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Highlights of the AIVC 2017 Conference:

- Ventilative Cooling
- Unhealthy Homes harm People's Health

Hybrid GEOTABS Benefits and Challenges

Hotel BREEZE Amsterdam, Aeon Plaza Hotels, OZ Architecten en Dutch Green Company, please see article on page 65

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Tourism or Carbon Emission Reduction by Renovating our Building Stock?

"Tourism is responsible for nearly one tenth of worlds carbon emission."

(The Independent 7 May 2018).

"The highest CO_2 level in earth atmosphere reached in 800.000 years, exceeding the monthly average value of 410 ppm" (Manna Loa Observatory Hawai).

Two statements that should encourage existing building owners/users to act. Statements that renovation of existing buildings could require financial investments that many people cannot afford may be true but not for those responsible for the massive tourism. I don't want to blame the hospitality industry. But investing more in our existing homes and travelling less will benefit the environment twice!

It is up to our building and HVAC industry, our designers, planners, consultants and innovating producers and installers to come forward with cost-effective and attractive renovation solutions. Solutions that are attractive and limiting the disturbance of the building user and are understandable for our customers. Offers that can convince them to travel a few years less to make the investment possible. And at the same time we should be able to convince these building owners and users that this improving of the Energy Performance will not only decrease their energy bill but also increase their general indoor environmental quality, benefiting their comfort and health at the same time.

There of course more issues to consider promoting renovation projects. A snapshot of national renovation strategies and examples from selected EU Member States can be found at bpie.eu (please see the long link below*). This briefing provides a snapshot of measures supporting building renovation in selected Member States as of September 2017.

To document the efforts made by Member States, BPIE partnered with the Renovate Europe Campaign to examine the strategies provided by selected countries (Croatia, the Czech Republic, France, Greece, Hungary, Ireland, Italy, Poland, Spain). The briefing reviews the steps taken to implement the 2014 version of the renovation strategies and what progress has been made with the 2017 update (for selected countries).

This REHVA Journal offers many articles focussing on IAQ and IEQ and energy performance. Smart use of ventilative cooling improves the IAQ and reduces the need for cooling. This is also the moment to mention the AIVC 2018 Conference "Smart Ventilation for Buildings" This 39th AIVC conference: "Smart ventilation for buildings" will be held on 18 and 19 September 2018 in Juan-les-Pins, France. It will also be the 7th TightVent conference and the 5th Venticool conference. If Smart ventilation, IAQ and health relationships; Ventilation and airtightness and Ventilative cooling is your field of interest, this is the place to go! See www.aivc2018conference.org.

This issue includes also the first article in a series on the Hybrid GEOTABS project. This series offers very promising information and tools to apply this sustainable technology. This Model Predictive Control and Innovative System Integration of GEOTABS in Hybrid Low Grade Thermal Energy Systems offer great prospects for renovation projects. By improving the thermal performance of the building envelope, it is obvious to use these low temperature heating and high temperature cooling systems. ■

JAAP HOGELING
Editor-in-Chief

* http://bpie.eu/publication/a-snapshot-of-national-renovation-strategies-examples-from-selected-eu-member-states/

Ventilative Cooling on the test bench – Learnings and conclusions from practical design and performance evaluation



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Ventilative Cooling is a strong option for passive cooling with minimal energy input. Yet, applications of Ventilative Cooling (VC) have to be designed with utmost care. Misinterpretations of bordering conditions and users' preferences may spoil the concept. The article in hand presents guidance derived from real applications and simulation. It is based on a paper presented at the 38th AIVC - 6th TightVent & 4th venticool Conference, 2017 "Ventilating healthy low-energy buildings" held on 13-14 September 2017 in Nottingham, UK.

Keywords: Ventilative Cooling performance indicators, Ventilative Cooling challenges

Pressure drop in the VC-system

A very low pressure drop is mandatory for successful VC application. 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.

Driving force by buoyancy equals: [1]

$$\Delta p = (\tfrac{1}{30}) \times \Delta T \times h$$

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

[1] 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 Pthermal / Pelectrical . 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. EN16798-3 (table 14) defines the second best category of Specific Fan Power (SFP) the SFP1 category which means lower than 500 W/(m^3.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 cate-

Figure 1. Air inlet window with chain actuator (left) Exhaust ventilator on roof (right).

gory "SFP 0+" with a specific fan power of lower than 200 W/(m^3.s), equalling a pressure drop of 100 Pa. [2]

A well performing example of a VC exhaust ventilation was monitored in a recent Viennese social housing project. Outdoor Air inlet via automated staircase windows. Ventilative Cooling of the central stairways. Extract Air led through less than 10 m ducts and being exhausted by a central exhaust ventilator. The monitoring proofed a Specific Fan Power (SFP) lower than 170 W/(m^3.s), equalling a total pressure drop of 85 Pa, resulting in COP = 24 at an extract air flow of 22.000 m^3/h. [3]

Air change rates in the VC-system

ACH > 3 h^{-1} is mandatory, ACH > 5 h^{-1} is desirable to achieve substantial heat removal and justify noteworthy investments.

In VC applications, the nightly air change rate very often is the bottleneck. The following picture shows the balance of temperature and energy flow in a standard room within a characteristic Central European summer.

A massive wall, ceiling or floor may store up to 70 Wh/m^2 within one day. To release this heat by night ventilation, seven hour duration of specific heat flow of 10 W/m^2 is necessary. In an exemplary 24 m^2 room this leads to the need of at least ACH 8,0 h^{-1}, better ACH 10,0 h^{-1}. This is 10 to 20 times higher than ACH for hygienic aspects. Thus, unlink the function of Night Ventilation from the function of hygienic ventilation. Besides, trusting on windows. Even in case of single sided ventilation in still air only 3 K temperature difference at a fully opened window of 2 m height and 0,5 m width will already provide an air exchange of approx. ≈300 m^3/h. [4]

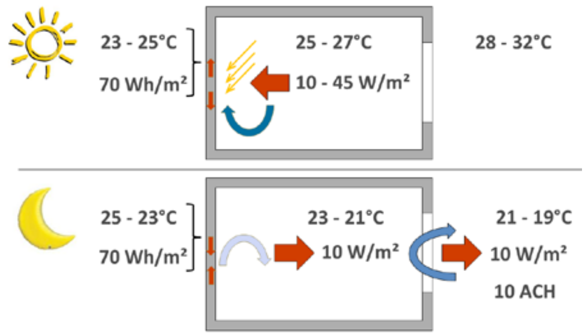

Figure 2. Scheme of typical VC temperatures, loads and airchangerates.

Operating schedule of mechanical VC

If mechanical, run the VC system only at a temperature difference potential of 2 K or higher. Do not shoulder the challenges of VC during periods of weak performance (with lower temperature differences).

Automated VC always consumes resources, such as energy and maintenance. Sometimes it interferes with the expectations of occupants, e.g. in case of noise.

Note: 1.000 m^3/h at ΔT of 1K carry the thermal load of 340 W. If driven mechanically at "SFP 1" at 500 Wel/(m^3.s) this will cause an electrical load of 140 W. Thus, running automated Ventilative cooling at low ΔT is only sensible in naturally driven systems. Even then, 2 K seems to be a recommendable threshold.

[2] Calculations based on an average ventilator efficiency ratio of 50% and air temperature rising by 3 K.

[3] Holzer, P. et al. (2016)

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

Figure 3 shows short time monitoring results from mechanical ventilative cooling in a Viennese office during a mild summer period. Outdoor Air Temperature (green) undergoes the extract air temperature (yellow) at 22:00. Ventilation runs from 22:00 to 06:00, which turns out to be a good choice regarding the start, but could have been extended regarding the end. [5]

Hybrid Ventilative Cooling

There's ongoing discussion, if Ventilative Cooling still is a good option, as soon as Air-conditioning is applied. And, furthermore, if Ventilative Cooling still is a good option, when climate change or urban heat island effect raise the ambient temperatures: The answer is two sided: Yes, it is, as long as air-conditioning is limited to moderate set point temperatures, e.g. 26°C and as long AC and VC are run strictly in alternative mode.

From one of our short time case studies we extrapolated the following scenarios of hybrid cooling: **Figure 4** (top) by green columns illustrates the days within a year with Ventilative Cooling being appropriate to keep the indoor set point temperature of 26°C. Sometimes VC won't be sufficient. If so, AC has to take over. **Figure 4** (bottom) illustrated the same, but against an outdoor temperature dataset with constantly plus 3 K. **Figure 4** shows, that the periods of necessarily running the AC are rising during summer, but cooling need also extends to early summer and late summer when, VC will take over. In fact, both the number of VC-days and the sum of thermal load being removed by VC stays constant.[6]

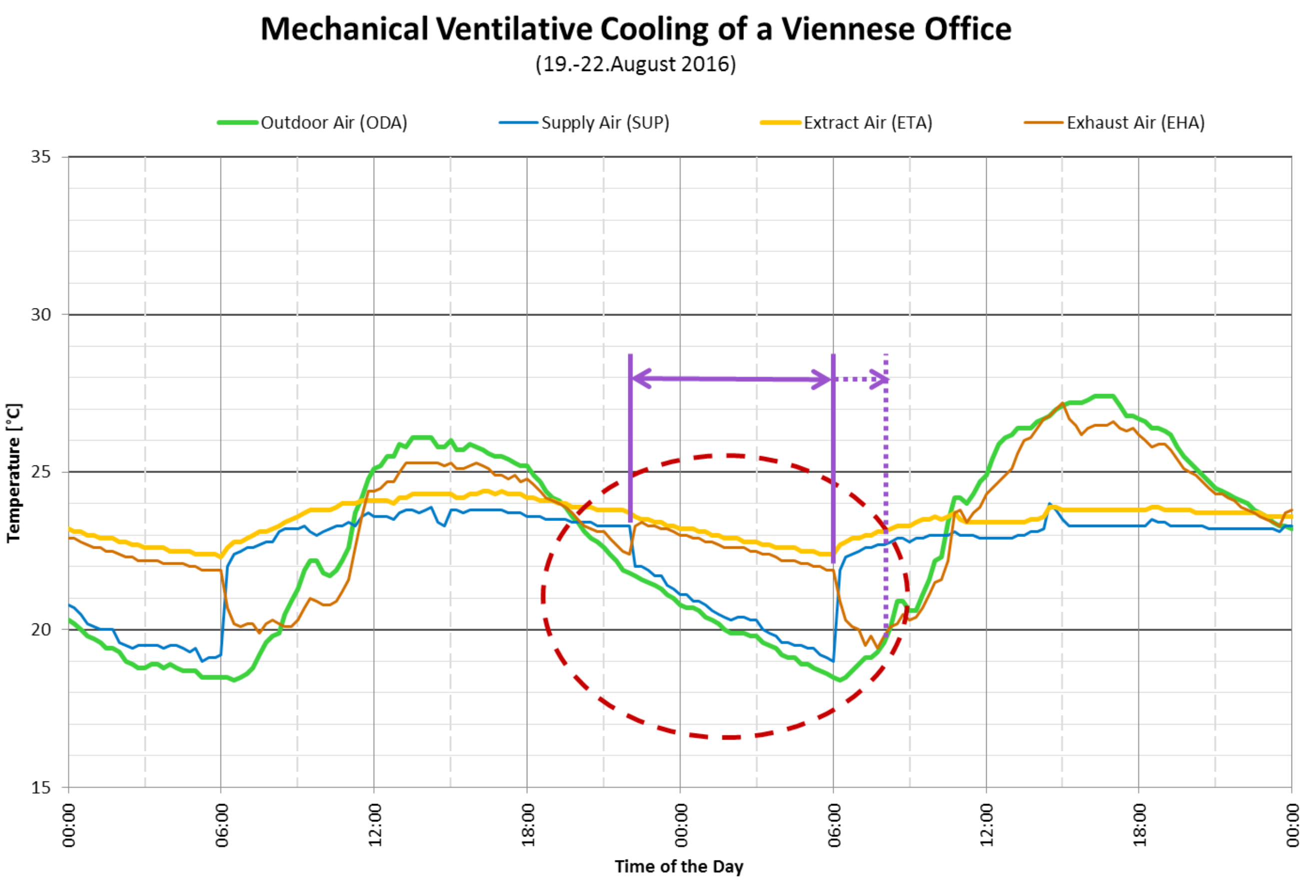

Figure 3. Temperature profile of mechanical Ventilative Cooling system in an office.

[5] Holzer, P. et al. (2016)

[6] Holzer (2016)

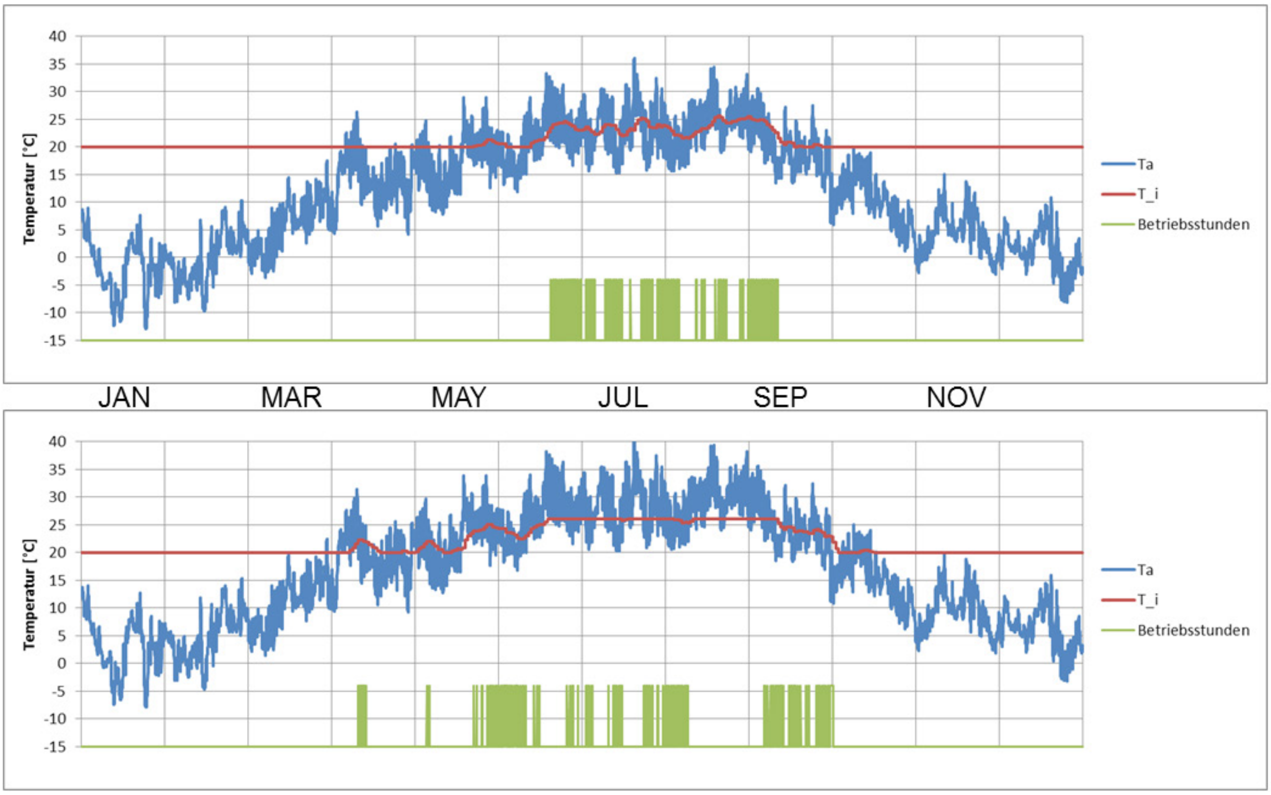

Figure 4. Days with climatic VC potential before and after a 3K outdoor climate change.

Ventilative cooling effects from adjacent rooms

There are promising examples for enhancing the effect of ventilative cooling by connecting adjacent rooms with deliberately high thermal conductivity.

This may be a very cost effective solution. It's comparably easy to effectively ventilate staircases and hallways, while it is costly and technically challenging to apply automated night ventilation to flats or to numerous single offices.

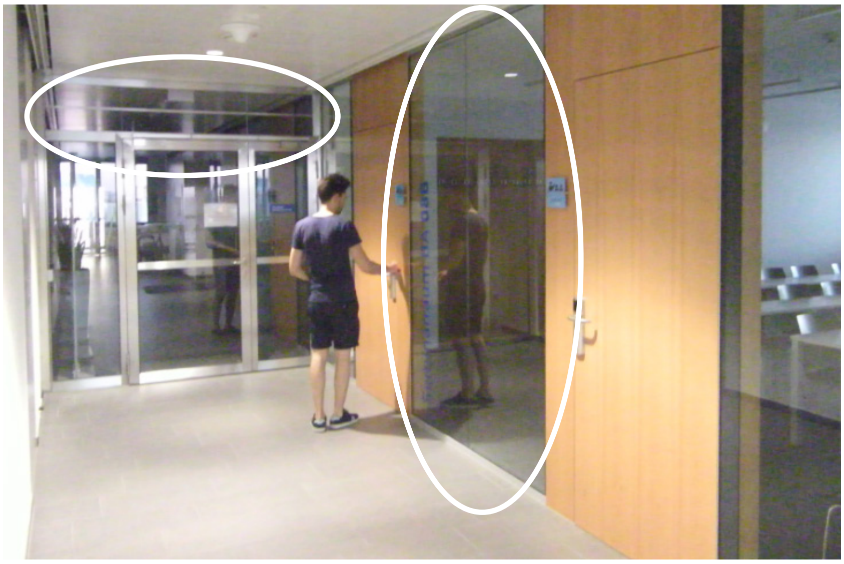

Figure 5. Glazed partition walls with high U-values and overflow orifice.

Figure 5 shows an example from a 1960's high-rise office building of Vienna's Technical University which has recently been refurbished to Plus-Energy-Standard, including buoyancy driven Night Ventilation of the staircases and hallways. The offices and seminar rooms are separated from the hallway by single-pane laminated safety glass. The overflow orifice for night ventilation is situated above the lockable hallway door. [7]

[7] Holzer, P. et al. (2016)

Thermal comfort at elevated air movement

Air movement is a strong driver of thermal comfort. It is well suitable to passive cooling.

Figure 6, taken from ISO 7730:2005 illustrates the medium airspeed necessary to elevate the comfort temperature from 26°C for standard summer clothing (0,5 clo) and for standard sitting tasks (1,2 met). Note: Airspeed of only 1 m/s without any technical cooling already elevates the comfort temperature by 3 K.

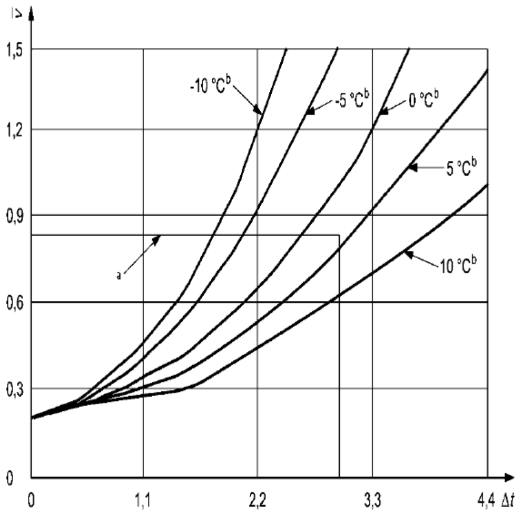

Figure 6. Mean air speed over elevation of comfort temperature.

Operability and reliability of VC-components

The operability of Ventilative Cooling Components, especially of the airflow guiding and airflow enhancing components, is a key success criteria.

The following aspects have been identified as critical in an operational context: [8]

- Safety & security aspects dealing with injury, burglary and vandalism
- Thermal Performance limitations
- Comfort aspects dealing with noise, dust and humidity
- Operational aspects dealing with (mis)adjustments in the control systems
- Economic aspects dealing with investment and maintenance

Keep operation strictly simple!
If VC is manually controlled, design ventilation openings free from interference with storage area and furniture, place opening handles very ergonomically, chose robust and long lasting mechanisms, always include anti-slam devices which prevent the ventilation openings slamming in case of draught.

If mechanical, put very intuitive operating devices at very intuitive places, be aware of stand by energy-consumption, operating noise levels, life cycles and maintenance; and find smart answers to questions relating to injury and vandalism.

Furthermore: Ensure strict rain protection: better by architecture than by rain sensors. Ensure burglary protection and consider needs for intimacy.

Figure 7 illustrates an example of protection against rain and burglary by a fixed metal grill in front of the window. But everyday operation of the window is handicapped by the exceptional deep windowsill, which invites users to use it as a shelf board, blocking the window.

Figure 7. Window for manual night ventilation secured against rain burglary and fall but blocked by books.

[8] Holzer, P. et al. (2015)

In our field research we found many examples how to deal with the risk of getting injured by automated ventilation openings, simple ones and sophisticated ones.

A high-tech example is shown in **Figure 8**: A window which can be operated both manually and automated. The handle is combined with an electro-mechanical device that disconnects the chain actuator from the window-frame, allowing manual operation. Furthermore, the window gaskets are equipped with internal electronic sensors, ensuring an immediate interruption of the closing process if dedecting an unexpected resistance. The windows are installed in a Viennese school. The flipside of the coin is the higher costs for this level of function, and the notable need for maintenance.

Another example showing the challenges of protecting against injuries was found at HCU "Hafencity University Hamburg": Pictograms tell users not to interfere with the automated bottom hung ventila-

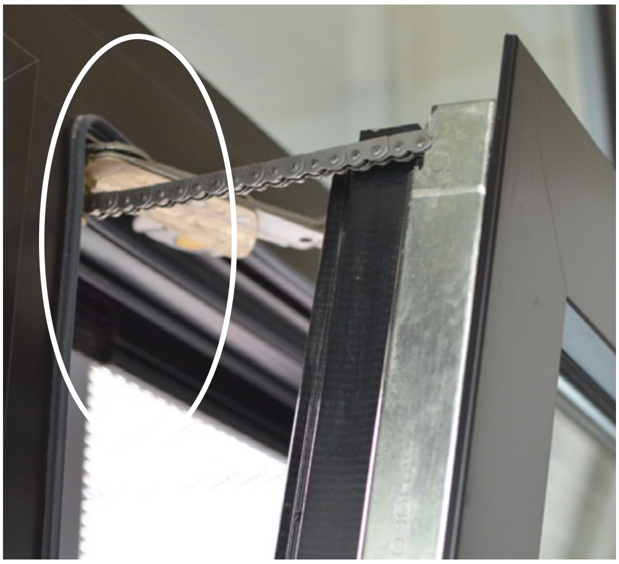

Figure 8. Automated window, with optional manual operation and resistance sensitive gasket.

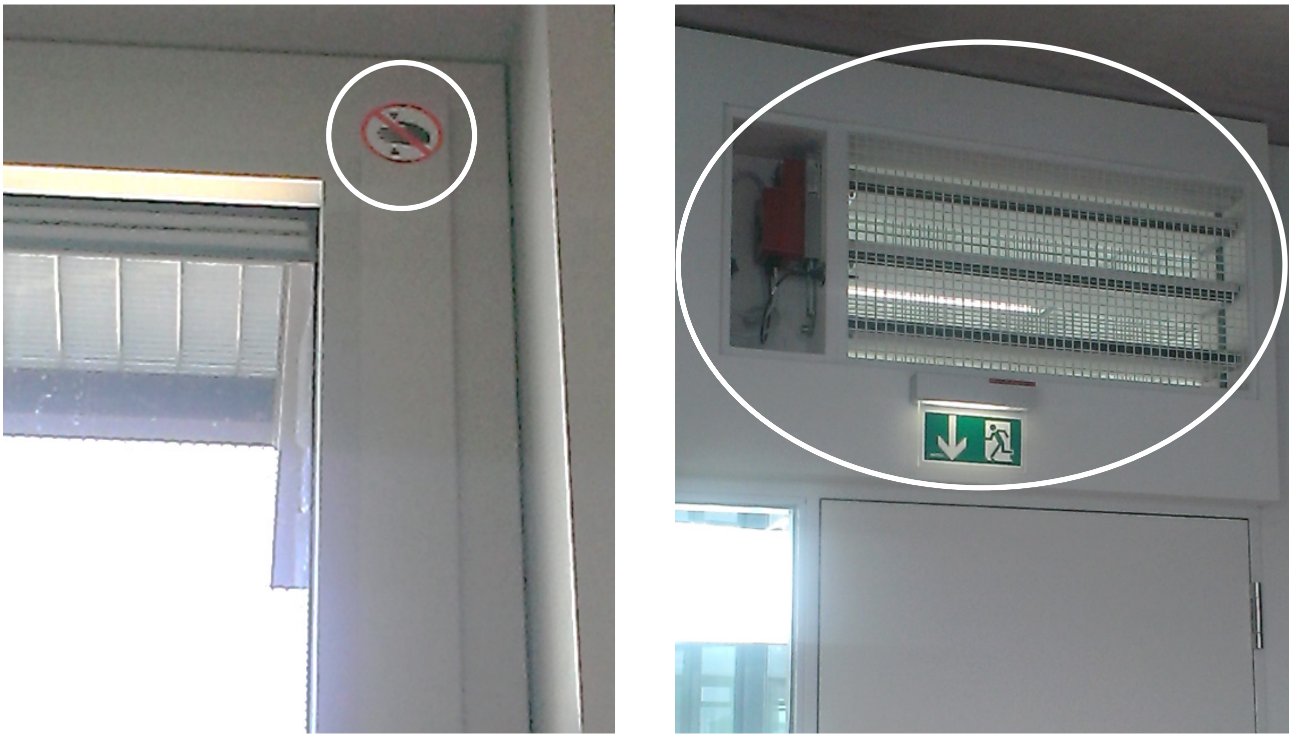

Figure 9. Ventilation flaps with additional warning pictogram and protective grid against finger injury.

tion windows, mounted already at elevations of > 2 m above floor level. Furthermore, protective grids secure venilation flaps (**Figure 9**).

Conclusions

Ventilative Cooling proofs to be a robust and highly energy efficient solution to support summer comfort in buildings, not at just in NZEB's. Ventilative Cooling furthermore proofs being applicable in both cool and warm temperate climate. An International VC Building Database has been elaborated within Annex 62, so far documenting 99 buildings using Ventilative Cooling from 8 European Countries.[9]■

[9] Holzer, P., Moherndl, P., Psomas, T., O'Sullivan, P. (2016)

Acknowledgements

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Ventilative Cooling in International Case Studies – Lessons Learned

During cooling seasons, a progressively warmer and increasingly urban world is leading to hostile internal thermal environments in many high-performance buildings. Correctly implemented, Ventilative Cooling can mitigate unwanted building overheating while minimising cooling loads. Identifying different solutions with proven performance can be invaluable to the building community.

Keywords: Ventilative cooling, Annex 62, lessons learned, natural ventilation, hybrid ventilation, cooling, overheating

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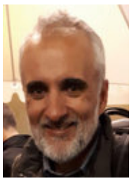

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The recent IEA-EBC Annex 62 State of the Art Review report recently defined Ventilative Cooling (VC) as, 'The application of ventilation flow rates to reduce the cooling loads in buildings. Ventilative Cooling utilizes the cooling and thermal perception potential of outdoor air. The air driving force can be natural, mechanical or a combination' [1]. Within Annex 62, the role of Subtask C was to analyse and evaluate the performance of real VC solutions as well as investigate design methods and tools adopted 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 the application and functioning of VC. In total 15 case studies were included in the Annex 62 project [2]. This article gives an overview of the characteristics and lessons learned of investigated case studies in Annex 62. A final project report is due to be published containing a detailed summary of the case studies along with a book of case study brochures. Further details are available at http://www.venticool.eu.

Overview of case studies: building properties, design and sizing

The 15 case studies that are presented here are located in 10 countries. Three were completed in 2014, four 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 seven have urban surroundings. Four case studies were refurbishment projects. **Table 1** summarises the key categorical information of the case study buildings.

The average elemental U-value for all 15 case studies is 0.35 W/m²K, which appears high but there is a large spread in individual values, with an average standard deviation across all elements of 0.27 W/m²K. Six of the case studies can be classified as having heavy or very heavy thermal mass according to ISO 13790:2008.

Table 1. Building Type, size and year of completion for all case studies.

No	Country	Building	Type	Year (New or Refurb)	Floor Area m²	Strategy
01	IE	zero2020	Office	2012(R)	223	Natural
02	NO.1	Brunla Primary school	Education	2011(R)	2500	Hybrid
03	NO.2	Solstadbarnehage	Kindergarten	2011(N)	788	Hybrid
04	CN	Wanguo MOMA	Residential	2007(N)	1109	Mechanical
05	AT.1	UNI Innsbruck	Education	2014(R)	12530	Hybrid
06	AT.2	wkSimonsfeld	Office	2014(N)	967	Hybrid
07	BE.1	Renson	Office	2003(N)	2107	Natural
08	BE.2	KU Leuven Ghent	Education	2012(N)	278	Hybrid
09	FR	Maison Air et Lumiere	House	2011(N)	173	Natural
10	IT	Mascalucia ZEB	House	2013(N)	144	Hybrid
11	JP.1	Nexus Hayama	Mixed Use	2011(N)	12836	Natural
12	JP.2	GFO	Mixed Use	2013(N)	399000	Hybrid
13	PT	CML Kindergarden	Education	2013(N)	680	Natural
14	UK	Bristol University	Education	2013(R)	117	Mechanical
15	NO.3	Living Lab	Residential	2014(N)	100	Hybrid

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}. **Table 2** gives some insight into the design influences for each of case studies in urban or rural surroundings.

Ventilation system sizing

Information on the recommended aperture area when sizing natural and hybrid 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 characterization 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

Table 2. Design Influences (R = Rural; U = Urban; *= residential).

Country	Building	Surroundings	Lower Initial costs	Lower Maintenance Costs	Lower Energy Costs	Reducing Solar Loads	Reducing Internal Loads	Reducing External Noise	High Internal noise propagation	Elevated Air Pollution	Avoiding Rain Ingress	Insect Prevention	Burglary Prevention	Reduced Privacy	Air Leakage
IE	zero2020	R	H	M	H	H	L	L	L	L	M	L	H	M	M
NO.1	Brunla 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
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
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
BE.2	KU Leuven Ghent	U	H	L	H	H	H	L	L	L	M	L	L	L	H
FR	MAL*	U	M	M	L	H	M	L	L	H	L	L	M	L	M
IT	Mascalucia ZEB*	R	H	M	H	H	L	L	L	L	L	L	M	L	M
JP.1	Nexus Hayama	R	M	M	H	H	L	L	L	L	M	H	H	M	M
PT	CML Kindergarden	U	H	L	L	M	M	L	L	L	M	M	M	M	L
JP.2	GFO	U	H	M	L	L	L	L	L	L	L	L	L	L	L
UK	Bristol University	R	H	H	H	L	H	L	M	L	M	M	H	L	L
NO.3	Living Lab*	U	L	L	H	H	M	L	M	L	H	L	L	L	H

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. We 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 climates with hot summers. 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.

VC strategies, control and performance

Table 3 gives an indication as the VC strategies used 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. The overall range of indoor 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 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 dependent 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.

All case studies completed performance evaluations involving various different measurement campaigns. Each case study adopted different approaches and investigated different phenomena. This included 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

Table 3. 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.1	Nexus Hayama	X					X			
JP.2	GFO Building	X				X	X			
PT	CML Kindergarden	X			X					
UK	Bristol University					X	X			X
NO.3	Living Lab	X								

ventilation etc. More information on specific studies can be found at http://www.venticool.eu. The 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 an overheating risk criteria. Two static thresholds were chosen with each case study quoting the percentage of hours exceeding this value. **Table 4** presents a selection of results from the case studies.

Lessons Learned -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.

Lessons Learned - 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

Table 4. Preliminary results of VC performance evaluation.

Country	Building	Summer Design Values		Overheating criteria / note	% Occ hrs above threshold		Occ hrs
		T_e	$T_{i,o}$		28°C	25°C	
IE	zero2020	26.0	25.0	T_i<28°C for 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°C	0.0	0.0	2860
AT.1	UNI Innsbruck	34.0	27.0	T_i< 26°C for 95% occ hrs	1.1	16.2	2600
AT.2	wkSimonsfeld	34.5	24.0	T_i> 26°C zone / T > 29 gallery	0.0	5.0	3250
JP.1	Nexus Hayama	26.0	26.0	T_i< 28°C for 99% occ hrs	1.0	40.0	8736
PT	Kindergarden	30.0	26.0	80% acceptability 99% hr occ	2.6	16.0	3640
UK	Bristol Uni	26.0	25.0	Adaptive TC Model	–	–	2600
BE.2	Renson Builing	–	–	Tz < 26°C for 95% of hocc Tz < 28°C for 99% of hocc	0.3	11.4	2600
BE.1	KU Leuven Ghent	–	25	T_i < 26°C for 95 % hr occ	0.3	5.1	1560
NO.3	Living Lab	25	26	T_i> 26°C	24	2.6	832

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.
- Each brochure includes lessons learned in a dedicated section at the end of the brochure.

More details related to specific lessons learned can be found in the final summary reports for IEA-EBC Annex 62 at http://www.venticool.eu.

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 presented here, and other existing examples, the potential of VC remains largely untapped. 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. A combination of automated and manual control seemed to be the most adaptable and reliable solution to providing a system that worked well with its users satisfied with its operation. 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. ■

Acknowledgements

The authors would like to acknowledge all IEA Annex 62 participants that provided a case study for the project. Further details are available at http://www.venticool.eu. This article is based on a paper presented at the 38th AIVC - 6th TightVent & 4th Venticool Conference, 2017 "Ventilating healthy low-energy buildings" held on 13-14 September 2017 in Nottingham, UK.

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Study shows that unhealthy homes lead to reduced health

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Today one out of six Europeans (84 million Europeans, or the equivalent of Germany's population), report deficiencies regarding the building status. In some countries, that number is as high as one out of three. This puts these buildings in the 'Unhealthy Buildings' category, which is defined as buildings that have damp (leaking roof or damp floor, walls or foundation), a lack of daylight, inadequate heating during the winter or overheating problems.

Keywords: Health, building, indoor climate, EU-SILC, European Union

Ten percent of Europeans report having poor perceived general health. And the probability that a person reports poor health increase up to 70% if that person also lives in an unhealthy building vs. a healthy one. The results of this study show a correlation between poor health and the specific unhealthy building factors:

- 1.7 times report poor health in a damp building
- 1.5 times report poor health when living in a building with insufficient daylight
- 1.3 times report poor health when perceiving overheating
- 1.7 times report poor health when living in uncomfortably cold temperatures

Introduction

The paper is based on the analysis of the correlation between health and buildings in 27 EU member states using the Eurostat database EU-SILC (Survey on Income and Living Conditions). The presented research is based on EU-SILC raw data. For the purpose of the study, Eurostat approved the research proposal behind the analysis and gave access to the data to Ecofys Germany GmbH.

Around 508 million European citizens (EUROSTAT, 2015) spend about 90% of their time indoors (living and working) (NEST, 2004). Therefore Europe's buildings have a major impact on Europeans' health. According to WHO's definition (since 1948) "Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity."

Yet, research assessing the statistical links between health and housing conditions is largely missing. Considering that building renovation is a huge intervention into the whole building system – cross-cutting technical aspects of the building itself and social as well as economic issues of the dwellers – it is necessary to fully grasp the implications, risks and chances. Therefore, a main research objective is to identify these links and to highlight which part of Europe's and MS's population is most in need of building renovation.

This insight triggered a detailed study on the relation between health and housing conditions across EU28 and its Member States. The results described here have been presented in the scientific report "The relation between quality of dwelling, socio-economic status and health in EU28 and its Member States" (Hermelink & John, 2017).

This article is based on a paper presented at the 38th AIVC – 6th TightVent & 4th venticool Conference, 2017 "Ventilating healthy low-energy buildings" held on 13-14 September 2017 in Nottingham, UK.

The results from the study are used in VELUX Healthy Homes Barometer 2017.

Methodology

The research is based on analysing Eurostat microdata from the EU-wide survey „Income and Living Conditions in Europe" (EU-SILC). EU-SILC is a Eurostat Survey, which is conducted in a European-wide household panel, to assess the status and development of Income and Living Conditions in Europe. The EU SILC survey covers amongst others the domains housing including economic issues and health. Data in EU-SILC are collected either on household or individual level. For this research, anonymised results for more than 100,000 individual households and more than 250,000 adults (16 +) across all EU Member States – except Germany - were made available by Eurostat.

The focus of this study lies on data from 2012, where more detailed information on housing conditions was collected. To handle the massive amount of data the statistical computing program R (version 3.3.0) was used for statistical analyses of the microdata.

Results

The research reveals that around 16% of Europeans report deficiencies regarding the building status; either because of dampness (leaking roof or damp floor, walls or foundation), lack of daylight, inadequate heating during the winter or overheating problems. The analysis also shows that around 44 Mio adults report poor perceived general health; this is equivalent to nearly 10% of the European population. As described above, the results will focus on the linkage between building status and health. Accordingly, the focal point of analysis described here are:

- health in damp buildings,
- health in dark buildings,
- health in overheated buildings,
- health in building with uncomfortably cold temperatures.

Detailed results of each of the mentioned topics will be described in the following subsections.

Health in damp buildings

15% of EU households (more than 30 Mio; or more than 60 Mio adults) report to live in damp buildings (leaking roof, damp floor/walls /roof/ foundation etc.).

- When adults report no dampness 9% report poor health.
- When adults report dampness 16% report poor health.

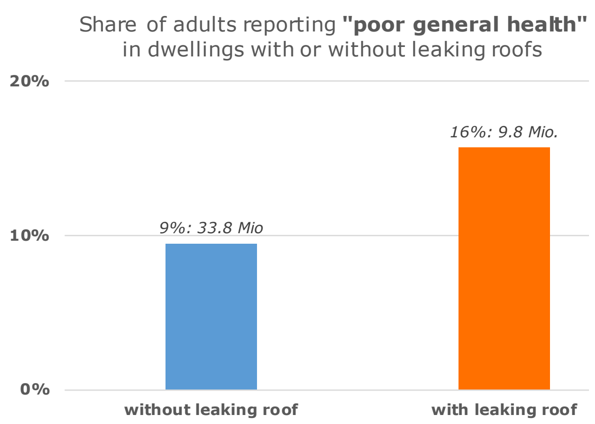

Figure 1. Health status in damp buildings for EU28 (share within subset and number of adults).

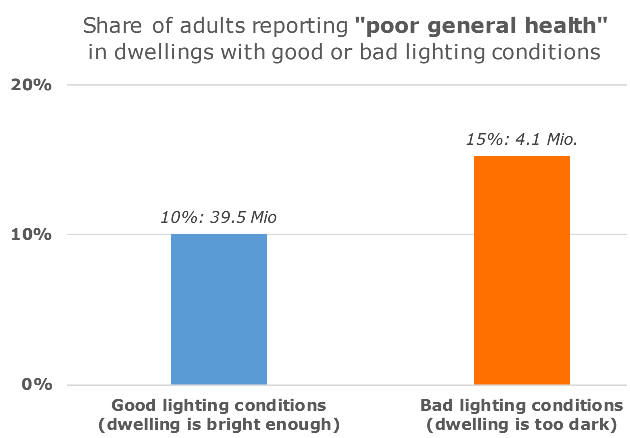

Figure 2. Health status in dark building for EU28 (share within subset and number of adults).

The probability that adults report poor health is significantly higher in homes with reported dampness; across the EU the probability is 1.7 times higher than with no dampness.

Health in dark buildings

Approx. 6% of all EU households (14 million; or approx. 30 Mio adults) report a lack of daylight

- When adults report no lack of daylight 10% report poor health.
- When adults report lack of daylight 15% report poor health.

The probability that adults report bad health is significantly higher when a lack of daylight is perceived; across the EU this probability is 1.5 times the one when no lack of daylight is perceived. Altogether approx. 10% of all adults reporting poor health live in buildings lacking daylight, where only 7% of all adults live.

Health in overheated buildings

Approx. 20% of all EU households (40 million; or approx. 84 Mio adults) report bad thermal comfort in summer.

- When adults report good thermal comfort (cool dwelling) in summer, 10% report poor health.
- When adults report bad thermal comfort (too hot dwellings) in summer, 13% report poor health.

The probability that adults report bad health is significantly higher when the bad thermal comfort is perceived; across the EU this probability is 1.3 times when good thermal comfort is perceived.

Health in too cold buildings during winter

Approx. 15% of all EU households (more than 30 Mio; or more than 60 Mio adults) bad thermal comfort in winter

- When adults report good thermal comfort (warm dwellings) in winter 9% report poor health.
- When adults report bad thermal comfort (too cold dwellings) in winter 16% report poor health.

The probability that adults report bad health is significantly higher when bad thermal comfort is perceived; across the EU this probability is 1.7 times the one when good thermal comfort is perceived.

Conclusion and discussion

The results described in this paper based on EU-SILC variables on quality of buildings and general health show statistically significant interdependencies. However, additional analysis are needed to understand for example the influence of economic issues of households and individuals, regional patterns or energy poverty on health. Based on the results shown here, we observed that structural problems of the building like leaking roofs, damp walls (etc.), buildings' ability to provide comfortable temperatures in winter, lack of daylight seem to act as similarly strong accelerators and/or indicators for health problems. On average the relative share of adults reporting poor health increases 30 to 70% when at least one of the above-mentioned deficiencies is reported compared to the group of people who do not perceive such deficiencies.

However, as indicated above this study so far focused on a small selected sample of relevant variables influ-

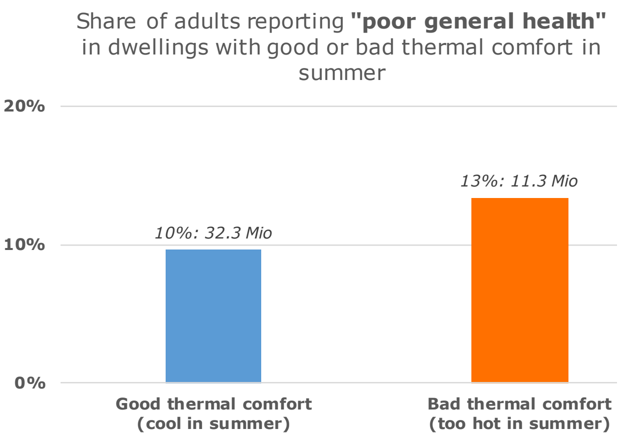

Figure 3. Health in overheated buildings for EU28 status (share within subset and number of adults).

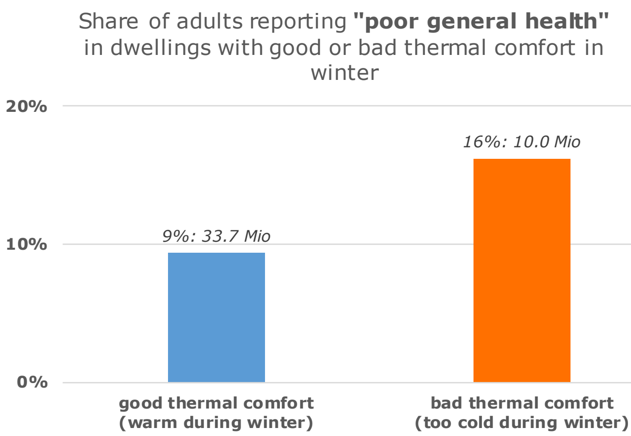

Figure 4. Health in too cold buildings for EU28 status (share within subset and number of adults).

encing health. On the other hand like in the analyses of Thomson and Snell (2012) who focused their EU SILC analyses on energy poverty, the strengths of the correlations are moderate. This is why on the one hand we found statistically highly significant correlations between the presented variables. This means, that there are many other variables apart from the ones analyzed in this study, also having a very significant impact on a person's perceived general health. Obviously personal and environmental variables determine health. Yet, we feel that buildings, which in this equation at least in Europe occupy 90% of the environmental variables' time are very much under-represented in today's overarching discussion about sustainability, which eventually is about shaping the world in a way that leads to sustained individual and societal health.

Above mentioned problems like dampness, darkness, too cold in winter or overheating in summer clearly hint at buildings in need of renovation. According to EUROSTAT (2012), ca. 58% of EU's population live in detached and semi-detached single-family homes; our results also show that around 4 out of 5 of these dwelling types are owned by private owners. This means, that this group is crucial to successfully increase the renovation rate as implicated in the proposal for the amending directive on energy performance of buildings (European Commission, 2016) and needs to be addressed by incentives, renovation policies and awareness raising as well as information campaigns.

To reveal more insights, further research is ongoing to examine the linkage between health and building status, but also considering the economic status of building's occupants. This analysis considers additional variables such as health prevalence of building occupants for example due to age, occupancy status and, economic status, income level, existing chronical illnesses, medical care system of respective country, etc. In this sense, a prediction model and additional multiple correlations for health considering selected variables of building and economic status and previous mentioned variables could reveal insights on the impact on health, but also more general insights into causes and effects within the triangle of clusters of variables described above. Furthermore, analysis shall evaluate the development of the building and economic status as well as general health aspects over time to observe the impact of policy measures and to derive recommendations for priority areas for action. This can also reveal insights on causal chains between building status, economic situation and health aspects explaining energy poverty. ■

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Analyses of 1,000 ductwork airtightness measurements in France

In France, a national database from qualified testers' data included in 2017 about 1,000 ductwork airtightness measurements that were performed mainly in new highly efficient buildings. This paper presents first analysis of this database, including ventilation system main characteristics and the most frequent results depending on the type of building. It is based on a paper presented at the 38th AIVC - 6th TightVent & 4th venticool Conference, 2017 "Ventilating healthy low-energy buildings" held on 13-14 September 2017 in Nottingham, UK.

Keywords: Ductwork airtightness, ventilation, building, measurements, database.

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Duct leakage is known to be detrimental to energy performance and indoor climate (Andersson, 2013) (Carrié, 1999). In order to limit the negative effects of leaky duct systems, French authorities developed an approach to improve ductwork airtightness which builds on the success and lessons learnt from the envelope airtightness approach, including mandatory justification of the airtightness level achieved with third-party testing, unless the default value is used (Charrier, 2017). These ductwork airtightness requirements are expected to boost the market similarly to what happened with the envelope airtightness market as described by Charrier (Charrier, 2015).

In the French EPB regulations, a default value for ductwork leakage class can be used. Based on leakage classes defined in EN standards 12237 and 1507, the default value corresponds to 2.5*class A. Since the current EPB regulation (RT2012), if a better-than-default class is used, it must be justified. Furthermore, the Effinergie+ and BEPOS-Effinergie labels, firmly based on the current regulation, require justifying achieving ductwork leakage Class A as a minimum (Carrié, 2016). **Figure 1** gives an overview of the evolution of the regulatory and voluntary requirements since 2000. Note that both residential and non-residential buildings are concerned. The Effinergie+ and BEPOS labels are meant to experiment requirements for future updates of the regulation, similarly to the past BBC-Effinergie label (tightening RT2005 regulatory levels) which has been very popular and useful to tune the requirements of the RT2012 regulation.

The RT2012 regulation gives two options to justify using a ductwork airtightness class different from the default value as input in the EPB calculation. The class achieved can be justified:

- Either with a ductwork airtightness measurement, performed by a certified tester;
- Or by the application of a certified quality manage-

ment approach (QMA) on ductwork airtightness that allows testing only a sample of buildings. Although a similar QMA option is popular for envelope airtightness (Charrier, 2014), it has never been used in practice for ductwork airtightness and is currently under revision. In both cases, ductwork airtightness tests must be performed by a third-party tester, qualified by the certification body Qualibat.

Presentation of the French national ductwork airtightness measurement scheme and its database

Qualification requirements

In 2012, Effinergie introduced a training scheme for testers within the creation of the Effinergie+ label. Then, the government created a qualification for ductwork airtightness testers. To be qualified, a tester has to:

- Undergo a qualifying State-approved training;
- Pass the training examination (the theoretical part, with a State-approved multiple-choice questionnaire; and the practical part, with a test performed in situ with a certified tester),
- Justify sufficient testing experience.

Once qualified, every tester is subjected to yearly follow-up checks, organized by the certification body. The follow-up checks include an analysis of some reports to verify their compliance with applicable standards and guidelines. Checks are based on the documentation sent every year, but also on site, in particular, in case of complaints or doubts about the quality of their work. Those checks can lead to de-qualification. As of February 2017, 58 testers have been qualified by Qualibat.

Tests have to comply with the European standards EN 12237, EN 1507, EN 13403 and EN 12599, and with the French technical report FD E 51-767. For the Effinergie labels, testers have to additionally comply with the Effinergie measurement protocol, and soon with the recently issued Promevent protocol. Whenever a test is performed, either for a certified QMA or for a systematic test, it must be performed after any works that could impact the final ductwork airtightness. FD E 51-767 specifies the reporting format. In particular, the report indicates if the ductwork airtightness complies with the input class used in the EP calculation. A new version of FD E 51-767 should be published soon. It has been modified to ease the measurement and avoid damage to the ductwork when preparing the section under test.

Development of a ductwork measurements database

Each qualified tester is required to fill in a register with all test results and communicate this register to the certification body every year for verification purposes. This register includes:

- Building general information: owner, location, use, year of the construction, year of the rehabilitation;

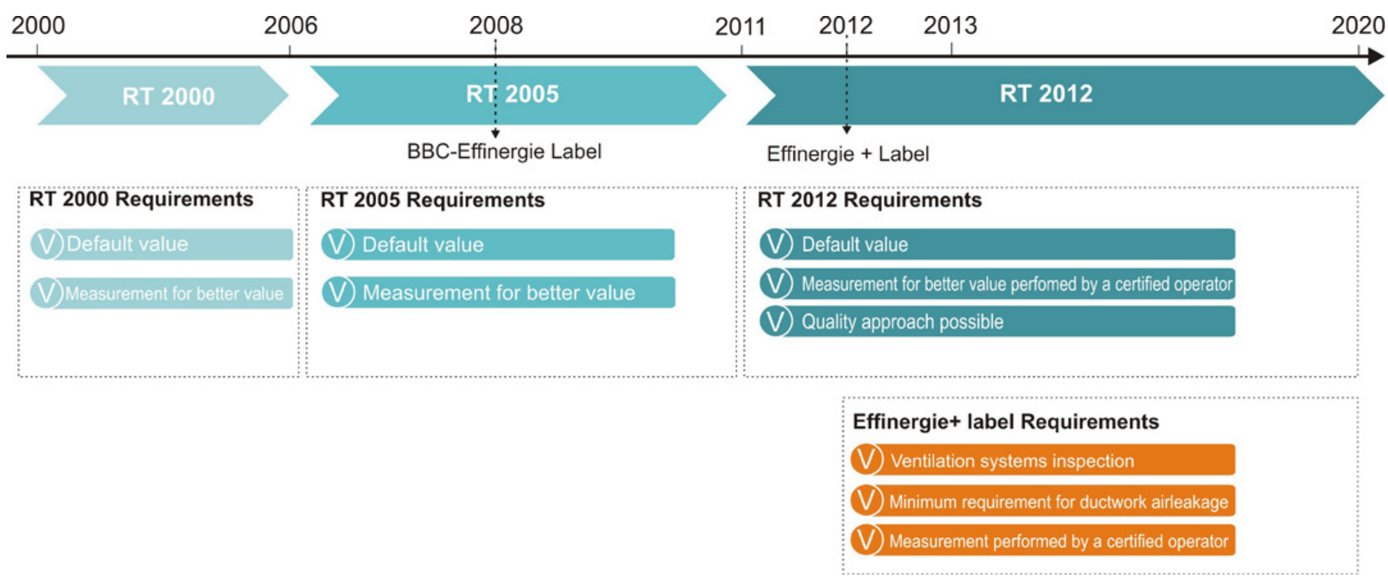

Figure 1. Evolution of French requirements on ductwork airtightness since 2000 for residential and non-residential buildings.

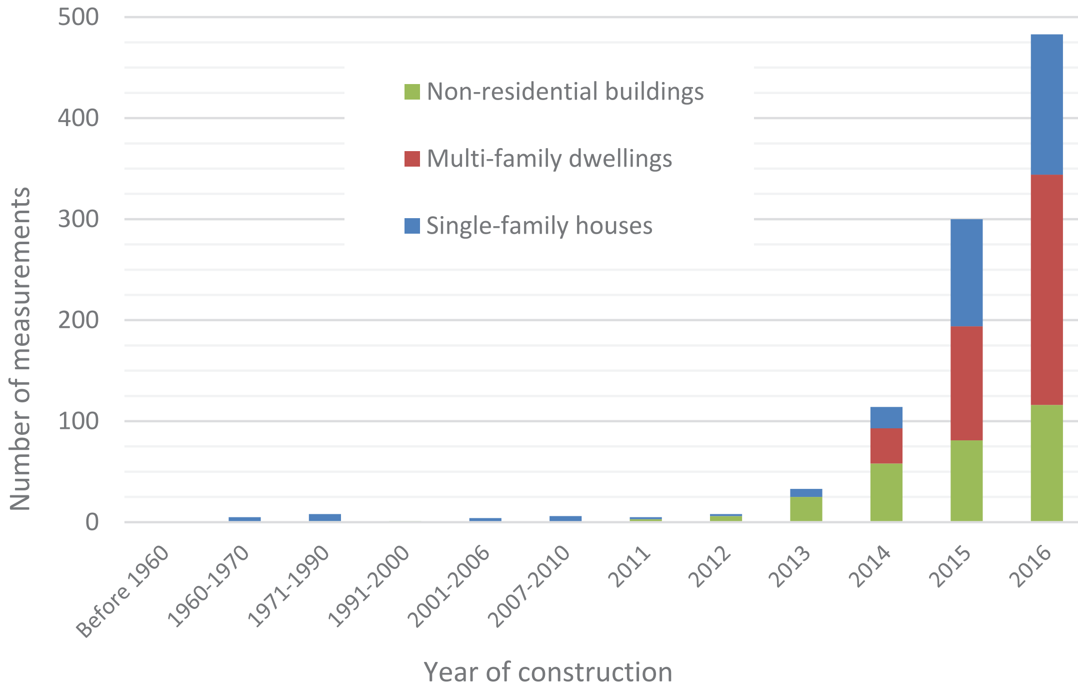

Figure 2. Number of ductworks airtightness measurements depending on the construction year and the use of the building.

- Special requirements: label, certification, ductwork airtightness class target;
- Ventilation system main characteristics: number of stories, type of system, nature, geometry and insulation of ducts, type of terminal devices;
- Measurement protocol: tester's name, date of measurement, measurement device, time of measurement (building state);
- Measurement input data: ductwork surface area, test pressure;
- Measurement results: leakage airflow, leakage factor f, airtightness class.

All registers are consolidated in a common database. Currently, 983 measurements have been recorded in the database. Those measurements were performed by certified testers since the introduction of the training scheme in 2012 (last updating in January 2017). A similar scheme exists since 2007 regarding building airtightness. It has led to a growing database of more than 100,000 tests (Bailly et al., 2016).

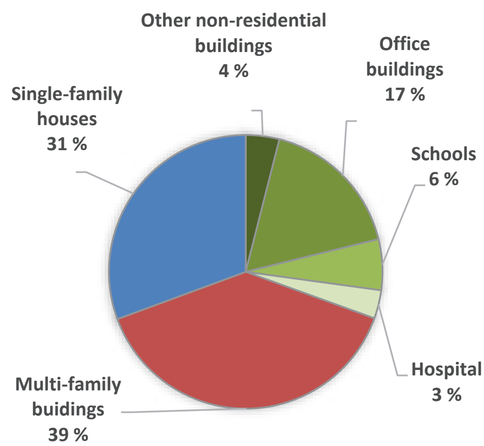

Figure 3. Distribution of buildings' use.

Results

Main characteristics of buildings and ventilation systems in the database

Measurements registered in the database were essentially performed in new buildings: 97% of measurements have been performed in buildings built after 2011 (see **Figure 2**). Although earlier ductwork airtightness measurements were only performed in non-residential buildings, we observe that the number of measurements performed in single-family houses and multi-family dwellings significantly increased the last 2 years. They represented 76% of the measurements performed in 2016.

Figure 3 shows that for non-residential buildings, measurements were essentially performed in office buildings, schools, and hospitals.

In new French buildings, either balanced ventilation systems or single-exhaust ventilation systems are implemented. **Figure 4** shows that residential buildings, both multi-family dwellings, and single-family houses, are mainly equipped with single-exhaust ventilation systems, and non-residential buildings are equipped with balanced ventilation systems.

Those figures cannot be generalized to all new French buildings. In fact, low-energy certified buildings represent 44% of the measurements recorded in the database but only 10% of the new building stock in France.

Three different types of ducts are used: rigid ducts, semi-rigid ducts, and flexible ducts. **Table 1** presents the distribution of the type of ductwork depending on the building's use and the type of ventilation system. Balanced ventilation systems are mainly connected to rigid ducts, especially in non-residential buildings. For single-exhaust ventilation system, it depends on the type of building. Rigid ducts are widely used both in non-residential buildings and multi-family buildings. On the contrary, flexible ducts are the main type of ductwork implemented in single-family houses equipped with single-exhaust ventilation systems. This practice is consistent with the type of ducts generally implemented in all buildings in France, as it corresponds to the French standards and professional recommendations.

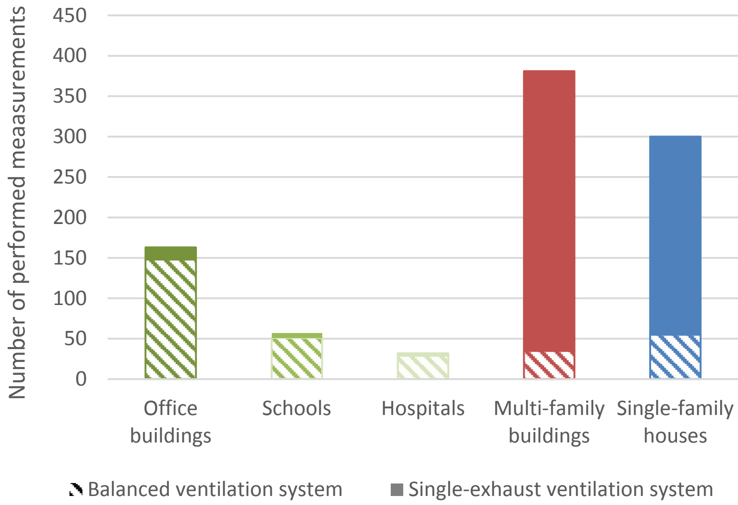

Figure 4. Type of ventilation system depending on buildings' use.

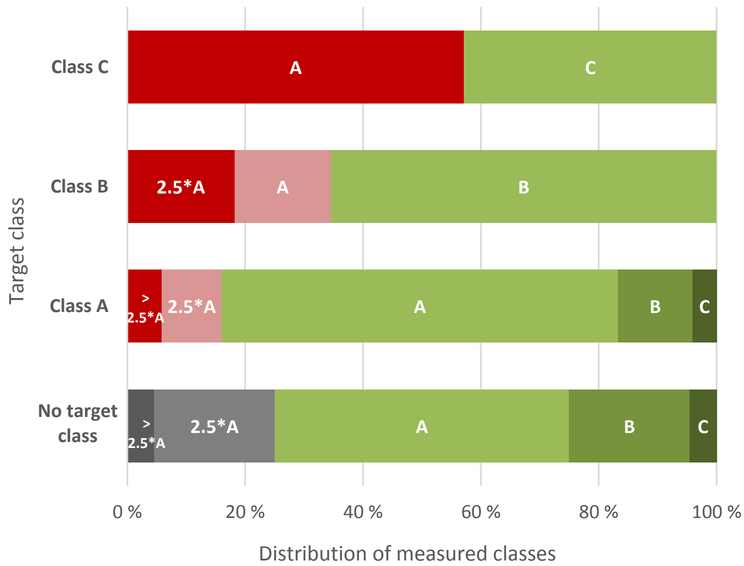

Figure 5. Specific ductwork airtightness measured class depending on target class.

Table 1. Type of implemented ducts depending on building's use and type of ventilation system.

	Balanced ventilation system			Single-exhaust ventilation system		
	Rigid ducts	Semi-rigid ducts	Flexible ducts	Rigid ducts	Semi-rigid ducts	Flexible ducts
Office buildings	**85%**	0%	5%	11%	0%	0%
Schools	**79%**	0%	11%	11%	0%	0%
Hospitals	**89%**	0%	0%	7%	0%	4%
Multi-family buildings	4%	2%	3%	**78%**	1%	12%
Single-family houses	7%	5%	6%	4%	3%	**75%**

Measured ductwork airtightness classes

Ductwork airtightness measurements are performed in order to justify either the respect of an certification requirement, the respect of an EP-calculation declaration, or without specific requirement. The information regarding target classes is available for about half of the measurements (521), amongst which 23 measurements target class C, 91 target class B, 305 target class A and 153 are declared as "no target class". As shown in **Figure 5**, the distribution of the specific ductwork airtightness measured class depends on the chosen target class:

- when the most airtight class (class C) was targeted, less than half of the measured ductworks meets the target (almost only hospitals). For the others, the quality of the ductwork is significantly poorer as they only achieve class A;
- when class B or class A was targeted, most ductworks meet this target class or better. However, 16% (target class A) and 35% (target class B) of the measured ductworks achieve worse classes;
- when the measurement was performed with "no target class", the results are quite good as 75% of the measured ductwork reach class A or better. Even thought there was no target class, mandating a measurement suggests a special awareness regarding ductwork airtightness for those buildings, i.e. presumably better results than the average. Again, it should be noted that these results only apply to the buildings of the database and cannot be generalized to all new buildings in France.

Figure 6 presents the results of ductwork airtightness measured class in residential buildings. For both single-family houses and multi-family buildings, most measured ductworks met leakage class A (respectively 64% and 54%). In multi-family buildings, 23% of measured ductworks achieved a better class (mainly B), whereas ductworks of higher classes are only 7% in single-family houses. The wide use of flexible ducts in single-family houses could explain these results (see **Table 1**).

Figure 7 presents the results of ductwork airtightness measured class in non-residential buildings. Ductworks in these buildings are overall tighter than in the residential sector: 48% of them meet class B. Even if our sample is too small to make statistics, we observe that the class C is more frequently achieved in hospitals where rigid ducts are widely used.

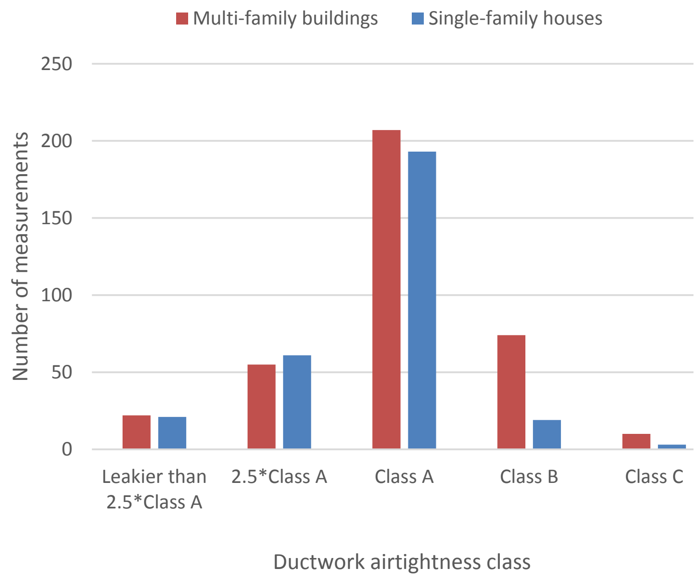

Figure 6. Specific ductwork airtightness measured class in residential buildings.

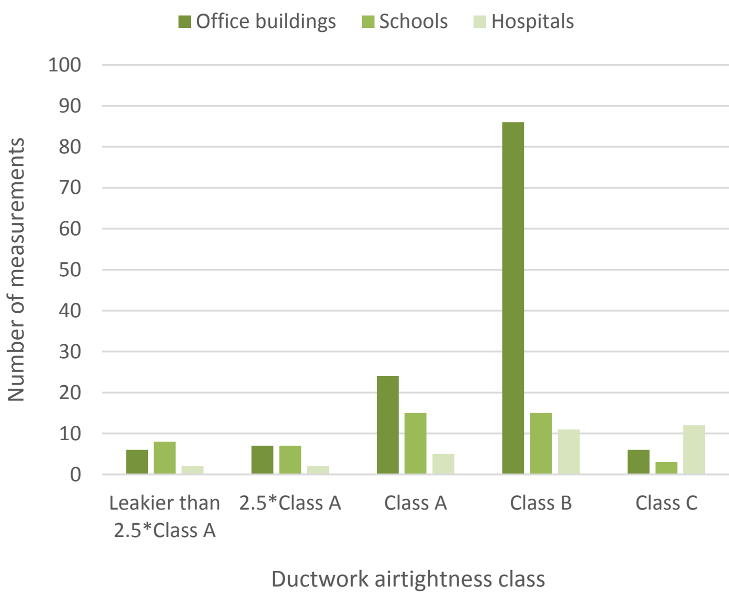

Figure 7. Specific ductwork airtightness measured class in non-residential buildings.

Conclusions

The French Ministry in charge of construction created a qualification scheme for ductwork airtightness testers since 2012. Each qualified tester is thereby required to feed a database with building general information, targeted certification and/or class, ventilation system's main characteristics, data on the measurement protocol, measurement input data and measurement output results. So far 983 measurements have been logged in the database. The number of ductwork airtightness measurements that are performed by qualified testers is growing each year, with almost 500 measurements in 2016.

All measurements considered in the database were performed:

- on new residential building: both multi-family buildings and single-family houses, mainly equipped with single-exhaust mechanical ventilation systems;
- on new non-residential buildings: mostly office buildings, schools, and hospitals, mainly equipped with balanced mechanical ventilation systems.

In residential buildings, most measured ductworks met leakage class A. In non-residential buildings, ductworks are overall tighter: almost half of them met class B. Nevertheless, when a target class was defined, it was not widely achieved, especially for the tightest class, class C.

All measurements in the database were performed according to specific and not common demands. Thus, all results presented in this paper only apply to the buildings of the database and cannot be generalized to all new buildings in France. ■

Acknowledgements

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Building and ductwork airtightness requirements in Europe



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Mandatory building airtightness testing comes gradually into force in Europe. This paper analyses recent developments in 10 European countries regarding building and ductwork airtightness. It shows how awareness on building airtightness has grown in the last 5 years, as opposed to ductwork airtightness which is not taken into account in most European countries. This article is based on a paper presented at the 38th AIVC - 6th TightVent & 4th venticool Conference, 2017 "Ventilating healthy low-energy buildings" held on 13-14 September 2017 in Nottingham, UK.

Keywords: airtightness measurement, regulation, European comparison, competent tester schemes

A questionnaire has been developed in the framework of the Tightvent Airtightness Association Committee (TAAC) to compare building and ductwork airtightness awareness in a broad manner, ranging from requirements to progress needed to promote building airtightness. Members from Belgium (BE), Czech Republic (CZ), Estonia (EE), France (FR), Germany (DE), Ireland (IE), Latvia (LV), Poland (PL), Sweden (SE) and the UK provided feedback to the questionnaire.

Building airtightness in EP-regulation

To compare requirements between countries, it is useful to know which airtightness indicators are used. The air change rate at 50 Pa – n_{50} – is no longer the primary indicator: 8 out of 10 countries (all but PL and CZ) have at least one indicator that uses the envelope area as reference value. However, the envelope area is not always calculated as defined in ISO 9972; for example in France, the reference area excludes the lowest floor and is calculated according to Energy Performance (EP) - calculation. In Germany, two reference values are used: either the internal volume for small buildings (below 1500 m³) or the envelope area for bigger ones.

9 out of 10 countries have kept the reference pressure at 50 Pa.

In most countries (7 out of 10 (all but CZ, SE and PL)) building airtightness is now taken into account in the EP- calculation. The number of tests in Europe is increasing (Leprince, Carrié, & Kapsalaki, 2017) due to:

- requirements on building airtightness with mandatory justification; or
- programmes; or
- incentive rewards.

In 6 countries out of 10 (CZ, EE, FR, DE, IE and UK) there are minimum requirements for building airtightness in EP-regulations. However, those minimum requirements do not necessarily need to be justified. Only France, Ireland and UK require systematic justification of airtightness levels either by testing or by applying a certified approach. **Table 1** compares requirements of building airtightness in European countries.

In Belgium, there were no minimum requirements before 2018 but the default value for airtightness was so high that 90% of new residential buildings were tested in 2016 in order to improve the result in EP calculations. In Germany, even if the test is not required, it is done in most new buildings.

Required values are most of the time much easier to achieve than the well-known n_{50} = 0.6 vol/h. The objective seems to be the growth of awareness rather than the hardness of the constraint.

Building airtightness tester schemes

Airtightness tester schemes now exist in 7 out of the 10 countries (excluding EE, LV and PL). The number of testers in Europe has almost doubled in 4 years and is increasing rapidly in Belgium, Ireland, France and UK, either because they are requiring airtightness testing (FR, UK, IE) or because they are promoting airtightness by rewarding the EP-calculation if a test is performed (BE).

In 4 countries out of the 7 qualification of testers is required for testing, either in the context of the regulation (Belgium Ireland and France) or in the context of a programme (Ireland, France and Poland). In the UK, this is not the case. However, if a test is performed by a qualified tester, a "standardised certificate" is automatically issued and the tester does not need to write a full report.

The evolution of number of testers per country is given in **Figure 1**. For Germany, the figure only includes Flib testers; however, other qualifications exist.

4 countries out of 10 have issued guidelines for airtightness testing in addition to test standard ISO 9972 (Belgium, France, Germany, and UK).

Table 1. Comparison of requirements on building airtightness in European countries.

< 10 m³/h.m² @ 50 Pa				
< 1500 m³ : n_{50}	< 3 1/h	< 1.5 1/h		
> 1500 m³ : q_{50}	< 4.5 m³/h/m²	< 2.5 m³/h/m²		
n_{50}	4.5 1/h	1.5 1/h	1 1/h	0.6 1/h
Recommendations: n_{50}	3 1/h	1.5 1/h		
The measured building airtightness should not be higher than the value used in EP-calculation				
$q_{50} \leq$ 7 m³/h/m²				
q_{4Pa_surf}	0.6 m³/h/m²	1 m³/h/m²		
Recommendations: q_{50}	3 m³/h/m²	2 m³/h/m²	1.5 m³/h/m²	

Single-family house/multi-family building / non-residential building (Blue: Retrofitted; Green: New)

With mechanical ventilation

Without mechanical ventilation

With heat recovery

Passive house

Relative area. Proportional to the q50 or calculated q50 if the requirement is not expressed in q50 (assuming V/S=1.1m).

Countries for which EP-regulation require a minimum airtightness level that has to be justified.

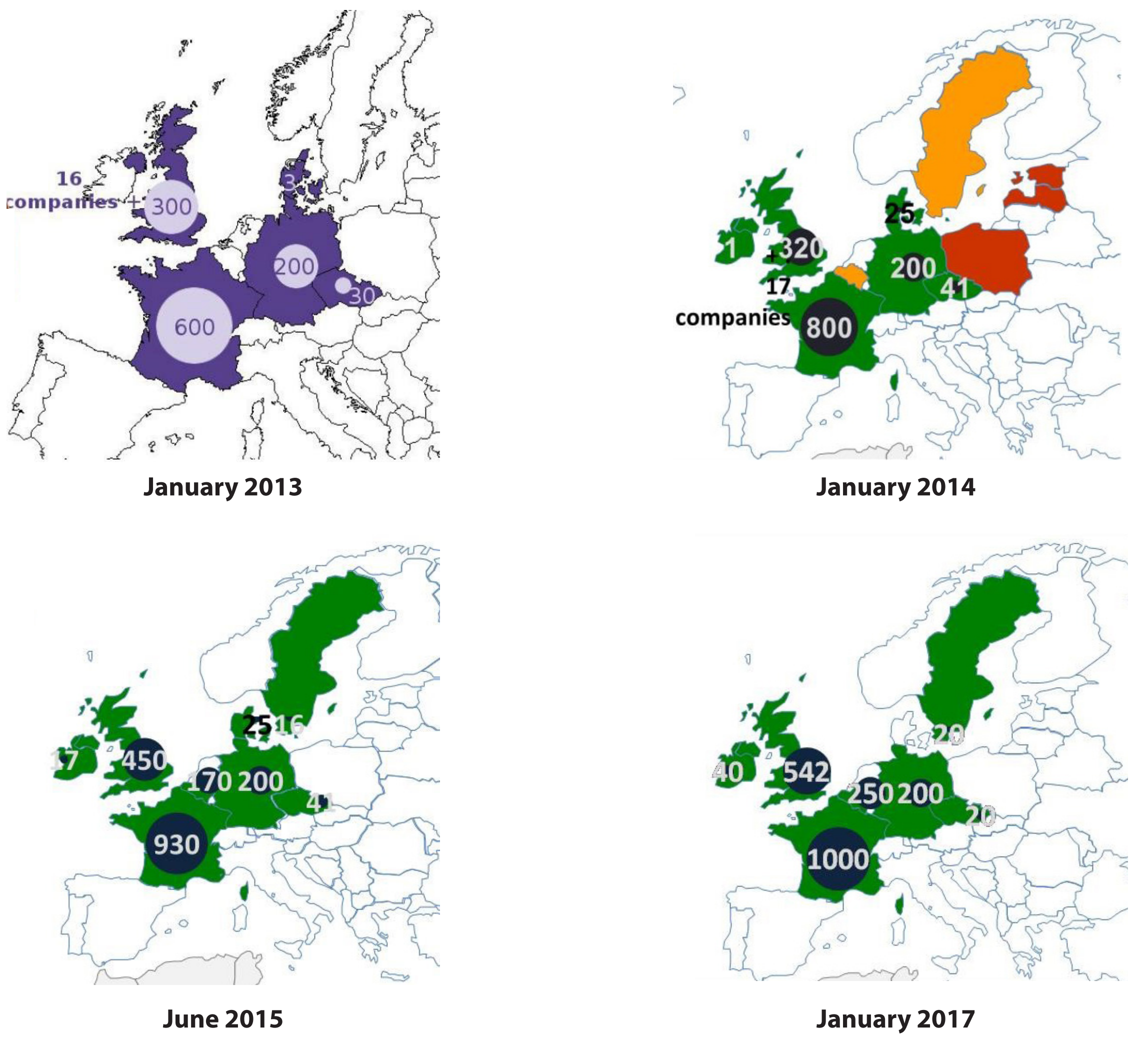

Figure 1. Increase of qualified airtightness testers in Europe in the the last 4 years.

Building Airtightness Databases

The development of airtightness testers' schemes goes together with the development of databases; in 5 out of the 7 countries with tester schemes, the qualification bodies manage a database. **Figure 2** summarizes whether or not countries have a database available and the amount of measured data it represents. In the UK, qualification bodies provide tools for automatic lodgement of data which automatically collects data from more than 500 tests per working day.

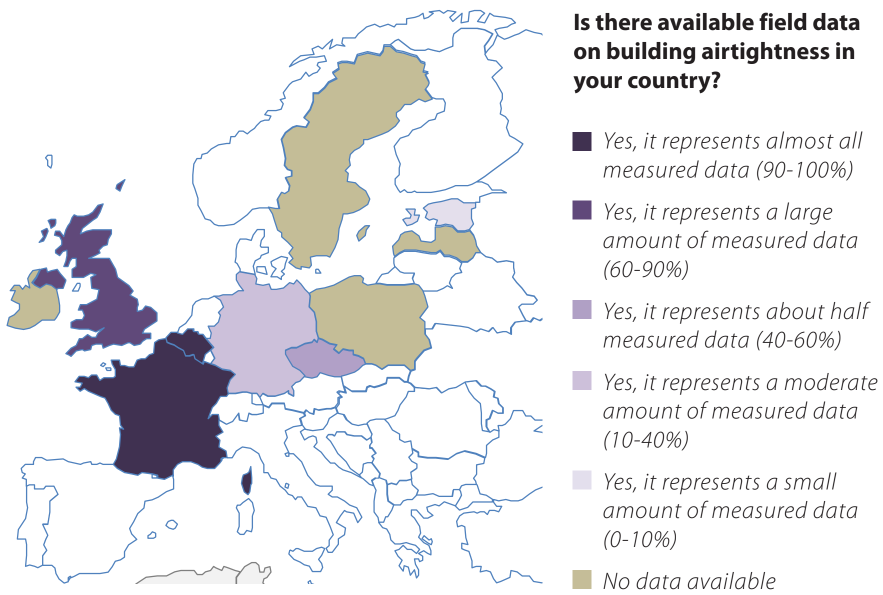

Figure 2. Database in countries and representativeness of measured data.

The benefits of a database managed by qualification bodies are:

- collecting reliable data as they are provided by qualified testers;
- representing a large amount of measured data if the qualification is required by regulation or programmes.

Building airtightness awareness

All countries' respondents agreed that things have changed in the last 5 years regarding building airtightness. The main driver is energy use and more work is needed in the field to better:

- quantify the impact of airtightness on energy use and
- take into account airtightness in the EP regulation.

The durability of airtightness is also a pending question that needs to be further studied (Leprince, Carrié, & Kapsalaki, 2017).

According to the respondents, national policy is also a main driver for change, while building damages and European directives are secondary drivers; indoor air quality comes last.

Ductwork airtightness

Regarding ductwork airtightness, concern is still low in the field. Only 4 respondents provided feedback to the ductwork airtightness questionnaire (Belgium, France, Latvia and Germany). According to respondents from the Czech Republic and Poland, ductwork airtightness is not really considered in their countries.

Only France (RT2012) and Belgium EPB consider ductwork airtightness as an input in the EP-calculation but there are no minimum requirements. In France, the programmes Effinergie + and Effinergie BEPOS require a justified class A for ductwork airtightness. Moreover, a qualification for ductwork testers (Qualibat 8721) exists with 35 qualified testers. Field data have been published in the end of 2017.

Excluding France, respondents agreed that very few things have changed regarding ductwork airtightness in the last 5 years. In Belgium, this is likely to happen in the near future because of the mandatory control of every ventilation system in new buildings and extensive renovation projects (awareness is broader regarding the efficiency of ventilation systems).

For building airtightness, the main driver for change will probably be the impact on energy use therefore progress is needed to quantify the impact of ductwork airtightness on cooling, heating and fan energy use. Studies on the impact of ductwork airtightness on indoor air quality were also requested.

Conclusions

Regarding building airtightness, we found that 7 out of the 10 countries have minimum requirements that have to be justified by testing or other means, either in the context of the EP-regulation (for 3 of them) or in specific energy performance programmes. Minimum requirements mostly apply to new buildings and only three countries have a regulation or programme dealing with airtightness of refurbished buildings. 7 countries out of 10 now have a quality framework for building airtightness testers; the number of qualified testers in Europe has almost doubled in 4 years. The development of qualification has induced the development of databases. Field measurement data are now available in 6 countries out of 10. Most of the time, databases are managed by testers' qualification bodies and contain mainly data of new residential buildings.

All respondents acknowledge that awareness regarding, building airtightness has grown in their country in the last 5 years. The main motivation remains energy use, however work on this topic is still needed to better quantify the impact of airtightness on energy use.

Conversely, ductwork airtightness does not seem to be taken into account (neither in regulation nor in energy performance programmes) in most European countries. In our survey, ductwork airtightness is only taken into account in the EP-calculation of France and Belgium; and only France has an EP- programme with requirements on ductwork airtightness and a qualification for testers. Progress is needed to better understand the impact of ductwork airtightness on energy use (fan, cooling and heating) and indoor air quality. ■

Acknowledgements

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Affordable and replicable renovation of social housing fulfilling indoor climate and energy targets thanks to seven replicable renovation elements

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RenovActive is a renovation project which took place in Brussels based on the concept of Climate Renovation that implies achieving an excellent indoor climate as well as a high energy performance. The house belongs to a social housing association and is renovated within the financial frame for social housing in Brussels, and renovated using standard solutions and products to facilitate future replications of the result. Seven generic replicable elements were applied; these elements can be used in other renovation projects and are described in the paper. The house is equipped with a mechanical extract ventilation system for winter use, and demand-controlled natural ventilation for warm periods and peak loads during winter. The house is occupied by a family, and physical measurements as well as social scientific enquiries are carried out during a two-year period from June 2017. This article is based on a paper presented at the 38th AIVC - 6th TightVent & 4th venticool Conference, 2017 "Ventilating healthy low-energy buildings" held on 13-14 September 2017 in Nottingham, UK.

Keywords: Renovation; indoor climate; ventilation; replicability, affordability

RenovActive House is a single family house of the social housing company Foyer Anderlechtois, located in Brussels, in the garden city of Bon Air in Anderlecht. The renovation is based on the concept of "Climate Renovation": to renovate houses to create an excellent indoor climate with a good energy performance. Several renovation scenarios were generated and the performance was analysed according to the Active House specifications.

RenovActive follows the Model Home 2020 project, for which five single-family houses were built during 2009-2011. The Model Home 2020 project demonstrated that 2020 building performance targets can be achieved with today's solutions (Feifer et al, 2014). It has previously been found that the Model Home 2020 houses provide good daylight conditions without compromising thermal comfort (Foldbjerg et al., 2014). It is the aim of the present project to extend the good performance in a renovation case that is affordable by using existing standard products and solutions.

A particular focus of the renovation was to identify generic elements that can be replicated in other renovation projects on a large scale. The renovation was completed in May 2016, and was followed by an open house period for academic and professional studies and visits. Since June 2017 a family has moved in, and the performance of the house is monitored for 2 years.

Methods

The design targets for indoor climate, energy and environmental impact are based on the Active House Specifications (Active House Alliance, 2011). As there was a strict financial frame for the renovation, different renovation scenarios were evaluated according to the Active House radar diagram. The scenario that was selected provided the best overall performance under the three Active House principles and fulfilled the financial frame for social housing in Brussels as well as the requirements for replicability.

Demand-controlled ventilation system and sun screening

To minimize energy consumption and to maximize thermal comfort during summer, a hybrid ventilation system was developed using both a mechanical ventilation system and natural ventilation with automated window opening. Supported by a study by Holzer (2014), the outdoor temperature is used to identify the most favourable mode of ventilation. Natural ventilation has been identified as the best solution when the climate is mild. During cold periods, the ventilation is a mechanical extract system (type C+). The "+" indicates demand-control based on sensors, a solution based on a product by the company Renson. The house is divided into different zones, each with dedicated sensors of temperature, humidity, CO_2 and VOC installed in the extract ducts.

When the outside temperature exceeds approximately 14°C, the flow through the C+ system is reduced to 25% to minimize electricity use although the sensors are still active. The control system then uses automated windows in each zone to maintain the target of CO_2 levels and prevent overheating thanks to the stack effect. Therefore, the system is a "hybrid" ventilation system, combining the benefits of both mechanical and natural ventilation. The switching between natural and mechanical ventilation modes is limited to once per morning and per evening.

External automatic solar shading is installed on façade and roof windows facing south and west. To ensure a simple and affordable control solution, the solar shading is controlled by pads in each room, providing manual control and timer-based control.

Results

Replicable elements

The seven generic replicable elements have been identified as the following:

Attic conversion: Growing from within

Utilizing the upper floor's potential; this first densification element identifies idle areas and converts them into first class living areas. For an attic conversion the space is designed with daylight in mind, creating more space with plenty of natural lighting, improved ventilation and heat control. From an energy perspective, an attic conversion is more energy efficient than a building extension, as the attic conversion provides more living area with less building envelope and thus less thermal transmission losses, as seen in **Table 1**. It is also the cost-optimum solution.

Staircase shaft for daylight & ventilation: Respiratory channel

An open stairwell provides enhanced daylight distribution and efficient airing via the stack effect. Daylight is distributed to all floors and central rooms of the home. The stack effect helps to expel humid exhaust air through the roof windows at the top of the staircase, while clean air enters the building via open doors and windows.

Table 1. Energy performance of different renovation scenarios.

	No attic conversion	Attic converted	Extension added	Attic converted + extension
Index of primary energy consumption	100	90	115	104
Primary energy consumption for heating [kWh/m^2]	34	31	39	36

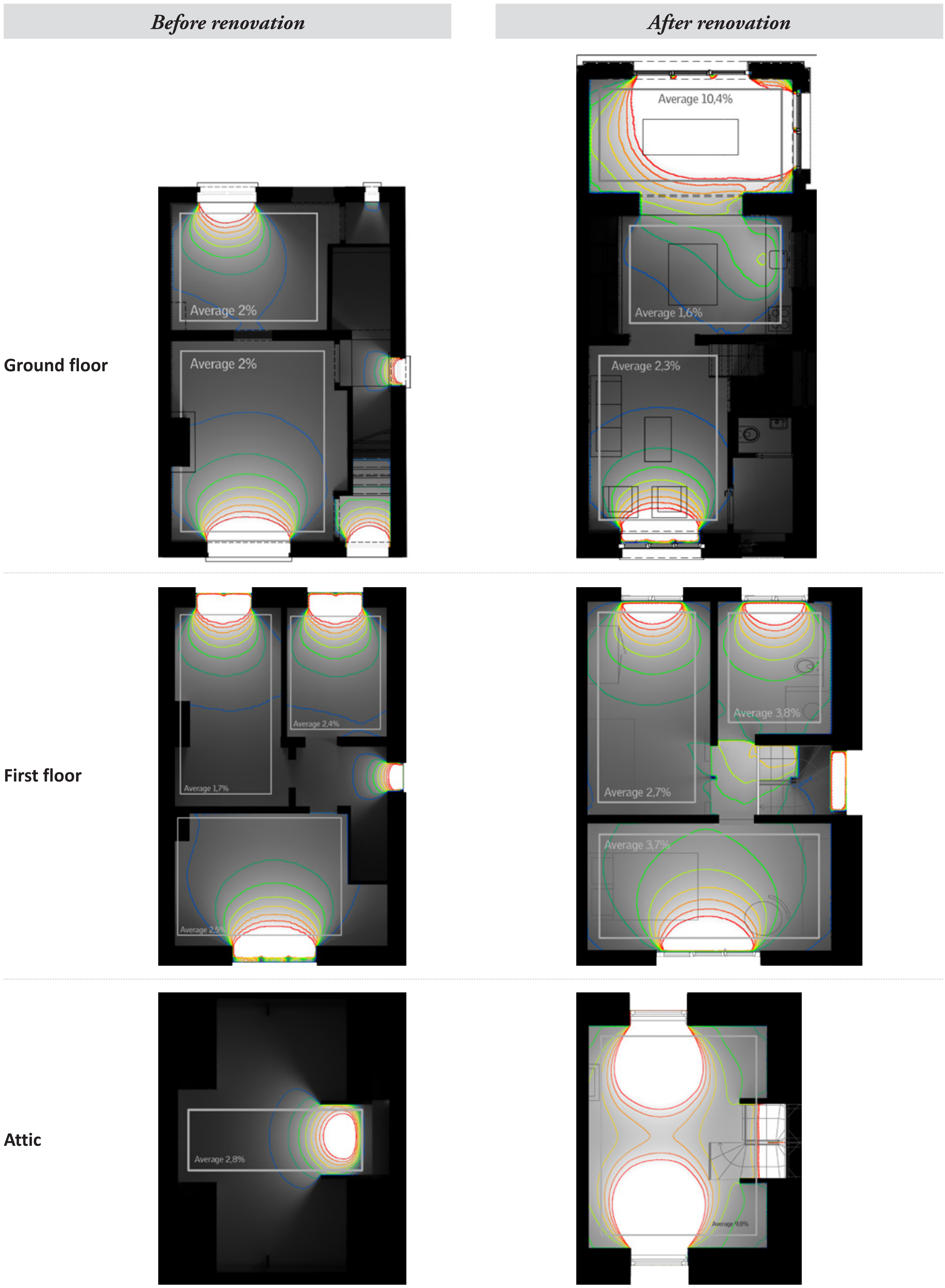

Figure 1. Daylight performance (average daylight factor) for the room on first and second floor in the existing (left) and renovated (right) situations.

Increased window area: Daylight treatment

Large façade and roof windows increase the level, and in particular the quality, of daylight. A balanced distribution of windows ensures a pleasant and bright indoor environment with plenty of daylight in every room and on every floor. Good daylighting results in less hours of artificial lighting (Christoffersen et al., 2014).

Building extension: new life space

Building an extension adds precious square meters to the home and creates room for extra people. An extension is subject to the size of the plot and surrounding terrain. A well-daylit extension gives also access to a new living experience and to a space with longer days with daylight and better connected to the outdoor (e.g. to a garden).

Dynamic sunscreening: third skin

A dynamic envelope is vital to ensure good indoor comfort with pleasant temperatures day and night as well as during all seasons, particularly in the shoulder seasons. Dynamic external sun screening, e.g. awning blinds, reduces overheating during summer.

Hybrid ventilation system: hybrid breathing

The hybrid ventilation system combines mechanical and natural ventilation with automated windows and heating. During the summer, windows and stairwell are used to provide natural cooling in the building, e.g. using the stack effect for efficient air replacement. Natural ventilation can provide high ventilation rates, which results in low CO_2-concentration in the house, with no use of electricity for fan operation. During the winter, mechanical ventilation helps to maintain good indoor air quality and reduce the risk of draught.

Improved thermal envelope

The thermal envelope consists of a façade climate shield and a modern heating system, optimizing energy performance and thermal indoor comfort. Work on the façade comprises extra surface insulation, a new roof construction and new windows. The upgraded heating system includes a new boiler, a floor heating as well as modern radiators on upstairs levels.

The energy cost for heating and ventilating the house would be reduced by 85% after the energy renovation of the house for the same comfort level. But a higher comfort level is expected after renovation, as occupants of poorly insulated houses often reduce the temperature to reduce the energy cost (lower heating set point, only heating of living room, temporary heating of bathroom). After renovation, a "rebound effect" is expected, which could mean that the real energy cost reduction will be in the order of 40–50%. **Table 2** presents the indoor climate and energy performance before and after renovation, calculated according to the Belgian PEB software. The energy performance before renovation is a theoretical energy consumption calculated for a whole house at a yearly average temperature of 19°C, and not the measured energy performance.

Figure 2 illustrates the performance of the house prior to renovation as well as the calculated performance for the renovated house according to Active House specifications.

The active House Radar shown in **Figure 2** is a good tool for displaying the ambition reached before and after renovation. The radar can be a useful tool for monitoring, evaluating and improving the renovation scenarios generated during the design. As communication tool, it can provide clarity and tare combinations of three principles: comfort, energy and environment.

Table 2. Indoor climate and energy performance before and after renovation.

	Before renovation	**After renovation**
U-values	No thermal insulation Double glazing	Improved thermal insulation, Low-e double glazing, Triple glazing on north
Net energy demand for heating	700 kWh/m²	25 kWh/m²
Primary energy consumption	1300 kWh/m²	82 kWh/m²
Ventilation	Not ok	Ok
Thermal comfort winter	Not ok	Ok
Thermal comfort summer	Ok	Ok
Energy class	G	B
Energy cost for building services (excluding light and plug loads)	5,000 €/year	800 €/year

The comfort principle sits for the indoor air quality, the thermal comfort and daylighting quality. The energy principle includes the energy demand, the energy supply and the primary energy performance. Last but not least the environment principle includes the sustainable construction dimension, the consumption of fresh water and the environmental load for which life cycle assessments of different scenarios are made.

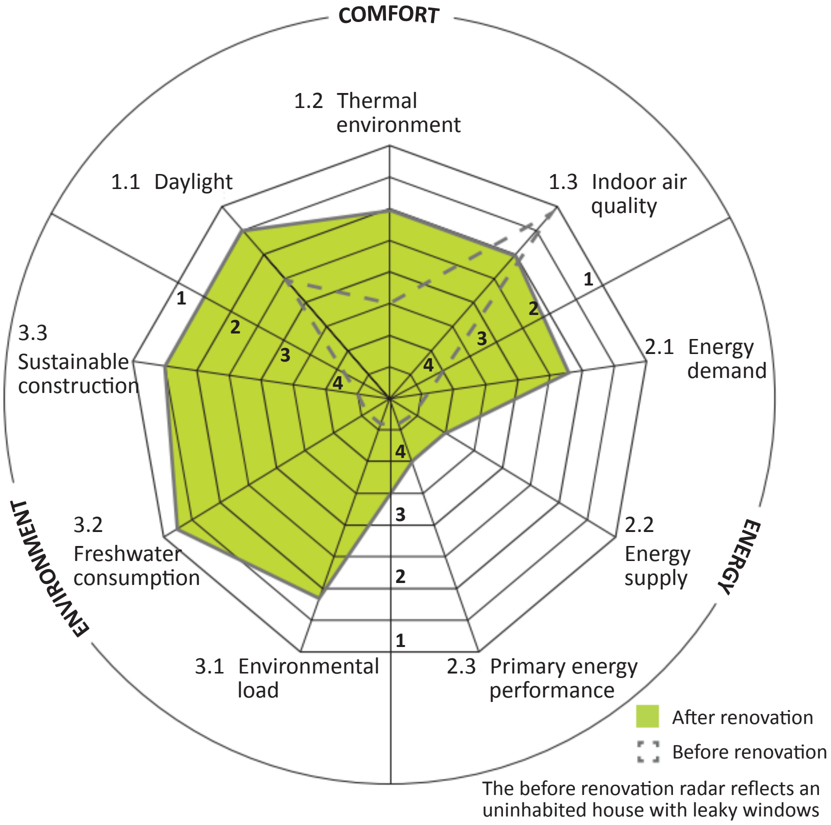

Figure 2. Performance of the non-renovated house according to the Active House Specification.

Occupation and post-occupancy evaluation

Since June 2017 the house has been be handed to the Foyer Anderlechtois and inhabited by a social housing beneficiary. During the first two years of occupation, the performance of the house is monitored; technically by measuring indoor climate parameters and energy performance, and also by psycho-social techniques including questionnaires and time diary. The monitoring is carried out by researchers from Humboldt University Berlin, Vreie University Brussels and Daidalos Brussels. The technical indoor climate monitoring is undertaken thanks to a room-based system.

Conclusions

The project is an example of an affordable and replicable renovation that not only improves the energy performance of the dwelling and perhaps more importantly, focuses on providing the best possible indoor environment. The seven replicable elements that have been applied are generic and can be replicated easily on a large scale. ■

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Reintroduction of Natural Ventilation to a Historic Opera House

The issue of providing fresh air to people in crowded situations is challenging; large theatres are an extreme example. This article explores the natural ventilation system designed into a 100+-year-old theatre through CFD analysis; calibration of the CFD predictions against measured data; and observation of the efficacy of design changes. It is based on a paper presented at the 38th AIVC - 6th TightVent & 4th venticool Conference, 2017 "Ventilating healthy low-energy buildings" held on 13-14 September 2017 in Nottingham, UK.

Keywords: Natural ventilation, passive, CFD, simulation

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An Overview of the Royal Wanganui Opera House Project

The Royal Wanganui Opera House (RWOH) built in 1899, is an 830-seat theatre in Whanganui, New Zealand. Due to its recent comfort complaints, seismic renovations, and a history of natural ventilation design, the owners of the RWOH, the Whanganui District Council, wanted to find a cost-effective solution to ensure the building's use as a performance space could continue.

The original design of the RWOH was explored, and changes through its life span that have affected the ventilation were identified. The basic geometry of the building was 3D computer modelled in Revit. Temperature and humidity sensors were placed throughout the auditorium itself to collect measured data regarding the building's existing operation. The measurements were taken at 5-minute intervals over a two-week period during winter. The goal was to obtain sufficient data to build quickly a trustable analytical model, which would enable the modification of the building prior to an early summer performance that has had a full house in past seasons and has engendered significant overheating complaints.

The geometry was imported into Autodesk Simulation CFD (Autodesk Inc., 2015), and selected situations (weather conditions, occupancy numbers, known openings, use of equipment) of the building were simulated. The CFD model was calibrated against a series of observations of the performance of the existing building. CFD modelling to test the likely success of new or restored interventions to the ventilation scheme was then undertaken. The input data was taken from weather data measured in the area at the same time as the measurements. The results of the CFD models were compared with the measured temperature and humidity data from inside the auditoria, entrance area, roof space, and back of stage. Once the model's geometry, materiality, solar exposure, and internal heat loads produced results aligned with the measured temperature data, these modelling conditions were confirmed and the design option modelling process could begin.

Once calibrated, the model was used in a fully occupied state to analyse performance in summer weather conditions. The goal was to assess key problem areas for overheating in the occupied space. This knowledge acquired from the analysis of the existing building helped identify the proposed ventilation alterations. The designs were then discussed with the building owners for construction feasibility, and the underlying geometry model was altered to reflect the proposed designs. The CFD analysis helped form design and operation recommendations focused on potential comfort hours in summer. From these recommendations, the project to mitigate the RWOH's overheating issues in summer months was split into two stages. Stage one necessitated immediate operational changes for an imminent heavily occupied performance. Stage two involves constructional changes to the building.

Figure 1. The Royal Wanganui Opera House (Wanganui Opera Week, 2016).

Use of Computational Fluid Dynamics (CFD) in Natural Ventilation Design

As a design tool, CFD is unique as it can predict the air motion at all points in the flow. CFD modelling can be used to predict temperature and velocity fields inside buildings for steady-state problems (Allard, 1998). Due to the intensive nature of the computations, CFD is normally only used to generate 'snapshots' of how the design would work at a given point in time (CIBSE, 2005). Accordingly, this software can be used to test extreme or representative conditions at a single point in time. This is different from thermal analysis programs, which today generally calculate an energy balance for each hour of a typical year. This is a key limitation of CFD, as the modelling does not take into account what is happening in the space before and after the analysis, making the specification of boundary conditions to define the existing space extremely important.

With the addition of thermal equations, CFD can predict the effects of buoyancy and the temperature field, addressing questions of stratification and local air movement (CIBSE, 2007). This is particularly important in auditoria such as RWOH, as inlet and outlet levels as well as the height of an auditorium, affect the stratification levels of air. Warm stale air collects below the ceiling; CFD can be used to test whether this air will remain above the occupied zone (Short & Cook, 2005). Since indoor conditions of naturally ventilated spaces are difficult to predict using alternative building simulation tools, the use of CFD simulation becomes necessary (Hajdukiewicz, Geron & Keane, 2013).

About the Case Study: The Royal Wanganui Opera House

The building has a large dome above the main seating area with a grille vent into the ceiling space. From the ceiling space, original plans show two penthouse louvres located above the stage space and seating area, seen in **Figure 2**. The large penthouse louvre over the seating area has been replaced with a curved ridge vent with a smaller aperture. The penthouse louvre over the stage has also been replaced with a ridge vent, however the opening was boarded up. Within the auditorium, multiple external openings are situated at the perimeter of the high-level seating space. These openings appear to be the main exhaust air location for the higher-level seating. Due to light and noise pollution, these openings are no longer opened, but are shut tight during performances. Despite comfort complaints, no mechanical system has been added. An upgrade to the system is urgently required.

3D Computer Geometry Modelling

A combination of original plans, updated drawings from the recent seismic renovations, photographs, and measurements taken on site contributed to the 3D modelling of the RWOH in Autodesk Revit Software. In order to import a 3D model into Autodesk CFD (the air flow assessment software) the 3D model needs

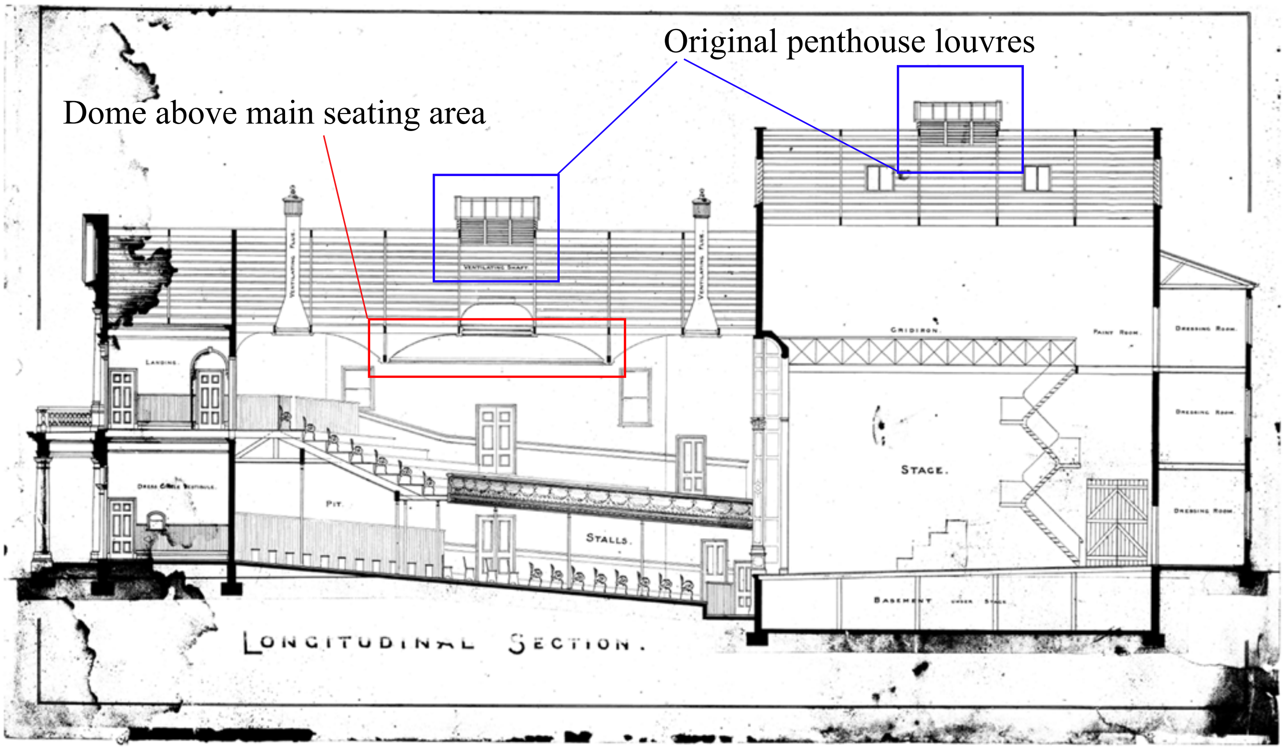

Figure 2. Longitudinal Section of the Wanganui Opera House, completed by architect George Stevenson, 1899.

to be as simple as possible. A basic Revit model has been completed of the space, maintaining volume, wall area and the shell geometry. Due to the hierarchy of importance of elements and low complexity level required for a CFD model, ensuring the external shell and volume within the occupied space is as closely aligned with reality as possible was the main priority. Elements such as columns within the seating area, individual seating and balustrades were not modelled due to their likely minimal effect on air flow. The operable area of openings has been modelled, and each external window and door has been modelled as a slot, even when closed, to account for air seepage.

Detail has been incrementally added to the model to more closely to align the simulated result with the measured data. The dome ceiling shape needed to be made more complex in order to reflect the pattern of air within the space, see **Figure 3**.

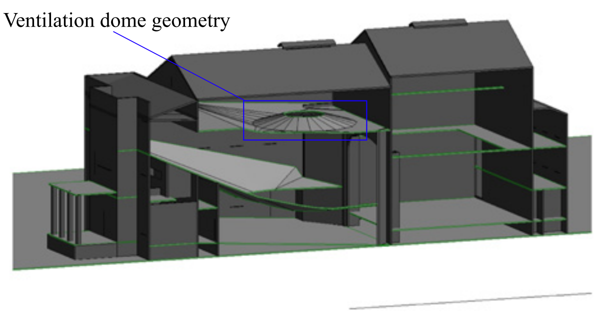

Figure 3. Longitudinal Section through the 3D Model, showing detail required for calibrated CFD analysis.

Collection of Temperature Data

To calibrate the CFD simulation of the existing situation, thirteen calibrated Testo-175-H2 temperature and humidity recording devices were placed throughout the RWOH for a period of two weeks, set to record at 5-minute intervals. The Testo devices were themselves calibrated against an aspirated hygrometer temperature standard prior. During the two-week period, several performances occurred including a local school production, where operational alterations to the ventilation of the space were made.

Recordings from these performances, as well as when the building was empty, and real time external data from the Whanganui Weather Station provide the calibration data (NIWA, 2016). The recorded data of the temperature measurements taken during the two performances, in different weather conditions, show stratification in air temperature. The major test for the CFD simulations was to ensure it could re-create this stratification of air temperatures.

CFD Calibration

Calibration of the CFD modelling for the RWOH consisted of two stages. First, the model of the existing building was calibrated for the building's simplest situation: an unoccupied space during temperate weather conditions. Following a series of simulated iterations, incrementally altering the boundary conditions, turbulence equations, solar radiation inputs, wind speed ratios, existing surface temperatures, assumed dimensions, and modelled materiality, the CFD outputs aligned with the measured data and fitted within the specified calibration tolerances and the limitations of the measuring devices.

The second stage of the CFD modelling involved calibrating two models of the RWOH during an occupied time, when the number of occupants and state of the openings were known. One of the models depicted the space occupied as it is in usual operation with the majority of the openings closed; the second occupied model simulated the space when several high-level openings had been opened. These models used the materiality, turbulence equations, solar radiation process, and assumed dimensions, that were confirmed in the stage one calibration. Following a series of simulated iterations, to determine the most effective way of modelling human heat gains within the space to decipher their influence on air temperature, the outputs from both models became aligned with the measured data and fitted within the specified calibration tolerances and the limitations of the measuring devices. The CFD output of a calibrated model of the occupied space was overlaid with the architectural drawings to identify the temperature measuring device location for numerical analysis.

Modelling Proposed Design Changes

The CFD analysis of the summer performance identified several key areas of overheating concern. Potential changes to the RWOH were considered including: operational changes to air inlets, and air outlets; constructional changes to inlets, and outlets; and major alterations to the building. The first alterations tested were operational. These included reopening the ridge vent above the stage space, opening the butterfly dampers above the dome, and operating the perimeter windows that had been prohibited. Allowing perimeter doors to be open during performances greatly improved the inlet air supply, but the operational issues of such a change restricted its uptake. Given the success of this last operational option, a construction change that was considered was operable louvres in these doors.

The major occupied area of concern noted in the CFD modelling, and confirmed by anecdotal evidence, was the high-level seating at the back of the auditorium, shown in **Figure 4**. The shape of the ceiling rising above the high-level seating creates a warm air trap. In the original design of the building, high level windows on the three perimeter walls surrounding this area were operable. Since the design of the building in 1899, the adjacent road has become significantly busier with motor vehicles. These windows are no longer opened during performances due to noise, as well as the light leak issues that will have existed from the outset. The constructional change agreed with the building owners was the addition of an airflow route from this high-level seating space into the ceiling, by the way of a pelmet slot.

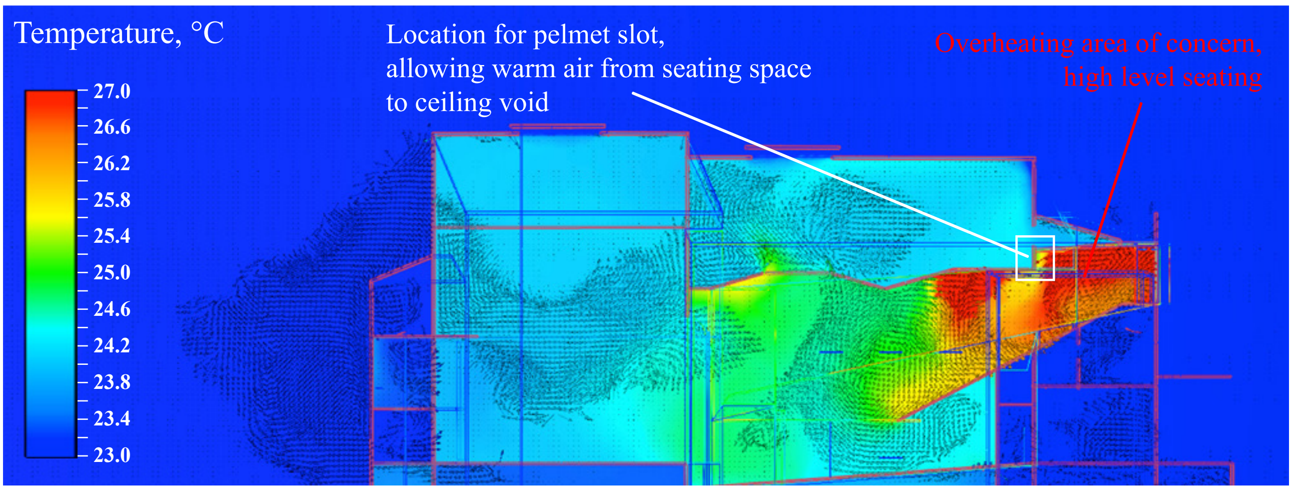

Figure 4. CFD Results from the Fully Occupied Summer Scenario, exposing the key problem area.

Major constructional changes tested with CFD included removing the ridge vents, and reintroducing the original penthouse louvres above the stage and dome ceilings, as seen in the original section of **Figure 2**. The free area of these vents was far greater than their ridge vent replacements, and the height of the penthouse structures likely created a chimney effect. Restoration of the penthouse outlets would be a historical, as well as functional, feature.

Conclusions

Natural ventilation systems often have a reduced cost in initial installation, as well as running and maintenance, over a fully mechanical heating, cooling and ventilation equivalent. Every town and city throughout New Zealand contains one, if not multiple, 100+ occupancy performance venues. Many are of similar historical value as the Royal Wanganui Opera House. Like the RWOH, as a result of recent severe earthquakes in New Zealand, many of these buildings are in the process of significant structural strengthening work. The RWOH experience has shown that the systems with which these buildings were originally designed have the potential to meet modern day standards of cooling and fresh air. The potential to restore not only the appearance but also the ventilation technology as a feature of historic preservation and earthquake strengthening is clear.

This project is applying the same analysis to a large, 1380 seat, brick Opera House building constructed in 1913 in Wellington. Designed by Australian architect, William Pitt, the auditorium originally had a dome like the RWOH, but in place of the ridgeline vent it possessed a sliding roof opening of some 4m x 4m free area. Like the RWOH, the Opera House in Wellington has no contemporary description of how effective its original system was. Initial analysis suggests that its original design lacked the air inlets to bring cooling air into the auditorium to match the hot air exiting through the roof. Calibration studies have established a quality assured model. Design studies are exploring ways to restore the operation of the sliding roof and sliding ceiling during earthquake strengthening in a manner that restores this historical curiosity so visitors can see the building as designed, but ensures effective cooling and fresh air delivery for 1380 people on three levels in the auditorium.

The applicability of a similar process to assess the passive ventilation potential of similar buildings is vast in New Zealand. Ultimately, with these practical case study demonstrations of the potential of CFD analysis, the aim of this research is to produce a user guide for the investigation, analysis, and subsequent recommendations for the ventilation improvement of similar large audience buildings. ■

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THE RIGHT PRODUCT
IN THE RIGHT PLACE

Development of a compact Counterflow Heat Recovery Fan

With the combination of two fans and a heat exchanger in one single component there is the possibility to design a compact and highly efficient ventilation system especially for use in building modernization. One crossflow fan generates both airflows (outdoor/supply and extract/exhaust air) and simultaneously acts as counterflow heat exchanger. The space between the fan blades is filled with elements which operate as regenerative heat exchanger. Based on the numerical optimization the first laboratory prototype of the single/double room unit was manufactured. This article is based on a paper presented at the 38th AIVC - 6th TightVent & 4th venticool Conference, 2017 "Ventilating healthy low-energy buildings" held on 13-14 September 2017 in Nottingham, UK.

Keywords: heat recovery fan, compact ventilation system, facade integrated, night ventilation, humidity recovery

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To ensure adequate air quality, ventilation is necessary in new buildings as well as in the modernization of existing buildings. Through the installation of a mechanical ventilation system with heat recovery it is possible to provide a controlled air exchange and to reduce the energy loss at the same time. Especially in the refurbishment of buildings space-saving solutions are beneficial. With the goal to construct a compact and cost-saving decentralized ventilation system the CHRF (Counterflow Heat Recovery Fan) was developed. The key component of the CHRF is a rotating crossflow fan, which generates both airflows (outdoor/supply and extract/exhaust) and simultaneously acts as a counterflow heat exchanger. The flow conduction and the manufactured laboratory prototype are shown in **Figure 1**. The system is divided into two levels. Supply and extract air are placed in the first level, outdoor and exhaust air in the second level. Through the stationary inner part of the fan the airflows perform a level change so that the crossflow fan

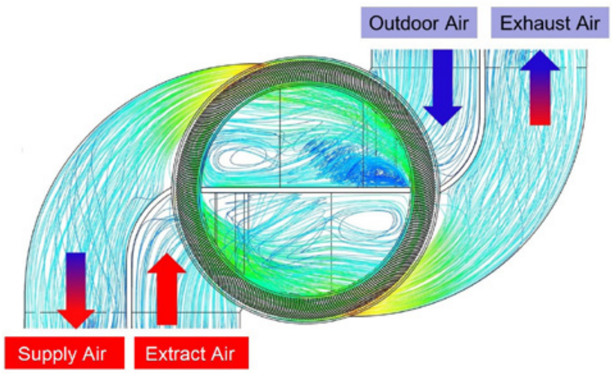


Figure 1. Concept of the Counterflow Heat Recovery Fan. Cross section of the flow conduction (top) [2] and manufactured laboratory prototype (bottom) [3]

acts as a counterflow heat exchanger at both levels. The developed concept of the CHRF, simulation results as well as the measurement results of the laboratory prototype are described collectively in (Speer, 2015a) [1].

The used crossflow fan has to fulfil two functions, generating both airflows as efficient as possible and acting as a highly efficient counterflow heat exchanger. Different possible concepts of this component are presented in (Speer, 2015b) [4], two promising variants are shown in **Figure 2**. Both variants consist of a cross flow fan with 30 blades which mainly generates the air flows and intermediate elements which are responsible for the regenerative heat recovery. These elements can for example be built out of foam material (**Figure 2** (top)), or horizontal thin layers (**Figure 2** (bottom)).

Within the framework of the development of a CHRF for the use as single/double room unit, the flow conduction concept was modified to improve the ventilation efficiency as well as the heat recovery rate by increasing the cross-sectional area used for in- and outlets of the fan. The air flows use a much larger surface area by entering the fan radially, perform a level change along a helix curve and exit the fan again radially. With this flow conduction concept, almost the entire available surface is used to reduce the pressure drop and to increase the heat recovery. The modified concept is shown in **Figure 3**. The cooling mode, described below, is a promising operating mode for night ventilation. Conventional ventilation systems are normally not designed for heat recovery mode in winter and night ventilation in summer because of the wide range of flow range necessary for that concept. The large diameter of the CHRF however provides the option for high flow rates without much additional effort for cost and space. If the unit is integrated in the external wall, the external pressure drop can be reduced to a minimum, which is necessary for high efficient night ventilation at large flow rates. As shown below, the flow rate can be increased by a factor of almost 10 from heat recovery mode to cooling mode.

Modelling and operating modes of the modified concept

In addition to the fluid mechanical and thermal demands we designed the modified concept to meet further requirements. Outdoor air and extract air intake are constructed with large openings to enable the implementation of filters inside the system with low pressure drops. Furthermore, acoustic elements can be installed along the spiral casing to reduce the sound pressure level as close as possible to the point of origin. The acoustic elements can be adjusted to the rotational speed of the main operating modes. The occurring characteristic frequencies of a CHRF and possible solutions to reduce the noise level are discussed in (Speer et al., 2016) [5]. The construction model consists of layers which are responsible for the flow conduction, the stationary inner part, adapters for in- and outlets, a crossflow fan and a metallic plate to connect motor and fan.

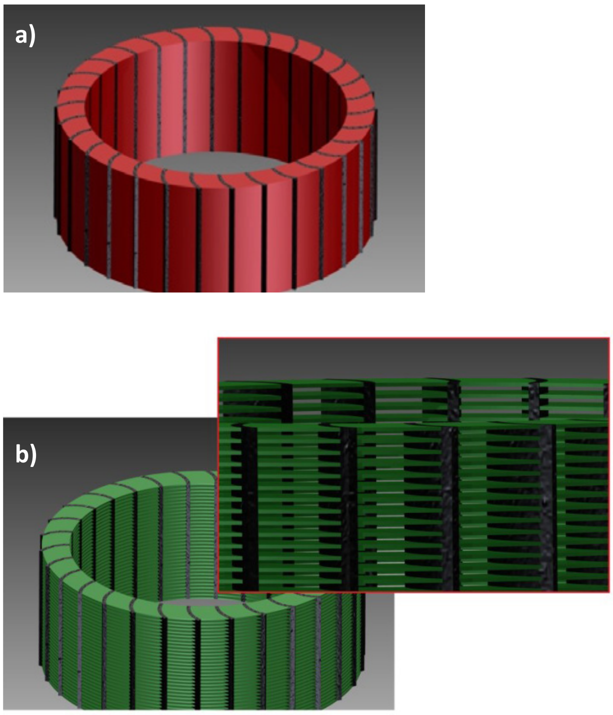


Figure 2. Fan model with 30 blades for the ventilation a) with implemented porous foam and b) with horizontal thin layers for the heat recovery. [4]

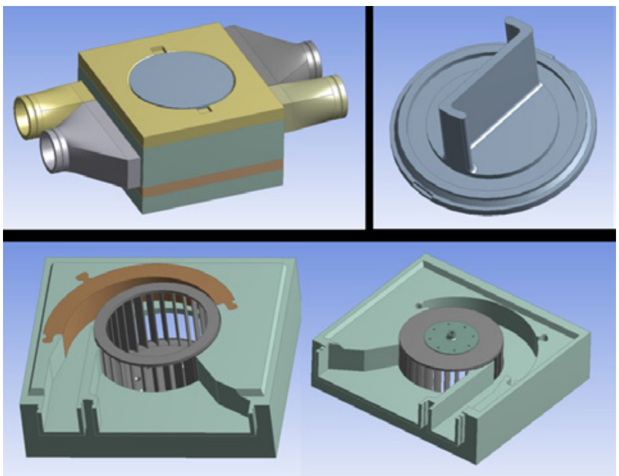


Figure 3. Construction model of the CHRF for the use as single/double room unit.

The flow conduction of the system in the normal heat recovery mode is shown in **Figure 4** (left). Air intake and exit is guided radially through the cross-flow fan. Furthermore, there is the possibility to operate the system in the cooling mode, shown in **Figure 4** (right). In this mode the air intake is guided axially to the centre of the crossflow fan and the air flow is blown out radially through all open flow paths.

The working principle of the CHRF allows generating high flow rates in for night ventilation in the so called "cooling mode" because the already installed fan can be used as a large radial fan and no longer as cross flow fan. There are still questions to work on so that this property can be used in an efficient way and without high installation effort. The definition of flow paths to be used and the implementation of the conduction for the axial outdoor air intake will be part of further research. The dimensions of the single/double room unit, shown in **Figure 3**, are about 350 x 400 x 200 mm with a fan diameter of 190 mm and small enough to integrate it in the external wall insulation.

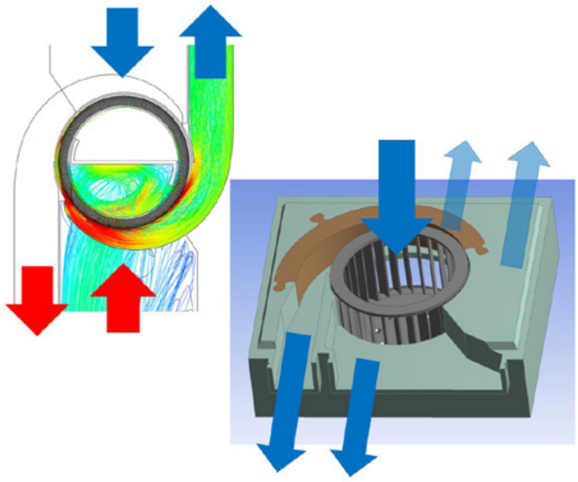


Figure 4. Flow conduction of one airflow of the heat recovery mode (left) [5] and schematic flow conduction of the cooling mode (right).

Simulation results of the modified concept

The fluid mechanical simulation model is based on the construction model in **Figure 3** and the intermediate elements of the crossflow fan are realized as porous media, described in **Figure 2a)**. The achieved flow rates without external pressure and with an external pressure of 50 Pa (at 50 m³/h) at each in- and outlet are shown in **Figure 5**. The flow resistance loss coefficient of the intermediate porous elements is varied between 0 and 300 m^{-1} and the rotational speed of the crossflow fan is set to 15 Hz. Higher rotational speeds up to about 30 Hz are considered, but to ensure the comparison with measurement results of the laboratory prototype we perform the parametric study with a lower speed. The correlation of the rotational speed with the generated flow rate is in this range nearly linear. The variant with external pressure drop and a flow resistance loss coefficient of 300 m^{-1} for the porous elements still leads to flow rates of 28 m³/h at a low rotational speed of 15 Hz. The resulting flow rates for the cooling mode are shown in **Figure 6**. The same variant with external

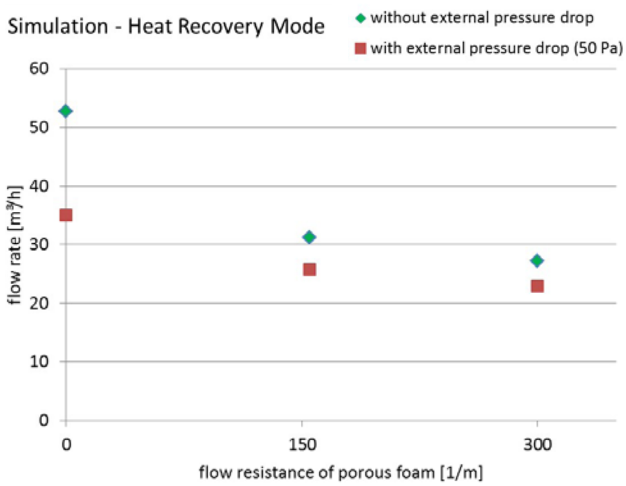


Figure 5. Flow rates of the heat recovery mode at different flow resistance loss coefficients for the porous elements without external pressure (green) and with an external pressure of 50 Pa (red) at each in-/outlet.

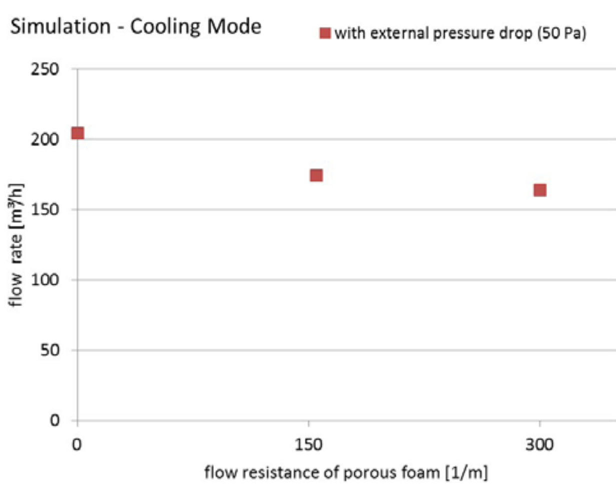


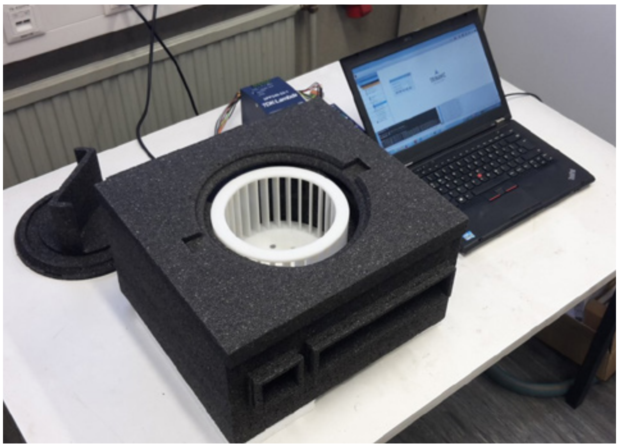
Figure 6. Flow rates of the cooling mode at different flow resistance loss coefficients for the porous elements without external pressure (green) and with an external pressure of 50 Pa (red) at each in-/outlet.

pressure drop and high flow resistance loss coefficient leads to flow rates of 165 m³/h for the cooling mode. If the external pressure drop is reduced and the intermediate porous elements are removed, the flow rate is increased up to 260 m³/h at a low rotational speed of 15 Hz. In order to compare the simulation results with the laboratory measurements which are performed without external pressure drop and porous elements, we get simulated flow rates for these boundary conditions of 53 m³/h for the heat recovery mode and 265 m³/h for the cooling mode.

Measurement results of the laboratory prototype

The manufacturing of the laboratory prototype is based on the construction model in **Figure 3**. All parts of the casing are cut out of polypropylene and the cross flow fan with 30 blades was built by rapid prototyping (3d-plotting). The assembled laboratory prototype is shown in **Figure 7**.

The following measurements are performed without external pressure drop and intermediate porous elements. The rotational speed of the fan is varied between 10 and 20 Hz and the averaged flow rates of the heat recovery mode and the cooling mode are measured. The results are shown in **Figure 8**. For the heat recovery mode, the flow rates are nearly linear in the range of 40–80 m³/h, for the cooling mode in the range of 150–400 m³/h.



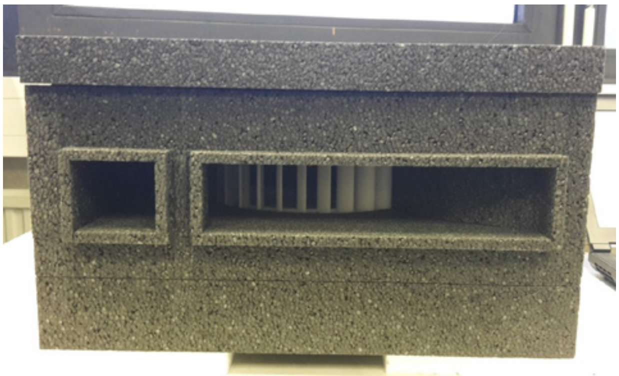
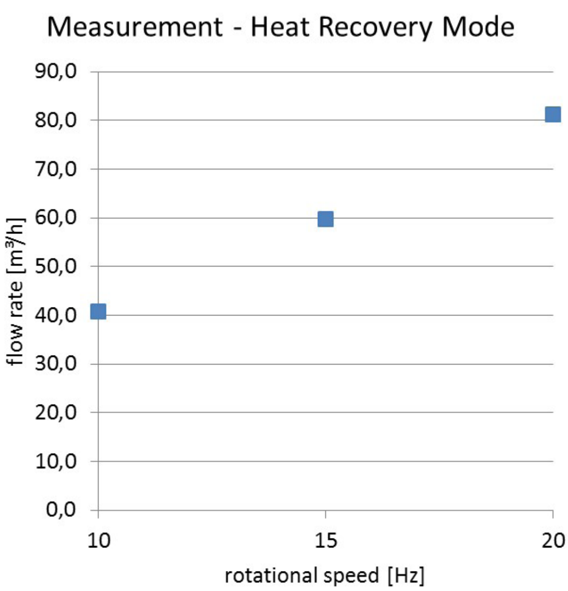


Figure 7. Photo of the manufactured laboratory prototype of the CHRF for the use as single/double room unit.



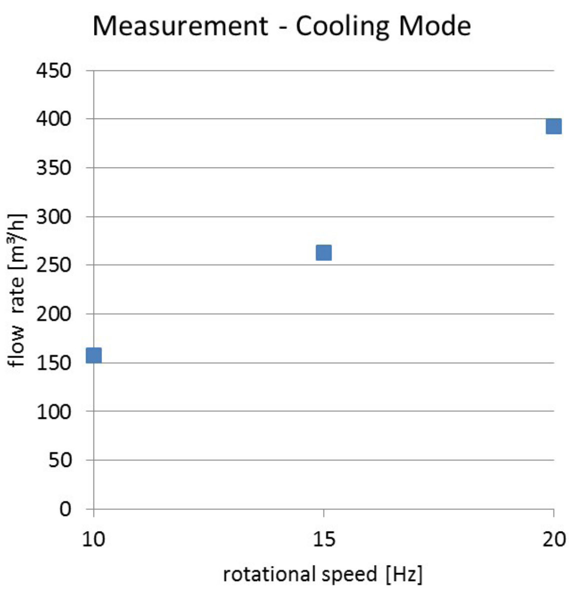


Figure 8. Measured flor rates of the laboratory prototype at different rotational speeds without external pressure and porous elements for heat recovery mode (left) and cooling mode (right).

In **Figure 9** the comparison of the measured flow rate values at a velocity speed of 15 Hz with the simulation results are shown for heat recovery and cooling mode. The measured flow rate of the heat recovery mode is slightly above, the flow rate of the cooling mode is slightly below the simulated value but agrees with good accuracy.

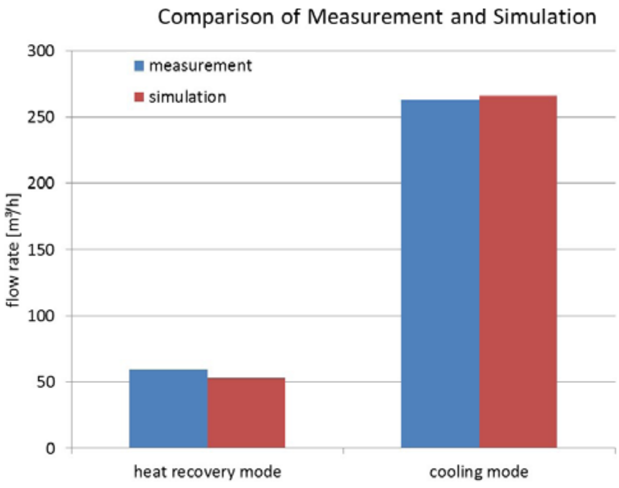


Figure 9. Comparison of measurement and simulation of the flow rates for heat recovery and cooling mode without external pressure and porous elements.

Conclusion

The development of the CHRF for the use as single/double room unit delivers successful simulation as well as measurement results in terms of flow rates which agree with good accuracy. Due to the high flow rates additional rooms could also be supplied. Further laboratory measurement with implemented porous elements are required to ensure adequate heat recovery rates and low internal leakage. Furthermore, the systemic power consumption of the modified concept must be measured to ensure high ventilation efficiency. The promising development of the modified CHRF concept can be scaled up for higher flow rates in order to open up further fields of application. The systemic advantage to generate high flow rates for the cooling mode should be used, hence a simple installation concept, e.g. for wall-integrated operation, should be developed to enable the axial outdoor air intake.

Acknowledgements

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Uncertainties due to steady wind in building pressurisation tests

This paper analyses the contribution of a steady wind to the uncertainties in building pressurisation tests, using the modelling approach developed in another paper (Carrié and Leprince, 2016). The uncertainty due to wind is compared to the uncertainties due to other sources of uncertainty (bias, precision and deviation of flow exponent). This article is based on a paper presented at the 38th AIVC - 6 th TightVent & 4th venticool Conference, 2017 "Ventilating healthy low-energy buildings" held on 13-14 September 2017 in Nottingham, UK.

Keywords: Airtightness; building; pressurisation test; infiltration; measurement; error; uncertainty

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With the increasing pressure of energy performance of buildings regulations, building pressurisation tests become more and more common. Yet, there remain unanswered questions regarding the quantification of uncertainties in practice. The sources of uncertainties include the model error due to wind, model error due to the deviation of the flow exponents, precision and bias error.

The objective of this study is to assess the impact of a steady wind on airtightness testing uncertainty and compare it to other sources of uncertainty. This paper uses the modelling approach proposed by (Carrié, et al., 2016).

This analysis assumes that:

- the building can be represented by a single zone separated from the outside by 2 types of walls: walls on the windward side of the building which are subject to the same upwind pressure; and walls on the leeward side which are subject to the same downwind pressure;
- the test is performed under isothermal conditions, and
- the airflow rate through the leaks of the envelope is given by a power-law with the same flow exponent.

To estimate combined uncertainty, we use a similar approach to that proposed by (Sherman, et al., 1995), which includes precision, bias and model error.

We have estimated the maximum error for a one-point measurement at 10 and 50 Pa and for a two-point measurement with the determination of flowrate at reference pressure 4 and 50 Pa. Constraints were applied to perform a test valid according to ISO 9972:2015. However, we have also plotted results without the constraint on the zero-flow pressure (named "constraint D") to see its impact. We assessed the uncertainties when averaging results of pressurisation and depressurisation tests. We analysed separately the maximum error likely to happen when testing a building zone with facades exposed to wind:

a) both upstream and downstream such as a detached house (called "restricted range")
b) either upstream only or downstream only (called "full range").

Results

The results are summarised in **Figure 1** to **Figure 4** and **Table 1**.

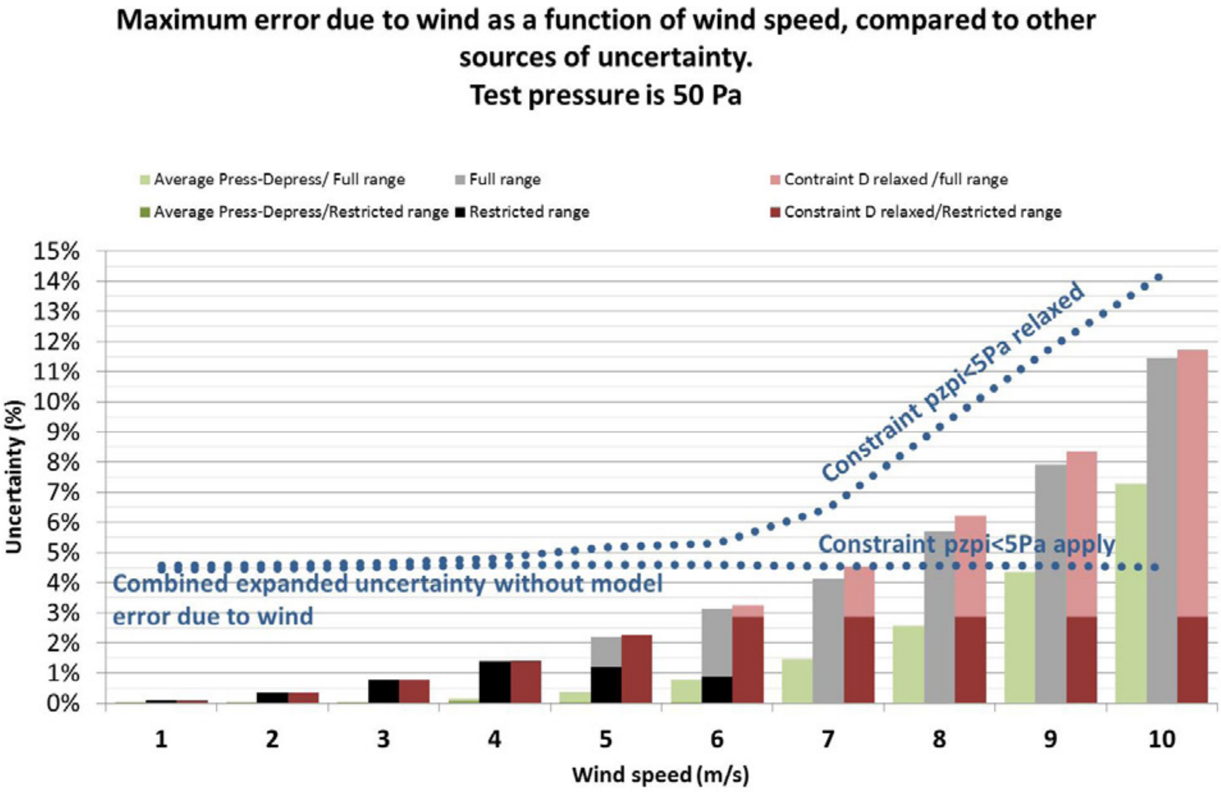

Figure 1. Model error due to wind at 50 Pa, one point measurement.

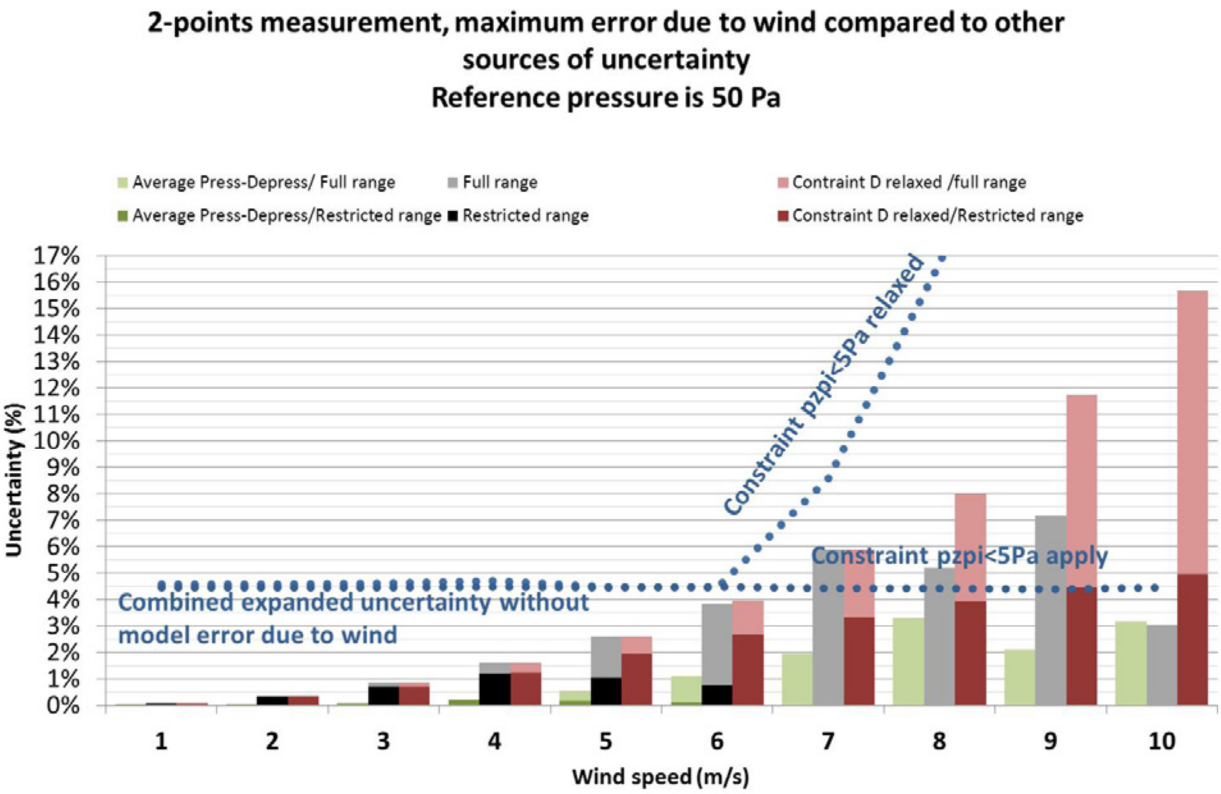

Figure 2. Model error due to wind at a reference pressure of 50 Pa with 2-points measurements.

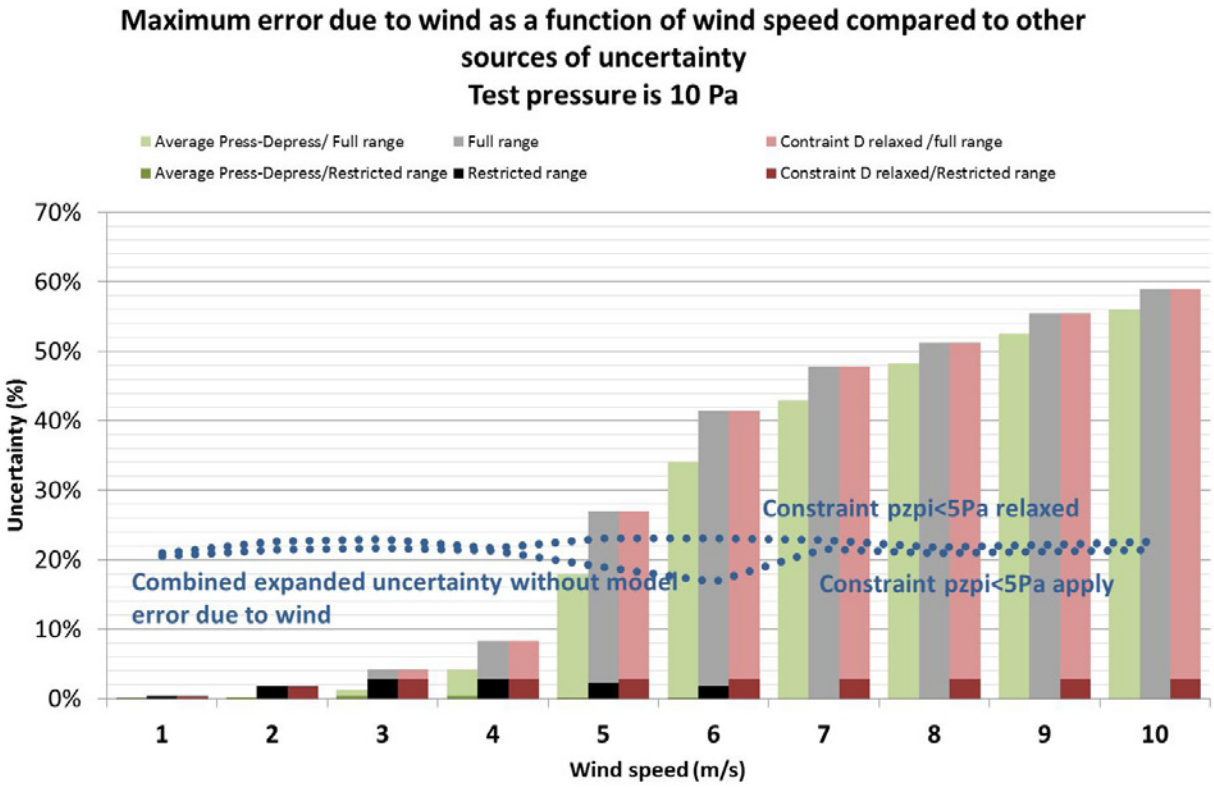

Figure 3. Model error due to wind at 10 Pa, one-point measurement.

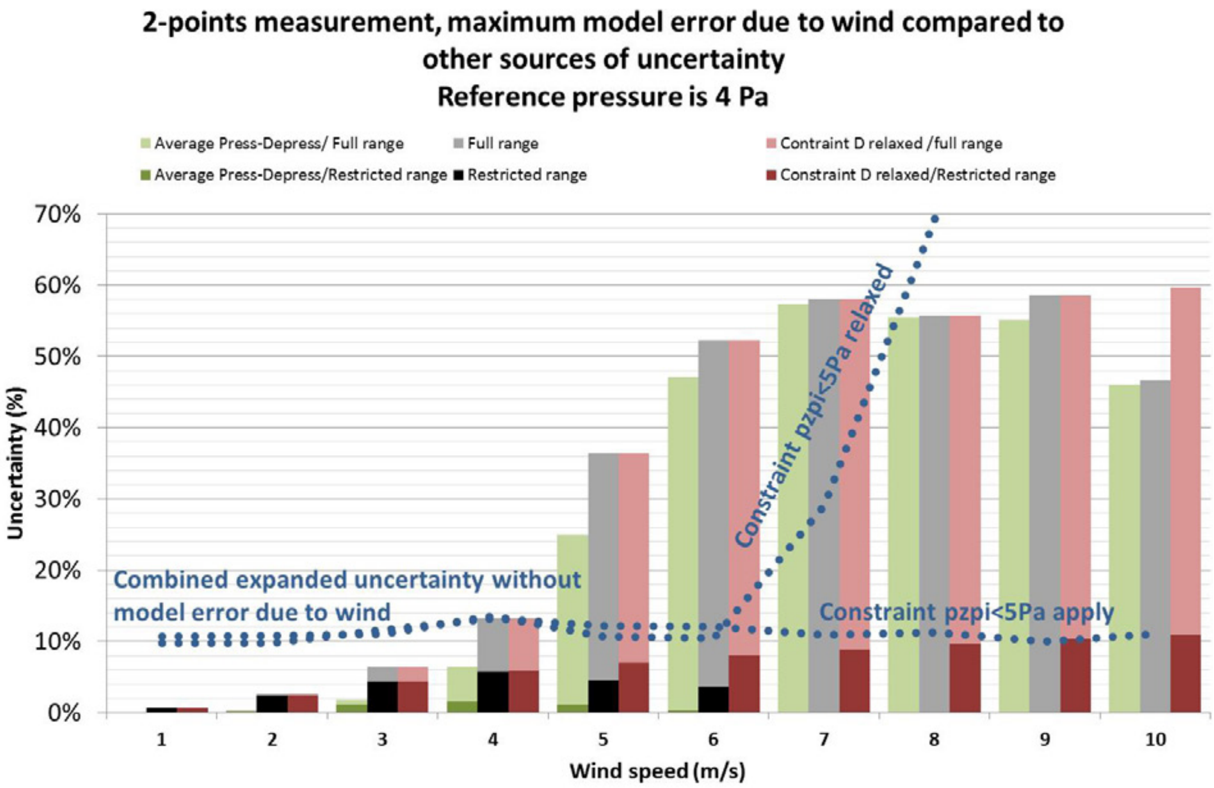

Figure 4. Model error due to wind at a reference pressure of 4 Pa with 2-point measurements.

Table 1. Summary of the result: maximum error due to steady wind.

		At 4 Pa				At 50 Pa			
		Constraint D		No constraint D		Constraint D		No constraint D	
	Range of z	Full	Restr.	Full	Restr.	Full	Restr.	Full	Restr.
1-point	6 m s^{-1}	3%	1%	3%	3%	3%	1%	3%	3%
	10 m s^{-1}	11%		12%	3%	11%		12%	3%
1-point combined	6 m s^{-1}	32%	30%	33%	32%	6%	5%	6%	6%
	10 m s^{-1}	34%		45%	44%	12%		15%	14%
2-point	6 m s^{-1}	52%	4%	52%	8%	4%	1%	4%	3%
	10 m s^{-1}	47%		60%	11%	3%		16%	5%
2-point combined	6 m s^{-1}	53%	15%	53%	42%	6%	5%	6%	5%
	10 m s^{-1}	48%		151%	139%	5%		44%	39%

Discussion

One key result is that alone, the model error due to the wind on the estimated airflow rate is relatively small for the high-pressure point, but it can become very significant with a low-pressure point. While the error lies within 12% for wind speeds up to 10 m s^{-1} at 50 Pa, it can reach 60% at the low-pressure point (10 Pa).

However, there are other sources of uncertainty that are not taken into account in this study such as:

- wind fluctuations,
- leaks that have different flow exponents,
- the linear regression,
- thermal draft,
- uncertainty on building preparation.

What happens over 6 m/s?

At 50 Pa, up to 6 m/s uncertainty due to wind remains below "other combined uncertainty". Therefore, the uncertainty due to wind has almost no impact on the quadratic sum. It is seen on one- and two-point measurement graphs.

The uncertainty due to wind becomes dominant at 5 m/s for 10 Pa (**Figure 3**) and at 4 m/s for 2-point test extrapolated at 4 Pa (**Figure 4**).

Therefore, 6 m/s is a relevant limit value for the high-pressure station (50 Pa) but is too high for low-pressure measurements.

Can we relax the zero-flow pressure constraint ("constraint D" on graphs) to allow testing in windy places?

The difference between with and without the zero-flow pressure constraint is the difference between the grey/black and the red bars on figures 1 to 4. Up to 6 m/s, there is not much difference between with and without applying this constraint. Constraint D limits the wind speeds for which the test can be performed to about 6.2 m s^{-1} with a restricted range of leakage distribution (see **Figure 1**, **Figure 2**, **Figure 3**, **Figure 4**) which is consistent with ISO 9972:2015 stating that constraint D is unlikely to be met above 6 m s^{-1}. Relaxing the constraint on the zero-flow pressure would allow one to perform a test above 6 m/s in detached houses.

In detached houses (restricted range of leakage distribution), the uncertainty due to wind remains low even with wind speeds up to 10 m/s and without constraint on zero-flow pressure. However, for 2-point tests above 6 m/s, the combined uncertainty without wind increases rapidly without constraint D; it passes over 10% at 7 m/s for a reference pressure at 50 Pa.

These results suggest it is necessary:

- either to have a constraint on wind speed (maximum 6 m/s); or
- to have a constraint on zero flow pressure (maximum 5 Pa)

Does averaging pressurisation and depressurisation have a significant impact on results?

The difference between green and grey bars in figures 1 to 4 shows the effect of averaging pressurisation and depressurisation tests. This averaging can decrease the uncertainty due to wind up to 5 percentage points. At low wind speed, when averaging, the uncertainty due to wind is negligible; therefore other sources of uncertainties dominate.

At high wind speed, averaging is not enough to make uncertainty due to wind in the same range of other sources of uncertainties.

Averaging is mostly beneficial at intermediate wind speed (around 4 m/s) when reference pressure is 4 Pa. It keeps the error due to wind far below the "other" combined uncertainty.

Is the uncertainty different between tests in detached houses and single-sided dwellings?

The maximum uncertainty in detached houses (restricted range) is given by dark bars in the figures, and the maximum uncertainty without restriction on the leakage distribution is given by light bars. The uncertainty in detached houses remains below 12% even for wind speeds up to 10 m/s with constraint D relaxed at 4 Pa, whereas for a single-sided dwelling the uncertainty due to wind may reach 60% at high wind speed. Therefore, the uncertainty due to wind is mostly critical for single-sided buildings or zones.

To calculate the infiltration air flowrate at 4 Pa and 50 Pa is it better to perform a 2 or a 1 point of the test (and extrapolate with constant n for 4 Pa)?

According to (Carrié, et al., 2016) ; figure 6), the uncertainty for a reference at 4 Pa (with n = 2/3) when testing at a single pressure station of 50 Pa remains between 31 and 34% up to 10 m/s when constraint D applies. When constraint D is relaxed, it increases from 5 m/s to reach 47% at 10 m/s.

Comparing this result with **Figure 4** suggests that, for a result at 4 Pa, up to 5 m/s, it is better to perform a 2-point test and extrapolate with a calculated flow exponent and above 5 m/s it is better to perform a test at 50 Pa and extrapolate with a default flow exponent (n = 2/3).

For detached houses, **Figure 4** suggests that a 2-point test is preferable up to 7 m/s (whether constraint D is relaxed or not).

If the reference value is 50 Pa, there is much less uncertainty due to wind if the test is performed at only one pressure point close to 50 Pa.

Still, it may be useful to test envelopes at multiple pressure stations to identify suspicious results, e.g. due to moving valves.

What is the impact of steady wind on uncertainty compared to other sources of uncertainty?

On figures 1-4, for detached houses (restricted range), the impact of steady wind is quite low compared to the other sources of uncertainty, but for a single-sided building (full range), it is important to check wind speed and/or pressure difference at zero flow to perform a reliable test. ■

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hybridGEOTABS project

– MPC for controlling the power of the ground by integration

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GEOTABS is an acronym for a GEOthermal heat pump combined with a Thermally Activated Building System (TABS). GEOTABS combines the use of geothermal energy, which is an almost limitless and ubiquitous energy source, with radiant heating and cooling systems, which can provide very comfortable conditioning of the indoor space. GEOTABShybrid refers to the integration of GEOTABS with secondary heating and cooling systems and other renewable and residual energy sources (R2ES), offering a huge potential to meet heating and cooling needs in office buildings, elderly care homes, schools and multi-family buildings throughout Europe in a sustainable way. Through the use of Model Predictive Control (MPC), a new control-integrated building design procedure and a readily applicable commercial system solution in GEOTABShybrid, the overall efficiency of heating and cooling will be significantly improved in comparison to current best practice GEOTABS systems and its competitiveness will be strengthened.

The present paper is the first of a series that first introduces the hybridGEOTABS project and then specifically focuses on the control-related aspects of the hybridGEOTABS solution, the MPC, providing some interesting insights of its potential development.

Keywords: hybridGEOTABS; geothermal heat pump; TABS; Model Predictive Control, integrated solution

GEOTABS benefits & challenges

GEOTABS are applied in low temperature heating and high temperature cooling of buildings. TABS is a radiant system, beneficial in terms of thermal comfort and energy efficiency. Its high thermal inertia allows load buffering and peak load shaving. When combined with a heat pump, it allows to make very efficient use of low grade R2ES (renewable and residual energy sources) (**Figure 1**). Therefore, GEOTABS represents an eco-innovative technology that allows to substantially decrease energy use and greenhouse gas (GHG) emissions from buildings while improving indoor environmental quality. The GEOTABS project [1] was a frontrunner in improving system design and control of GEO-HP-TABS in office buildings by using monitoring, comfort surveys and simulation data. The resulting design guidelines were included in REHVA Guidebook 20 "Advanced system design and operation of GEOTABS buildings [2].

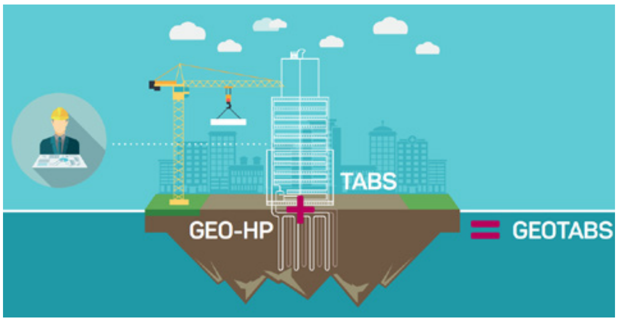

Figure 1. The GEOTABS concept. Image credits: hybridGEOTABS project (www.hybridgeotabs.eu)

Nonetheless, a number of bottlenecks currently prevent a real breakthrough of the GEOTABS concept in a broad range of building types. Current GEOTABS solutions are perceived too investment-expensive and they are often not operating at their full potential. Because of their high thermal inertia, TABS require flexible complementary heat emission systems to swiftly react to variations in heating or cooling setpoint, ensuring thermal comfort and efficient operation. On the production side, investments can be more competitive when providing a hybrid supply, and heat pump operation can be more efficient. The GEOTABS system is thus an inherently hybrid system when we want to use it in a broad range of building types, including those buildings with highly variable and often unpredictable heating and cooling loads. Challenges however need to be tackled to integrate the primary and secondary systems. A first challenge is the lack of design guidelines

hybrid GEOTABS

hybridGEOTABS

– Model Predictive Control and Innovative System Integration of GEOTABS in Hybrid Low Grade Thermal Energy Systems

hybridGEOTABS is a four-year project started in 2016 by an active team of SMEs, manufacturers and research institutes. The project, led by the University of Gent, is a Research and Innovation Action funded under the EU's Horizon 2020 programme.

The goal of hybridGEOTABS is to optimise the predesign and operation of a hybrid combination of geo-thermal heat-pumps (GEO-HP) and thermally activate building systems (TABS), alongside secondary heating & cooling systems, including automated Model Predictive Control (MPC) solutions.

To know more about the project visit www.hybridgeotabs.eu and contact hybridgeotabs@ugent.be

hybridGEOTABS project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 723649.

on the sizing of the hybrid GEOTABS system to allow a proper tuning between heating and cooling originating from the GEOTABS and that provided by the complementary system. Today case-by-case dynamic simulations are required in design phase, resulting in excessive engineering costs. Secondly, the resulting oversizing of the heat pump and borefield leads to higher investment costs. Thirdly, for the concept to work at its most efficient point, all components need to be engineered as a package, which is rarely the case since they are developed by different companies, leading to higher investments and lower efficiencies. Fourthly, traditional Rule-Based Control strategies are not able to harvest the full potential of the system and result in high commissioning costs and higher operational costs. Finally, previous studies have shown potential benefits of the system in terms of thermal comfort, health and productivity, yet those have not been fully validated yet.

hybridGEOTABS solution & project

The hybridGEOTABS project [3] brought together a transdisciplinary team of SME's, large industry and research institutes, experienced in research and application of design and control systems in the combined building and energy world (**Figure 2**). Their aim is to take away the bottlenecks to allow a wide implementation of the hybridGEOTABS concept. The overall solution consists of an optimal integration of GEOTABS with secondary systems and a white box approach for model predictive control (MPC) of this integrated system. The main objectives of the project are to develop, demonstrate and validate the hybridGEOTABS system.

hybridGEOTABS key objectives are:

1. The hybridGEOTABS system will be developed and supported by a new holistic control-integrated design procedure, with the overall efficiency for heating and cooling improved by 25 % as compared to current best practice GEOTABS. This coherent strategy will allow to provide feedback about the HVAC systems in the feasibility study/pre-design stage of the design process, as well as a significant reduction of engineering costs for hybridGEOTABS buildings.
2. A method of choosing the appropriate components for hybridGEOTABS, e.g. bore holes, heat pumps, TABS, control, and secondary supply and emission systems, is developed in order to achieve optimal performance of the integrated system. These components are also optimised and developed for use in hybridGEOTABS, and an energy dashboard is developed to involve and inform building operators and users. As an alternative for the use of TABS in building retrofit, the potential of using radiant ceiling panels with integrated Phase Change Materials is being investigated.
3. A suitable control system with the MPC as the high-level controller and state-of-the-art low-level controllers is developed. A semi-automated MPC toolchain for the development of this controller is developed. The MPC is based on a white-box model and will be adaptive and robust. Therefore, it will reduce the implementation cost of MPC to competitive levels, by reducing both design and commissioning costs, and maximise building performance. The white-box

Figure 2. The hybridGEOTABS consortium includes four universities, four SMEs, one professional association, one SME cluster and two large companies.

MPC also allows for an immediate start-up of the control with the start-up of the building (with no need for training data).

4. A people-planet-profit validation of the hybridGEOTABS approach on high-visibility demonstration and case-study buildings. The evaluated performance indicators include energy and environmental indicators, indoor environmental quality indicators (thermal comfort, acoustics, lighting…, and importantly, also health and productivity are evaluated), financial costs and other performance indicators such as smart grid readiness.
5. The groundwork for the establishment of a trade body to promote the concept and help to establish the best practices according to the project will be laid down.
6. A detailed business plan will be developed to promote the product and maximize the project impact.

hybridGEOTABS demonstration buildings

The hybridGEOTABS implementation, demonstration and validation takes place in 3 demonstration buildings:

- Ter Potterie elderly care home in Bruges (Belgium) (**Figure 3A**),
- Solarwind office building in Windhof (Luxembourg) (**Figure 3B**),
- the elementary school of Libeznice (Czech Republic) (**Figure 3C**).

In these buildings, the newly developed control strategies are implemented and validated and the overall building performance (in terms of energy, environment, costs, comfort, health and productivity) is evaluated via on-site measurements and building data. These three demonstration buildings, together with two extra case-study buildings, Infrax office building in Dilbeek (Belgium) (**Figure 3D**) and Haus M multi-family building in Zürich (Switzerland) (**Figure 3E**), populate a virtual test bed consisting of emulator models of these buildings, that are used in the development, demonstration and validation of the concept.

Why Model Predictive Control?

MPC is a control methodology that can be used to control thermal systems (heating, cooling and ventilation) in buildings and which is an alternative for Rule-Based Control (RBC). The principle of MPC is fundamentally different from RBC since MPC uses a mathematical optimization problem at its core instead of a set of fixed control rules. The optimization problem minimizes a cost function, e.g. the energy use of the building, by choosing the control variables, e.g. the supply water temperature of floor heating, optimally. Furthermore, constraints can be enforced in the optimization problem, such as a minimum and maximum zone temperature. This way thermal comfort is guaranteed. Finally, MPC includes an internal forecast of the system state (temperatures) such that it can anticipate the influence of future disturbances (e.g. outdoor temperature and occupancy).

Figure 3. hybridGEOTABS demo buildings: A) TerPotterie, Bruges B) Solarwind, Windhof C) Libeznice primary school, D) Infrax building, Dilbeek E) Haus M, Zurich. Image credits: hybridGEOTABS project (www.hybridgeotabs.eu)

To be able to implement an MPC, the controller has to know how 'the system' behaves. I.e. the controller has to know how a change in control variables affects the constraints and the objective function. This information is contained by a 'controller model', which is a mathematical representation of the controlled system. **Figure 4** presents a schematic illustration of MPC.

An analogy can be made with a Formula 1 car (see **Figure 5**). The pilot is then the optimal controller. His cost function (objective) is to complete the track as quickly as possible. Control variables are the steering wheel, the throttle and the brakes. Constraints are the edges of the circuit and the maximum traction of the tires. The pilot knows how the car reacts to his 'control signals' and is thus able to complete the track quickly. The better its controller model (driving skills), the better the results (lap times) will be.

In the case of a building it is not feasible to have a person operating the building full time. Computers can however take over this task. Computers can also use machine learning to learn the behavior of the building, similar to how a Formula 1 pilot learns the behavior of his car. However, just like a pilot, a computer requires a lot of training to achieve these skills. In the case of a complex building this may take multiple years of training data, which is not a practically workable solution. This is an important disadvantage of such a data driven approach. These data driven approaches are often classified as 'black-box' approaches since the controller knows nothing about the controlled system. White-box and grey-box approaches are an alternative to black-box by including more physical knowledge about the system.

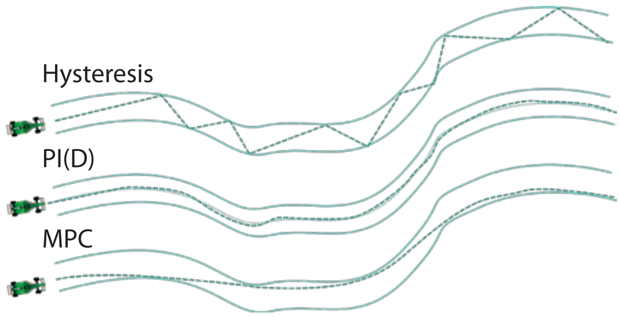

Figure 5. Formula 1 car analogy: Rule-Based Control (Hysteresis) vs. proportional control (PI(D)) vs. Model Predictive Control (MPC).

The white-box approach to MPC

White-box is the other extreme of the controller model spectrum, where knowledge about the physical system is included as much as possible. This knowledge is used as a substitute for measurement data. We do this by describing the system mathematically, using equations that express conservation of energy, COP or efficiency curves and the thermal inertia of the building. This approach allows developing controller models in a systematic way using building schematics and technical data, even before the building has been constructed. A disadvantage of this approach is that the computation time for the optimization of these detailed models rises strongly. The development of these models also requires some expertise in optimization and building energy simulation. Every building is different and therefore the controller model development is a recurring cost, which should be limited.

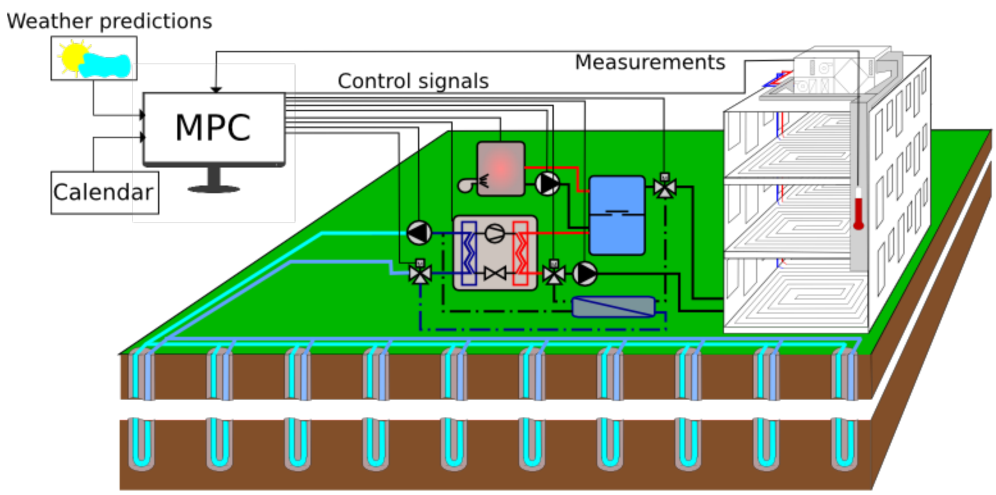

Figure 4. Schematic illustration of MPC in the larger system.

Scientific research within the hybridGEOTABS project and at the Thermal Systems Simulation (The SySi's) research group of the KU Leuven has however developed a solution for these problems. They developed a methodology that splits the controller model development work in three parts, using the modelling language Modelica.

1. PART 1. The first part is IDEAS, an open-source Modelica library of component models [4]. The library contains mathematical models for heat pumps, valves, windows, walls, solar shading, etc. These models are parameterized using easily interpretable parameters such as type numbers, wall surface areas and U-values. The models have been developed specifically for optimization purposes, by modelling experts.
2. PART 2. As the second part, users such as engineering firms and control companies can use this library by configuring components and by connecting them using connections that correspond to physical reality, e.g. using pipes. Similarly, window models and wall models can be connected to a room model. This leads to a structured mathematical description of the building, including its HVAC equipment and building envelope.
3. PART 3. In a third step, a computer program translates this structured description into an optimization code. Since the model library and the program are tailored to each other, very efficient optimization code can be generated such that problems related to the optimization problem computation time are largely resolved. Furthermore, users require a lot less expertise since the optimization problem complexity is encapsulated in the component model mathematical descriptions.

MPC current and future potential

Why is this important? MPC has multiple advantages compared to RBC, of which energy savings are the easiest to quantify. Research studies typically report energy savings of 15 to 30 % in practical demonstration cases, but some studies have reported energy savings of more than 50 % [5-9]. Since the ventilation, heating and cooling of buildings is responsible for about 15 % of the world wide final energy use [10], MPC can lead to significant energy and cost savings. These savings are obtained by operating the systems more efficiently and by better anticipating external factors such as weather influences. The thermal mass of the building can for instance be used to store 'free' energy of the sun on sunny days, due to which the heating requirements are reduced.

Furthermore, MPCs are able to use the available systems to their full potential. E.g. excess heat in one side of the building can be actively rerouted to other zones through floor heating or concrete core activation. In the future such energy exchanges may even occur at a larger scale between buildings, when using thermal networks. Other advantages are the increased thermal comfort and reduced wear on components that operate in part-load or by avoiding cyclic behavior.

There are additional advantages that have not been shown systematically but for which we see a large potential. The commissioning cost of a building could be reduced significantly compared to RBC. MPCs are more flexible and are better able to cope with changing set points and malfunctioning equipment than RBC. MPC supports multiple cost functions such that the energy cost (EUR) could be minimized instead of the energy use (kWh). This is particularly interesting when a day/night tariff or even time-dependent electrical energy pricings are available. MPC is hence a technology that is compatible with the smart grids of the future, and also with demand response. Companies with a heart for the environment can also modify the cost function such that locally generated renewable energy sources are put to use as much as possible. This could be a very useful tool for policies during the transition to a CO2-neutral society. Policy goals can be translated into a gradual increase in the share of renewable energy that should be used. MPC can then automatically control hybrid systems (such as hybrid heat pumps) such that this gradual increase is achieved. Furthermore, the mathematical models can also be used for other purposes such as fault detection and diagnosis or simply for predicting the indoor air temperature during the coming days. This is possible since an MPC internally predicts the future behavior of the building to implement the optimization, which thus takes into account the impact of the current control actions on the future behavior of the building.

hybridGEOTABS project for boosting MPC development

The hybridGEOTABS project incorporates an overall and integrated system approach, it considers all stages of the building process (from predesign to operational stage) and validates the concept from many perspectives via a people-planet-profit validation. The project will play a pivotal role particularly for the future development and market uptake of MPC. Indeed, MPC is ready for the early adopters, but for a large-scale deployment based on the white-box approach some issues have to be resolved first. The library of component models has to be extended and the user-friendliness of the toolchain can be improved. Furthermore, the technology should be demonstrated in practice. These aspects are planned for the coming months within the scope of the hybridGEOTABS project, where in three demonstration buildings the hybridGEOTABS concept with MPC will be implemented, demonstrated and validated. ■

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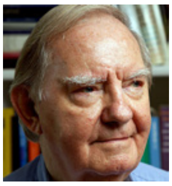
This article is follow-up part of the article published in REHVA Journal 2018-02 “Natural air conditioning: What are we waiting for?”

Earth, Wind & Fire: The Evolution of an Innovation (1)

– ‘Earth’: Natural ventilation and air-conditioning using the climate cascade



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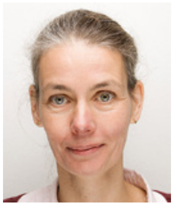

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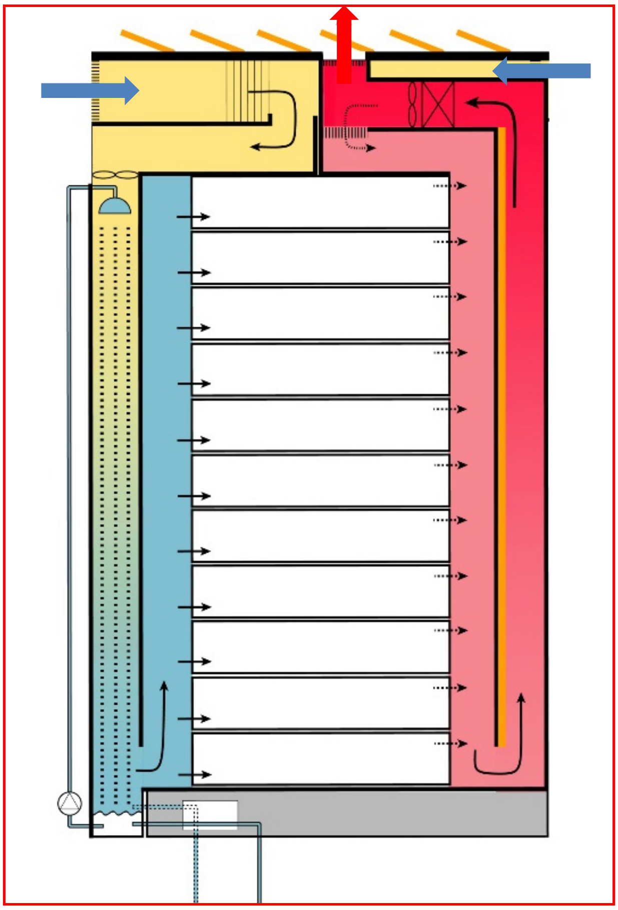
The climate cascade is a gravity-driven heat exchanger for conditioning ventilation air. It is installed in a structural shaft in a building. In the climate cascade, the ventilation air is cooled or heated and dried or humidified as required. In summer and winter, water of approx. 13°C is sprayed at the top of the system using spray nozzles. Due to the high heat transfer coefficient of the falling water droplets and the large active surface area of the millions of droplets in the spray spectrum, the climate cascade can exploit the tiniest of temperature differences between air and water to do its work.

The principle of cooling air through direct contact with water is far from new; it was conceived in the early 20th century when the first air-conditioning systems were developed.



An old principle is given a new life.

The climate cascade provides the three primary functions of air-conditioning: ventilation, cooling and drying, heating and humidification. It can thus replace a traditional air-conditioning unit with air filter, fan, silencer and humidifier (Bronsema, B. *et al.* 2017).

Climate cascade 3.0

The doctoral thesis extensively describes the design and performance of the innovative climate cascade 1.0 in generic applications, (Bronsema, B. 2013/A, B, C). The design team was given the interesting challenge of fleshing out the concept for a specific project: Hotel BREEZE Amsterdam. It's all about making detailed specifications. Thanks to the valued input of the partners in the team, a robust design for a climate cascade 3.0 was conceived, in which energy efficiency played a dominant role.

The experiences gained during the design, detailing and implementation phases will be meticulously recorded, and the thermal, psychrometric, aerodynamic and energy performance of the climate cascade will be monitored for the period of one year after completion of the project. The design documents will be continuously updated based on these experiences and progressive insights. The final design documents will then be made available for wide application of the climate cascade in the air-conditioning sector, hopefully in the form of an ISSO/SBR1 publication. In the meantime, the authors hope that the climate cascade will be implemented in various new-build or renovation projects in the short term, because '*Natural Air-conditioning: What are we waiting for?'* (Bronsema, B. *et al.* 2017).

Design principles

The total ventilation rate for hotel rooms and general-purpose rooms is 25,000 $m^3.h^{-1}$, which is equivalent to ≈ 6.95 $m^3.s^{-1}$ or ≈ 8.33 $kg.s^{-1}$

The design principles of the climate cascade are:

▶ ***Cooling of ventilation air in the cool season***

The design condition for the cooling season is 28°C at 55% RH. The ventilation air must be cooled to ≈ 17°C. Assuming a temperature increase of ≈ 1K in the air displacement system, the temperature of the supply air will be ≈ 18°C.

▶ ***Using geothermal cooling***

The cooling is extracted from the ground, which has a temperature of ≈ 12°C at the extraction point. Using a heat exchanger with an LMTD2 of 1K, this results in a constant spray water temperature of 13°C. No geothermal cooling is required for outdoor temperatures lower than ≈13°C. In this situation, the spray water is cooled by the cold outdoor air and reheated to 13°C outside the climate cascade.

▶ ***Pressure build-up for air displacement in the building***

The positive pressure at the foot of the climate cascade is an important contributor to the air displacement throughout the building. The relevant parameters are the water/air ratio ($R_{W/A}$) and the cross-section of the cascade. Increasing the $R_{W/A}$ results in a denser water/

1 ISSO/SBR Dutch Research Institute for Building Services en Construction www.isso.nl

2 Logarithmic Mean Temperature Difference

air mixture which in turn increases the positive pressure gradient in relation to air. A smaller cross-section using the same $R_{W/A}$ achieves the same effect. However, the pump power increases proportionally with the spray water flow rate, which entails an energetic disadvantage.

The pressure loss of the air supply system, including the initial pressure of the farthest removed supply inlet, is ≈ 100 Pa. In previous versions of the design, it was assumed that under all circumstances, a positive pressure gradient at the foot of the climate cascade of minimum 100 Pa would be achieved. Simulations with the Excel model revealed that this requires a high $R_{W/A}$ in combination with a high air velocity of ≈ 4.5 $m.s^{-1}$. This has the following disadvantages:

- the capacity of the spray pump and associated energy consumption is high
- the spray nozzles cannot be turned off because this has direct consequences for the pressure gradient
- there is relatively high pressure loss in the U-bend at the foot of the cascade
- there is a real risk of water aerosols being sucked into the supply system due to the high air velocity

For these reasons, it was decided to opt for spray nozzles with the lowest possible spray water flow rate, which means that the positive pressure gradient of 100 Pa cannot be reached. To compensate for this, an adjustable auxiliary fan will be installed in the central air supply shaft. This decoupling of capacity control from pressure build-up also makes it possible to turn off some spray nozzles when capacity demand decreases, which saves pump energy.

▶ ***Minimal energy consumption in all seasons***

The conventional method of heat recovery using twin-coil evaporators does not work in this concept. Instead, heat recovery is achieved by cooling the exhaust air as much as possible and efficiently using the recovered heat.

▶ ***Maximising the Coefficient of Performance (COP)***

The COP of the climate cascade is the quotient of the psychometric energy performance and the power consumption of the spray water pump plus the auxiliary fan.

Spray system

Droplet distribution

The distribution of droplet diameters in the climate cascade can be expressed with a few indices that characterise droplet size distribution (the spray spectrum) in a single number.

- d_{10}: average droplet diameter
- d_{20}: average droplet diameter by surface area, or SMD (Surface Mean Diameter); the cumulative surface area of the droplets, expressed in d_{20} (SMD), determines the heat exchanging surface area of the climate cascade
- d_{30}: average droplet diameter by volume, or VMD (Volume Mean Diameter); the fall velocity of the droplets (which partly determines the heat transfer coefficient) depends on d_{30} (VMD)
- d_{32}: Sauter Mean Diameter (SMD); the diameter with the same volume to surface area ratio as the total volume/surface area of the droplets in the spray spectrum (this relationship between SMD and VMD is important for the heat transfer)

Excel model

One unique characteristic of the climate cascade is that the active surface area is not a fixed value, as is the case in conventional heat exchangers. The heat exchanging surface area can be increased or decreased by varying the water/air factor and the spray spectrum. The volume flow rate and the temperature range of the cooling water can be influenced to achieve the required cooling performance, resulting in optimum energy consumption. To achieve this, a user-friendly Excel model was created that can visualise the many combinations of variables and their effects on the design and dimensions of the climate cascade with a single mouse click3. The input parameters of the model are the height of the climate cascade, the volume flow rate, and the temperature and relative humidity of the air. The variables are the air velocity, the water/air factor, the spray spectrum and the water temperature. The required air condition given the relevant energetic or otherwise optimum conditions can be determined by iterating through the variables. Hydraulic and thermal draught are derivatives of this calculation. The model was validated against measurements in a physical model and the results with respect to the sensible cooling capacity are sufficiently reliable for practical use. However, the calculation of the latent capacity is less accurate (Bronsema, B. 2013).

CFD simulation model

Spraying Systems GmbH, the supplier of the spray nozzles, developed a CFD simulation model that was also validated against measurements in the physical model. This simulation also produced reliable results (Bronsema, B. 2013).

3 Designed by Wim van der Spoel.

Design

The following design was produced following extensive trial-and-error simulations using the Excel model and in consultation with Spraying Systems GmbH (see **Figure 1**).

- climate cascade cross-section of 1300 × 1300 mm and an air velocity of ≈ 4.1 m.s-1
- 9 spray nozzles, type FullJet® 1-1/2HH-30250. The drop size distribution (DSD) of this model is known which meant that extra costs for this measurement could be avoided4. The spray spectrum of this type, with a water flow rate of 0.7 dm³.s-1 and initial pressure of 0.5 bar, is characterised by d10 = 0.581 mm, d30 = 1.708 mm (VMD) and d32 = 1.377 mm (SMD). The spray angle of this model is 15°.
- Fluid flow rate of 9*0.7 = 6.3 dm³.s-1, with a water/air ratio (RW/A) = 0.756.

The thermal, psychrometric and aerodynamic performance of this design were analysed using the Excel model. The calculations were verified by Spraying Systems GmbH using CFD simulations.

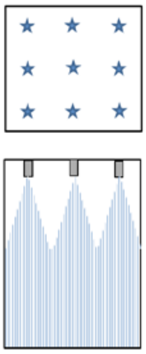


Figure 1. Basic design Climate Cascade.

Spray pump

The spray pump must be able to pump the cooling water up to the 10_{th} floor and compensate for pressure losses in the spray pipes and nozzles. Some of the pump energy is used to displace the ventilation air by transferring the momentum of the water droplets falling on the air in the climate cascade. It is expected that a much larger portion of this energy is converted into heat when the droplets fall into the cooling water reservoir.

Under a spray pressure of 50 kPa and with some loss of pressure in the pipes, the total head of the pump ≈ 40 m. At an efficiency of the pump and electric motor of 75%, the required pump power is ≈ 3.3 kW.

[4] Measured for the purposes of the Earth, Wind & Fire research programme.

System specifications

The spray pump is dimensioned based on the psychrometric performance of the climate cascade under design outdoor conditions of 28°C and 55% RH. The spray nozzles can be turned off at lower outdoor temperatures to save energy. The number of active spray nozzles that is required to maintain an air temperature of ≈ 17.5°C at the foot of the climate cascade was calculated using the Excel model (see **Figure 2**). The model shows that at an outdoor temperature $\theta_e \approx$ 18°C only one active spray nozzle is required. The climate cascade could theoretically be shut down at this temperature, but this is not recommended in connection with the continuous operation of the system. When $\theta_e \leq \approx$ 6°C, the spray nozzles are turned on one by one to guarantee a Relative Humidity of minimum 30% indoors.

Thermal performance

The temperature of the spray water was set to 13°C. When $\theta_e \geq \approx$ 14°C, the spray water is cooled to 13°C using water from the TES system. When $\theta_e \leq \approx$ 13°C, the spray water is cooled back to this temperature by the air and must be heated to 13°C by an external heat exchanger in the spray system. To avoid the risk of the spray spectrum freezing, at outdoor temperatures of < 3°C the air is preheated externally to ≈ +3°C. See **Figure 2**.

Hygric performance

The humidity in the room (RH_i) is a result of the humidity outdoors (RH_e) and the hygric performance of the climate cascade. In **Figure 3** an RH_e of 90% is assumed. From θ_e = 18°C, this decreases to the design summer conditions of 55% where θ_e = 28°C. The resultant RH_i is between the ideal values of 30% and 70%. This is without taking account of indoor humidity development. Note: Minimum humidity is controlled by the number of spray nozzles that are turned on or off.

Aerodynamic performance

The pressure at the foot of the climate cascade is determined by aerodynamic, hydraulic and thermal pressure differences, where the hydraulic pressure difference plays the most important role. The hydraulic pressure difference is mainly determined by the mass of the water in the climate cascade, which is a result of the water/air ratio ($R_{W/A}$) and the area of the cross-section, that is in turn derived from the chosen air velocity. Thermal pressure differences depend on the outdoor temperature and play a minor – but not negligible – role here.

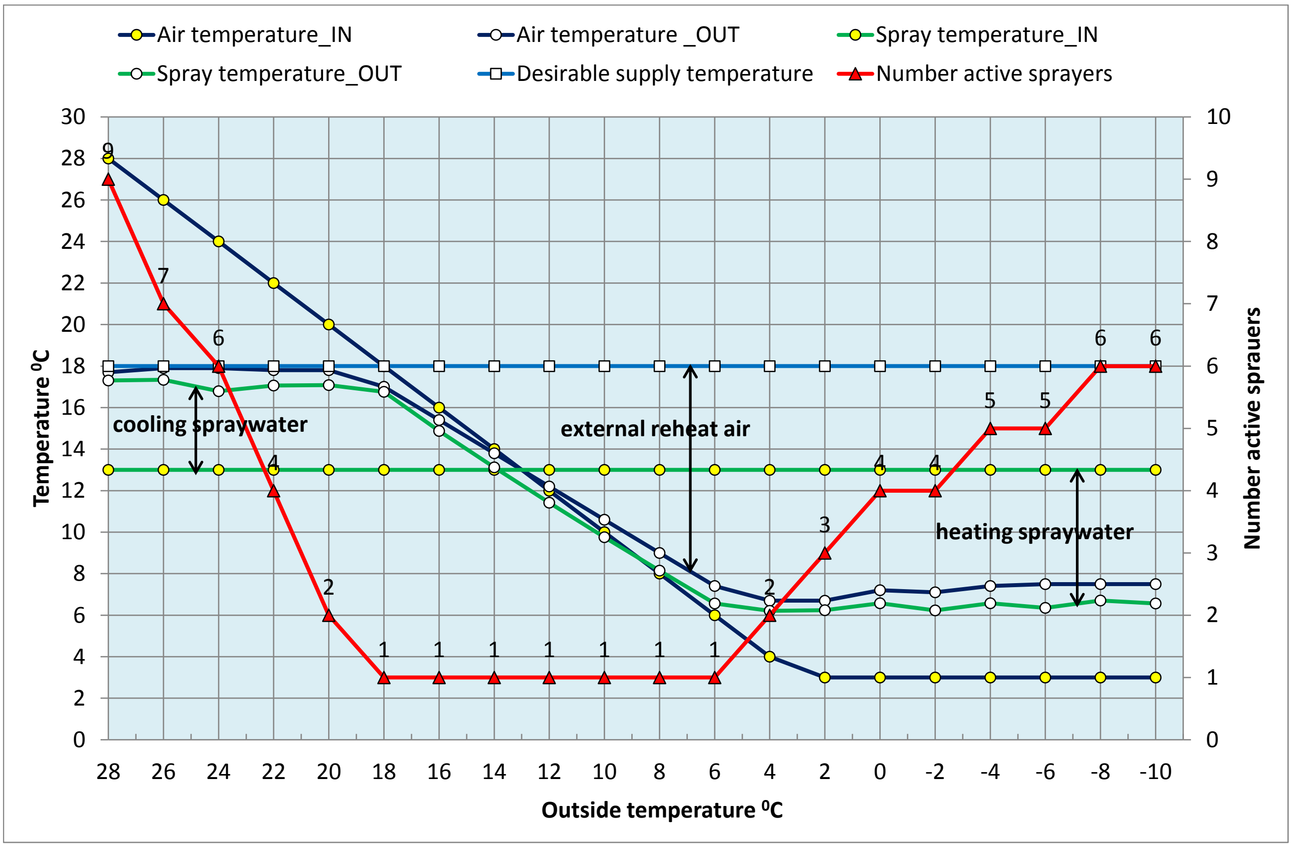


Figure 2. Temperatures in the climate cascade as a function of the outdoor temperature and number of active spray nozzles.

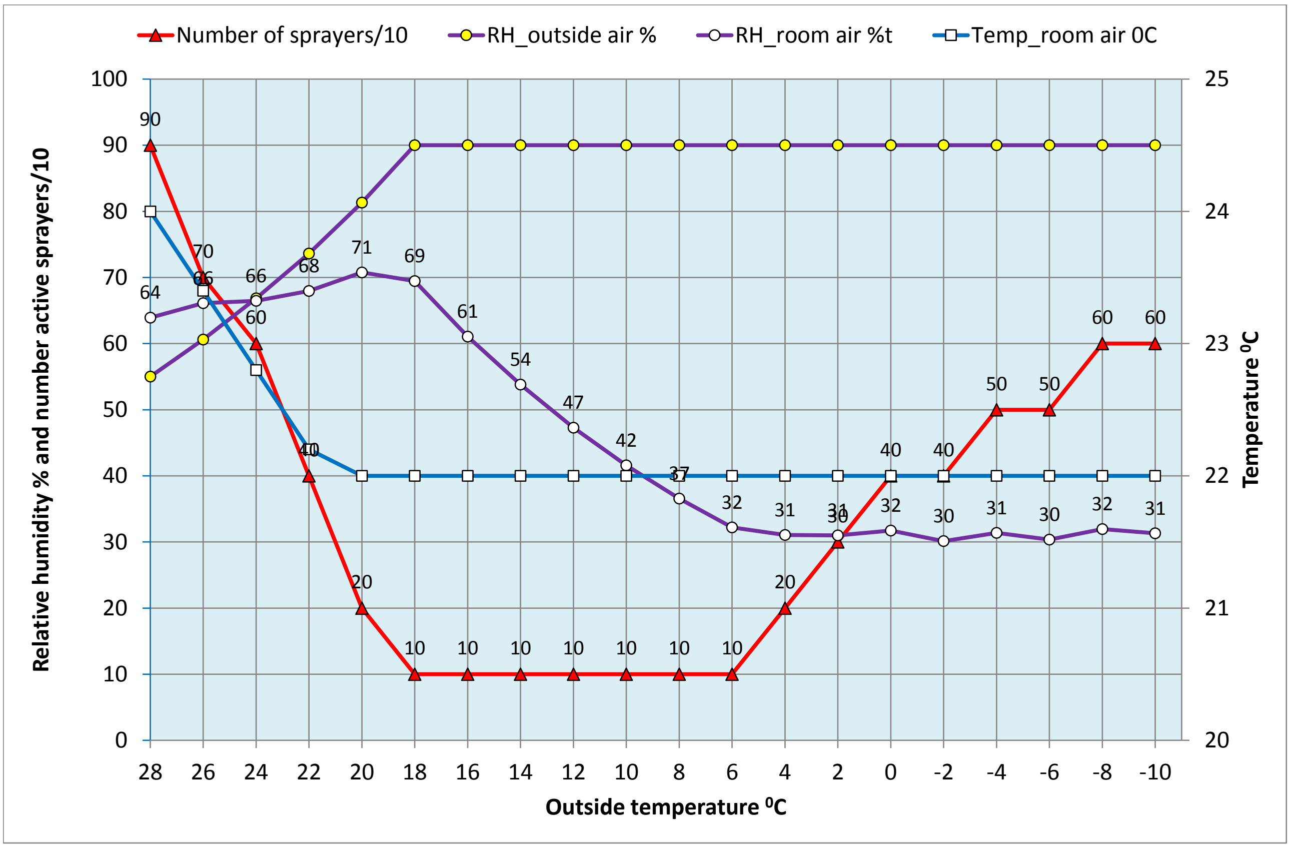


Figure 3. Relative humidity and the number of active spray nozzles as a function of the outdoor temperature.

The pressure loss in the supply system is ≈ 50 Pa and the required initial pressure of the connections to the hotel rooms (with fire damper and constant volume control damper) is also ≈ 50 Pa. The required pressure in the supply shafts is therefore ≈ 100 Pa. The thermal draught in the supply shafts, that varies with the outdoor temperature, must also be considered. The maximum (negative) thermal draught on the 10th floor ≈ -14 Pa in the summer, which means that the pressure at the foot of the climate cascade must be increased to ≈ 114 Pa. In the winter, the maximum thermal draught on the ground floor ≈ +9 Pa, so that the pressure at the foot of the climate cascade can be reduced to 91 Pa.

The pressure build-up at the foot of the climate cascade as a function of the outdoor temperature, based on this design and system specifications, is displayed in **Figure 4**. Under high outdoor temperatures and with 9 active spray nozzles, the climate cascade generates 82 Pa. If the outdoor temperature falls, some spray nozzles are turned off in accordance with the aforementioned algorithm, which results in a reduction of the hydraulic pressure difference. If the outdoor temperature ≥ ≈ 16°C, a positive thermal draught is created in the climate cascade so that the pressure at the foot of the climate cascade increases to 90 Pa at the design winter temperature. The difference between the required pressure in the supply system and the resulting pressure difference at the foot of the climate cascade must be generated by an auxiliary fan. In principle, the wind pressure at the outdoor air inlet could also be used to generate this difference.

Energy performance

The psychrometric capacities at outdoor temperatures of θ_e = 28°C to −10°C, calculated with the Excel model, are displayed in **Table 1**.

The nominal power of the spray pump (kW_{pump}) with 9 active spray nozzles is 3.3 kW. It is assumed that the power decreases proportionally with the reduction of the number of spray nozzles. The resultant pressure difference in the climate cascade will reduce the demand on the supply fan, which has not yet been considered. To calculate this effect, the unused fan power ($kW_{contribution}$) is set off against the power of the spray pump. This 'virtual' pump power (kW_{net}) can now be used to calculate the COP. The calculated COP values vary between -46 (cooling and drying) and +90 (heating and humidifying) at outdoor temperatures of 28°C to −10°C (see **Table 1**). The frequency of the outdoor temperature θ_e is derived from the frequency tables of the KNMI (Royal Netherlands Meteorological Institute) for De Bilt, the

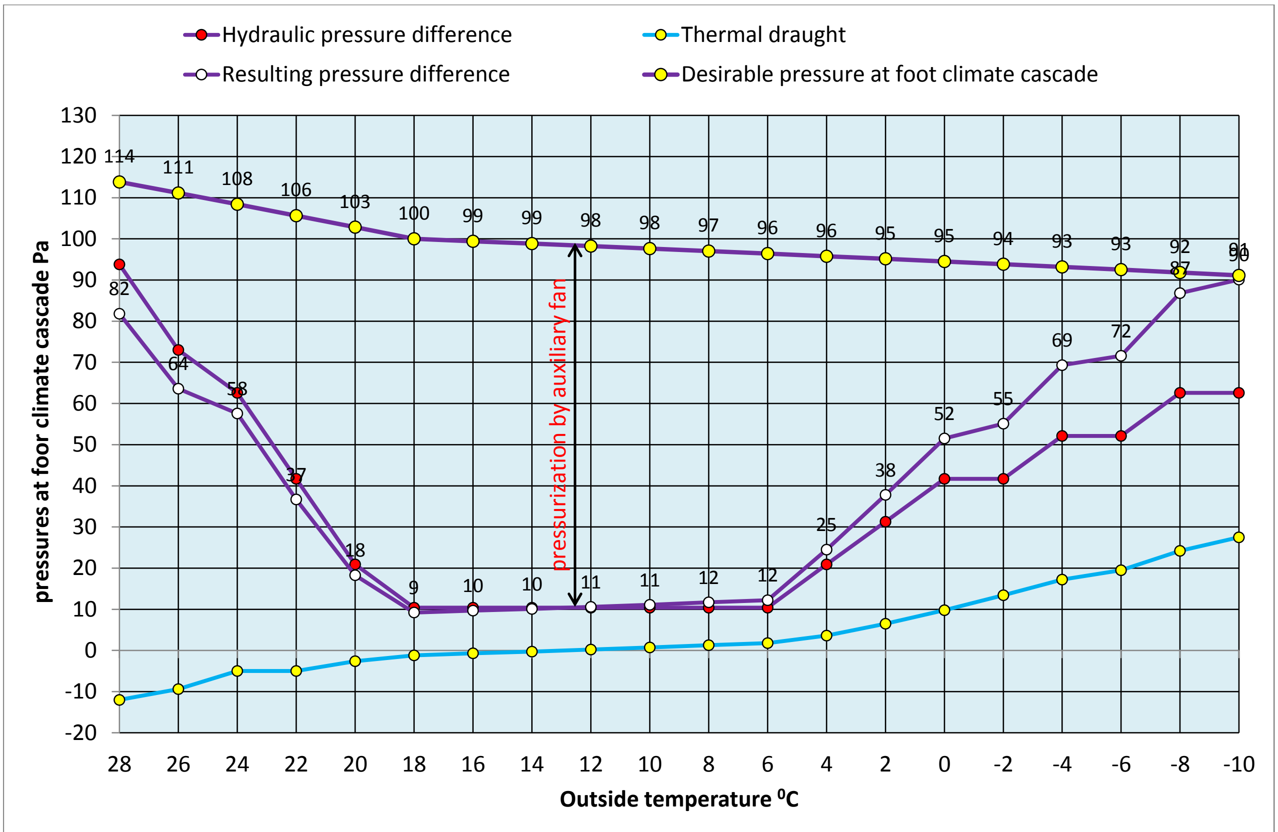


Figure 4. Pressure build-up in the climate cascade as a function of the outdoor temperature.

Netherlands for the period 1981–2000. The calculated COP values cannot easily be compared with those of conventional air-conditioning. For Hotel BREEZE, an energy consumption of ≈ 10 MWh.a^{-1} was calculated, approx. 20% of the consumption of conventional air-conditioning (Bronsema. B. *et al.* 2018, A).

Reheating the ventilation air

The air temperatures at the foot of the climate cascade as a function of the outdoor temperature are displayed in **Figure 5**. To achieve the desired supply air temperature of ≈ 17.5°C, the air will need to be reheated for outdoor temperatures of < ≈ 18°C.

Table 1. Psychrometric and energy performance.

Temperature		Psychrometric performance, kW			Psychrometric performance, kWh.a^{-1}			Energy performance				
θ_e,°C	hours/a	Q_{total}	$Q_{tangible}$	Q_{latent}	Q_{total}	$Q_{tangible}$	Q_{latent}	kW_{pump}	$kW_{contrib.}$	kW_{net}	kWh/a	COP
		Cooling and drying										
28	64	–114	–86	–28	–7,295	–5,491	–1,804	3.3	0.81	2.48	159	–46
26	77	–89	–67	–21	–6,822	–5,195	–1,627	2.6	0.63	1.93	149	–46
24	116	–72	–51	–21	–8,388	–5,894	–2,494	2.2	0.57	1.63	189	–44
22	198	–52	–35	–17	10,267	–6,927	–3,340	1.5	0.36	1.10	218	–47
20	329	–22	–18	–4	–7,286	–6,029	–1,257	0.7	0.18	0.55	181	–40
18	557	–10	–8	–1	–5,358	–4,640	–719	0.4	0.09	0.27	153	–35
16	754	–6	–5	–1	–4,341	–3,768	–573	0.4	0.10	0.27	204	–21
14	897	–2	–2	0	–1,530	–1,494	–35	0.4	0.10	0.27	239	–6
		Heating and humidifying										
12	920	2	2	1	2,221	1,533	688	0.4	0.11	0.26	240	9
10	960	7	5	2	6,357	4,798	1,559	0.4	0.11	0.26	246	26
8	945	11	8	3	10,775	7,872	2,903	0.4	0.12	0.25	236	46
6	910	15	12	3	13,766	10,612	3,153	0.4	0.12	0.25	223	62
4	688	37	22	14	25,174	15,474	9,701	0.7	0.24	0.49	337	75
2	521	58	31	27	29,991	16,058	13,933	1.1	0.38	0.72	377	80
0	382	75	35	41	28,837	13,365	15,472	1.5	0.51	0.95	364	79
–2	209	80	34	46	16,770	7,138	9,632	1.5	0.55	0.92	192	87
–4	112	96	37	60	10,794	4,105	6,689	1.8	0.69	1.14	128	84
–6	59	102	37	64	6,002	2,212	3,790	1.8	0.67	1.17	69	87
–8	35	114	37	77	4,000	1,312	2,688	2.2	0.86	1.34	47	86
–10	31	118	37	80	3,652	1,162	2,489	2.2	0.89	1.30	40	90
Hours	8764										3,991	

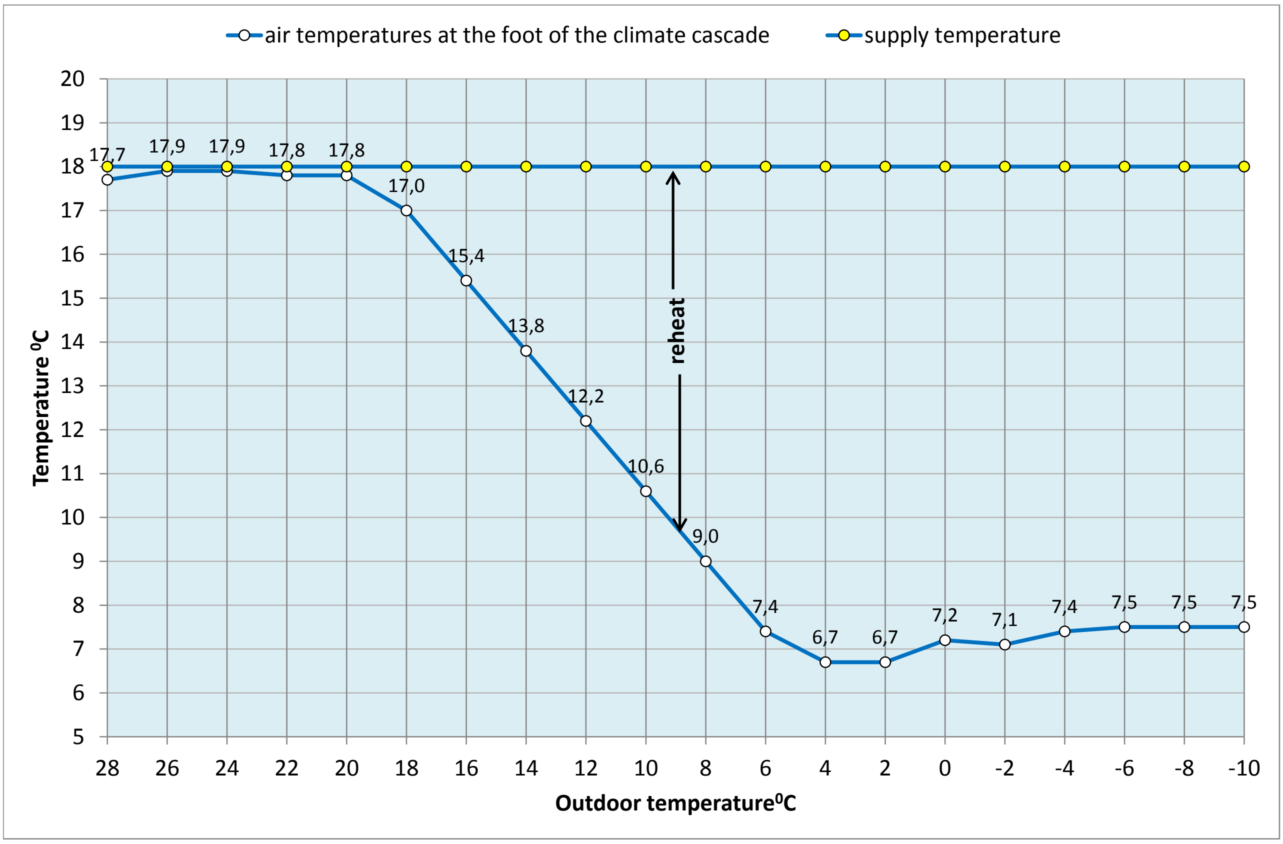


Figure 5. Air temperatures as a function of the outdoor temperature.

Hydronic performance

The air temperatures as a function of the outdoor temperature are displayed in **Figure 6**. For the design summer conditions and when using 9 active spray nozzles of 6.3 kg.s^{-1}, the spray water will have to be cooled from ≈ 17.3°C to 13°C. The thermal capacity is provided by the heat exchanger in the TES system with an LMTD of 1 K in the thermal-hydraulic cycle.

For the design winter conditions and when using 6 active spray nozzles of 6.3 × 6/9 = 4.2 kg.s^{-1}, the spray water will have to be heated from ≈ 6.6°C to 13°C. The required thermal capacity of [4.2 × 4.182 × (13–6.6)] ≈ 112 kW is provided by a heat exchanger in the spray system.

Annual energy performance

The spray pump and the fan jointly ensure the conditioning and displacement of the ventilation air.

The annual energy consumption of the spray pump and fan as a function of the outdoor temperature are displayed in **Figure 7**. The share of the pump in total

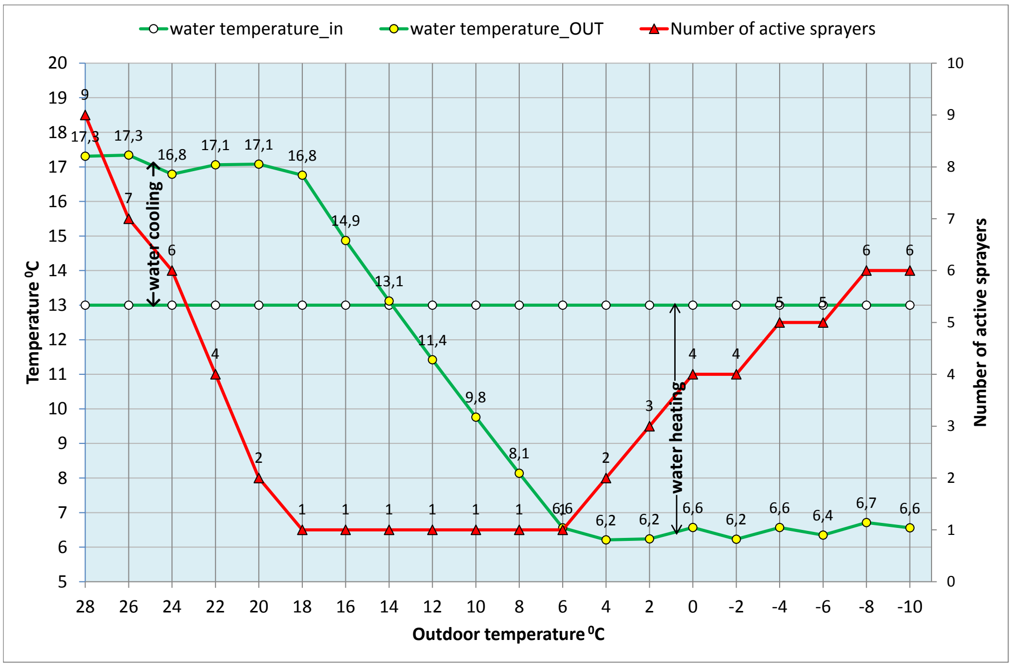


Figure 6. Water temperatures as a function of the outdoor temperature.

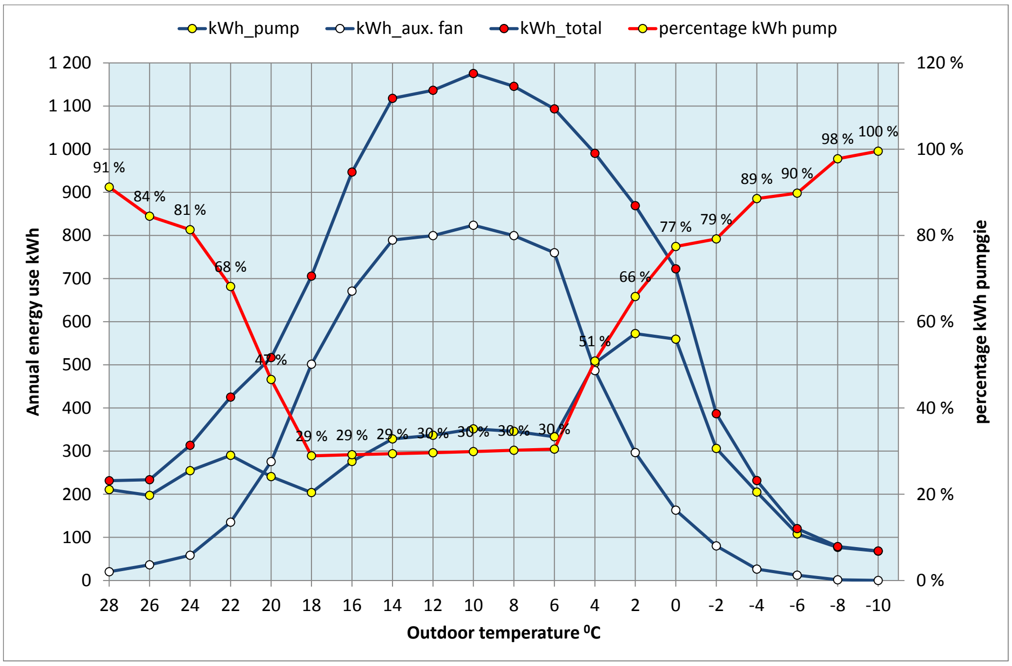


Figure 7. Annual energy consumption for air transport distributive.

energy consumption corresponds to the number of active spray nozzles in accordance with **Figure 2**. The figures clearly show the influence of the number of active spray nozzles on fan energy consumption. Note that the air displacement is completely generated by the climate cascade for an outdoor temperature of −10°C, in part due to the thermal draught in the supply shafts.

The annual energy consumption of the fan and spray pump is calculated at 12.5 MWh. According to EU regulation 1253/2014, as of 2018, a conventional air-conditioning system fitted with air filter, silencers, heat wheel and heating and cooling coils may have a maximum internal specific fan power of 800 W.(m³.s⁻¹)⁻¹, based on a flow rate of 25,000 m³.h⁻¹ and continuous operation, which corresponds to an annual energy consumption of 48.7 MWh, about four times the consumption of the climate cascade. The energy required to displace the air in the climate cascade is only (12.5/48.7)×100 ≈ 25% of the energy consumption of a conventional air-conditioning system. It should be mentioned here that the complex air distribution and extraction system with constant flow and check valves in each hotel room will result in considerably more pressure loss than in an office building. Nor has the energy consumption of the chilled water pumps in a conventional system been taken into account the comparison.

Psychrometric processes

The psychrometric processes for the summer and winter design conditions are displayed in **Figure 8 and 9**.

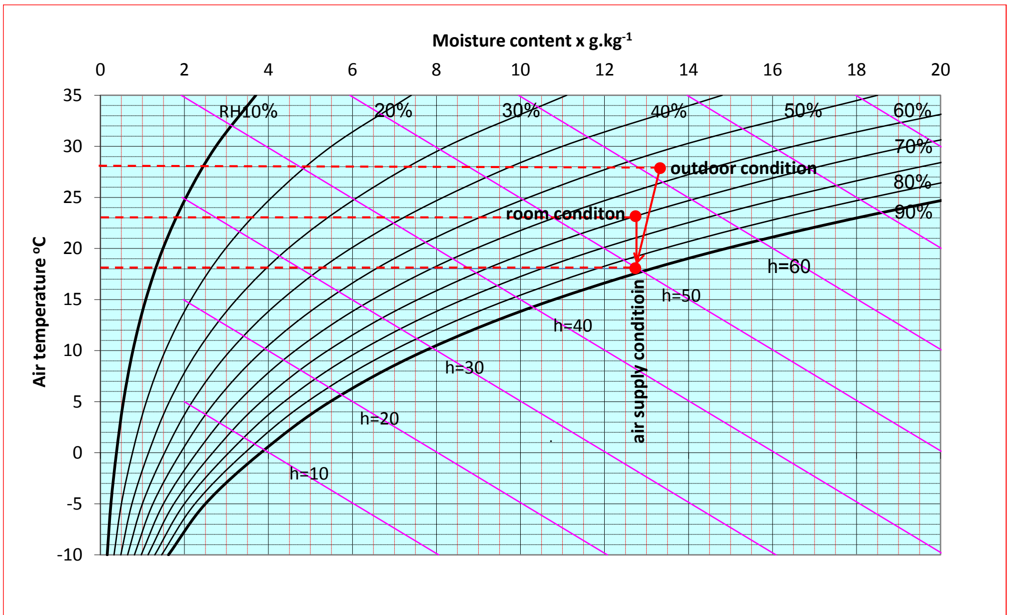


Figure 8. Design summer conditions -28°C/55% RH.

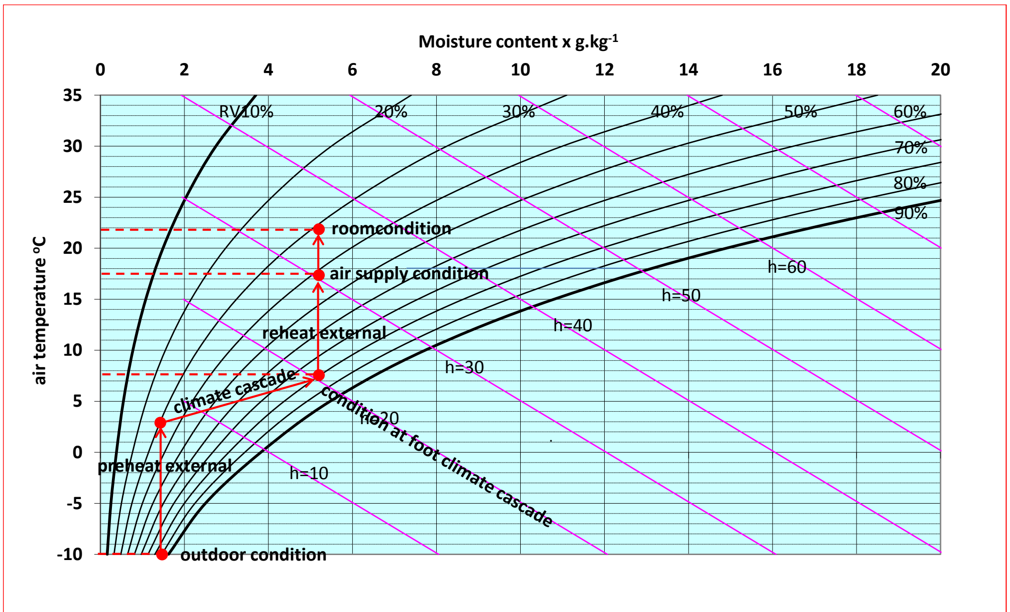


Figure 9. Design winter conditions -10°C/90% RH.

Air quality

In the spray spectrum several pollutions in the ventilation air will be absorbed, which will improve the air quality. Because of the low temperature levels, the climate cascade is legionella-safe, and a hygienic operation is guaranteed by filtering and disinfection of the spray-water. Possible positive effects through the waterfall- effect, ionisation and/or ozonisation will be investigated later. ■

This article is follow-up part of the article published in REHVA Journal 2018-02 "Natural air conditioning: What are we waiting for?"

This article is part 1 of a short series.

1. Earth, Wind & Fire: The Evolution of an Innovation (1)
   'Earth': Natural ventilation and air-conditioning using the climate cascade
2. Earth, Wind & Fire: The Evolution of an Innovation (2)
   'Wind': Natural ventilation and energy using the roof
3. Earth, Wind & Fire: The Evolution of an Innovation(3)
   'Fire': Natural ventilation and energy using the solar chimney

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REHVA 2018 General Assembly

The 62nd REHVA General Assembly took place in Brussels, Belgium on the 22 April 2018. This year more than 50 participants from 28 countries attended the meeting. The President of ATIC, Joris Mampaey, which has hosted the REHVA Annual Meeting 2018, opened the works with a welcome speech. The General Assembly continued with the agenda, focusing on the general overview of REHVA activities in 2017 and on the key points of REHVA's 2018 activities.

The most relevant outcome of the General Assembly has been the election of the President-elect, **Frank Hovorka**, former REHVA Treasurer, whose mandate will start in 2019. Until now, Mr. Frank also contributes to research projects on net zero energy buildings and on financial indicators of buildings »green value« (RICS UNEP FI, IISBE and REHVA). Since September 2010, Frank Hovorka worked for the French group 'Caisee des Depots', where he was in charge of the real estate sustainability policy development. Currently he is working as Strategic director at Quartus.

During the whole REHVA Annual meeting, the main strategic issues were discussed also during the REHVA Member Associations plenary meeting, Advisory meeting between Past Presidents, Supporters Committee and the discussions on activity plan by REHVA Board of Directors, followed by a General Assembly. This year's annual meeting was also linked with the 80th Anniversary of ATIC, which was celebrated with a special Gala Dinner. ■

The new REHVA President-elect, Frank Hovorka.

REHVA professional awards and special awards at the 2018 REHVA Annual Meeting

The REHVA Professional awards 2018 took place during the REHVA Annual meeting on 21-23 of April in Brussels, Belgium. Professional awards were handed over during the Gala Dinner by the President of REHVA, **Stefano Corgnati**.

Serafin Grana (OEP-Portugal) received a REHVA professional award in design; **Ivan Chmúrny** (SSTP-Slovakia) received a REHVA professional award in education; **Bernd Pasterkamp** (VDI-Germany) and **Risto Kosonen** (FINVAC-Finland) received a REHVA professional award in technology and **Aleksandrs Zajacs** (AHGWTEL/LATVAC-Latvia) and **Tuomo Niemelä** (FINVAC-Finland) received a REHVA Young Scientist Award. All were recognized for their outstanding scientific achievements and for their contributions to improve energy efficiency and the indoor environment of buildings.

Serafin Grana (OEP Portugal)

Ivan Chmúrny (SSTP-Slovakia)

Bernd Pasterkamp (VDI-Germany)

Risto Kosonen (FINVAC-Finland)

Aleksandrs Zajacs (AHGWTEL/LATVAC-Latvia)

Tuomo Niemelä (FINVAC-Finland)

Jyri Luomakoski, Uponor CEO

SCANVAC award by Siru Lönnqvist to SWEGON Group

REHVA President Stefano Corgnati handed out two special awards to REHVA supporters. One of them to Uponor CEO, **Jyri Luomakoski** to celebrate the company's 100-years anniversary and acknowledge their longstanding collaboration with REHVA. Swegon Group Competence Director, **Mikael Börjesson** received 2 awards: one from REHVA as a tribute for being our committed supporter for more than a decade, and a second award from SCANVAC, represented by **Siru Lönnqvist**, who handed out a SCANVAC award for the Swegon Air Academy. ■

In Memoriam
Wim J. F. Oudijn

REHVA learned with sadness that former TVVL director Ing. W.J.F. Oudijn passed away on 28 February 2018 at the age of 93. Mr. Oudijn was appointed as General Secretary of TVVL in 1980 and from 1982 to 1990 held the position of director of the TVVL association. Mr Oudijn was involved in REHVA from 1981-1996 and has served as the first 'real' Secretary General of our association. REHVA honours his legacy with gratitude.

REHVA Student Competition 2018

During the REHVA Annual Meeting 2018, the REHVA 2018 Student Competition took place between 21-23 of April in Brussels, Belgium.

This year the twelve representatives from 10 different countries took a part at the competition. The Jury was composed by **Manuel Gameiro da Silva** (Portugal), **Uwe Schulz** (Switzerland), **Murat Çakan** (Turkey), **Dusan Petras** (Slovakia), **Milos Lain** (Czech Republic) and **Francis Allard**. After very intense deliberation, the jury declared winner **Kristian Martin** from Finland for his work on "*Demand Response of Heating and Ventilation within Educational Office Buildings*". The second prize was awarded to the Italian team, **Matteo Rodighiero** and **Matteo Naldi**. The third prize was awarded to **Alexandra Ene** and **Claudiu Stanciu** from Romania. Manuel Gameiro da Silva also thanked all contributors for their excellent work and emphasized the high quality of the works presented and the members of the jury for their excellent task.

The winner of REHVA Student competition 2018 Kristian Martin from Finland

Memorandum of Understanding between KIAEBS and REHVA

KIAEBS, the Korean Institute of Architectural Sustainable Environment and Building Systems, and REHVA the Federation of European Heating, Ventilation and Air-conditioning Associations have signed a Memorandum of Understanding (MoU) on Saturday, May 21st 2018.

This MoU was signed by REHVA President, Stefano Corgnati and KIAEBS representative Kwang Woo Kim in the name of KIAEBS President Seung-Yeong Song, during the REHVA Annual Meeting in Brussels, Belgium. REHVA and KIAEBS commit themselves to formalise their relationship by becoming member/supporter of each other's associations activities and aim to jointly increase contacts with the international institutions.

The official signature of MoU by REHVA and KIAEBS representatives.

REHVA

Federation of European Heating, Ventilation and Air Conditioning Associations

SUPPORTERS

LEADERS IN BUILDING SERVICES

Network of 27 European HVAC Associations
joining 120 000 professionals

REHVA Office: Rue Washington 40, 1050 Brussels - Belgium

Tel: + 32 2 514 11 71 - info@rehva.eu - www.rehva.eu

Send information of your event to Ms Chiara Girardi cg@rehva.eu

Events in 2018-2019

Exhibitions 2018

Sep 3–5	ISH Shangai & CIHE 2018	Shangai, China	https://ishs-cihe.hk.messefrankfurt.com/shanghai/en/visitors/welcome.html?nc
Oct 10–12	FinnBuild 2018	Helsinki, Finland	http://finnbuild.messukeskus.com/?lang=en
Oct 16–18	Chillventa	Nuremberg, Germany	https://www.chillventa.de/en
Nov 22–24	REFCOLD India 2018	Gandhinagar, India	http://www.refcoldindia.com/home

Exhibitions 2019

Feb 28 – Mar 2	ACREX 2019	Mumbai, India	http://www.acrex.in/home/

Conferences and seminars 2018

Jun 2–5	ROOMVENT & VENTILATION 2018	Espoo, Finland	http://www.roomventilation2018.org/
Jun 7–10	RCEPB International Conference	Bucharest, Romania	http://www.rcepb.ro/
Jun 25	1st BIM EPBD Conference "BIM and energy performance of buildings"	Brussels, Belgium	http://qualicheck-platform.eu/
Sep 11–12	Building Simulation and Optimization 2018	Cambridge, UK	https://www.bso2018.event.cam.ac.uk/
Sep 11–13	ENERGODOM 2018	Cracow, Poland	http://www.energodom.eu/
Sep 18–19	39th AIVC Conference: "Smart ventilation for buildings"	Juan-les-Pins, France	http://aivc2018conference.org/
Sep 25–27	Global District Energy Days	Helsinki, Finland	http://www.2018dedays.org/
Sep 25–28	Eurovent Summit 2018	Sevilla, Spain	https://eurovent-summit.eu/en/
Nov 12–13	REHVA Brussels Summit 2018	Brussels, Belgium	https://bit.ly/2IrswJR

Conferences and seminars 2019

May 26–29	CLIMA 2019	Bucharest, Romania	http://www.clima2019.org/congress/
Sep 5–7	IAQVEC 2019	Bari, Italy	https://www.iaqvec2019.org/

Getting ready for CLIMA 2019

The 13th REHVA World Congress, CLIMA 2019, will be held from 26th till 29th of May 2019 in Bucharest, Romania. The hosts are convinced that all CLIMA participants will be charmed by Bucharest urban diversity and kindness of its inhabitants.

Under the congress theme Built environment facing climate change, the 4 main topics of the 13th CLIMA Congress will highlight discussions around the capacity of new and existing refurbished buildings, and HVAC&S&R technical systems to mitigate climate change in an energy efficient manner while respecting the comfort and security requirements of occupants:

- Modern HVAC&R&S Technology and Indoor Environment Quality
- High Energy Performance and Sustainable Buildings
- Information and Communication Technologies (ICT) for the Intelligent Building Management
- Sustainable Urbanization and Energy System Integration

Expected figures of CLIMA 2019 congress:

- more than 100 CLIMA 2019 ambassadors and 50 partners promoting this event worldwide;
- more than 1000 attendees (researchers, engineers, architects, students, etc.)
- more than 750 papers (with a special care for the selection of those to be published in Scopus or Web of Science indexed journals);
- more than 20 technical and scientific workshops.

CLIMA 2019 sessions and side events

- Keynote sessions with notorious international speakers
- Scientific sessions with presentations on recent research findings
- Technical sessions with short technical communication on practical applications
- Workshops on concurrent and future challenges focusing on international possibilities for solving them
- Industry forums to discuss the major scientific questions and challenges in the industry
- An exhibition for sponsors and industry will be arranged in conjunction with the congress
- Technical Tours to research laboratories and certified green buildings in the area
- Student activities allowing future stars in the built environment field to discuss their interests and share their talents
- Training courses for HVAC&S&R professionals with leading experts during the congress sessions
- Social Program to experience Bucharest and neighborhoods

Submit your abstract

As a researcher, do not miss the opportunity to publish your paper at CLIMA 2019. **Abstract submission is open until the 1st of September 2018**, full paper submission will close on the 1st of November 2018.

Important notes to authors:

- all CLIMA 2019 articles will be published in proceedings indexed in main databases (Web of Science, EBSCO, ProQuest, Scopus, Google Scholar …)
- at least one author of each published article should attend to the conference
- a maximum of two articles per author is accepted without additional costs

Organise a workshop

The organizers offer the possibility to promote research and know-how by organising one of the 20 Workshops. The duration of a Workshop is 1.5–2 hours and may approach themes that are specific for the companies/ institutions/ associations or research groups. **Contact the organisers for more information**.

Become a sponsor

As an HVAC sector organization, you have the possibility to sponsor CLIMA and gain visibility in the European HVAC market. During CLIMA 2019, the organizers offer promotion services in three sponsorship levels: Diamond, Emerald and Ruby. Contact the organisers for more information.

You can find more details on the event website www.clima2019.org or ask for more information at our e-desk: info@clima2019.org.

Important dates and deadlines

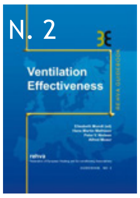
Third call for papers (abstracts + full papers)	July, 2018
Deadline for submission of abstracts	September 1st 2018
Deadline for full papers submission	November 1st 2018
Registration opening	December 1st 2018
Deadline for early registration	February 1st 2019
REHVA Annual Meeting	May 24-26 2019
REHVA World Congress CLIMA 2019 & Exhibition	May 26-29 2019
Additional social programme	May 29-31 2019

CLIMA 2019
Built environment facing climate change
REHVA 13th HVAC World Congress
26 - 29 May, Bucharest, Romania

REHVA GUIDEBOOKS

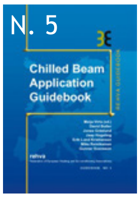
written by teams of European experts

REHVA Federation of European Heating, Ventilation and Air Conditioning Associations



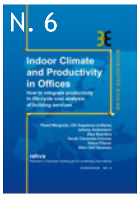
Ventilation Effectiveness

Improving the ventilation effectiveness allows the indoor air quality to be significantly enhanced without the need for higher air changes in the building, thereby avoiding the higher costs and energy consumption associated with increasing the ventilation rates. This Guidebook provides easy-to-understand descriptions of the indices used to measure the performance of a ventilation system and which indices to use in different cases.



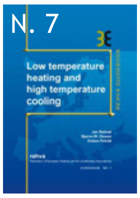
Chilled Beam Application Guidebook

Chilled beam systems are primarily used for cooling and ventilation in spaces, which appreciate good indoor environmental quality and individual space control. Active chilled beams are connected to the ventilation ductwork, high temperature cold water, and when desired, low temperature hot water system. Primary air supply induces room air to be recirculated through the heat exchanger of the chilled beam. In order to cool or heat the room either cold or warm water is cycled through the heat exchanger.



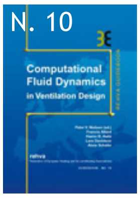
Indoor Climate and Productivity in Offices

This Guidebook shows how to quantify the effects of indoor environment on office work and also how to include these effects in the calculation of building costs. Such calculations have not been performed previously, because very little data has been available. The quantitative relationships presented in this Guidebook can be used to calculate the costs and benefits of running and operating the building.



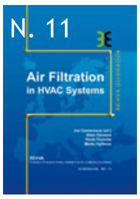
Low temperature heating and high temperature cooling

This Guidebook describes the systems that use water as heat-carrier and when the heat exchange within the conditioned space is more than 50% radiant. Embedded systems insulated from the main building structure (floor, wall and ceiling) are used in all types of buildings and work with heat carriers at low temperatures for heating and relatively high temperature for cooling.



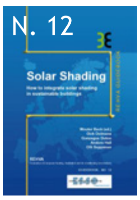
Computational Fluid Dynamics in Ventilation Design

CFD-calculations have been rapidly developed to a powerful tool for the analysis of air pollution distribution in various spaces. However, the user of CFD-calculation should be aware of the basic principles of calculations and specifically the boundary conditions. Computational Fluid Dynamics (CFD) – in Ventilation Design models is written by a working group of highly qualified international experts representing research, consulting and design.



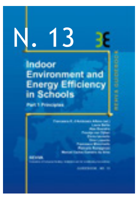
Air Filtration in HVAC systems

Air filtration Guidebook will help the designer and user to understand the background and criteria for air filtration, how to select air filters and avoid problems associated with hygienic and other conditions at operation of air filters. The selection of air filters is based on external conditions such as levels of existing pollutants, indoor air quality and energy efficiency requirements.



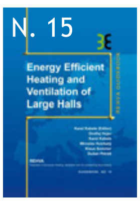
Solar Shading

Solar Shading Guidebook gives a solid background on the physics of solar radiation and its behaviour in window with solar shading systems. Major focus of the Guidebook is on the effect of solar shading in the use of energy for cooling, heating and lighting. The book gives also practical guidance for selection, installation and operation of solar shading as well as future trends in integration of HVAC-systems with solar control.



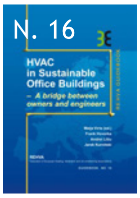
Indoor Environment and Energy Efficiency in Schools

School buildings represent a significant part of the building stock and also a noteworthy part of the total energy use. Indoor and Energy Efficiency in Schools Guidebook describes the optimal design and operation of schools with respect to low energy cost and performance of the students. It focuses particularly on energy efficient systems for a healthy indoor environment.



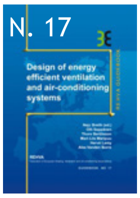
Energy Efficient Heating and Ventilation of Large Halls

This Guidebook is focused on modern methods for design, control and operation of energy efficient heating systems in large spaces and industrial halls. The book deals with thermal comfort, light and dark gas radiant heaters, panel radiant heating, floor heating and industrial air heating systems. Various heating systems are illustrated with case studies. Design principles, methods and modelling tools are presented for various systems.



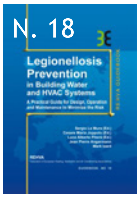
HVAC in Sustainable Office Buildings

This Guidebook talks about the interaction of sustainability and heating, ventilation and air-conditioning. HVAC technologies used in sustainable buildings are described. This book also provides a list of questions to be asked in various phrases of building's life time. Different case studies of sustainable office buildings are presented.



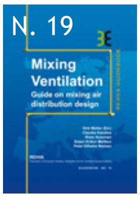
Design of energy efficient ventilation and air-conditioning systems

This Guidebook covers numerous system components of ventilation and air-conditioning systems and shows how they can be improved by applying the latest technology products. Special attention is paid to details, which are often overlooked in the daily design practice, resulting in poor performance of high quality products once they are installed in the building system.



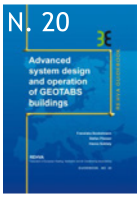
Legionellosis Prevention in Building Water and HVAC Systems

This Guidebook is a practical guide for design, operation and maintenance to minimize the risk of legionella in building water and HVAC systems. It is divided into several themes such as: Air conditioning of the air (by water-humidification), Production of hot water for washing (fundamentally but not only hot water for washing) and Evaporative cooling tower.



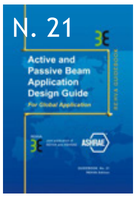
Mixing Ventilation

In this Guidebook most of the known and used in practice methods for achieving mixing air distribution are discussed. Mixing ventilation has been applied to many different spaces providing fresh air and thermal comfort to the occupants. Today, a design engineer can choose from large selection of air diffusers and exhaust openings.



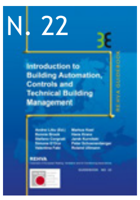
Advanced system design and operation of GEOTABS buildings

This guidebook provides comprehensive information on GEOTABS systems. It is intended to support building owners, architects and engineers in an early design stage showing how GEOTABS can be integrated into their building concepts. It also gives many helpful advices from experienced engineers that have designed, built and run GEOTABS systems.



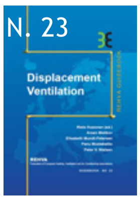
Active and Passive Beam Application Design Guide

This Guidebook is the result of collaboration by worldwide experts. It provides energy-efficient methods of cooling, heating, and ventilating indoor areas, especially spaces that require individual zone control and where internal moisture loads are moderate. This publication provides up-to-date tools and advice for designing, commissioning, and operating chilled-beam systems to achieve a determined indoor climate and includes examples of active and passive beam calculations and selections.



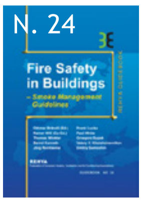
Introduction to Building Automation, Controls and Technical Building Management

This Guidebook provides an overview on the different aspects of building automation, controls and technical building management and steer the direction to further in depth information on specific issues, thus increasing the readers' awareness and knowledge on this essential piece of the construction sector puzzle. It focuses on collecting and complementing existing resources on this topic in the attempt of offering a one-stop guide.



Displacement Ventilation

The aim of this Guidebook is to give the state-of-the art knowledge of the displacement ventilation technology, and to simplify and improve the practical design procedure. The Guidebook discusses methods of total volume ventilation by mixing ventilation and displacement ventilation and it gives insight of the performance of the displacement ventilation. It also shows practical case studies in some typical applications and the latest research findings to create good local micro-climatic conditions.



Fire safety in buildings. Somke Management Guidelines

This guidebook describes the different principles of smoke prevention and their practical implementation by way of natural and mechanical smoke extraction systems, smoke control by pressurization systems and appropriate partition measures.

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