Façade design for the Solar Decathlon 2012

Is an adaptive façade able to cool adiabatically?

Jeroen Egberts
Delft, 24 June 2011
Faculty of Architecture
Building Technology

ŤUDelft Delft University of Technology

Façade design for the Solar Decathlon 2012

Master track Building Technology "Façade Design"

Author:	Jeroen Egberts Student number: 1549553 J.E.M.Egberts@student.tudelft.nl
Main mentor:	Dipl. Ing. M. Bilow Building Technology "Façade Design" M.Bilow@tudelft.nl
Second mentor:	Dr. Ir. A. van Timmeren Green Building Innovation "Product Development & Sustainability" A.vanTimmeren@tudelft.nl
Third mentor:	Dipl. Ing. F. Heinzelmann Building Technology "Integrations and Coordination of constructions" F.Heinzelmann@tudelft.nl
Commissioner:	Sjoerd W. Bijleveld Building Economics S.W.Bijleveld@tudelft.nl

Preface

This document present the Master thesis report of Jeroen Egberts, student building technology at the Faculty Architecture of the Technical University Delft. This Master thesis is related and researched for the Solar Decathlon team of the Technical University which is participating in the Solar Decathlon competition of 2012.

Thanks to Marcello Bilow, Arjan van Timmeren, Florian Heinzelmann, Willem van der Spoel, Martin Tenpierik and John van der Vliet.

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1. INTRODUCTION

1.1 Introduction

The worldwide population (population of human people on earth) is growing yearly. In 2009 the population growth rate was 1,12%, this is a growth of 76.101.949 people over the total world population. In most major areas the increase of percentage of population growth is shrinking, but even the estimations for the future the world population will increase. In 1950 the measured world population was 2.5 billion, in 2000 this is more than doubled to 6 billion people. If the estimations of the United Nations are right the world population will increase in 2050 with more than 9 billion people on planet earth.[1]
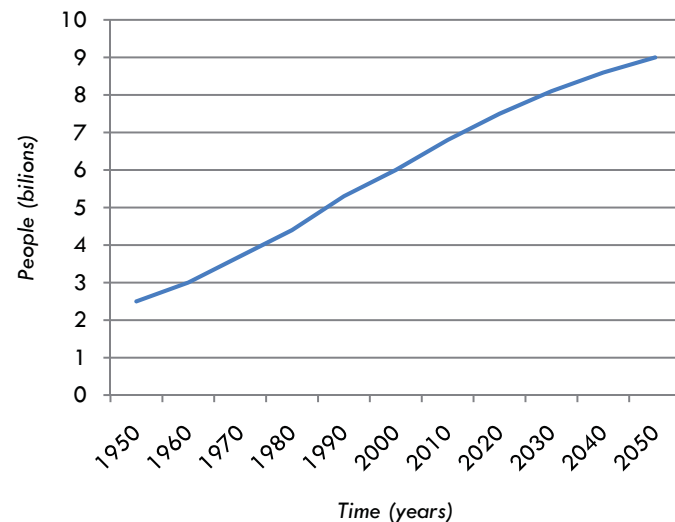
Fig. 01 Worldwide population (human people on earth)

Also the energy demands world-wide rise yearly[2] (fig 2), estimations shows a further grow of the energy consumption in the future. Europe and North America are next to Asia the leading continental in terms of energy consumption (fig 3).[3]
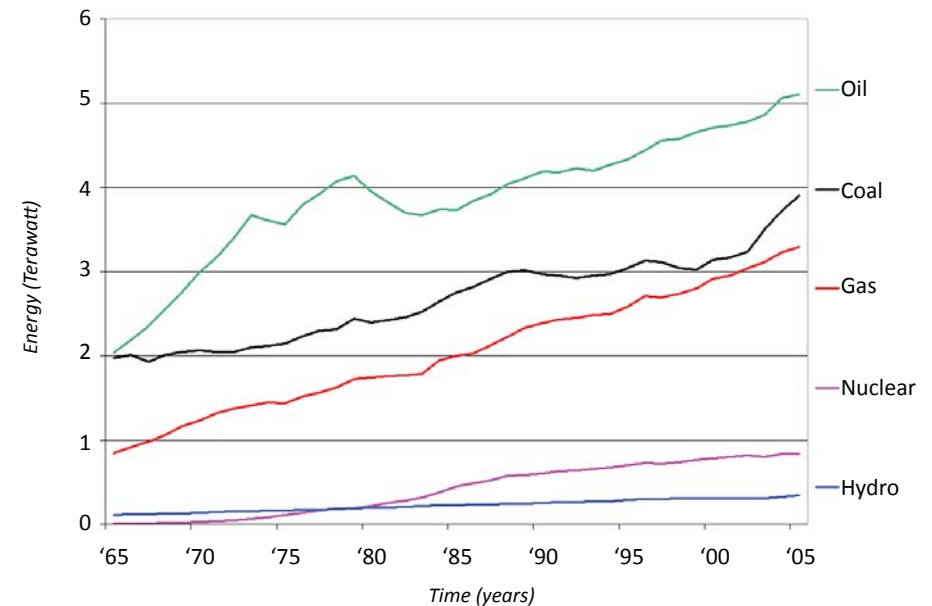
Fig. 02 World energy consumption
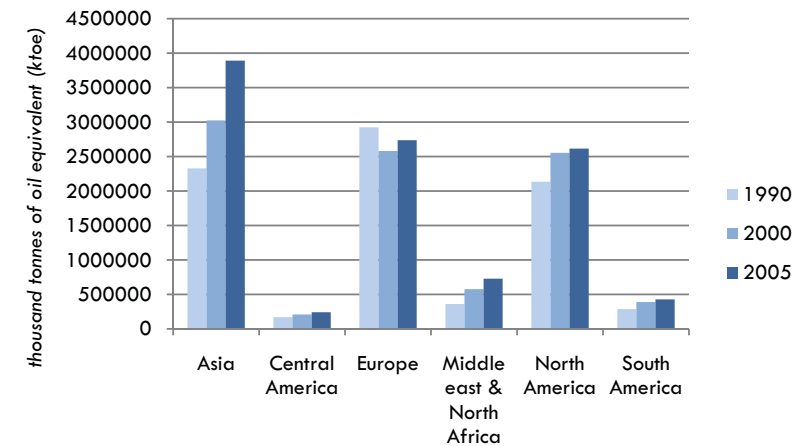
Fig. 03 All primary source of energy consumption

1 (Nations, 2004)

2 (Wikipedia, 2007)

3 (World Research Institute , 2007)
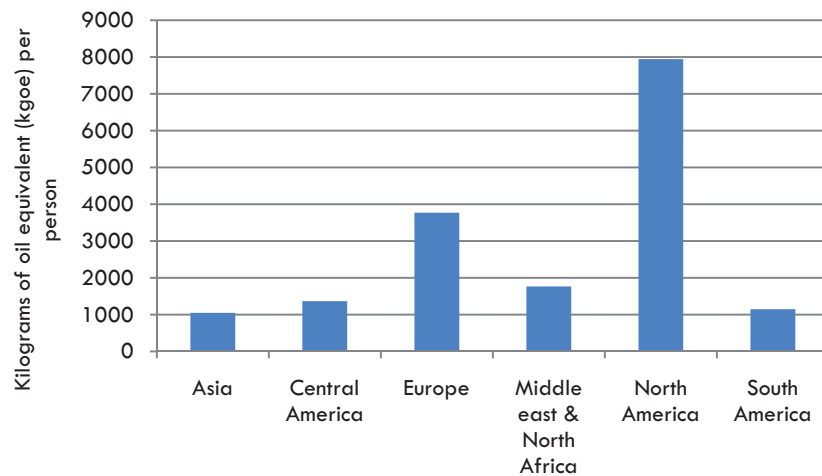
Fig. 04 Total energy consumption per captia (2005)

North America is the biggest energy consumer per capita, also Europeans are using a lot of energy per person.

In 2007 21% of the total world energy use is consumed by residential housing.[4]
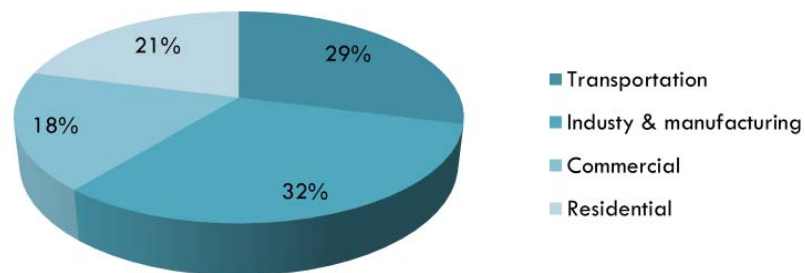
Fig. 05 World energy consumption by sector (2007)

Most of the domestic energy in residential housing is consumed by the heating- and cooling systems.
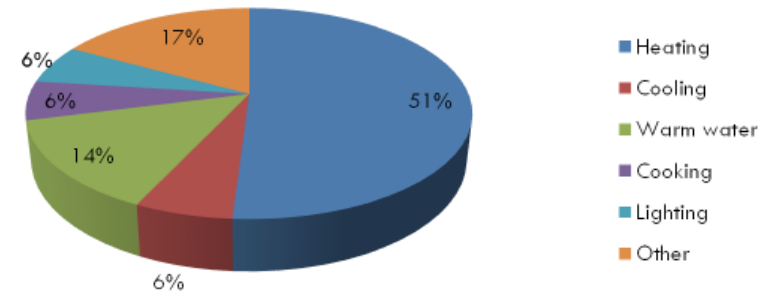
Fig. 06 Total energy consumption residential Netherlands[5]

In climates like Spain air-conditioning systems are common in the building sector, these systems are using a lot of energy. During summer periods more than 30% of all the needed energy in Madrid is used for cooling. Also in the Netherlands the air-conditioning systems are getting more used, but the heating capacity is much higher, because of the different climate. Not only Spain and the Netherlands scuffle with the high energy demands in residential buildings, this is a common issue worldwide.

This is the main reason why the Spain ministry of housing improved the "Solar Decathlon" competition. In this competition a self-sufficient house will be designed, for the circumstances during the dry and warm summer period in Madrid (see climate analysis). After the completion the self-sufficient house will be moved to the Netherlands. For that reason the self-sufficient house should also be able to adapt the Dutch climate conditions. This to provide the best comfort conditions, also in this climate.

4 (US Green Building Council, 2010)

5 (Milieu Centraal, 2010)

1.2 Solar Decathlon competition

This is the main reason why the Spain ministry of housing improved the "Solar Decathlon" competition. Spain shows it`s at the forefront of investigation and application of renewable energy in building and implementation of energy efficient systems in housing. The objective of this international competition, in addition to generating new knowledge, is to create awareness among the general public on intelligent energy use. To show that a more efficient energy use is possible and accessible, if buildings are made to lose less heat in winter and stay fresh in summer, therefore using less central heating and air conditioning, using appliances that consume less, and getting the energy needed through renewable sources such as the sun. In this competition 20 Universities from across the globe meet to design and build in 2012 an energetically self-sufficient house at the Ponte del Rey in Madrid. The houses solely run on solar energy and incorporate technologies that maximize its energy efficiency. Each house is then built and evaluated during the course of the event according to ten contests, ranging from architectural design, engineering & construction, Solar systems & hot water, energy balance, comfort conditions, appliances & functionality, communication & social aware, industrialization & marketability, innovative and sustainability. Also the Technical University of Delft is participating within the Solar Decathlon competition of September 2012.

This Master thesis is related to the Solar Decathlon team of Technical University Delft. The team exist of 25 students from the TU Delft who started in September 2010 with the Solar Decathlon competition. The team were random split in groups, each group designed a concept house for the competition in 2012 (phase 1). In the end of November 2010 one of the six designs was chosen by the jury. The chosen design is further developed and will be worked out till shop drawings and finally built and tested in September 2012 in Madrid. After the Solar Decathlon competition in Madrid the house will be disassembled and rebuilt in the Netherlands. In the next chapter the winning design shortly described.

Fig. 07 Solar Decathlon competition 2010, Madrid[6]

Analyzes of the construction method and the building envelope of the first, second and third winners of the Solar Decathlon of 2010 are reflected in the appendix.

6 (SolarDecathlonEU, 2010)

1.3 Design Solar Decathlon 2012 "Revolt House"

At the Technical University of Delft a competition was held to designed a concept for an energy self-sufficient house for the Solar Decathlon of 2012. The "Revolt House" is the winning concept out of six participating teams, chosen by the jury. The concept is a circular shaped one story high house which is floating in a pond. The total house is rotating during the day to optimize the climate comfort inside for each function. By making use of climate software the sun can be tracked and the house will positioned in the right direction. During the summer a closed façade will face to the sun to protect the house from solar radiation. In winter the open parts of the façade will rotated against the sun, to let solar heat entering the building. This could be in between in autumn and spring.

The house is surrounded by a fixed deck in the middle of the pond, only the house will rotate. The water of the pond can bodies maintain a relatively fixed temperature. This could be used during summer to cool (Excluded during the competition in Madrid) and during winter to warm the house to some extent. Using the sun`s reflections on the water would enable to get more sunlight for all purposes (lightning, heating and electricity).

Fig. 08 "Revolt house"
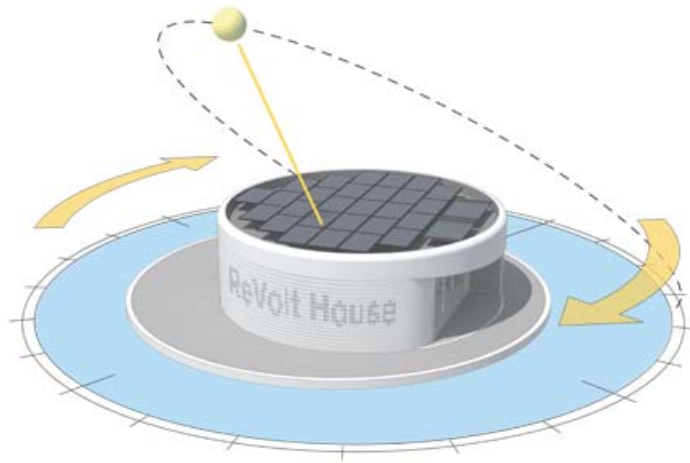
Fig. 09 Orientation summer situation
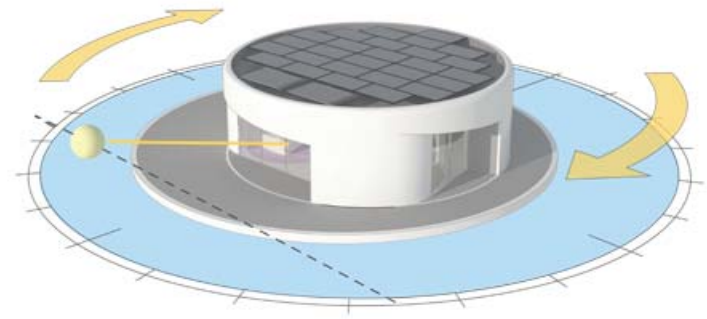
Fig. 10 Orientation winter situation

1.4 Cooling concept

The building will be designed and build for the climate of Madrid. Because the competition will be held in September the cooling system is an important aspect of the indoor comfort conditions. During the test period the building needs to provide a stable comfortable indoor climate on a sustainable way. The concept of the "Revolt House" is to make use of a passive adiabatic cooling method which will be integrated within the building envelope. Passive cooling methods in terms of minimum or no assistance from non-renewable or electric energy sources. During the competition the building will be disconnected from the utilities and need to operates on own generated power.
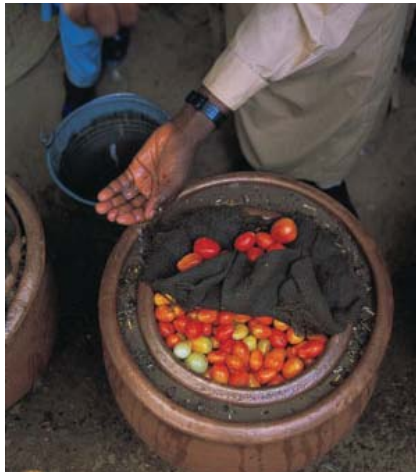
Fig. 11 Zeer pot

Fig. 12 Coolgardie safe

Two examples of passive adiabatic cooling methods are the "Zeer pot" and the "Coolgardie safe" (fig. 11 and 12).[7,8]
The "Zeer pot" is already used by the Egyptians, 2500 before Christ. A terracotta pot is placed in another, surrounded by a layer of sand. By keeping the sand layer saturated, the water will evaporate and extract heat from the inner pot. On top of the pot a damp cloth close off the pot and keep the heat outside. For optimum cooling a well-ventilated and dry location in the shadow is recommended. This method gives the possibility to keep food longer fresh (tomatoes 20 days, meet 14 days) by making use of natural cooling without electricity. The zeer pot system is nowadays still used in third world countries.

The "Coolgardie safe", named to the place where it was invented, by Arthur Patrick McCormick in 1890. A steel or wooden frame is covert with a wire mesh or textile, whit on top a tray filled with water. The top ends of the cover are placed into the tray, soak up the water, and saturated the whole wire mesh or textile cover. A wind breeze penetrated trough the cover, evaporate the soaked water, and cool the air inside the system. Also a well-ventilated, dry, shaded location is recommended.

Both passive adiabatic cooling methods are used in warm and dry climate conditions.

7 (Meister, 2006)
8 (Victoria, 2008)

1.5 Master thesis

The main objective is to design a device, by using a technique which is able to cool adiabatically. The world population and the energy consumption is growing yearly, more fossil energy is needed to fulfill the energy demand. Which lead to a higher carbon dioxide emission what will have negative environmental influences. Nowadays it`s important to designing sustainable wise, to minimize the environmental pollution. This Master thesis shows if and how it`s possible to cool a building on a passive way, by making use of an adiabatic cooling method. The final results of this thesis can be used in the design of the TU Delft for the Solar Decathlon competition of 2012.

Main research question: How and with which methods can an adaptive facade be developed that is able to cool with the principle of adiabatic cooling?

When this adiabatic system is able to produce a passive cooling in Madrid without deteriorating the indoor climate conditions, than it needs to be integrated in the building envelope (façade/ceiling). How is this possible and what are the needed strategies to cool adiabatically? After the competition the house will be placed in the Netherlands, will this cooling system operate also under the Dutch climate conditions. Where else in the world can this system be used? Are there other places where this cooling technique can replace the common air-conditioning system? What are the requirements for this kind of passive adiabatic cooling?
These questions will be answered in this report.

2. ANALYSIS

2.0 Adiabatic cooling

An adiabatic cooling process is realized by making use of evaporation. When air passes over water, some of the water will be absorbed by the passing air. This is a natural process what also occurs near lakes, oceans, waterfalls, est. The drier the air, the more water can be absorbed. Evaporation is the phase change from liquid to gas molecules, this process uses energy to change the physical state. The gas extract the heat from the wet surface and surrounding air, which results in cooling.
This also occurs with the human body, when cooling is necessary the skin gets to sweat, which will evaporate and extract heat from the body.

Evaporation of water may be an important cooling method within the building sector. Because the latent heat evaporation of water is large, 2.260 KJ/kg at 20 °C. A quick calculation shows 1 liter evaporated water can generate 0,63 kWh cooling.

When the vapor pressure at the surface of the water is greater than that of the adjacent atmosphere evaporation takes place. The air temperature change without removing or adding heat, the heat content/enthalpy in the air stays the same, than an adiabatic process takes place.

Important aspects for an adiabatic cooling process are the atmospheric conditions;
Dry bulb temperature: The temperature of air measured with a thermometer, shielded from moisture and radiation.
Relative humidity: The percentage of water vapor present in a volume of air to the amount of water vapor that would result in saturation.
Absolute humidity: The exact amount of water that present in given volume of air.
Wet bulb temperature: The temperature where the air is maximum saturated, through evaporation of water, the relative humidity is 100%.[9]

Carrier introduced in 1911 the psychrometric chart, where the relationship between the moisture content and temperature are present graphically (fig. 13). In this chart an example of an adiabatic process is shown. The measu-
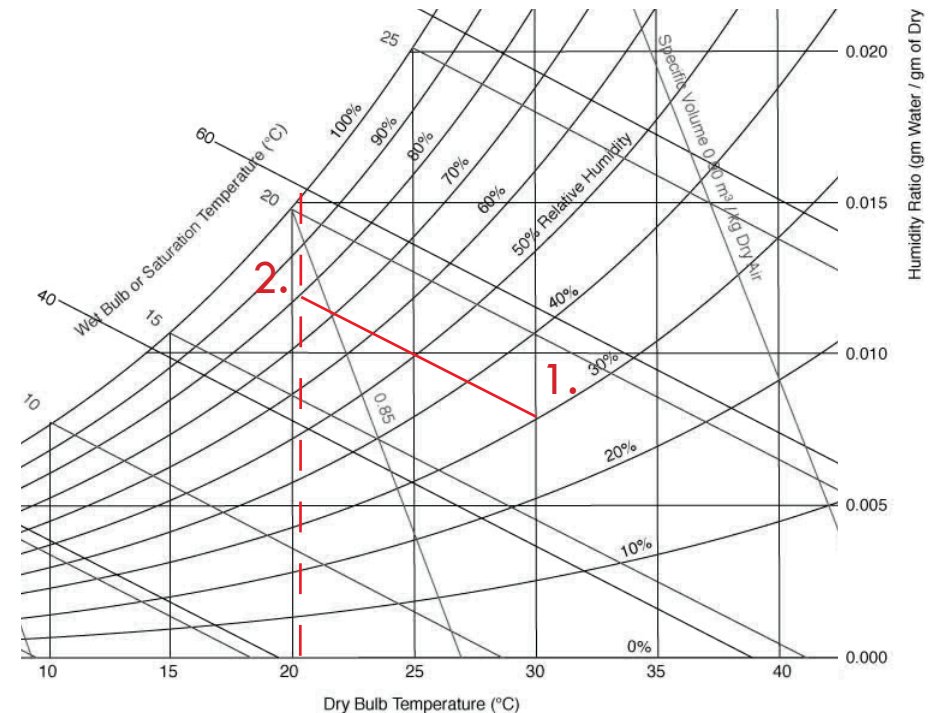
Fig. 13 Psychrometric chart

red air temperature is 30 °C, by a relative humidity of 30%, the absolute humidity is 7,8 g/kg (point 1). When the air gets humidified till a relative humidity of 80%, the absolute humidity increase to 12,01 g/kg, the air temperature cools to 20,5 °C, without changing the heat content (point 2).

The lower the absolute- and relative humidity is, the lower temperatures can be reached by using adiabatic cooling. Thus dry & hot climate conditions are preferred.

9 (Erell, 2007)

2.0.1 History adiabatic cooling

Adiabatic cooling is one of the oldest cooling methods. Since there is water there is adiabatic cooling, in consistency with atmosphere. Lakes, seas, rivers, but also vegetation, trees, est. are evaporating daily millions of liters water, which extract heat from the surface and the surrounded air. This is the main reason why the temperature at the coast is mostly lower than inland by the same climate conditions (depending on the wind direction). Temperatures close to waterfalls are considered lower, due to the higher evaporation effect of falling water which change phase from liquid to gas.

Also in the building sector is adiabatic cooling an old traditional cooling method. The first examples are shown on Egyptian plaster paintings, where slaves fanning jars of water to cool the room for the royalty. From here the cooling method (Zeer pot, pools and water ponds) spread out to other countries with a hot and dry climate (Iran, India, South Spain). Later on in Egypt water jars, made of terracotta, where placed behind screened windows, to cool the room. The screens protect the jars from solar radiation but allows ventilation. The water from the jar evaporate, cools the incoming fresh air and the water inside the jar.

Fig. 14 Water jar[1]

The Romans used the same method, but the jar is replaced by wetting mats, which generates a higher evaporation/cooling capacity.
The Romans are famous for their advanced engineering constructions. One of the well-known Roman accomplishments are the famous aqueducts, which they were able to manage the water for luxury residential houses and bathhouses. They improved the first façade cooling technique by integrating a water channel from the aqueducts through the façade.

In the medieval times high towers where build to catch the cooler wind and funneled it past water located at the base. The water, kept on top of a massive stone, evaporates and cools the stone and air.

10 (Oliver, 1997)
11 (Evaporcool, 2008)

In Muslim towns water was raised to a high level and circulated via channels to the houses. Water from the Ziandeh rivers were partially diverted, leaded through buildings over fountains made from marble. The marble was edited with grooves, this creates a spray effect to increase the evaporation process.[10]

In the 16th century Leonardo Da Vinci improved the first mechanical air cooler. A hollow water wheel was attached to air duct, splashed water cools the air and lead this trough the duct into his wife's boudoir.

In 1800 the textile manufactures in New England used water evaporators to cool the air in the mils. The mills where designed to capture wind and tunnel it through water.

The "Coolgardie safe", was invented, by Arthur Patrick McCormick in 1890.

The first swamp cooler, was implemented in the Adams Hotel in Downtown Phoenix, Arizona, 1916. A frame filled with excelsior (wool and wood) is saturated with water. Outside air go`s through the swamp cooler, gets humidified and cooled.
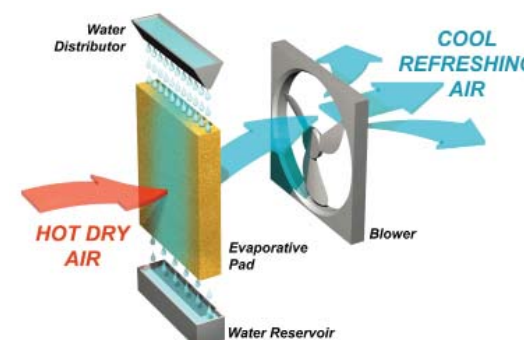
Fig. 15 Swamp cooler[2]

In the 1920s and 1930s people from Southwest America hung wet sheets in and around the houses to generate evaporation during the night. But these method causes high risks on pneumonia.

Till nowadays evaporative cooling methods are still used, to precool and humidify the incoming air in air handling units on a hybrid way.[11]

1. www.museumofmythology.com

2. www.pinnacleint.com

2.0.2 Direct- & indirect adiabatic cooling

Adiabatic cooling systems are classified in two ways, they can be direct or indirect. This according to the contact of the cooled air with the evaporated water.

Direct:
The "Coolgardie safe" is a direct way of adiabatic cooling. The incoming air is in contact with the evaporated water, the humidity of the cooler air increases.
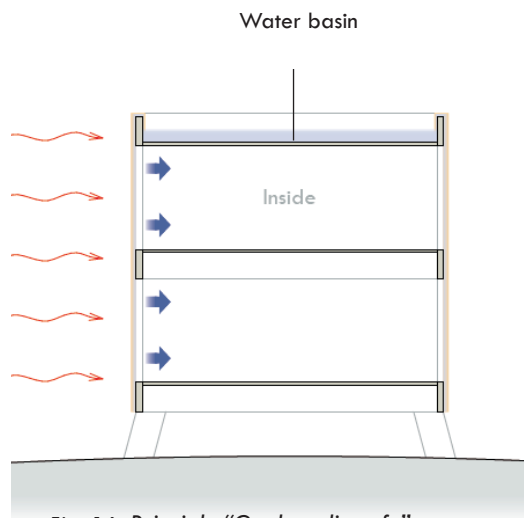
Fig. 16 Principle "Coolgardie safe"
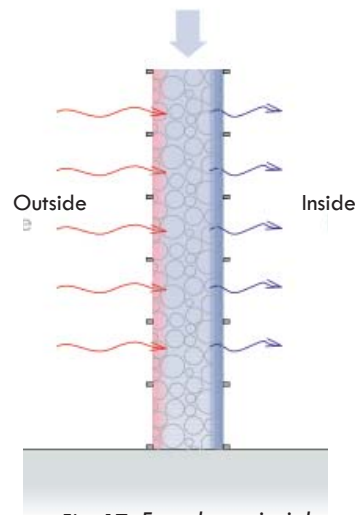
Fig. 17 Facade principle, direct

Other direct adiabatic cooling methods are fountains, pools, basins, ponds and vegetation's which are common placed around or on the buildings. Specially vegetation roofs and façades are getting more used nowadays, it cools during the summer and insulate in winter.

For a direct adiabatic cooling system it`s important to create an open water absorption layer where outside air is able to penetrate and humidify the air (fig. 16).

Indirect:
The "Zeer pot" is an indirect adiabatic cooling method. The inside air and evaporation process are not in direct contact, but separated by another material, in this case the inner glazed terracotta pot. The indirect adiabatic
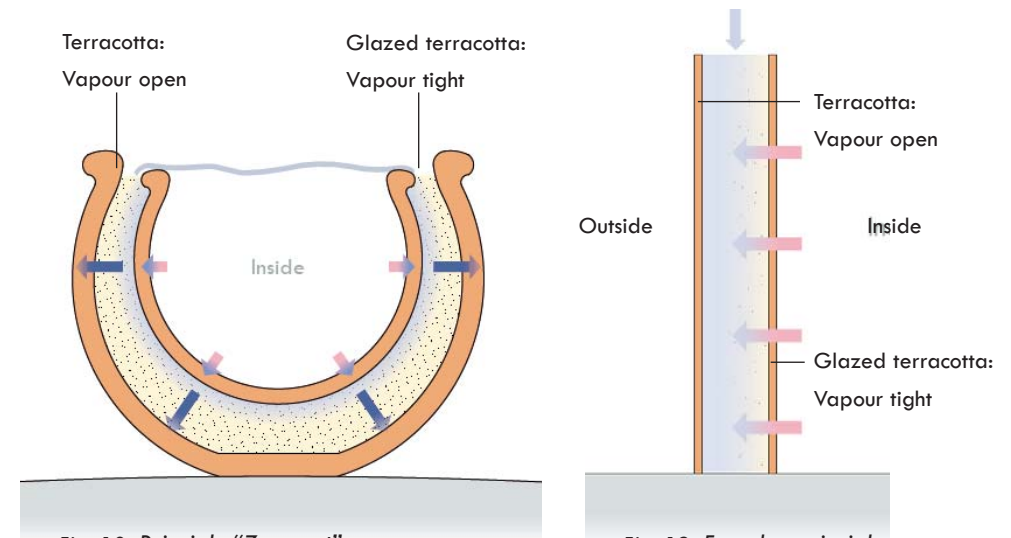
Fig. 18 Principle "Zeer pot"
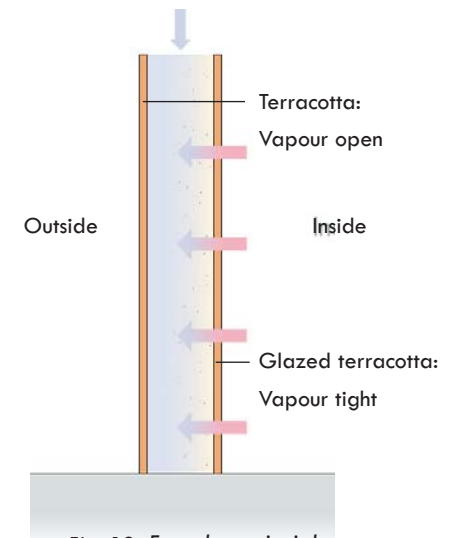
Fig. 19 Facade principle, indirect

cooling doesn`t affect the humidify of the inside air. The evaporation process which occurs in the sand layer, extract heat from the inside space. In air-handling units this method is common used, the cooled air will transferred by using heat exchangers, which is not passive and thus not adiabatic anymore. To integrate an indirect adiabatic cooling system in the façade the absorption layer needs to be separated by a material, in this case the glazed terracotta, and need to be totally watertight isolated from the inside space.

As well the direct – as the indirect adiabatic cooling method are able to be

integrated within a façade system, but by using a direct method the air in the room gets humidified. This can, till a certain height, be a problem. When the relative humidity rises too high it has negative influences on the comfort conditions inside the building. In fig. 20 the comfort conditions according to the climate conditions of Madrid in Summer are shown in the Psychrometric chart, based on a diagram made by M. Milne and B. Givoni. To realize an indoor climate which is comfortable a temperature from 19,3 °C till 25,5 °C with a relative humidity between 20% and 85% needs to be reached. Direct adiabatic cooling will humidify the inside air, which causes negative indoor comfort, what needs to be prevented.

Besides increasing the humidity of the inside air, bacteria & smells are able to enter the inside space. This won`t happen by an indirect adiabatic cooling because the evaporation process is separated from the inside space.

Therefore the possibility of using the indirect adiabatic cooling will be tested to see if it`s able to realize enough cooling, and how can this be integrated in the building envelope.
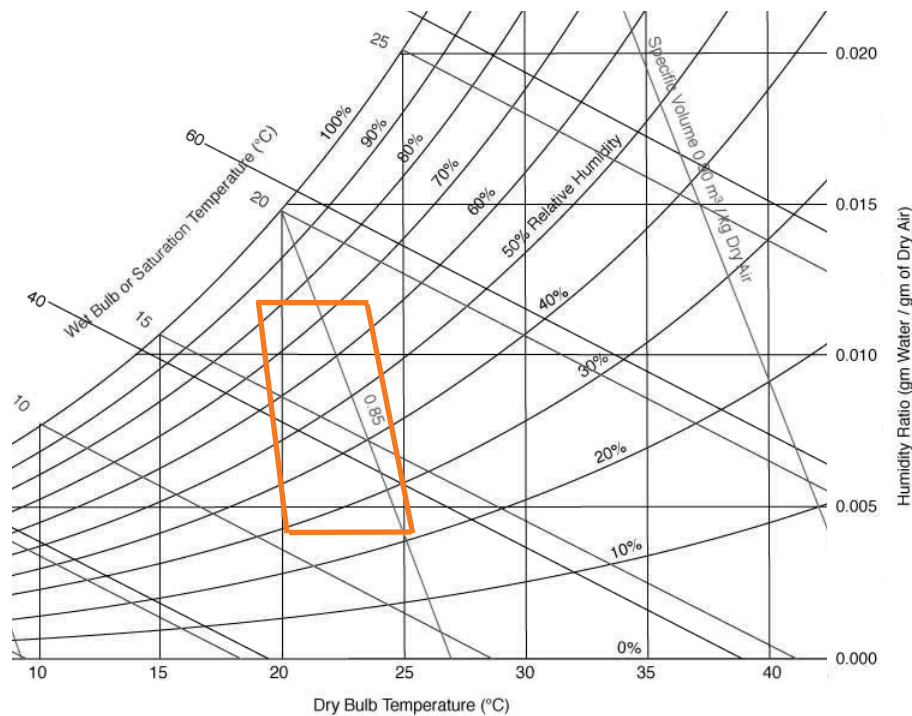
Fig. 20 Psychrometric chart, comfort zone, Madrid

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2.1 Climate Madrid

According to the Köppen classification, the globe is divided in different climate zones. Because of the occur climate changes this will be checked and when necessary adjusted every 30 years. Currently the main part of Europe is classified in a maritime climate (fig. 21). Madrid is classified in a Continental Mediterranean climate (fig. 22).[12]

The Madrid region features a Continental Mediterranean climate with cold winters due to altitude, including sporadic snowfalls and minimum temperatures often below freezing. Summer tends to be hot and dry with temperatures that consistently surpass 30 °C in July and August and rarely above 40 °C.

The tests for the Solar Decathlon competition will be held in September, this means an average maximum outside temperature of 27 °C. This leads with peak temperatures above the 30 °C.[13]

Fig. 21 Maritime climate zones

Fig. 23 Temperature Madrid (AV. 1971-2000)
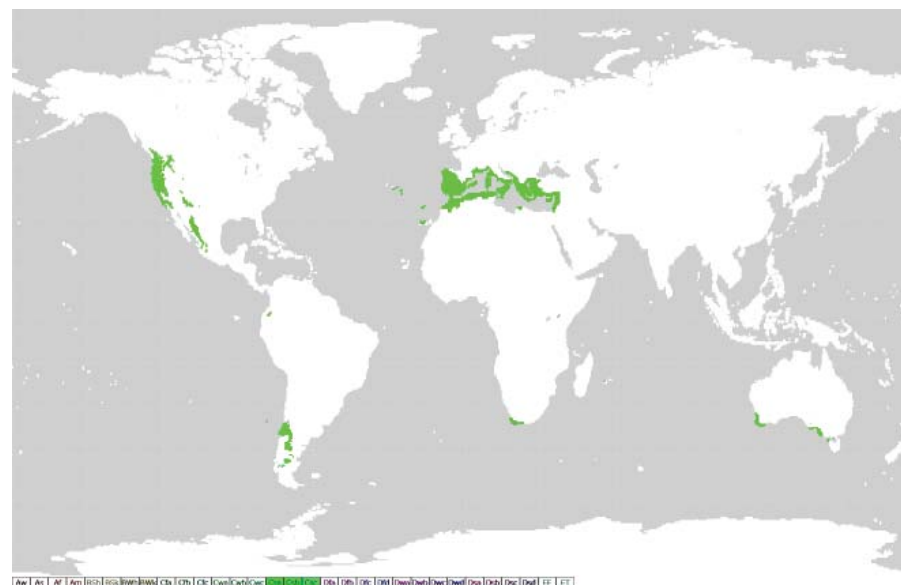
Fig. 22 Continental Mediterranean climate zones

12 (Wikipedia,2010)

13 (AEMET, 2009)

The climate conditions for an adiabatic cool method are very important. The dryer and warmer the climate the higher the cool capacity. Because the Solar Decathlon competition will be held in September 2012, the climate conditions, of the first 15 days of these month are analyzed. The used climate data is exported from Energy Plus (a building energy simulation program). The original data is from American Society of Heating, Refrigerating and Air-Conditioning Engineers. They measured the climate conditions and picked the month September 1999 as an average September month.[14]

The maximum dry bulb temperatures are measured between 12.00 and 18.00 PM, temperatures above 27 °C are no exception in September. From 9 till 13 September temperatures of 30 °C and higher are measured. During the nights the dry bulb temperatures drops under 20 °C, what makes it possible to cool during the night with air from outside.

The relative humidity and the absolute humidity varies daily, during a foggy/rainy period (1 till 5 September) the absolute humidity can increase till almost 14 g/kg with a relative humidity of 90%. These circumstances accompanied with lower temperatures, meaning no or less cooling is probably needed. The average relative humidity during the warmest time of the day is around 30%, but when the dry bulb temperature reaches high temperatures the relative humidity decrease sometimes even under the 20%.

In Madrid the average wind speed is low, around 2 m/s. Maximum air speeds of 8 m/s are reached, but these are exceptions. When there are wind peaks, they are mostly at the warmest part of the day (between 12.00 and 18.00 pm).
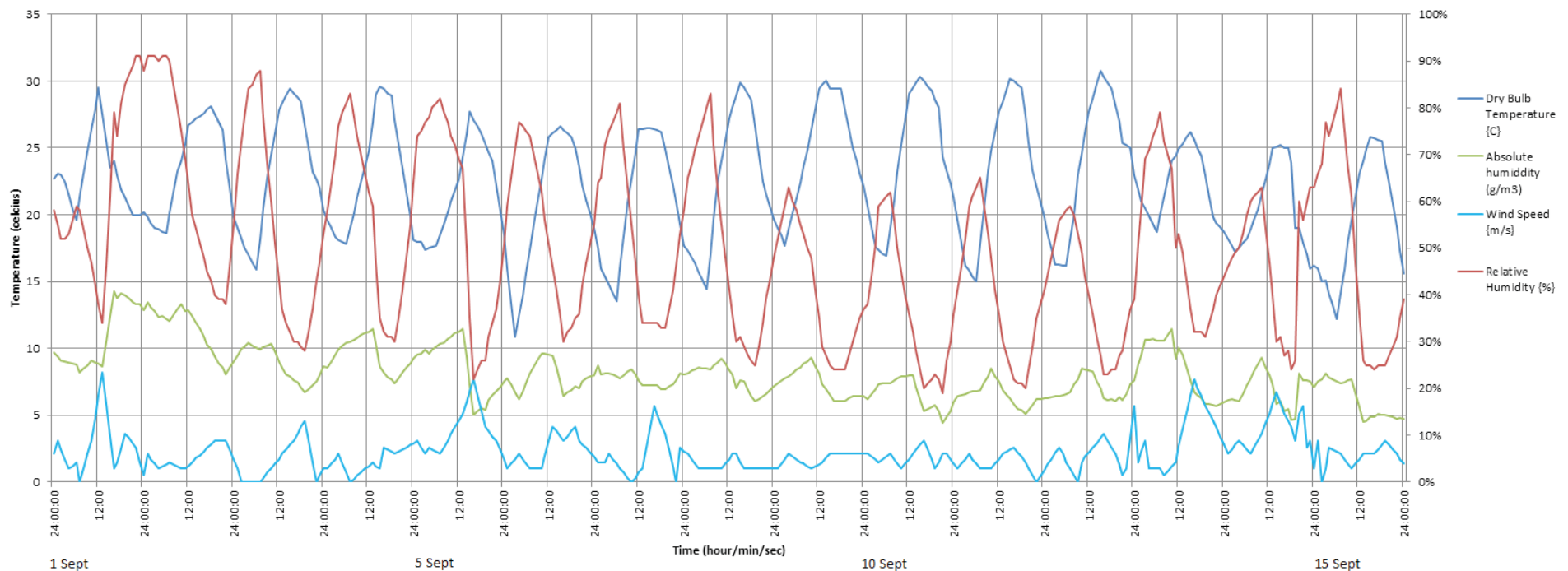
Fig. 24 Temperature, windspeed, relative - & absolut humidity of Madrid

3. PROTOTYPE

3.0 Prototype

Before building a prototype of the indirect adiabatic cooling system the "Zeer pot" is translated to a façade element as shown in the previous chapter. Every layer of the this façade concept has different properties. The inside layer needs to have a high heat coefficient to transfer the extracted heat from the inside. This layer needs to be totally vapour tight. Glazed terracotta is a fragile material when it`s preformed in a thin layer, to reduce weight. Besides the watertight connections which needs to be solved, the production techniques nowadays are known and common use with a material like steel. Therefor the inside terracotta layer is replaced for a thin metal sheet, fig. 26.

The outside terracotta layer is also replaced by a metal sheet, but for this layer it`s important to ventilate the underlying, in this case sand, to generate evaporation. Therefor the metal sheet on the outside is perforated in the first place, and sealed off with a mesh, to keep the sand in. The sand layer is in this case in direct contact with the outside air, which increases the evaporation and thus the cooling. But only where the outside sheet is per-

forated evaporation arises, this surface needs to be as large as possible. And because the evaporation takes place at the outside of the sand layer and will extract heat from the out – and not from the inside. For this reason an extra air cavity is integrated, to make the evaporation layer as large as possible and to keep the cooler air inside the structure. The incoming air in the cavity will be humidified and cooled, air will drops and extract fresh air from the top naturally, fig. 28.

With these assumptions the first prototype of an indirect adiabatic cooling system is built.
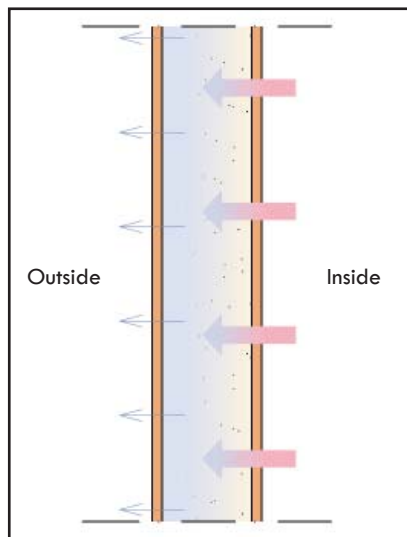
Fig. 25 Facade principle "Zeer pot"
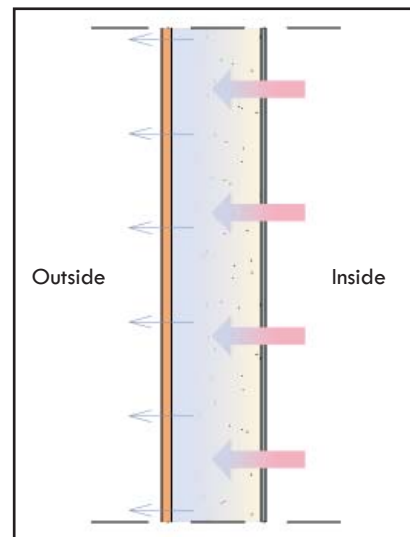
Fig. 26 Inside terracotta replaced a for steel plate
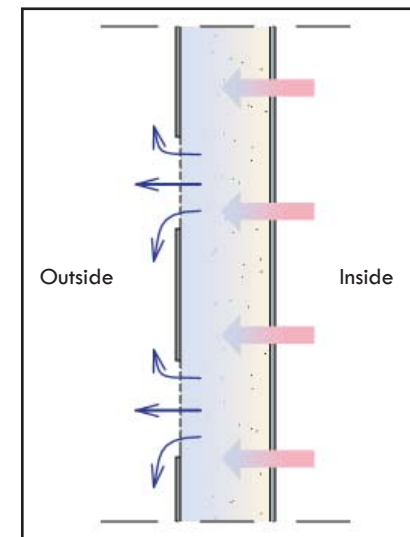
Fig. 27 Outside terracotta replaced a perforated steel plate
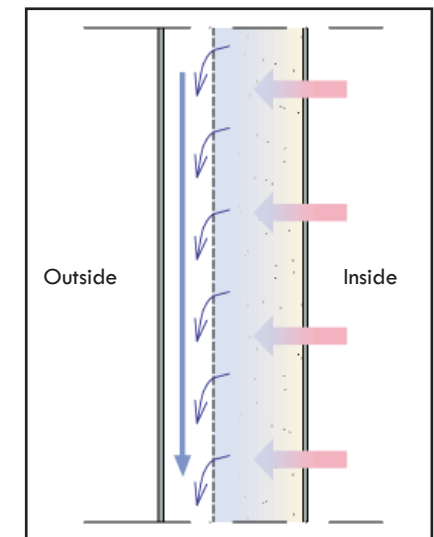
Fig. 28 Air cavity introduced, more evaporation surface

3.0.1 Test prototype

The first prototype consist of a simplified construction, to see if this system is able to create cooling.

The outside layer is an empty 2,5 liter steel paint can which is perforated to generate a ventilation flow in the underlying air cavity, this to provide the evaporation. In the center of the 2,5 liter paint can a smaller 1 liter can is placed. This can is surrounded by a 10 mm layer of masonry sand, which is hold in position by a mesh. The top and bottom of the can are on both sides at the inside insulated, to prevent thermal bridges.

Two data loggers are used, both measuring the temperature and the relative humidity. One of the loggers is placed in the 1 liter paint can to measure the inside climate conditions, the second is placed on top of the prototype which is logging the outside temperature and relative humidity.

From this first prototype important aspects are concluded.

- Protect the absorption layer from direct solar radiation. The sun heats the absorption layer, which is positive for the evaporation process, but the heat will be transferred to the inside of the inner space.
- A ventilation flow is recommended. The ventilation accelerate the evaporation process and realize lower air temperatures.

Steel can 2,5L (perforated)
Cover
Insulation

Steel can 1L
Sand layer (± 1cm)
Mesh/netting
Insulation

Fig. 29 Section test prototype
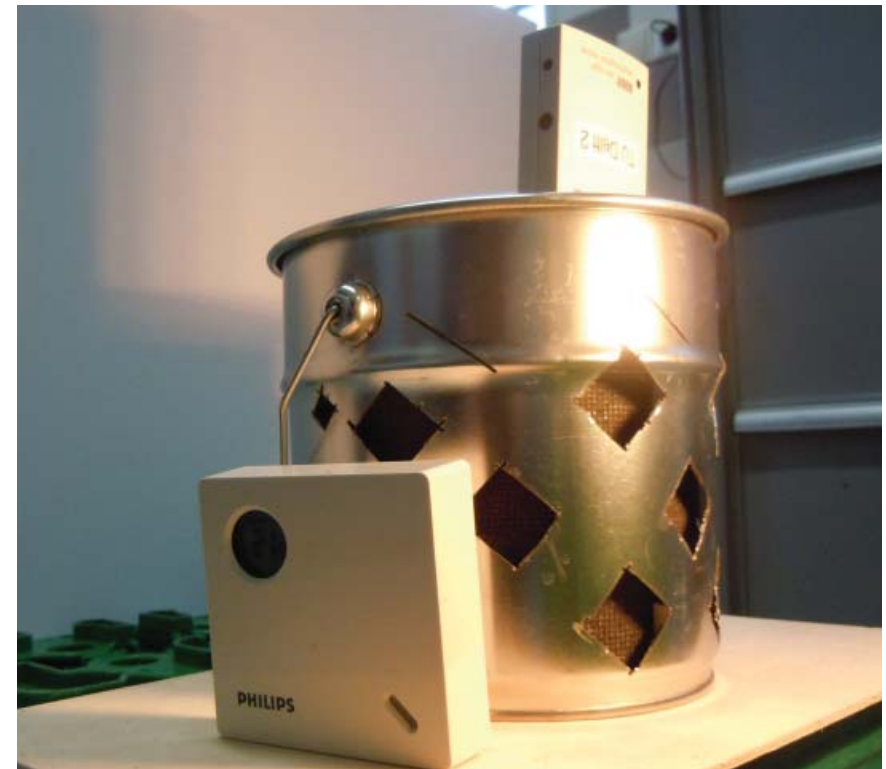
Fig. 30 Picture test prototype

3.0.2 Prototype facade element

This prototype is based on the test principle (see previous chapter), translated to a flat 405 x 444mm façade element.
For this prototype a box is build where more accurate measurements can be done. Part of the box is insulated with 80mm of EPS. Test elements can be placed at the front of the opening (213 x 284 x 245mm), where they will be tested. All the seams are closed by sealant, to prevent influences on the measurements.

Dimensions and insulation properties of the testbox are shown in the diagrams, these are necessary to make physical calculations.

More pictures of the prototype are added in the appendix
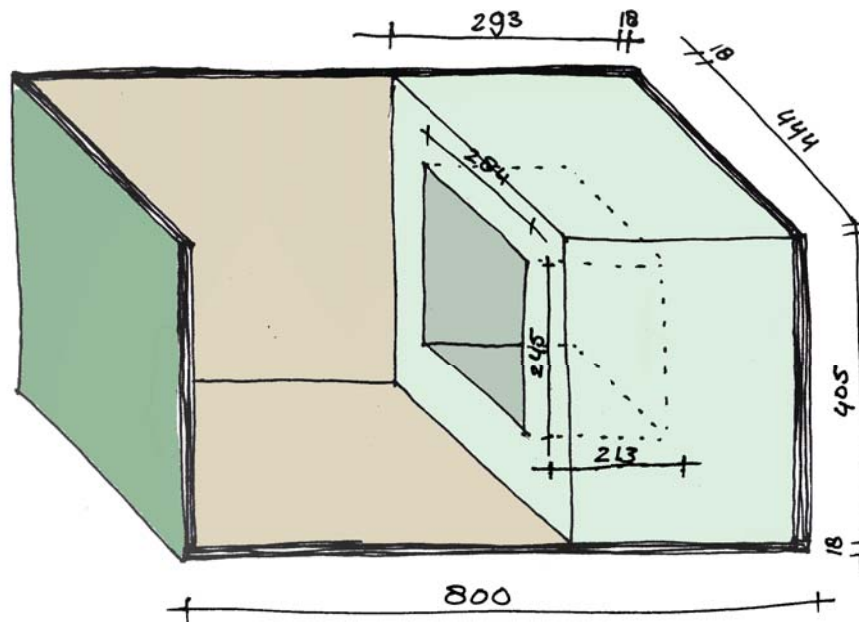
Testbox properties

Dimensions:

	Length (mm)	Width (mm)	Height (mm)	Volume (m³)
Insulation	293	444	405	0,053
Opening	213	284	245	0,015

Insulating:

	Material	Thickness (m)	Thermal con. (W/m.K)	Thermal res. (m².K/W)
Insulation	EPS	0,08	0,032	2,5
Box	Plywood	0,018	0,2	0,09
Total		0,098		2,59

Fig. 32 Testbox properties

Fig. 31 Sketch testbox

Fig. 33 Insulated box

3.0.3 Measurements

To see what happens with the climate circumstances in and around the prototype several measurement tools are used:

- Data logger for the temperature and relative humidity with 2 external temperature channels which can be used for sensors. The second data logger measured only temperature, but has 4 external temperature channels.
- 6 sensors for the data loggers. The sensors are able to place them anywhere where is necessary, which needs to be connected to the data loggers.
- Aquarium thermometer, to temp the water which will be used for the evaporation process.
- Anemometer, to measure the wind speed of the used fan.

During the test period measurements on several locations in and around the mock-up are done.

1. Inside temperature: Air temperature in the 0,148m³ is measured. The measurement device is positioned in the centre of the opening.
2. Sand temperature, mesh: Temperature in the 7mm thick sand layer at the side of the mesh.
3. Sand temperature, steel: Temperature in the 7mm thick sand layer at the side of the steel sheet.
4. Top temperature: Air temperature behind aluminium cover.
5. Top back temperature and humidity: Air temperature and humidity on top of the insulation.
6. Temperature right: Air temperature 25 cm from the insulated box, at a height of 15cm (bottom box).
7. Temperature back: Air temperature 25 cm behind the box, at a height of 15cm (bottom box).
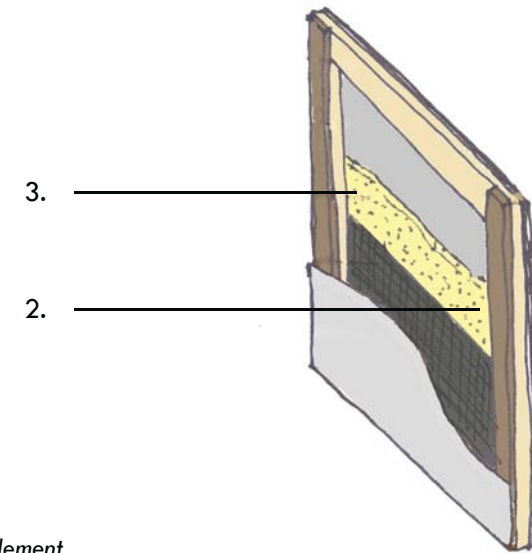
Fig. 34 Sketch testelement
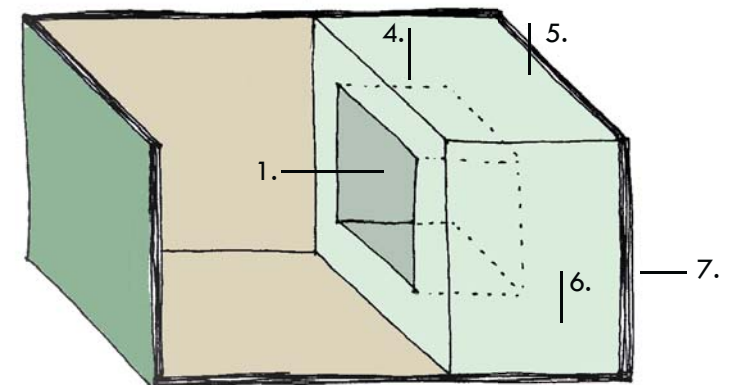
Fig. 35 Location sensors

3.0.4 Test element

The façade element consist of several layers. The insulated opening in the box is closed by a steel plate, with a high thermal conduction coefficient. At the front a 7 mm (masonry) sand layer, surrounded by a wooden frame, pent-up by a vapour open fabric mesh. The sand layer is used as absorption layer, when the sand gets moisture. Wooden spacers create a ventilation cavity which is closed by a 2 mm aluminium plate.

The aluminium cover is on top and bottom open to provide a better ventilation flow. During the test the sand layer gets humidified. Air which ventilates the cavity accelerate the evaporation process, this leads to a cooler humidified air flow. As a result of the higher humidity and the lower temperature, the air flows naturally downwards.

Expected as shown in the first prototype, heat will be extracted from the insulated inside space and lower the air temperature.

Wooden frame

Steel plate 1,5 mm

Sand layer 7 mm

Mesh, Fabric

Aluminium 2 mm

Wooden spacer

Fig. 36 Materials test element

Fig. 37 Sketch test setup
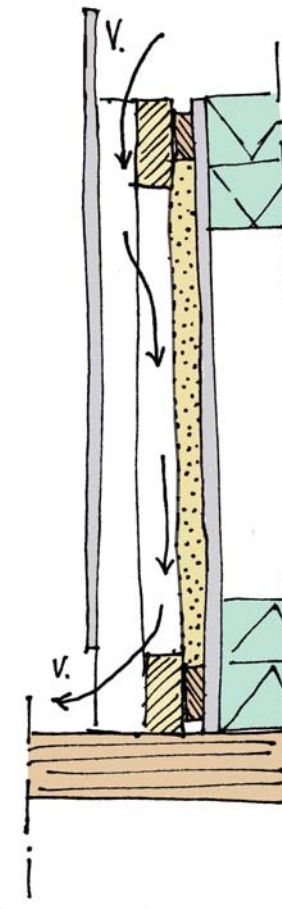
Fig. 38 Sketch section test element

3.1 Prototype test 1

The first prototype of the façade element is tested on a cloudy day in the garage on the North side of our house. During the ten hour measurements the mean air temperature around the prototype varies between 18,7 and 19,5 °C with an air humidity of averaging 46%. The measurement results of test 1 are shown in fig. 46.Every adjustment is numbered in periods, each period is explained according to the proceedings.

During the test period several adjustments occurred;

Humidify

Ventilation on

Ventilation off
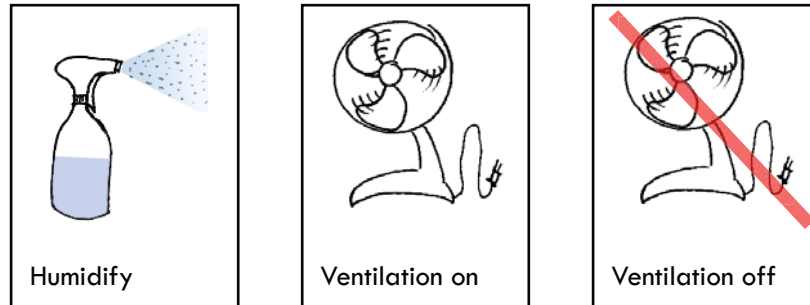
Circumstances test 1:

- Date: 3-3-2011
- Time: 10:15 – 19:55
- Location: Garage (North)
- Temperature: 18,7 - 19,5 °C
- Humidity: Between 45 - 48%
- Water temperature: 18,5 °C
- Distance fan: 2400mm
- Fan speed: 0,2 & 0,3 m/s

P1. After positioning the test element, the sand layer is humidified with ± 20 ml sprayed water (room temperature, 18,5 °C). During this period the inside air temperature decrease with 1,7 K (18,4 to 16,7 °C), by an average outside temperature of 18,7 °C. The temperature drop stops when the water in the sand layer is evaporated. The temperature in the sand layer, at the side where the evaporation process arises, reach 15,1 °C. After two hours the cooling process decreases because the moist in the sand layer is evaporated and not able to cool anymore.

0.00.00 till 2.30.00

	Temp 1 (°C)	Temp 2 (°C)	Diff. (K)
Outside	19,2	18,8	-0,4
Inside	18,4	16,7	-1,7

Fig. 39 Start & end temp. measurements

Temp. diff.
In- & out
2,1 K

P2. After 2:30 hours the fan, located 2400 mm from the backside of the prototype, is turned on. The averaged measured wind speed in the air cavity is 0,2 m/s. The in – and outside temperature increases. The temperatures in the prototype is increased because the moisture in the sand layer is already evaporated, and the outside temperature probably because of the warm air which is blown by the fan.

2.30.00 till 3.15.00

	Temp 2 (°C)	Temp 3 (°C)	Diff. (K)
Outside	18,8	19	0,2
Inside	16,7	17	0,3

Fig. 40 Start & end temp. measurements

Temp. diff.
In- & out
2,0 K

P3. After 3:15 hours the sand layer is humidified, sprayed with ± 20 ml water on room temperature (18,5 °C), while the fan is running. The outside temperature stays stable, but the measured temperature in the sand layer drops immediately from 16,0 to 14,8 °C in 30 minutes. After 5 minutes also the inside temperature increase, and goes gradually from 17,1 to 16,8 °C.

	Temp 3 (°C)	Temp 4 (°C)	Diff. (K)
Outside	19	19	0
Inside	17	16,8	-0,2

Fig. 41 Start & end temp. measurements
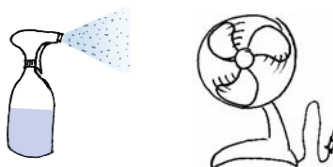
Temp. diff.
In- & out
2,2 K

P4. After 3:45 hours the sand layer is humidified, sprayed with ± 20 ml water on room temperature (18,5 °C), while the fan is running. The sand temperature and the inside temperature are still declining. Small peaks in the sand layer measurements are visible, this is probably because the aluminium sheet is shortly removed to humidify the sand layer

	Temp 4 (°C)	Temp 5 (°C)	Diff. (K)
Outside	19	18,9	-0,1
Inside	16,8	16,4	-0,4

Fig. 42 Start & end temp. measurements
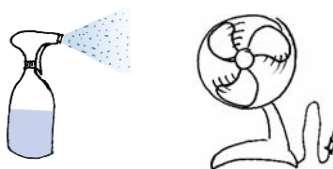
Temp. diff.
In- & out
2,5 K

P5. After 4:15 hours the sand layer is humidified, sprayed with ± 20 ml water on room temperature (18,5 °C), while the fan is running. The sand temperature and the inside temperature are still declining.

	Temp 5 (°C)	Temp 6 (°C)	Diff. (K)
Outside	18,9	19	0,1
Inside	16,4	16,1	-0,3

Fig. 43 Start & end temp. measurements
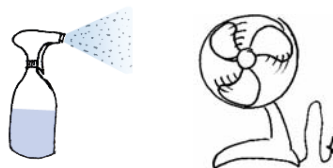
Temp. diff.
In- & out
2,9 K

P6. The aluminium sheet at the front of the prototype is removed to see what`s happening. Because of the buffer effect the insulated inside air temperature is still decreasing in the first couple of minutes, while the sand temperature increase directly. But after 7 minutes also the inside temperature rises.

	Temp 6 (°C)	Temp 7 (°C)	Diff. (K)
Outside	19	19	0
Inside	16,1	16,1	0

Fig. 44 Start & end temp. measurements

Temp. diff.
In- & out
2,9 K

P7. After 5.00 hours the sand layer is humidified with a double quantity of ± 40 ml sprayed water (room temperature, 18,5 °C) The fan is turned on high speed (0,3 m/s) and the aluminium sheet is placed back in position. The temperature in the sand layer drops directly to the minimum measured temperature during test 1 (13,9 °C), a temperature difference with outside from 5,1 K (19 °C). Also the inside air temperature reaches its lowest temperature (15,8 °C), difference of 3,2 K with outside temperature. After 8.30 hours the water in the sand layer is evaporated, which lead to an increasing sand layer - and inside air temperature.

	Temp 7 (°C)	Temp 8 (°C)	Diff. (K)
Outside	19	18,9	-0,1
Inside	16,1	16,9	0,8

Fig. 45 Start & end temp. measurements

Temp. diff.
In- & out
2,0 K

P8. After 10.40 hours the first tests of this prototype are finished.
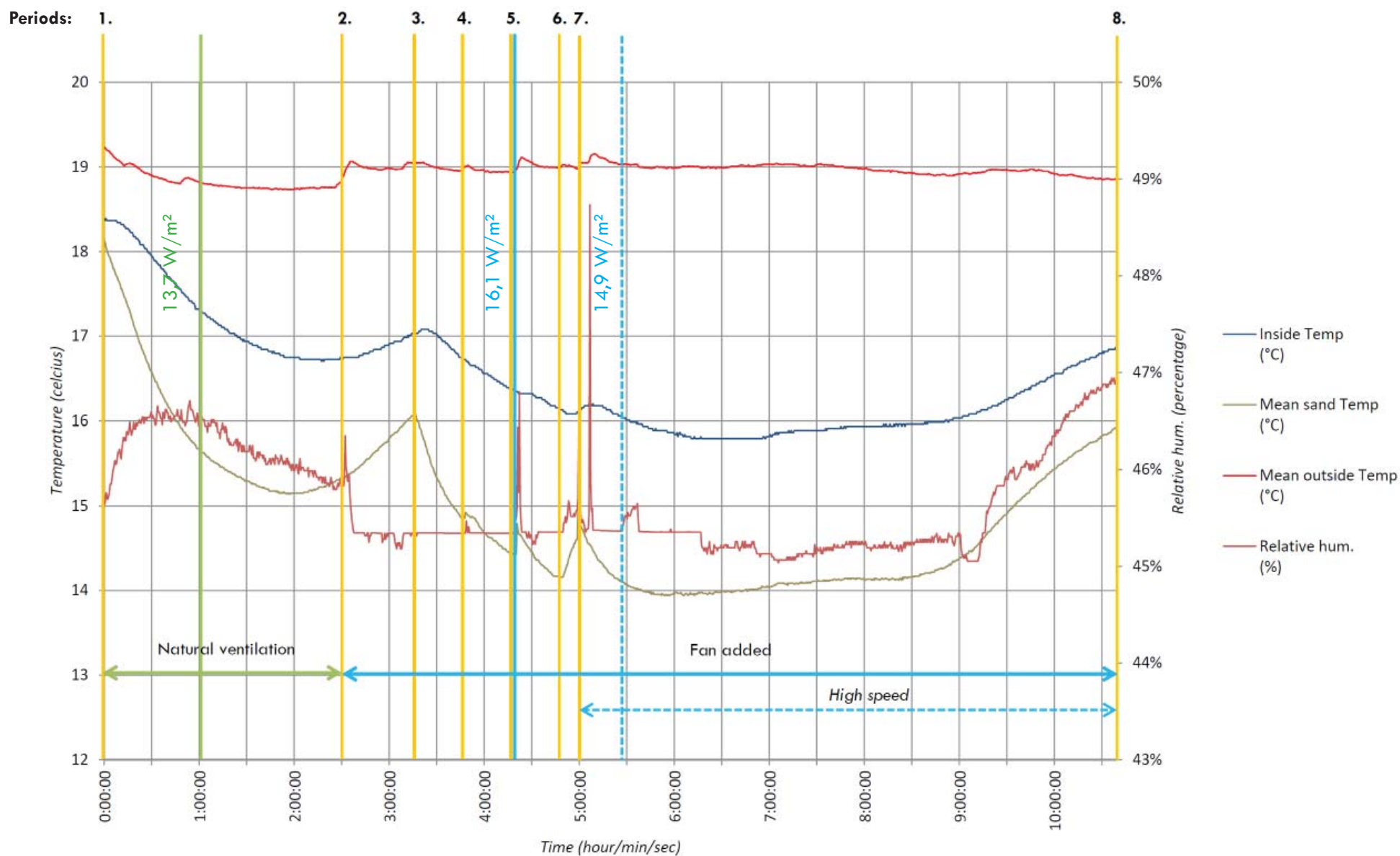
Fig. 46 Mean measurements of test 1, detailed measurements are retrievable in the appendix

3.1.1 Calculations test 1

During the test three different ways of ventilation are used;
- Natural ventilation: In this case there is no extra fan added.
- Fan low speed: A fan is used to create extra ventilation, the fan produces 0,2 m/s
- Fan high speed: The fan produce a high ventilation flow 0,3 m/s.

To see what kind of influences this three approaches has on the cooling capacity, calculations are made. To calculate the cooling capacity the insulation value of the evaporation layers (U) and the temperature difference of the sand layer - and the inside air (ΔT) are required.
The cooling load for this prototype is calculated by the formula: $Q = U \cdot \Delta T$

Sandlayer		Steelplate		hroom	7,8
Thickness	0,007 m	Thickness	0,0015 m	Rroom	0,128205128 W/(m²/K)
Lamda	2 W/m·K	Lamda	50 W/m·K		
Rsand	0,0035 W/(m²/K)	Rsteel	0,00003 W/(m²/K)	**Ucon**	**7,59098969 W/(m²/K)**

The maximum cooling capacity during test 1, with natural ventilation (0:00:00 till 2:30:00 hr) is reached after 1:00:30 hours (Indicated with a green line in fig 46).

Measured conditions highest cooling cap.		Measured conditions highest coolingcap.	
Time:	1:00:30		
Tinside	17,32 °C	Toutside	18,818 °C
Tsand	15,509 °C	Rel. hum	46,556 %
ΔT	**1,811 K**		

Cooling capacity:

$Q = U \cdot \Delta T$
$Q = 7,59098969 \cdot 1,811$
Q = 13,747 W/m²

Tsand:15,5 °C

Tout:18,8 °C   Tin:17,3 °C
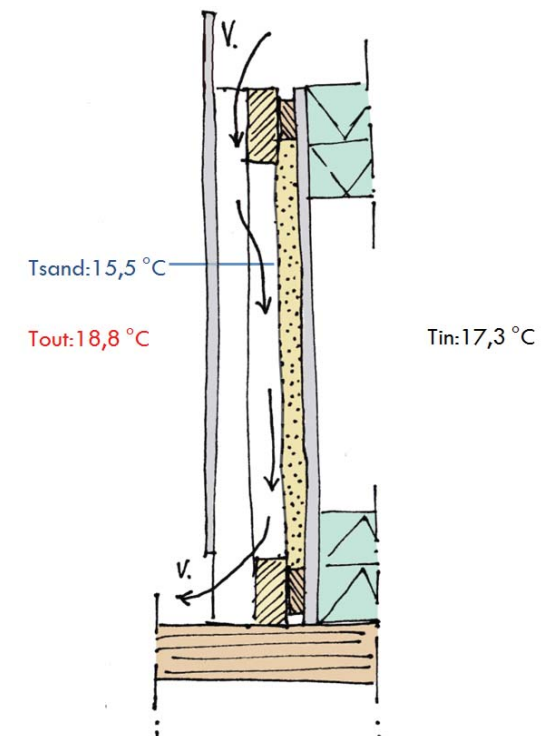
Fig. 47 Temperatures test 1 natural ventilation

The maximum cooling capacity during test 1, by adding a fan on low speed (0,2 m/s 2:30:00 till 5:00:00 hr) is reached after 4:15:30 hours (Indicated with blue line in fig. 46).

Measured conditions highest cooling cap.	
Time:	4:15:30
Tinside	16,392 °C
Tsand	14,266 °C
ΔT	**2,126 K**

Measured conditions highest coolingcap.	
Toutside	18,937 °C
Rel. hum	45,343 %

Cooling capacity:

$Q = U \cdot \Delta T$
$Q = 7,59098969 \cdot 2,126$
Q = 16,138 W/m²

The maximum cooling capacity during test 1, by adding a fan on high speed (0,3 m/s 5:00:00 till 10:40:00 hr) is reached after 5:28:30 hours (Indicated with blue dotted line in fig. 46).

Measured conditions highest cooling cap.	
Time:	5:28:30
Tinside	16,034 °C
Tsand	14,074 °C
ΔT	**1,96 K**

Measured conditions highest coolingcap.	
Toutside	19,03825 °C
Rel. hum	45,524 %

Cooling capacity:

$Q = U \cdot \Delta T$
$Q = 7,59098969 \cdot 1,96$
Q = 14,878 W/m²

Tsand:14,3 °C

Tout:18,9 °C

Tin:16,4 °C
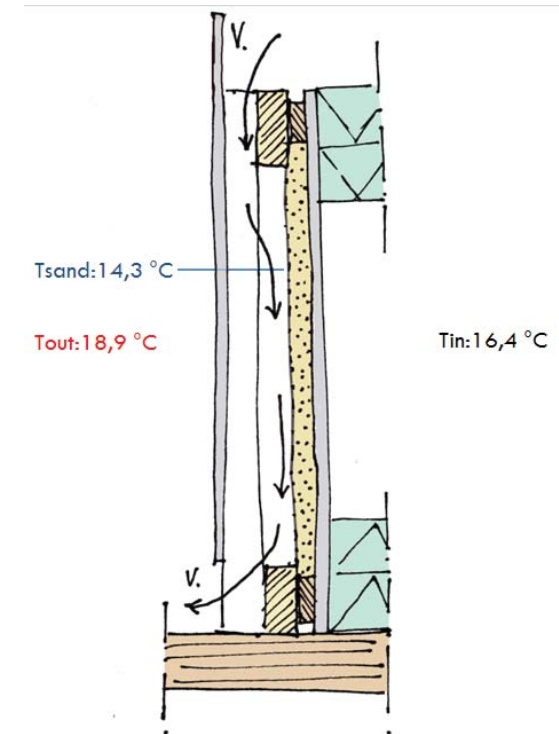
Fig. 48 Temperatures test 1 fan added (low speed)

3.1.2 Results test 1

The test results of the prototype 2, test 1 (§ 3.1, page 29), shows how this passive way of indirect evaporative cooling lower the inside air temperature with 2,6 K (18,4 to 15,8 °C), by a relative humidity between 45 and 48% and average outside air temperature of 18,9 °C. The dryer the air, less absolute humidity, the better it is to cool with evaporative cooling. Dry air is able to absorb more moisture and accelerate the evaporation- and thus the cooling process.

The temperature where the evaporation process take place, at the surface of the mesh, is during the test period colder than the inside air temperature. At the start of the measuring the difference is 0,3 Kelvin, but in most measuring's this is above 1,5 Kelvin. The temperature difference is not only because of thermal leaks within the prototype also the 7mm thick sand layer plays a role. The thicker the sand layer the lower the heat transfer. But the sand layer function also as an insulator when the evaporation process is over.

In the first period (0:00 – 2:30) the sand temperature drops from 18,1 to 15,2 °C, a difference of 2,9 Kelvin, without using extra ventilation. Also the inside air temperature decrease with 1,7 Kelvin (18,4 to 16,7 °C). By making use of in this case a fan with a wind speed of 0,3 m/s (after 3:15 hour) it`s possible to reach lower temperatures 13,9 °C is the lowest measured temperature within the sand layer at the evaporation surface.

After 1:55:00 hr the evaporation process decreases, which means the humidified sand layer desiccate and reduced the cooling capacity. Even when the fan is turned on, this hasn`t got any cooling influences, the sand- and inside temperature rises even faster.

During the evaporation process the measured temperature in the sand layer at the surface of the mesh stays cooler than on the side of the steel plate. At the side of the mesh the evaporation process takes place, the ventilation flow accelerate the cooling effect.

After 5:00:00 hours the fan is turned on high speed, this doesn`t influence the cooling effect much. Out of the calculations is concluded that in this case to much ventilation brings negative influences on the cooling capacity.

The double amount of sprayed water is not effective for the cooling capacity, but extend the evaporation process. 40 ml sprayed water in combination with a fan needs under these circumstances needs at least 3:30:00 hours to evaporate (40 ml and probably also water from previous adjustments).

3.2 Prototype test 2

The second test (test 2) is done with the same prototype, on a sunny day in the living, located at the South side of our house. The climate circumstances where different than the first test. During the 5:40:00 hour measurements the mean air temperature around the prototype varies between 22,7 and 24,7 °C with an average relative humidity of averaging 39% (first test was between 18,7 and 19,5 °C with a mean relative humidity of 45 – 48%). The measurement results of test 2 are shown in fig. 58. Every adjustment is numbered in periods, each period is explained according to the proceedings.

During the test period several adjustments occurred;

Humidify	Ventilation on	Ventilation off
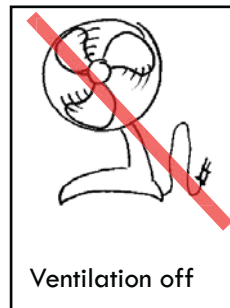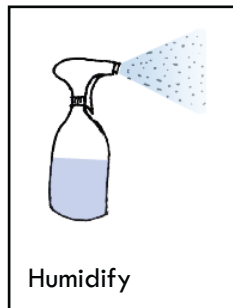
Circumstances test 2:

- Date: 11-3-2011
- Time: 12.00 – 17.40
- Location: Living (South)
- Temperature: 22,7 - 24,7 °C
- Humidity: Between 39%
- Water temperature: 22,7 °C
- Distance fan: 1500mm (angle 90°)
- Fan speed: 0,35 & 0,45 m/s

P1. After positioning the test element, the sand layer is humidified with ± 20 ml sprayed water (average room temperature 22,7 °C).

During a period of 60 minutes the inside air temperature decrease with 1,1 K (21,2 to 20,1 °C), while the mean outside air temperature rises from 22,7 to 23 °C. The temperature in the sand layer, at the side where the evaporation process arises, reach 18 °C.

0.00.00 till 1.00.00

	Temp 1 (°C)	Temp 2 (°C)	Diff. (K)
Outside	22,7	23,3	0,6
Inside	21,2	20,1	-1,1

Fig. 49 Start & end temp. measurements

Temp. diff.
In- & out
3,2 K

P2. After 1:00 hour the sand layer is humidified, sprayed with ± 20 ml water on room temperature (22,7 °C). The inside air temperature and the temperature in the sand layer decreased softly, when the outside temperature is increasing.

1.00.00 till 1.40.00

	Temp 2 (°C)	Temp 3 (°C)	Diff. (K)
Outside	23,3	23,8	0,5
Inside	20,1	20	-0,1

Fig. 50 Start & end temp. measurements

Temp. diff.
In- & out
3,8 K

36

P3. After 1:40 hours the sand layer is humidified, sprayed with ± 20 ml water on room temperature (22,7 °C). During these 20 minutes all the measured temperatures approximately even.

	Temp 3 (°C)	Temp 4 (°C)	Diff. (K)
Outside	23,7	23,7	0
Inside	20	20	0

Fig. 51 Start & end temp. measurements

Temp. diff.

In- & out

3,7 K

P4. After 2:00 hours the sand layer is humidified, sprayed with ± 20 ml water on room temperature (22,7 °C) and turned on the fan (low speed 0,35 m/s). The fan is placed at a distance of 1,5 m perpendicular to the back of the prototype at the same height. The sand layer temperature drops immediately because the ventilation accelerates the evaporation process. Also the indoor air temperature decrease, but less and with a delay.

	Temp 4 (°C)	Temp 5 (°C)	Diff. (K)
Outside	23,7	23,9	0,2
Inside	20	19,7	-0,3

Fig. 52 Start & end temp. measurements

Temp. diff.

In- & out

4,2 K

P5. After 2:35 hours the sand layer is humidified, sprayed with ± 20 ml water on room temperature (22,7 °C), while the fan is running. The sand temperature and the inside temperature are still declining, while the average outside temperature is rising slowly.

	Temp 5 (°C)	Temp 6 (°C)	Diff. (K)
Outside	23,9	24,1	0,2
Inside	19,7	19,5	-0,2

Fig. 53 Start & end temp. measurements

Temp. diff.

In- & out

4,2 K

P6. After 3:00 hours the sand layer is humidified, sprayed with ± 20 ml water on room temperature (22,7 °C), while the fan is running. The measured temperatures stays stable during these 15 minutes.

	Temp 6 (°C)	Temp 7 (°C)	Diff. (K)
Outside	24,1	24,3	0,2
Inside	19,5	19,6	0,1

Fig. 54 Start & end temp. measurements
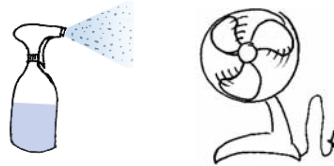
Temp. diff.
In- & out
4,7 K

P7. After 3:15 hours the sand layer is humidified with ± 40 ml sprayed water (room temperature, 22,7 °C), while the fan is running. The temperature in the sand layer stays stable, the outside and inside air temperature rises slowly.

	Temp 7 (°C)	Temp 8 (°C)	Diff. (K)
Outside	24,3	24,6	0,3
Inside	19,6	19,9	0,3

Fig. 55 Start & end temp. measurements
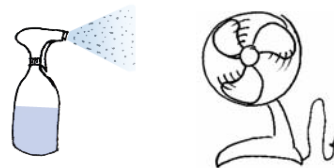
Temp. diff.
In- & out
4,7 K

P8. A fter 4:05 hours the sand layer is humidified with ± 20 ml sprayed water (room temperature 22,7 °C), the fan is turned on high speed (0,45 m/s). In this 50 minutes period the highest temperature difference between inside air and the sand layer is reached, a difference of 3 Kelvin. With these data the maximum cooling demand is calculated (see calculations at page 42). The fan speed has influence on the cooling method, but also the climate circumstances are important. The maximum cooling capacity is reached by the highest temperature during the measurements with the lowest relative humidity.

	Temp 8 (°C)	Temp 9 (°C)	Diff. (K)
Outside	24,6	24,6	0
Inside	19,9	20	0,1

Fig. 56 Start & end temp. measurements
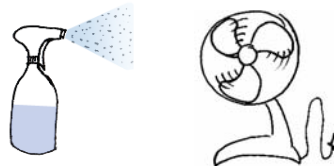
Temp. diff.
In- & out
4,6 K

P9. After 5:07 hours the sand layer is humidified with ± 20 ml sprayed water (room temperature 22,7 °C), fan on high speed. The average outside temperature decreases and the relative humidity rises. After a small temperature increasing in the sand layer, the temperature turns back to where it was at the end of step 8.

	Temp 9 (°C)	Temp 10 (°C)	Diff. (K)
Outside	24,6	24,2	-0,4
Inside	20	20,1	0,1

Fig. 57 Start & end temp. measurements

Temp. diff.

In- & out

4,1 K

P10. After 5.40 hours the second test is finished.
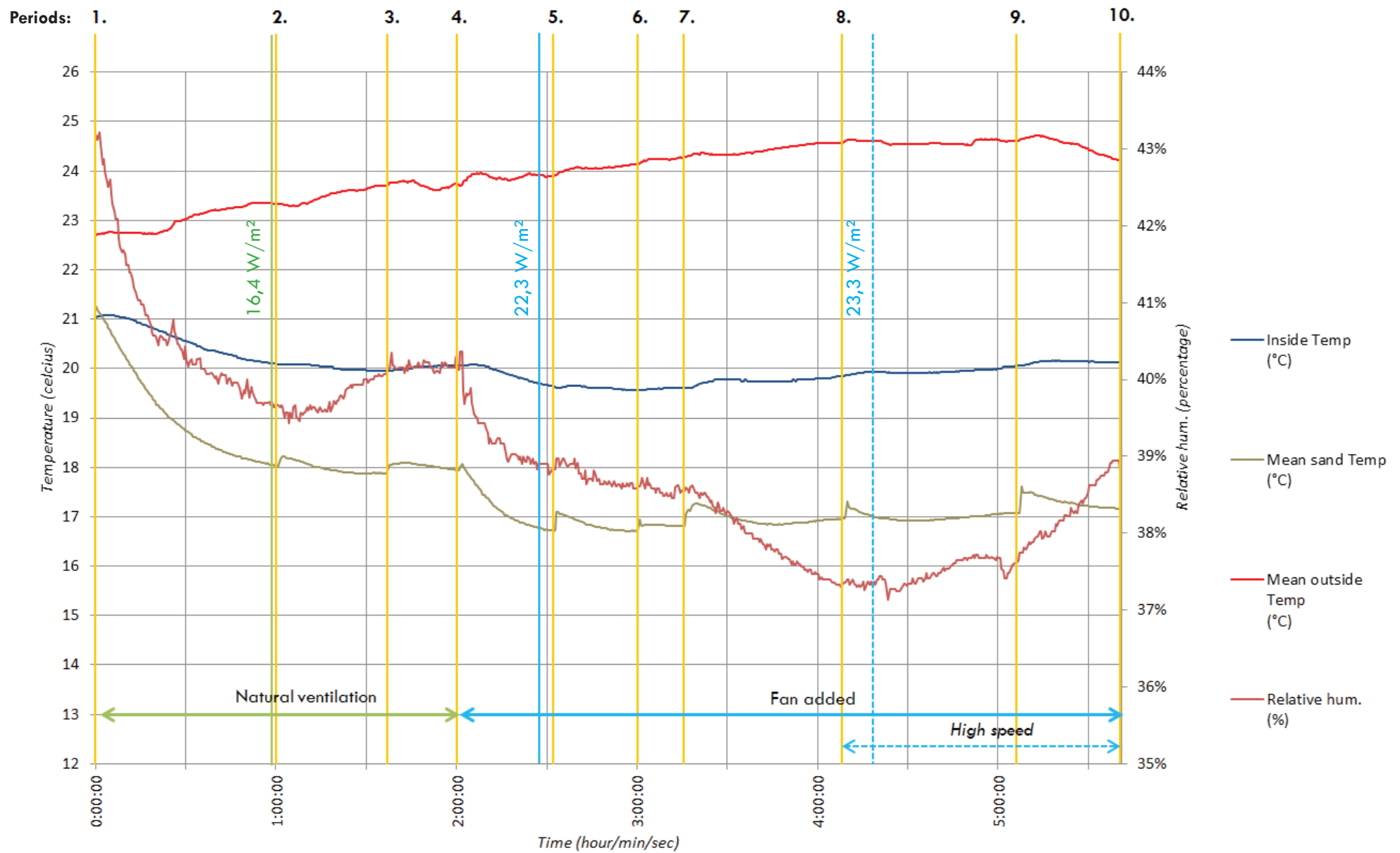
Fig. 58 Mean measurements of test 2, detailed measurements are retrievable in the appendix

3.2.1 Calculations test 2

In test 2 are the same three different ways of ventilation used (natural ventilation, fan high- and low speed). But because the fans position is changed the airspeed increased.
- Low speed 0,35 m/s, instead of 0,2 m/s
- High speed 0,45 m/s, instead of 0,3 m/s

To calculate the capacity for these three ventilation approaches the same formulas and material properties which are used in the first test:

$Q = U \cdot \Delta T$

Sandlayer			Steelplate			hroom	7,8
Thickness	0,007 m		Thickness	0,0015 m		Rroom	0,128205128 W/(m²/K)
Lamda	2 W/m·K		Lamda	50 W/m·K			
Rsand	0,0035 W/(m²/K)		Rsteel	0,00003 W/(m²/K)		**Ucon**	**7,59098969 W/(m²/K)**

The maximum cooling capacity during test 2, with natural ventilation (0:00:00 till 2:00:00 hr) is reached after 0:59:30 hours (Indicated with a green line in fig 58).

Measured conditions highest cooling cap.		Measured conditions highest coolingcap.	
Time:	0:59:30		
Tinside	20,103 °C	Toutside	23,341 °C
Tsand	17,938 °C	Rel. hum	39,668 %
ΔT	2,165 K		

Cooling capacity:

$Q = U \cdot \Delta T$
$Q = 7,59098969 \cdot 2,165$
$Q = 16,434 \ W/m^2$

Tsand:17,9 °C

Tout:23,3 °C   Tin:20,1 °C
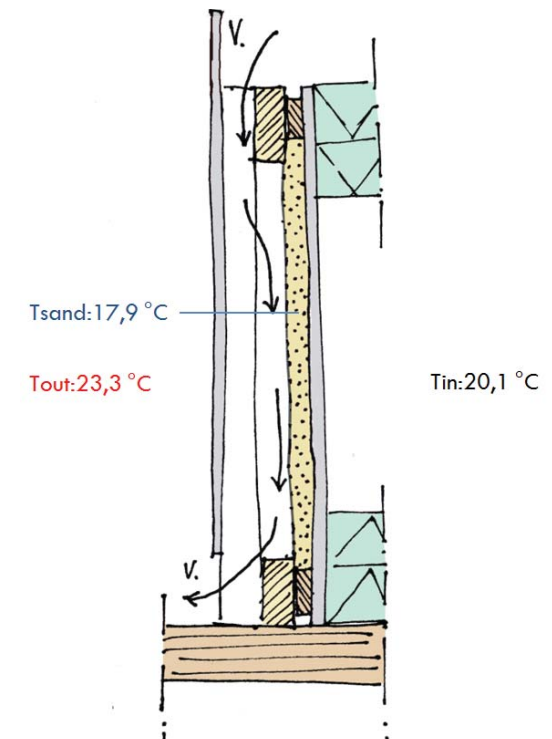
Fig. 59 Temperatures test 2 natural ventilation

The maximum cooling capacity during test 2, by adding a fan on low speed (0,35 m/s 2:00:00 till 4:10:00 hr) is reached after 2:26:00 hours (Indicated with blue line in fig 58).

Measured conditions highest cooling cap.	
Time:	2:26:00
Tinside	19,722 °C
Tsand	16,7845 °C
ΔT	**2,9375 K**

Measured conditions highest cooligcap.	
Toutside	23,924 °C
Rel. hum	38,933 %

Cooling capacity:

$Q = U \cdot \Delta T$
$Q = 7,59098969 \cdot 2,9375$
Q = 22,299 W/m²

The maximum cooling capacity during test 2, by adding a fan on high speed (0,45 m/s 4:10:00 till 5:40:00 hr) is reached after 4:17:30 hours (Indicated with blue line in fig 58).

Measured conditions highest cooling cap.	
Time:	4:17:30
Tinside	19,912 °C
Tsand	16,844 °C
ΔT	**3,068 K**

Measured conditions highest cooligcap.	
Toutside	24,557 °C
Rel. hum	37,409 %

Cooling capacity:

$Q = U \cdot \Delta T$
$Q = 7,59098969 \cdot 3,068$
Q = 23,289 W/m²

Tsand:16,8 °C

Tout:24,6 °C

Tin:19,9 °C
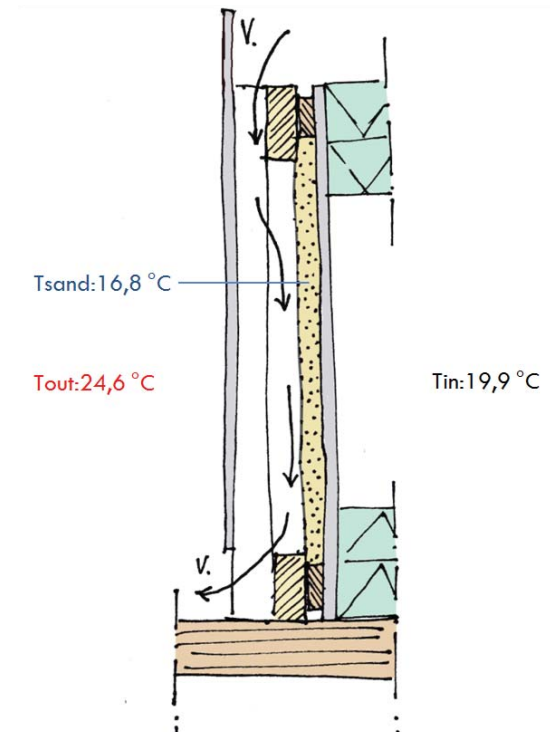
Fig. 60 Temperatures test 2 fan added (high speed)

3.2.4 Results test 2

The results of the prototype 2, test 2 (§ 3.2, page 36), shows how effective the passive cooling system is under different climate circumstances. This test is made on a sunny day at the South side of the house (living room). The prototype and the measurement sensors aren`t exposed to direct solar radiation (positioned in the shadow).

During the test the inside air temperature reduces with 1,5 Kelvin (21,1 to 19,6 °C), by a relative humidity between 37,1 and 43,2 % and average outside air temperature of 24 °C.

By natural ventilation (0:00:00 - 2:00:00 hr) a cooling effect is generated, the sand layer temperature decreases with 3,7 K (21,5 to 17,8 °C) by evaporating water with a temperature of 22,7 °C. The air temperature inside the prototype lowered with 1,1 Kelvin (21,1 to 20 °C). The cooling capacity increase when the fan is turned on (2:00:00 till end) the temperature of the sand layer drops with 1,4 Kelvin in the first 35 minutes, also the inside air temperature decrease with 0,5 Kelvin. The fan speed has influences on the cooling process.

Also in these measurements the temperature in the sand layer are lower than the inside air temperature. The temperature in the sand layer at the mesh surface are lower than at the steel plate.

The double quantity of sprayed water doesn`t affect the cooling capacity on short terms (3:15:00 hours), the temperatures stays the same, but the evaporation time will be extended.

3.3 Conclusion & comparison tests

The climate circumstances where an adiabatic cooling method is used are important, these influences the evaporation process and thus the cooling capacity. In the first test the air temperatures where colder, with a higher relative humidity than in the second test. This can be reflected to the calculations of the cooling capacity, which are higher in test 2, by dryer and warmer climate circumstances (fig 61).

Average climate conditions	Test 1:	Test 2:	Differences
• Outside temp. (°C)	18,946	23,974	5,028
• Relative hum. (%)	45,659	38,931	-6,728
Max cooling cap.			
• Natural (W/m²)	13,747	16,434	2,687
• Fan low speed (W/m²)	16,138	22,299	6,161
• Fan high speed (W/m²)	14,878	23,289	8,411

In the Psychrometric chart both tests are shown (test 1 red line, test 2 green line), the enthalpy stays the same. The starting temperature of the incoming air in the first test was 19 °C with a relative humidity of 45,6%. The evaporation process decrease the temperature till a minimum of 13,8 °C, what results in a Relative humidity of 92% (fig 61). In test two the starting temperature of the incoming air was 23,9 °C and a relative humidity of 38,9%. The temperature decreases till 16,6 °C and a relative humidity of 86%.

In the first test the maximum relative humidity of 92% is reached, in the second the maximum was 86%. This can be declared because of the absolute humidity which is in test 2 is higher. The higher the absolute & relative humidity the less evaporation.
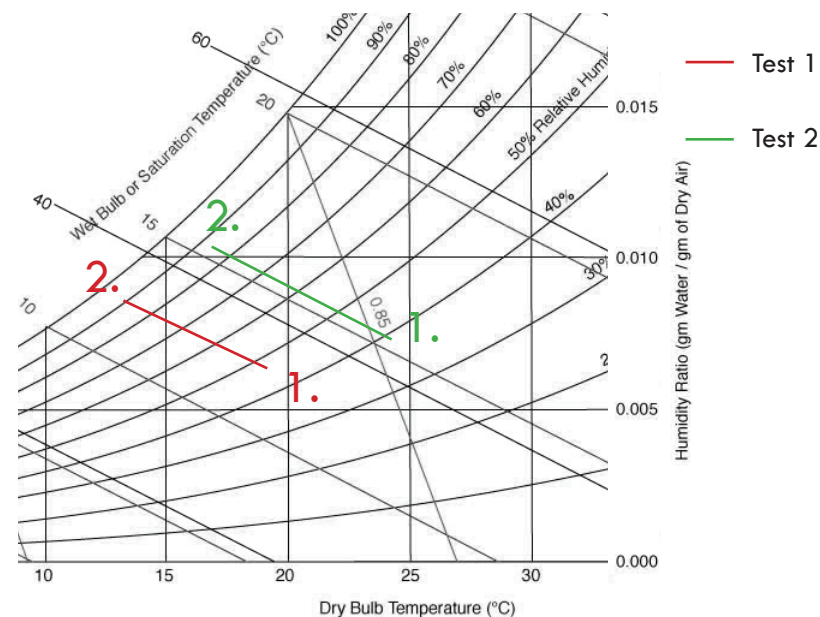
Fig. 61 Psychrometric chart, test 1 & 2

Ventilation is an important aspect for adiabatic cooling, this is also shown in the tests. In test 1 the difference between the maximum cooling capacity (with fan, without or on high speed) are not much. Even with a high ventilation fold a lower cooling capacity is reached than the with the fan on low speed. But in the second test the ventilation speed is very significant. The fan, on high speed is able to cool 6,9 W/m² more than without.

In both tests the absorption layer is humidified with water at room temperature. The amount of added water doesn`t affect the cool influences, unless it`s to less to evaporate. But the more water added, the longer the evaporation process takes place. In test 1 (fig 46) this is clearly visible. After 2:00:00 hours the cooling process ended because 20ml added water in the absorption layer is mostly evaporated. After 5:00:00 hours the absorption layer is humidified with a double amount of water (40ml + the water what was not evaporated), which takes more than 3,5 hours to evaporate.

The aluminium plate at the front of the prototype is needed to generate a better cooling capacity. During the humidifying process the aluminium plate is removed for a few seconds (30 – 50 sec.), which results in higher temperatures. Every time when the absorption layer gets humidified a temperature jump is shown in the graphics (fig 46 & 58).

4. CONCEPT DESIGN

4.0 Design requirements

The results of the prototype shows that an indirect adiabatic cooling method is able to work promising, especially in countries with a dry and warm climate.

According to the results of the prototype, requirements for integrate an adiabatic cooling in the façade are made. Several layers with different properties are necessary to create an ideal cooling performance.
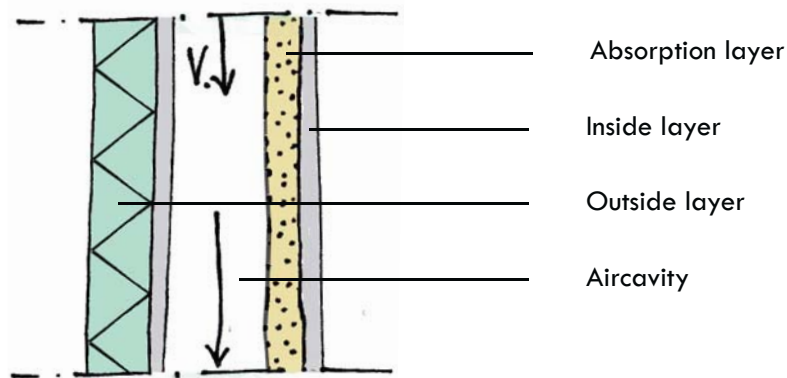
Fig. 62 Section adiabatic cooling

Absorption layer
Inside layer
Outside layer
Aircavity

Absorption layer: This layer is able to absorb and to distribute water over a surface which is used for the evaporation process, in this case sand. Besides an absorption function a high heat transfer coefficient is desirable to extract as much heat as possible, from the back laying area. The thinner the layer, the less it insulate, the more it extract heat. Flowing water can also be used, instead of saturated sand, but costs more energy by re-pumping the water and makes it more difficult to control and integrate within the façade.

Inside layer: The layer behind the absorption layer needs to be water tight & - resistant, rot must be prevented. Direct contact with the room which need to be cooled is a must. Also this layer needs to have a high heat transfer coefficient and can be as tin as possible. Steel would be eligible for this.

Air cavity: Through the air cavity an air ventilation flow will be created to generate and accelerate the evaporation process. Humidified air will be exhaust and fresh dry air will enter the cavity.

Outside layer: This layer separates the cooled air in the cavity with the outside air. To keep the temperature in the cavity cool an insulation material (in steed of aluminum plate) prevents heat transfer. Besides an insulator this layer is also needed to generate an optimum air movement through the cavity. This air gets humidified, so a water resistant material, to protect the insulation layer is required.

The hole cooling system needs to be protected from solar radiation, to prevent heat transfer to the inside, from the sun.

Humidifying system: A humidifying system needs to be integrated to saturate the absorption layer, to starts the evaporation process. There are two ways of humidifying:

Sprinkler system: The absorption layer can be humidified with a sprinkler system, located in the air cavity. The sprinkler saturate the absorption layer and also humidify the air in the cavity directly what leads to cooler air temperatures. But a this system needs high pressure to sprinkle, what leads to high energy consumption and is also more sensitive for legionella.
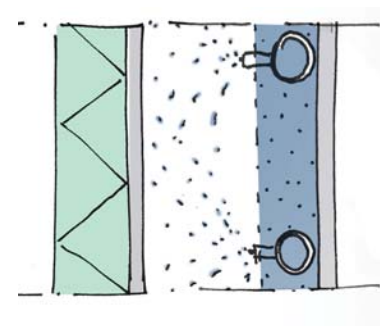
Fig. 63 Sprinkler system   *Fig. 64 Drip system*
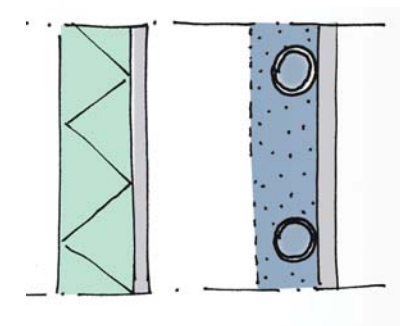
Drip system: A drip system uses less energy, high pressure is not required, and doesn`t have the problems with legionella. This system is integrated in the absorption layer and only saturate the needed surface, less water is therefore needed which is preferable.

A pump is needed to transport the water through the dripping system. Depending on the quantity of water what will evaporate a pump type can be selected and integrated in the design.

Air velocity: To create an air velocity in the air cavity a fan needs to be integrated. Extraction at the end of the duct is preferred instead of a blowing fan in the beginning. When there is a leak it extracts air from the inner space and doesn`t blow the humidified air from the cooling system inside.

Control system: During the season the cooling demand in the building varies. On warm sunny summer days lots of cooling is needed, but also in spring and autumn cooling can be desirable, especially in warm climate zones like Madrid. The capacity of this cooling system reacts naturally on the climate conditions during the season. The warmer and dryer the air, the more evaporation, the higher the cooling capacity. For this evaporation process the quantity of water which is used to saturate the absorption layer influences the cooling capacity in cooperation with the air velocity. These two factors are adjustable and are not dependent on the weather conditions. What makes it possible to control the cooling amount, based on the demands of the user. This is reflected to the results of the tests with the prototype. In the first test a lower air velocity was needed to generate the maximum cooling capacity than in the second test. And also the time it took to evaporate the same amount of water was shorter in the second test.

To control the cooling capacity the air velocity from the inlet and water supply needs to be managed. Sensors located inside the building measures the room temperature. When this is rising above a certain boundary a computer indicates this, and starts the cooling process, by changing the air velocity and saturating the absorption layer. Dripping pipes integrated in the absorption layer driven by a pump humidifying the surface. The air velocity is changeable by adjusting a fan.

Insulation

Air cavity
Absorption
Steel plate
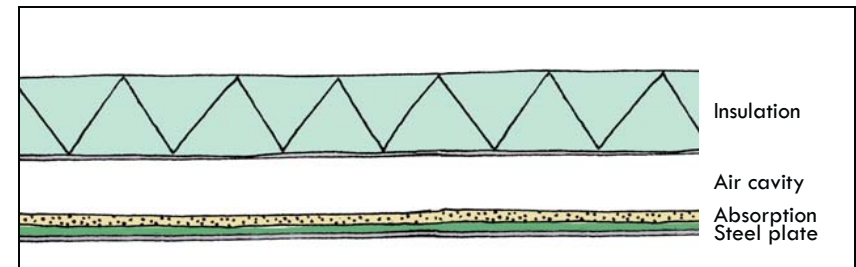
Fig. 65 No cooling
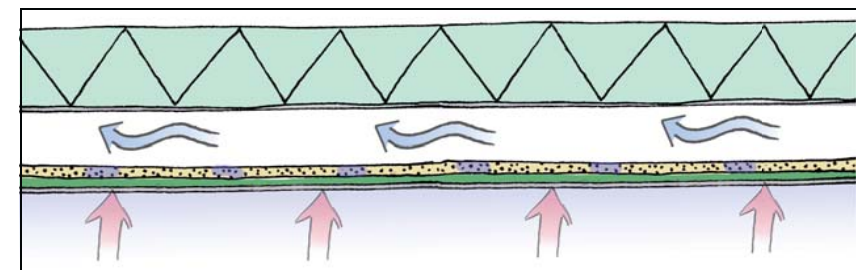
Fig. 66 Evaporation process starts
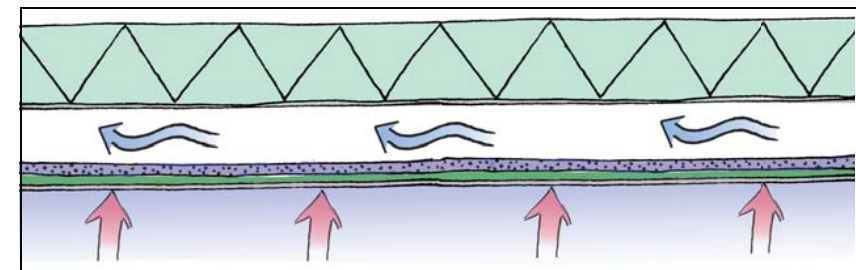
Fig. 67 More evaporation, more cooling
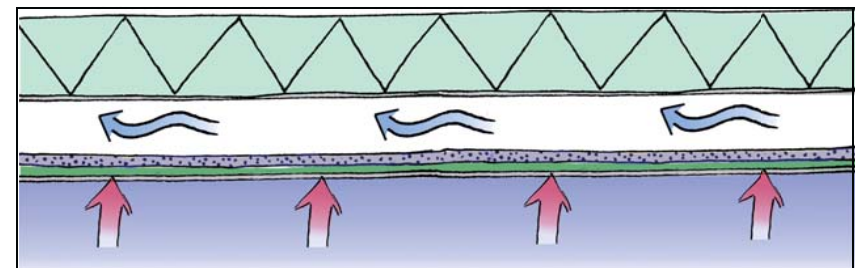
Fig. 68 Maximum cooling

4.1 Design integration

The concept design of the cooling system starts to shape, the next step is to integrate this in the façade. An important aspect is to protect this cooling system from solar radiation, for this reason an insulation is used. This insulation layer can be the same insulation which is normally used to insulate the building thermally.

A surface, covered by the adiabatic cooling system, influences the cooling capacity. By enlarging the surface more cooling can be generated.

Closed and free standing façades surfaces are often covered by furniture, and blocks the cooling system, so why not using the ceiling. The ceiling covers the total building and is able to generate cooling in every place of the room, and not only from the sides. Another advantage of making use of the ceiling is the higher heat transfer coefficient when the ceiling is colder than the inside temperature. In practice the heat transfer coefficient for a wall is 7,8 W/m² K, by an emission coefficient of 0,9 (basic material). This is the sum of the heat coefficient of convection (2,5 W/m² K) and radiation (5,3 W/m² K). The heat transfer coefficient of a ceiling is 11 w/² K, because the convection is 3,2 W/m² K higher[15].

The different heat transfer coefficients influences in this case the cool capacity with almost 40%, fig. 69.

Cool capacity ceiling: 19,18 W/m²
Cool capacity wall: 13,75 W/m²

A simplified section is used to show how this system can be integrated in a building.
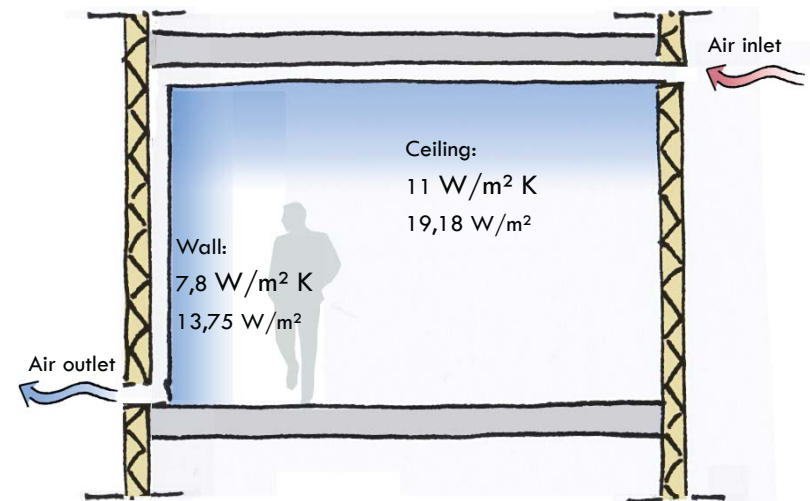
Fig. 69 Integration coolingsystem

To control the air velocity inside the cooling system the speed of the fan can be adjusted according to the cooling demand. To ensure the air velocity is evenly in the cavity, the cooling surface is split in a ducts system, like they are used in air-conditioning systems. A duct system makes it easier to control the air velocity instead of using a whole façade/ceiling surface. Duct systems has les connections than a pre- wall/ceiling, what means it`s easier to keep the system watertight. These systems are common used as air ducts, products like fans, but also connections and corner ducts are market available. And in case of maintenance it`s easier to open a duct system than a whole façade/ceiling.

The width of the ducts is variable, this is depending on the building grids sizes, each size is producible. The span of the duct for a ceiling needs to be taken into account, the wider the duct, the more bending, the bigger the spanning structure.

- Duct
- Dripping system
- Absorption layer

Air inlet

Absorption & watering system

Water pump

Temp. sensor

Control system

Fan

Air outlet
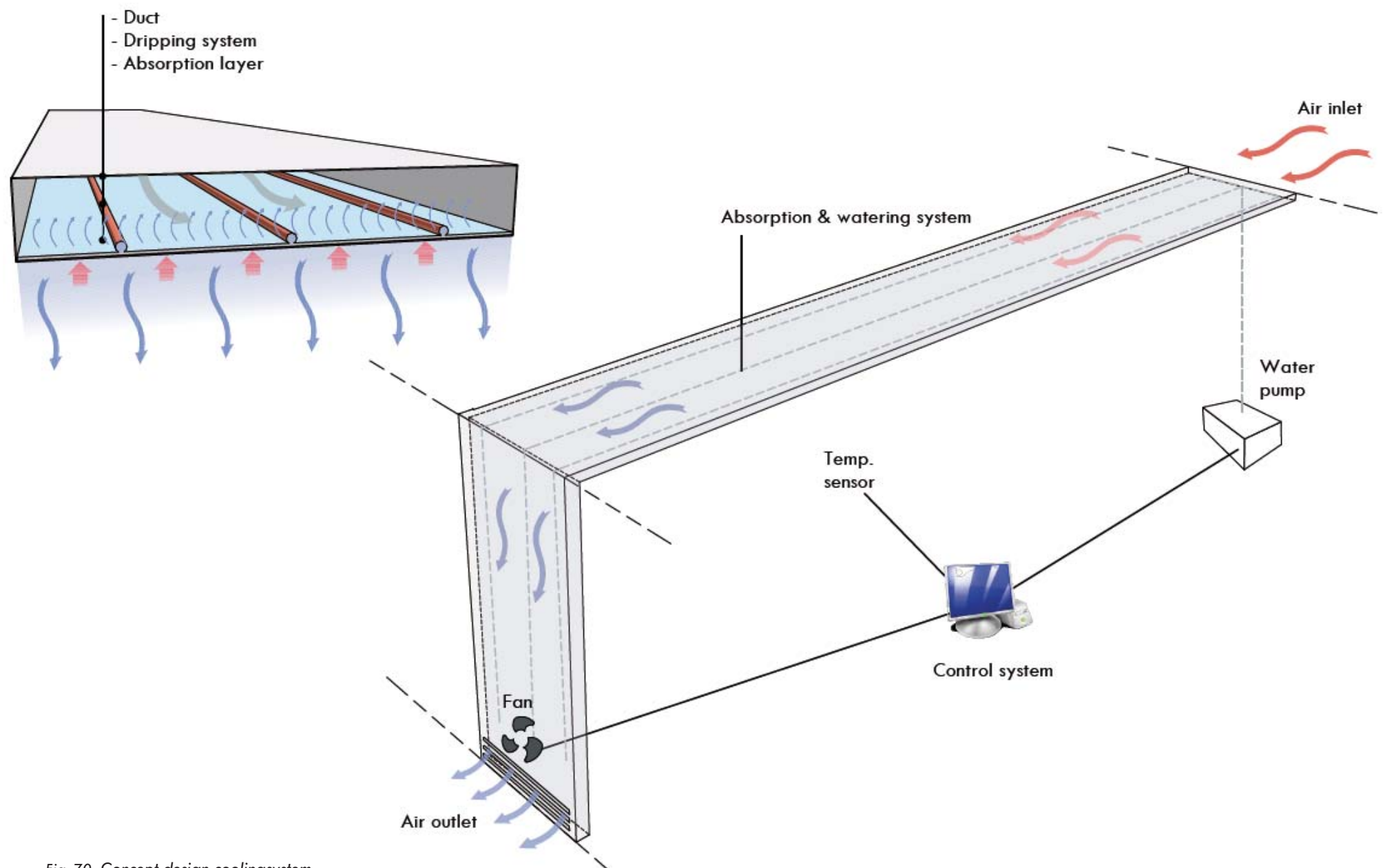
Fig. 70 Concept design coolingsystem

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Duct properties:

The used ducts for the adiabatic cooling system are performed in coated steel. Steel air ducts are nowadays common used in the building industry. Standard dimensions and water tight connections are available. A steel duct is able to make spans without bending, what yields in a smooth surface at the in- and outside of the duct, with a very thin layer. In the future this steel can maybe be replaced by a material which also has a high heat transfer coefficient, and is able to make spans without bending.
By enlarging the cooling surface of the system the capacity increases.
Because the complete adiabatic cooling system is depending by the size of the available surface, the duct profile should create as much surface as possible. Think about the radiator design of the heating systems in the houses. Of course this surface makes it more difficult to humidify the absorption layer. Also the appearance from inside the room gets influenced.

Fig. 71 Enlarging surface

The cooling system uses external air, from outside to generates the evaporation process. This because it reacts automatically on the climate circumstances. The warmer and dryer the air the faster the evaporation and thus the cooling process. A bypass can be applied to use not only outside air, but when it`s more efficient also air from inside. This can occurs when the outside air is humid and warm, while the humidity inside is less.
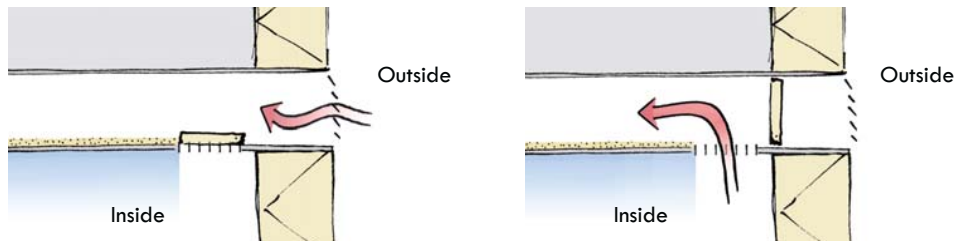
Fig. 72 Air from the room

Heat exchanger:

Heat exchangers are used to transfer heat from one to another medium. In the building sector this medium is often used to pre cool or – heat the incoming fresh air from outside, to save energy. In winter the warm air from inside go`s through the heat exchanger where it conveys the heat to the incoming cold air from outside, fig. 73. Nowadays the high efficiency heat exchangers generates an efficiency of 95 %.
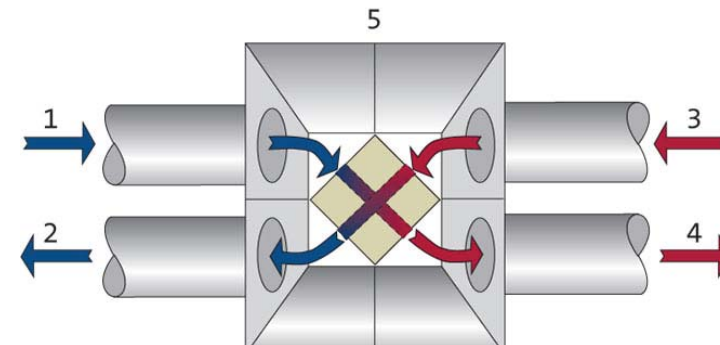
Fig. 73 Heat exchanger[3]

| 1. | Cold fresh air | 3. | Warmed used air |
| 2. | Cold used air | 4. | Pre warmed fresh air |

During the evaporation process the air within the cavity will be humidified and cooled. The cooled air can`t be used directly because it`s to humid, what results in negative inside air conditions. But it should be a huge energy waste to release the cooled air without using it. A heat exchanger is able to use this air to precool the fresh and warm outside air to ventilate the building.

Filtered water:

An important subject for an adiabatic cooling system is water. In this case water needs to be pumped and saturate the absorption layer. Clean water for the evaporation system is recommended to prevent pollution and finally clogging in the system. Rain water and grey water are both usable for evaporation when they are filtered correctly.

3. www.cbs.grundfos.com

Passive techniques:

When this adiabatic cooling method will be used for the Solar Decathlon competition, it needs to be able to cool without using energy from the utilities. Which means, the system needs to be as passive as possible.

The factors which are using energy to let this system operates are the ventilation and water supplies.
The easiest method of making use of a passive ventilation flow is using wind energy. Persians uses for many centuries a wind catcher to ventilate there houses naturally. A multi directional wind catcher, placed on top of the roof, is able to capture the wind from any direction and lead this into the system. Nowadays wind catchers are a more common product, which can be installed on almost every building.
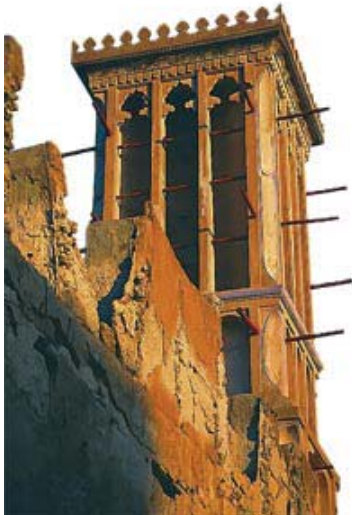
Fig. 74 Wind chatcher middle East[4]

Fig. 75 Wind chatcher nowadays[4]

But not in every dry and warm climate wind is presented and when it is, wind is always unpredictable.

Another method is using a solar chimney, which consist of an heat absorption layer, covered by a glass sheet. The air inside the chimney heats up during the day by the sun and creates a natural draft. The suction at the base of the chimney can be used to extract air from the cavity of the cooling method, fig. 76.
The stack effect, created by the solar chimney, increases by adding a eaves which generates a venturi effect. When wind passes through the smaller channel it increases the wind speed and extract air from the solar chimney.

All these passive techniques are able to work, when the climate conditions are suitable. But a backup system, like a fan, is still recommended.
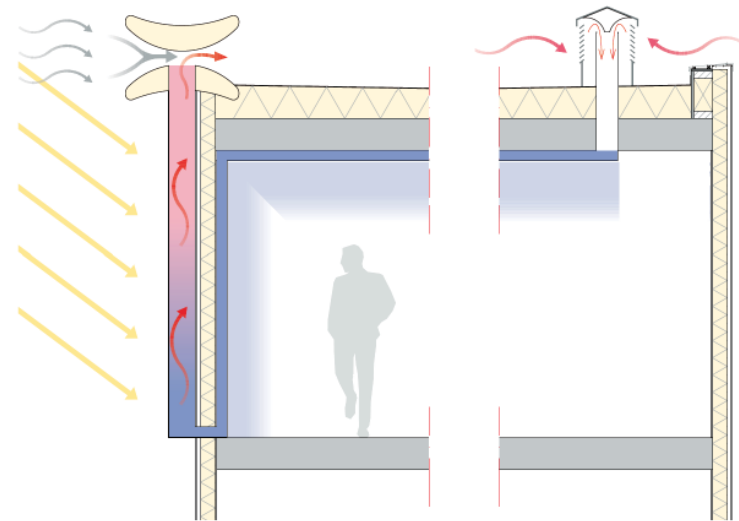
Fig. 76 Section passive techniques

4. www.monodraught.com

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5. SIMULATIONS

5.1 Simulations

According to the test results of the prototype and the first conceptual ideas a simulation model, made by Dr. Ir. Willem van der Spoel, (Building physical specialist from the Technical University of Delft) is used to calculate the cooling capacity. The outcome of the calculations are based on the climate conditions and duct - and airflow properties. The calculations of the prototype tests are compared with the simulation model, to check if these are matching.

	Natural	Fan	Fan high speed
Prototype (W/m²)	13,75	16,14	14,88
Simulation (W/m²)	13	19	19

Fig. 77 Comparison test 1

	Natural	Fan	Fan high speed
Prototype (W/m²)	16,43	22,3	23,29
Simulation (W/m²)	16	23	24

Fig. 78 Comparison test 2

In both simulations the differences between the calculations of the prototype and the results out of the simulations, doesn`t differ much. In the first comparison according to test 1 the capacity in the prototype are a little less than in the simulations, in the second test this is vice versa. The difference can be a result of the position of the fan. In the first test the fan was positioned under an angle of 30 degrees, what will decrease the air speed and then subsequently the cool capacity.

Because this cooling method will be build and applied in September 2012 in Madrid, the climate conditions of Madrid on a warm day (3rd of September) are insert in the simulation model, fig. 80. Subsequently a duct system (dimension: 6 x 1 x 0,05m l,w,h) with the same insulation value as in the prototype (0,004 m² K/W), the required inside room temperature (24 °C) and heat transfer coefficient are filled in. Finally the air velocity inside the duct in combination with the water quantity determined the cooling capacity. Air velocity is needed to accelerate the evaporation process, the higher the air velocity the more cooling. A higher air velocity also generates

a higher heat transfer between the inside air in the duct and the material of the duct. But as shown in fig. 79 the cooling increase reduces by higher air velocities. Meaning, more energy is needed to create higher velocities to increase the cooling capacity, while this slower rises.

In the same figure the quantity of needed water for the evaporation process is shown. The higher the air velocity the more water will evaporate, this increases with a linear growth. According to the cooling demand the needed surface, air velocity and water quantity can be determined for each climate conditions.

In this simulation, according to the climate conditions of the warmest time on the 3rd of September 1999, a cool capacity of 48 W/m² is feasible, by an air velocity of 1,5 m/s. 0,13 liters water per hour per square meter are needed for the evaporation process.
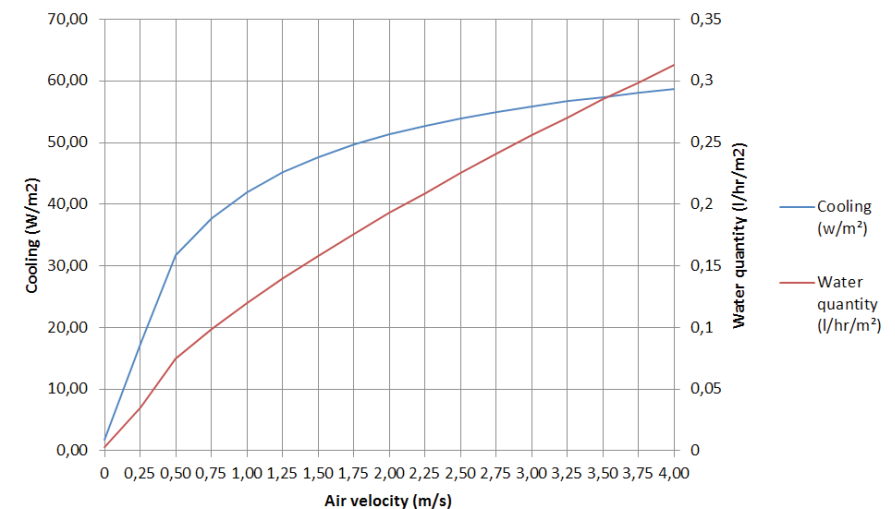
Fig. 79 Response air velocity

In the simulation model the climate behavior of the air inside the duct (relative humidity and temperature) and the temperatures of the duct under the evaporation layer are calculated for each 0,3 m¹.

5.1.1 Simulation 1

RECTANGULAR ZEER POT DUCT
length 6 m
width 1 m
height 0,05 m
R_c 0,004 m²K/W
dx 0,3 m

OUTSIDE AIR
m_air_in 0,09 kg/s
t_air_in 29,4 °C
rho_air 1,2 kg/m3
c_air 1007 J/kgK
v_air 1,50 m/s

VAPOUR OUTSIDE AIR
cv_air_in 0,0073 kg/kg
RH_in 30 %
rho_v_in 0,0088 kg/m3
c_vap 1864 J/kg/K
L_wat 2,49E+06 J/kg

INSIDE AIR
t_room 24 degr C

HEAT TRANSFER
h_c 8,2 W/m2K
h_room 11,0 W/m2K

Start calculation

COOLING POWER
total 285,7 W
specific 48 W/m² duct

air properties at 20 C
nu_air 1,50E-05 m2/s kinematic viscosity
la_air 2,57E-02 W/mK heat conduction coeffic
Pr_air 7,05E-01 Prandtl number

flow / duct properties
Re_flow 9,52E+03 Reynolds number
d_h 9,52E-02 m hydraulic diameter
Nu_flow 3,05E+01 Nusselt number

AIR + VAPOUR

length in duct m	temp air °C	rho vapour kg/m³	p_d_l vapour in air Pa	RH %
0	29,4	0,00876	1224,456	29,87405
0,3	29,11948	0,008977	1253,564	31,08339
0,6	28,84799	0,009188	1281,953	32,29035
0,9	28,58526	0,009395	1309,647	33,49399
1,2	28,33101	0,009597	1336,666	34,69341
1,5	28,08499	0,009794	1363,033	35,88773
1,8	27,84693	0,009987	1388,767	37,07614
2,1	27,6166	0,010175	1413,888	38,25784
2,4	27,39376	0,010359	1438,415	39,43209
2,7	27,17818	0,010539	1462,366	40,59819
3	26,96963	0,010715	1485,758	41,75546
3,3	26,76791	0,010888	1508,609	42,90328
3,6	26,5728	0,011056	1530,935	44,04107
3,9	26,3841	0,011221	1552,75	45,16826
4,2	26,20163	0,011382	1574,071	46,28434
4,5	26,02518	0,011539	1594,912	47,38884
4,8	25,85458	0,011693	1615,287	48,48131
5,1	25,68966	0,011844	1635,209	49,56133
5,4	25,53023	0,011991	1654,692	50,62854
5,7	25,37613	0,012136	1673,748	51,68259
6	25,2272	0,012277	1692,389	52,72317

INNER WALL DUCT

t_room °C	t_wall temperature at wall °C	p_d_w vapour pres at wall Pa	control	control
24	19,0831094	2207,26565	2207,266	4,5314E-06
24	19,1288471	2213,57585	2213,576	4,4867E-06
24	19,1738606	2219,80154	2219,802	4,4429E-06
24	19,2181751	2225,94549	2225,945	4,3998E-06
24	19,2618143	2232,01031	2232,01	4,3576E-06
24	19,3048005	2237,99851	2237,999	4,316E-06
24	19,3471552	2243,91245	2243,912	4,275E-06
24	19,3888985	2249,75439	2249,754	4,2345E-06
24	19,4300497	2255,52647	2255,526	4,1946E-06
24	19,470627	2261,23072	2261,231	4,1551E-06
24	19,5106479	2266,86909	2266,869	4,1161E-06
24	19,5501288	2272,44341	2272,443	4,0774E-06
24	19,5890855	2277,95544	2277,955	4,0391E-06
24	19,6275328	2283,40686	2283,407	4,001E-06
24	19,665485	2288,79926	2288,799	3,9632E-06
24	19,7029557	2294,13416	2294,134	3,9256E-06
24	19,7399579	2299,413	2299,413	3,8882E-06
24	19,7765038	2304,63716	2304,637	3,8509E-06
24	19,8126053	2309,80796	2309,808	3,8138E-06
24	19,8482735	2314,92666	2314,927	3,7768E-06
24	19,8835192	2319,99446	2319,994	3,7399E-06

HEAT TRANSFER WALL

surface area per m³ m²/m³	mass tranf. v->w kg/(m³s)	P latent W/m³	P sensible walls W/m³
20	-0,00108	-2733,686566	1697,56018
20	-0,00106	-2670,364976	1643,8768
20	-0,00103	-2608,801732	1591,79917
20	-0,00101	-2548,941408	1541,27715
20	-0,00099	-2490,730591	1492,26232
20	-0,00096	-2434,117794	1444,70793
20	-0,00094	-2379,053375	1398,56882
20	-0,00092	-2325,489457	1353,80138
20	-0,0009	-2273,379855	1310,36349
20	-0,00088	-2222,680006	1268,21443
20	-0,00086	-2173,3469	1227,31484
20	-0,00084	-2125,33902	1187,62669
20	-0,00082	-2078,616277	1149,1132
20	-0,00081	-2033,139956	1111,7388
20	-0,00079	-1988,872659	1075,46911
20	-0,00077	-1945,778256	1040,27083
20	-0,00075	-1903,82183	1006,1118
20	-0,00074	-1862,969633	972,960846
20	-0,00072	-1823,189041	940,787838
20	-0,00071	-1784,44851	909,563596
20	-0,00069	-1746,717533	879,259875

ROOM COOLING

P_cooling sensible room W	
15,5419	-1,624E-05
15,3973	-1,587E-05
15,255	-1,55E-05
15,115	-1,514E-05
14,977	-1,48E-05
14,8411	-1,446E-05
14,7073	-1,413E-05
14,5753	-1,381E-05
14,4452	-1,35E-05
14,317	-1,32E-05
14,1905	-1,291E-05
14,0657	-1,262E-05
13,9425	-1,235E-05
13,821	-1,208E-05
13,7011	-1,181E-05
13,5826	-1,156E-05
13,4657	-1,131E-05
13,3501	-1,106E-05
13,236	-1,083E-05
13,1233	-1,06E-05
	-1,037E-05
285,651	-0,7596739 kg/h
	-0,1266123 kg/h/m2

Fig. 80 Simulation model made by W. van der Spoel

Outside air conditions:
Temperature 29,4 °C
Relative humidity 30 %

Duct properties:
Length 6 m
Width 1 m
Height 0,05 m
R_duct 0,004 m² K/W

Others:
Temp inside 24 °C
Air speed 1,5 m/s
H_room 11 W/m² K
H_c 8,2 W/m² K

Results:
Cooling cap. 48 W/m²
Water quant. 0,13 L/hr/m²

In the previous simulation the warmest hour of 3 September 1999 is calculated, but how does the behavior of the cool method function over a hole day? In the next example the recommend maximum cooling* only according to the outside heat is taken into account (without solar - and internal heat), by a maximum required inside temperature of 24 °C. From 11.00 till 21.20 hour outside temperatures reached above 24°C. The cooling process operates from 10.00 till 22.00 hour, fig. 81. The same duct properties are used as in the previous simulation.

During the day the relative humidity decreases and the outside air temperature rises till 16.00 pm. Simultaneously with the air velocity and water quantity and thus the cooling capacity.

The cooling capacity is calculated with low air velocities (0 – 1,5 m/s), this costs less energy. Besides saving energy it`s also recommended to have extra cool capacity for the higher peaks. According to the calculations of the 3rd September 861 g/m² water is needed to provide the achieved cool capacity, as shown in fig. 82.

Depending on solar - and internal heat losses, the cooling demand for a building can be calculated and then the minimum surface for the cool system determined.
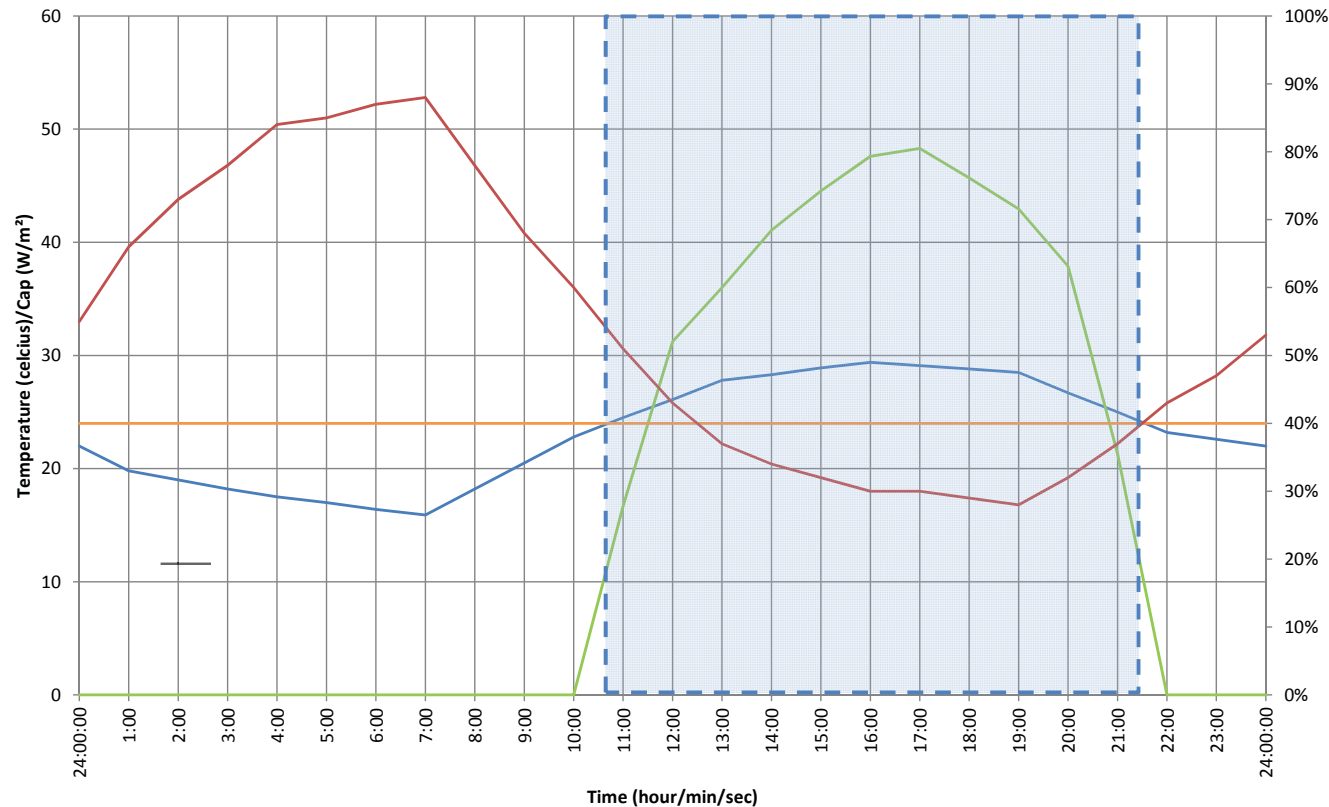
Fig. 81 Conditions 3rd September 1999, Madrid

HH:MM	Dry Bulb Temperature (C)	Relative Humidity (%)	Cooling cap. (W/m²)	Air velocity (m/s)	Water amount (kg/m²/hr)
11:00	24,50	51%	17	0,25	0,021
12:00	26,10	43%	31	0,5	0,05
13:00	27,80	37%	36	0,75	0,07
14:00	28,30	34%	41	1	0,089
15:00	28,90	32%	45	1,25	0,108
16:00	29,40	30%	48	1,5	0,127
17:00	29,10	30%	48	1,5	0,126
18:00	28,80	29%	46	1	0,099
19:00	28,50	28%	43	0,75	0,083
20:00	26,70	32%	38	0,5	0,061
21:00	25,00	37%	21	0,25	0,027
				Total	0,861 kg/m²
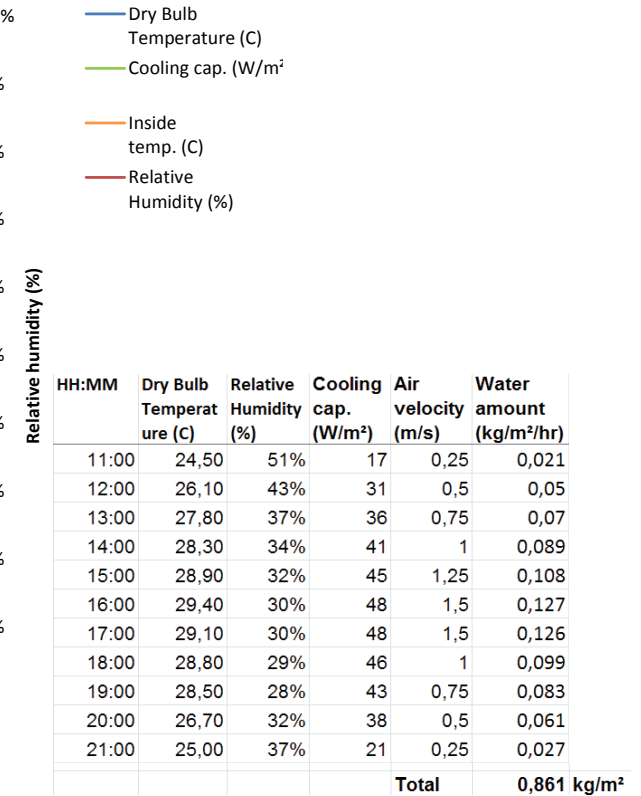
Fig. 82 Results 3rd Sept '99, Madrid

5.1.2 Simulation 2

RECTANGULAR ZEER POT DUCT

length	6	m
width	1	m
height	0,05	m

R_c	0,004	m²K/W

dx	0,3	m

OUTSIDE AIR

m_air_in	0,09	kg/s
t_air_in	30,3	°C

rho_air	1,2	kg/m3
c_air	1007	J/kgK
v_air	1,50	m/s

VAPOUR OUTSIDE AIR

cv_air_in	0,00513128	kg/kg

RH_in	20	%
rho_v_in	0,0062	kg/m3
c_vap	1864	J/kg/K
L_wat	2,49E+06	J/kg

INSIDE AIR

t_room	24	degr C

[Start calculation]

HEAT TRANSFER

h_c	8,2	W/m2K
h_room	11,0	W/m2K

COOLING POWER

total	350,7	W
specific	58	W/m² duct

air properties at 20 C

nu_air	1,50E-05	m2/s	kinematic viscosity
la_air	2,57E-02	W/mK	heat conduction coeffic
Pr_air	7,05E-01		Prandtl number

flow / duct properties

Re_flow	9,52E+03		Reynolds number
d_h	9,52E-02	m	hydraulic diameter
Nu_flow	3,05E+01		Nusselt number

length in duct	AIR + VAPOUR temp air	rho vapour	p_d_l vapour in air	RH	INNER WALL DUCT t_room	t_wall temperature at wall	p_d_w vapour pres at wall		HEAT TRANSFER WALL surface area per m³	mass tranf. P v -> w per m³	latent	P sensible walls	ROOM COOLING P_cooling sensible room
m	°C	kg/m³	Pa	%	°C	°C	Pa		m²/m³	kg/(m³s)	W/m³	W/m³	W
								control control					
0	30,3	0,006158	863,2491	20	24	17,9398111	2054,55469	2054,554 0,00080633	20	-0,00131	-3310,821805	2033,76826	19,1558 -1,969E-05
0,3	29,96174	0,00642	899,048	21,2373	24	17,9992109	2062,25492	2062,254 0,00088881	20	-0,00128	-3232,873095	1968,33652	18,968 -1,922E-05
0,6	29,6346	0,006676	933,9331	22,48009	24	18,0575659	2069,84427	2069,843 0,00097516	20	-0,00125	-3157,146829	1904,90706	18,7836 -1,877E-05
0,9	29,31824	0,006927	967,9347	23,7271	24	18,1149113	2077,32609	2077,326 1,8245E-08	20	-0,00122	-3083,568495	1843,4157	18,6023 -1,833E-05
1,2	29,0123	0,007171	1001,082	24,97709	24	18,1712915	2084,70503	2084,705 2,0928E-08	20	-0,00119	-3012,070663	1783,79876	18,4241 -1,791E-05
1,5	28,71645	0,00741	1033,403	26,22884	24	18,226738	2091,9841	2091,984 2,3868E-08	20	-0,00117	-2942,584438	1725,99666	18,2488 -1,749E-05
1,8	28,43038	0,007643	1064,924	27,48118	24	18,2812839	2099,16662	2099,167 2,7065E-08	20	-0,00115	-2875,044838	1669,95141	18,0764 -1,709E-05
2,1	28,15378	0,007871	1095,671	28,73299	24	18,3349606	2106,25572	2106,256 3,0541E-08	20	-0,00111	-2809,389325	1615,60707	17,9067 -1,67E-05
2,4	27,88635	0,008094	1125,67	29,98318	24	18,3877977	2113,25437	2113,254 3,4299E-08	20	-0,00109	-2745,5577	1562,90971	17,7397 -1,632E-05
2,7	27,6278	0,008311	1154,943	31,23071	24	18,4398236	2120,16543	2120,165 3,8342E-08	20	-0,00106	-2683,491998	1511,80732	17,5753 -1,595E-05
3	27,37786	0,008524	1183,514	32,47457	24	18,4910649	2126,99156	2126,992 4,2693E-08	20	-0,00104	-2623,136385	1462,24968	17,4133 -1,559E-05
3,3	27,13625	0,008732	1211,405	33,71381	24	18,541547	2133,73534	2133,735 4,735E-08	20	-0,00102	-2564,437068	1414,18834	17,2537 -1,524E-05
3,6	26,90272	0,008935	1238,637	34,94751	24	18,5912939	2140,39919	2140,399 5,2321E-08	20	-0,00099	-2507,342208	1367,57656	17,0965 -1,49E-05
3,9	26,677	0,009134	1265,23	36,1748	24	18,6403286	2146,98543	2146,985 5,7617E-08	20	-0,00097	-2451,801829	1322,36916	16,9415 -1,457E-05
4,2	26,45887	0,009328	1291,204	37,39487	24	18,6886728	2153,49625	2153,496 6,3234E-08	20	-0,00095	-2397,767748	1278,52255	16,7887 -1,425E-05
4,5	26,24808	0,009518	1316,579	38,60691	24	18,7363471	2159,93376	2159,934 6,9189E-08	20	-0,00093	-2345,193491	1235,99461	16,638 -1,394E-05
4,8	26,04441	0,009704	1341,371	39,8102	24	18,7833713	2166,29995	2166,3 7,5479E-08	20	-0,00091	-2294,034226	1194,74465	16,4893 -1,363E-05
5,1	25,84763	0,009886	1365,599	41,00403	24	18,829764	2172,59671	2172,597 8,2114E-08	20	-0,00089	-2244,246693	1154,73335	16,3427 -1,334E-05
5,4	25,65754	0,010064	1389,279	42,18776	24	18,875543	2178,82586	2178,826 8,9089E-08	20	-0,00087	-2195,789139	1115,92272	16,198 -1,305E-05
5,7	25,47393	0,010238	1412,428	43,36076	24	18,9207254	2184,98911	2184,989 9,6416E-08	20	-0,00085	-2148,621258	1078,27603	16,0552 -1,277E-05
6	25,29659	0,010408	1435,062	44,52247	24	18,9653272	2191,08813	2191,088 1,0409E-07	20	-0,00083	-2102,704129	1041,75776	
													350,698 -0,9180738 kg/h
													-0,1530123 kg/h/m2

Fig. 83 Simulation model made by W. van der Spoel

Outside air conditions:		
Temperature	30,3 °C
Relative humidity	20 %

Duct properties:	
Length	6 m
Width	1 m
Height	0,05 m
R_duct	0,004 m² K/W

Others:	
Temp inside	24 °C
Air speed	1,5 m/s
H_room	11 W/m² K
H_c	8,2 W/m² K

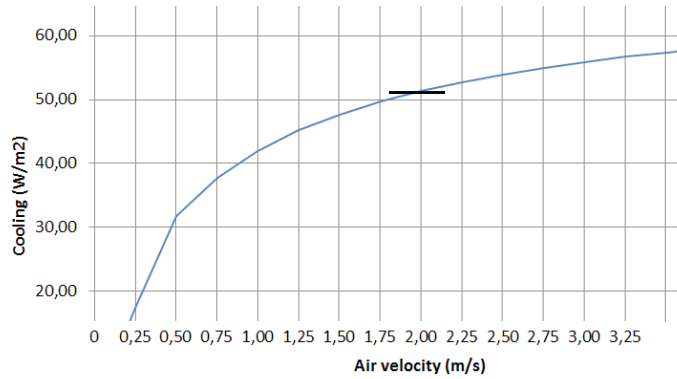| Results:	
Cooling cap.	58 W/m²
Water quant.	0,15 L/hr/m²

Fig. 84 Maximum recommended cool capacity

* Maximum recommended cooling is the ultimate ratio between the obtained cool capacity in relation with the adding the energy which is needed for the air velocity in the duct, fig. 84.

In the next simulation the climate data of the warmest day of September (10th of September 1999) in Madrid is insert, to see what the effect is in warmer and dryer conditions. In this simulation the properties of the used system are the same as in the previous simulation (dimensions, air velocity, material properties). During this day the cool period is an hour longer than the 3rd of September (10.00 - 23.00 instead of 10.00 - 22.00 hr).

In this simulation the peak cool capacity reaches during the warmest period of the day (16.00 hr) till 58 W/m². For these climate circumstances a quantity of 1028 g/m² water a day is evaporating.
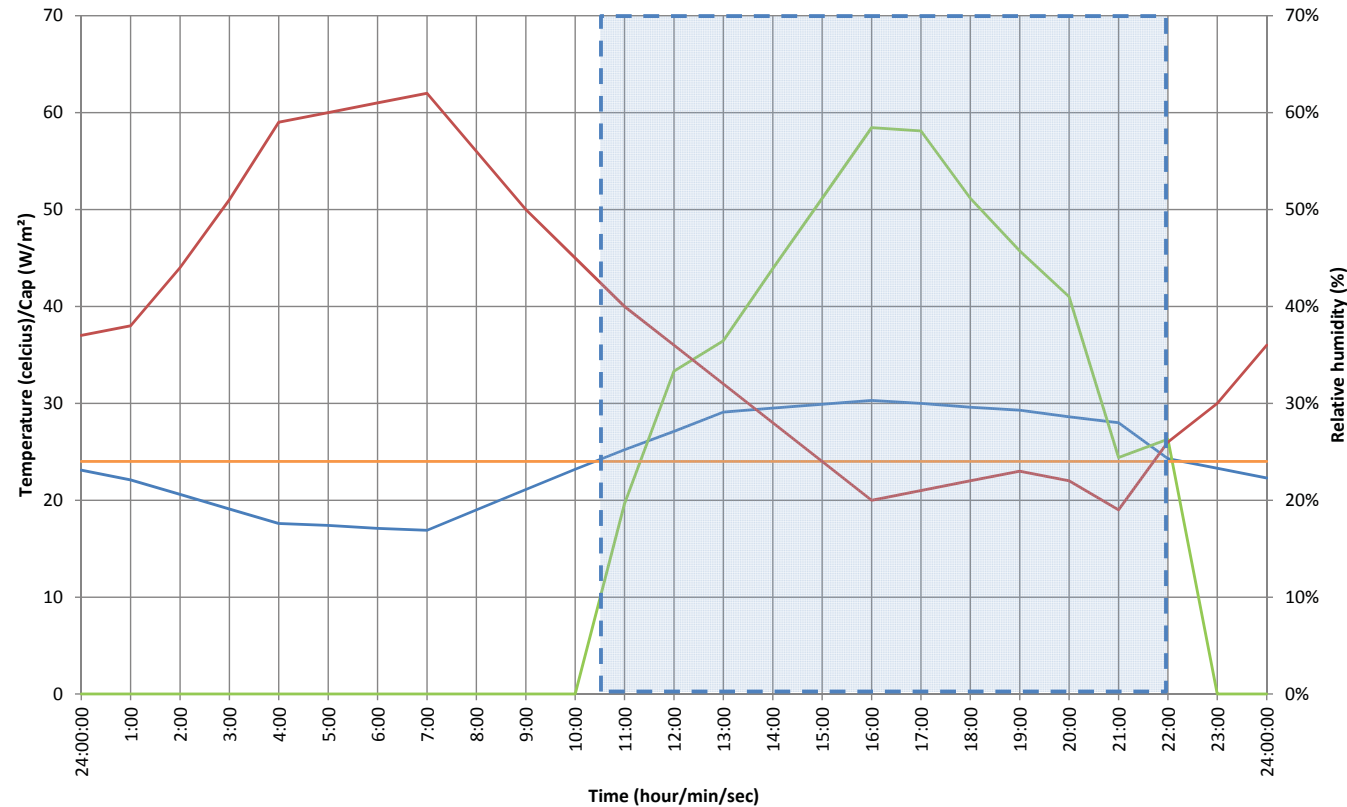
Fig. 85 Conditions 10th September 1999, Madrid

HH:MM	Dry Bulb Temperature (C)	Relative Humidity (%)	Cooling cap. (W/m²)	Air velocity (m/s)	Water quantity (kg/m²/hr)
11:00	25,20	40%	20	0,25	0,026
12:00	27,10	36%	33	0,50	0,056
13:00	29,10	32%	36	0,75	0,076
14:00	29,50	28%	44	1,00	0,100
15:00	29,90	24%	51	1,25	0,125
16:00	30,30	20%	58	1,50	0,153
17:00	30,00	21%	58	1,50	0,150
18:00	29,60	22%	51	1,00	0,112
19:00	29,30	23%	46	0,75	0,091
20:00	28,60	22%	41	0,50	0,071
21:00	28,00	19%	39	0,37	0,035
22:00	24,30	26%	26	0,25	0,033

1,028 kg/m²

Fig. 86 Results 10th Sept '99, Madrid

5.1.3 Simulation 3

In the next simulation the climate data of a warm summer day of August (13th of August 1993) in Madrid is insert, to see what the effect is in warmer conditions. Due to the fact of longer solar radiation during the day, the cool period is 3:00 hour longer than the 3rd of September (10.30 – 22.00).

In this simulation the peak cool capacity doesn`t match with the peak temperature, what would be desirable. This is in this case not only related to the relative humidity, but due to the temperature difference between the in – and outside is the influence factor. The highest temperature difference is more than 10 °C, meaning lots of energy is needed to generate this temperature difference, what detracts of the cool capacity. It`s still cooling 40 W/m² by an indoor temperature of 24 °C. By shifting the boundary of 24 °C up to a higher temperature, the amount of cooling will increase, fig. 87.

For this day 1300 g/m² water is needed to generate the maximum cooling at an indoor temperature of 24 °C. In this case 50% more water is used for evaporation than at the 3rd of September, while the cool capacity is lower. This can be clarified by the fact that the system cools 3 hours longer and the average air temperature is 5 °C higher.

Fig. 88 Conditions 13th August 1993
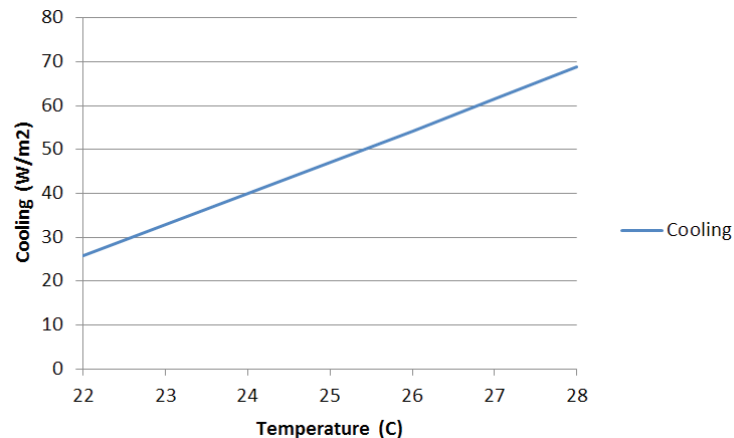
Fig. 87 Increasing cool capacity by shifting inside temperature
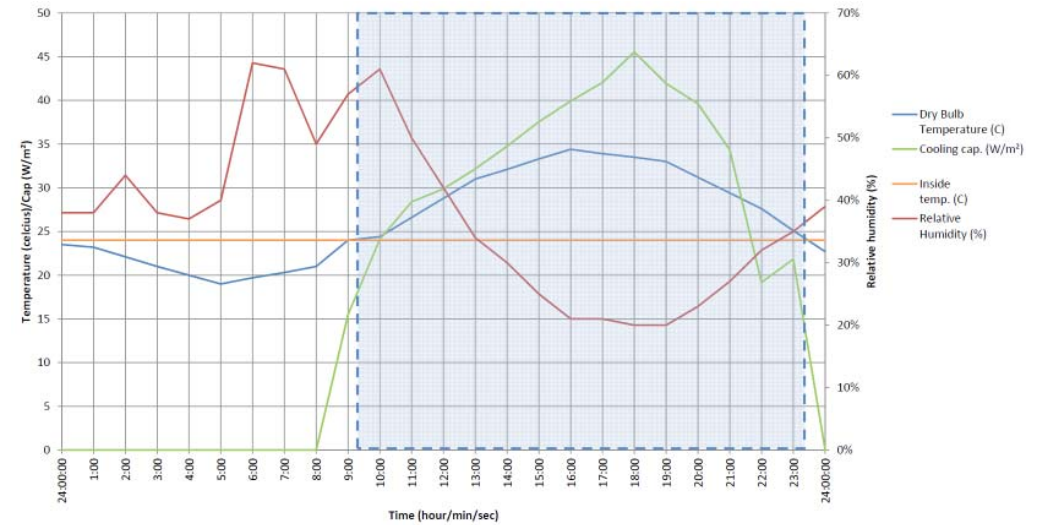
HH:MM	Dry Bulb Temperature (C)	Relative Humidity (%)	Cooling cap. (W/m²)	Air velocity (m/s)	Water amount (kg/m²/hr)
9:00	24,00	57%	15	0,25	0,019
10:00	24,40	61%	24	0,5	0,035
11:00	26,60	50%	28	0,75	0,054
12:00	28,80	42%	30	1	0,073
13:00	31,00	34%	32	1,25	0,099
14:00	32,10	30%	33	1,25	0,108
15:00	33,30	25%	38	1,5	0,137
16:00	34,40	21%	40	1,5	0,149
17:00	33,90	21%	42	1,5	0,149
18:00	33,50	20%	46	1,5	0,153
19:00	33,00	20%	42	1	0,115
20:00	31,20	23%	40	0,75	0,089
21:00	29,40	27%	34	0,5	0,064
22:00	27,60	32%	19	0,25	0,028
23:00	25,10	35%	22	0,25	0,028
24:00:00	22,70	39%	0	0	0

1,3 kg/m²

Fig. 89 Results 13th Aug 1993, Madrid

By shifting the desired room temperature boundary, in this case 24 °C, during the high outside peak temperatures, the capacity be influenced. In this simulation the indoor room temperature is shifted from 24 to 25 °C when the outside temperature passes 29 C. When it rises higher than 32 °C, the indoor temperature shifts to 26 °C. The adjustment of the room temperature boundary generates at the warmest hour of the day (16.00 hr)14 W/m² extra cooling.

When the indoor temperature is fixed at 24 °C 1300 g/m² water evaporates. By shifting the indoor temperature during the day till 26 °C, higher cool capacities are feasible, 1375 g/m² water evaporates.
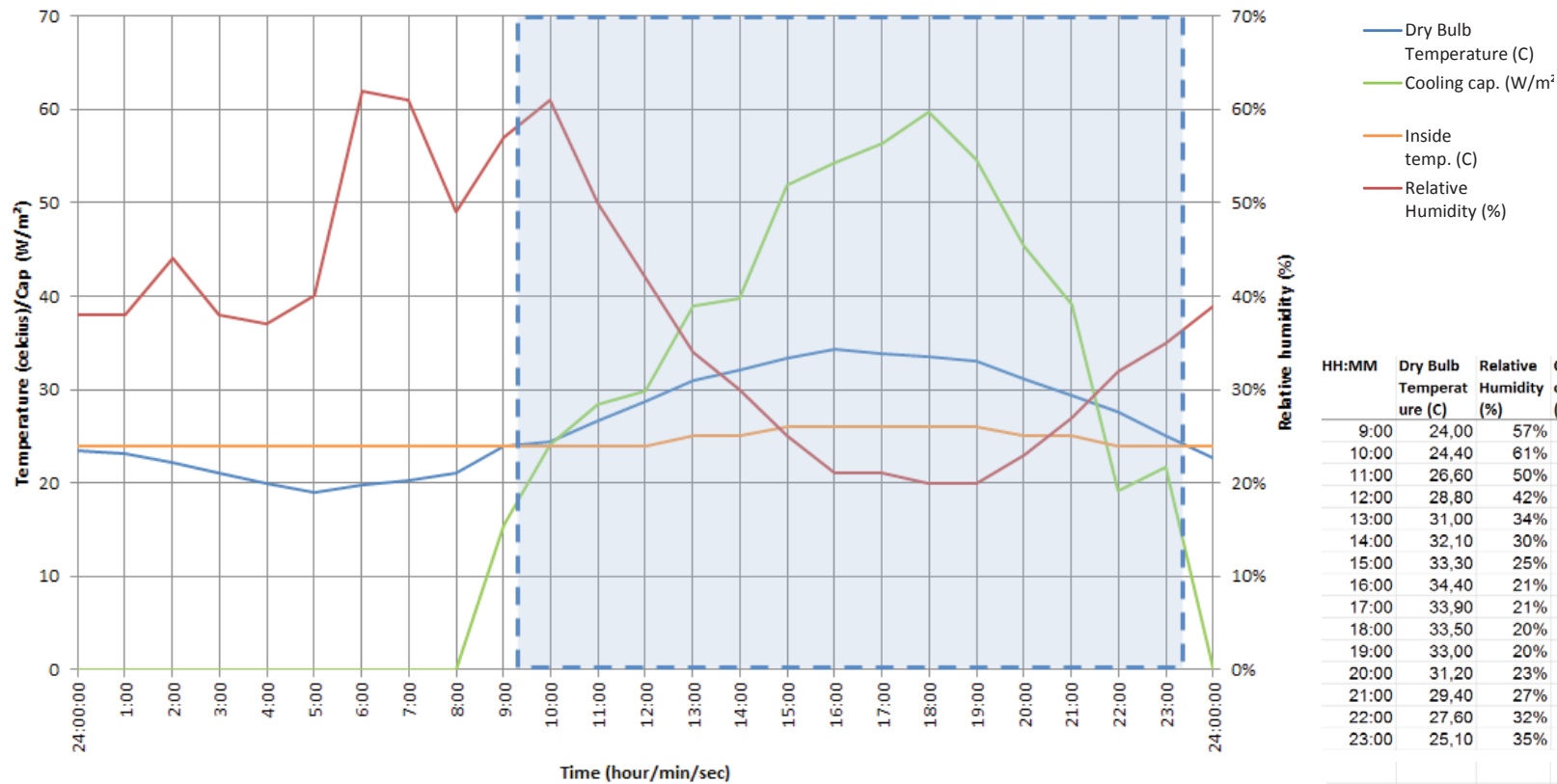
Fig. 90 Conditions 13th August 1993, Madrid

HH:MM	Dry Bulb Temperature (C)	Relative Humidity (%)	Cooling cap. (W/m²)	Air velocity (m/s)	Water amount (kg/m²/hr)	Inside temp. (C)
9:00	24,00	57%	15	0,25	0,019	24
10:00	24,40	61%	24	0,5	0,035	24
11:00	26,60	50%	28	0,75	0,054	24
12:00	28,80	42%	30	1	0,073	24
13:00	31,00	34%	39	1,25	0,105	25
14:00	32,10	30%	40	1,25	0,113	25
15:00	33,30	25%	52	1,5	0,148	26
16:00	34,40	21%	54	1,5	0,16	26
17:00	33,90	21%	56	1,5	0,161	26
18:00	33,50	20%	60	1,5	0,164	26
19:00	33,00	20%	55	1	0,125	26
20:00	31,20	23%	45	0,75	0,094	25
21:00	29,40	27%	39	0,5	0,068	25
22:00	27,60	32%	19	0,25	0,028	24
23:00	25,10	35%	22	0,25	0,028	24
					1,375 kg/m²	

Fig. 91 Results 13th Aug '93, Madrid

6. DESIGN

6.1 Design implementation

According to the simulations this adiabatic cooling concept shows promising cooling results which are able to work under the tested climate conditions. This means the concept design is working so far, but from now on it needs to be implemented in a realistic design. In this chapter the whole system is split in parts, each part is explained.

Ducts: The ducts are used to separate the humidified air inside the duct with the space which need to be cooled, no air transport between both spaces are desirable. Steel is a material with a high heat transfer coefficient and is able to separate both atmospheres. A problem with humidified air in contact with untreated steel, unless it`s stainless steel, is it will corrode. Stainless steel is an expensive possibility with a lower heat transfer coefficient. A less expensive solution is using a coating to protect a normal steel, besides the coating provides a higher emission coefficient what results in higher cool capacities (Ɛ Stainless steel = 0,85, Ɛ Paint = 0,9 – 0,96 depending on the color).[16]
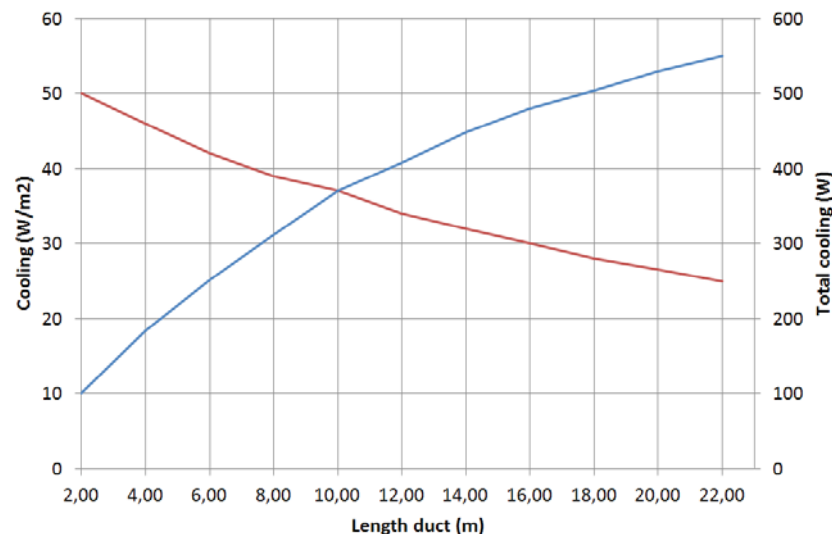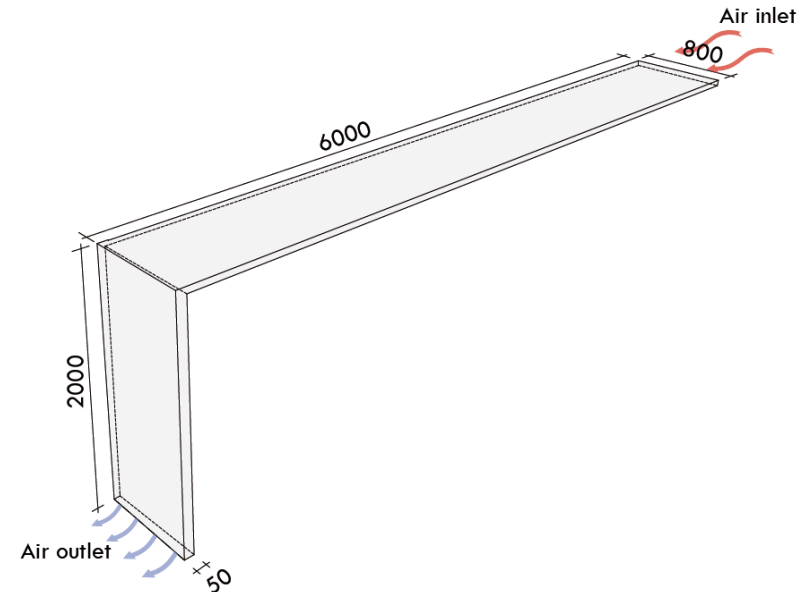
Fig. 93 decreasing cool capacity by enlarging ducts

According to the simulations the cool capacity decreased when the length of the duct increase. In fig. 92 is the length of the duct versus the cooling capacity is shown. The width of the duct doesn`t influence the cooling, according to the span a seconder structure can be added. The minimum height of the duct is 30mm, but because of the needed absorption layer inside the duct a height of 50mm is chosen.
The ducts in the system needs to be opened to maintain the absorption layer, which means watertight connections are required!

In this example a duct with a dimension of 8000x800x50mm (2000mm vertical, 6000 horizontal) is used to calculate the cool capacity, fig. 93. The width (800mm) is chosen according to the absorption layer.

Fig. 92 decreasing cool capacity by enlarging ducts

16 (Emissioncoefficient, 1999)

Absorption layer: The absorption layer needs to absorb and distribute water over a surface which is used for the evaporation process. In the agricultural sector an irrigation is used to water the vegetation. A new product of irrigation is the "Eco Rain", a dripping system which distribute water efficiently through a 4 layered textile surface. Two water pipes included drip outlets are integrated. The irrigation occurs when the textile is saturated and results in capillary action. Normally a textile is a good insulated material, but it loses this property when it`s getting wet, the heat transfer coefficient increases.

Properties Eco Rain:[17]
- 2 water pipes 16mm
- Distance between water pipes: 400mm
- Distance between drip outlets: 330mm
- Maximum drip cap. per outlet: 2,2 l/hr
- Width: 800mm

Fig. 94 Eco Rain product

17 (Wildkamp)

Air inlet

Air outlet
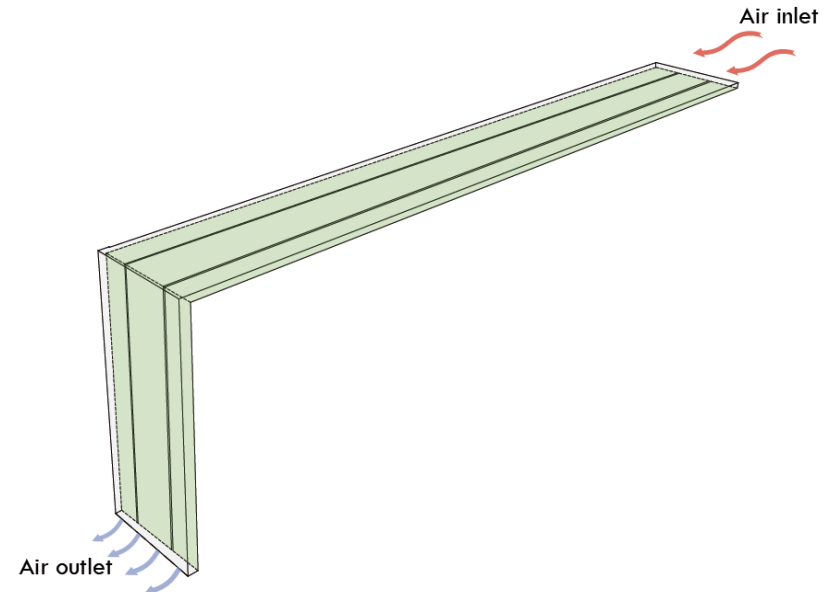
Fig. 95 decreasing cool capacity by enlarging ducts

Fan: A fan is needed to generate the recommended air velocity inside the duct. Extraction at the end of the duct is preferred instead of a blowing fan in the beginning. When there is a leak it extracts air from the inner space and doesn`t blow the humidified air from the cooling system inside. To reduces noise a low speed fan is recommended. Centrifugal fans are low speed fans which are able to transfer high volumes of air.

The duct itself and specially the corner connections and the inlet of the duct generates resistances, which needs to be calculated for choosing a fan or other passive system to provide the needed air velocity. By a turbulent flow the resistance of a duct can be calculated with the formula of Coolebrook-White:

$$1/(\sqrt{\lambda}) = -2 * \log (\varepsilon/(3,72*D) + 5,74/(Re * \sqrt{\lambda t}))$$

$\varepsilon_{steel} = 0,15 * 10^{-3}$
$Re (1,5 m/s) = 9,52 * 10^{3}$
$\lambda t = 3500$

Resistance steel duct with seams by 1,5 m/s = 0,37 Pa/m[1]

But because an absorption layer will be used inside the duct system a higher resistance arises. For this calculation the same surface roughness as masonry is used

εmasonry = 0,45 * 10^-3
Resistance masonry duct by 1,5 m/s = 0,46 Pa/m[1]

53% of the duct consist of a smooth steel surface (duct with = 800mm + 2 x 50 duct height), the other 47% is the absorption layer, located at the bottom of the duct.
Resistance steel duct included absorption layer by 1,5 m/s = 0,41 Pa/m[1]
Every corner generates a resistance, depending on the form.[18]

ζ =1,25 ζ =0,5
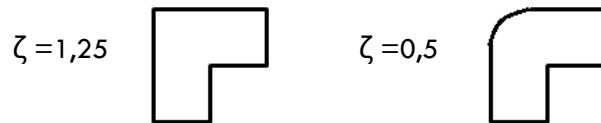
The resistance can be calculated with the formula $\Delta P = \zeta * \frac{1}{2} * \rho * v^2$
ΔP = Resistance (Pa)
ζ = Zeta
ρ = 1,29 kg/m³
v = Airspeed = 1,5 m/s

ΔPcorner = 0,5 * ½ * 1,29 * 1,5² = 0,72 Pa = 1,44 Pa for 2 corners
ΔPoutlet = 0,35 * ½ * 1,29 * 1,5² = 0,51 Pa
ΔPinlet = 1 * ½ * 1,29 * 1,5² = 1,45 Pa
ΔPduct = 8 * 0,41 Pa = 3,28 Pa
Resistance of the duct = 6,68 Pa

By humidify the air in the vertical duct a natural draft will be created, this draft can be calculated with this formula:
$\Delta P = \Delta h * \Delta \rho * g$

Δh = height difference m
$\Delta \rho$ = rho difference kg/m³
g = 9,81 Newton

ΔP = 2 * (1,19-1,18) * 9,81 = 0,196 Pa
Total resistance of one duct = 6,67 – 0,196 = 6,484 Pa.

The calculated resistance of a duct is without the resistance of an air filter. Depending on the type of filter extra resistance needs to be taken into account. Filter = ± 20 Pa.
The resistance with an air filter and a safety factor will have a maximum resistance of 30 Pa.

The maximum air velocity in the duct (800 x 50mm) is 1,5 m/s, this is 216 m³/hr (0,8 x 0,05 x 1,5 x 3600).

The R3G225, a centrifugal fan from Ebmpapst, is able to ventilate 470 m³/hr by a pressure of 32 Pa with 11 Watt.

U	f	n	P_1	I	$\dot{V}$	P_{fa}
[V]	[Hz]	[min⁻¹]	[W]	[A]	[m³/h]	[Pa]
230	50	2495	80	0.60	1170	0
230	50	2390	87	0.67	935	125
230	50	2290	95	0.75	600	250
230	50	2400	85	0.66	300	350
230	50	2000	41	0.31	940	0
230	50	2000	51	0.39	785	88
230	50	2000	63	0.48	525	191
230	50	2000	49	0.38	250	242
230	50	1600	21	0.16	750	0
230	50	1600	26	0.20	625	56
230	50	1600	32	0.25	420	122
230	50	1600	25	0.20	200	155
230	50	1200	8.88	0.07	565	0
230	50	1200	11	0.08	470	32
230	50	1200	14	0.10	315	69
230	50	1200	11	0.08	150	87

Fig. 96 Centrifugal fan Ebmpapst   *Fig. 97 Specs R3G225[19]*

18 (Issodigitaal, 2011)

19 (Ebmpapst, 2011)

A mechanical valve at the inlet of the duct driven by a servo motor opens the air inlet when cooling is necessary. When undesirable wind forces entering the valve, sensors note this and send this to the control panel. The control panel (computer) drive the servo motors to reduced or closes the valve.

Water transportation: An important subject for an adiabatic cooling system is water. In this case water needs to be pumped and saturate the absorption layer. Rain water and grey water are both usable for evaporation when they are filtered correctly and stored under room- or lower temperatures. By higher water temperatures the water pipes in the ducts provides heating instead of cooling.

According to the simulations of the warmest day in September 1999 (10th) the maximum recommended cool capacity is calculated for the whole day. During the cooling process (from 10.00 till 22.00) 1028 gram water per square meter is evaporating a day. Besides water for the evaporation process which needs to be pumped also water for saturate the absorption layer needs to be transported. 1m² Eco Rain absorb ± 2 liters water a day. This water doesn`t evaporate and can be reused. Depending on the size of the duct the quantity of pumped water can be calculated. A low accelerating pump with an energy label A is the Wilo-Stratos Eco 25/1-5BMS. This pump is able to transport 200 liter water 3 meters high per hour by using 10 Watt. According to the simulations of the warmest period on the 10th of September 1999 a maximum 160 g/m²/hr water evaporates. Meaning when for secure 250 g/m²/hr water needs to be pumped 3 meters high, this pump is able to saturate 800m² absorption layer with 10 Watt energy.

According to the cooling demand, the length and the amount of cooling elements, can be determined.
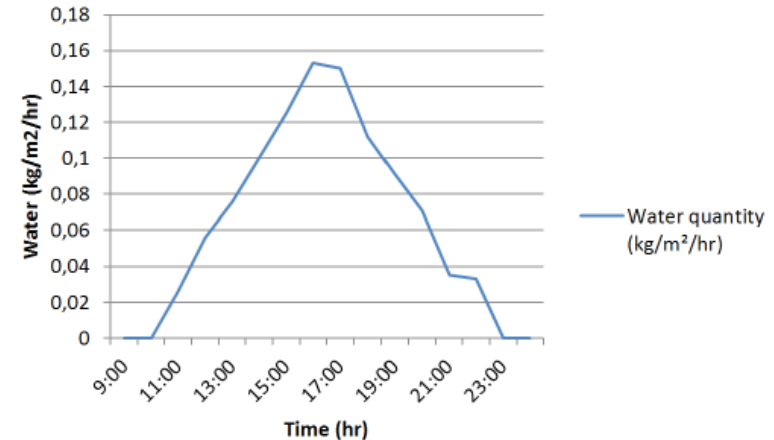
Fig. 98 4 Water quantity evaporation process, 10th September 1999
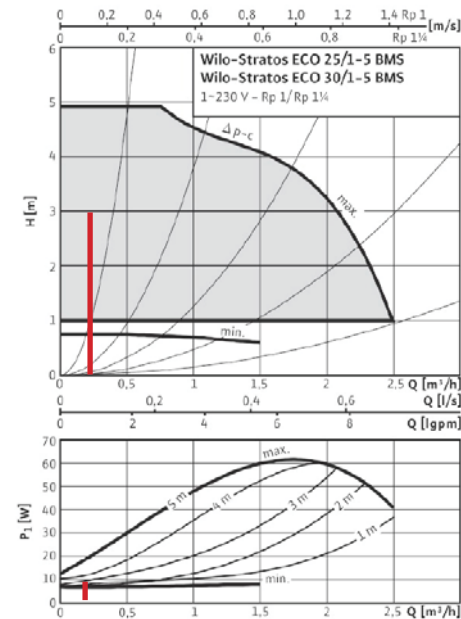
Fig. 99 Capacity Wilo-Stratos ECO pump[20]

Dimensions Wilo-Stratos ECO pump: 220 x 180 x 185mm (l x w x h)

Fig. 100 Wilo-Stratos ECO pump

20 (Wilo, 2011)

Air inlet
+ Valve

Pump:
Wilo Stratos
Eco

Fan:
Ebmpapst
R3G220

Air outlet
+ Valve
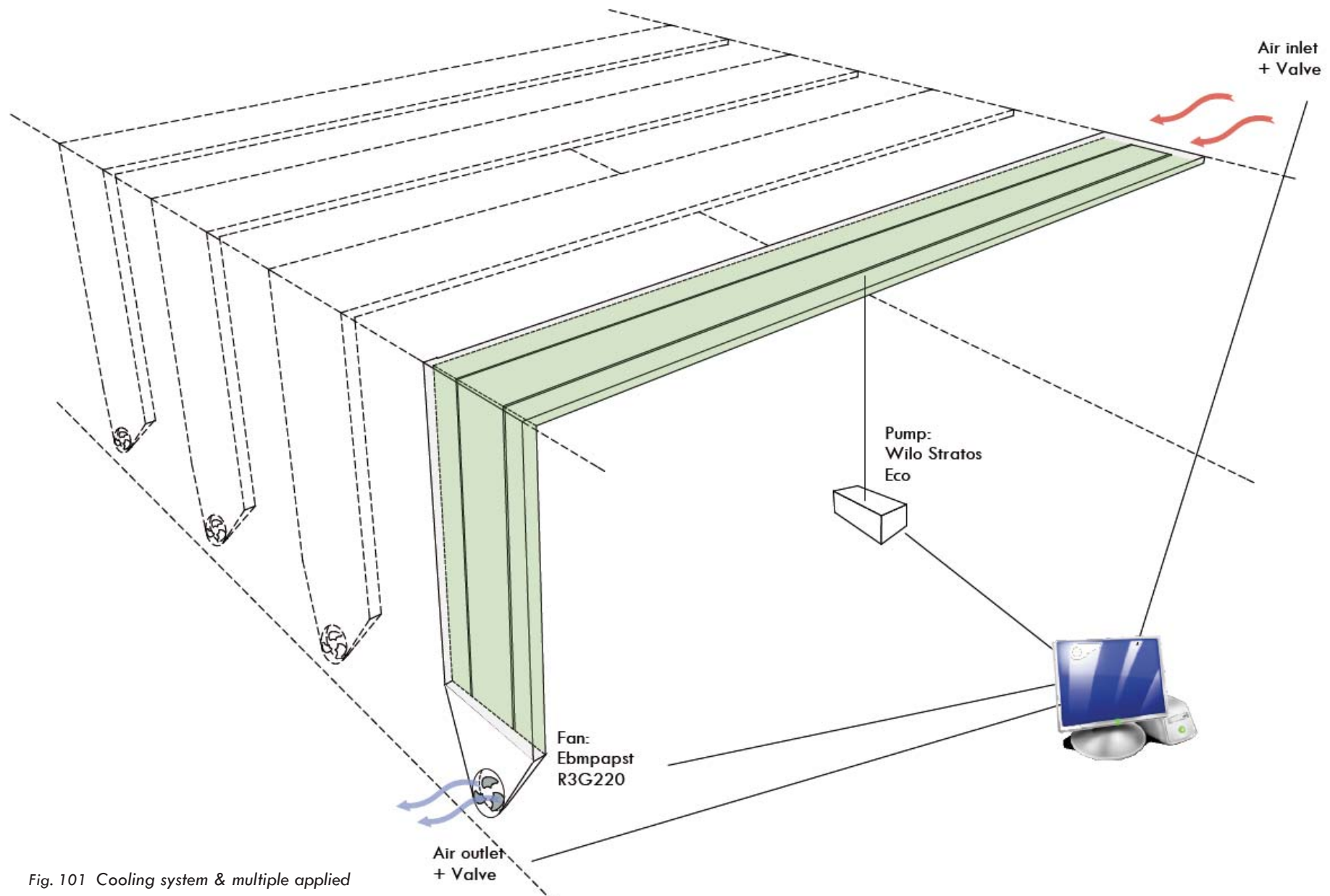
Fig. 101 Cooling system & multiple applied

6.2 Total capacity

3rd of September 1999

In the next example the maximum cool capacity of an 8 meter adiabatic cooling system as shown in fig. 93 is calculated. The system consist of a 6 meter horizontal and 2 meter vertical cooling duct. The air velocity at the highest peak temperature (17:00 hour) is 1,5 m/s. For this calculation the climate data of the 3rd of September 1999, from Madrid are used.

Max. cooling horizontal duct   226 Watt
Max. cooling vertical duct   59 Watt

Max. total cooling capacity   285 Watt

Assuming the necessary equipment is running during the cooling period.

- Willo-Stratos Eco pump   5 Watt
- Ebmpapst R3G225   11 Watt

Total energy capacity: 269 Watt

A total energy capacity of 269 Watt is generated according to the climate data of 3rd of September 1999 (an average September day). In this energy calculation is the control system, like a computer, is not included, because probably this is also needed for other electronic devices in the building. To produce these high capacities 6,44 kg of water is needed a day.

HH:MM	Dry Bulb Temperature (C)	Relative Humidity (%)	Air velocity (m/s)	Cooling cap.hor (W/m¹)	Cooling cap.hor 6m (W)	Cooling cap. vert (W/m¹)	Cooling cap.vert 2m (W)	Total cool capacity (W)	Water am. hor (kg/m¹/hr)	Water am. hor 6m (kg/hr)	Water am. vert (kg/m¹/hr)	Water am. ver 2m (kg/hr)	Total water quantity (kg/hr)
11:00	24,50	51%	0,25	12	74	11	22	97	-0,02	-0,12	-0,02	-0,04	-0,16
12:00	26,10	43%	0,5	24	142	20	40	182	-0,05	-0,28	-0,05	-0,09	-0,37
13:00	27,80	37%	0,75	28	166	23	46	212	-0,07	-0,39	-0,06	-0,13	-0,52
14:00	28,30	34%	1	32	191	26	51	242	-0,08	-0,50	-0,08	-0,17	-0,67
15:00	28,90	32%	1,25	35	208	28	56	264	-0,10	-0,61	-0,10	-0,20	-0,81
16:00	29,40	30%	1,5	37	223	30	59	282	-0,12	-0,71	-0,12	-0,24	-0,95
17:00	29,10	30%	1,5	38	226	30	59	285	-0,12	-0,71	-0,12	-0,24	-0,94
18:00	28,80	29%	1	35	212	29	58	270	-0,09	-0,56	-0,09	-0,19	-0,74
19:00	28,50	28%	0,75	33	198	27	54	252	-0,08	-0,47	-0,08	-0,16	-0,62
20:00	26,70	32%	0,5	29	173	25	50	222	-0,06	-0,34	-0,06	-0,11	-0,45
21:00	25,00	37%	0,25	16	95	14	29	124	-0,03	-0,15	-0,03	-0,05	-0,20
22:00	23,20	43%	0	0	0	0	0						
23:00	22,60	47%	0	0	0	0	0						-6,44 kg/day
24:00:00	22,00	53%	0	0	0	0	0						

Fig. 102 Cooling capacity and water quatity ,3rd of September 1999

To calculate the efficiency of this cooling system the COP (Coefficient of performance) can be calculated. The COP describe the cooling efficiency of air-conditioning systems. If a cooling system generates from 100 Watt electricity 400 Watt cooling a COP of 4 is obtained.

COP = Qcooling/W

Qcooling = 269 Watt
W = 16 Watt
COP = 18

A high efficiency air-conditioning system nowadays reach a COP of 4. This designed adiabatic cooling system is during a cooling period over 4 times more efficient than an air-conditioning system. By the start and the end of the cooling process the COP is around 10, during the highest cool capacity a COP of 19 is reached.

HH:MM	Total cool capacity (W)	Power fan (W)	Power pump (W)	Generated energy (W)	COP
11:00	97	6	5	86	9
12:00	182	7	5	170	15
13:00	212	8	5	199	16
14:00	242	9	5	228	17
15:00	264	10	5	249	18
16:00	282	11	5	266	18
17:00	285	11	5	269	18
18:00	270	9	5	256	19
19:00	252	8	5	239	19
20:00	222	7	5	210	19
21:00	124	6	5	113	11

Fig. 103 COP 3rd of September 1999

Air in
T: 29,4 °C
RH: 29,9 %

28,5 °C
27,7 °C
26,9 °C
26,3 °C
25,7 °C
25,2 °C
24,7 °C

Air out
T: 24,3 °C
RH: 59,5 %
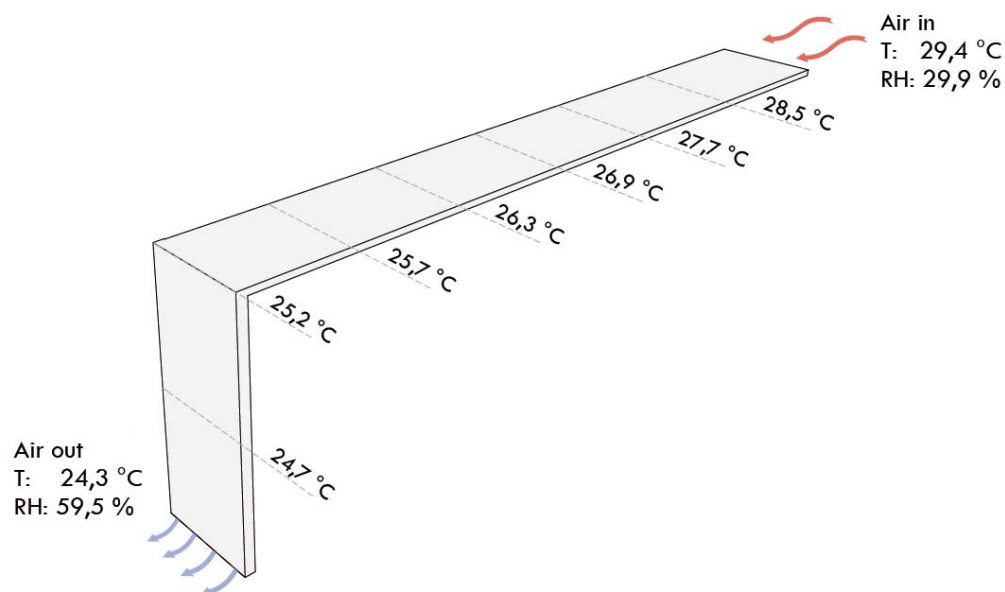
Fig. 104 Air temperature in the duct (evaporation surface is 19 - 20 C)

10th of September 1999

In this calculations the same properties are used as the previous, but the climate conditions of 10th of September 1999 are insert. The highest cooling capacity is reached at 16:00 hour.

Max. cooling horizontal duct   273 Watt
Max. cooling vertical duct   86 Watt
Max. total cooling capacity   359 Watt

Assuming the necessary equipment is running during the cooling period.
- Willo-Stratos Eco pump   5 Watt
- Ebmpapst R3G225   11 Watt
Total energy capacity: 343 Watt

A total energy capacity of 343 Watt is generated according to the climate data of 10th of September 1999 (the warmest September day).
To produce these high capacities 7,35 kg of water is needed a day.

A COP of 23 is reached at 17:00 hour.

HH:MM	Total cool capacity (W)	Power fan (W)	Power pump (W)	Generated energy (W)	COP
11:00	115	6	5	104	10
12:00	203	7	5	191	17
13:00	224	8	5	211	17
14:00	271	9	5	257	19
15:00	315	10	5	300	21
16:00	359	11	5	343	22
17:00	358	11	5	342	22
18:00	316	9	5	302	23
19:00	281	8	5	268	22
20:00	251	7	5	239	21
21:00	145	6	5	134	13
22:00	152	6	5	141	14

Fig. 106 COP 10th of September 1999

HH:MM	Dry Bulb Temperature (C)	Relative Humidity (%)	Air velocity (m/s)	Cooling cap. hor (W/m¹)	Cooling cap.hor 6m (W)	Cooling cap. vert (W/m¹)	Cooling cap.vert 2m (W)	Total cool capacity (W)	Water am. hor (kg/m¹/hr)	Water am. hor 6m (kg/hr)	Water am. vert (kg/m¹/hr)	Water am. ver 2m (kg/hr)	Total water quantity (kg/hr)
11:00	25,20	40%	0,25	15	87	14	27	115	-0,02	-0,14	-0,02	-0,04	-0,19
12:00	27,10	36%	0,50	25	152	26	51	203	-0,05	-0,31	-0,04	-0,08	-0,39
13:00	29,10	32%	0,75	28	168	28	56	224	-0,07	-0,42	-0,06	-0,12	-0,54
14:00	29,50	28%	1,00	34	204	34	67	271	-0,09	-0,56	-0,08	-0,15	-0,71
15:00	29,90	24%	1,25	40	238	38	77	315	-0,12	-0,71	-0,10	-0,19	-0,90
16:00	30,30	20%	1,50	46	273	43	86	359	-0,14	-0,86	-0,12	-0,24	-1,10
17:00	30,00	21%	1,50	45	272	43	86	358	-0,14	-0,85	-0,11	-0,23	-1,07
18:00	29,60	22%	1,00	40	237	39	78	316	-0,10	-0,63	-0,09	-0,17	-0,80
19:00	29,30	23%	0,75	35	210	35	70	281	-0,08	-0,51	-0,07	-0,14	-0,65
20:00	28,60	22%	0,50	31	187	32	64	251	-0,07	-0,39	-0,06	-0,11	-0,51
21:00	28,00	19%	0,25	18	108	18	37	145	-0,03	-0,19	-0,03	-0,06	-0,25
22:00	24,30	26%	0,25	19	117	18	35	152	-0,03	-0,18	-0,03	-0,06	-0,24
23:00	23,30	30%	0,00										
24:00:00	22,30	36%	0,00										-7,35 kg/day

Fig. 105 Cooling capacity and water quatity ,10th of September 1999

03   06   05   02   01

04
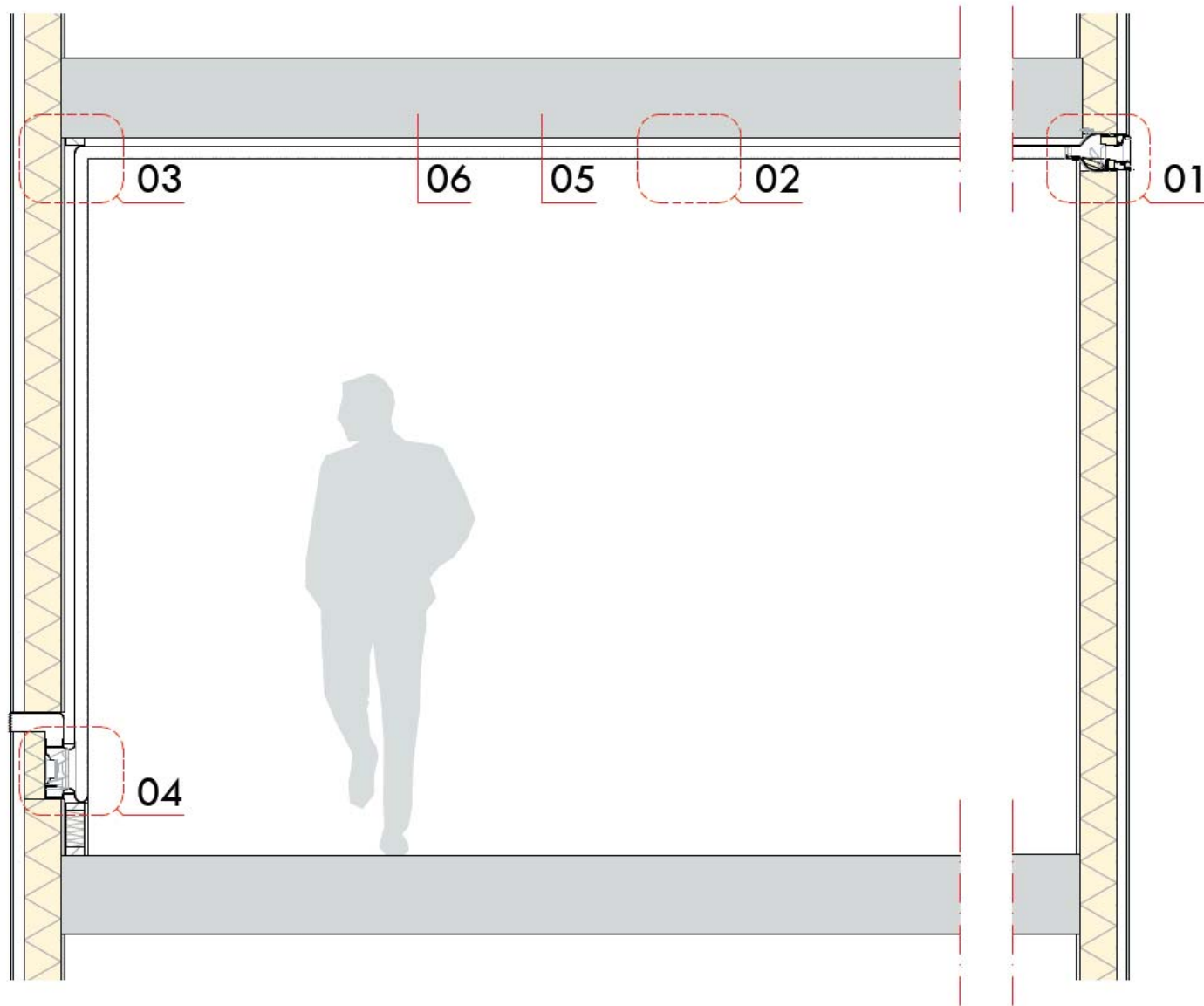
Fig. 107 Principle section, shows details, no scale

- Structure (floor/roof)
- Insulation
- Water pipe, 16mm
- Coated steel
- Eco Rain, abs. layer
- Coated steel

- Ventilation box:
Mechanical adjustable air
supply, based on Duco
ventilation system.

- Polyester connection

- Water fitting

- Rubber

- L profile 15x15x2mm

- Mechanical valve

- Demountable
gril

- Replacable
air filter

30
1,5
50
42
5
1,5
1,5

45
50
140
45
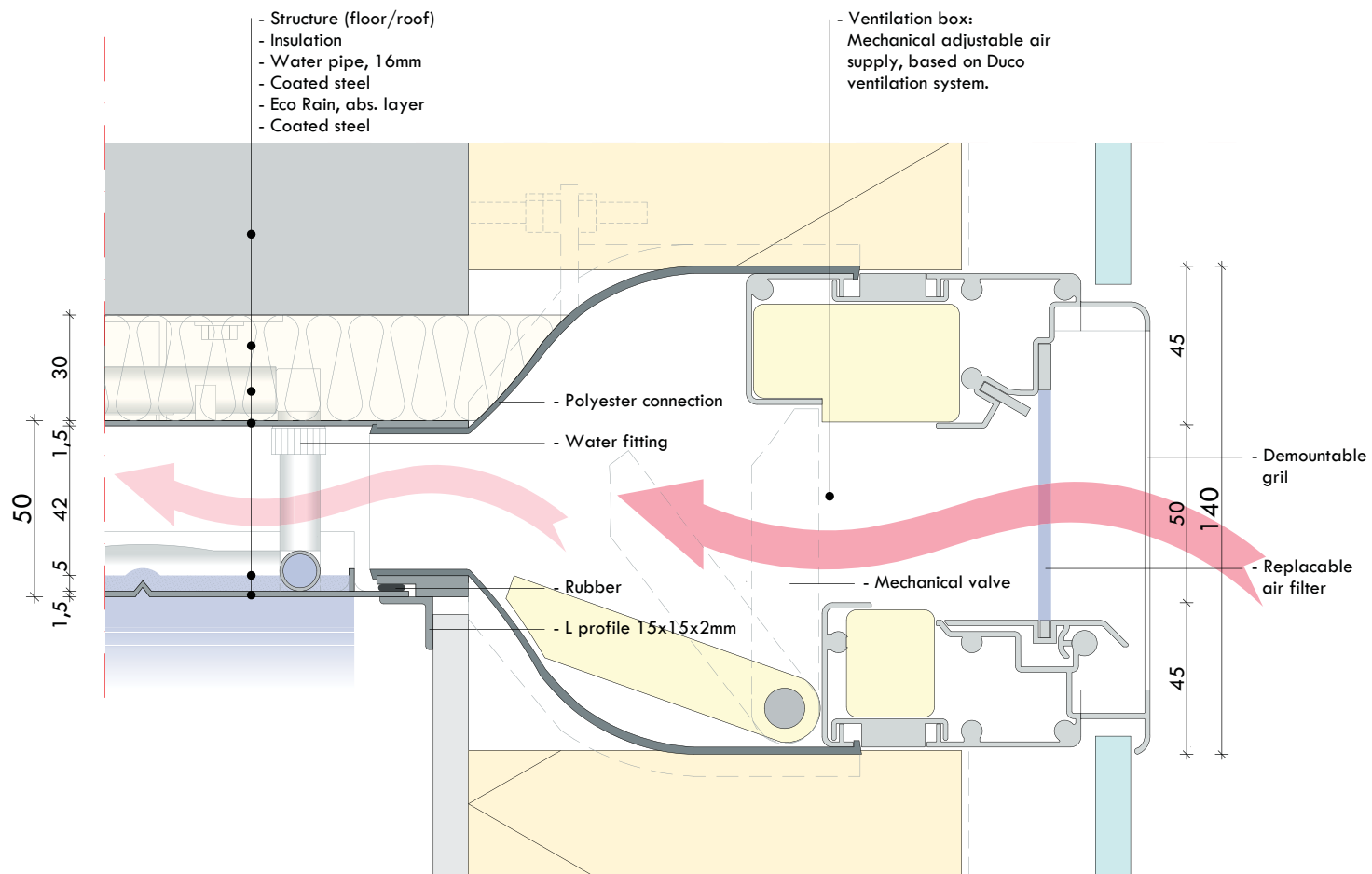
Fig. 108 Detail 1: Air inlet, scale 1:2

71

- Adjustable connection,
  incl. suspend system
- Duct connection, bolted,
  rubber inbetween
- Duct connection, rivited,
  rubber inbetween

28 x 70 mm

- Coated steel
- Eco Rain, abs. layer
- Coated steel
- Insulation
- Finishing

30

1,5

42

5

1,5

50

1,5   42   5   1,5

50
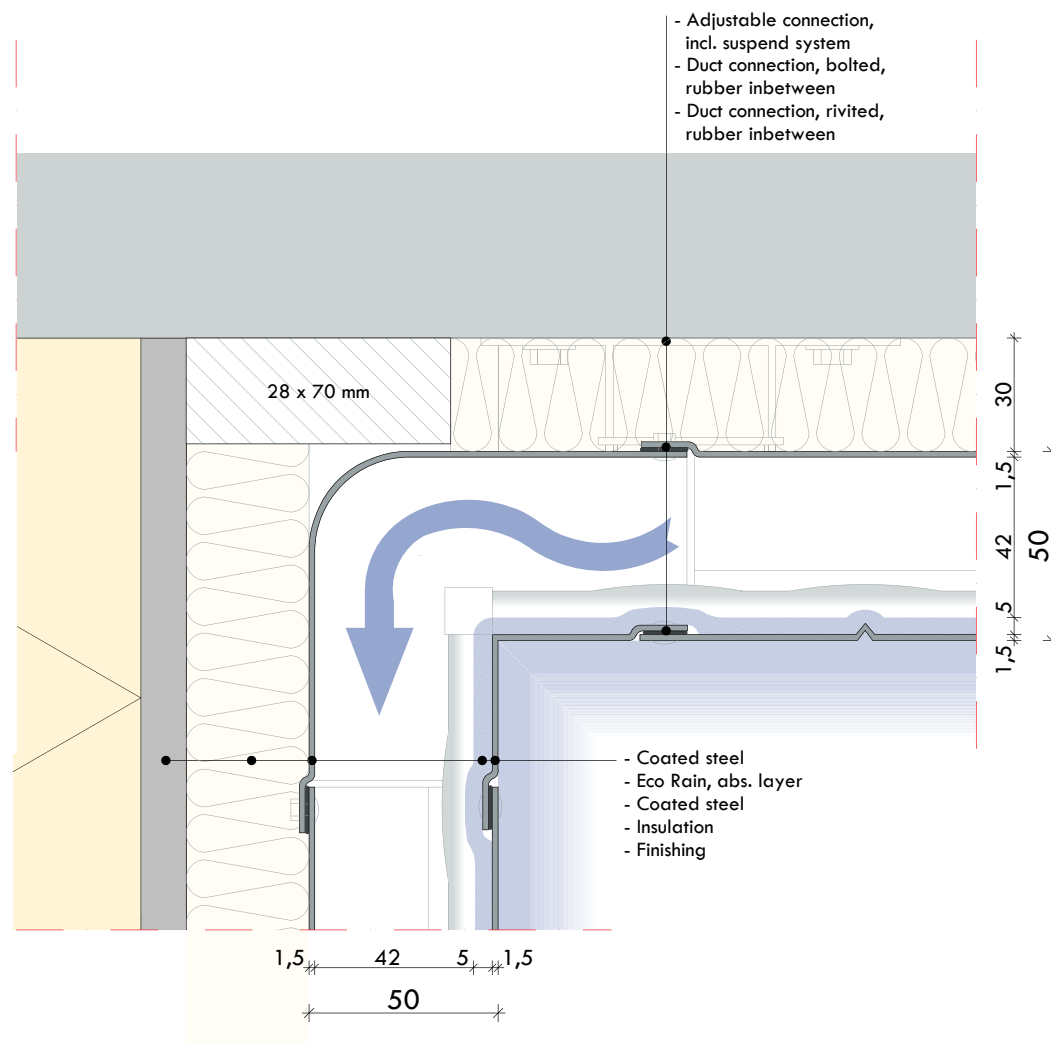
Fig. 109 Detail 2: Corner connection top, scale 1:2

50				
33	1,5	42	5	1,5

- Coated steel
- Eco Rain, abs. layer
- Coated steel
- Insulation
- Finishing

- Standard fan connection

- Ebmpapst R3G225

- Plug fitting

- Water guide

- Drain to water storage (incl. gooseneck)
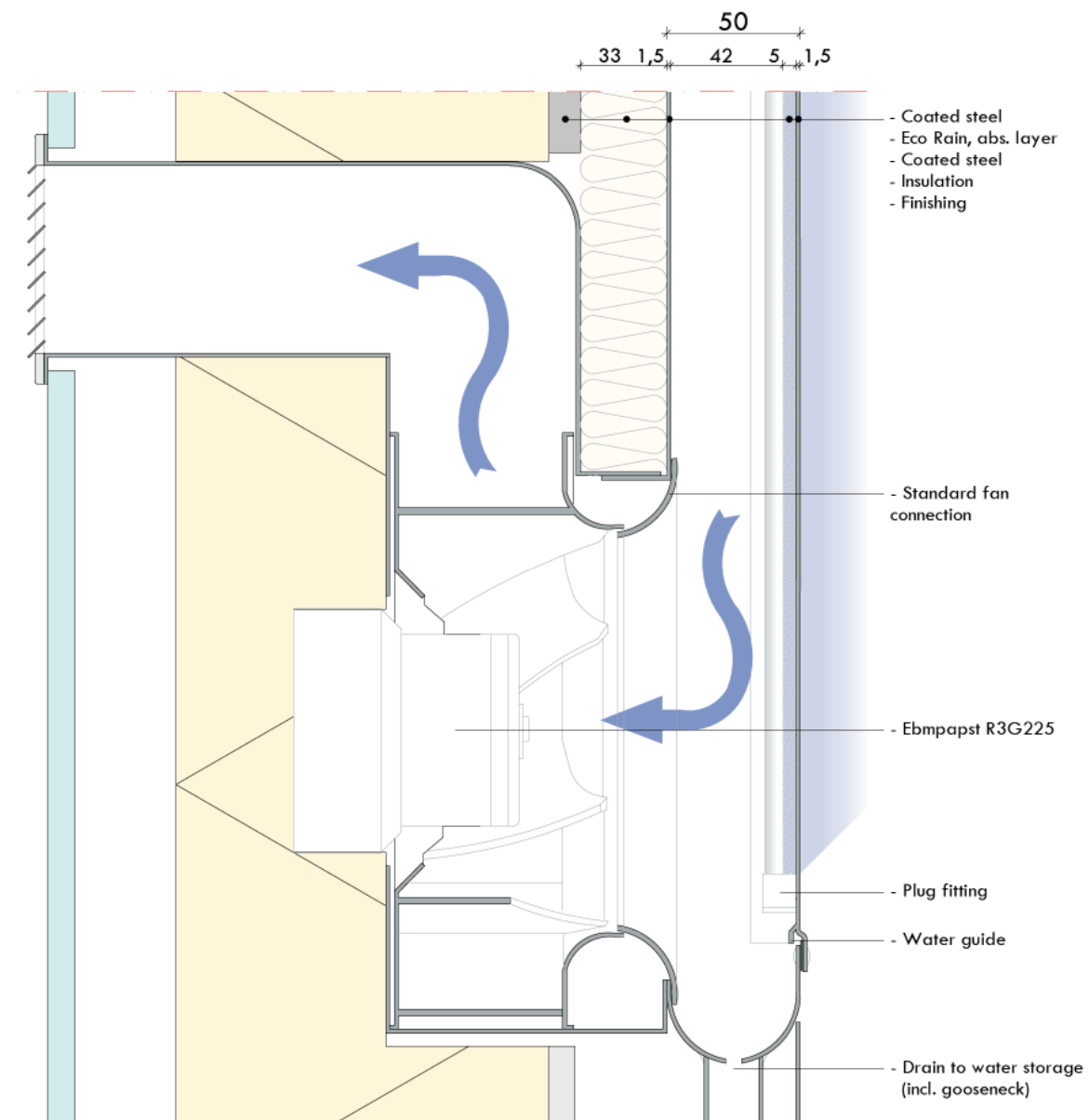
Fig. 110 Detail 3: Corner connection bottom, scale 1:3

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- Lowered ceiling.
  Remove to disassemble or
  open the cooling system

- Adjustable connection,
  incl. lock mechanism

- Structure (floor/roof)
- Insulation
- Coated steel
- Eco Rain, abs. layer
- Coated steel

1,5

30

1,5

17

30

50

1,5

200

1,5

796

793

400

800
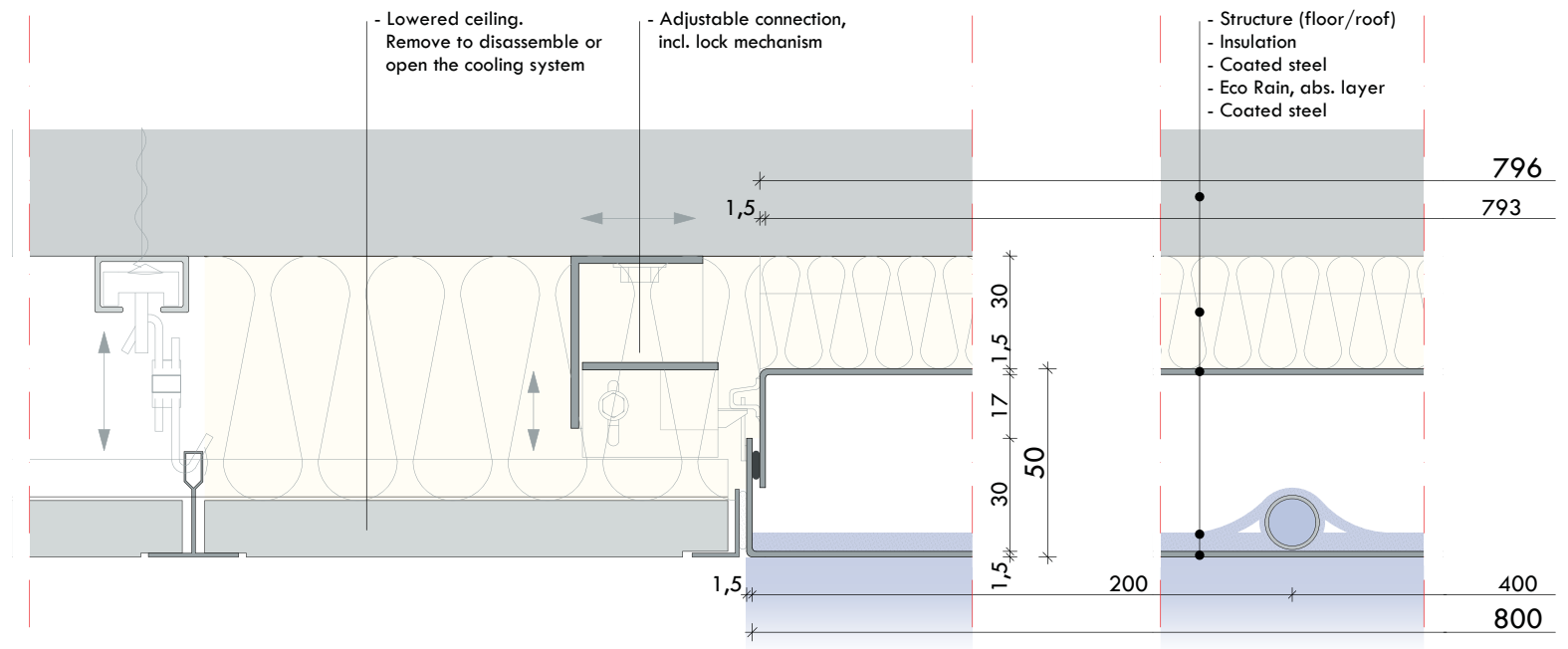
Fig. 111 Detail 4: Floor connection, left, scale 1:2

74

- Clamb mechanism.
  To open the cool system

- Hinge
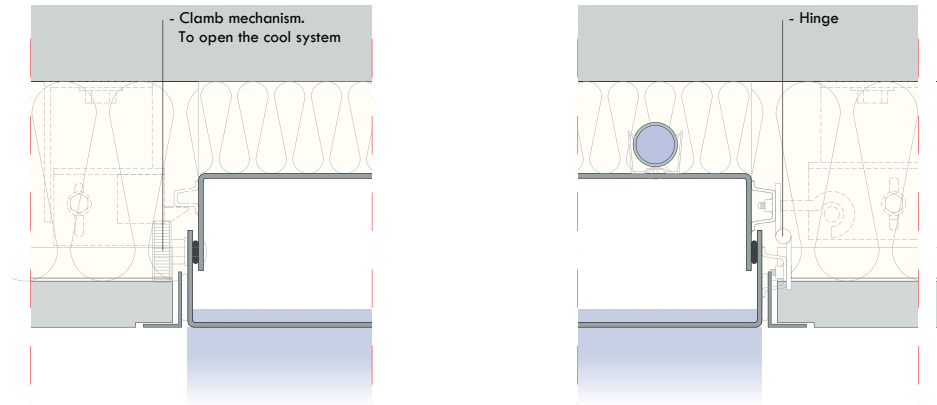
Fig. 113 Detail 6: Maintenance door, no scale

- Structure (floor/roof)
- Insulation
- Coated steel
- Eco Rain, abs. layer
- Coated steel

- Water pipe, 16mm

- Adjustable connection,
  incl. suspend system

1,5

30

1,5

30

50

17

1,5

200

1,5

1,5
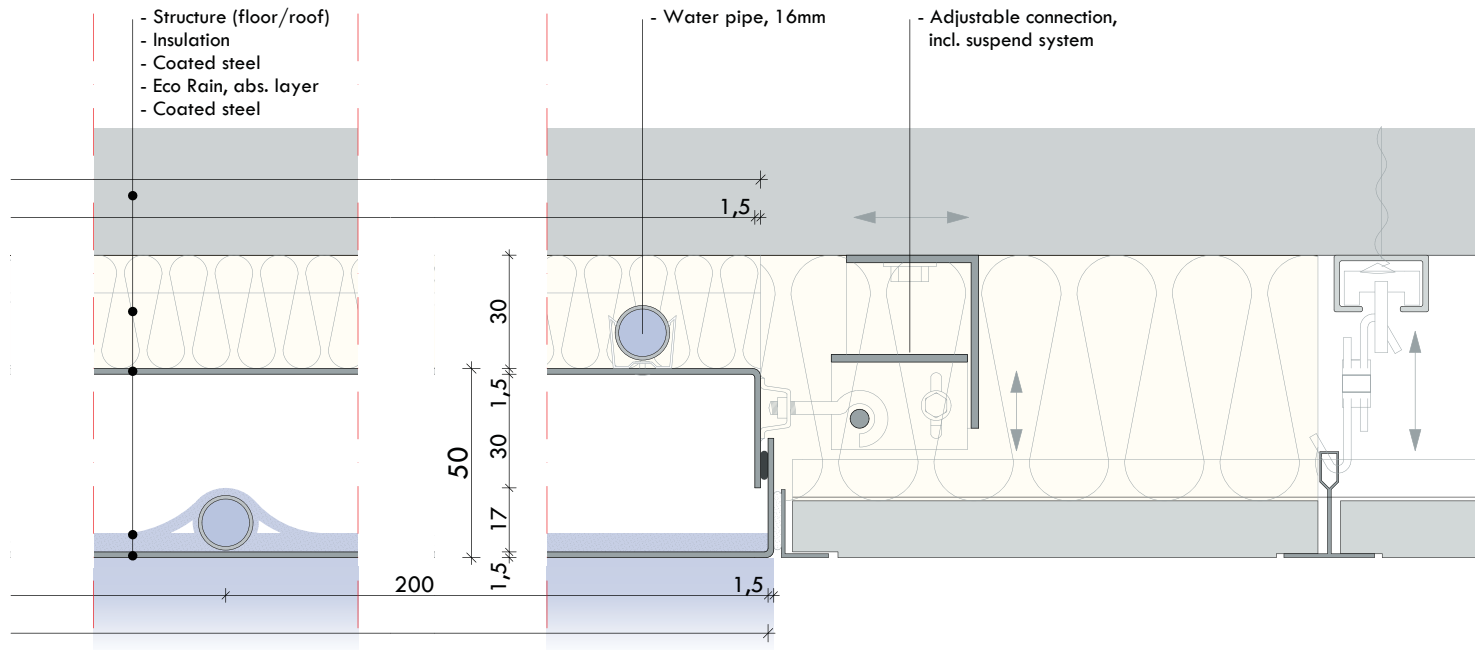
Fig. 112 Detail 5: Floor connection, right, scale 1:2

75

6.4 Building sequense

Fig. 115 First duct system in place

Fig. 114 Adjustable connection
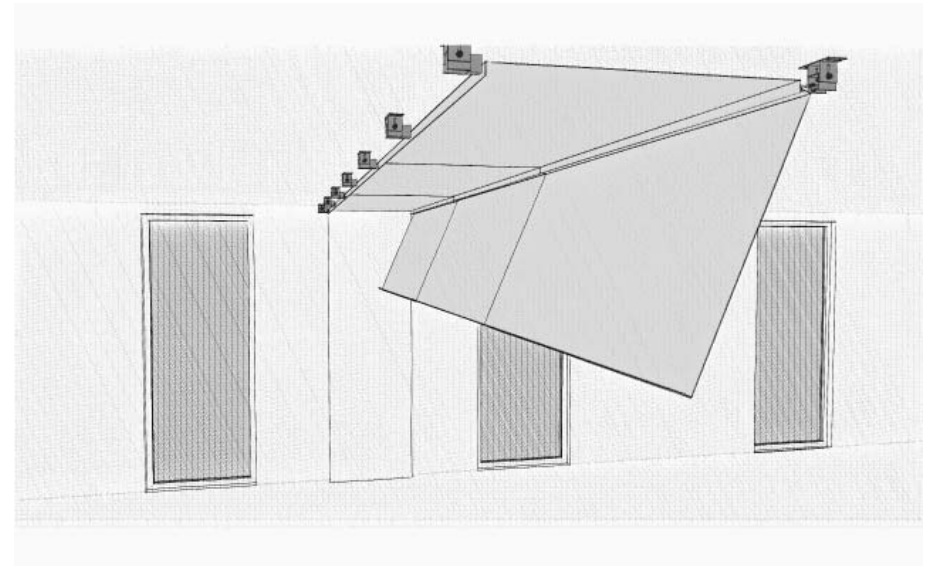
Fig. 116 All ducts connected

Fig. 118 Placing the absorption layer in the duct

Fig. 117 Closing the cooling system
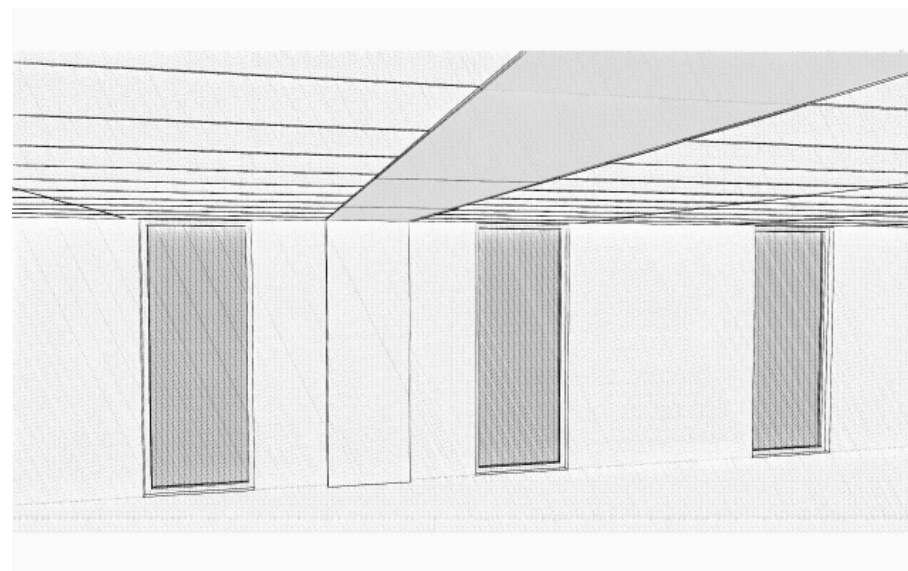
Fig. 119 Finishing by placing a lowerd ceiling

7. OTHER CLIMATES

According to the results of the simulations, this adiabatic cooling system perform promising during the warm and dry periods in Madrid. How effective is this system in other climate zones? Three different locations over the world are selected and tested by using the simulation model. Each location with a different climate classification:

Amsterdam: The capital of the Netherlands. According to the Köppen classification the Netherlands has a Maritime climate (Mild winters & cool summers). But even in the Netherlands, especially in offices and meeting spaces cooling is required.

Las Vegas: A big city located in Nevada, West America. Las Vegas has a subtropical arid climate. With short mild winters and hot and dry summers.

Singapore: The smallest country of South East Asia. According to the Köppen classifications it`s classified in equatorial climate, also known as tropical rainforest climate. The temperature is during the year broadly similar, which is warm, an average of 27 °C. It`s a very humid climate.

Out of each location an average weather condition day is used.

For this simulation the first 15 days of June 1996, according to the climate data of ASHRAE, are analyzed. In this period the temperature fluctuate between 5 and 33 °C. The 10th of June 1996, an average day is picked, where the outside temperature is rising above 24 °C, which needs to be cooled. The temperature on the 10th of June is between 10 and 26,4 °C with a relative humidity of 47 till 98%. Between 12.00 and 19.00 hour the temperature rises above the 24 °C, this period the cooling process starts.

The cooling capacity is calculated with low air velocities (0 − 1,5 m/s). According to the simulations of the 10th of June 515 g/m² water is needed to provide the achieved recommended cool capacity, as shown in fig. 122. These results shows that the cooling system can be used in Maritime climate zones, where cooling is needed. But less cool capacity is generated than in the climate conditions of Madrid.
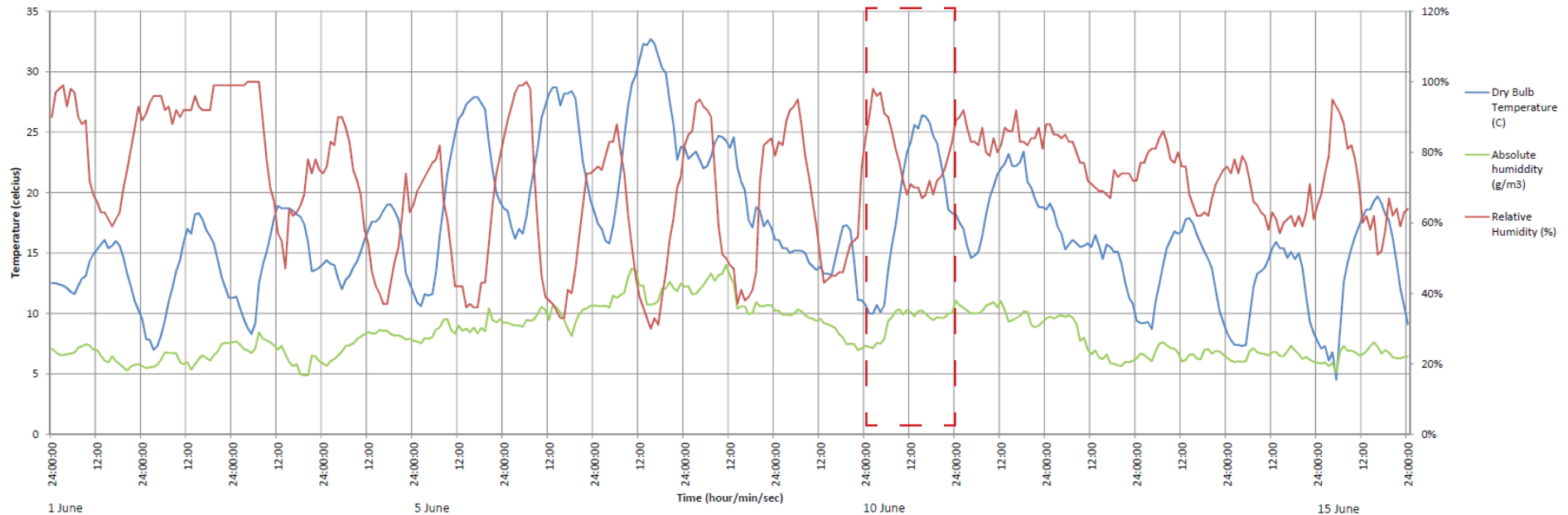
Fig. 120 Climate conditions Amsterdam 1 t/m 15 June 1996
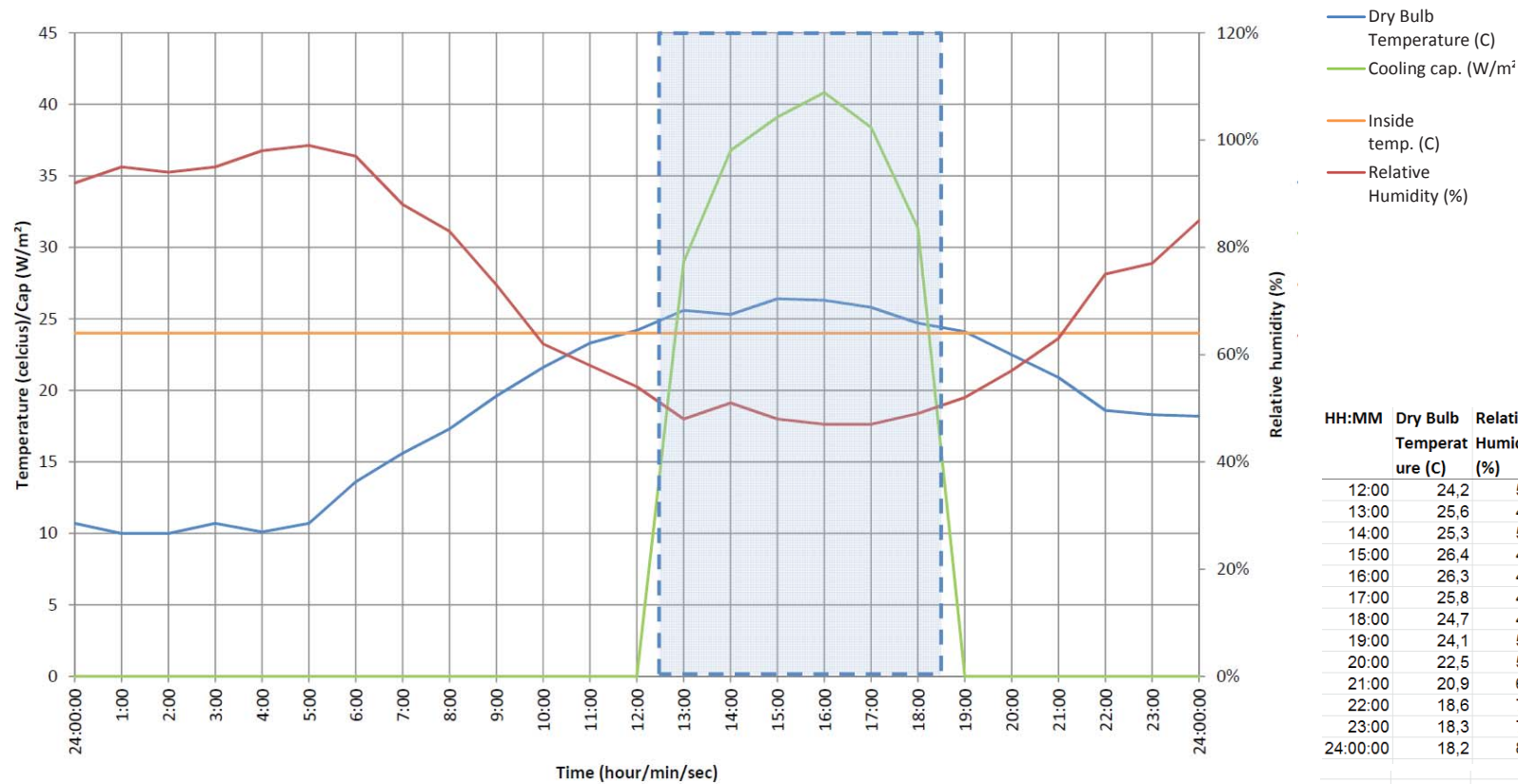
Fig. 121 Cooling capacity on 10th June 1996 in Amsterdam

HH:MM	Dry Bulb Temperature (C)	Relative Humidity (%)	Cooling cap. (W/m²)	Air velocity (m/s)	Water amount (kg/m²/hr)
12:00	24,2	54%	0	0	0
13:00	25,6	48%	29	0,5	0,057
14:00	25,3	51%	37	1	0,083
15:00	26,4	48%	39	1,5	0,112
16:00	26,3	47%	41	1,5	0,115
17:00	25,8	47%	38	1	0,09
18:00	24,7	49%	31	0,5	0,058
19:00	24,1	52%	0	0	0
20:00	22,5	57%	0	0	0
21:00	20,9	63%	0	0	0
22:00	18,6	75%	0	0	0
23:00	18,3	77%	0	0	0
24:00:00	18,2	85%	0	0	0
					0,515 kg/m²
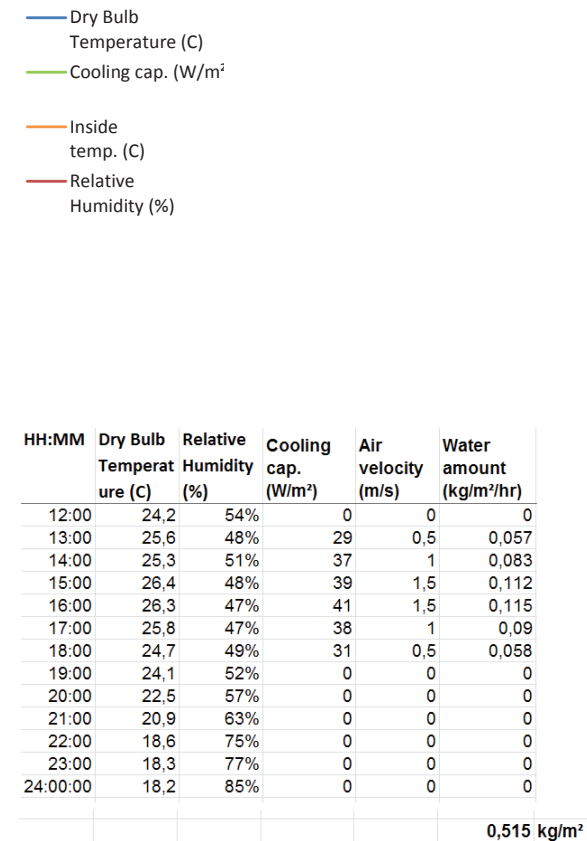
Fig. 122 Results 10th June `96, Amsterdam

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7.2 Climate Las Vegas

To conclude if this system is also able to generate cooling under very hot and dry circumstances, the climate conditions of Las Vegas are used for the next simulation. The 22 th of July, an average day in the period from 16 till 31 July 1991 is used (climate data from ASHRAE). The whole day the temperature rises above the 24 °C, what means lots of cooling is recommended. The relative humidity is during these warm periods low.

Also in this simulations low air velocities (0 – 1,5 m/s) are applied. From 24:00 till 6:00 hour the temperature stays equal, the relative humidity is between 17 and 22%. After 6:00 the temperature and the cool capacity rises while the relative humidity decrease. In the night the relative humidity rises, the temperature and cool capacity decreases. According to the simulations of the 22th of July 4829 g/m² water is needed to provide the achieved recommended cool capacity, as shown in fig. 125.

The dryer and the warmer the climate conditions, the more water evaporates, the more cooling is generated.
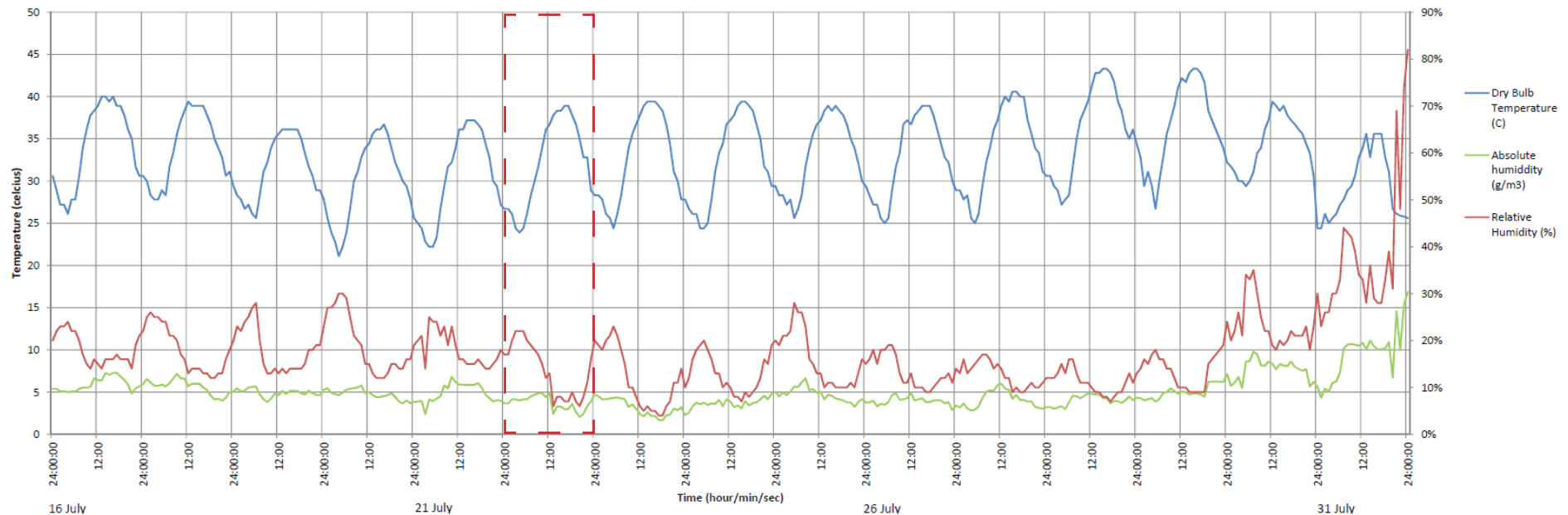
Fig. 123 Climate conditions Las Vegas 16 t/m 31 July 1991
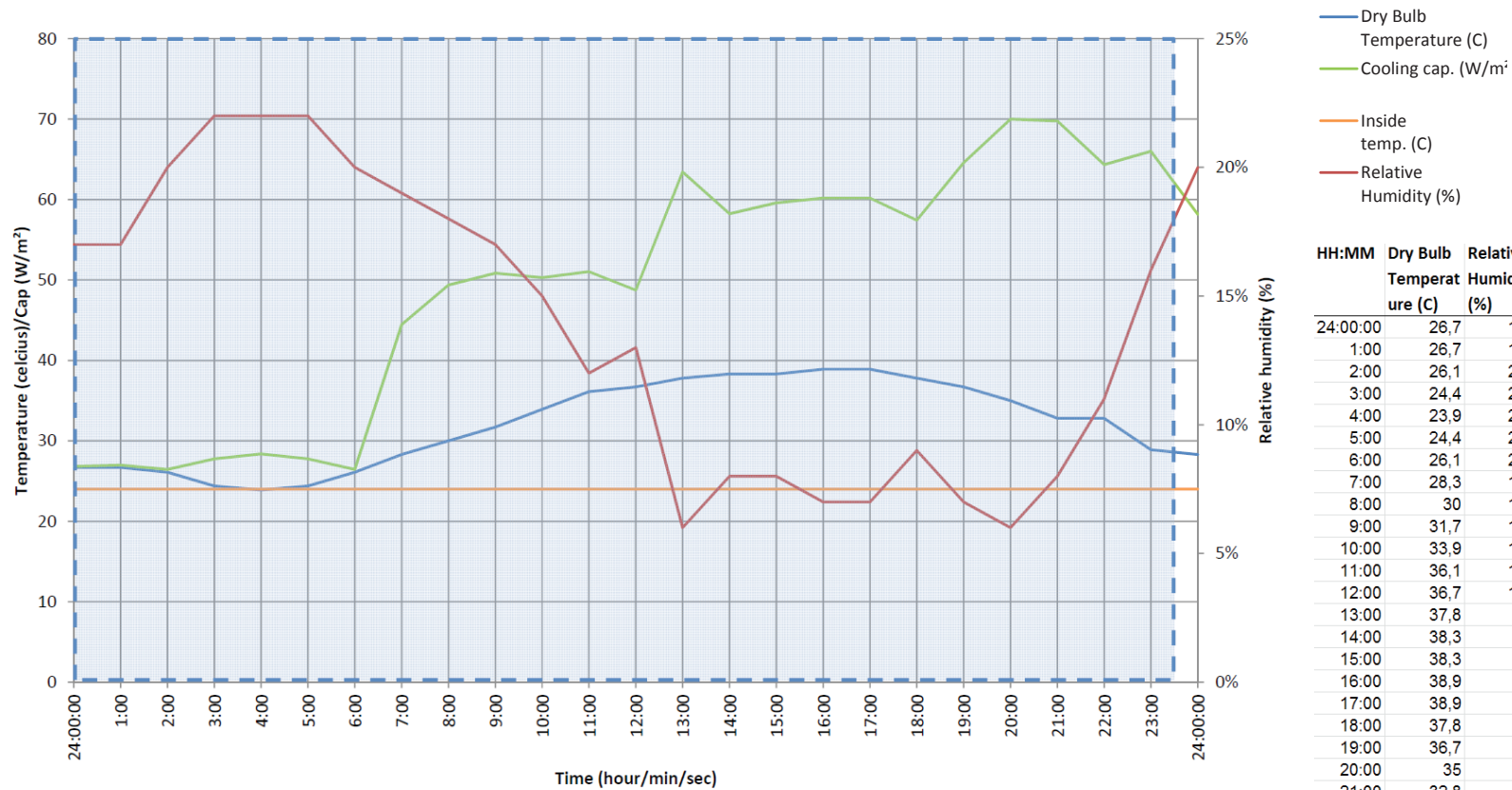
Fig. 124 Cooling capacity on 22 July 1991 in Las Vegas

HH:MM	Dry Bulb Temperature (C)	Relative Humidity (%)	Cooling cap. (W/m²)	Air velocity (m/s)	Water amount (kg/m²/hr)
24:00:00	26,7	17%	27	0,25	0,045
1:00	26,7	17%	27	0,25	0,046
2:00	26,1	20%	26	0,25	0,044
3:00	24,4	22%	28	0,25	0,044
4:00	23,9	22%	28	0,25	0,044
5:00	24,4	22%	28	0,25	0,044
6:00	26,1	20%	26	0,25	0,044
7:00	28,3	19%	44	0,5	0,093
8:00	30	18%	49	0,75	0,123
9:00	31,7	17%	51	1	0,153
10:00	33,9	15%	50	1,25	0,186
11:00	36,1	12%	51	1,5	0,227
12:00	36,7	13%	49	1,75	0,25
13:00	37,8	6%	63	2	0,321
14:00	38,3	8%	58	2,25	0,338
15:00	38,3	8%	60	2,5	0,366
16:00	38,9	7%	60	2,5	0,376
17:00	38,9	7%	60	2,5	0,376
18:00	37,8	9%	57	2,25	0,32
19:00	36,7	7%	65	2	0,311
20:00	35	6%	70	1,75	0,283
21:00	32,8	8%	70	1,5	0,24
22:00	32,8	11%	64	1,5	0,228
23:00	28,9	16%	66	1,25	0,181
24:00:00	28,3	20%	58	1	0,146

4,829 kg/m²

Fig. 125 Results 22th July `91, Las Vegas

7.3 Climate Singapore

Also for Singapore a period of 15 days is selected (16 till 31 July 1999). In tropical rainforest climate zones like these the weather conditions over the year are almost equal. The temperatures and relative humidity are high during the year. For this simulation the 22th of July is selected, as an average day, to use for the simulation. The temperature on the 22th doesn`t decline under the 27 °C, the relative humidity is extremely high (70 till 90%). The results of the simulation model are negative, during the day the adiabatic cooling system is not able to evaporate. The air is to humidified to absorb enough water to generate cooling. Even the driest time of the year, an evaporative cooling system is not able to cool in tropical rainforest climate zones.

7.4 Conclusion climate

Out of these climate results can be concluded that the combination of a warm and dry climate are required to make use of this adiabatic cooling system. In Maritime climates the adiabatic cooling system is also working during the drier seasons. However according to the results, in Maritime climates, the cool capacity is significantly lower than in the dry climate zones. In too humidified climate conditions, like tropical rain forest climates an adiabatic cooling system doesn`t function.

The dryer the outside air, the more vapour it can absorb, the more evaporation an thus the higher the cool capacity. In fig. 127 the cool capacity is calculated with different relative humidity steps. The incoming air from outside, with a temperature of 30 °C, enters with a velocity of 1,5 m/s.
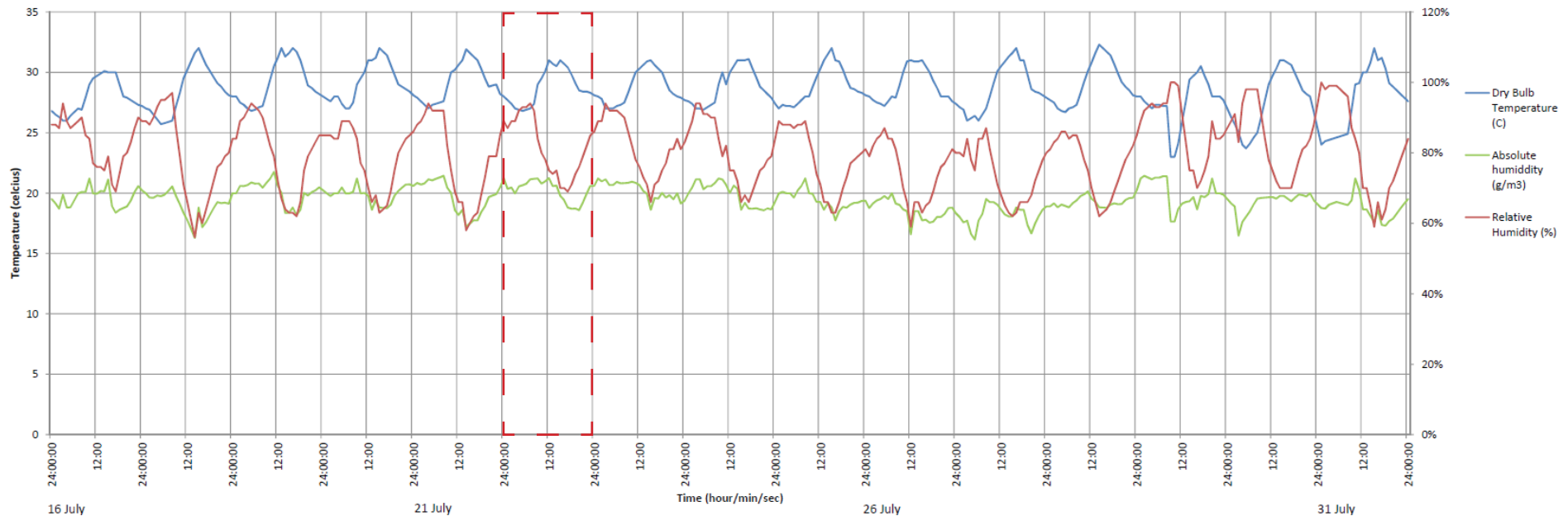
Fig. 126 Climate conditions Signapore 16 t/m 31 July 1999

By dry air with a relative humidity of 5% this generates a capacity of 83 W/m², what results in 0,25 kg/hr/m² of water evaporates. The higher the relative humidity, the higher the absolute humidity, the less evaporation. By a relative humidity of 62% and higher there is no water evaporating possible, and thus an adiabatic cooling system is not working.

In fig. 128 the cool capacity is calculated by a different outside air temperature, which is entering the adiabatic cooling system. The incoming air from the outside with a relative humidity of 30%, enters the adiabatic cooling system with 1,5 m/s. The lower the incoming temperature, the higher the cool capacity. This is because the absolute humidity increases when the temperature rises and the relative humidity stays 30%. The water quantity which evaporates decreases slowly when the temperature is rising.
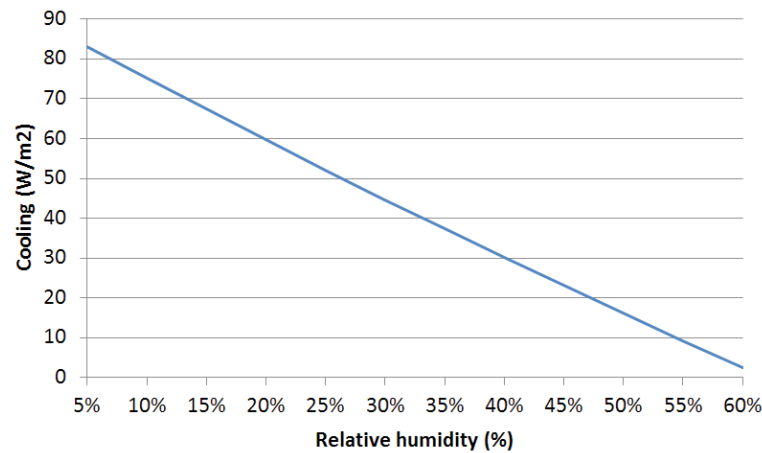
Outside Temp (C)	Relative humidity (%)	Absolute humidity (g/kg)	Cooling capacity (W/m²)	Water quatity (kg/hr/m2)
30	5%	1,26	83,13	-0,25
30	10%	2,52	75,18	-0,23
30	15%	3,79	67,36	-0,21
30	20%	5,05	59,67	-0,19
30	25%	6,31	52,11	-0,17
30	30%	7,57	44,68	-0,16
30	35%	8,84	37,37	-0,14
30	40%	10,10	30,18	-0,12
30	45%	11,36	23,11	-0,11
30	50%	12,62	16,16	-0,09
30	55%	13,88	9,32	-0,08
30	60%	15,15	2,60	-0,06

Fig. 127 Coolcapacity according to relative humidity
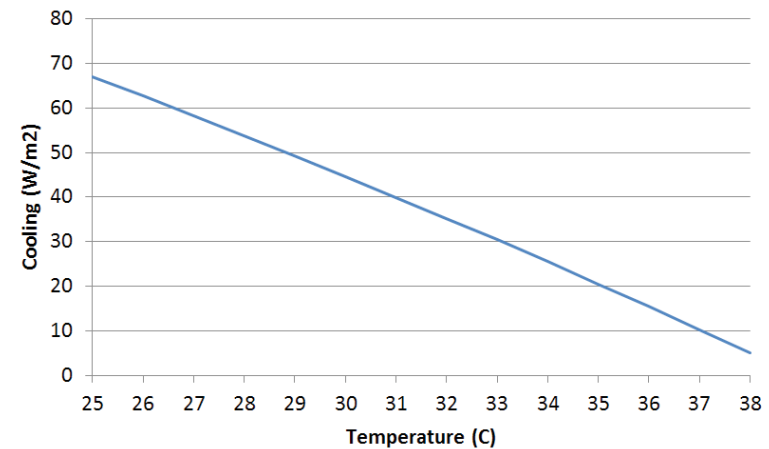
Relative humidity (%)	Outside Temp (C)	Absolute humidity (g/kg)	Cooling capacity (W/m²)	Water quatity (kg/hr/m2)
30	25	5,75	67,07	-0,16
30	26	6,08	62,72	-0,16
30	27	6,43	58,31	-0,16
30	28	6,79	53,84	-0,16
30	29	7,17	49,29	-0,16
30	30	7,57	44,68	-0,16
30	31	7,99	39,99	-0,16
30	32	8,43	35,23	-0,15
30	33	8,89	30,39	-0,15
30	34	9,37	25,48	-0,15
30	35	9,87	20,49	-0,15
30	36	10,40	15,41	-0,15

Fig. 128 Coolcapacity according to temperature

8. APPLICATIONS

8.0 Global applications

According to the results mentioned in chapter 7, page 79., the boundaries of the climate conditions can be determined on the world map.
Assuming that cooling on the North and South pool isn't required, the focus is on the rest of the world.
The red shaded surfaces are zones with the perfect balance between high temperature and low humidity, suitable for an adiabatic cooling system.

In the pink surfaces the adiabatic cooling system can be used, however the system is less efficient. First because of the higher humidity, but also because the efficiency for example the summer periods only.
In grey are mentioned the areas where no cooling demand is required and/or the humidity is too high (tropical rainforest).

■ Suitable	■ Moderately	■ Inappropriate
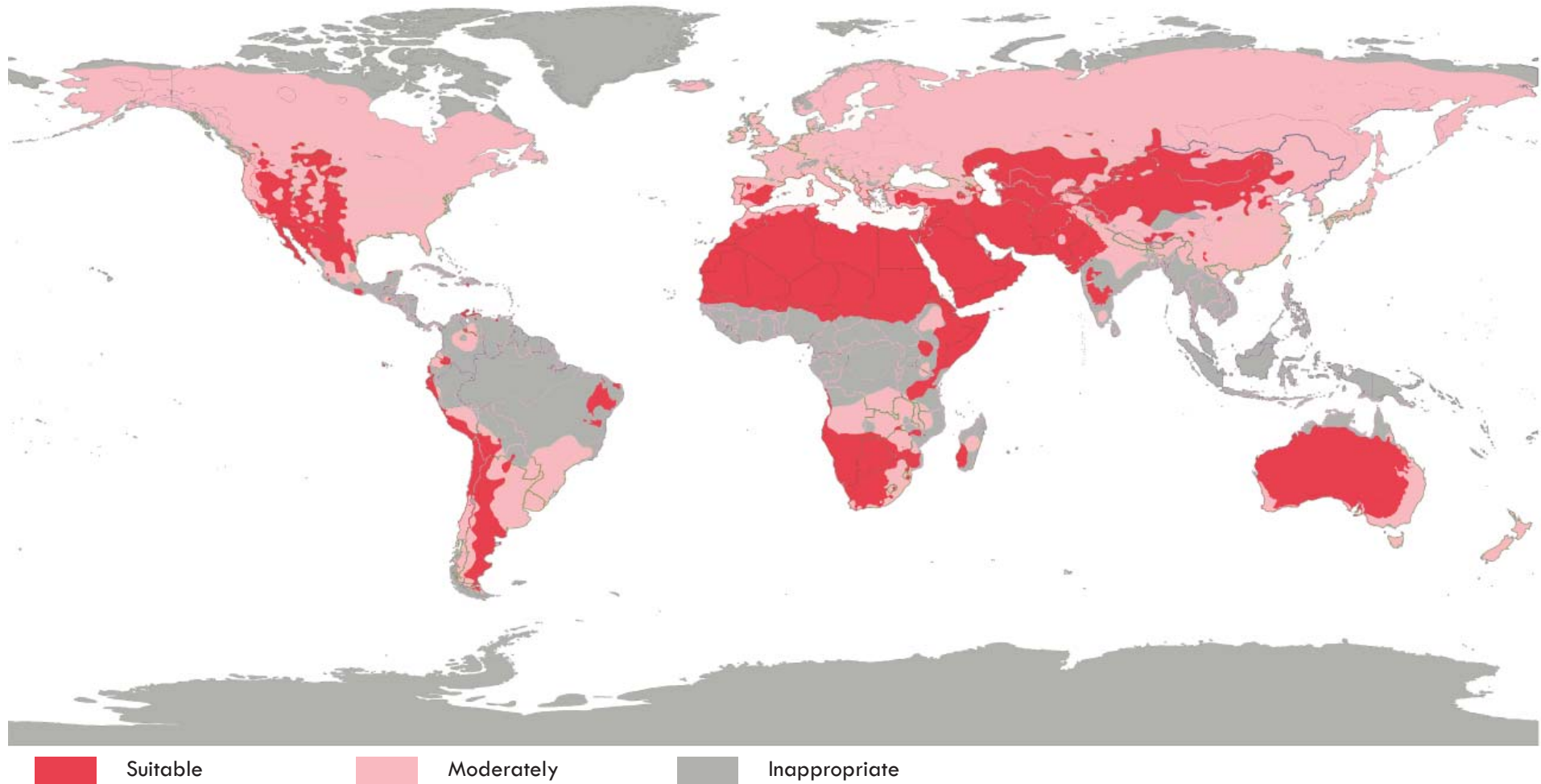
Fig. 129 Application adiabatic cooling world wide

8.1 Building application

For implementation in the building sector the adiabatic cooling system can be used in two different ways, as primary and secondary cooling system.

Primary adiabatic cooling system: The adiabatic cooling system will provide a direct influence on the cooling demand. The temperature inside the building will continuously be cooled till a desired- or minimum temperature is reached. Because of the long response time of the adiabatic cooling system, it`s difficult to fine tune the temperature on short notice. The primary adiabatic cooling system is the perfect solution for cooling buildings on a certain and stable temperature for a longer period. Individual short term preference will need a secondary cooling system.
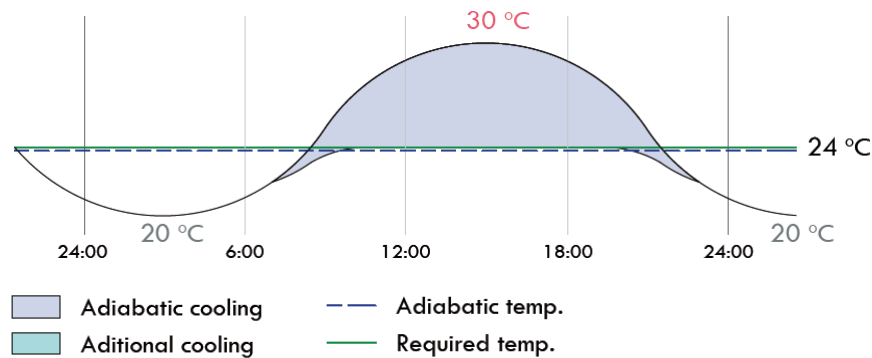
Fig. 130 Primary adiabatic cooling system

This adiabatic cooling system is the perfect solution and can for example be implemented in public buildings (shopping malls, libraries, museums, theatres, schools), sport facilities and residential houses (fig. 131).
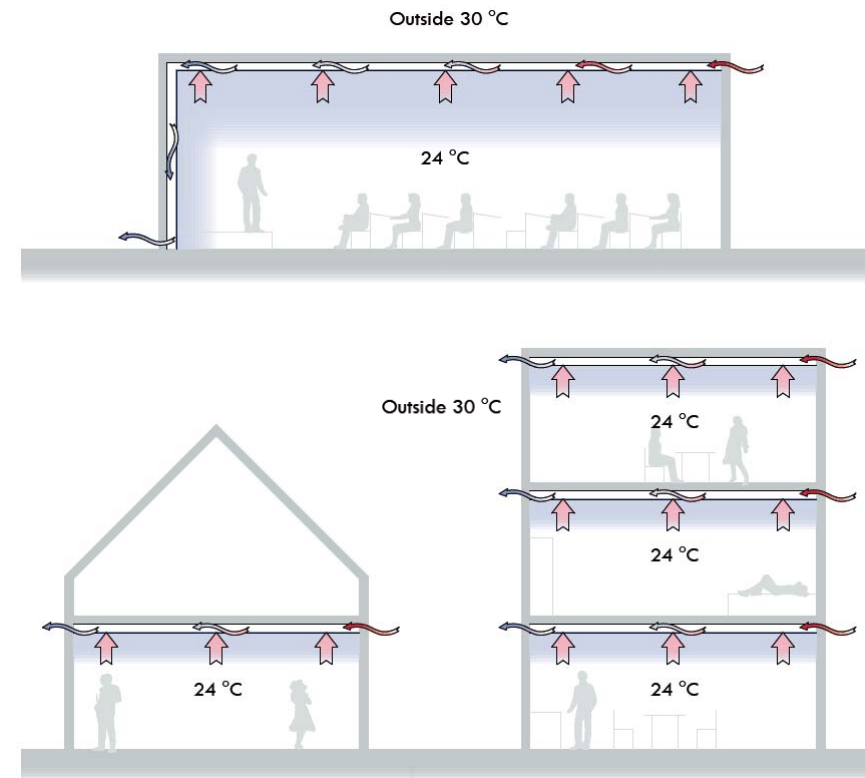
Fig. 131 The primary adiabatic cooling system cools the interior temperature within the comfort zone.

Secondary adiabatic cooling system: In the secondary adiabatic cooling system, two individual cooling systems will be used. The main cooling system will be the adiabatic system, working as the primary adiabatic cooling system, however supported by a second cooling system. The second cooling system is for short term individual temperature preferences. This can be for example a small air-conditioning system.

This combination of adiabatic cooling system and a small air-conditioning result in a very high energy efficient cooling system.
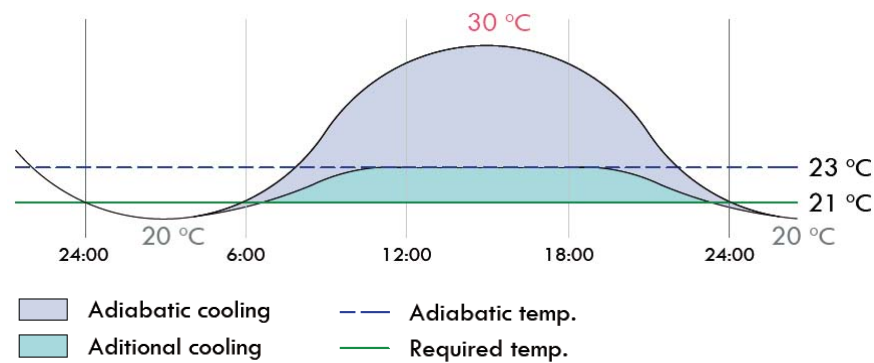
Fig. 132 Secundary adiabatic cooling system

A secondary adiabatic cooling system is a good solution for example offices, hotels and schools. (fig. 133).

Compared to the traditional air-conditioning system the adiabatic cooling system works different. Instead of using only convection by an cool air flow from a certain point or direction, the adiabatic cooling system is using the larger surfaces for a comfortable and better cooling distribution.

Another advantage of the adiabatic cooling system is the noise. Comparison with the traditional air-conditioning only a low flow velocity is required (max. 1,5 m/s). No addition fan is required for cooling the system as with the tradition air-conditioning system.
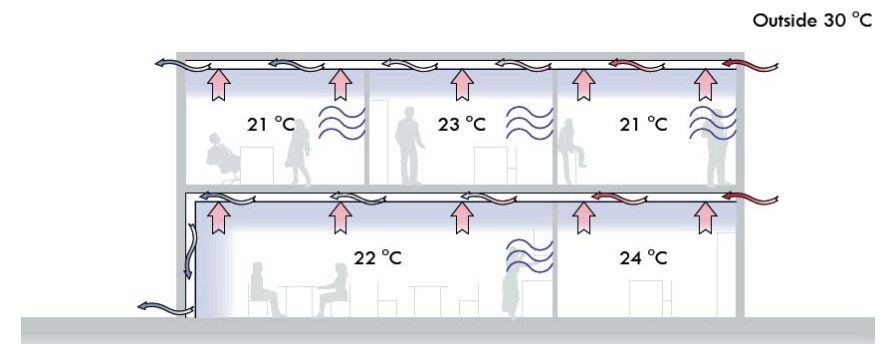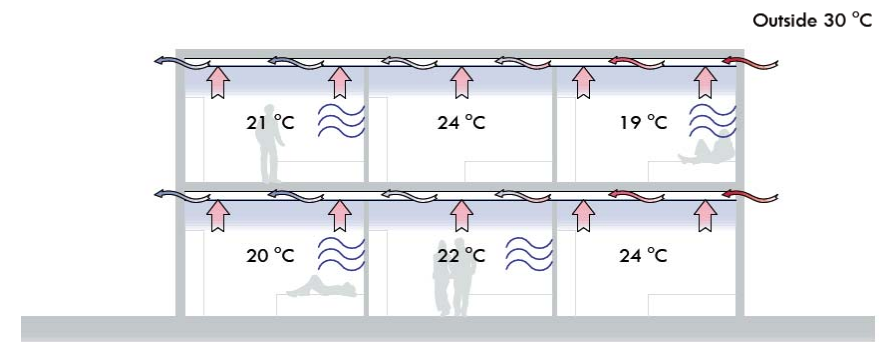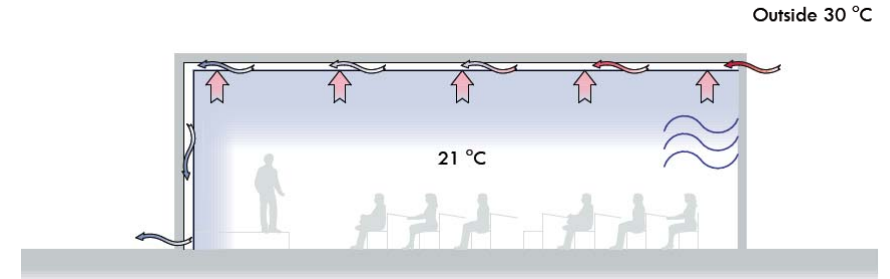
Fig. 133 The secondary adiabatic cooling system keeps the inside temperature within the comfort zone. A second cooler is added for individual preferences.

90

9. CONCLUSION

9.1 Conclusion

The answer to the question if and how it`s possible to cool a building on a passive way, by making use of an adiabatic cool method is yes.

From this master thesis can be concluded that an indirect adiabatic cooling method is a high energy efficient way to cool a building in dry and warm climate conditions.

As a result of the measurements with the prototype we know that the climate circumstances where an adiabatic cooling method will be used are important. Further we see that adiabatic cooling needs a balance between temperature and relative humidity. The temperature and humidity in combination with the air velocity are responsible for the evaporation process. The evaporation process will be limited by the saturated air. So the lower the humidity the more water can evaporate, the better the adiabatic cooling system will work.
Another conclusion from the tests is that a higher outside temperature will not always result in more energy required for cooling. This because a high temperature in combination with an decreasing humidity results in more evaporation. More evaporation results in a higher cooling capacity.

According to the result of the prototype and concept study a simulation model is made. This simulation model first of all proves that the prototype is working. In the same simulation model different climate conditions from over the world has been simulated. The result was that a high temperature in combination with a limited humidity will determine the most suitable climate zones on the world map (fig. 129).

Another question at the begin of this master thesis was; Is it possible to integrate this adiabatic cooling system in the "Revolt House" located in Spain (Madrid) and the Netherlands.
The conclusion of the simulations prove that although the temperature and humidity are different in the two countries, an adiabatic cooling system can be used in the "Revolt House" for cooling in both countries.

9.2 Advantages & disadvantages of the adiabatic cooling system

According to the results of the prototype and simulations a complete adiabatic cooling system is designed, include all the advantage and disadvantage.

Design advantages:

1. The first conclusion from the simulation is the low air velocity required for the evaporation process in the adiabatic cooling system. This proves that very less energy is required for the air velocity through the system.
2. Because of the low air velocity the sound level for this adiabatic cooling system, compared with a tradition system is very low.
3. Because of the large cooling surfaces at the indirect adiabatic cooling system, diffusion of the cool air temperature in a room creates a much better comfort than the traditional air cooling system.
4. However this system is not finalized, the process of adiabatic cooling doesn`t required a complex control system.

Design disadvantages:

1. An adiabatic cooling system needs besides electrical energy also water.
2. The advantages mentioned at point 3, because of the surfaces has also disadvantages in the design and construction of the building.
3. Quick temperature fluctuations are difficult to create with only a "primary" adiabatic cooling system.
4. The balance between the high temperature required for this adiabatic cooling system result in a limitation of the areas where this system can be used.

9.3 Reflection

In the first weeks a study is done to research what adiabatic cooling is and how it functions. What is the history and what kind of adiabatic cooling principles are available? After this period I concluded that the climate conditions I researched where not really relevant. More specific details, specially about relative humidity and dry bulb temperatures, are required for designing and simulating an adiabatic cooling method. Meaning, if I was started with researching adiabatic cooling before I deep into the climate conditions of Madrid, I was able to focus on specific climate properties, and don`t have to research it twice. Finally Energy plus, a climate software, is used to collect the specific needed climate data.

During the research to adiabatic cooling I discovered two different classifications (direct – and indirect). Both are able to cool, but to provide plausible indoor climate the indirect way offered more perspective. From here I was specific focused on indirect adiabatic cooling.
Because there wasn`t much know about an indirect adiabatic cooling system, specially not in the building sector and on scientific research, I changed the methodology and started with making prototypes to be sure if this system is able to cool. After testing the prototypes in different climate conditions, I was able to calculate the cool capacity and make conclusions out of the results. According to the results of the prototype a program of requirements is made for the first concept design of the system.

Based on the researches, the results of the prototypes and the concept design a simulation model is made which is able to calculate the cooling capacity according to different climate conditions.

Subsequently a final design is made and shown how this system can be integrated within the building envelope. What kind of materials and products are used and how are these included in the design. The total efficiency of this system is calculated and compared with a traditional air conditioning system.
Besides this graduation project is a recommended proposal/design for the

Solar Decathlon team of the TU Delft, this project explains how cooling can be created sustainable wise without deteriorating the indoor climate conditions. It provides a new way of using evaporation to generate high cooling power with low energy input. Which isn`t only useful for the competition in Madrid, but also can be applied in other buildings in dry and warm climate conditions, and be integrated within the building envelope.

In retrospect this graduation project is in research of the Solar Decathlon competition, what gives extra effort to deliver a good result. But in the last month I was more focused on the adiabatic cooling system itself than the integration with the Solar Decathlon. This because I wanted to be sure that I had the system optimized and not depending on other disciplines.

During this graduation project I`ve had a lot of feedback from building physical, climate- and façade design professionals where I`m really pleased with. But to make it a real product, influences from an industrial designer are recommended.
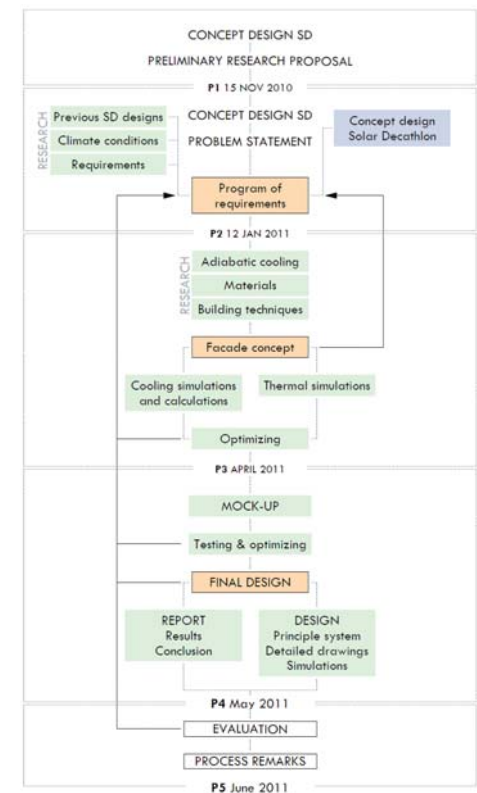
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10. APPENDIX

I Previous Solar Decathlon projects (2010)

The first Solar Decathlon competition was held in 2002 in America organized by the department of energy.

In June 2010 ministry of housing from Spain in cooperation with the department of energy from America organized the first Solar Decathlon competition in Europe, located in Madrid. Each house is built and evaluated during the course of the event according to ten contests, which are ranging from: architectural design, engineering & construction, Solar systems & hot water, energy balance, comfort conditions, appliances & functionality, communication & social aware, industrialization & marketability, innovative and sustainability.

The three best projects of the twenty participating universities are analyzed.

Fig. 134 1st, 2nd and 3rd place, Solar Decathlon 2010

l.l Virginia

The winner of the Solar Decathlon competition of 2010 is the University of Virginia. They designed the "Lumenhaus".

Lumenhaus does more than literally deliver a brighter day, however. Lumenhaus epitomizes a "whole building design" construction approach, in which all the home's components and systems have been designed to work together to maximize user comfort with environmental protection. Lumenhaus uses technology optimally to make the owner's life simpler, more energy efficient and less expensive. On the cutting edge of responsive architecture, Lumenhaus can operate completely self-sufficiently, responding to environmental changes automatically to balance energy efficiency with user comfort. Lumenhaus is a zero-energy home that is completely powered by the sun. Other sustainable features include the use of passive energy systems, radiant heating and building materials that are from renewable and/or recyclable sources.

Fig. 135 Winning design "Lumenhaus", Virginia

The Lumenhaus is arrived as one prefabricated unit, transported on a trailer and by arrival placed on the right position, like a caravan. The house is orientated with the long transparent façades to the North and South direction, this will lead to extra sunshading on the transparent South

façade. The photovoltaic' s and thermal solar collectors are located on an adjustable structure on top of the roof, this optimize the angle of the energy producers to get a higher energy production. The photovoltaic' s making use of the bifacial effect, meaning both sides of the photovoltaic panel will be

used to capture energy. The top of the panel use direct sunlight to convert this to electricity, the backside is making use of indirect light. This realized a higher energy efficiency.
The load bearing structure is made of steel. The close parts of the house are filled in with SIPs (Structural Insulated Panel).
Façade: The load bearing structure is made of a steel frame. façade consist of several layers

The Lumenhaus adapt on the climate during the season and day. The North and South façade exists of several layers with different properties who slides during climate changing to achieve the optimum climate conditions inside the house. The transparent parts of the façade consist of glass windows, fixed in an aluminum window frame.
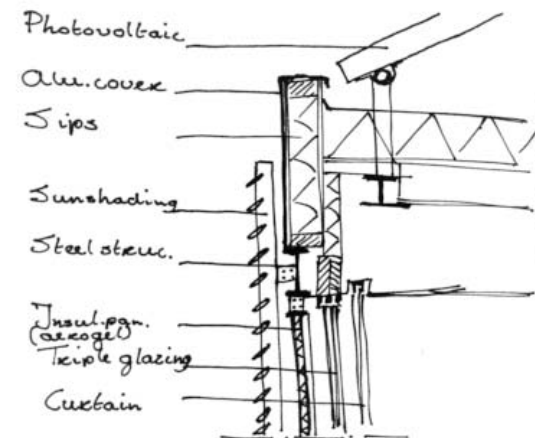

Fig. 136 Sketch detail "Lumenhaus"

Insulation: The West and East façades are totally closed (opaque), these consists of SIP panels which achieves a high insulation value. The transparent façades are made of triple layered glass which can afford an g value of 0.3. Before the transparent façade a sliding translucent polycarbonate panel (fig. 137) filled with aero gel provides the house during the cold days with an extra insulation layer.

Sunshading: The sunshading consist of a sliding eclipses perforated stainless steel shutter (fig. 138) positioned at the front of the polycarbonate insulation panel. This shutter shades slides along the façades, providing protection from direct sunlight, while indirect sunlight will be naturally reflected inside the house.

My assumption of final score concerns the façade:
The Lumenhaus arrived as one unit, I think this will decrease the total score of engineering & construction and sustainability because of the huge exceptional convoy. When the building was able to be dismounted and transported on a more common way the score would be higher.
Also the use of materials have aan impact on the sustainability score. The North and South façade consists of five several movable layers, less is more. But due to this façade system it keeps the architecture, energy balance and comfort score higher.
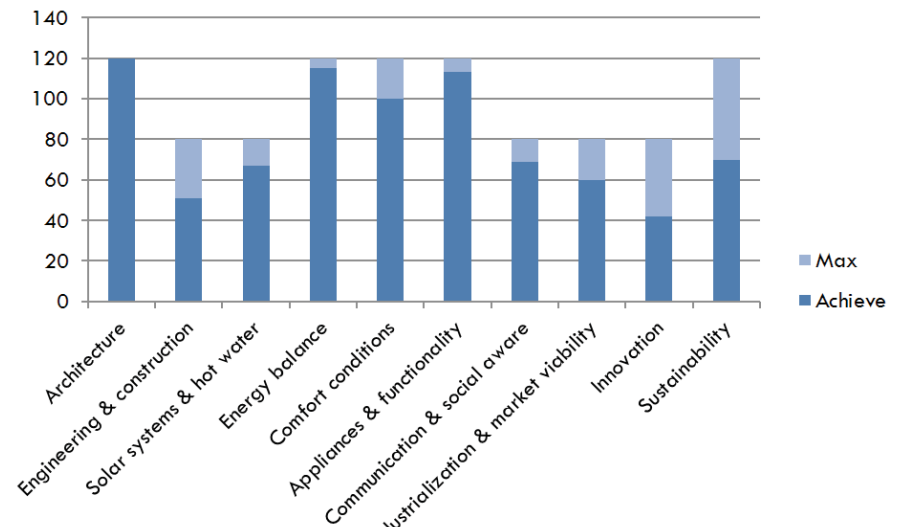

Fig. 137 Polycarbonate

Fig. 138 Eclipsis shutter

Fig. 139 Final score Virginia, 2010

At the inside of the glazing a fabric curtain is used, perhaps to reduce the acoustics reverberation and shut of the area from day light. Between the glass and the polycarbonate panel a bug protection layer is added.

By opening the window and/or sliding doors natural ventilation is possible, even when the eclipses sunshading and polycarbonate insulation panel are closed.

The sliding façade elements (sunshading, insulation panels and curtains) are totally controlled by mechanical drives. These drives reacts on sensors which transmit the optimum situation according the climate conditions. Windows and doors are manually open able by user.

I.II Rosenheim

The second place of the Solar Decathlon competition 2010 is for team Ikaros Bavaria from the University of Rosenheim.

The basic idea of the house is a flexible living space, with the floor plan being designed to adjust to the needs of the inhabitant. Several occasions, which do not take place simultaneously in everyday life, are accommodated in one space. Principally, the living area is designed as an open space. However, there is always the option of creating privacy by separating the private rooms for sleeping and working. This results in great freedom of design and an efficient use of space in the interior.

The special feature of the house is the newly developed zigzag facade. It gives the building its unique character and also functions as a visual/sun protection. It ensures an ideal use of the daylight as it changes throughout the day and the seasons, creating different effects of light and shadow.

Fig. 140 2nd place, team Ikaros Bavaria, Rosenheim

This design consist of a modular system which can be extended by connecting extra modules. Each module is prefabricated and constructive because each module provides its own wooden load bearing structure.

The house is orientated with the short façades to the North and South.

On top of the roof photovoltaic modules and thermal solar collectors are placed, they are invisible from street level. The photovoltaic modules, made of monocrystalline cells, generates the highest amount of electricity, but has also the longest energy payback time of all pv technologies.
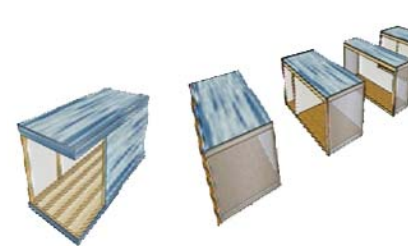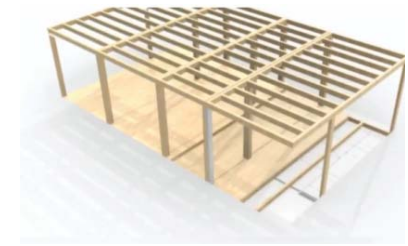

Fig. 141 Modules Rosenheim

Fig. 142 Structure Rosenheim

At the South façade an internal loggia is designed, this loggia works as a thermal buffer during the winter and will be ventilated and protected from the sun during the summer.

The closed façades are insulated with VIP (Vacuum Insulated Panels), these panels can be thinner than the usual insulations and reach a much higher insulation value (Lambda rockwool = 0,04 W/(m•K), lambda VIP = 0,005 W/(m•K)).
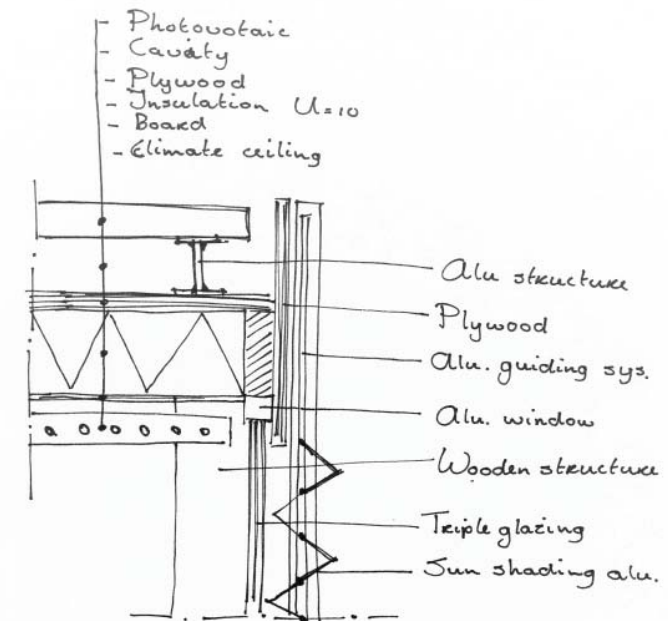

Fig. 143 Sketch detail "Rosenheim"

The spectacular part of the façade design is the vertical sliding sunshading system. The sunshading system, consisting of white aluminum hinged zig zag shapes, around the building is on every façade the same, but gives another effect. The sunshading system is simulated and tested on sun transmission at the West, South and East façade during summer season. When the sun is positioned on the South façade this sunshading system transmit only 3% of the total solar transmission.
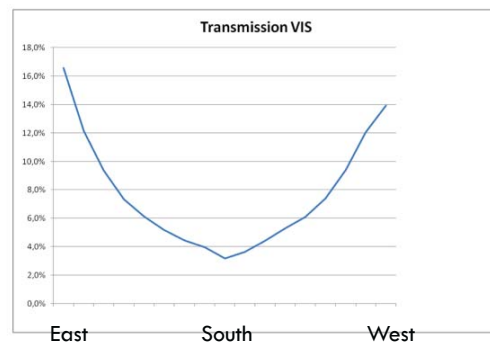

Fig. 144 Simulated sun transmission

The sunshading system adapt on different climate situations, in June the sun will be as good as blocked. The lower the sun is positioned (winter) the more solar radiation entering the building.

Fig. 145 Test model zig zag sunshading system

The ventilation system is totally controlled by a balanced ventilation system, ventilation openings in the façades are omitted.

My assumption of final score concerns the façade:
The sunshading system functions very good, seen the energy balance and comfort conditions, of course this isn`t only done by the sunshading system, but it plays a big role. Also the natural light effects within the building results in a high architecture and comfort conditions score.
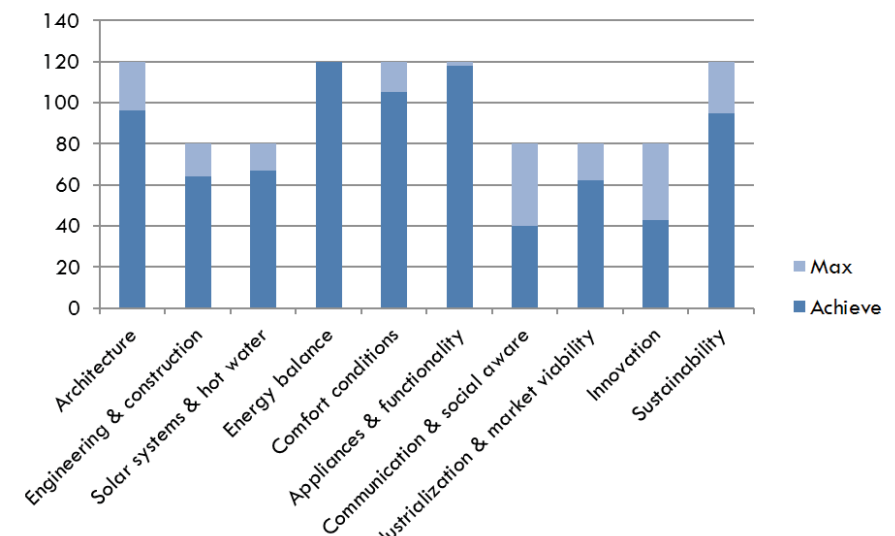

Fig. 146 Final score Rosenheim, 2010

The third place of the Solar Decathlon competition 2010 is for the University of Stuttgart.

The draft is designed for a one- or two-person household and is based on creative and energy consumption considerations. An emphasis is put on the integration of solar energy technologies. The starting point is a compact, highly insulated volume, which has a relatively large inner surface in relation to the overall area. It uses the basic principles of traditional examples from similar regions, like the wind towers in the Arab world and patios, which are widespread in Spain. The combination of new materials and technologies available today makes it possible to create an element that allows high level of comfort together with low energy consumption significantly shaping the design and spatial perception of the building.

The volume is divided into modules, which are arranged with some distance from each other. The resulting gaps are used for lighting, ventilation, heating in winter and passive cooling in summer. A special role is played by the climatically-active gap, the so-called energy tower, which contributes to the interaction of wind and evaporative cooling producing a pleasant indoor climate in hot and dry regions, such as Madrid.

Fig. 147 3rd place, team Home +, Stuttgart

This design exist of a modular system which are connected by climate boxes. Each module consist of a different function (fig. 123).

Fig. 148 Floorplan, Stuttgart

The climate boxes, consists of glass, provide the user natural daylight and ventilation which will enter through the chimney façade. This gives the user possibilities to control the comfort by opening a window or shut down the sunshading to block the sun. On top of these climate boxes thermal solar collectors are mounted, where natural daylight shines through. A ventilation tower, based on evaporative cooling techniques, is located in the middle of the building. Through this tower warm dry air will be humidified and cooled before it enters the building. Also this system is located on top of a climate box. In the middle of the building fresh air will be supplied, at the façades of this climate box the polluted air will be exhausted (fig.149)
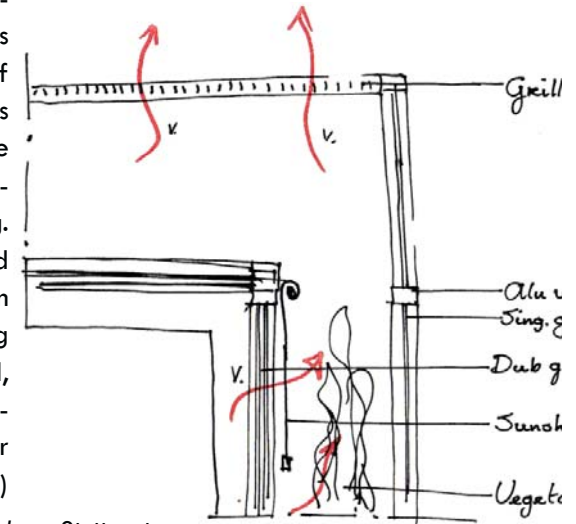

Fig. 149 Sketch detail climate box, Stuttgart

On top of the roof and at the East and West façade photovoltaic's mounted.

Building sequence:

1. Floor will be balanced out
2. Modules functions will be positioned: The modules are structured by a wooden frame, insulated by VIPs (Vacuum insulated panels) and closed by wooden panels.
3. Climate boxes will be installed
4. The shell (outside finishing of the roof and East & West façade) will be connected to the modules. The whole shell consist of photovoltaic's.
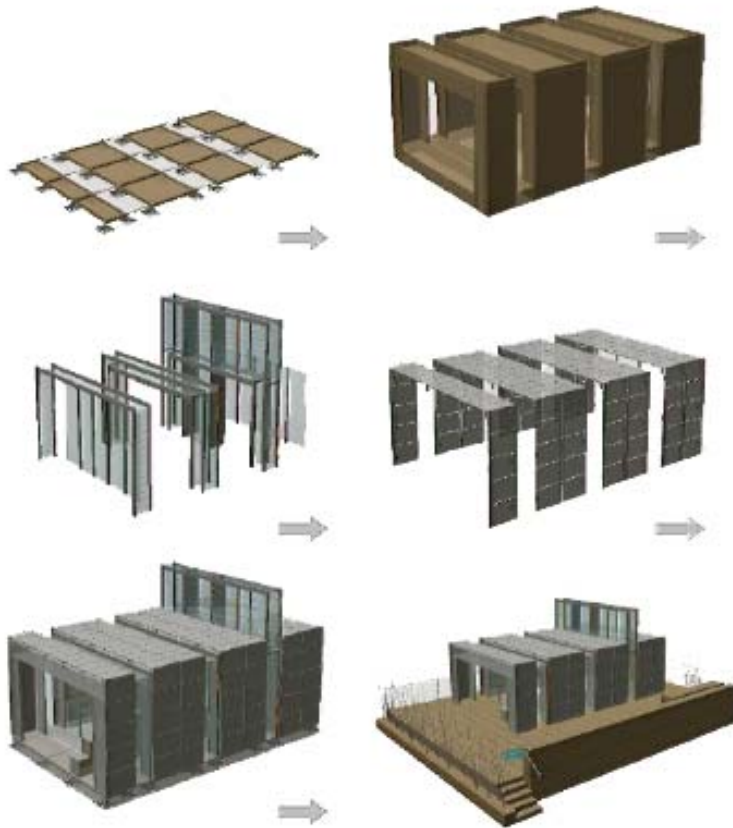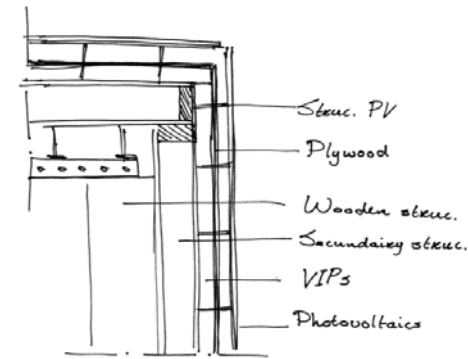

Fig. 150 Building sequence Stuttgart

Struc. PV
Plywood
Wooden struc.
Secundairy struc.
VIPs
Photovoltaics

Fig. 151 Sketch detail facade - roof

My assumption of final score concerns the façade:

The architecture score isn`t that high, I don`t think this has to do with the representation, but more the division of the house. The photovoltaic's and thermal solar collectors lifted up the energy balance, solar systems and sustainability. Also the ventilation tower brought good results, but doesn`t completely satisfy the expectations and lowered the score in comfort.
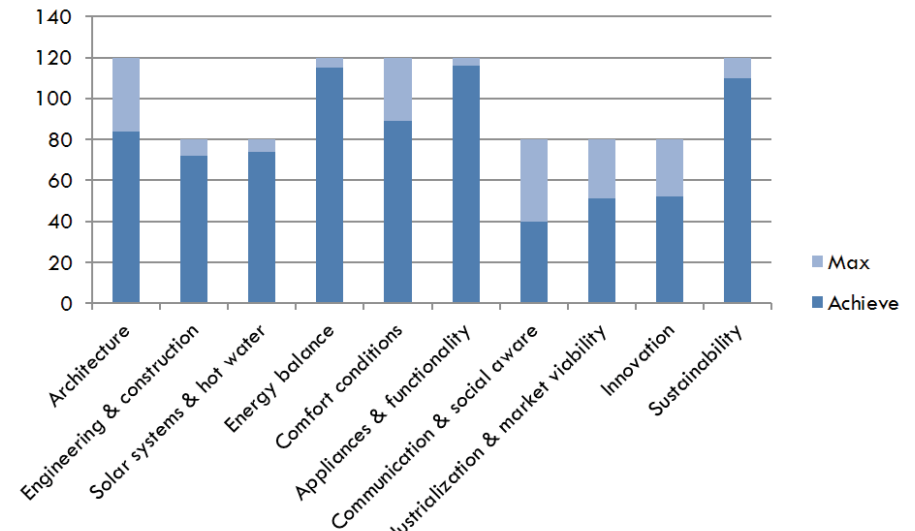

Fig. 152 Final score Stuttgart, 2010

I.IV Conclusion Solar Decathlon 2010

The battle for the first place was a neck a neck race between the participating teams. This is the final score of the Solar Decathlon 2010:

1st Virginia: 812
2nd Rosenheim: 810
3rd Stuttgart: 808

My assumption of the final score concerns the façade:

Architecture: The building envelope needs to be applicable, functional and be designed in the right proportion. Virginia scored full points.
Engineering & construction: By making the building easily demountable and assemble the score will be higher. Certainly when it`s compact and easy to transport, this is a necking thing for Virginia.
Solar systems and hot water: Worked perfectly on the roof.
Energy balances: As well monocrystalline as double hit photovoltaic` s gives a positive effect for generating energy, it`s enough for the used appliances and the climate systems. Photovoltaic` s on the façade are not a must.
Comfort conditions: Movable sunshading systems can help to realize the wished comfort. Watch out with new climate systems, be sure they are tested and can provide the expectations.
Industrialization & market viability: If new systems are used, try to use existing industrialization products and techniques which are common use.
Innovation: Stuttgart used new climate techniques which lifted up the innovation score, but generally the score for innovation are quite low.
Sustainability: Avoid materials which needs a lot of fossil fuels and release lots of CO2 during the production. Virginia used a lot of steel (structure and sunshading) and polystyrene (insulation in SIP`s), this keeps out point.

Innovation, sustainability and industrialization scored generally quite low, this can be a directive for the next generation. But past performance is no guarantee for the future.
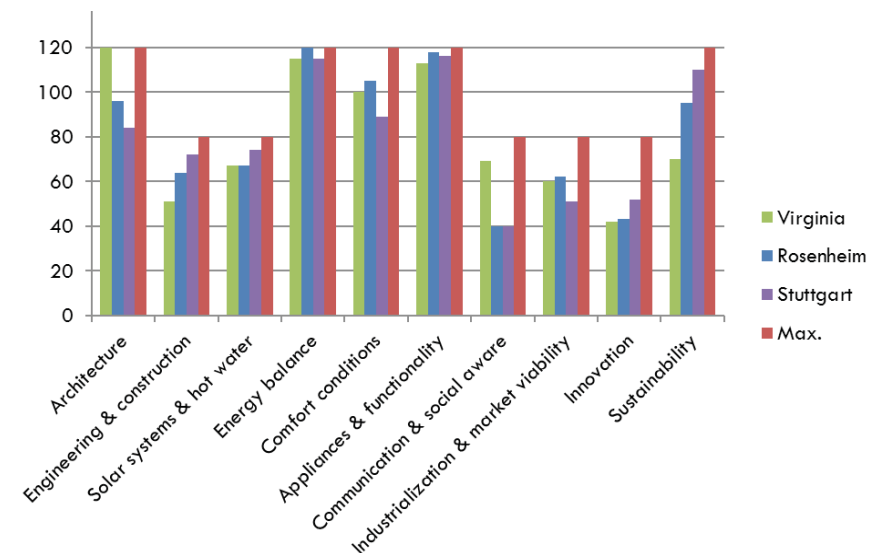

Fig. 153 1st, 2nd and 3rd place score out of max.

Fig. 154 Prototype setup without shield

Fig. 155 Prototype setup with aluminium shield

Fig. 156 Radiation (from light) provides negative cooling influences

Fig. 157 Prototype setup without aluminium shield

Fig. 158 Test element, inside metal plate

Fig. 159 Absorbtion layer behind metal plate

Fig. 160 Test element with hydro grains as absorption, (negative effect)

Fig. 161 Prototype setup in the living room

III Detailed measurements

These graphics are the detailed measurements, which shows the exact data of all the used dataloggers.
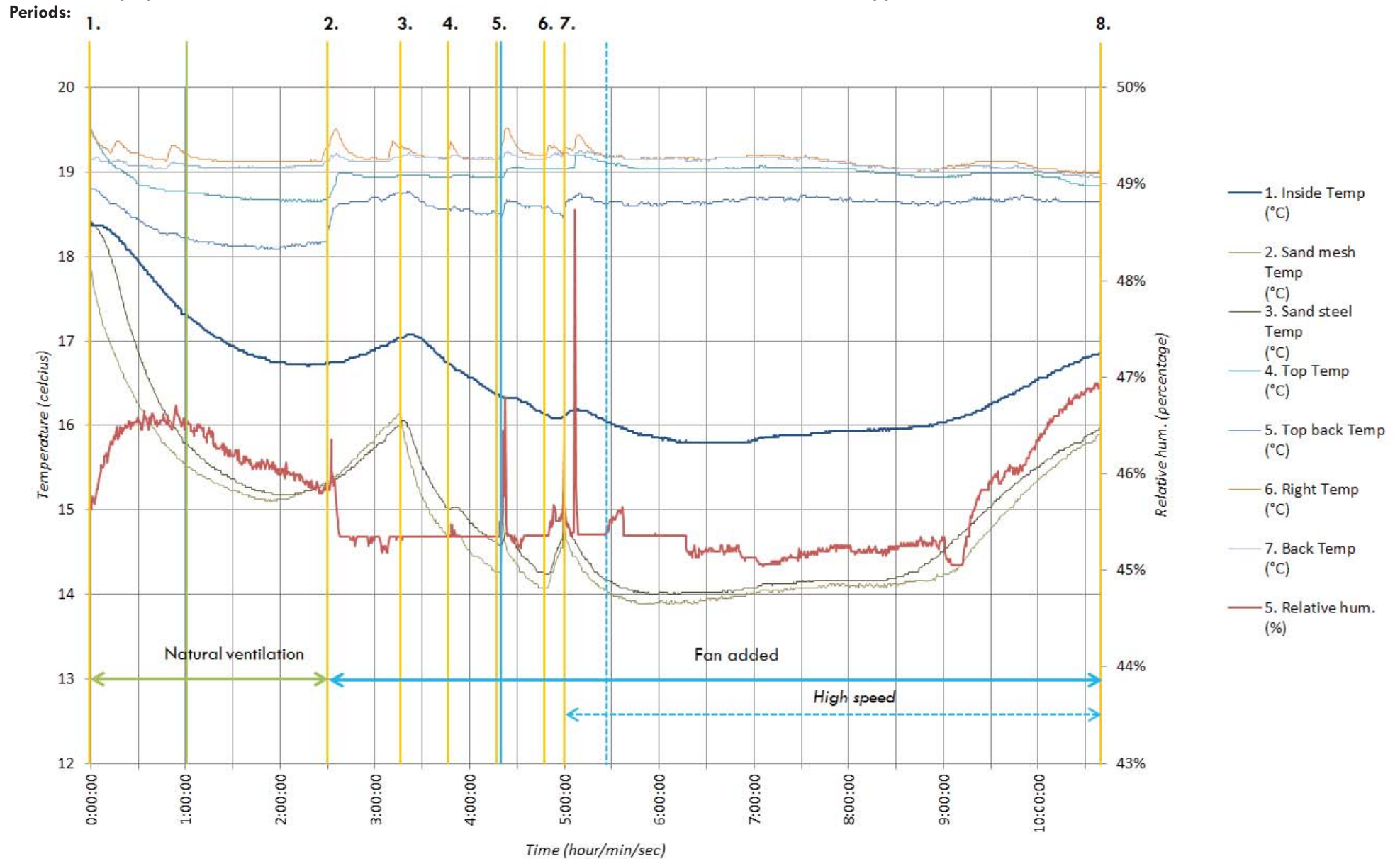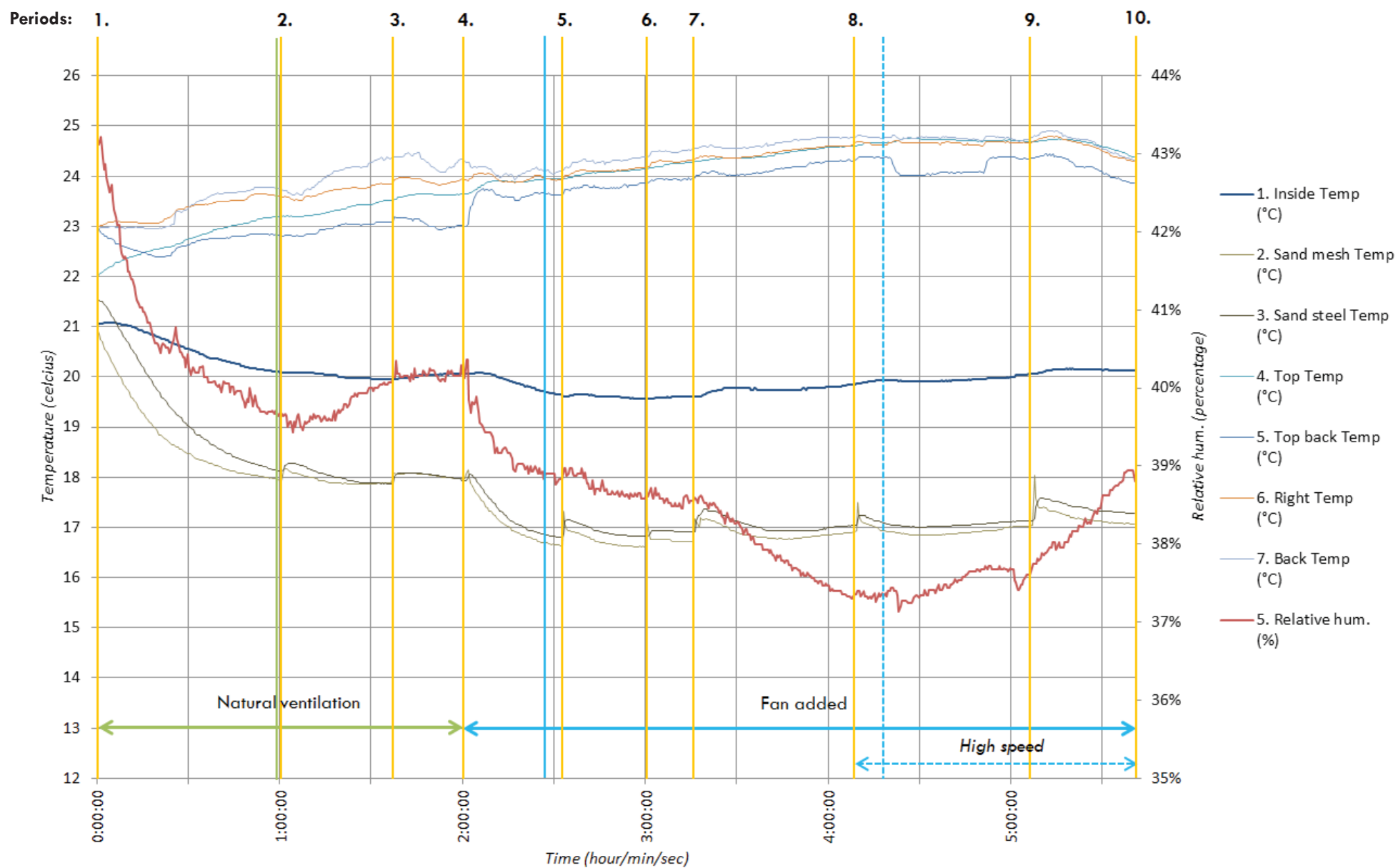

Fig. 162 Detailed measurements of test 1

Fig. 163 Detailed measurements of test 2