP
Dfb	Cold with warm summers and no dry season	3	Stavern, NO; Trondheim, NO; Innsbruck, AT
Dfc	Cold with no dry season and cold summer	1	Larvik, NO
Csa	Temperate with dry, hot summers	2	Sicily, IT; Lisbon PT

Table 2: Building Type, size and year of completion for all case studies

Country	Building	Type	Year (New or Refurb)	Floor Area m^2	Strategy
IE	zero2020	Office	2012$^{(R)}$	223	Natural
NO.1	Brunla Primary school	Education	2011$^{(R)}$	2500	Hybrid
NO.2	Solstadbarnehage	Kindergarten	2011$^{(N)}$	788	Hybrid
CN	Wanguo MOMA	Residential	2007$^{(N)}$	1109	Mechanical
AT.1	UNI Innsbruck	Education	2014$^{(R)}$	12530	Hybrid
AT.2	wkSimonsfeld	Office	2014$^{(N)}$	967	Hybrid
BE.1	Renson	Office	2003$^{(N)}$	2107	Natural
BE.2	KU Leuven Ghent	Education	2012$^{(N)}$	278	Hybrid
FR	Maison Air et Lumiere	House	2011$^{(N)}$	173	Natural
IT	Mascalucia ZEB	House	2013$^{(N)}$	144	Hybrid
JP	Nexus Hayama	Mixed Use	2011(N)	12836	Natural
PT	CML Kindergarden	Education	2013$^{(N)}$	680	Natural
UK	Bristol University	Education	2013$^{(R)}$	117	Mechanical
NO.3	Living Lab	Residential	2014$^{(N)}$	100	Hybrid

3.1 Design Influences

What influences the design of a building that aims to adopt ventilative cooling? A range of factors can have varying levels of influence on building design. A list of those deemed as having properties that will affect the type of strategies and components adopted for cooling is presented in Table 3. For each case study, the relative importance of different factors on the design of the building was ranked qualitatively using High, Medium or Low classifications. In this table we can see that initial costs and energy costs were consistently important design influences across most case studies. Solar loads and air leakage were also important factors for most case studies. However, even in urban case studies external and internal noise did not appear to influence the building and ventilation designs. Rain ingress was however, relatively important in many locations. Finally, internal loads were important in about half of the case designs. It is difficult to draw global conclusions from the matrix in Table 3 but energy and initial costs along with internal and solar loads are key factors when considering design solutions.

3.2 Morphology

Some of the case studies are small, dedicated research spaces or studies using small isolated parts of a building such as the lecture rooms in KU Leuven, Bristol University computer room and the zero2020 testbed in Ireland.

Table 3: Design Influences (R dentoes Rural; U denotes Urban; *dentoes residential)

Country	**Building**	**Surroundings**	**Initial costs**	**Maintenance Costs**	**Energy Costs**	**Solar Loads**	**Internal Loads**	**External Noise**	**Internal Noise**	**Air Pollution**	**Rain Ingress**	**Insect Prevention**	**Burglary Prevention**	**Privacy**	**Air Leakage**
IE	zero2020	R	H	M	H	H	L	L	L	L	M	L	H	M	M
NO.1	Brunla Primary school	R	H	H	H	L	M	L	L	H	M	L	L	L	H
NO.2	Solstadbarnehage	R	L	L	H	L	L	L	M	H	L	L	L	L	H
AT.2	wkSimonsfeld	R	H	H	H	M	L	L	L	L	L	L	L	L	M
BE.1	Renson	R	L	M	L	H	H	H	L	L	L	L	L	L	L
IT	Mascalucia ZEB*	R	H	M	H	H	L	L	L	L	L	L	M	L	M
JP	Nexus Hayama	R	M	M	H	H	L	L	L	L	M	H	H	M	M
UK	Bristol University	R	H	H	H	L	H	L	M	L	M	M	H	L	L
CN	Wanguo MOMA*	U	H	M	H	H	L	L	L	L	M	L	M	L	H
AT.1	UNI Innsbruck	U	H	H	H	M	L	M	L	L	M	L	L	L	H
BE.2	KU Leuven Ghent	U	H	L	H	H	H	L	L	L	M	L	L	L	H
FR	Maison Air et Lumiere*	U	M	M	L	H	M	L	L	H	L	L	M	L	M
PT	CML Kindergarden	U	H	L	L	M	M	L	L	L	M	M	M	M	L
NO.3	Living Lab*	U	L	L	H	H	M	L	M	L	H	L	L	L	H

Others are grand in scale such as Nexus Hayama in Japan and The University of Innsbruck. In almost all cases, except arguably the Chinese case study in Changsha, the buildings can be classified as low rise with typically 2-4 floors. The average floor area for the buildings is 2,468m^2. However, when we remove Nexus Hayama in Japan (the largest case study at 12,836m^2) and University of Innsbruck this reduces to 765m^2. The smallest case study is the living lab in Trondheim at 100m^2, this is a research test facility for residential dwellings in cold climates. The shape coefficient, a measure of the building shape and efficiency of external building surface to floor area, is shown in Figure 1. We can see that the small Italian zero energy home has a disproportionately high shape coefficient compared with the other values. Excluding this we have a minimum shape coefficient of 0.18 and a maximum shape coefficient of 0.96, still a good spread. Figure 2 shows the window to wall area ratios for each case study. Four of the case studies have relatively high window to wall area ratios at or greater than 50% while the average is 34%.

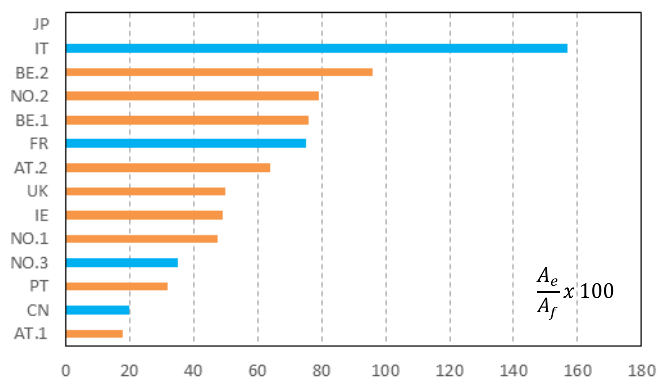

Figure 1: Building Shape Co-efficient for all Case Studies. (Residential shown in Blue)

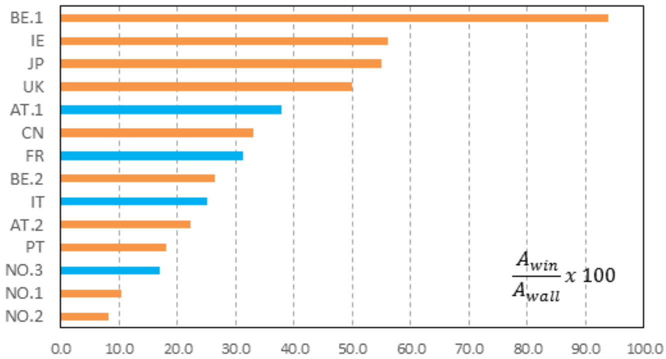

Figure 2: Window to Wall area ratio for all Case Studies. (Residential shown in Blue)

3.3 Thermal Properties

The case study buildings overall can be classified as high performance. Most buildings were designed as low energy or sustainable buildings. The average elemental U-value for all 14 case studies is 0.41 W/m^{2}K, which appears high but there is a large spread in individual values, with an average standard deviation across all elements of 0.34 W/m^{2}K. Some buildings such as the zero2020 testbed in Cork, have very high fabric performance (Wall U-value of 0.09 W/m^{2}K) while other buildings have lower performance, in part due to their respective national building regulations, such as the Nexus Hayama (wall U-value of 0.86 W/m^{2}K). This variation is in some part due to the different performance requirements and construction types for different climates. Six of the case studies can be classified as having heavy or very heavy thermal mass according to ISO13790. Good air tightness is a recurring feature of most case studies with the average Air Change Rate (ACR) from infiltration at 1.13 h^{-1}, ranging from 0.51 to 1.85 h^{-1}.

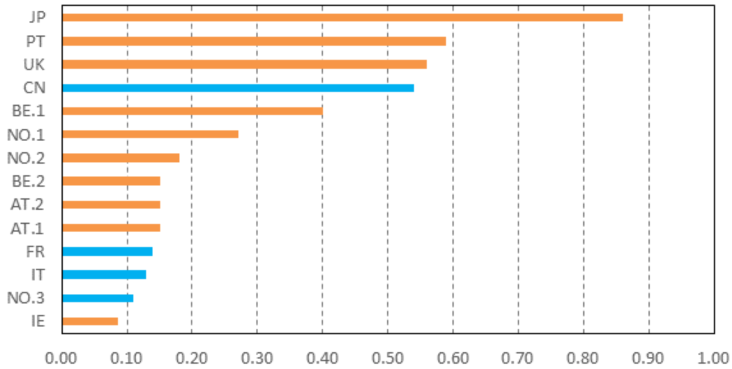

Figure 3: External Wall U-values for all Case Studies. (W/m^{2}K) (Residential shown in Blue)

4 VC STRATEGIES, COMPONENTS& CONTROL

4.1 Strategies & components

The case studies present a rich variety of VC solutions across a range of building types, morphologies and climates. Table 4 summarises VC concepts used in the case studies. The large majority, 86%, of the case studies use natural ventilation for VC strategies. The sensible internal loads for these case studies are all below 30 Wm^{-2} except for the Kindergarten in Portugal. The average is 25 Wm^{-2}. All the climates were temperate. The number of days with the maximum daily external temperature greater than 25°C was less than 30 in all cases except Portugal and the cooling season humidity is also low throughout except in Japan. The most prevalent strategy was hybrid ventilation with 50% of buildings using this approach for ventilative cooling. Many of these systems used mechanical exhaust ventilation when conditions required an increased airflow through the building.

Table 4: VC Strategies in all Case Studies

Country	Building	VC Strategies								
		Natural driven	**Mech. Supply Driven**	**Mech. exhaust driven**	**Natural night ventilation**	**Mech. night ventilation**	**Air conditioning**	**Indirect Evap. Cooling**	**Earth to Air Heat Exch.**	**Phase Chang eMaterials**
IE	Zero2020	X			X					
NO.1	Brunla Primary school	X			X					
NO.2	Solstadbarnehage	X		X	X	X				
CN	Wanguo MOMA		X	X		X	X			
AT.1	UNI Innsbruck	X		X	X					
AT.2	WkSimonsfeld	X		X						
BE.1	Renson	X			X					
BE.2	KU Leuven Ghent	X		X				X		
FR	Maison Air et Lumiere	X								
IT	Mascalucia ZEB	X			X				X	
JP	Nexus Hayama	X					X			
PT	CML Kindergarden	X			X					
UK	Bristol University					X	X			X
NO.3	Living Lab	X								

The internal loads in these spaces were greater than 40 Wm^{-2} in Norway and Belgium, while in Austria and Italy there were less than 10 Wm^{-2}. Two out of the 14 case studies use mechanical ventilation as a VC strategy.

A number of unique systems are employed in particular case studies such as the integrated manual and automated slot louvres at zero2020 in Ireland (O'Donovan, O'Sullivan, and Murphy 2017; O'Sullivan and Kolokotroni 2014, 2016), the displacement ventilation system at CML Kindergarten in Portugal (Mateus et al. 2016); the earth to air heat exchanger at the ZEB Home in Italy (Causone et al. 2014) and the PCM mechanical ventilation system in the UK (Santos, Hopper, and Kolokotroni 2016).

4.2 VC system control

The control strategies used varied depending on the ventilation strategy of each case study building. Figure 4 conveys which parameters were used depending on the ventilation strategy as a percentage of all case studies. Thermal comfort was the main driver for controlling all ventilation systems. Temperatures and relative humidity were the main parameters considered by control systems for comfort, while CO_2 was main parameter considered when controlling for air quality. Internal temperature was used by all cases studies with set-point control, one case study had a purely manual system. In addition, over 60% of case studies used an external temperature as part of their control strategy, this was typically a low temperature limit where the outside air was to be below the zone internal air temperature. Another point to note is the fact that exclusively mechanical systems did not consider precipitation or wind, while natural and hybrid systems did not incorporate external relative humidity levels into their control strategies.

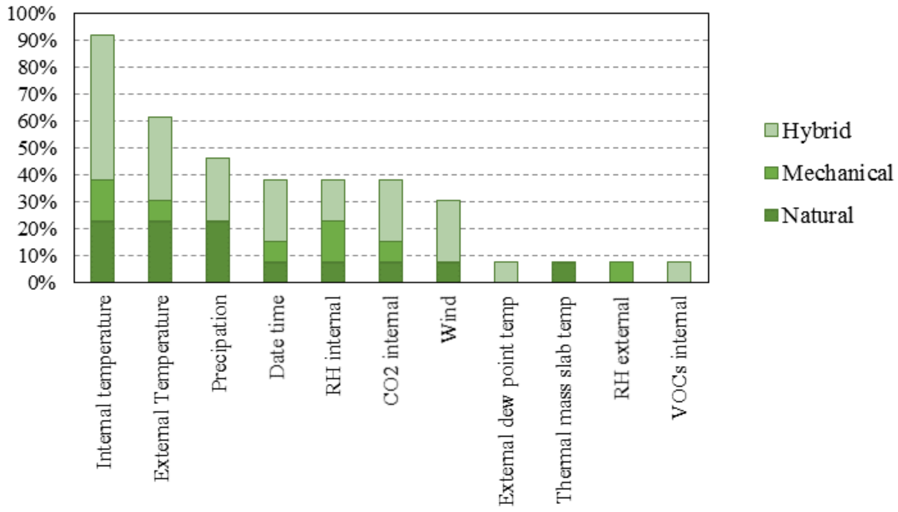

Figure 4: Summary of parameters used in VC control strategies for all case studies

Most control strategies for occupied periods used the internal zone temperature and an external temperature low limit as controlling parameters in ventilation strategies. There was no major correlation between the set-point used and the climate. The overall range of set-point temperatures were observed to be between 20-24°C where the mean internal air temperature set-point was around 22°C. The range of low temperature limits for outside air was between 10-18°C, with a mean external low temperature limit set-point of around 14°C. Around 54% of the case study buildings had a manual override switch or allowed occupant controlled ventilation during occupied hours as part of their typical occupied control strategies. All natural ventilation case studies allowed a form of occupant interaction with the ventilation system while 60% of hybrid systems allowed occupant interaction with the ventilation system. For systems that controlled depending on relative humidity an average set-point of 60% was observed. There were differing ranges of acceptability depending on whether the VC system was mechanical or natural. 69% of the case studies investigated incorporated a night ventilation strategy as well as an occupied ventilation control strategy. Typically, night ventilation strategies had different control parameters than ventilation strategies during occupied hours. The night ventilation strategies incorporated typically had a set-point for the zone as well as a limit on the properties of the air brought into the building also. The mechanical night ventilation strategies observed only used a combination of internal and external air temperature. The range of internal temperatures used for night ventilation strategies was between 15-23°C while the low limits on the external air temperature were between 10-18°C. Night ventilation was also dependant on the presence or absence of rain and wind speeds above a certain value. Typically, the wind speed had to be below 14m/s or 10m/s respectively and with no rain for night ventilation systems to operate. In cases where relative humidity was the control parameter night ventilation would not be activated unless the relative humidity was below 70% for a given zone. Parameters specifically related to indoor air quality were not considered in any of the night ventilation strategies.

5 SIZING AND SIMULATION OF VC

5.1 Sizing of VC systems

Information on the recommended aperture areas when sizing a VC systems is critical for the building designer. For almost all case studies, natural ventilation was adopted as either the sole source of VC or as part of a wider strategy, with, for example, natural supply and mechanical exhaust. It is generally beneficial to identify possible dimensionless parameters that provide a characterisation of the system, thus allowing for similarity investigations across multiple different systems. Owing to this and the inherent importance of the ventilation opening geometry to the delivered airflow rate, a parameter calculated as the percentage opening area to floor area ratio, or POF, was obtained for each case study. The opening area used is the maximum available geometric opening area and does not incorporate the flow effects of the opening. Figure 5 presents POF values for all cases where this was relevant.

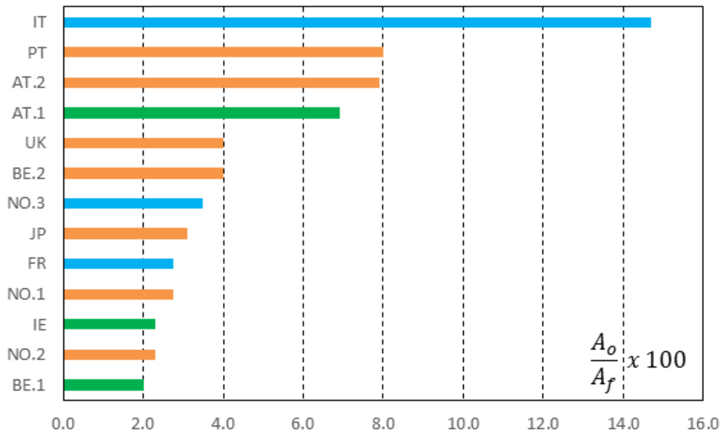

Figure 5: Percentage openable area to floor area for selected case studies. (Residential shown in blue, offices shown in green)

We can see a large spread of values for the case studies. 65% of buildings had POF values less than 4%. There seems to be no correlation with building category. The two highest values are from Csa climates. Two of the lowest three values are from fully naturally ventilated offices. Natural ventilated buildings had a POF of 3.6% while hybrid buildings had a POF of 4.6%, or 6.0% when the Italian case study is included. Although several building regulations impose a minimum floor to opening area ratio of 5% there is a generally accepted rule of thumb for designers when sizing openings at the concept stage of 1-3%. The low end of this range appears inadequate when compared with these case studies. A range of 2-4% seems more reasonable. Discharge coefficients range from 0.25 to 0.7 across the case studies although these were only measured in a few cases with many estimated.

5.2 Simulation of VC systems

Both the airflow performance and capacity sizing of the VC strategies and components, along with the building thermal performance, was investigated at various stages of the design using appropriate simulation tools. At the scope development stages national standards and engineering guidance documents, such as those published by CIBSE in the UK, were used by some countries. Some countries begun to develop models in different design packages such as PHPP and TAS while the Portugal case study used EnergyPlus from the initial stage right through to the operational performance evaluation stage. There was no single dominant tool for modelling VC across all case studies. For example, at the detailed design BSim was used for the naturally ventilated house in France, WindmasterSIMIEN was for all three cases in Norway, EnergyPlus was used in Portugal and in Italy. IES Apache was used in Ireland and the UK for the detailed design but TRNSYS was adopted for the Irish case study for operational performance evaluations. Only in Japan was CFD used. IDA Ice was adopted in Norway for all operational performance evaluations. A more thorough analysis of feedback from the use of the tools is underway but currently unavailable.

6 PERFORMANCE EVALUATION

All case studies completed performance evaluations involving various measurement campaigns. Each case study adopted different approaches and investigated different phenomena, including ventilation rate measurements, thermal comfort studies, analysis of internal thermal environments, investigation of the performance of specific solutions such as displacement ventilation, chimney-stacks, hybrid systems, cross flow ventilation etc. It is not possible to present in this paper the individual findings from these campaigns.
The Annex research project identified that, in order to assess the minimum performance of the VC strategy, one cooling season of internal air temperatures data should be obtained. This data should then be compared with a previously defined overheating risk criteria based on two static thresholds. Table 5 presents a selection of results from the case studies. There are some measuring campaigns still under way and as such results are unavailable for these. Overall there is very good performance from the VC solutions adopted in all case studies.

Table 5: Preliminary results of VC performance evaluation

Country	**Building**	**Summer Design Values**		**overheating criteria**	**% Occ hrs above threshold**		**Occ hrs**
		T_e	**$T_{i,o}$**		**28°C**	**25°C**	
IE	zero2020	26.0	25.0	T_i<28°Cfor 99% occ hrs	0.7	5.5	2600
NO.1	BrunlaSchool	25.0	26.0	T_i> 26°C	0.0	0.0	2600
NO.2	Solstad	25.0	24.0	T_i> 26	0.0	0.0	2860
AT.1	UNI Innsbruck	34.0	27.0	T_i< 26 for 95% occ hrs	1.1	16.2	2600
AT.2	wkSimonsfeld	34.5	24.0	T_i> 26 zone / T > 29 gallery	0.0	5.0	3250
JP	Nexus Hayama	26.0	26.0	T_i< 28 for 99% occ hrs (check)	1.0	40.0	8736
PT	Kindergarden	30.0	26.0	80% acceptability for 99% hr occ	2.6	16.0	3640

7 LESSONS LEARNED

The case studies analysed in this project yielded over sixty four key lessons learned, the majority of which were considered important. Thirty one lessons were contributed based on the design and construction and 33 lessons contributed from case studies buildings during operation and post occupancy. These are summarised separately.

7.1 Lessons from design and construction

Designing a building to incorporate VC can be challenging and may require a lot of detailed building information. While each challenge was different the main key lessons were as follows:

- Detailed building simulation is important when simulating VC strategies. Most case studies analysed highlighted the need for reliable building simulations in the design phase of a VC system. This was considered most important when designing for hybrid ventilation strategies where multiple mechanical systems need harmonization. Some studies also said that simulating the window opening in detail was important.
- Customisation may be an important factor in designing a VC system. In order to ventilate certain buildings it may be necessary to design custom components. Some case studies highlighted the need to have custom design systems that were specific to country regulations and the use of a building or space. Some consideration should also be given to the clients expectations around specific issues like rain ingress and insect prevention.
- VC systems were considered a cost-effective and energy efficient in design by most case studies, but particularly with naturally ventilated systems. It was indicated that designing

with the integration of manual operation and control was important, particularly in a domestic setting.

7.2 Operation and Post Occupancy

While systems may be designed to have high levels of comfort, IAQ and energy performance, achieving this was difficult. All case studies emphasised that monitoring a buildings performance post occupancy is important if not essential in building performance optimisation. While some key lessons were more specific than others the following general observations were made;

- Engaging with the building owners or operators as soon as possible is integral to guaranteeing building performance for IAQ, comfort or energy savings. For some case studies this specifically meant educating or working with the facilities operator or manager for the building, for others it meant educating the building occupiers themselves.
- It was suggested by some that this engagement should occur already in the design stage.
- VC in operation is generally a good option. Case studies comment on the reduction of overheating and improvement of comfort conditions in the buildings that used outside air. However, correct maintenance and calibration of the systems is integral to maintaining performance.
- Some case studies highlighted the need to exploit the outside air more with lower external air control limits during typical and night-time operation. Others suggested that exploiting the thermal mass of a building was key. However, it was noted that care must be taken with considering these low temperatures as some case studies, particularly in cold climates observed more incidences of overcooling than overheating.

8 CONCLUSIONS

In the last two decades, the use of VC has been slowly increasing. The best contemporary designs combine natural ventilation with conventional mechanical cooling. When properly designed, and implemented, these hybrid approaches maximize the VC potential while avoiding overheating during the warmer months. Yet, despite the potential shown in the case studies analysed in this study, and other existing examples, the potential of VC cooling remains largely untapped. This study showed that a lot can be learned from collecting information about VC case studies that have demonstrated through measurement that they perform well and their internal environments are comfortable for an acceptable period of the occupied time. However, due to the heterogeneity of the cases analysed, it is difficult to draw general conclusions regarding recommendations for designers. The characteristics of each case study appeared unique due to the need for the approach to respond to a specific climate, the building usage, morphology and client criteria. Hybrid systems are the most common type of system for VC and the use of mechanical fans to compliment a passive system should be strongly considered where possible. The use of simulation in the VC system design phase can reduce the uncertainties that are usually associated with natural ventilation systems. A POF value in the region of 2 – 8% was recorded and choosing a value on the larger end of this range at the concept design stage may be appropriate.

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