Cooling of schools – results from a demonstration project using adiabatic evaporative cooling with harvested rainwater

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Abstract. This paper reports on a demonstration project where a section of a school building with eight classrooms and three other rooms was retrofitted with a mechanical balanced ventilation system with an integrated evaporative cooling unit. The floor area was 537 m². Especially in temperate climates, evaporative cooling has unreleased potential as an alternative solution to conventional cooling technologies, and by combining it with harvesting of rainwater, the solution aligns well with a future with higher cooling needs, need for climate adaptation, and the overall sustainability agenda. The cooling unit works by storing, filtering and spraying rainwater into the return air. The water evaporates, cools the return air, and through an innovative corrosion-resilient plastic heat exchanger, the return air then absorbs heat from the supply air. In this way indoor climate problems caused by humidification of the indoor air are avoided. The demonstration was running in the May and June 2019. The results show that the specific fan power increased approx. 500 J/m³ when the evaporative cooling pumps were activated and that the available cooling power – depending on the moisture content of the return air – was fluctuating in the range 20-30 W/m². The peak rainwater consumption was approx. 1 m³/day. The results show that implementation of evaporative cooling with harvested rainwater is an attractive and sustainable alternative to mechanical compressor cooling.

1 Introduction

The indoor environment is one of the main factors that determines building functionality and economics. Good indoor environment in buildings affects occupants; and many studies have proven that excess heat negatively affects the health, well-being and productivity of people. Too high temperatures affect the performance because warmth lowers arousal, exacerbates sick building syndrome (SBS) symptoms, distracts attention and generates complains [1]. In schools, a reduction of indoor air temperatures above 22°C by 1°C can increase the performance of pupils by 0.5-2% [2-3].

Thus, it can be foreseen that indoor climate in schools and other educational buildings will receive increased attention, which in turn will increase the ventilation and cooling demand. Such demands are costly to achieve with mechanical cooling solutions without violating international, national and local energy efficiency targets. Furthermore, mechanical cooling is counter-productive considering the EU-induced step-down phase out of synthetic refrigerants in the EU. Replacing the synthetic refrigerants with natural refrigerants like ammonia, isobutane, CO₂ or ground water is possible but often too costly for smaller scale cooling plants.

Adiabatic cooling is the humidification of air under adiabatic conditions, which means that heat energy is neither added nor removed from the system [4]. The

process occurs when the supply air is humidified, so the heat required for water evaporation is taken from the air. Consequently air temperature decreases, but moisture content increases. This is referred to in the literature as direct evaporative cooling (DEC). To avoid increased water content in the primary (supply) air, a combination of heat exchange and humidification of the return air may be used. This is referred to as indirect evaporative cooling (IEC).

In general there is a multitude of methods and technologies in evaporative cooling [5]. There is also many numerical and experimental investigations reported in the literature [6-9], but much of the development is focused on dry climates where the cooling potential is less bounded by the humidity of the ambient air. There is less work published of real scale demonstrations in temperate climates [10-11] and the uptake of evaporative technologies is limited to very specific applications, e.g. data centers [9].

In dry climates, the water sources are not abundantly available. However, in temperate climates, the water sources are usually not the limiting factor. Rainwater – in comparison with ground water – contains low level of salt/calcium carbonate so the use of rainwater instead of ground water provides considerable maintenance savings, because there is no need for desalination and/or decalcification. Additionally, rainwater is “borrowed” for a short time from the natural water cycle of

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precipitation/evaporation and saves both tap water costs and waste water drainage costs. The temperate climate of Denmark is characterized by having the highest rainfall during spring and summer periods when the need for cooling in the buildings is the highest.

The main objective of the project was to evaluate the potential for adiabatic cooling with rainwater in public buildings in Danish temperate climatic conditions regarding system implementation, energy consumption, cooling capacity and water consumption. Most of the results reported in this paper are also published in the project's final report [12].

2 Methods

2.1. Test case building

An adiabatic cooling system with rainwater harvesting was established in Solbjerg school located in Aarhus, Denmark. The adiabatic air handling unit (AHU) was installed to service the top floor of section D of the school (Fig. 1) - 8 classrooms along the Southeast façade and three smaller rooms (Fig. 3). The dimensions of the bigger classrooms are 6.4 x 7.8 x 2.9 m, the smaller ones 6.4 x 7.0 x 2.9 m. The total ventilated floor area (excluding the corridor) is 537 m².

Two main ducts installed in the attic distributes ventilation air to each room and supplies the air to the room by diffuse ceiling ventilation. The ceiling is made from cement-bonded wood fiber boards. Exhaust is through a ducted diffuser. Variable-air-volume dampers control air supply to each room; the exhaust dampers run as slaves. The dampers are controlled by CO₂ and temperature setpoints of 800 ppm and 23°C, respectively. If either setpoint is exceeded, the dampers will open from 20% to 100%.

Fig. 1. Southeast facade of section D of the school

The classrooms are equipped with large windows facing Southeast with Microshades [13] mounted in between the panes as solar shading. The Microshades are made from thin metal sheets with tiny perforations, in effect creating a shade from the direct sun similar to an overhang. However, the solar radiation is then absorbed in the glazing, causing the windows to act as vertical radiant heating panels.

2.2. Adiabatic air handling unit

A new adiabatic cooling unit – Adconair adiabatic zero GWP produced by Menerga – was installed.

The cooling system can run in different modes dependent on the amount of cooling needed and it can utilize the by-pass of the heat exchanger at any point in time if needed. During normal cooling loads the system runs like a simple IEC as described above and shown in Fig. 2(a). In this mode the outdoor air (OA) flows through a dry channel where heat is transferred to a wet channel with cooler air. The cooled air is the return air (RA) from the classrooms. The return air is sprayed with water and humidified to almost 100% saturation, which leads to its cooling to around the wet bulb temperature of the return air. The wet bulb temperature denotes the lowest temperature the air can achieve by water evaporation only. The cooled return air then flows through the heat exchanger receiving the heat from the warmer outdoor air. Afterwards the warmer return air is exhausted to the outside (EA) and the cooled outside air is supplied to the classrooms (SA).

(a) Solbjerg system running as a standard adiabatic IEC

(b) Extra supply air is extracted and used in the adiabatic loop to cool the return air

Fig. 2. Adconair adiabatic zero GWP at Solbjerg school

During the humidification process the return air is cooled to achieve the supply air setpoint. However, in some cases the wet-bulb temperature will be higher than the supply air setpoint resulting in the system turning on the second mode – Fig. 2(b). In this second mode the plant recirculates part of the cooled supply air – now with lower air temperature – and mix it with the return air, to achieve a lower wet-bulb temperature of the return air. This is often referred to as regenerative indirect evaporative cooling, R-IEC [4]. The temperature of the rainwater has only negligible influence on the performance as the energy embedded in the vaporization is approx. 50 times higher.

Fig. 3. Section D of the school with 8 classrooms (room 11-18) and three smaller meeting rooms

2.3. Cooling capacity

The total cooling capacity E_{tot} depends on the temperature difference between room temperature and supply air temperature (for ease, the average temperature of the classrooms is represented by the mass-averaged return air).

$$E_{tot} = \dot{V} \rho c_p (T_{exh} - T_{sup}) \quad (1)$$

The total cooling capacity consists of ventilative and adiabatic parts. The ventilative part comes from the outdoor air being colder than the exhaust air. In a Danish summer climate, this is often the case, but the ventilative cooling is not necessarily enough to cool the classrooms; for that the supply air should be even lower than the outdoor air. The latter is possible by cooling the supply air through adiabatic evaporation. The adiabatic cooling part E_{ad} comes from the temperature change of the supply air when the air passes through the AHU when the adiabatic system is active:

$$E_{ad} = \dot{V} \rho c_p (T_{out} - T_{sup}) \quad (2)$$

The ventilative cooling part E_{vent} is the difference between E_{tot} and E_{ad} :

$$E_{vent} = E_{tot} - E_{ad} \quad (3)$$

2.4 Harvesting rainwater

Rainwater from the roof was collected in the existing gutters fixed along the roof and routed in a pipe system to an underground rainwater storage tank of 10 m³. From the storage tank it was pumped through a coarse and a fine filter to a small water reservoir ("day water tank") that fed the adiabatic cooling unit. A water meter installed on the pipe leading to the heat exchanger registered the amount of rainwater use for cooling. UV disinfection was installed as a safety precaution on the day water tank to eliminate possible bacterial contamination. To ensure the possibility of using adiabatic cooling also in drought periods without precipitation as experienced in spring and summer 2018, additional supply of tap water was implemented with a reverse osmosis plant to remove

minerals. The osmosis plant constitutes an additional cost which ideally should be balanced with operation safety margins (schools are less critical infrastructures), expected drought periods in that particular location and cost of oversizing the storage tank. This is not further analysed in this paper.

The rainwater catchment surface is the roof over section D, approx. 800 m². With a run-off coefficient of 0.8, a rainfall of 15 mm will fill the tank. The run-off coefficient describes the losses due to evaporation, overflow, splashes and leakage. It is usually set to 0.8 [13]. From the boxplot in Fig. 4, it is clear that the monthly precipitation is at least 25 mm in 3 out of 4 years (75% fractile). From Fig. 5 the duration of a dry period is less than 11 days in 3 out of 4 years (disregarding the holiday month of July). There have been dry periods of extreme duration and for this reason the rainwater is supplemented with tap water through reverse osmosis in these periods.

Fig. 4. Precipitation statistics for Solbjerg location 2001-2015. Boxes denote 25-75% fractiles. Whiskers denote min/max

Fig. 5. Occurrences of dry periods for Solbjerg location 2001-2015

Fig. 6. Ventilation air flow rate, main supply and return. May and June 2019. The periods of active cooling is also illustrated.

2.5 Measuring equipment

In order to experimentally verify the performance of the system, measurements were carried out in the adiabatic AHU. To identify the system capabilities, energy meters were installed in the adiabatic cooling system. In order to check the efficiency of exhaust air humidification, air temperature and humidity sensors in outside air, supply air to the rooms, return air from the rooms and exhausted air were connected to BMS and logged. In each classroom also PIR, temperature, CO₂ and window opening sensors are used as input to the BMS and logged. For the project an wireless IC-meter sensor box measuring CO₂, temperature, relative humidity and noise was placed in each of the 8 classrooms, making it possible to compare indoor climate before and after implementation of the new ventilation system.

3 Results and Discussion

3.1 Ventilation flow rate

The ventilation supply airflow is fixed pressure-controlled and return flow is running as slave. This means that when the classroom-mounted dampers are activated, the AHU responds to dropping pressure, and increases the airflow rate when either CO₂ or temperature setpoint is exceeded. This causes the overall airflow rate to increase from approx. 8000 to 11000 m³/h. This is depicted in Fig. 6, where it is also possible to see how the AHU increases the overall airflow rate (first week of June) before the cooling unit is activated. The adiabatic unit was active every day the last week of June.

3.2 Thermal comfort

The overall objective of the cooling system is to provide better thermal comfort to the pupils in the classrooms. Fig. 7 illustrates the indoor temperature in the 8 classrooms from the month of June in 2017 and 2019. The year 2018 was disregarded because the ventilation system was serviced several times and the measurements uncertain. In

order to make the years comparable, the indoor temperatures of each year are divided with the outdoor temperature the same year. We deem this simplified approach acceptable in a Danish context because the outdoor temperature correlates well with the solar radiation. Thus, this normalization method illustrates that the indoor temperatures of 2019 was significantly lower than in 2017. In overall, the mean temperature in June 2019 was 23.4°C±1.2.

Fig. 7. Normalized indoor temperatures from 2017 (orange) and 2019 (blue).

3.3 Cooling power

The cooling power is partly ventilative and partly adiabatic as explained in Section 2.3.

Fig. 8. illustrates the operation of the AHU throughout a week in June. It shows how the supply air temperature drops approx. 5°C below the outdoor temperature when the adiabatic cooling is activated and it shows how the adiabatic cooling unit increases the total cooling when it is activated. The adiabatic cooling power amounts to approx. 20-30 W/m² in the figure. Depending on the outdoor temperature, ventilative cooling adds most days additional cooling of 10-15 W/m².

It is seen in Fig. 8 that the night ventilation is activated every morning for a few hours to bring the indoor temperature (exhaust air) down. Then outdoor temperature rises. When return temperature reaches setpoint of 23°C, the adiabatic systems is activated, forcing the supply temperature down to follow the wet bulb temperature of the return air by a small offset.

Fig. 8. Supply, outdoor (intake) and exhaust air temperatures and cooling capacity of the system during the warmest working days 24-28th of June 2019

The total cooling power as well as the adiabatic part of the total cooling are summed up Fig. 9. In the month of June, adiabatic cooling ratio of the total supplied cooling was 29%, and in the warmest week, it was 44%.

Fig. 9. Ratio of ventilative and adiabatic cooling for the whole June 2019 and for five warmest working days 24-28th of June.

3.3 Water consumption

For the whole summer of 2019, approx. 24 m³ of water was used. During the warmest week of June, the accumulated usage was 5 m³, meaning that the consumption is approx. 1 m³/day when the adiabatic system is running at maximum capacity (Fig. 10).

Fig. 10. Daily water consumption by adiabatic system during peak load 24-28th of June 2019

3.4 Energy consumption

To calculate the efficiency of the total system, the specific fan power for the month of May and June is depicted in Fig. 11. The SFP from May, which was completely without adiabatic cooling, is approx. 1300 J/m³, rising to approx. 1800-1900 J/m³ in the last week of June, where the adiabatic system was active every school day. This means the cooling unit causes SFP to increase by approx. 500 J/m³.

Fig. 11. Average daily specific fan power in May and June 2019

Fig. 12. Energy consumption for ventilation, rainwater pump and reverse osmosis system for May (cooling inactive) and June (cooling active)

The combined ventilation and cooling system installed in the school consumed electrical energy in the AHU fans,

the adiabatic spraying pumps, the rainwater pump and the reverse osmosis plant. The energy consumption of these components are illustrated for May and June 2019 as well as the typical working weeks in Fig. 12. The energy difference between the week in May and the week in June is due to the internal spraying pumps in the adiabatic cooling unit. The reverse osmosis plant runs scheduled tests every day independent of the operation of the adiabatic cooling system. The daily consumption for the tests is approx. 0.25 kWh. The volume of the rainwater storage tank was big enough to avoid using tap water for cooling for the whole month of June 2019.

Table 1. Cooling electricity usage for one week

	Electricity consumption	Comment
Week May 20-24	0.22 kWh/m ²	Only fans active
Week June 24-28	0.52 kWh/m ²	Fans and IEC active
Difference	0.30 kWh/m ²	Extra electricity usage for IEC
IEC electricity 20 weeks	6.0 kWh/m ²	IEC running 20 weeks
Compressor cooling 20 weeks	4.5 kWh/m ²	Average COP = 3

The extra cooling electricity consumption from Fig. 12 is summed up in Table 1. The weeks of May and June are used as reference to calculate the expected yearly electricity usage for cooling. This estimate is very preliminary because it assumes the adiabatic cooling to be fully active for 20 weeks between May-Sept. However, the table values may be used for comparison with mechanical compressor cooling system. Assuming the cooling load for the warmest week in June (1.5 kWh/m², Fig. 9) represents the cooling load for 20 weeks in May-Sept, the adiabatic system removes approx. 45% of the cooling load. This corresponds to 0.68 kWh/m² per week. To remove this using a mechanical compressor system with a COP of 3, it will use 4.5 kWh/m² electricity in 20 weeks.

4 Conclusion

The main conclusion from the present project is that the adiabatic cooling capacity is 20-30 W/m² in a Danish climate. The results from the project showed that the indoor temperature in the classrooms was significantly lower due to the mechanical ventilation and adiabatic cooling unit. The system demonstrated in here is also applicable to other public or commercial buildings with similar ratio between internal moisture production and airflow rate, i.e. this is valid for airflow rates designed for approx. CO₂ 1000 ppm. The cooling electricity usage is on par with conventional compressor cooling due to the high pressure of the spraying pumps in the adiabatic cooling unit. In total, the incurred costs amount to the

adiabatic AHU, the underground storage tank connected to the rainwater gutter, the day water tank, UV-filter and osmosis plant. This installation was not economically competitive to an AHU with built-in chiller. However, the global warming potential of the adiabatic system is much smaller, because no potent cooling refrigerants are used. This calls for a more thorough investigation of total costs, life-cycle assessment, and other benefits of adiabatic cooling in temperate climates.

This research was conducted as part of ELFORSK grant 349-061. The authors wish to extend their gratitude to the evaluation committee of ELFORSK and compliment the drive and skills of Menerga A/S and Aarhus Kommune and the good human resources at Solbjerg School.

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