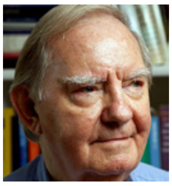
This article is follow-up part of the article published in REHVA Journal 2018-02 "Natural air conditioning: What are we waiting for?"

Earth, Wind & Fire:
The Evolution of an Innovation (1)
– 'Earth': Natural ventilation and air-conditioning using the climate cascade



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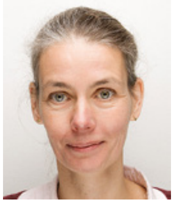

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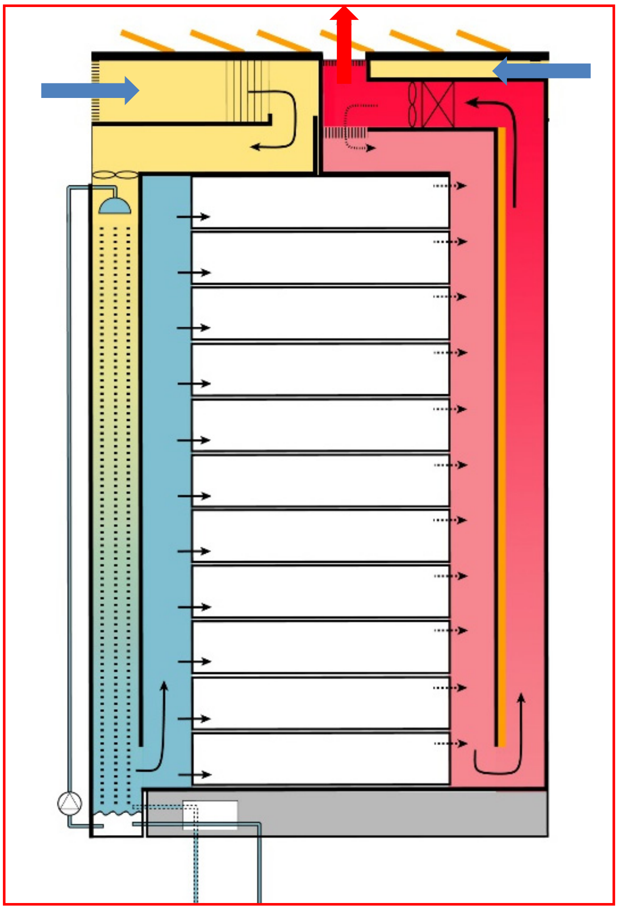
The climate cascade is a gravity-driven heat exchanger for conditioning ventilation air. It is installed in a structural shaft in a building. In the climate cascade, the ventilation air is cooled or heated and dried or humidified as required. In summer and winter, water of approx. 13°C is sprayed at 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/SBR[1] 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 LMTD[2] 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/

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[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).

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[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 avoided[4]. 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.

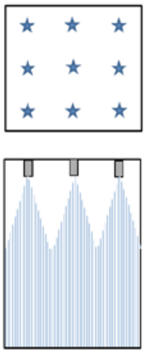

Figure 1. Basic design Climate Cascade.

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.

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.

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

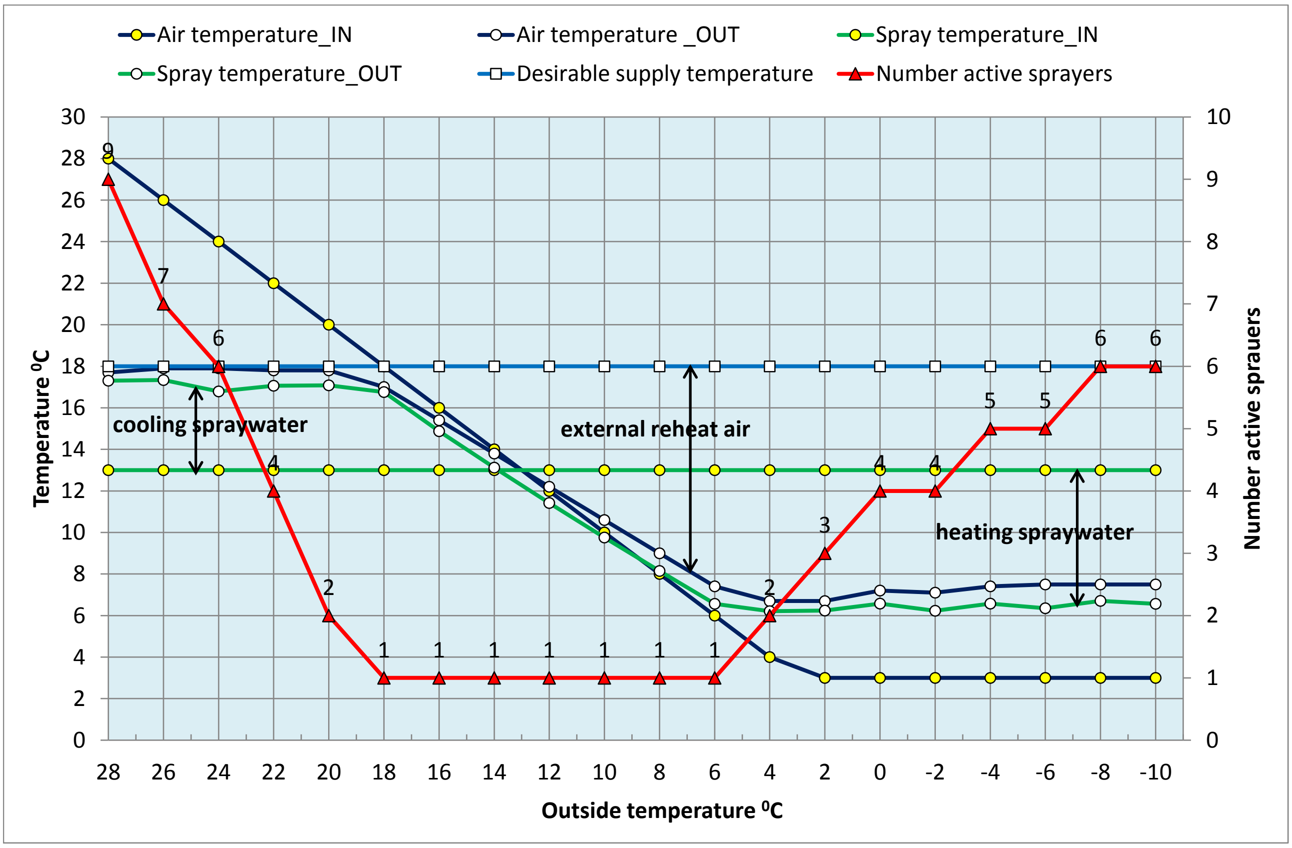

Figure 2. Temperatures in the climate cascade as a function of the outdoor temperature and number of active spray nozzles.

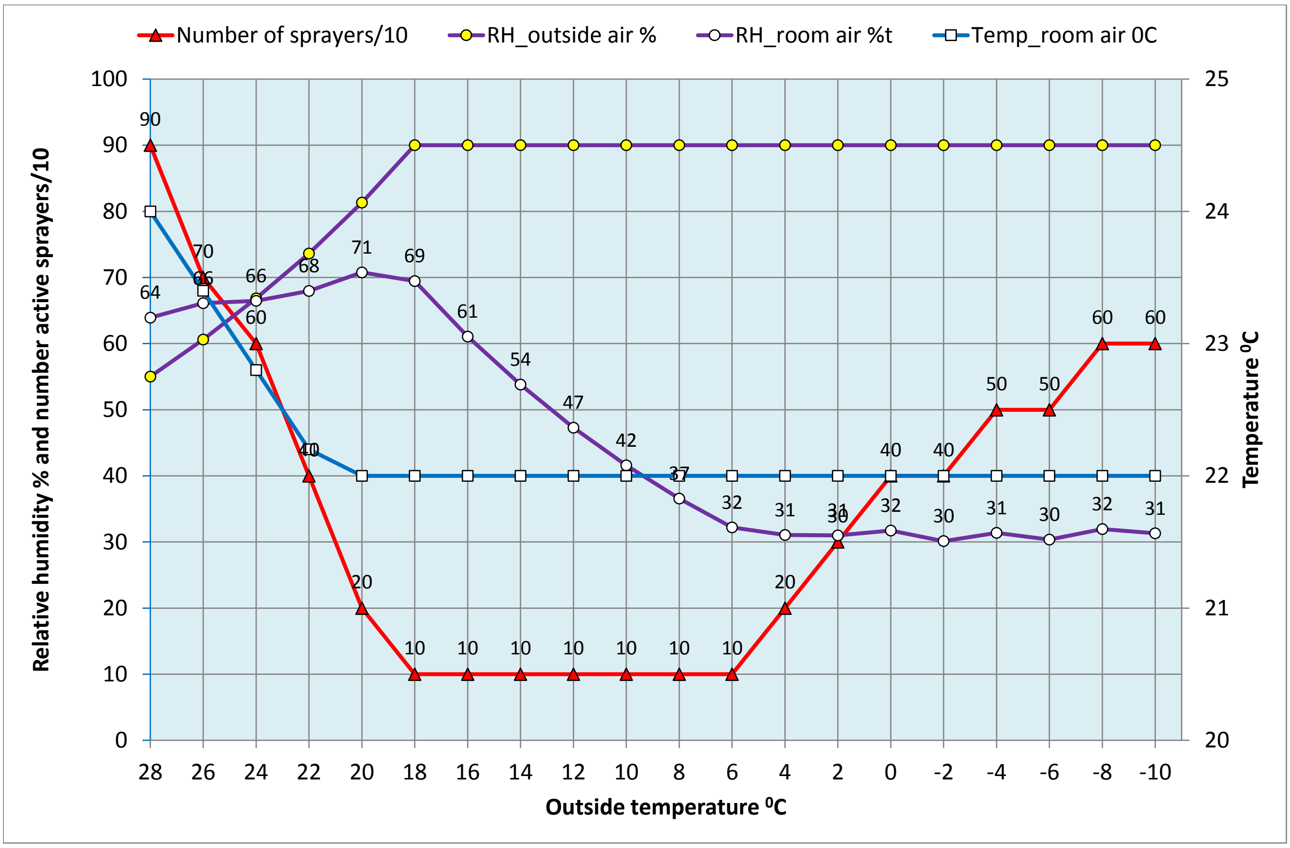

Figure 3. Relative humidity and the number of active spray nozzles as a function of the outdoor temperature.

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 $\theta_e = 28°C$ 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

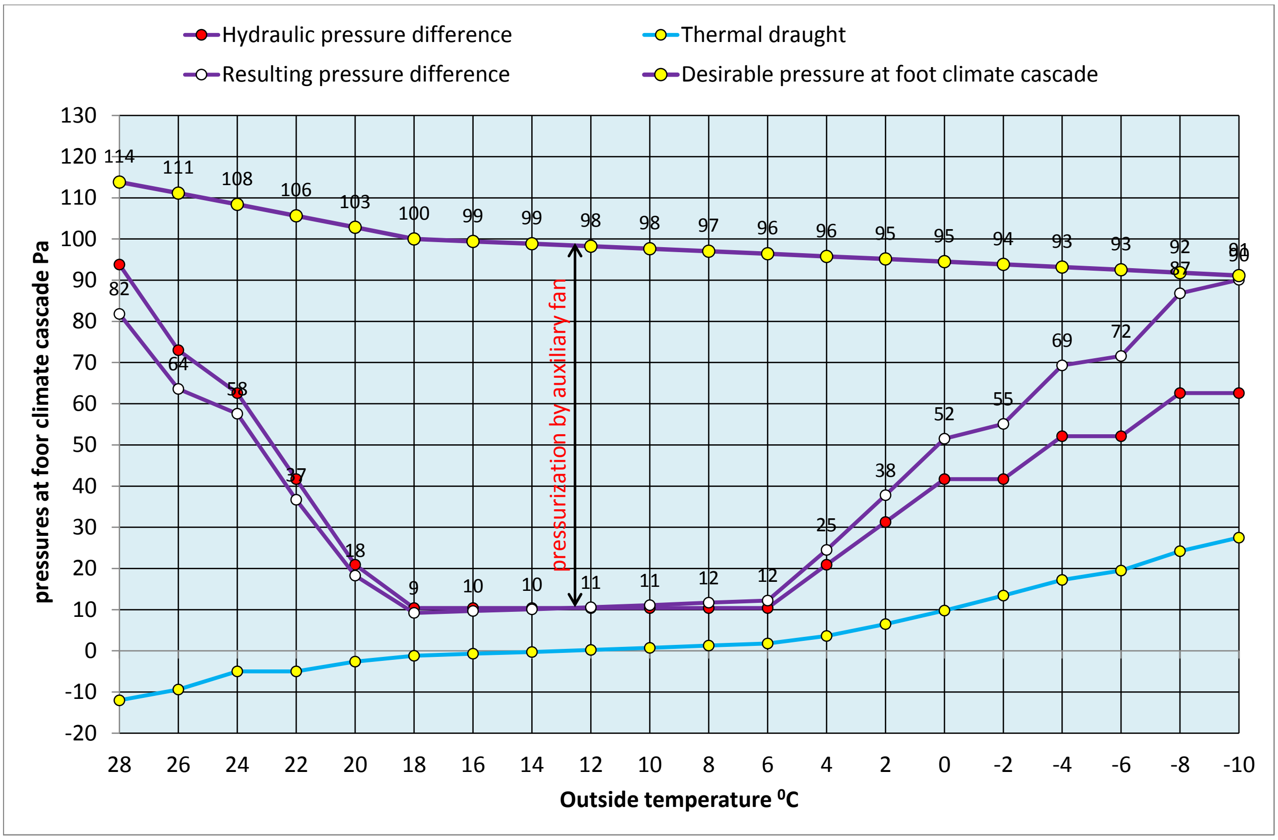

Figure 4. Pressure build-up in the climate cascade as a function of the outdoor temperature.

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	

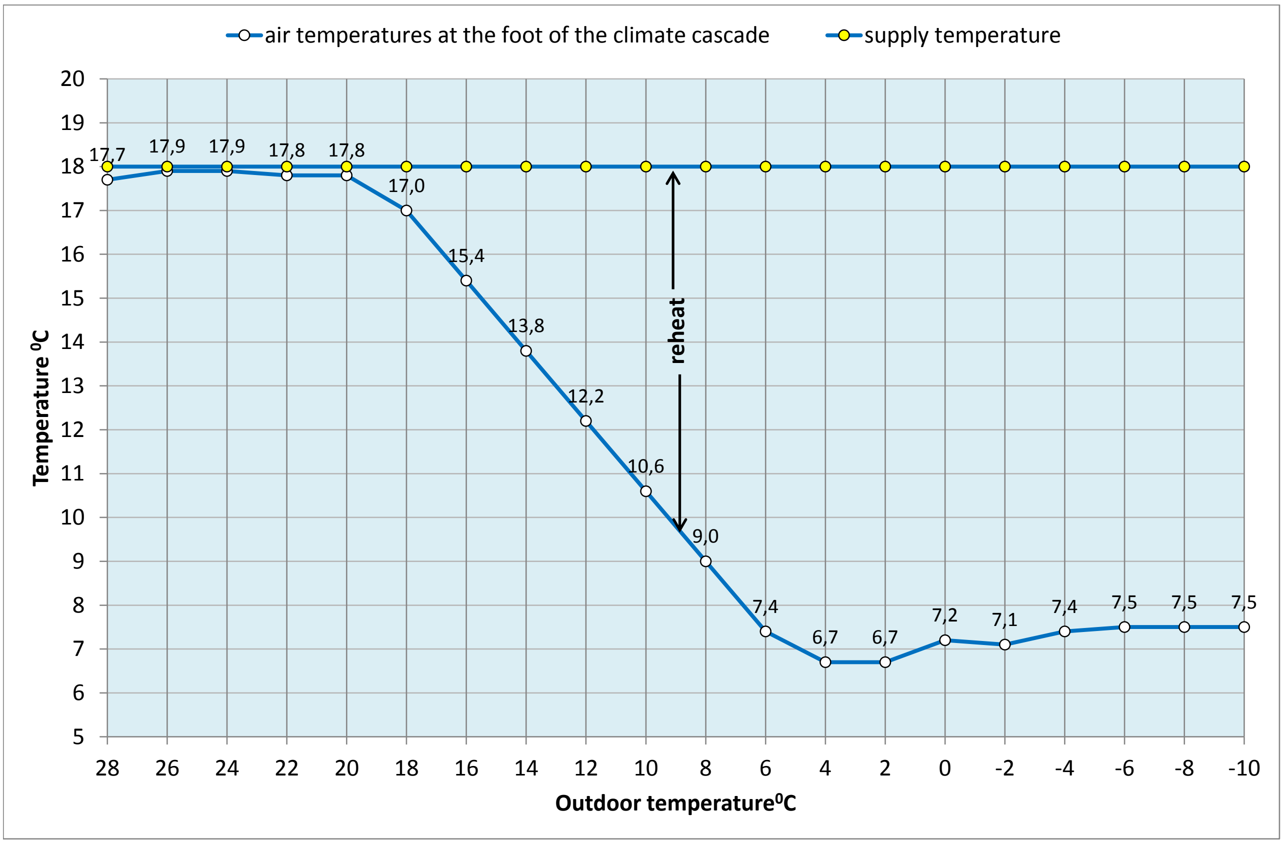

Figure 5. Air temperatures as a function of the outdoor temperature.

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 $6.3 \times 6/9 = 4.2\ kg.s^{-1}$, 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

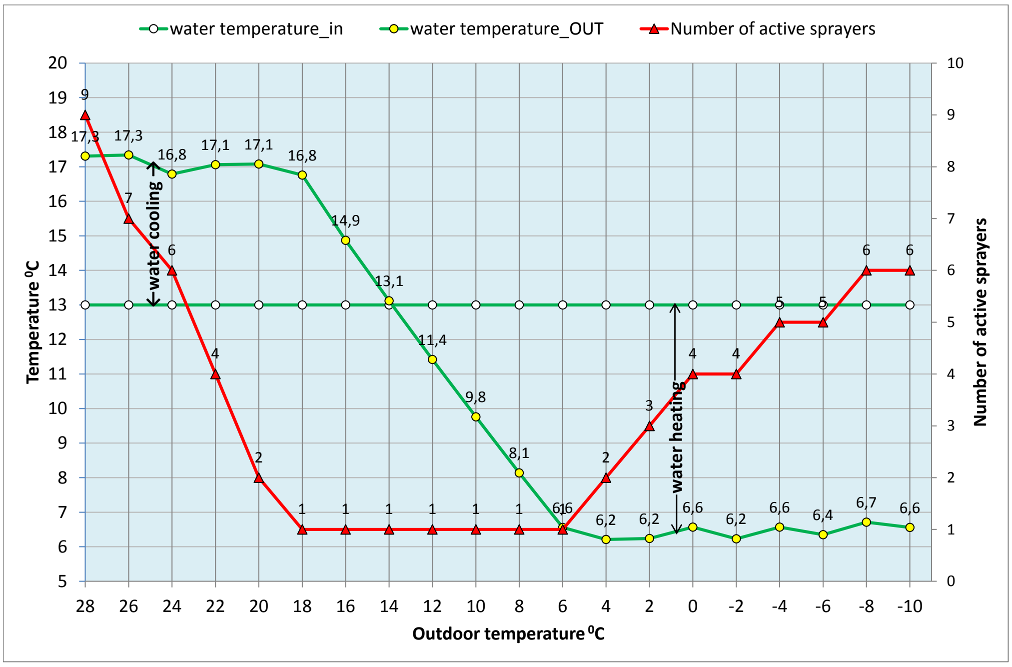

Figure 6. Water temperatures as a function of the outdoor temperature.

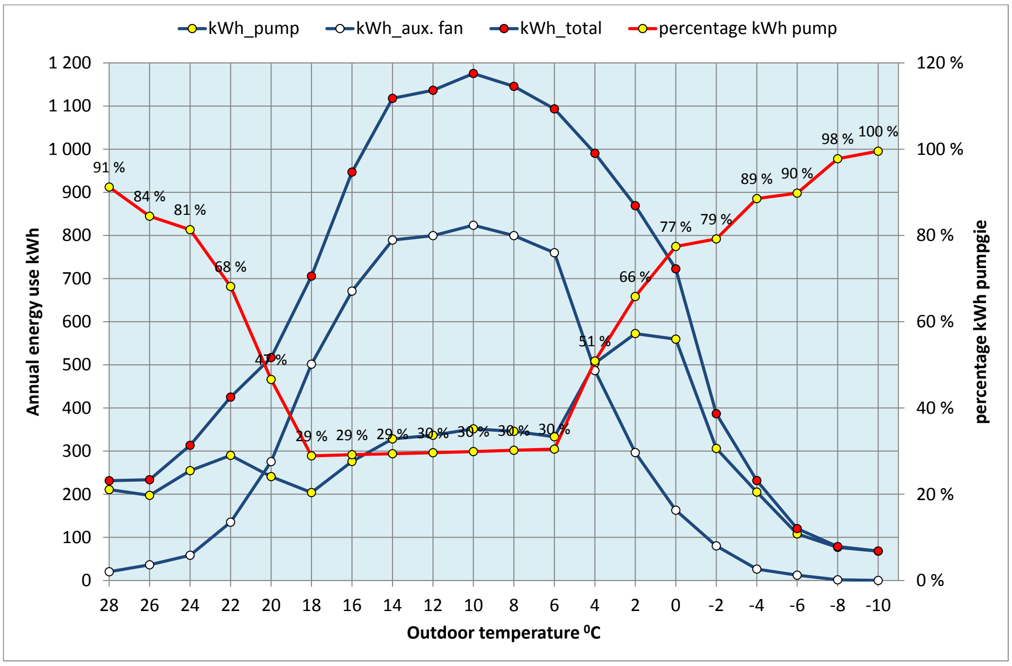

Figure 7. Annual energy consumption for air transport distributive.

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.($m^3.s^{-1}$)$^{-1}$, based on a flow rate of 25,000 $m^3.h^{-1}$ 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**.

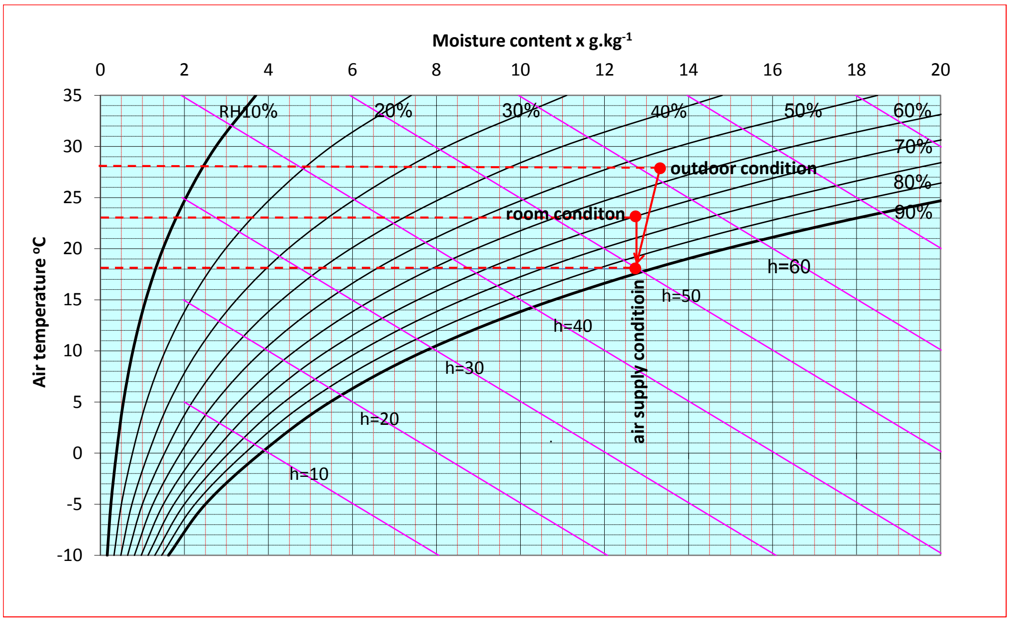

Figure 8. Design summer conditions -28°C/55% RH.

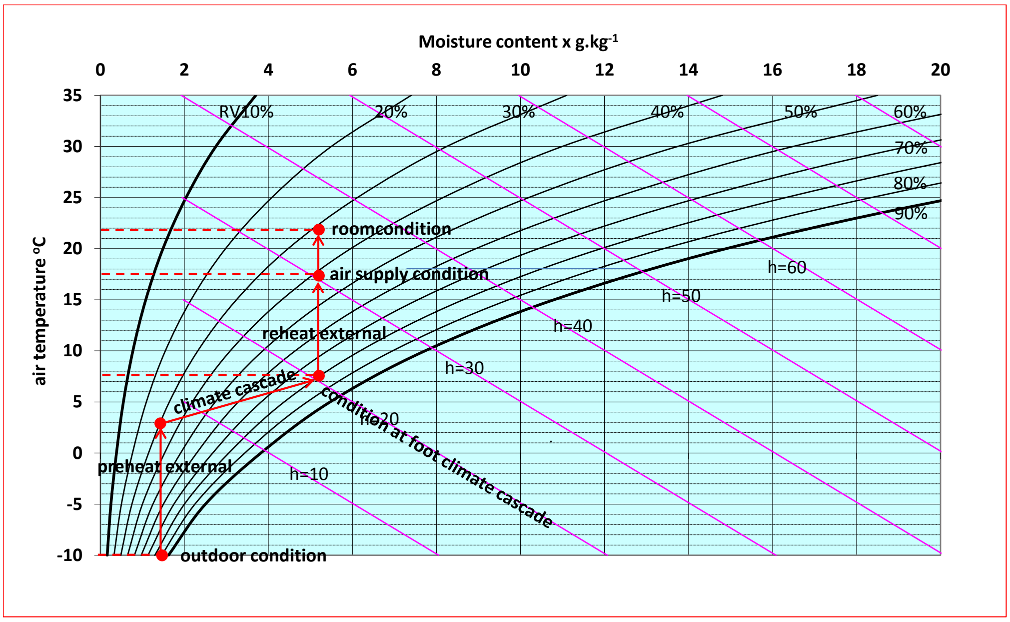

Figure 9. Design winter conditions -10°C/90% RH.

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. ■

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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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