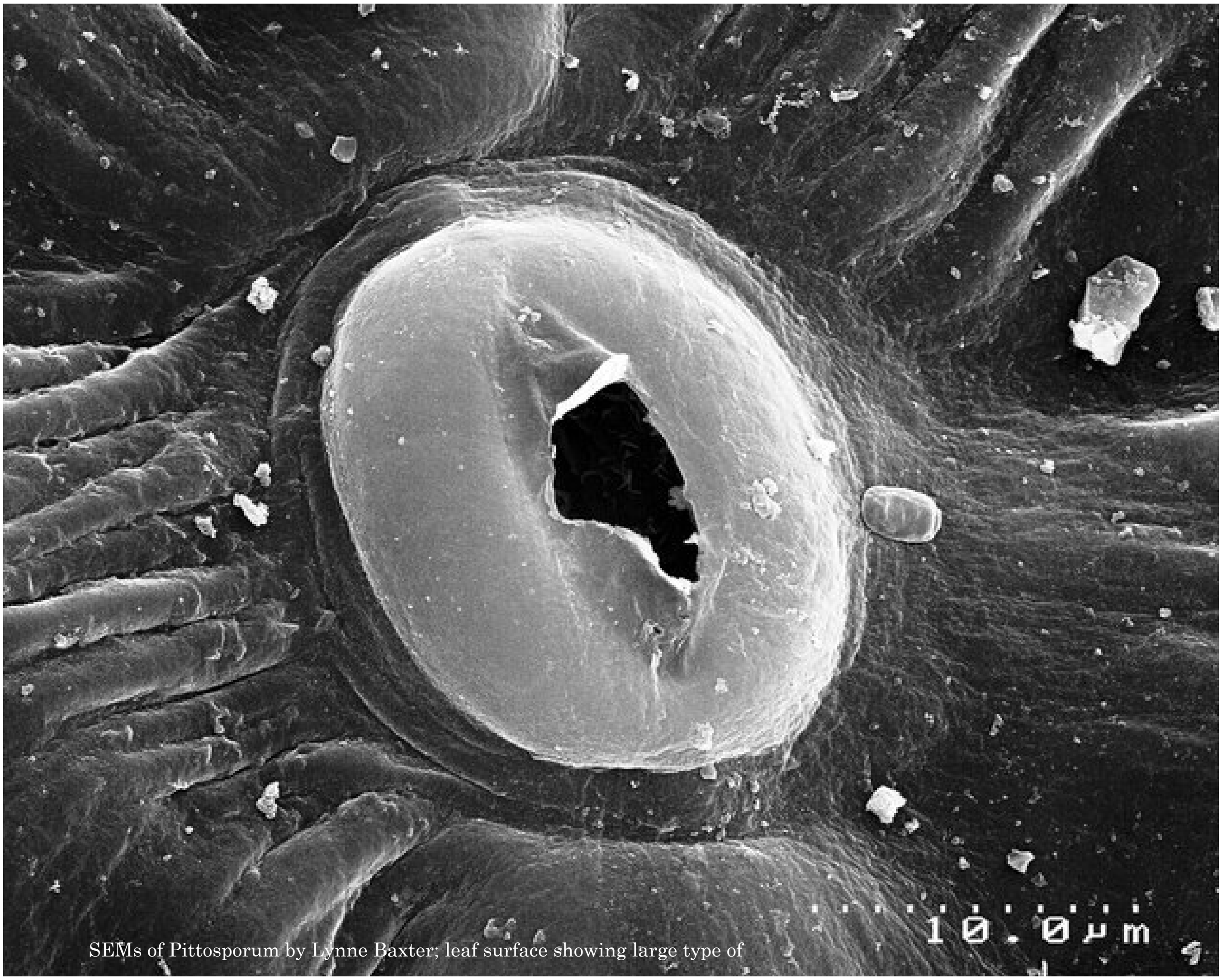
Learning from nature - Thermoregulation Envelopes



SEMs of Pittosporum by Lynne Baxter; leaf surface showing large type of

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Content:

1. Introduction

Nature uses as little as possible of anything' Johannes Kepler

1.1 Subject area

Learning from nature has always been a key feature of inventions and solutions to different problems of scientists and engineers in different fields. There are numerous examples of biomimmetic successes including some that are simple copies of nature. Through 3.5 billion years of evolution (*Schopf,1993*) nature has "experimented" with various solutions to challenges and has improved upon successful solutions (*Bar Cohen Yoseph,2006*).although various forms of biomimmecry design are discussed in the field of sustainable architecture(*Reed,2006 ,Berkebile,2007*) the practical application are usual unrealized . Examples of successful developments inspired from nature are typically products or materials rather than of buildings or building systems (*Maibritt Pedersen Zari, 2007*) .Over the course of history many different spatial arrangements of building envelopes have been conducted, many strategies have been taught and endless ways of designing the fragments took place. Manufacturing of elements which usually perform one principle function is one of the outcomes of mass production systems in the building industry. Dominated by the efficiency design approach in using minimum amount of material and energy, it usually produces a relative cheap and simplistic performance system. On the Other hand, few examples, tailored to different schemes, are becoming very sophisticated and by that become technologically vulnerable mechanisms. This complex variety together with old fashioned notion of natural phenomena's as hostile to people usually leads to- a façade concept of a barrier between the outside climate and the inside climate of a building.
A buildings outer skin, or envelope has many functions .one of its most important is to protect its occupants from the outer surroundings and to fulfil their notion of comfort. In order to do so one of the aspects to deal with is thermo regulation of temperatures'. Building envelopes need to control the inner temperature of the building by responding to the outer variables and the inner ones. Looking at the systems of thermoregulation in nature can give a new insight on how to develop strategies toward newly sustainable design. ***Versatility*** (the capability of adaptation) as in nature could lead to it. The relations between form material and performance should be more of a synergy that aspires to integral design. A critical revision in the understanding of optimization, efficiency and redundancy in relation to multi performative material systems can open new spatial organization and sustainable systems (*Michel Hansel, Achim Menges, 2008*).

The focus of this study is to explore the different systems and behaviours that organisms have evolved in order to regulate body temperature. Through literature comparative reviews, building conceptual models and investigating them, new knowledge can be obtained. This could eventually lead to a fully developed paradigm of adopting or translating different operating systems and behaviours of nature mechanisms that regulate heat and transform it into the world of façade constructions.

1.2 Research objectives

Heat is a form of transferred energy that arises from the random motion of molecules and is felt as temperature. Heat is transmitted by conduction, convection, or radiation. By responding to the outer variables and the inner ones building facades control the inner surroundings.
These controlled environments use a great deal of time and energy in order to manipulate the changes in temperature.
Analyzing the increasing complexity of façade systems one can ask if this complication is an improvement for the user or for the manufacturer?
Facades have been introduced as heat collectors (*trombe wall, Steven Baer, new Mexico 1973*) while others to shield the building from the outer influences -from the climatically active façade (Mur *neutralisant, Le Corbusier, 1929*) to the different double facades or integrated facades (*Capricorn house,Dusseldorf,Gatermann+Schossig, 2006*)
In spite of these different attempts (and many more) towards "the adaptive facade", there is usually an increase in the amount of separate building services and not a real responsive, adaptable and integral element facade.

The main objective of this research is to explore the different systems and behaviors that organisms have evolved in order to regulate body temp', in response to temp' variations in the surrounding environment.
Understanding of such natural manipulation of heat gain against heat loss can eventually be transformed to technical, structural and material performance.

1.3 specific objectives

a) To investigate and analyse existing heat regulating systems in building envelopes
b) To explore natures ways of dealing with thermoregulation in order to adopt systems to the built world.
c) To seek for a better definition for building envelopes (in different regions), not just as a barrier.
d) To provide options for future solutions, in regard to thermoregulation systems, for designers and manufacturers in sustainable building envelopes and architecture.

1.4 academic objectives and relevance

The hypothesis of this thesis is that through studying and implementing the researched biological data –in relation to thermoregulation mechanisms- of nature's organisms, we will achieve a new perspective on built envelopes. After assessing its potential, it can be implemented in façade systems and address new questions regarding the capabilities of architectural design and construction in a new sustainable approach.

1.5 Research question

Main question-

- **What can we learn and adopt from temperature managing systems in nature in order to develop a temperature regulating envelope for buildings?**

Other key questions-

- How do organisms respond to the changes of thermal energy in the environment in order to maintain their own fairly narrow thermal requirements? What are nature principles?
- What are the passive and active ways of natural systems to regulate temperature?
- Can the natural adaptability to different conditions (of a particular organism) be influenced both in terms of place (different location) and in terms of time (seasons, day-night)?
- What are the requirements of building envelopes in response to temperature?
- What are the exterior and the interior requirements and properties in regard to user comfort?
- How do we interpret the bio-mechanisms into building envelope models?
- What form, structure and material can be integrated into the new temp regulating envelope?

1.6 Approach and methodology

The following research will comprise of four main investigating and analysing chapters and one chapter for final results and conclusions.

1.6.1 Data collection - Narrowing the research boundaries by literature research on nature, biomimics, heat regulation and facades.

- Summarizing indoor temperature range standards for buildings.
- Investigation of existing building envelopes.
- Investigating temperature regulating systems in facades.

- Investigation of living organisms and their bio-thermal mechanisms.

1.6.2 Analyzing and abstraction

- Summarizing **key methods, structure, material and functionality** in regard to temperature regulations of natural organisms.
- **Analyzing** and specifying the preformative thermal requirements for a specific envelope. Formulating the design problems.
- **Abstracting** the main **deep principle**.

1.6.3 Elaborating on design solutions

- Based on the abstraction and analysis of the key principles from natural systems Programming design requirements should take place through **emulation**. The requirements should consider functionality, form and structure and Combine possible solutions to a coherent concept.
- **Generating a main design**- selecting and evaluating design variants towards a final design through possible solutions to the formulated problems.

1.6.4 Simulation and evaluation

- **Simulations and calculations** of final design.
- Investigation of different climatic situations for optimization of the suggested system.
- Comparing between the suggested envelopes and other known facades or systems.

2. Literature review

2.1 Key methods for maintaining temperature

Variable internal temperature could impose serious constraints on biological design. Temperature, both extremes and fluctuations, might affect the operation of organisms (*Steven Vogel, 2005*). The various physical agencies that could move heat to, from, and within organism are

- ***Radiation***: All objects above absolute zero radiate energy. A net radiative transfer of heat from warmer objects to colder ones occurs even if the objects are in a vacuum.
- ***Conduction***: Heat moves from warmer to colder parts of a material (or a contacting material) by direct transfer of the kinetic energy of its molecules.
- ***Convection***: Heat moves from warmer to colder places by direct transfer of the warmer material itself. Ordinarily its place is taken by either cooler material to close the cycle or yet more material from elsewhere.
- ***Phase change***: Vaporization takes energy, so it can absorb heat and leave a body cooler than otherwise. Fusion, likewise, takes energy, so melting a solid will cool either the rest of the solid or something else. Solid-to-gas change, sublimation, combines the two, absorbing even more energy.
- ***Ablation***: The average temperature of an object of non-uniform temperature can be reduced by discarding some of its hotter-than-average portion, in effect exporting heat.
- ***Gas expansion cooling*:** A contained gas exerts some pressure on the walls of its container; if it pushes those walls outward, thus doing work, either its temperature will drop or it will absorb heat. (vii) *Cooling by unstressing an elastomer*: If an elastomer is stressed (stretching rubber, for instance), it warms. Elastic recoil as it is released cools the elastomer.
- ***Changing the composition of a solution***: Dissolving one substance in another – mixing two different liquids or dissolving a solute in a solvent – may either absorb or release heat.

2.2 Thermal comfort

That condition of mind which expresses satisfaction with the thermal environment (ISO 7330, ASHRAE 552004)

- Thermal comfort and thermal sensation are not the same
- Thermal sensation depends on skin temperature (cold through hot)
- Thermal comfort depends on the desired physiological state (Uncomfortable through comfortable)
- Users can be comfortably hot or cold!

The notion of comfort that has been standardised in the last decade is being questioned in the last years. Although heat balance models and the ISO7730 based on Fanger's predicted mean vote (PMV/PPD) equations are mathematical, there are many comfort studies that show descriptencies .Field surveys give different results than climate chambers do (*Humphreys 1976, Oseland 1994, Nicol, 2004*) and the differentiation in climatic zones around the globe raise a question on this standardization .when passive methods of environmental modulation are disscused, it is often in an apologetic tone. ASHRAE 552004 and ISO 7730 view thermal comfort as: a specific combination of thermal conditions that will elicit the desired physiological state of comfortable (Thermal comfort temperature). ASHRAE 552004and ISO 7730 accepts the notion that 80% satisfaction is adequate.

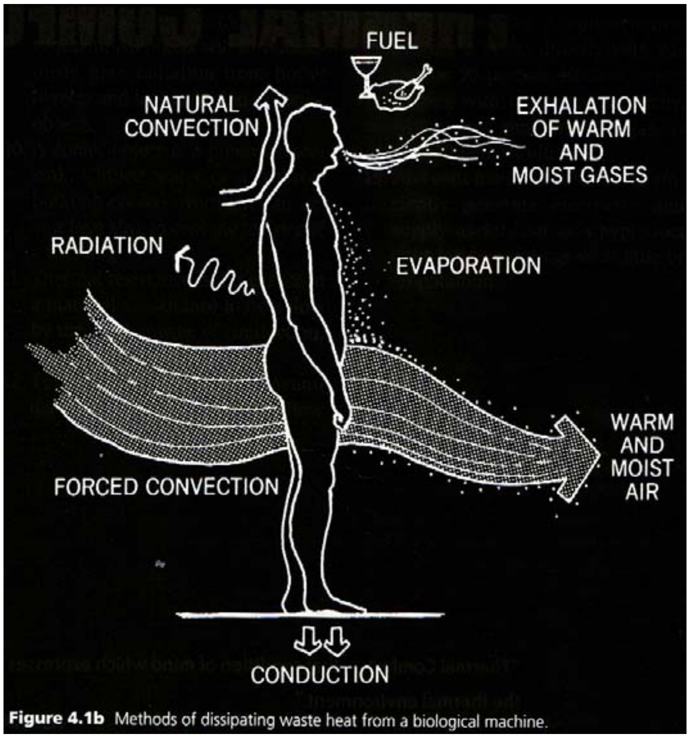


Figure 4.1b Methods of dissipating waste heat from a biological machine.

Influencing Factors

- Activity
- Clothing
- Air temperature
- Mean radiant temperature
- Air velocity
- Air humidity
- Operative temperature-average of air and mean radiant temp'
- seasons

*** Psychological factors

Psychometric chart –design strategies

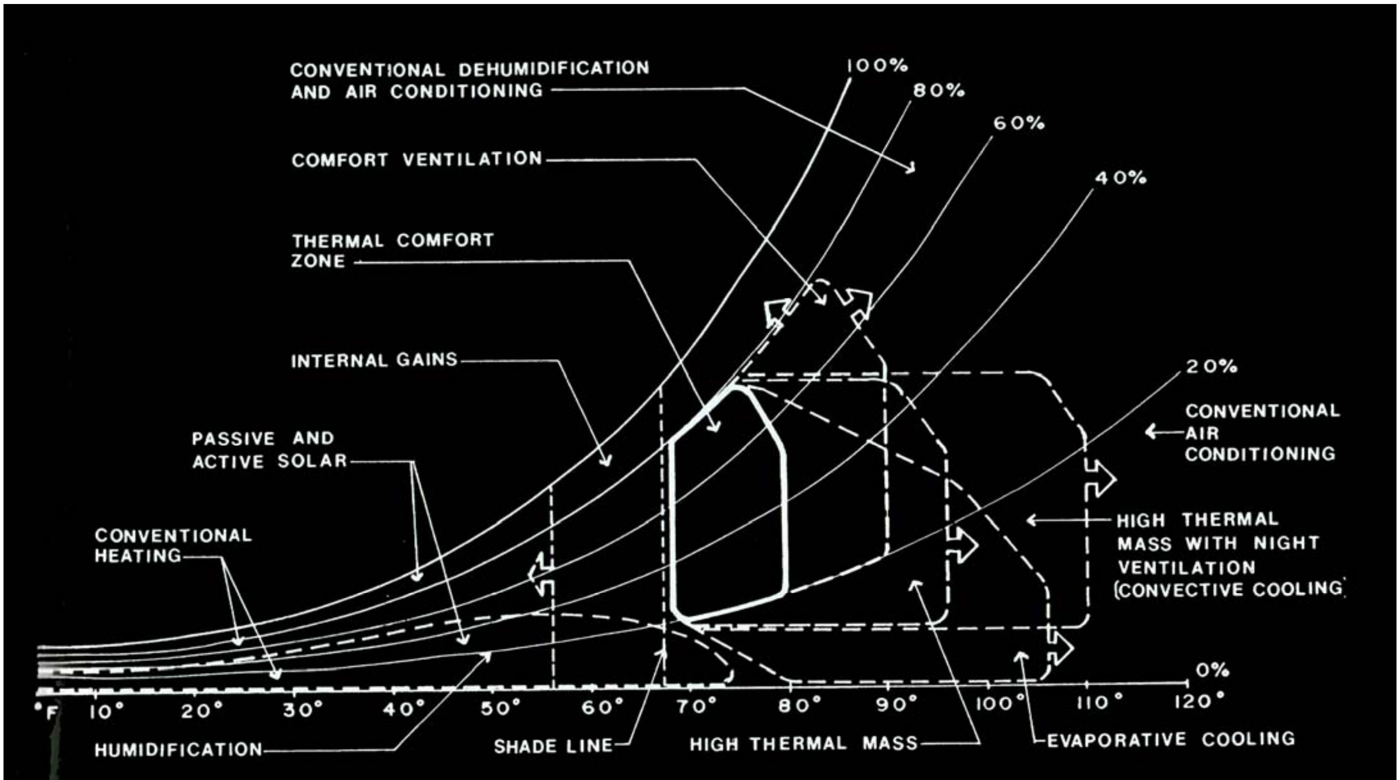
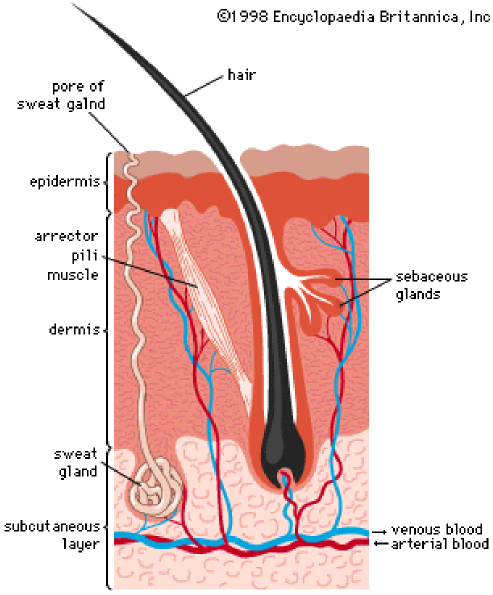


Figure 4.11 Summary of design strategies as a function of ambient conditions (climate). (From *Psychrometric-Bioclimatic Chart,* copyright by Baruch Givoni and Murray Milne.)

2.3 Thermoregulation

is the ability of an organism to keep its body temperature within certain boundaries, even when temperature surrounding is very different. This process is one aspect of homeostasis: a dynamic state of stability between an animal's internal environment and its *external* environment (the study of such processes in zoology has been called ecophysiology or physiological ecology).
Whereas an organism that *thermoregulates* is one that keeps its core body temperature within certain limits, a *thermoconformer* is subject to changes in body temperature according to changes in the temperature outside of its body. It was not until the introduction of thermometers that any exact data on the temperature of animals could be obtained. It was then found that local differences were present, since heat production and heat loss vary considerably in different parts of the body. (*Steven Vogel, 2005*)

2.3.1 Thermoregulation in humans



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The skin assists in homeostasis (keeping different aspects of the body constant e.g. temperature). It does this by reacting differently to hot and cold conditions so that the inner body temperature remains more or less constant. Vasodilatation and sweating are the primary modes by which humans attempt to lose excess body heat. The effectiveness of these methods is influenced by the character of the climate and the degree to which the individual is acclimatized.

In hot conditions

- Sweat glands under the skin secrete sweat (a fluid containing mostly water with some dissolved ions) which travels up the sweat duct, through the sweat pore and onto the surface of the skin. This causes heat loss by evaporation; however, a lot of essential water is lost.
- The hairs on the skin lay flat, preventing heat from being trapped by the layer of still air between the hairs. This is caused by tiny muscles under the surface of the skin called arrector pili muscles relaxing so that their attached hair follicles are not erect. These flat hairs increase the flow of air next to the skin increasing

heat loss by convection. When environmental temperature is above core body temperature, sweating is the only physiological way for humans to lose heat.

- Arterioles Vasodilatation occurs; this is the process of relaxation of smooth muscle in arteriole walls allowing increased blood flow through the artery. This redirects blood into the superficial capillaries in the skin increasing heat loss by radiation and conduction.

Note: Most animals can't sweat efficiently. Cats and dogs only have sweat glands on the pads of their feet. Horses and humans are two of the few animals capable of sweating. Many animals pant rather than sweat, this is because the lungs have a large surface area and are highly vascularised. Air is inhaled, cooling the surface of the lungs and is then exhaled losing heat and some water vapors

In cold conditions

- Sweat stops being produced.
- The minute muscles under the surface of the skin called arrector pili muscles (attached to an individual hair follicle) contract (piloerection), lifting the hair follicle upright. This makes our hairs stand on end which acts as an insulating layer, trapping heat.
- Arterioles carrying blood to superficial capillaries under the surface of the skin can shrink (constrict), thereby rerouting blood away from the skin and towards the warmer core of the body. This prevents blood from losing heat to the surroundings and also prevents the core temperature dropping further. This process is called vasoconstriction. It is impossible to prevent all heat loss from the blood, only to reduce it.
- Muscles can also receive messages from the thermo-regulatory center of the brain (the hypothalamus) to cause shivering. This increases heat production as respiration is an exothermic reaction in muscle cells. Shivering is more effective than exercise at producing heat because the animal remains still. This means that less heat is lost to the environment via convection. This process consumes energy. This is why animals store up food in the winter.

2.3.2 Thermoregulation in animals

a. **poikilotherms** – (cold blooded)
    1. **Ectothermy** - This refers to creatures that control body temperature through external means, such as the sun, or flowing air/water.
    2. **Poikilothermy** - This refers to creatures whose internal temperatures vary, often matching the ambient temperature of the immediate environment
    3. **Bradymetabolism** - This term refers to creatures with a high active metabolism and a considerably slower *resting* metabolism. Bradymetabolic animals can often undergo dramatic changes in metabolic speed, according to food availability and temperature. Many bradymetabolic creatures in deserts and in areas that experience extreme winters are capable of "shutting down" their metabolisms to approach near-death states, until favourable conditions return.

b. **hometherms** – (hot blooded)
    1. **Endothermy** is the ability of some creatures to control their body temperatures through internal means such as muscle shivering, fat burning, drawing and panting.
    2. **Homeothermy** is thermoregulation that maintains a stable internal body temperature regardless of external influence.
    3. **Tachymetabolism** is the kind of thermoregulation used by creatures that maintain a high **resting** metabolism.
    4. Few creatures actually fit all of the above criteria. Most animals use a combination of these aspects of thermophysiology, along with their counterparts to create a broad spectrum of body temperature types.

2.3.3 Thermoregulation in plants

Plants use evaporative cooling to manage with high temperature. Hot and dry weather, however causes water Deficiency resulting in closing of stomata, thus plants suffer in such conditions.

Most plants have adaptive to survive in heat stress as plants of temperate regions face the stress of 40 degree centigrade.

Heat shock proteins -These proteins embrace enzymes and other proteins thus help prevent denaturizing.

In low temperature the fluidity of the cell membrane is alters because lipids of the membrane become locked into crystalline structure which effect the transport of solute. Plants respond to cold stress by increasing proportion of unsaturated fatty acid, which help membrane to maintain structure at low temperature by preventing crystal formation.

Adaptations to freezing temperature

freezing temperature causes ice crystal formation. The confinement of ice formation around cell wall does not effect as badly and plant survive, however, formation of ice crystals with in protoplasm perforates membranes and organelle hence killing the cells. Plants cannot gain carbon dioxide without simultaneously losing water vapor

Other mechanisms

- inflorescence as heat storage
- Leaves are thin to maximize surface area exposed to sun.
- The leaf epidermis is covered by the waxy cuticle to prevent desiccation.
- Leaves have stomata with guard cells so they can control the amount of CO2 entering and water leaving the leaf.
- Air spaces in the leaves allow circulation of CO2 throughout the leaf.
- Vertically-oriented leaves to catch early- and late-day sun rather than mid-day sun.
- Spines or **pubescence** to trap air close to the plant and keep it cooler and more humid.
- Pubescence is colored to reflect light. plants
- **Mechanism-**transpiration involves regulation of osmotic pressure.
- **Desert plants (** CAM)open stomata by night.

2.4 The thermal envelope

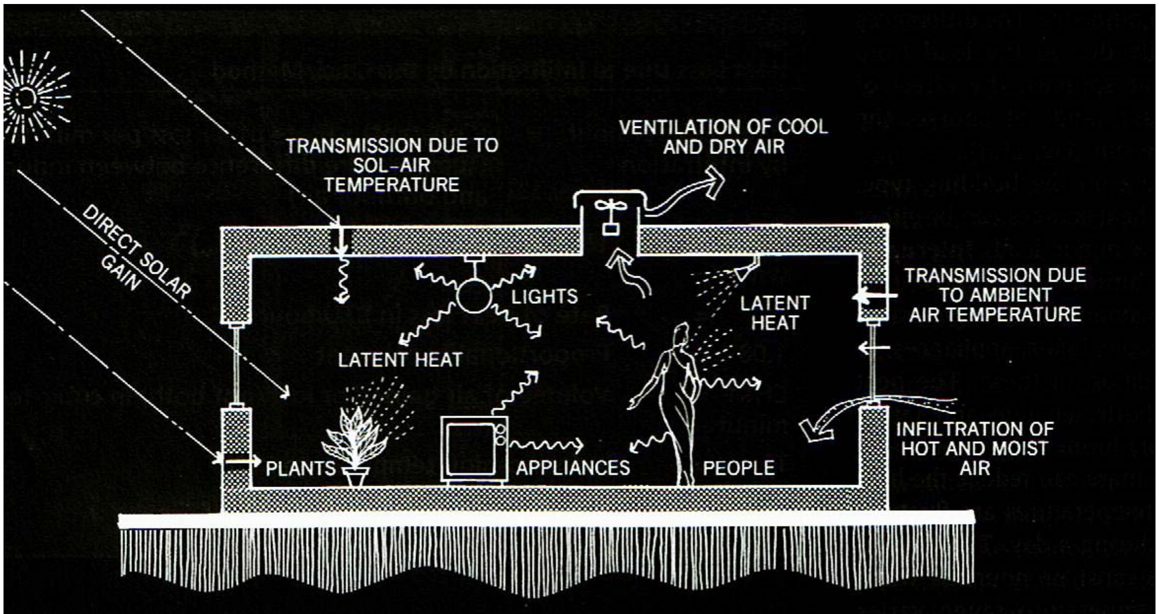
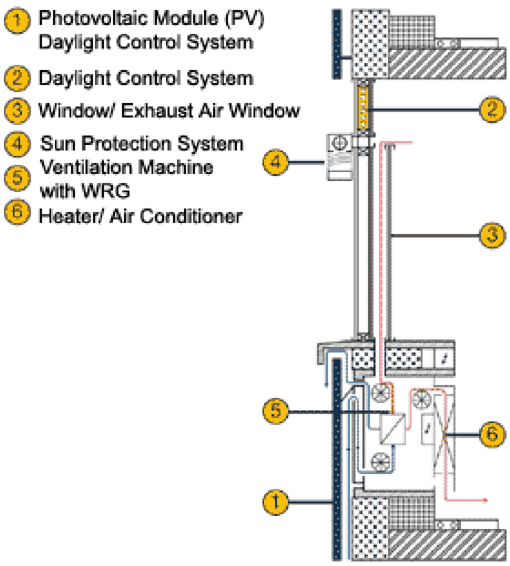


Figure Sources of sensible and latent heat gain.

Much has been written and researched in the field of façade construction. In order to evaluate the design several aspects have been investigated. Main assumptions that were confronted were:

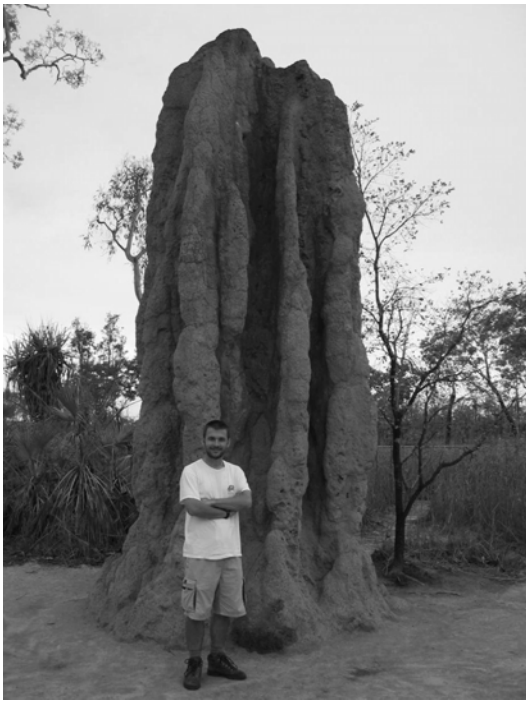
- mass production systems
- efficient design approach
- Mechanical systems for thermoregulation.
- technologically vulnerable mechanisms
- Separate building services and not a real responsive, adaptable and integral element facade.



2.5 Biomimetics -design inspired from nature

Biomimicry (from bios, meaning life, and mimesis, meaning to imitate) is an ancient concept recently returning to scientific thought that examines nature, its models, systems, processes, and elements— and emulates or takes inspiration from them to solve human problems sustainably. Scientific and engineering literature often uses the term **Biomimetics** for the process of understanding and applying biological principles to human designs. This includes biomaterials, biomechanics, biological systems composed of individuals of one species and many others.

Learning from nature and emulating termite mounds' in architecture is one of the few attempts, in the scientific field of architectural engineering, in order to get inspired for new innovations. In this attempt engineers researched the ability of termites to maintain virtually constant temperature and humidity in their Sub-Saharan Africa homes despite an outside temperature that varies from 3 °C to 42 °C (35 °F to 104 °F). Project TERMES (Termite Emulation of Regulatory Mound Environments by Simulation) scanned a termite mound and created 3-D images of the mound structure, which revealed construction that may ultimately influence human building design. The Eastgate Centre, a mid-rise office complex in Harare, Zimbabwe, (highlighted in this Biomimicry Institute case-study) stays cool without air conditioning and uses only 10% of the energy of a conventional building its size.



This research tries to_**analyze, abstract and emulate** nature's thermoregulation systems in order to accomplish a new insight on thermoregulation of facades**.**

3. Research and results

3.1 Introduction: Research approach

After summarizing the data collection, different natural discoveries, especially in the field of thermoregulation had challenged the extreme climatic and thermal problems in a particular, interesting way. From these systems and their strategies further investigation lead to a deeper understanding of its principle. **Analyzing and abstraction** of the **deep principle** together with an understanding of the build environment and the natural phenomena's a building skin should overcome – was the next step.

3.2 Thermoregulation cases in nature

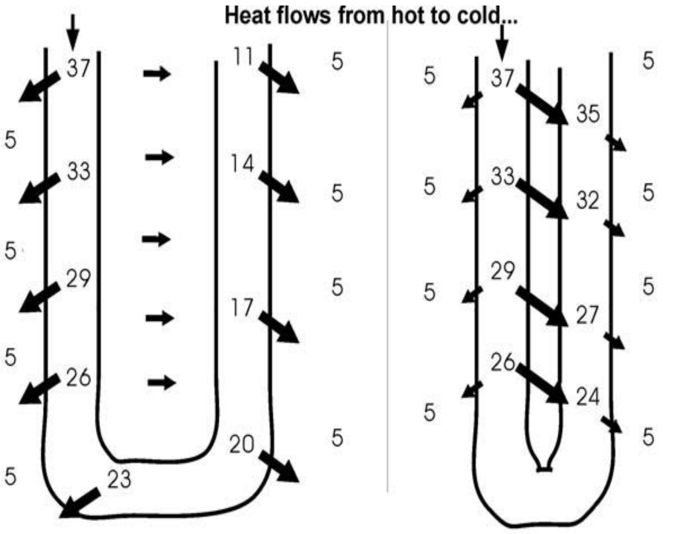
The specified performance and requirements for a desired envelope dealt with heat gains and heat loss through a sustainable approach. The research focused on different organisms that fulfilled that criterion.

This function was investigated in three main systems:

1. the human skin
2. the heat exchanger of tuna fish
3. the guard cells "stomata" of desert plants (CAM)

3.2.1 Thermoregulation Countercurrent heat exchangers in tuna fish

Countercurrent heat exchangers transfer entities between inflow and outflow using only passive processes."(*CD Moyes, PM Schulte Benjamin Cummings 2006)* We see these primarily in the arrangement of arteries and veins in situations of heat (thermal) conversions .A convective link between hot and cold locations need not transfer heat. The agency can be turned against itself – if it can carry heat one way, it should be able to



Arteries and veins separated, minimizing heat exchange between.

Arteries and veins close, maximizing heat exchange between.

carry it in the other quite as well. In the context of a warm animal in a cold place, the trick consists of transferring heat from blood flowing peripherally, not to the environment, but to blood flowing axially. The engineering literature refers to the device for doing that as a **counter flow exchanger**; (*recognized by Claude Bernard, in 1876)* physiologists prefer the word 'countercurrent'. Exchange is not limited to heat – diffusion, again, follows the same rules as conduction – and countercurrent exchangers conserve such substances as dissolved oxygen and water. (*Steven Vogel, 2005*).

Tuna fish

When you consider that the blood of fishes passes over the gills which are bathed in the surrounding water, it is easy to see why fishes are "cold-blooded". Nonetheless, some marine fishes (e.g., the tuna) are able to keep their most active swimming muscles warmer than the sea by using a countercurrent heat exchanger.

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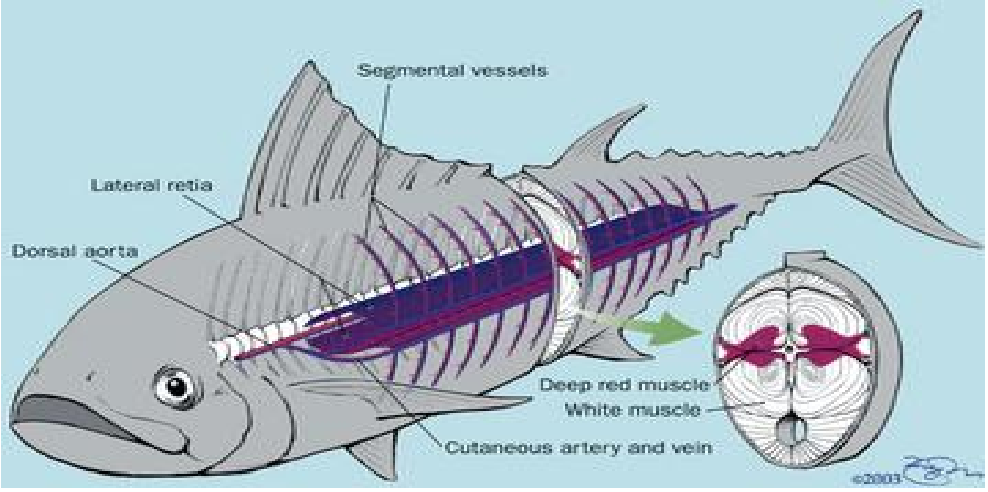
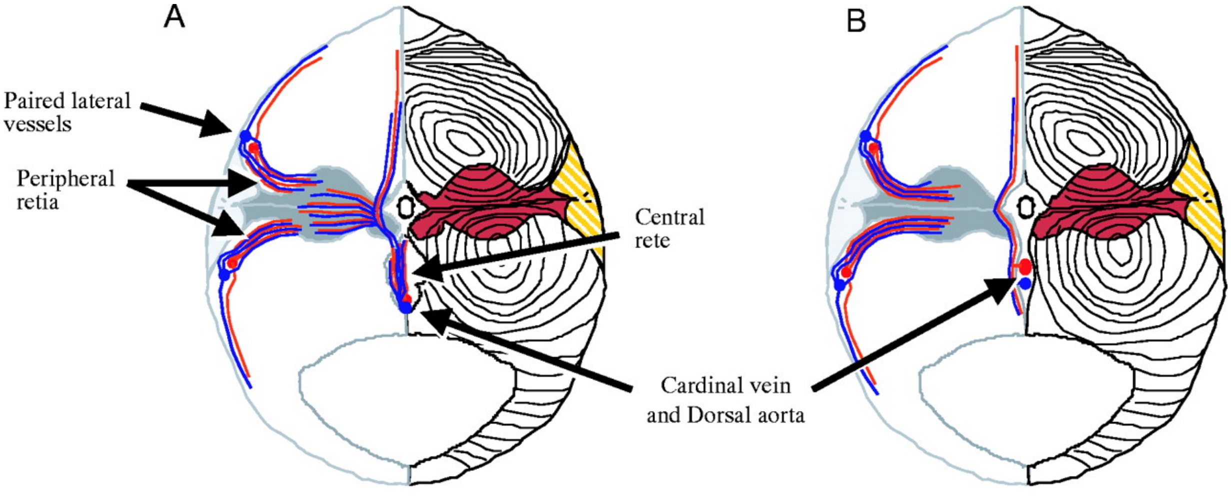
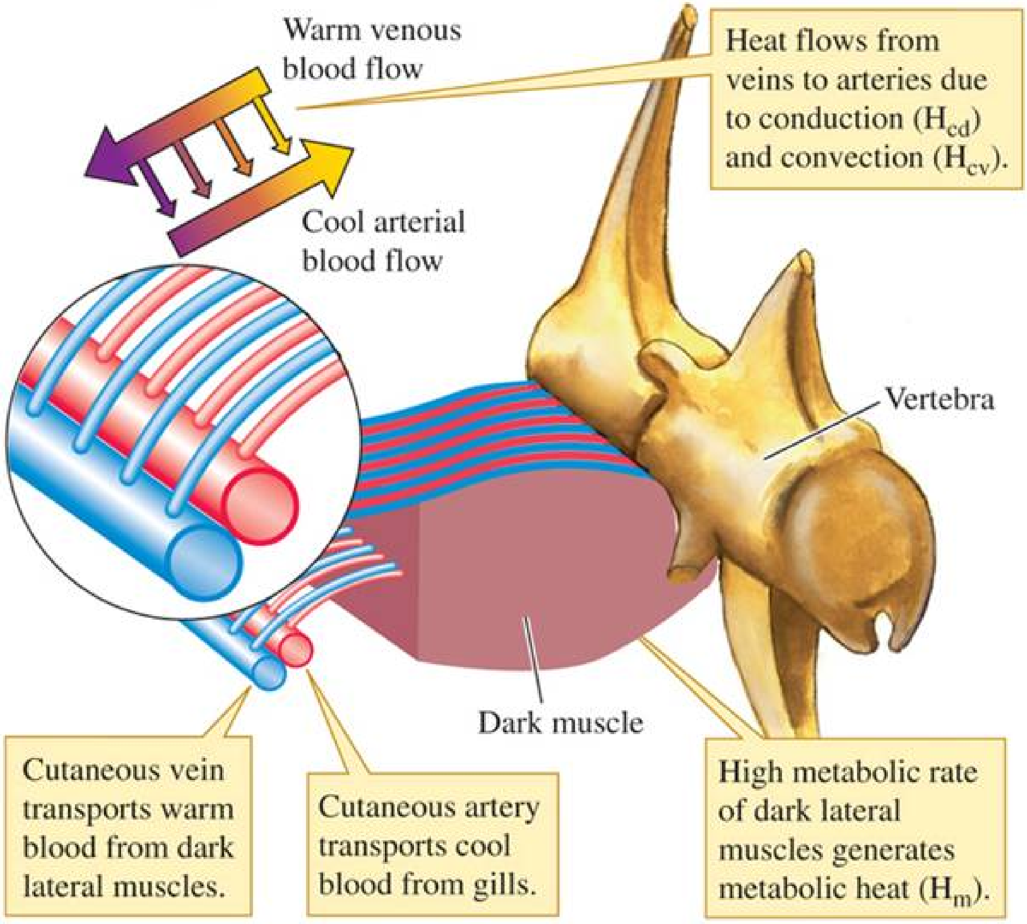


A cross section through a skipjack tuna



Thunnus albacares *Thunnus thunnus*

Thanks to its countercurrent heat exchanger the dark muscle on either side of the vertebral column is maintained at a higher temperature than the rest of the fish. Exchangers isolate the warm, dark, lateral muscles of large, fast-swimming tuna and mako sharks from the colder water passing along the body and across the gills (*Carey and Teal 1966, 1969; Dewar etal 1994).*



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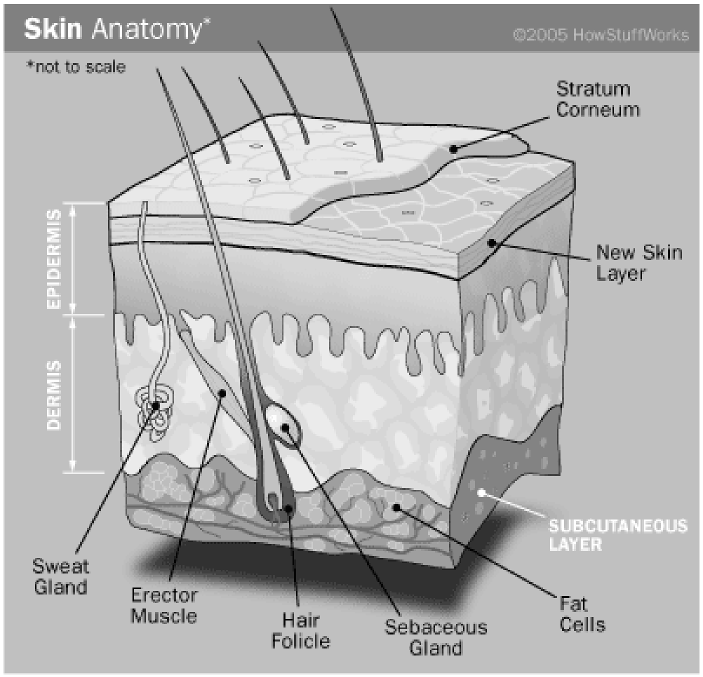
3.2.2 Thermoregulation of human skin

Skin performs the following functions:

1. Protection: an **anatomical barrier** from pathogens and damage between the internal and external environment in bodily defense; Langerhans cells in the skin are part of the adaptive immune system.
2. **Sensation**: contains a variety of nerve endings that react to heat and cold, touch, pressure, vibration, and tissue injury; see somatosensory system and haptics.
3. **Heat regulation**: the skin contains a blood supply far greater than its requirements which allows precise control of energy loss by radiation, convection and conduction. Dilated blood vessels increase perfusion and heat loss while constricted vessels greatly reduce cutaneous blood flow and conserve heat. Erector pili muscles are significant in animals.
4. **Control of evaporation**: the skin provides a relatively dry and semi-impermeable barrier to fluid loss. Loss of this function contributes to the massive fluid loss in burns.
5. **Aesthetics and communication**: others see our skin and can assess our mood, physical state and attractiveness.
6. **Storage and synthesis**: acts as a storage center for lipids and water, as well as a means of synthesis of vitamin D by action of UV on certain parts of the skin.
7. **Excretion**: sweat contains urea, however its concentration is 1/130th that of urine, hence excretion by sweating is at most a secondary function to temperature regulation.
8. **Absorption**: Oxygen, nitrogen and carbon dioxide can diffuse into the epidermis in small amounts, some animals using their skin for their sole respiration organ. In addition, medicine can be administered through the skin, by ointments or by means of adhesive patch, such as the nicotine patch or iontophoresis. The skin is an important site of transport in many other organisms.
9. **Water resistance**: The skin acts as a water resistant barrier so essential nutrients aren't washed out of the body.

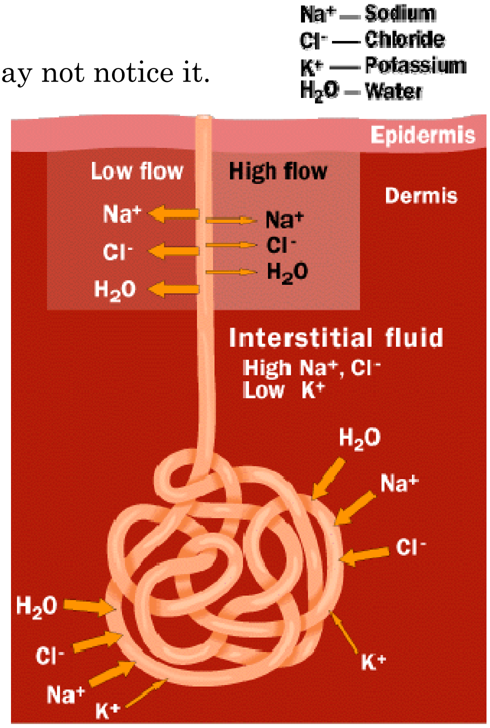
Excretion Sweat

Perspiration, or **sweat**, is the body's way of cooling itself, whether that extra heat comes from hardworking muscles or from over stimulated nerves.



The average person has **2.6 million sweat glands** in his skin! Sweat glands are distributed almost over the entire body -- The sweat gland is in the layer of skin called the **dermis** along with other "equipment," such as nerve endings and hair follicles. The sweat gland is a long, coiled, hollow tube of cells. The coiled part in the dermis is where sweat is produced, and the long portion is a **duct** that connects the gland to the opening or **pore** on the skin’s outer surface. Nerve cells from the **sympathetic nervous system** connect to the sweat glands. These are the sensors for the operation to take place.

We are constantly sweating, even though we may not notice it.



Movement of ions and water in making sweat

Sweating is the major way of getting rid of excess body heat, which is produced by metabolism or working muscles. The amount of sweat produced depends upon our states of emotion and physical activity.
When the sweat gland is stimulated, the cells secrete a fluid (**primary secretion**) that is similar to plasma -- that is, it is mostly water and it has high concentrations of sodium and chloride and a low concentration of potassium -- but without the proteins and fatty acids that are normally found in plasma. The source of this fluid is the spaces between the cells (**interstitial spaces**), which get the fluid from the blood vessels (capillaries) in

the dermis. This fluid makes a travel from the coiled portion up through the straight duct and to the outer perimeter.

Thermoregulation

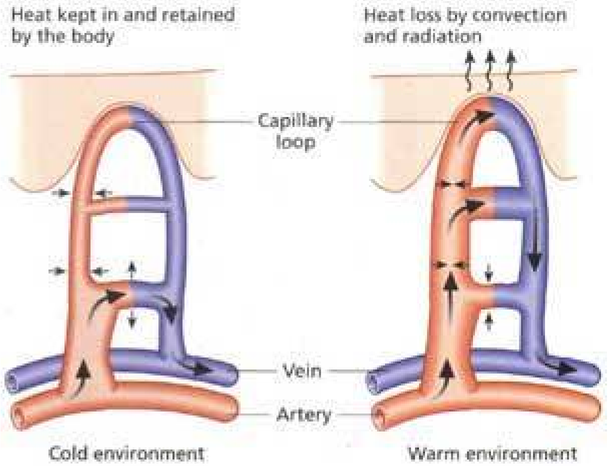
When sweat evaporates from the surface of the skin, it removes excess heat and **cools** the skin. The mechanism- **vaporization** - takes a certain amount of heat. The value of vaporization is about 540 calories/gram or 2.26 x 10^6 joules/kilogram. So producing one liter of sweat, which is equal to 1 kg (density of water is 1 g/ml or 1 kg/l) in one hour, then 540,000 calories of heat can be removed from one body. This is an extreme example using the maximum amount of sweat that a person can make. Typically, all of the sweat does not evaporate, but rather runs off the skin. In addition, not all heat energy produced by the body is lost through sweat. Some is directly radiated from the skin to the air and some is lost through respiratory surfaces of the lungs. A major factor that influences the rate of evaporation is the relative humidity of the air.

The hairs

When it is hot: the hairs on the skin lay flat, preventing heat from being trapped by the layer of still air between the hairs. This is caused by tiny muscles under the surface of the skin called arrector pili muscles relaxing so that their attached hair follicles are not erect These flat hairs increase the flow of air next to the skin increasing heat loss by convection. When it is cold: The minute muscles under the surface of the skin called arrector pili muscles (attached to an individual hair follicle) contract (piloerection), lifting the hair follicle upright. This makes our hairs stand on end which acts as an insulating layer, trapping heat.

Blood vessels

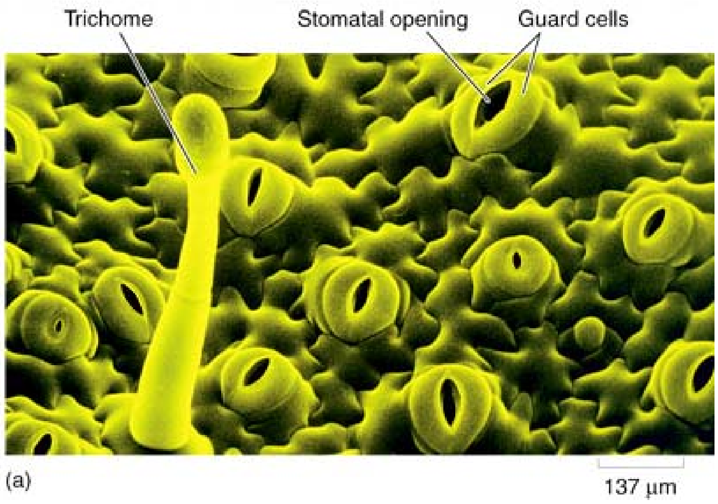
When it is hot -: the Arterioles Vasodilatation occurs; this is the process of relaxation of smooth muscle in arteriole walls allowing increased blood flow through the artery. This redirects blood into the superficial capillaries in the skin increasing heat loss by radiation and conduction. When it is cold: the Arterioles carrying blood to superficial capillaries under the surface of the skin can shrink (constrict), thereby rerouting blood away from the skin and towards the warmer core of the body. This prevents blood from losing heat to the surroundings and also prevents the core temperature dropping further. This process is called vasoconstriction. It is impossible to prevent all heat loss from the blood, only to reduce it.



3.2.3 Thermoregulation of stomata in plants

Stoma

In botany, a **stoma** (also **stomate**; plural **stomata**) is a pore, found in the leaf and stem epidermis that is used for gas exchange. The pore is formed by a pair of specialized parenchyma cells known as guard cells which are responsible for regulating the size of the opening. Air containing carbon dioxide enters the plant through these openings where it is used in photosynthesis and respiration. Oxygen produced by photosynthesis in the **spongy layer** cells (parenchyma cells with pectin) of the leaf interior exits through these same openings. Also, water vapor is released into the atmosphere through these pores in a process called transpiration. Stomata are present in the saprophyte generation of all land plant groups except liverworts. Dicotyledons usually have more stomata on the lower epidermis than the upper epidermis. Monocotyledons, on the other hand, usually have the same number of stomata on the two epidermes. In plants with floating leaves, stomata may be found only on the upper epidermis; submerged leaves may lack stomata entirely. Most plants require the stomata to be open during daytime. The problem is that the air spaces in the leaf are saturated with water vapor, which exits the leaf through the stomata (this is known as transpiration) (N*.S. Christodoulakis; J. Menti and B.Galatis 2002)*. Therefore, plants cannot gain carbon dioxide without simultaneously losing water vapor. This for itself has nothing to do with heat regulation but as a mechanism that dates back to the time when vegetation grew in moist habitats.

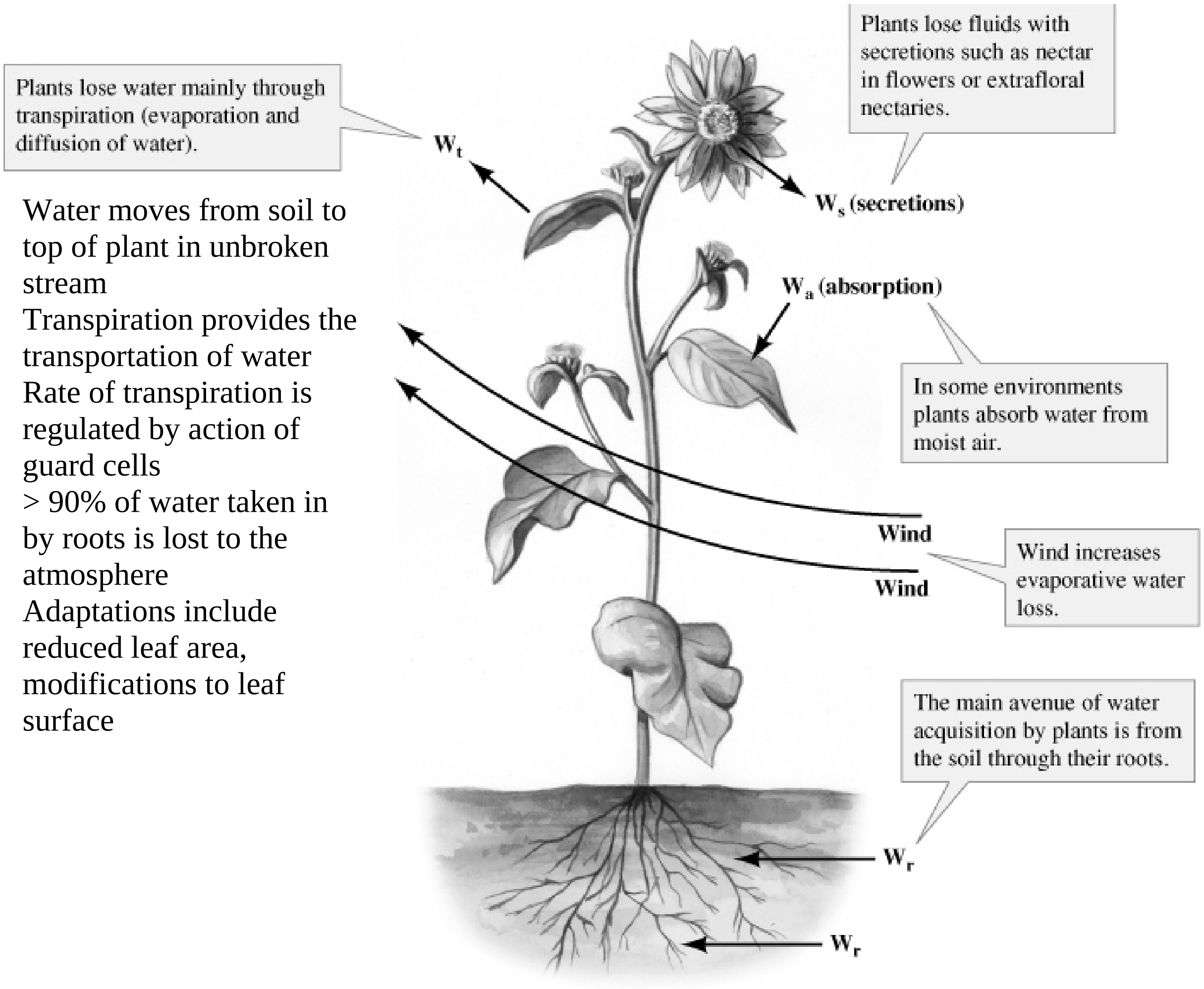


Guard cells

Paired cells with openings between them (stomata) Allow gas exchange.the basic mechanism involves regulation of osmotic pressure.

Water, air, wind and plants

- Water moves from soil to top of plant in unbroken stream
- Transpiration provides the transportation of water
- Rate of transpiration is regulated by action of guard cells
- > 90% of water taken in by roots is lost to the atmosphere
- Adaptations include reduced leaf area, modifications to leaf surface



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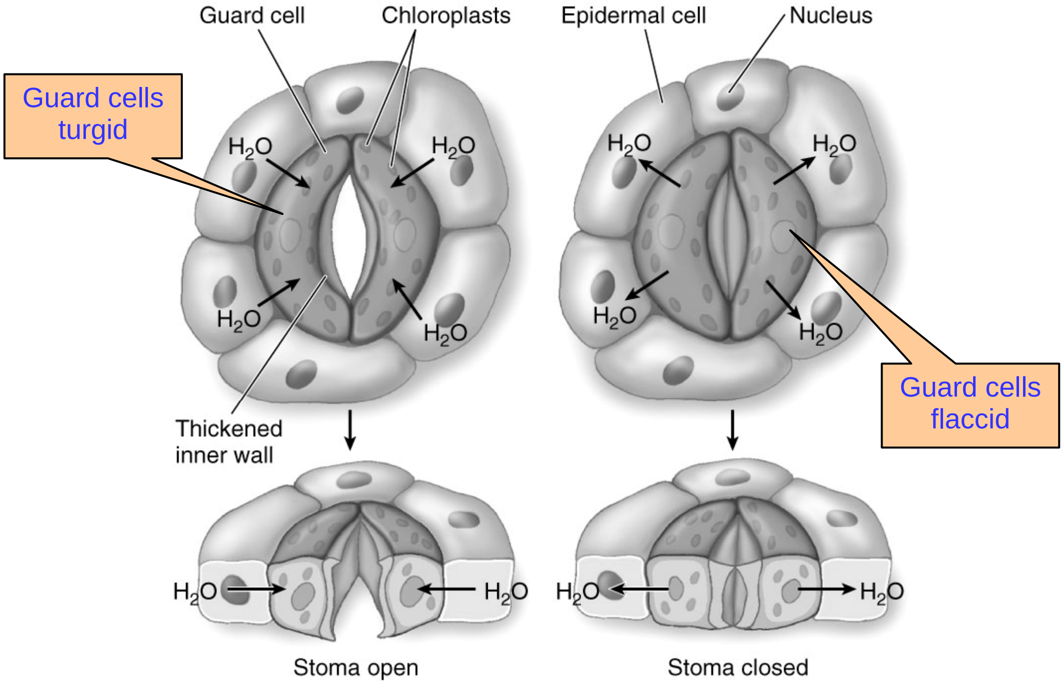
Regulating heat:

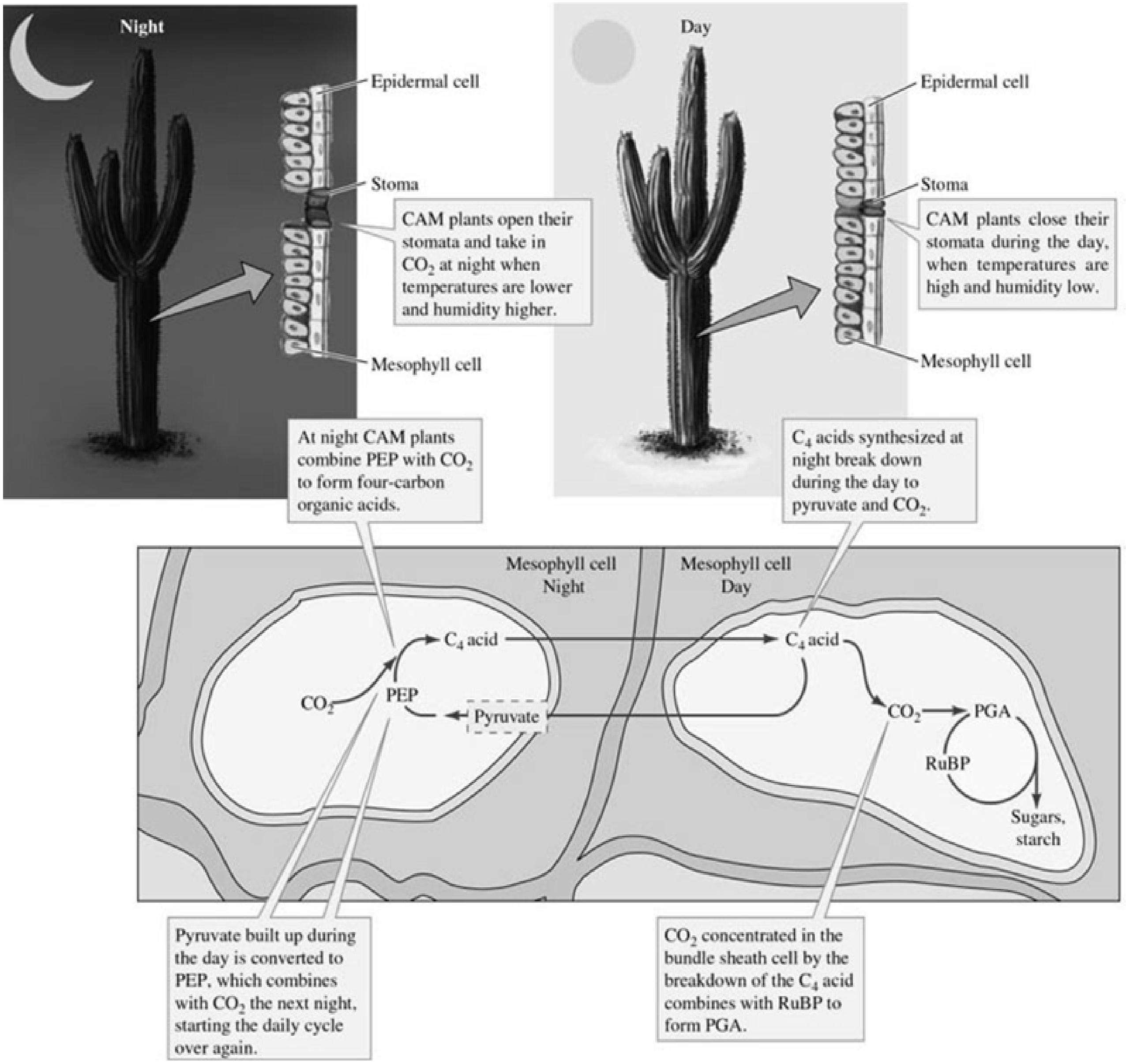
- The leaf epidermis is covered by the **waxy cuticle** to prevent desiccation.
- Leaves have stomata with guard cells so they can control the amount of CO2 entering and water leaving the leaf.
- **Mechanism-transpiration** involves regulation of osmotic pressure.
- **Desert plants (** CAM)open stomata by night.
- Air spaces in the leaves allow circulation of CO2 throughout the leaf
- Spines or pubescence to **trap air** close to the plant and keep it cooler and more **humid.**
- Desert plants- **"hairy fur"** to withstand winds and sand.

A representative value for water-use efficiency (*Nobel 1999*) is about 6 g CO2 per kg H2O. Functioning leaves have to lose water, whatever the thermal consequences. Indeed, transpiration sometimes depresses leaf temperatures 10°C or more below ambient. The situation resembles evaporative heat loss from our breathing, something of minor use (since we do not pant).



Some Species (6 or 7% of all vascular plants) open their stomata at night, when temperatures are lower and relative humidities higher. A group of mostly desert plants called **"CAM"** plants (Crassulacean acid metabolism, after the family Crassulaceae, which includes the species in which the CAM process was first discovered) **open their stomata at night** (when water evaporates more slowly from leaves for a given degree of stomatal opening), use PEPcarboxylase to fix carbon dioxide and store the products in large vacuoles as organic acids. The following day, they close their stomata and release the carbon dioxide fixed the previous night. Decarboxylation provides the input for photosynthesis. The trick can push water-use efficiency up an order of magnitude. So the adaptive significance of evaporative water loss from leaves remains uncertain (*Steven Vogel, 2005*).

C.A.M –desert plants:



CAM plants open their stomata and take in CO$_2$ at night when temperatures are lower and humidity higher.

CAM plants close their stomata during the day, when temperatures are high and humidity low.

At night CAM plants combine PEP with CO$_2$ to form four-carbon organic acids.

C$_4$ acids synthesized at night break down during the day to pyruvate and CO$_2$.

Pyruvate built up during the day is converted to PEP, which combines with CO$_2$ the next night, starting the daily cycle over again.

CO$_2$ concentrated in the bundle sheath cell by the breakdown of the C$_4$ acid combines with RuBP to form PGA.

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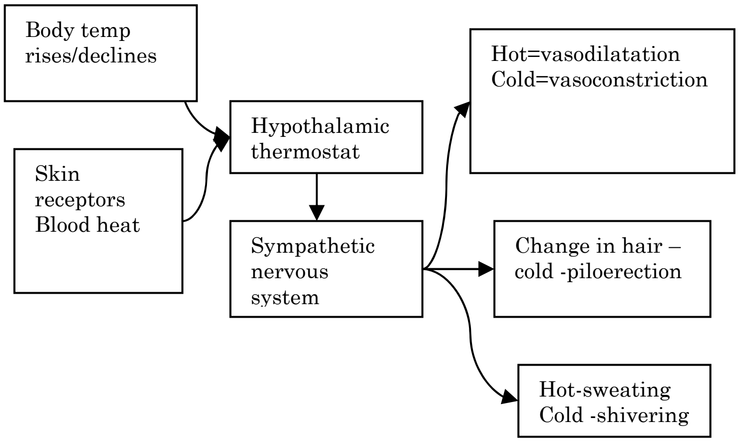
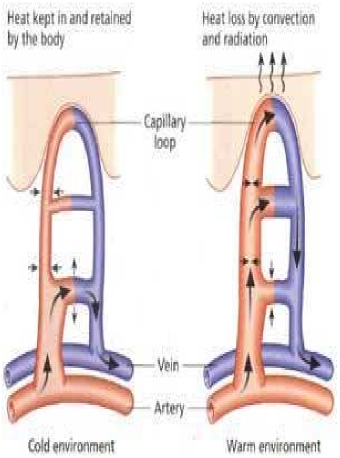
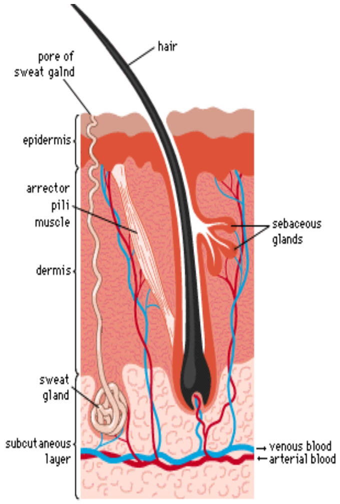
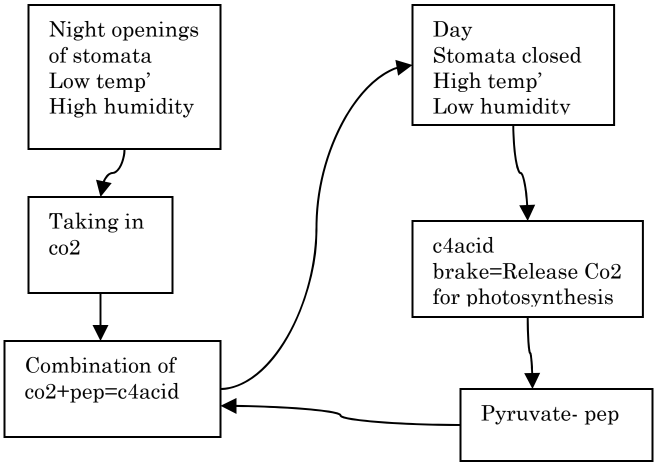
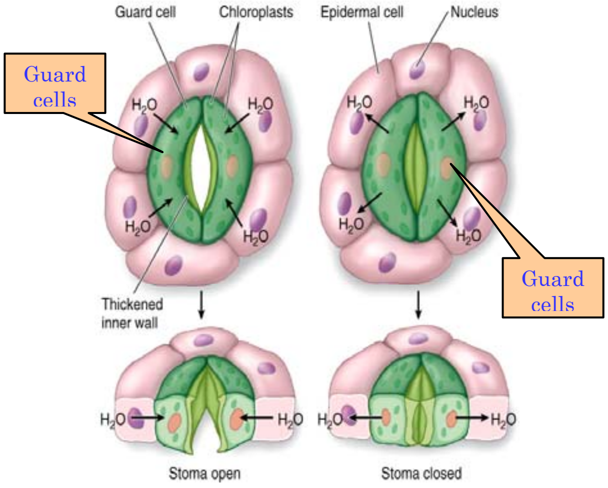
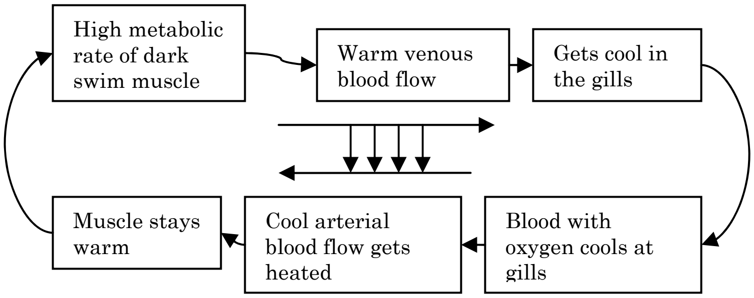
SUMMERY

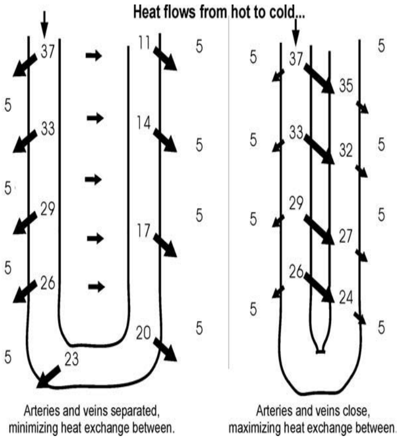
Specifying the main performance of the desired envelope in the field of thermoregulation led to main methods, major principles and key words .these were processed and are given in the following tables.

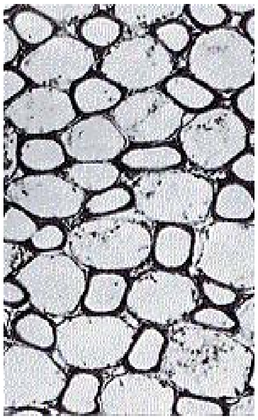
3.2.4 Abstraction-Key methods of natural systems

System	Human skin
Scheme	
Principle methodes	**Fluid flow**- Sweat from gland in ducts goes to sweat pore **Mechanism 1**=evaporation **Air flow**- preventing or trapping still air between the hairs –done by arrector pili muscles. **Directing flow**- vasodilatation, vasoconstriction- smooth muscles in the arteriole walls allowing differentiation in the amount of blood flow. **Mechanism 2-** Heat loss is through radiation and convection. Sweating animals loose a lot of water
Scketch	 
Key - words	Pore, tissue, Circulation, membrane ,evaporation, sweat ,fluid flow, air flow ,muscles
Deep principle	Two principles humidified cooling through evaporation and convective thermoregulation

System	Stoma-special CAM desert plants
Scheme	
Principle methodes	**transpiration** sometimes depresses leaf temperatures 10°C **Paired cells** in the leaf and stem epidermis - with openings between them (stomata) Allow gas exchange. **Mechanism-**transpiration involves regulation of osmotic pressure. **Desert plants** open stomata by night plants cannot gain carbon dioxide without simultaneously losing water vapor
Scketch	
Key - words	Expansion ,contraction ,openings ,transpiration, gas exchange,
Deep principle	Osmotic pressure openings control evaporation

<table>
<tr><th>System</th><th>Countercurrent heat exchange-tuna fish</th></tr>
<tr><td>Scheme</td><td>


</td></tr>
<tr><td>Principle methodes</td><td>Rete-Net work- of arterial blood supply
Heat exchange -maintains a low or high temp’ in one part of body.
Exchangers- isolate the warm dark lateral swimming muscle from outer cold water.
Diffusion- Dissolve oxygen can pass through counter current exchangers.
Mechanism -Heat flows from hot to cold-convection</td></tr>
<tr><td>Scketch</td><td>



</td></tr>
<tr><td>Key - words</td><td>fluid /gas exchange ,tubes ,diffusion, countercurrent</td></tr>
<tr><td>Deep principle</td><td>Counter current flow manipulates heat gains and heat losses.</td></tr>
</table>

3.2.5 Transformation of systems- Structure, material and form of natural systems

Based on the abstraction the design of an innovative envelope starts with the transformation of the deep principle into form, material, construction, process and function.

“**Human skin**”

Organisms	Human skin
form	• Layers of materials, • An inner porous material • a “hairy” Outer layer.
material	• Part of the materials must be flexible or adaptable. • Tubes can be rigid (Inner-part of the tube-adaptable foam)
construction	• Made in the same layering system as in skin. With tubes crossing and connecting inner to outer part. • The cross tubes can act as ” bone” construction. • Outer layer has evaporation openings.
process	• **Evaporation**-The outer layer corresponds to the change in temperature • The inner tubing change their dimension through change in temp’ • Tubing system carries fluid in different times. Option of Movement of tubing from inner part to the more outer part.
function	Internal conditions become stable through the use of Passive cooling. This could be achieved by sweating and by mimicking the change in distance of the tubing system (blood vessels) from the outer surroundings.

Tuna fish countercurrent

Organisms	tuna fish- Countercurrent heat exchanger
form	• Two directional -Net works with a differentiation in its diameter.
material	• All materials can be rigid • There should be fluid and/or gas in inner tubing or containers.
construction	• Network system is the main construction. It holds the form from collapsing. • Like a Tree growth pattern. • Different filling options or different materials.
process	• **Convection**-Heat exchanges in through flows in different directions, depending on the period of year. • Fluid or gas is pressurized during the different seasons or different times in a day cycle through the tubes. .
function	Maintaining Inner temperatures and humidity conditions through the flow of fluid/gas in the tubing system, the opposite flow direction permits a high degree of heat balance.

“Stoma”

Organisms	dessert “CAM” plants- Stoma
form	• A net of Opening/closing diaphragm.
material	• Diaphragm/shaft-flexible material • Basic support structure-rigid construction
construction	• Basic support structure holds in side a secondary permeable skin • 1 st option -**Operating system** an air muscle or other kind of muscles that operate the closing and openings of the Diaphragm. • 2nd option- **Operating system** responsive surface structure to thermal conditions and humidity.
process	• Opening and closing of shafts • **Transpiration-** of fluid and air
function	Maintaining Inner temperatures and humidity conditions through regulating openings. The shafts in the envelope should open passively. (Responsive surface structure).

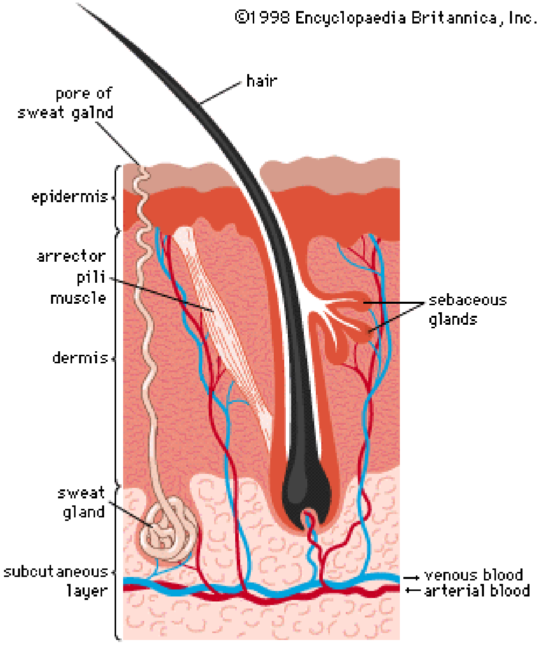
3.3 Emulation of basic systems

The second step of transformation was designing primary conceptual envelopes from the mimicked system and its operative performance. There were five concepts two for the skin, two for the heat exchangers and one for the stoma.

3.3.1 "Human skin" conceptual façade 1

Key –words- Pore, tissue, Circulation, membrane, evaporation, sweat, fluid flow, air flow, muscles.

Deep principle -Two principles humidified cooling through evaporation and convective thermoregulation.



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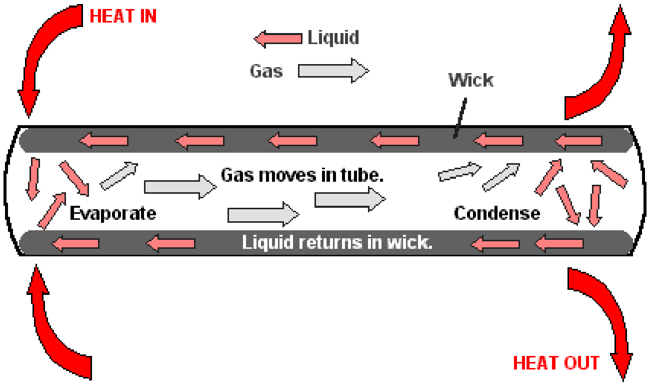
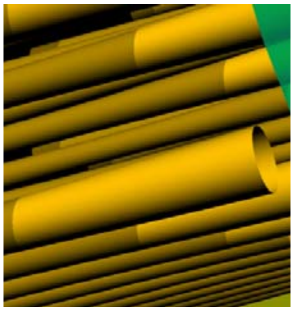
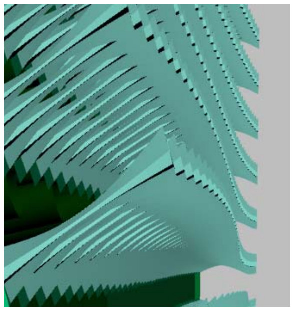
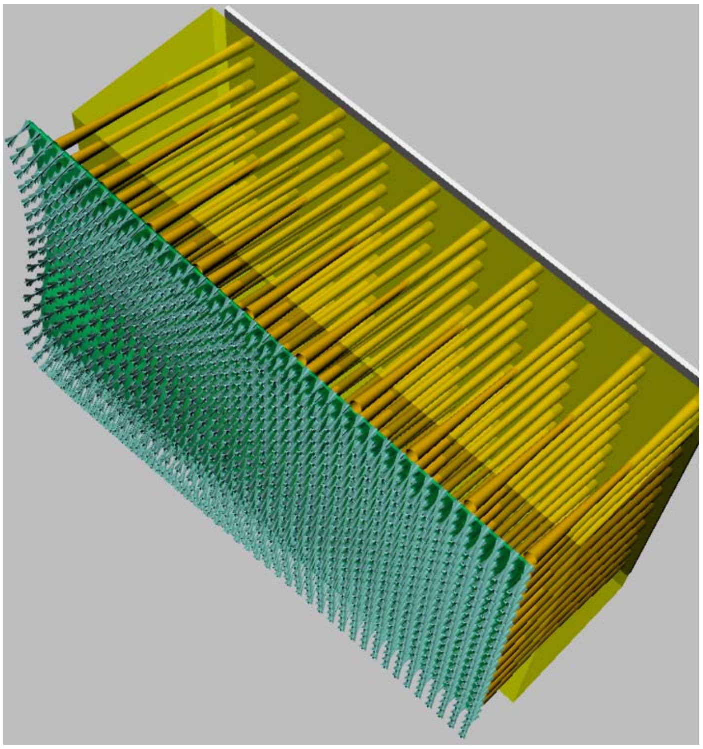


- Skin heat pipes like "sweat glands"
- Cooling through evaporation.
- "Hairs" help air circulation on the outer facade



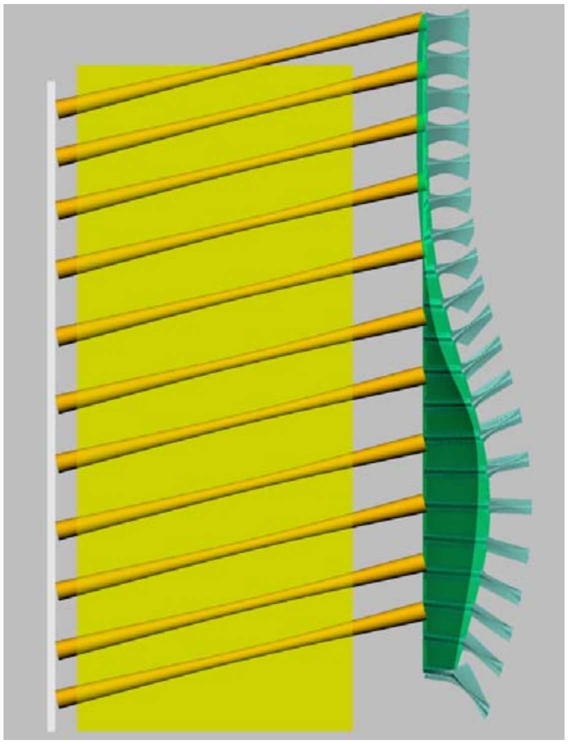


Heat pipe tubes **"hair" layer**



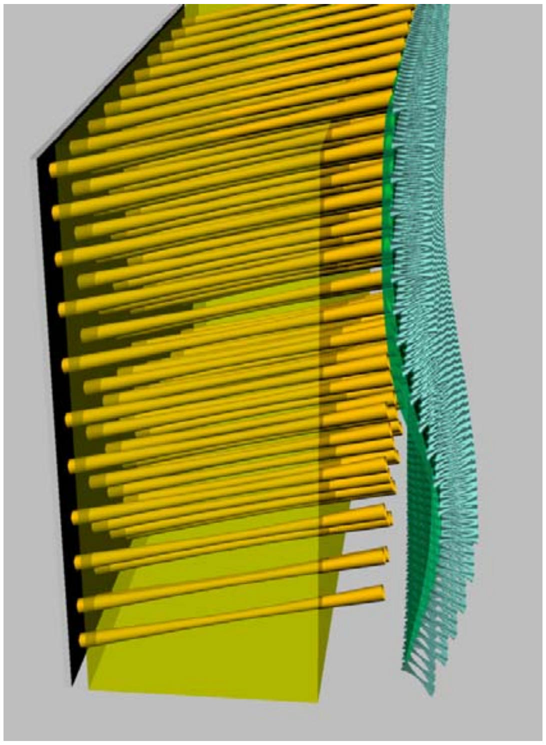
3d view

The first "human skin" envelope concept dealt with a layering system of three main materials /systems. The inner layer, the middle heat pipes and foam insulator and the outer flexible hair membrane. The outer membrane should change position in time in order to adapt to climatic changes. The hairs trap air for more insulation and suitable humid atmosphere. The middle layer is the thermoregulation system consisting of many heat pipes.



Section

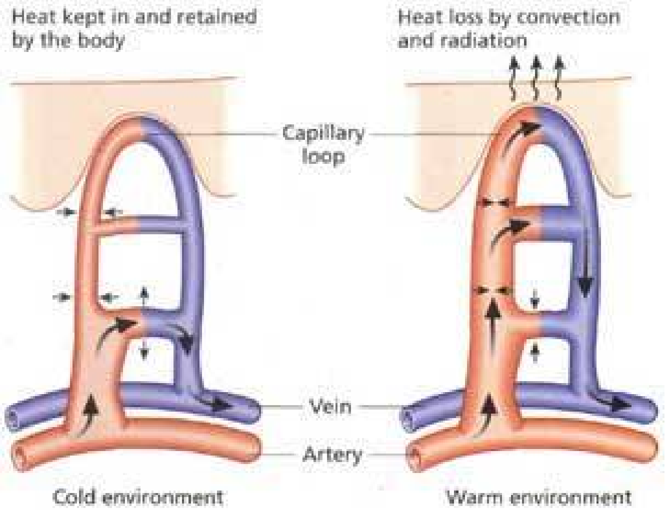
3d view



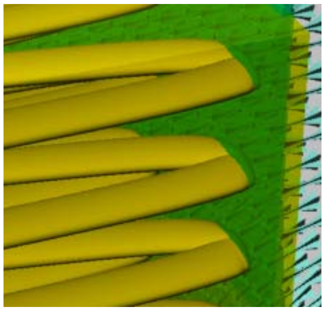
3.3.2 “Human skin” conceptual façade 2

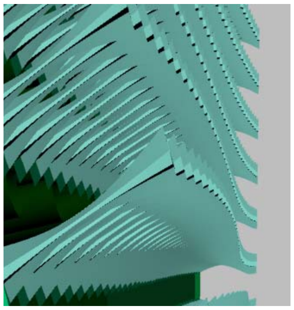
Key –words- Pore, tissue, Circulation, membrane, evaporation, sweat, fluid flow, air flow, muscles.

Deep principle -Two principles humidified cooling through evaporation and convective thermoregulation



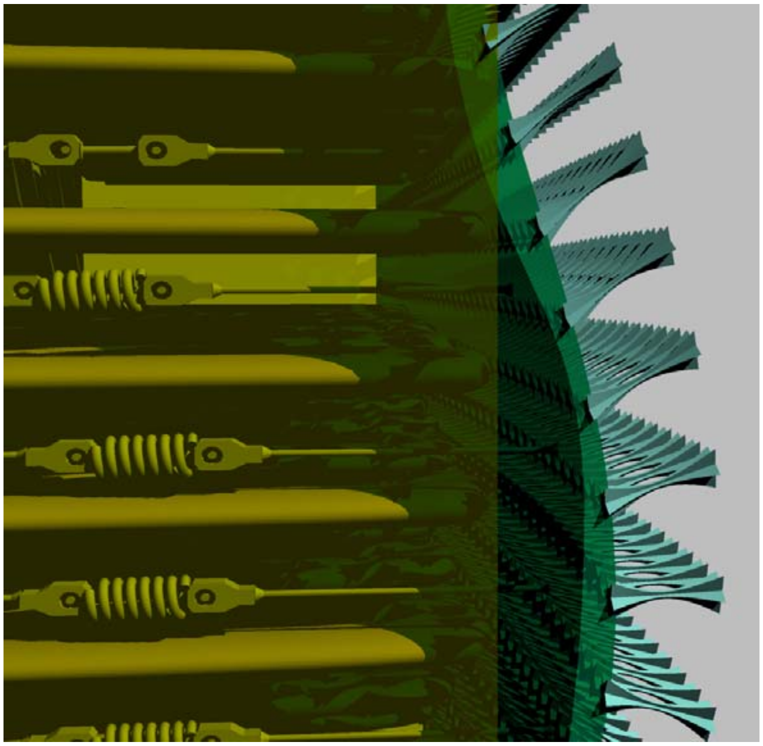
- Inner skin “blood vessels”
- Cooling through convection and radiation.
- “Hairs" help air circulation on the outer facade



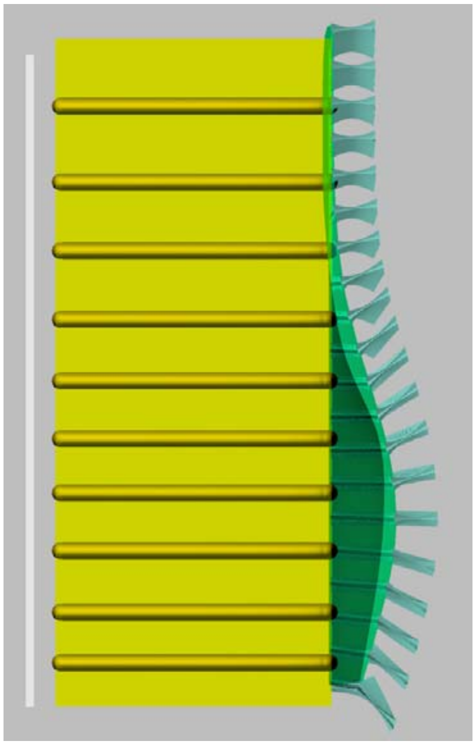


“Blood vessels” layer **“hair” layer**

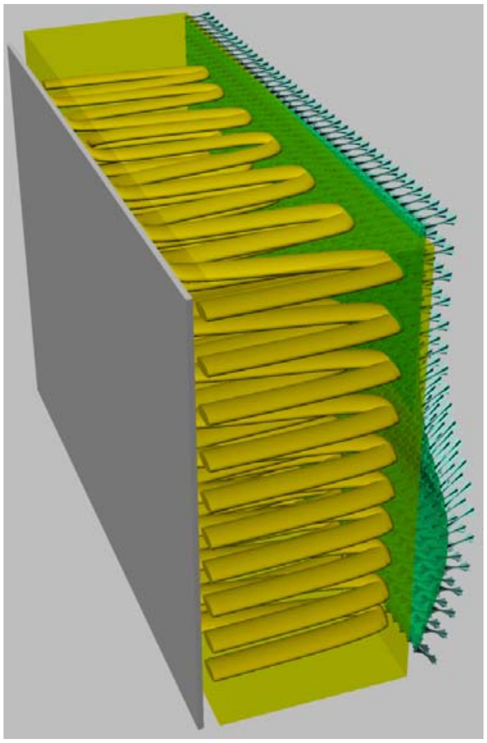
the kinetic "muscle



section



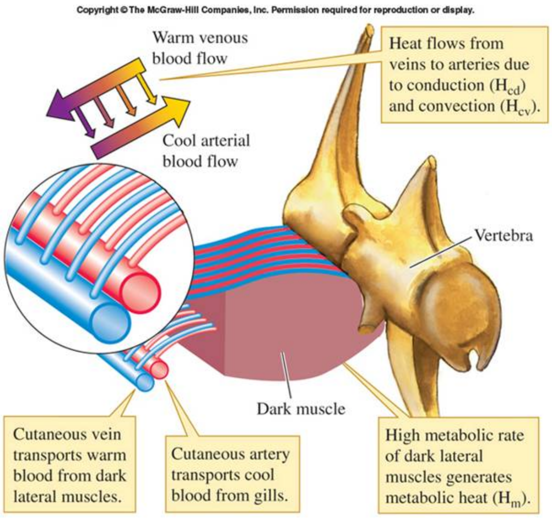
The second "human skin" envelope concept dealt with a three layering system consisting of an inner layer ,a middle "blood vessels" tubing system and the flexible outer hair" membrane. The outer membrane should change position in time in order to adapt to climatic changes. The middle layer is the thermoregulation layer which works as a convection radiator, for cooling and heating.
The outer membrane could move with a kinetic "muscle" or a memory shape material.

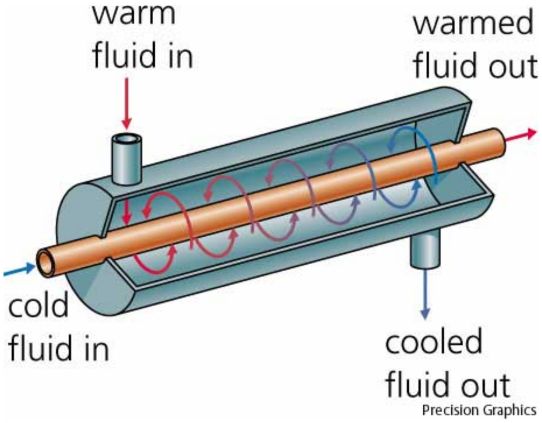


3d view

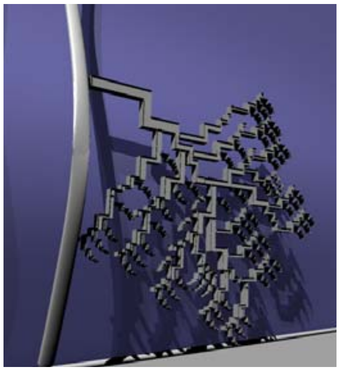
3.3.3 Tuna fish heat exchanger’s conceptual façade 1

Key –words- fluid /gas exchange flow, tubes, diffusion, countercurrent
Deep principle - Counter current flow manipulates heat gains and heat losses.

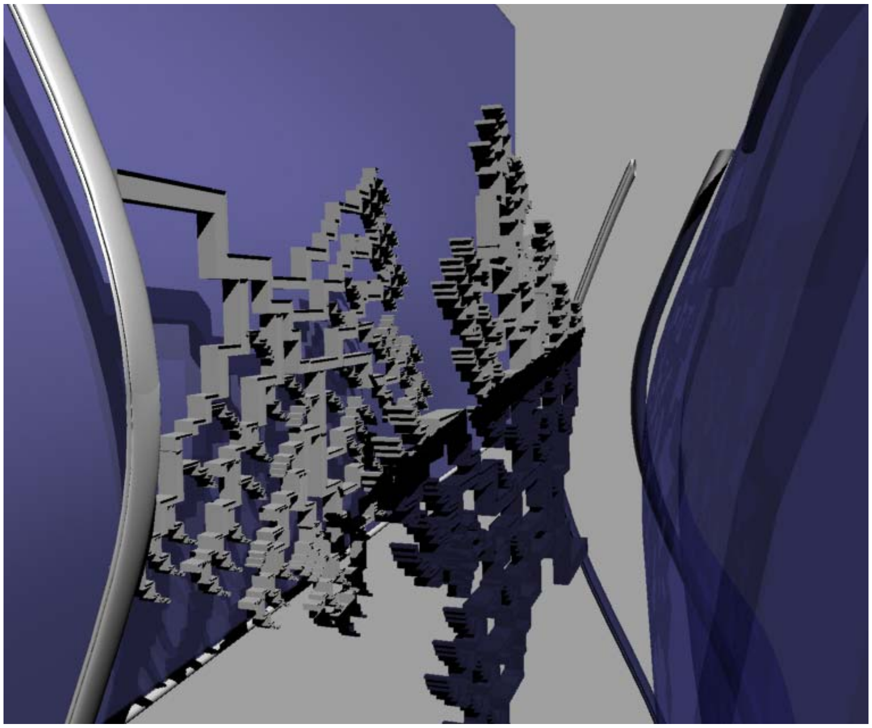




- Curved wall countercurrent”
- Cooling through convection.
- “tree shape" more surface connections in the inner parts



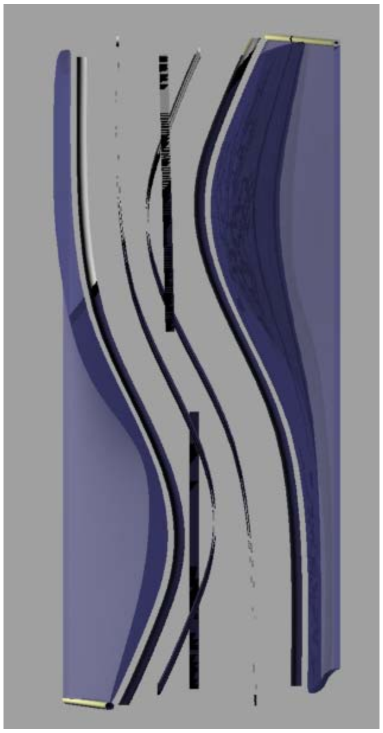
Tree shape tubes



The first Tuna fish heat exchangers concept deals with a double curved inner walls that consist of 2 layers. The main countercurrent layer is made of steal “tree” shape tubing which slides one to wards the other for heat regulation.

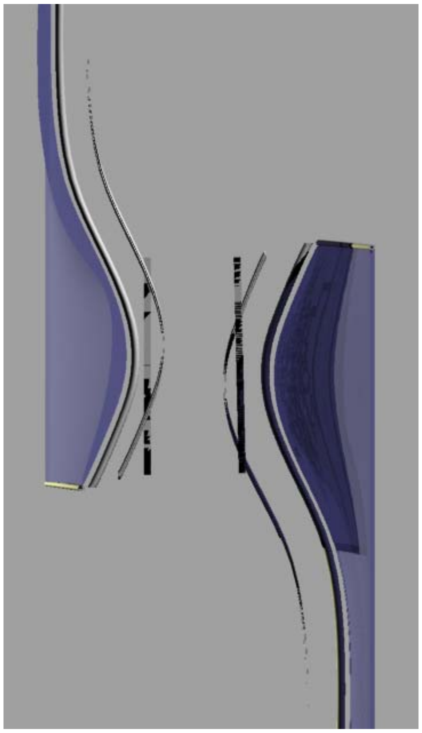
The inner tubing in two positions. The first, side by side –no heat regulation .the second overlapping phase the counter current heat is in work.

1



section /plan

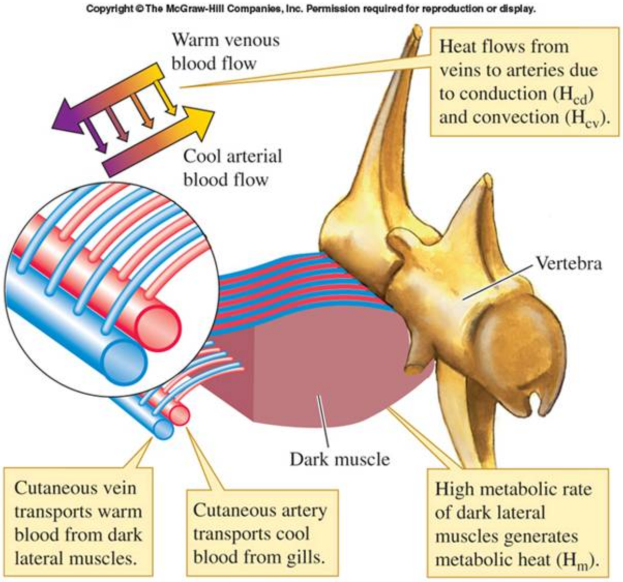
2



section/plan

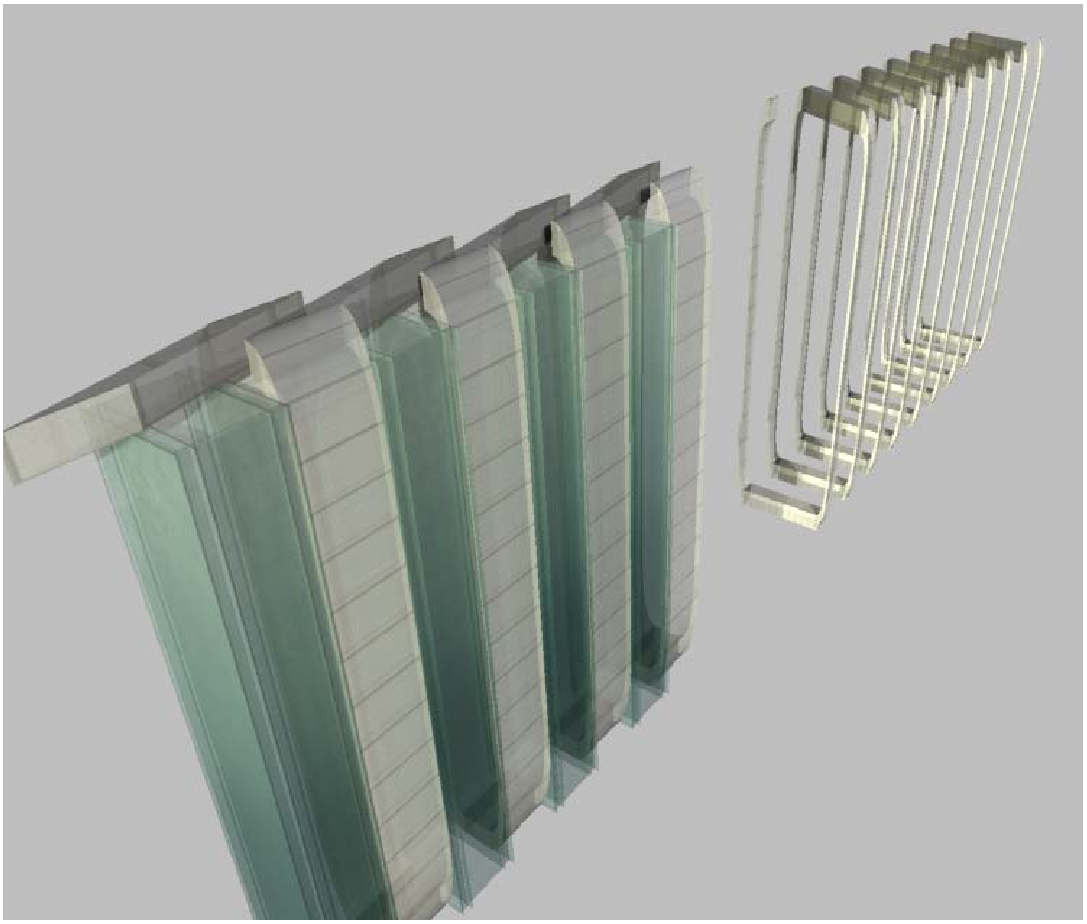
3.3.4 Tuna fish heat exchanger's conceptual façade 2

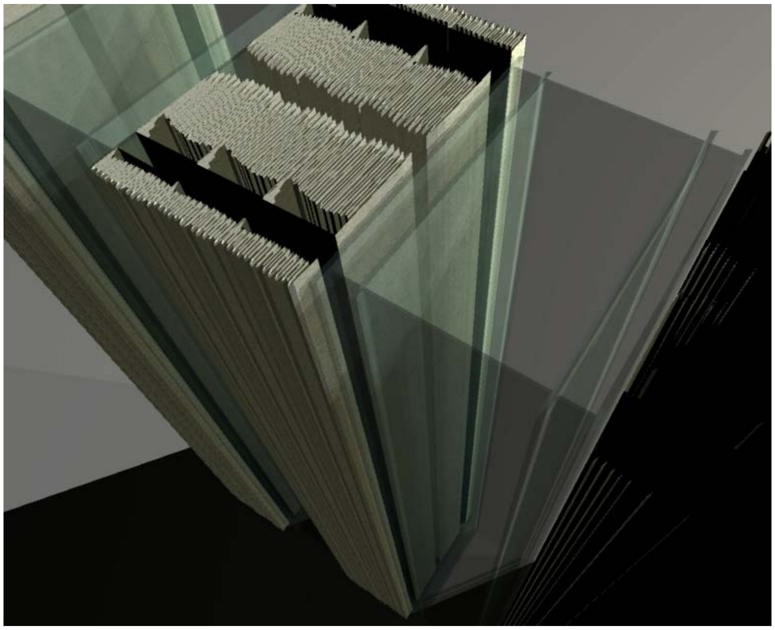
Key –words- fluid /gas exchange flow, tubes, diffusion, countercurrent
Deep principle - Counter current flow manipulates heat gains and heat losses.



- Tube and containers countercurrent"
- Cooling through convection.
- Wet "fins" cool air circulated in the inner container

Porous ceramic tubing system.



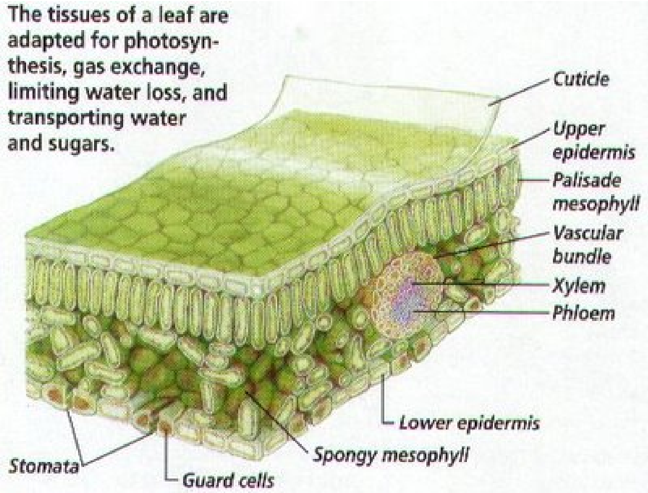


The second Tuna fish heat exchangers concept deals with double tubing and containers surfaces. Ceramic fin containers in a rounded helix configuration are attached to glass boxes. The air entering through the glass boxes is cooled when passing the wetted surface of the ceramic tube walls. Fluid or gas is pressurized during the different seasons or different times in a day cycle through the tubes.

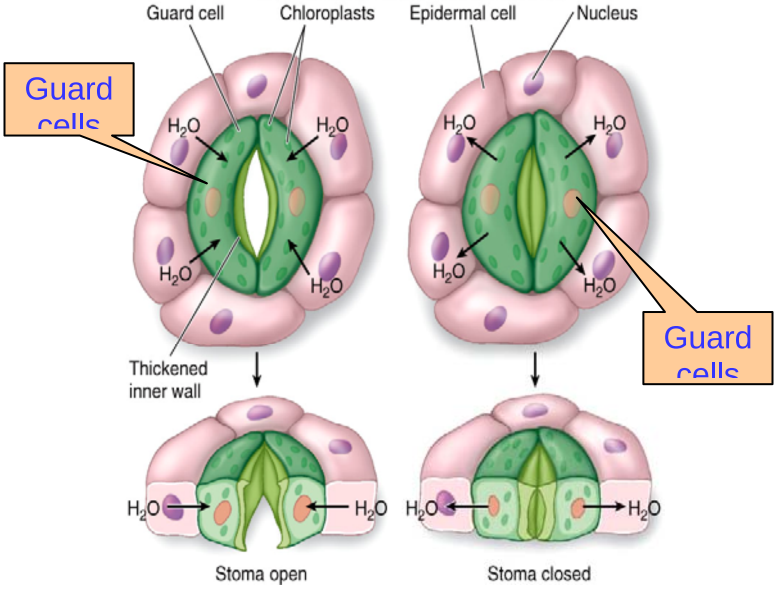
3.3.5 “Stoma” conceptual façade

Key –words- Expansion, contraction, openings, transpiration, gas exchange,

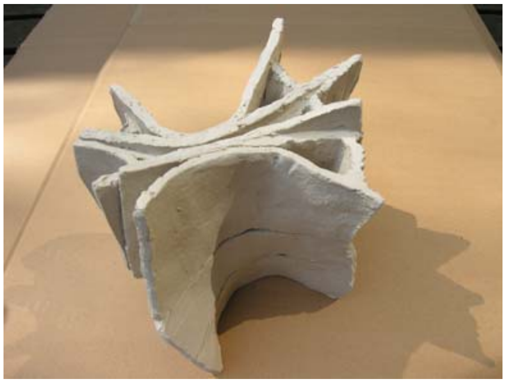
Deep principle - Osmotic pressure openings control evaporation



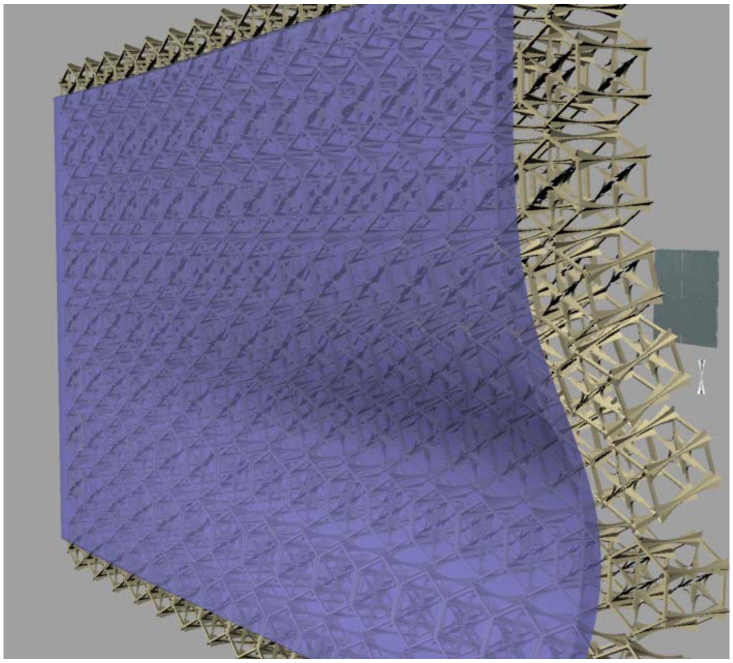
-Research of responsive surface structures –Steffen Reichert Hochschule Fur Gestaltung 2006-2007 GERMANY



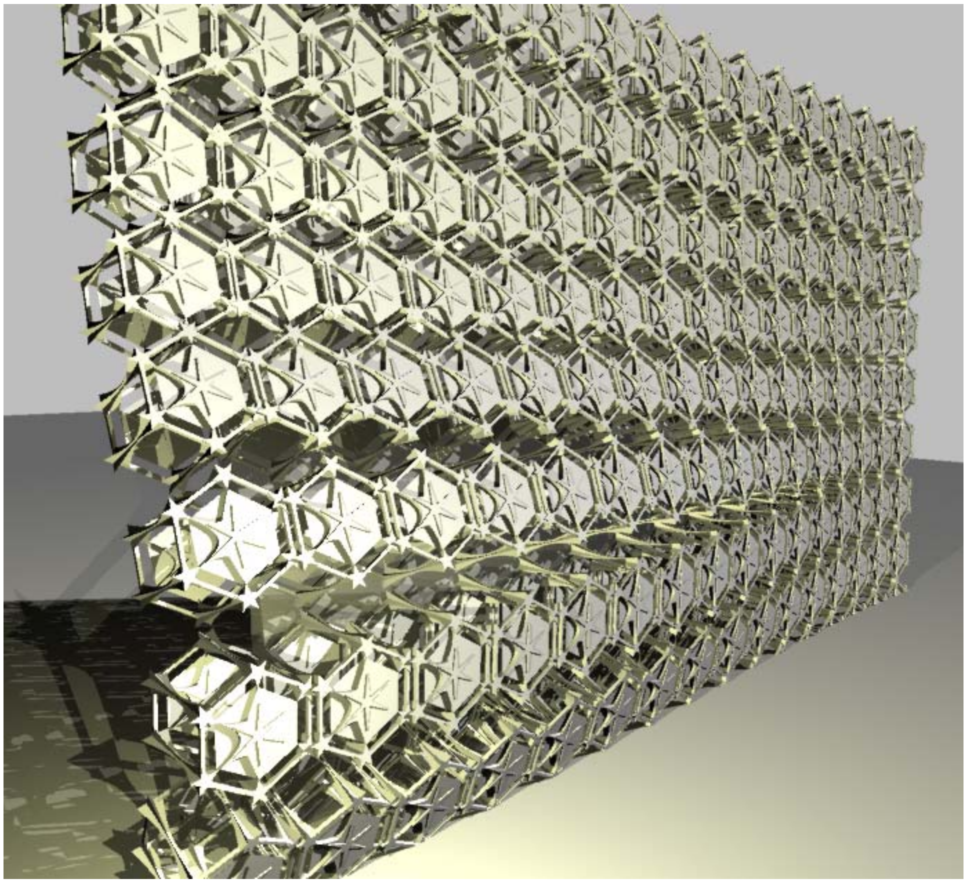
- Open-close cells
- Cooling through evaporation
- Wet “sponge" cool air circulated through it



Porous ceramic free form system



The “stoma” concept deals with a brick configuration. Each brick consists of a “sponge wetted by an irrigation tubing system.
The air that is surrounding the outer layer helps cooling the evaporated water.



The outer surface

SUMMERY

This second critical phase consisted out of trail and errors. It is a phase which made a 3 dimentional transformation from the written abstract.

Taking into account opportunities versus limitations two main façade systems were to be challenged in the last phase of transformation.

The decision was to further evaluate the countercurrent heat exchanger façade and the “stoma” evaporator brick façade.

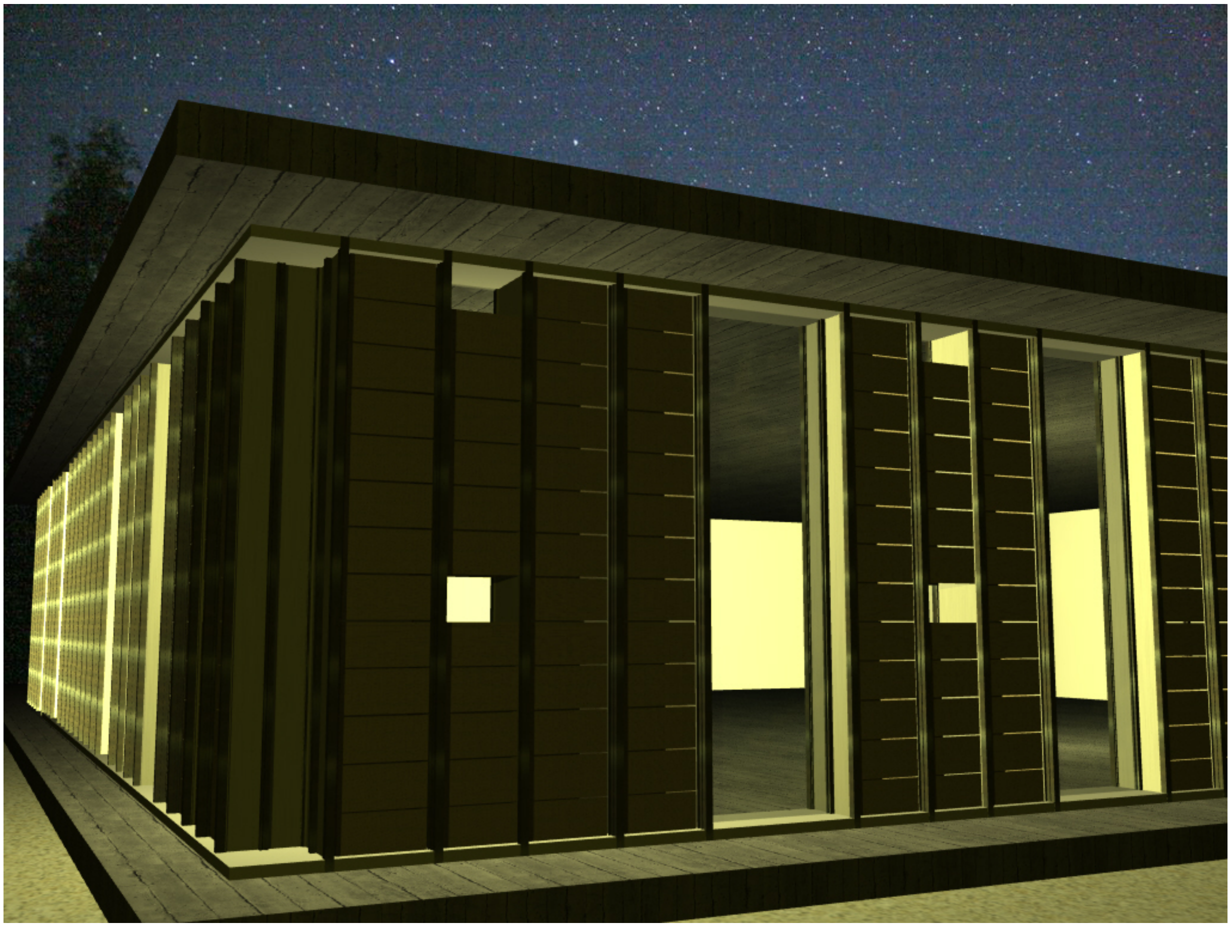
3.4 Design phase-optimization

3.4.1 countercurent Heat exchange block

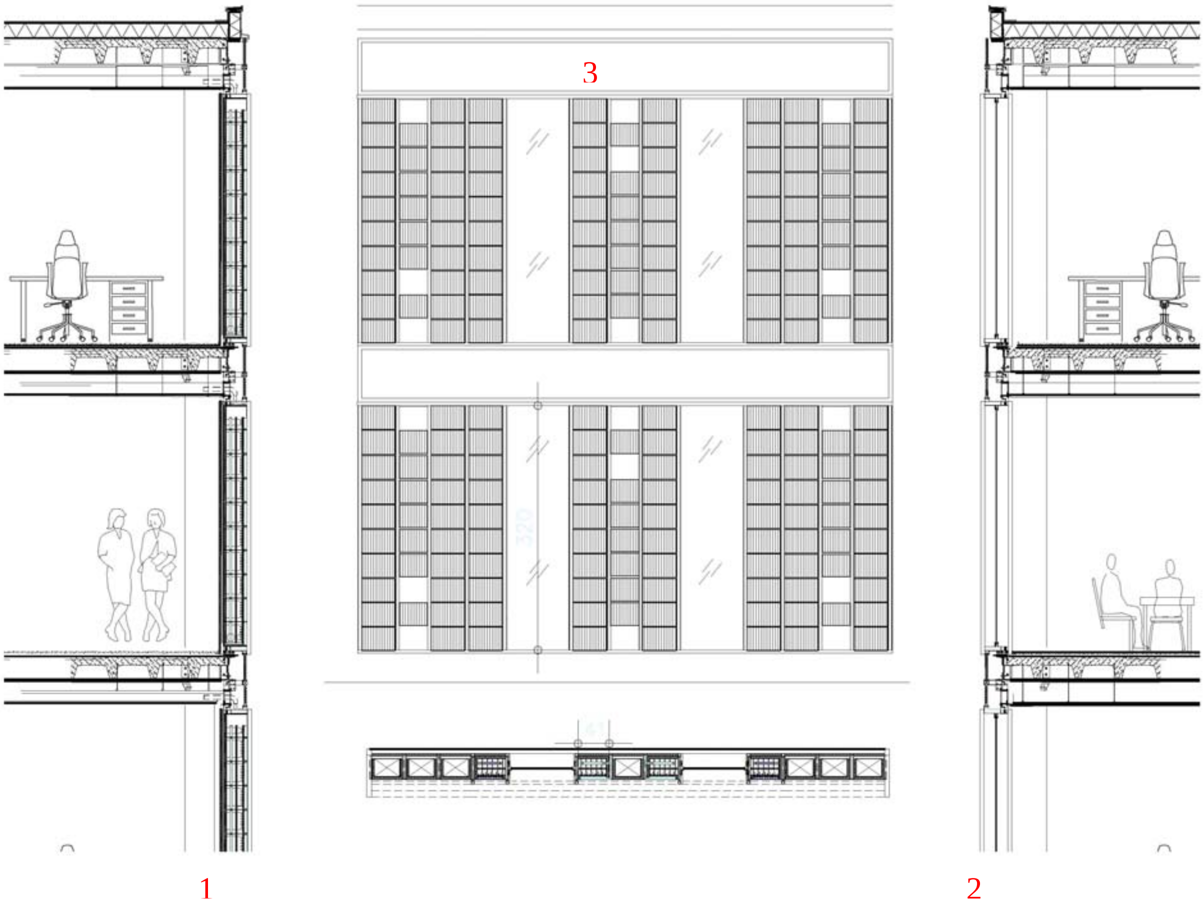
Key –words- fluid /gas exchange flow, tubes, diffusion, countercurrent
Deep principle - Counter current flow manipulates heat gains and heat losses.

Maintaining Inner temperatures and humidity conditions through the flow of fluid/gas in the tubing system, the opposite flow direction permits a high degree of heat balance.

- **Mechanism**-Indirect-direct evaporator
- **Convection-**Heat exchanges energy through flows in different directions, depending on the period of year.
- Air is sucked in one direction from the outer perimeter to the inner one.
- Fluid is pressurized during the different seasons or different times of the day cycle through the block system to cool the air.
- Porous material allow sweating and thus-cooling

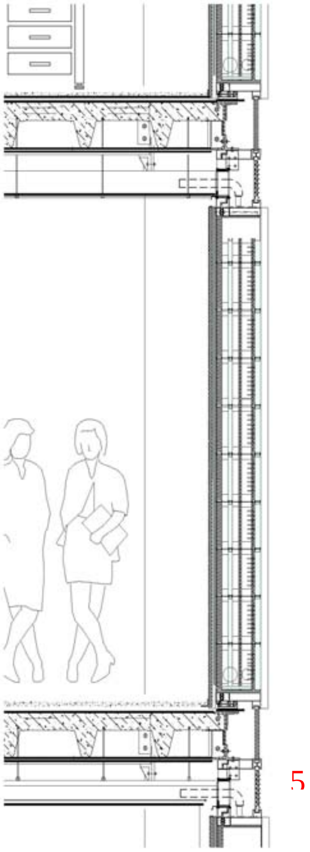


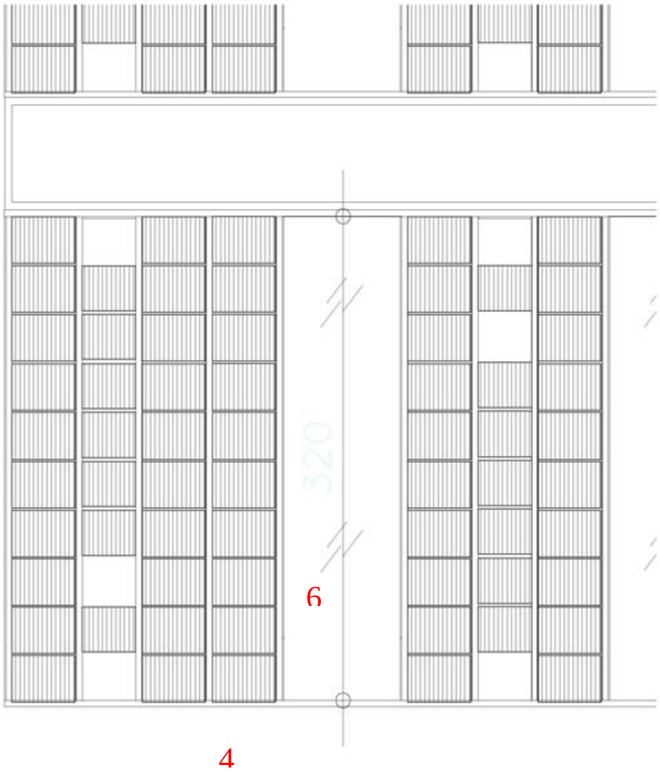
1- Facade section of clay blocks
2 - Facade section of glass wall
3 - Main facade elevation



The system is made out of porous ceramic blocks one on top of the other inside an insulation box. This configuration of a “cooling tower” or a cooling duct is the main apparatus. Each block is divided into two separate cooling devices. The first, facing the outer perimeter, is an indirect cooler and the second one, facing the inner part of the building, is a direct cooling part. There are 4 cooling block towers for a 64 cubic meter office.

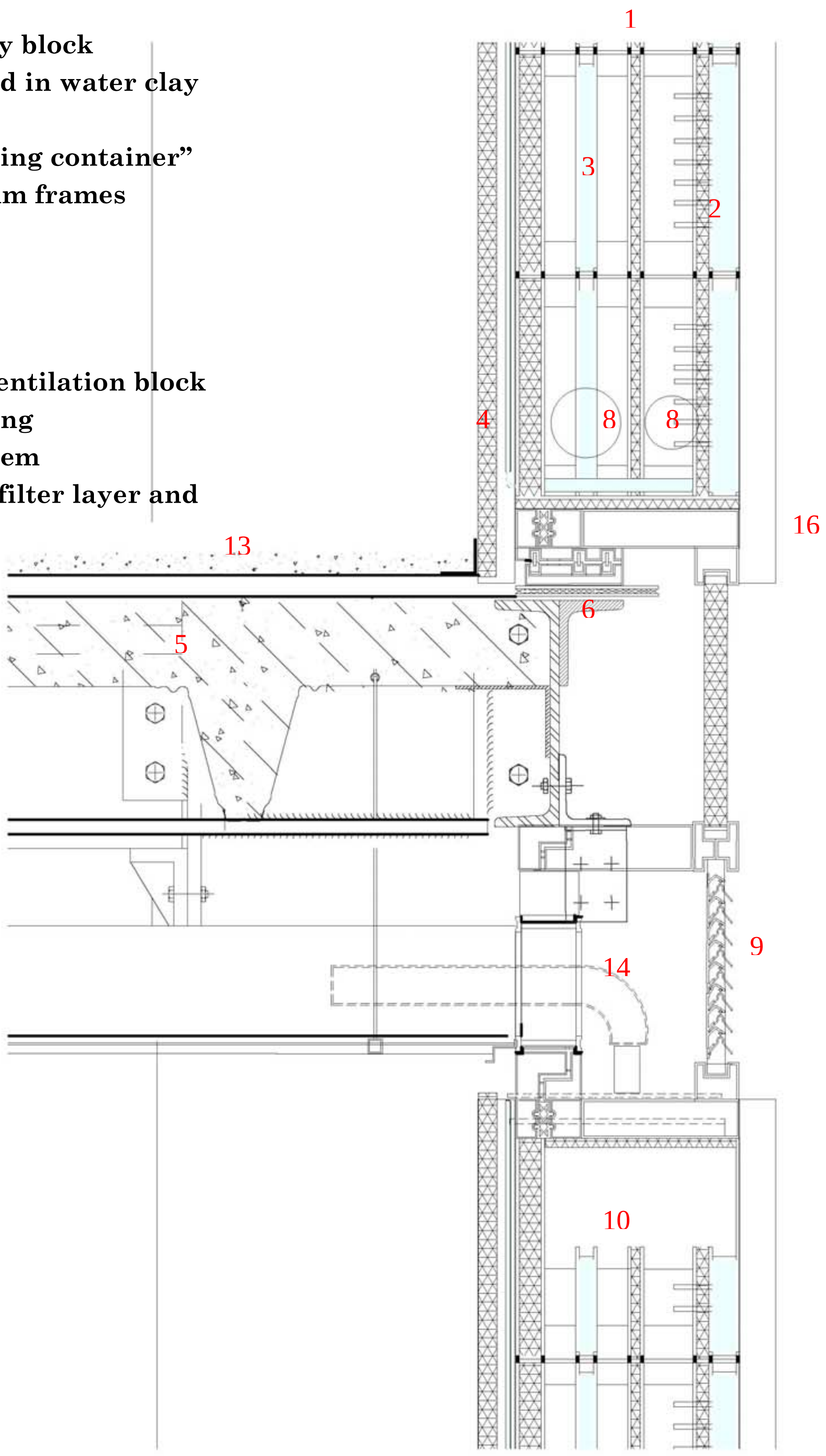
1:20 layers of porous clay blocks





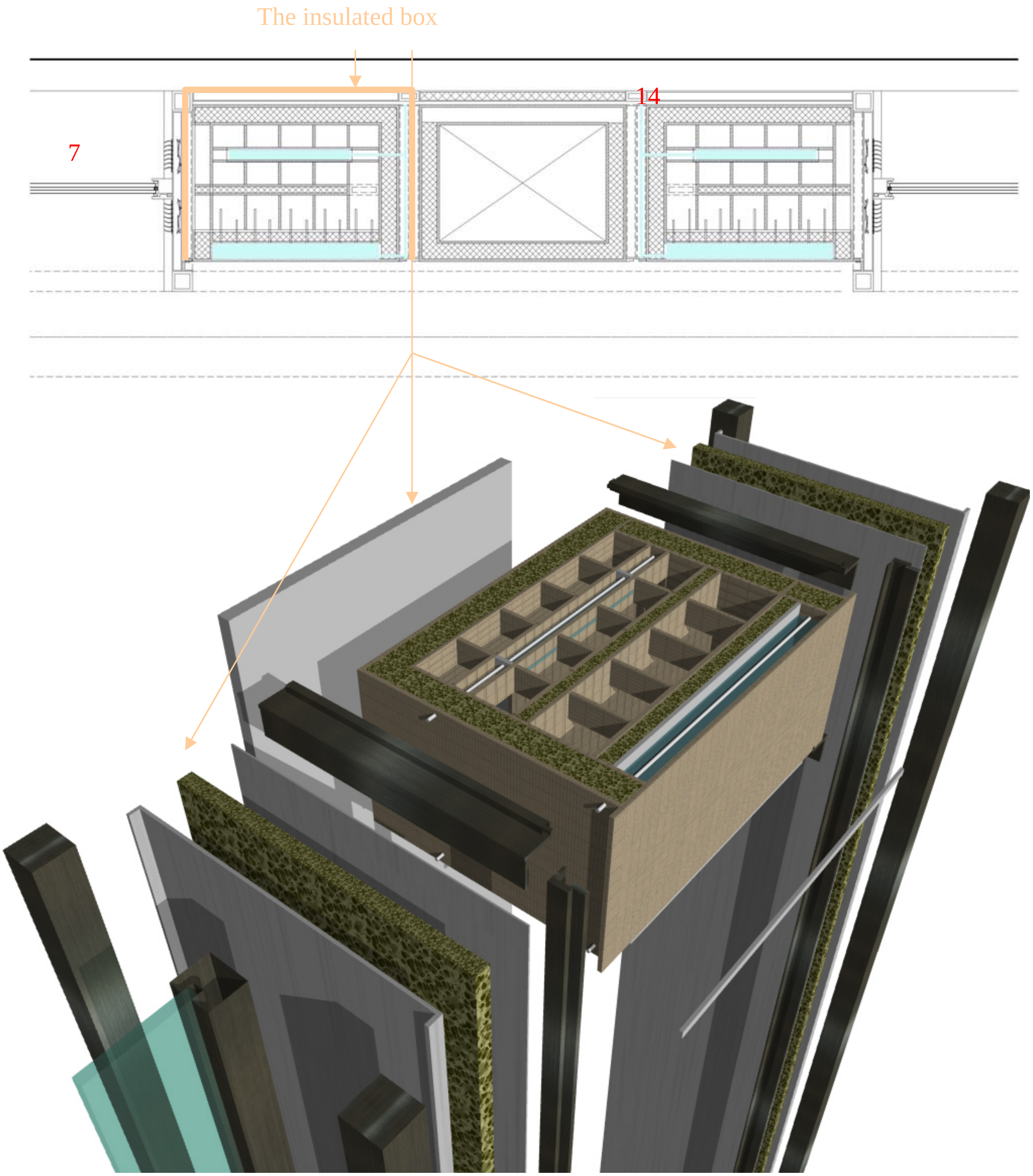
4 - Aluminum construction
5 – Floor
6 – Double glazing 2x8 mm
Toughened glass

1 - Double porous clay block
2 - Heat pipes inserted in water clay container
3 -porous clay “sweating container”
4 - Insulated aluminum frames
5 -steal floor beam
6 – Mounting shoe
8 – auto-vents
9 - Outer air exhaust
10- Inner upper air ventilation block
13- Concrete top coping
14- Water supply system
15- Waterproof mat +filter layer and drain pipe
16- Water pump

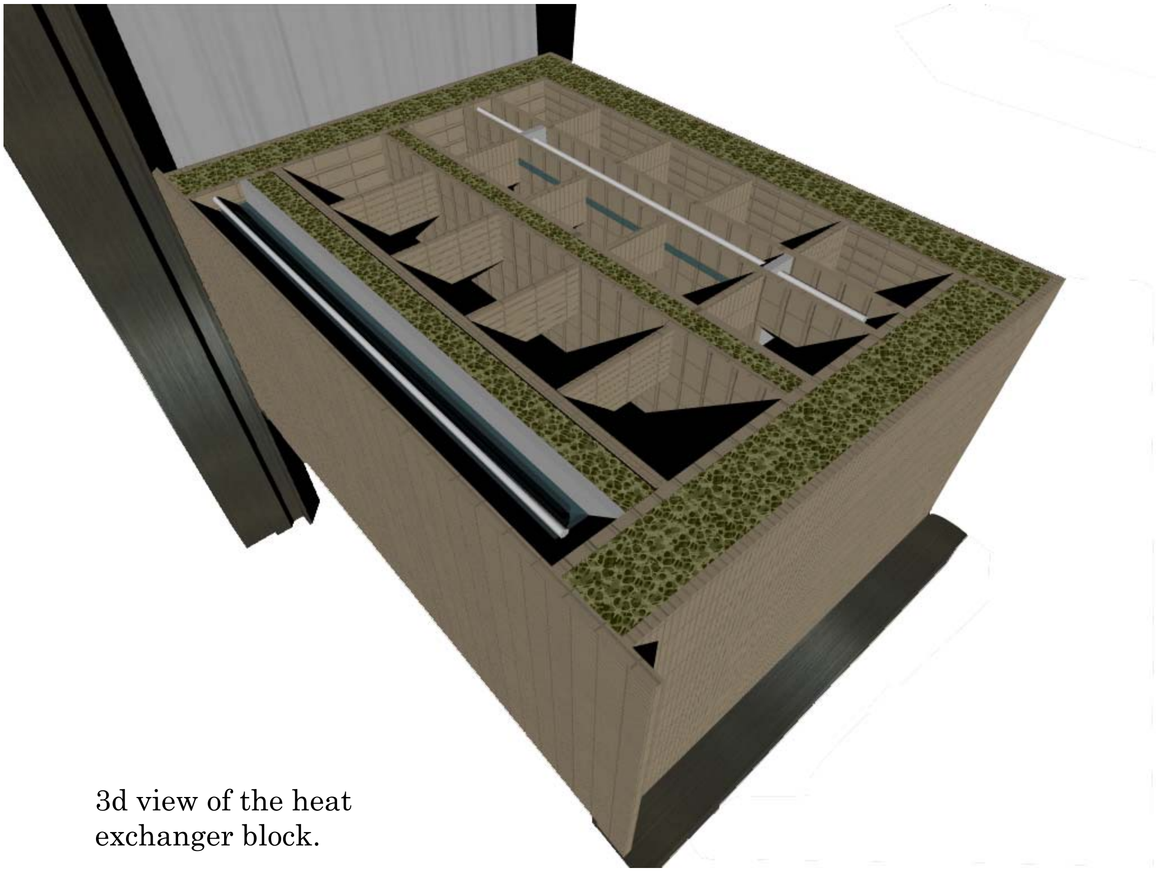


7 – Double glazing 2x8 toughened glass

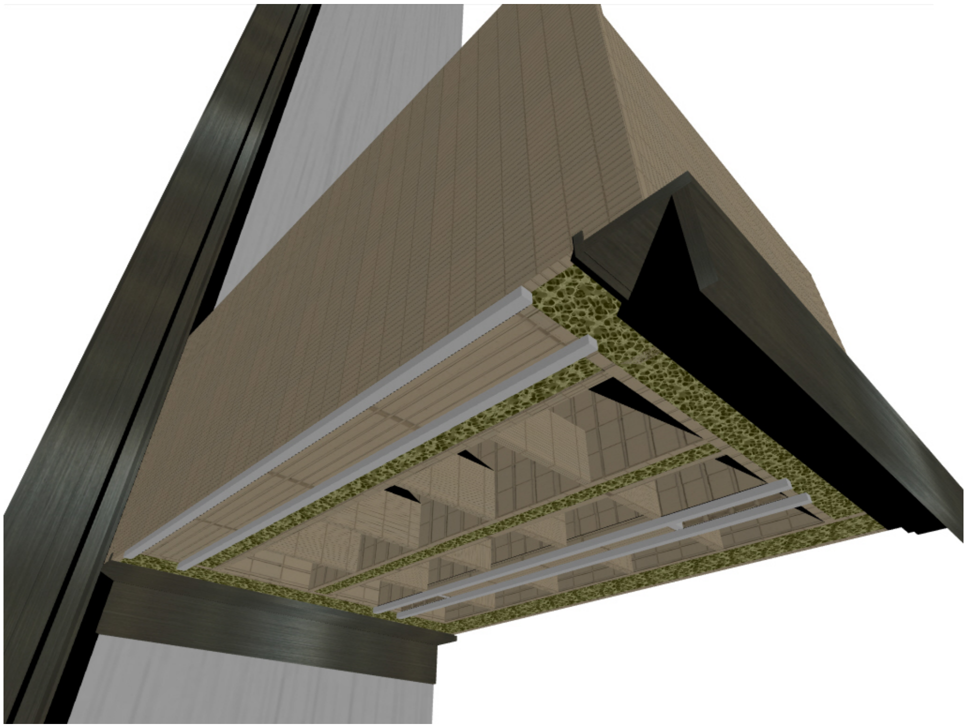
11-inner air ventilation of clay block

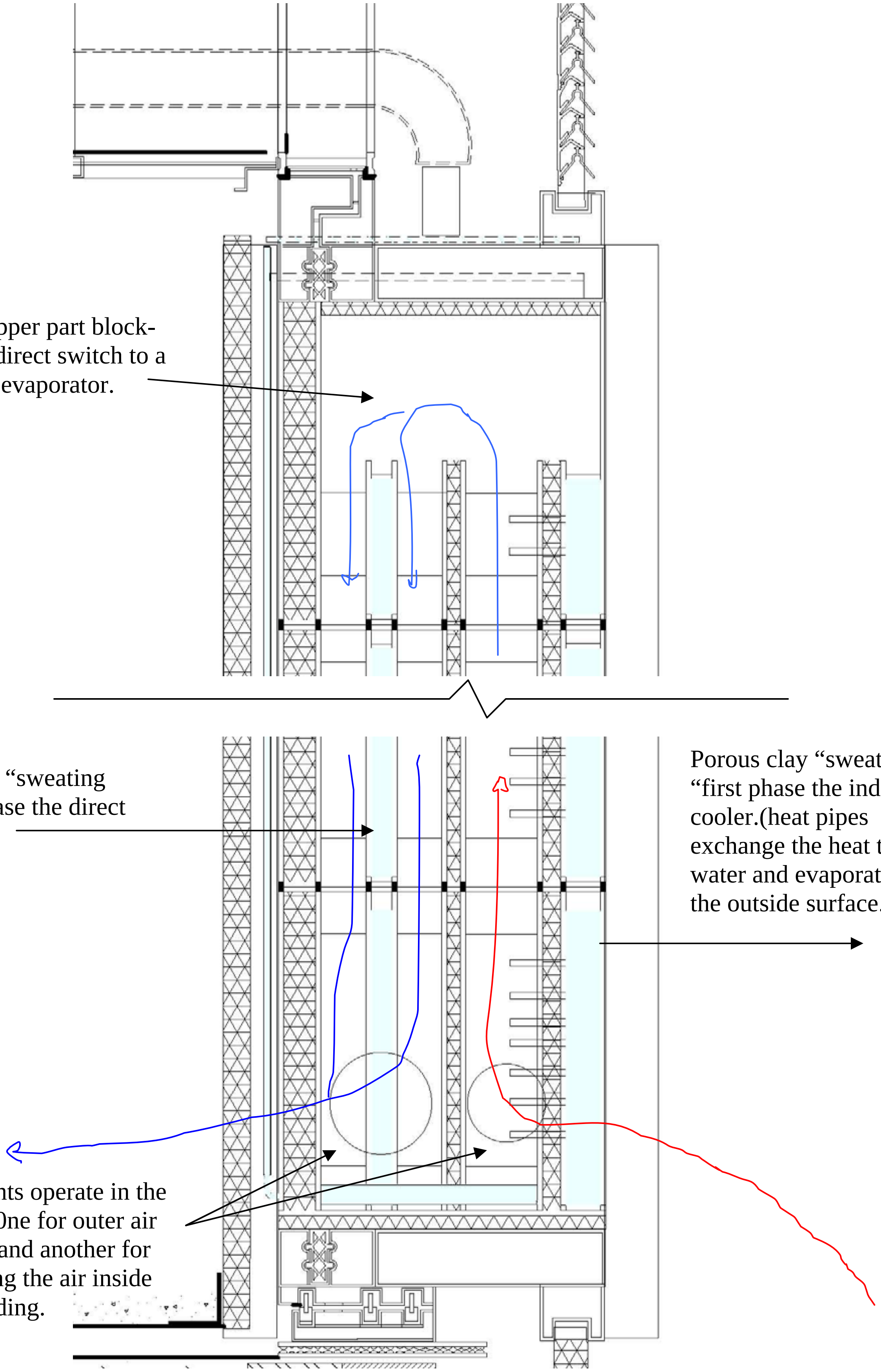


Exploded view -



3d view of the heat exchanger block.



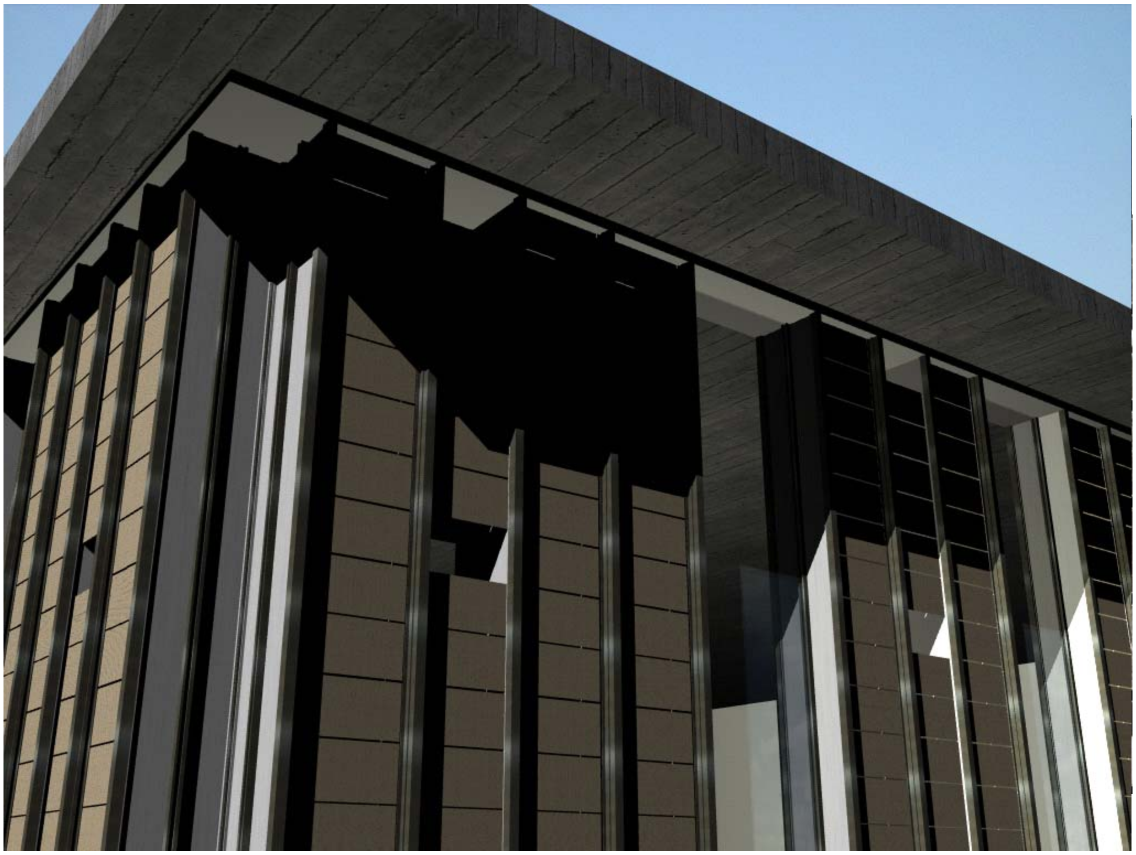


The upper part block-
the indirect switch to a
direct evaporator.

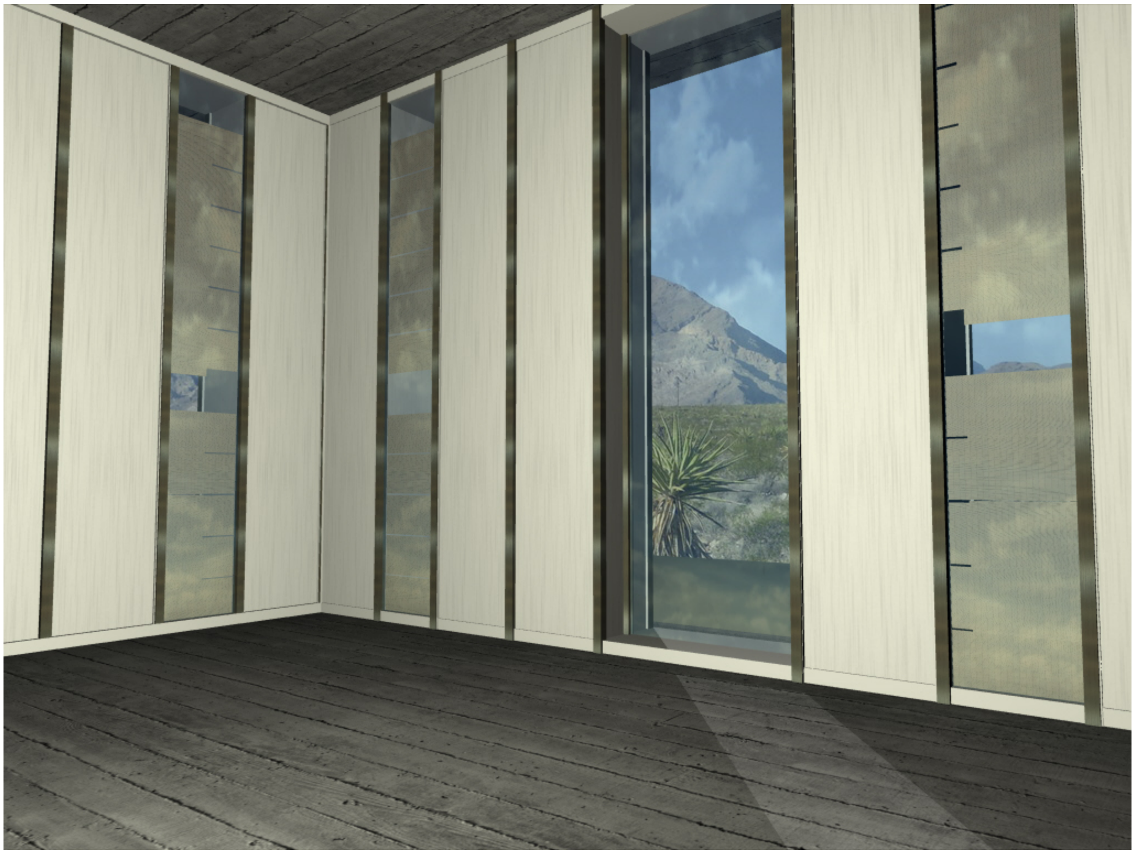
Porous clay “sweating
“second phase the direct
cooler.

Porous clay “sweating
“first phase the indirect
cooler.(heat pipes
exchange the heat to the
water and evaporating to
the outside surface.

Two vents operate in the
system 0ne for outer air
suction and another for
spreading the air inside
the building.



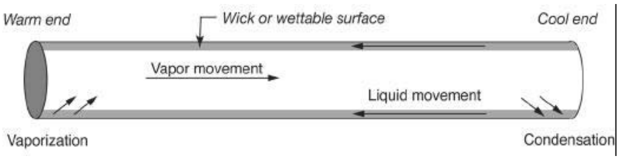
Optional Outside view



Inside view

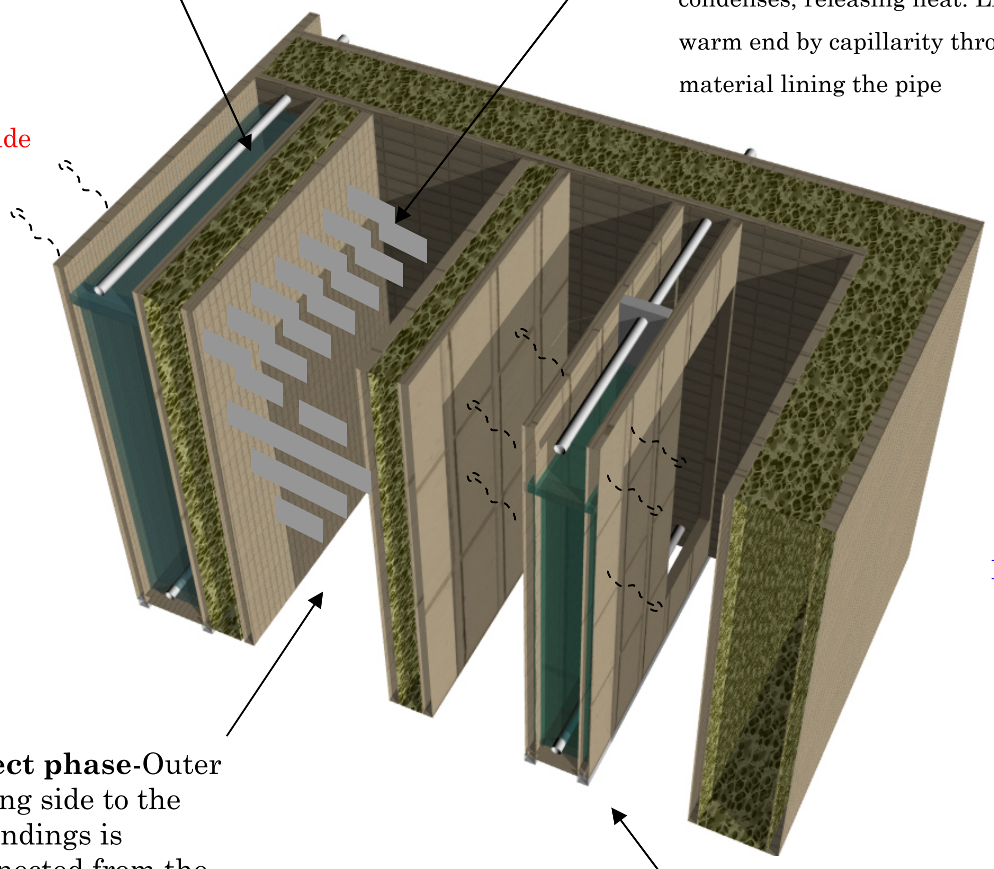
Summery

The potential for an indirect direct heat exchange block in the field of heat regulating envelopes is high .The integrated system as part of the construction and the functional systems is its main advantage. This together with many design opportunities of clay block façades can eventually lead to a more sustainable approach .the main evaluation and comparative analysis to other indirect direct evaporators is given in the ending chapters.



A **heat pipe is** device that combines phase change and convection. A liquid vaporizes at the warm end, absorbing heat. Vaporization produces a pressure difference that drives gas toward the cool end. There it condenses, releasing heat. Liquid then returns to the warm end by capillarity through some wicking material lining the pipe

Water tubing system-
“irrigation system”



Outside

Inside

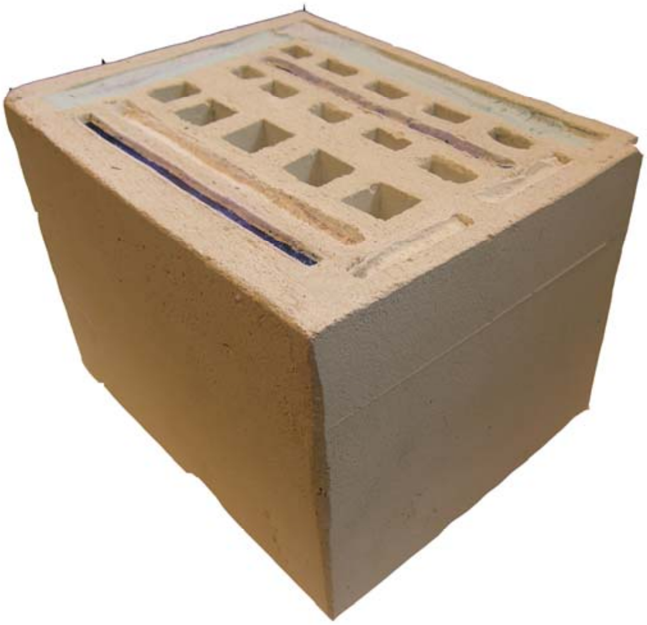
Indirect phase-Outer sweating side to the surroundings is disconnected from the inner duct and the heat pipe exchangers by insulation.

Direct phase-middle sweating ceramic container is disconnected from the indirect duct by insulation

Working models

Outer part

Inner insulation box



A gypsum model for one block

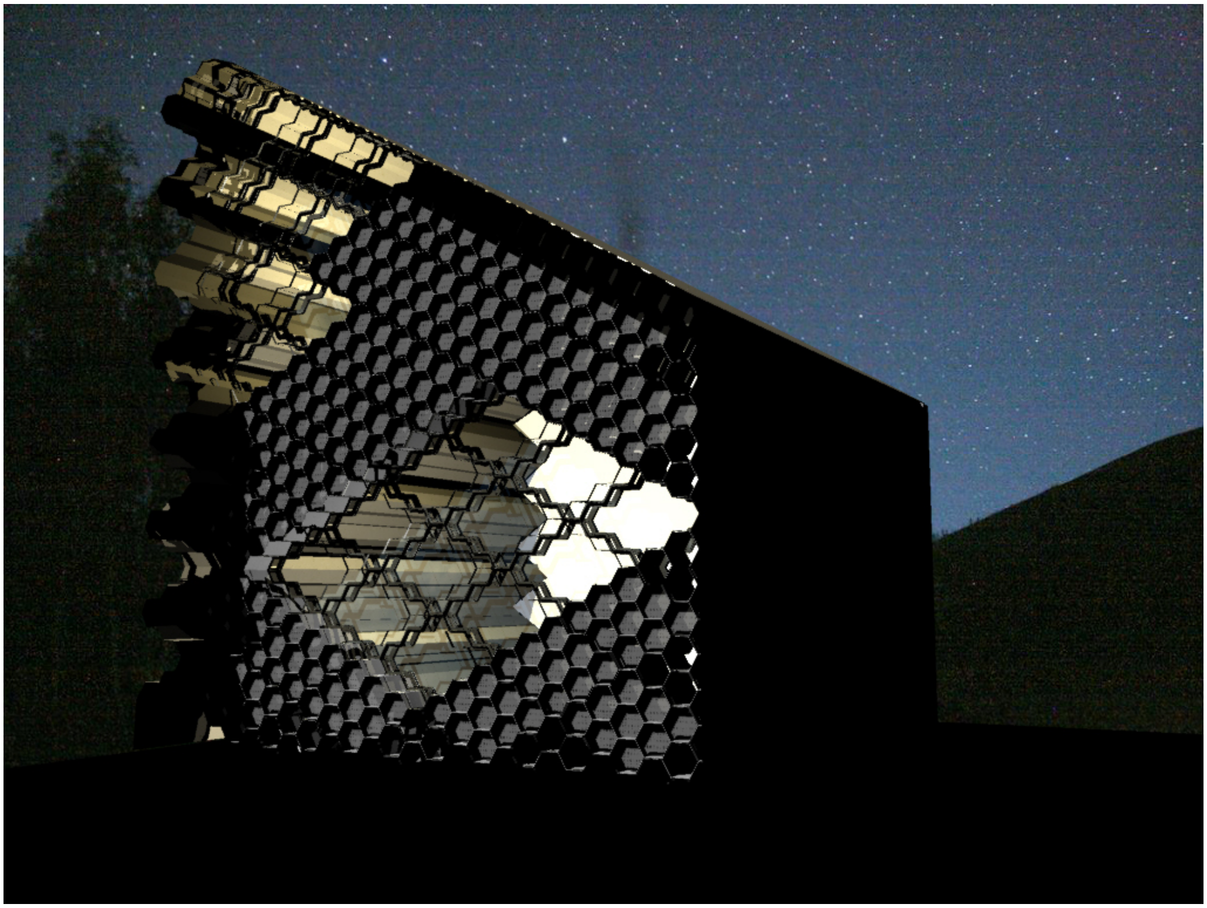
3.4.2 Design phase 2 -optimization of "stoma bricks"

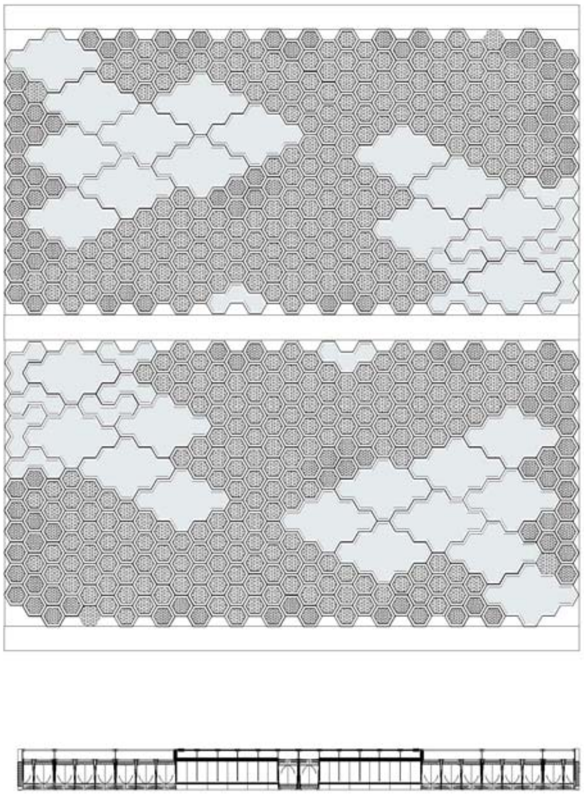
Key –words- Expansion, contraction, openings, transpiration, gas exchange,
Deep principle - Osmotic pressure openings control evaporation

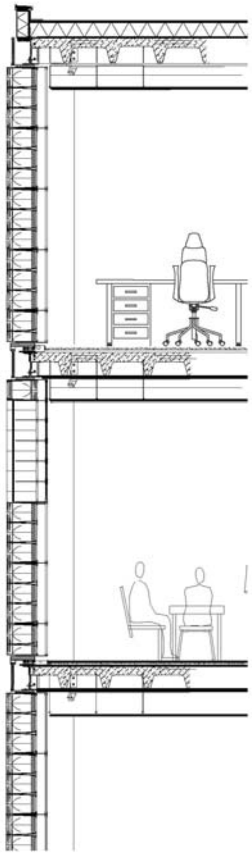
Maintaining Inner temperatures and humidity conditions through Evaporative cooling or transpiration of water. The opening and closing should be influenced by the change in humidity or air pressure.

This should operate

- Evaporation-cooler through a net of Opening/closing diaphragm.
- Passive direct cooling with water irrigation system
- Material-a 3d print of a porous sponge.
- Hairs block dust/sand in arid regions





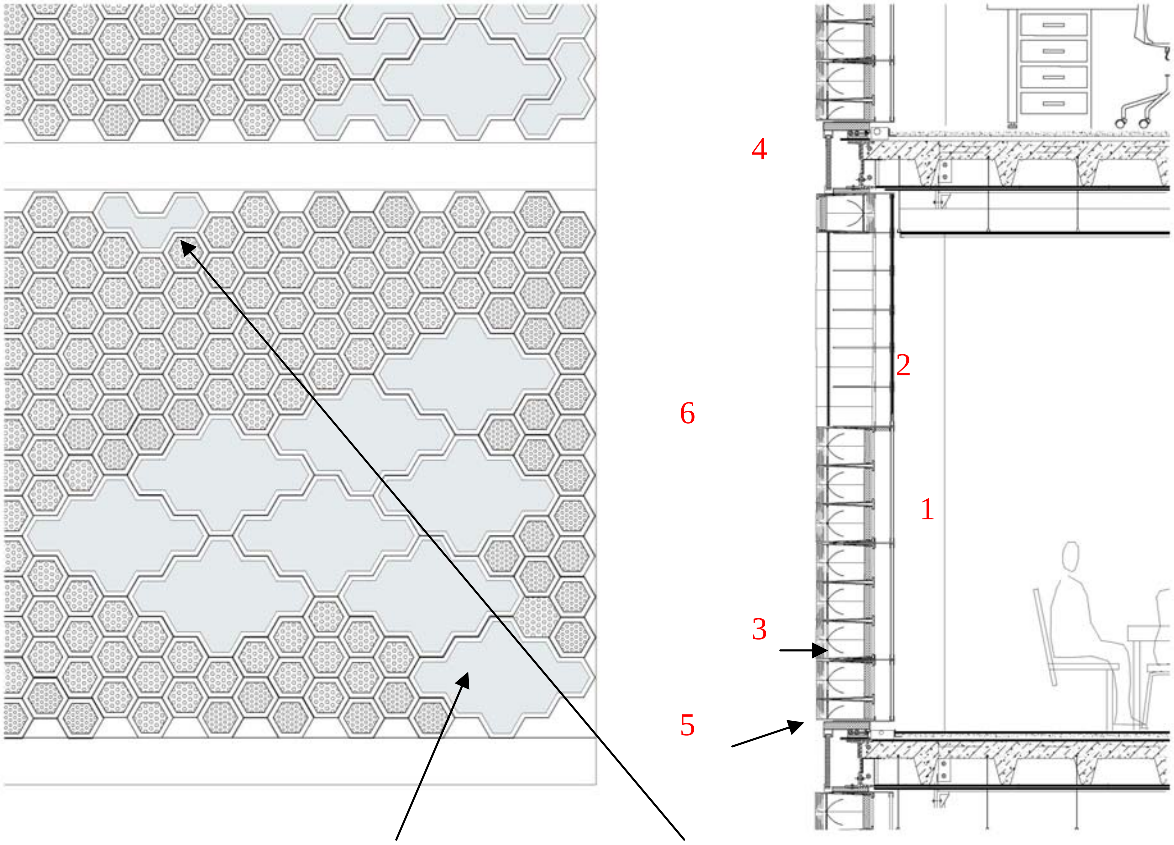


Main section

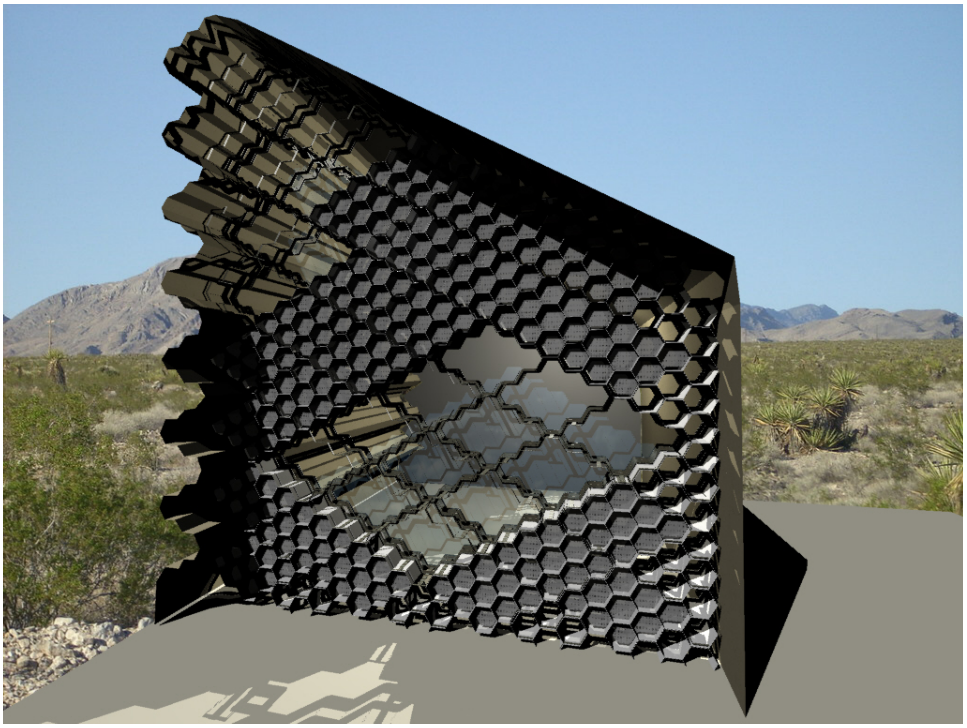
The system is made out of 3d printed “stoma” bricks. There are 2 configurations a 3 monobrick and a 9 monobrick. These are held inside a steal framing system.
The monoblock is a closed water system that is responsible like an irrigation system to wetting some parts when humidity is needed. The parts are the porous evaporator and the Vanier door.

Main parts

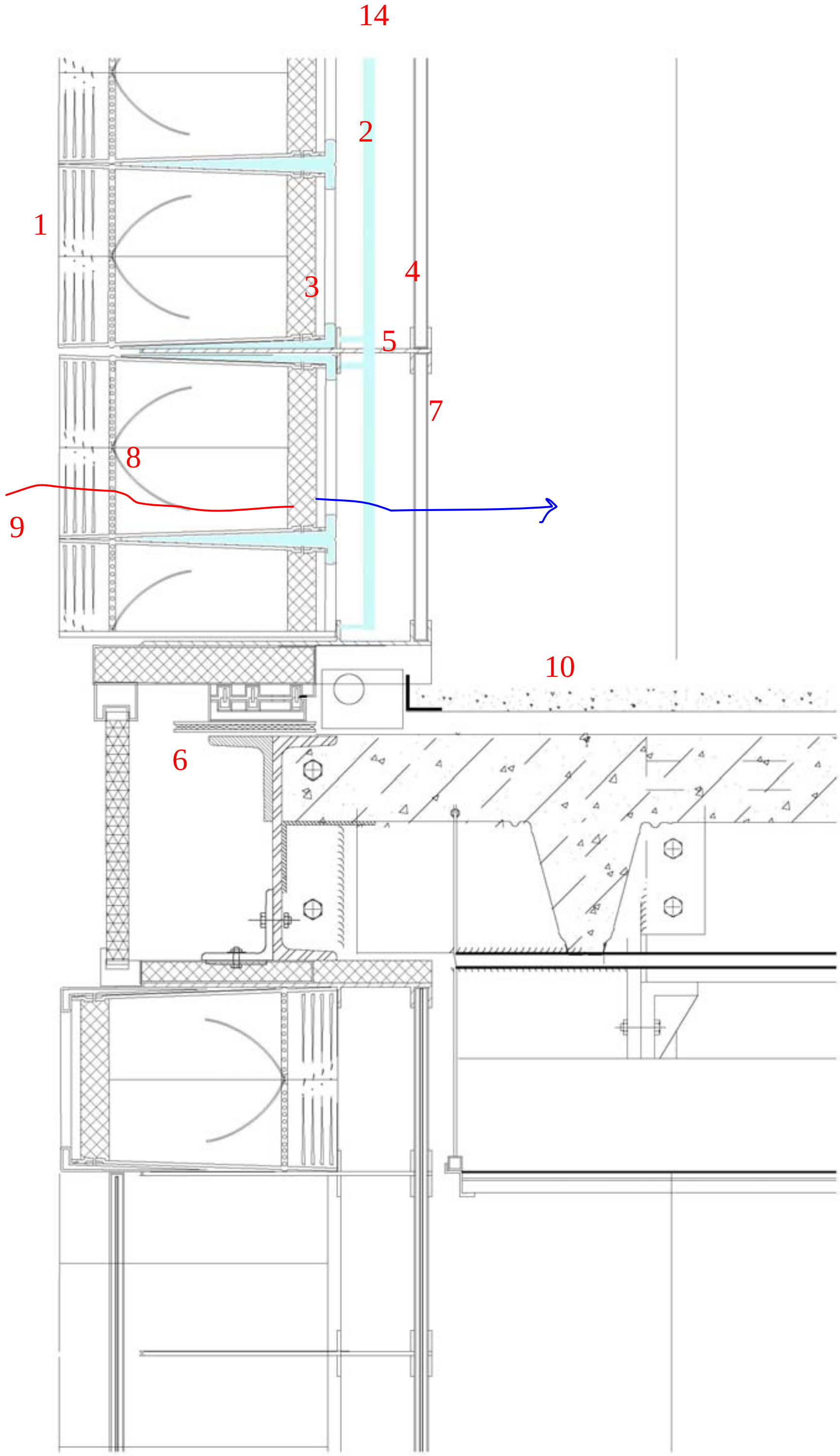
1. “stoma bricks façade system
2. 20 mm acrylic glass in aluminium framing.
3. air ventilation through bricks
4. floor
5. Constructions steal framing.

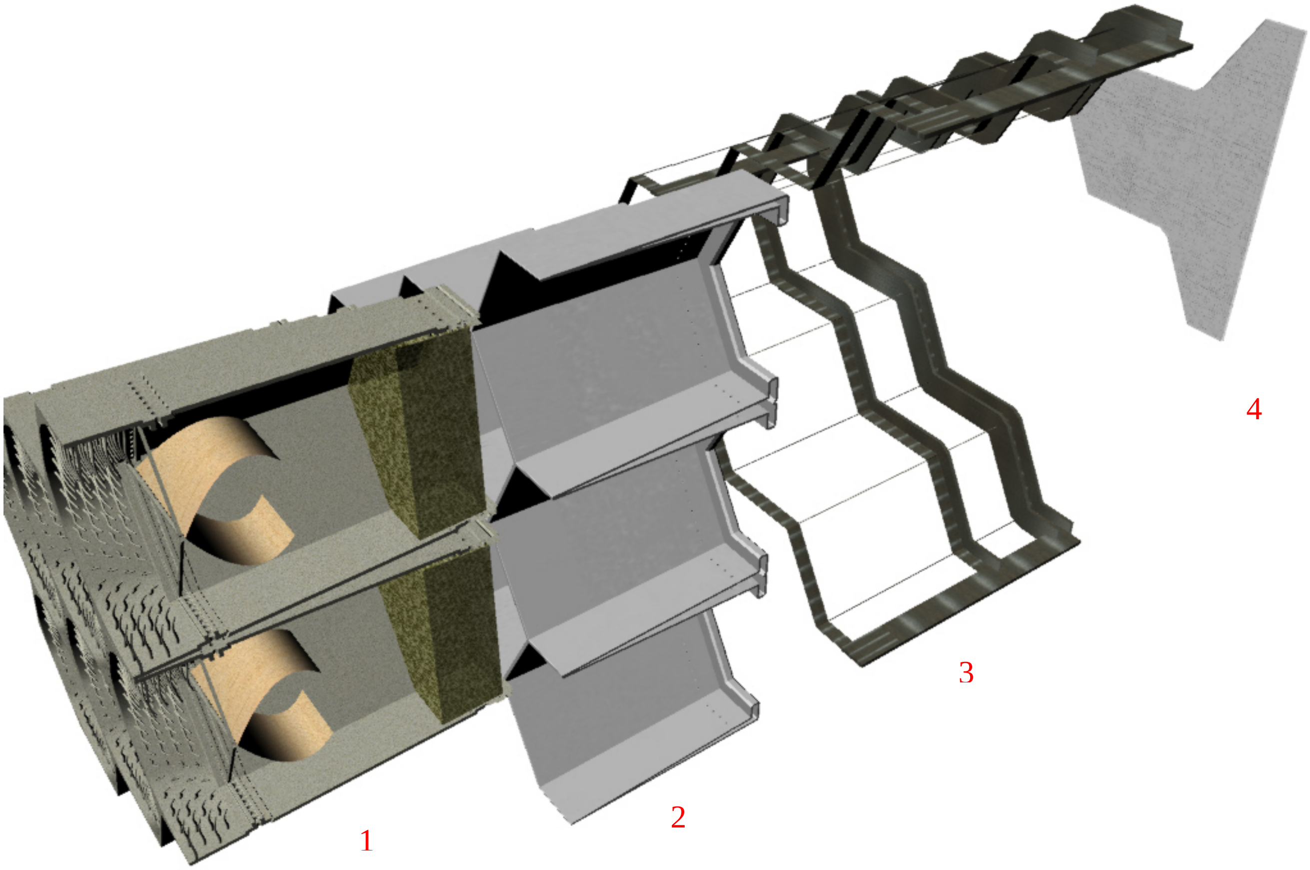


Main elevation a nine monobrick and a three monobrick



1 - Extruded/3d print stoma brick section
2 -water "irrigation system" embedded in brick
3 -porous sponge
4 - Insulated hepa filter or glass in metal frames
5 -Steal frame
6 – Mounting shoe
7 – Double acrylic glass.
8 – Wooden veneer- responsive to humidity
9 - Outer air intake
10-floor system
13- Concrete top coping
14- Water supply system





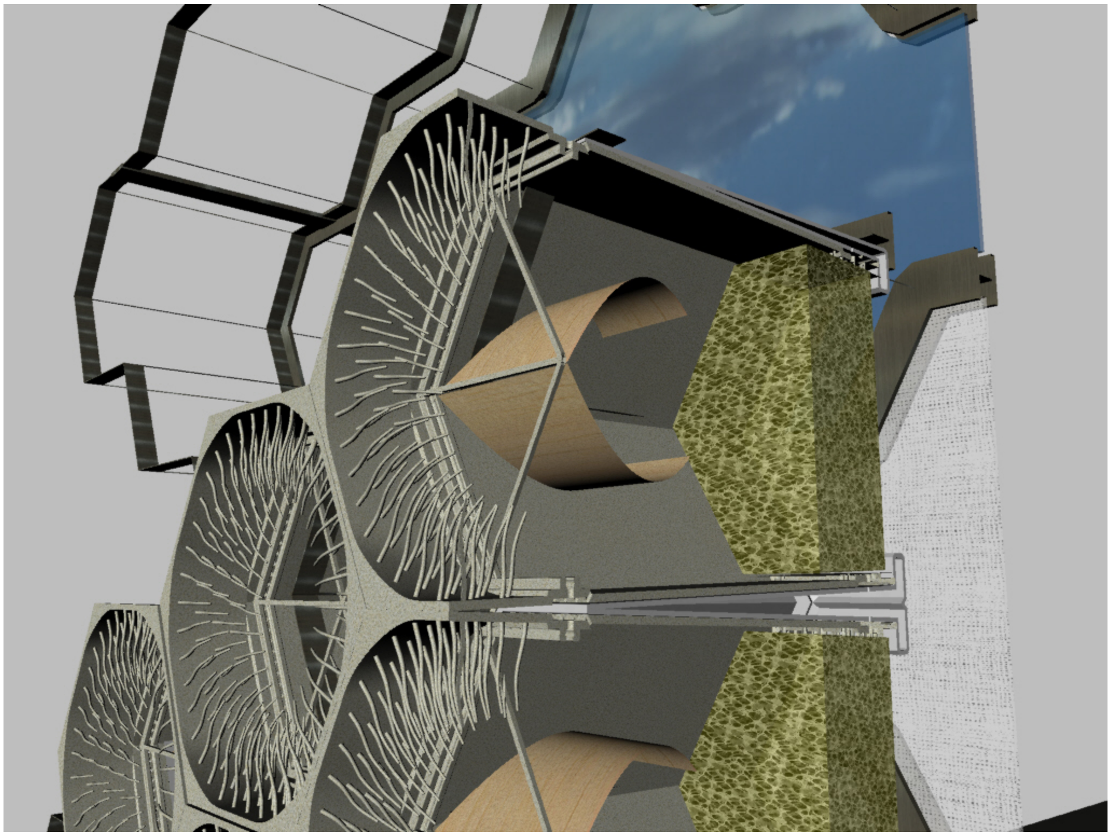
The four main parts

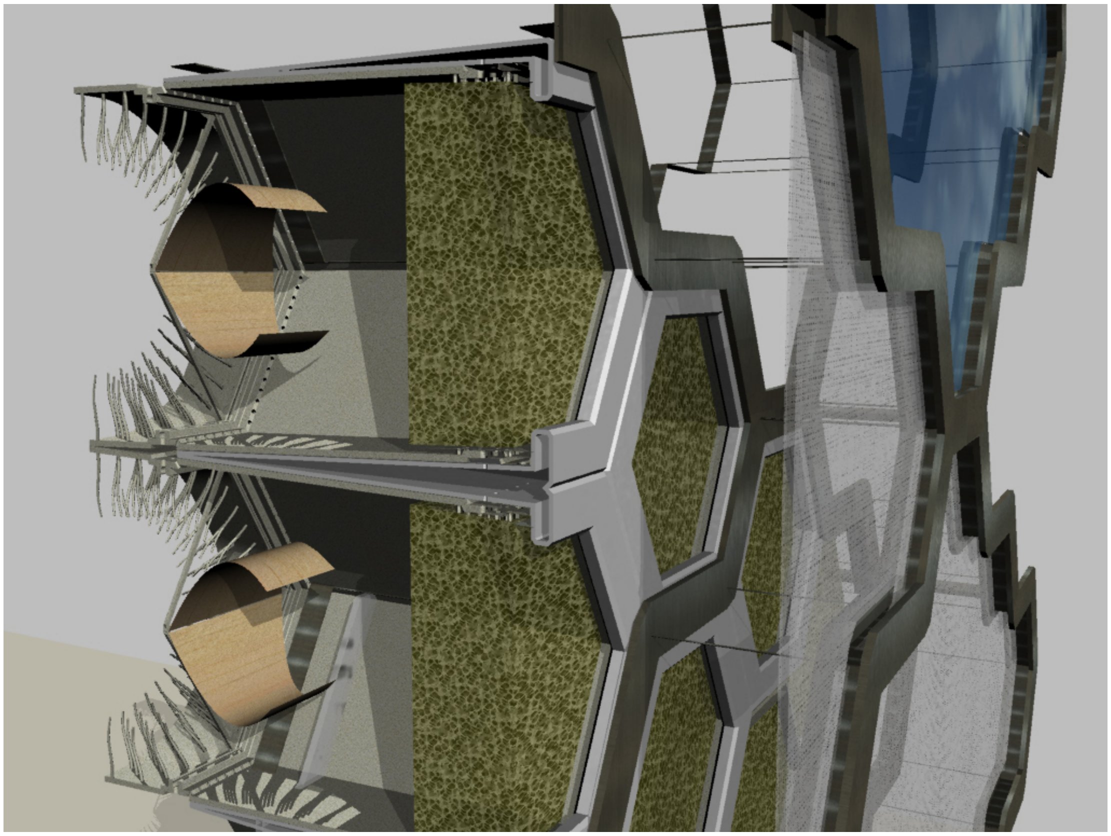
1. the brick
2. the monobrick
3. the steal framing
4. the hepa filter or double glazing

The 3d printed block is made out of a porous material .the part for the evaporator can act as an insulator when it is dry.

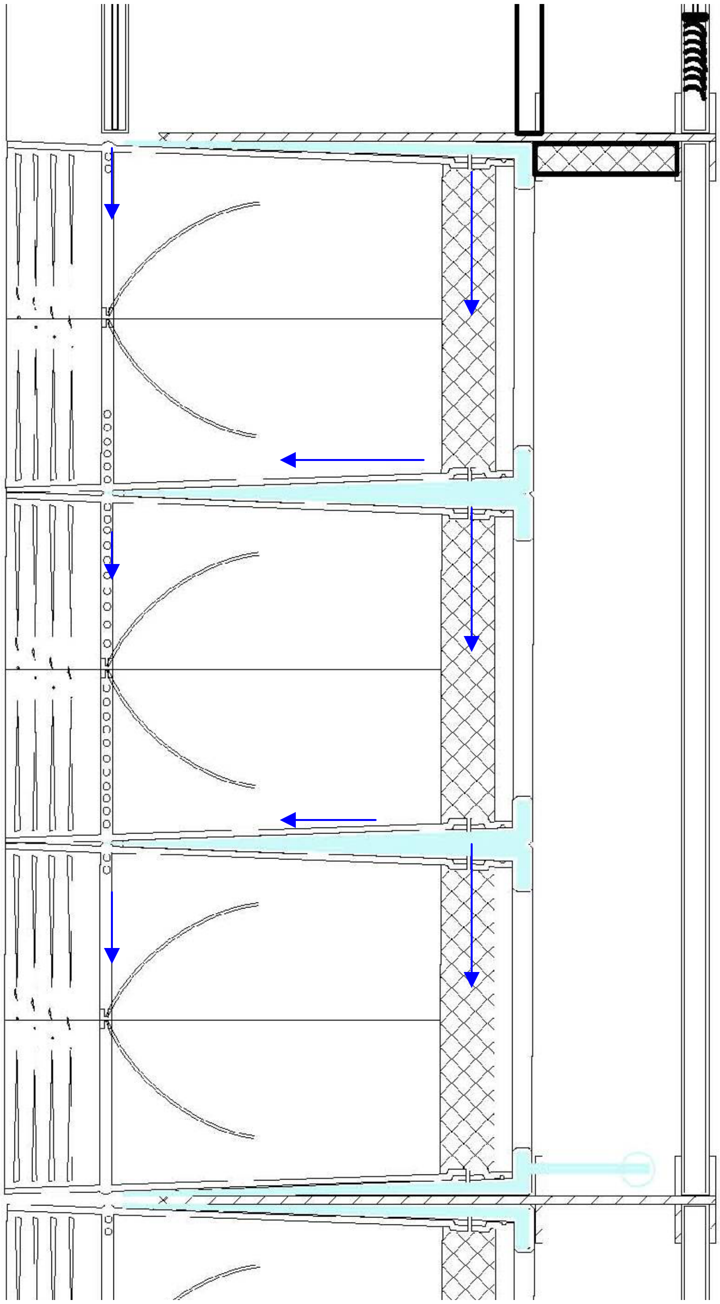
The Vanier wooden door is a self responsive material which shrinks and expands depending on the dryness or humidity of the air. This happens because of the way it is cut and because of its fibber direction. *-Research of responsive surface structures –Steffen Reichert Hochschule Fur Gestaltung 2006*-2007 GERMANY.

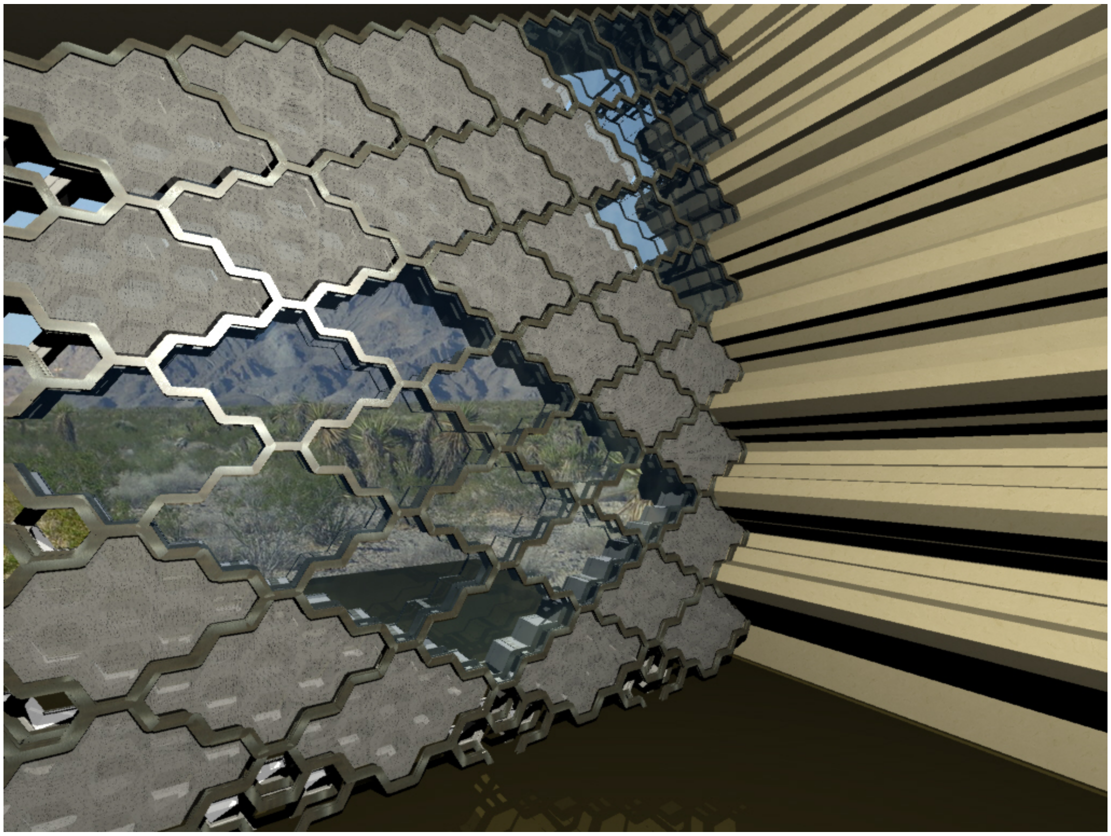
The hepa filter helps the air to enter clean into the building.

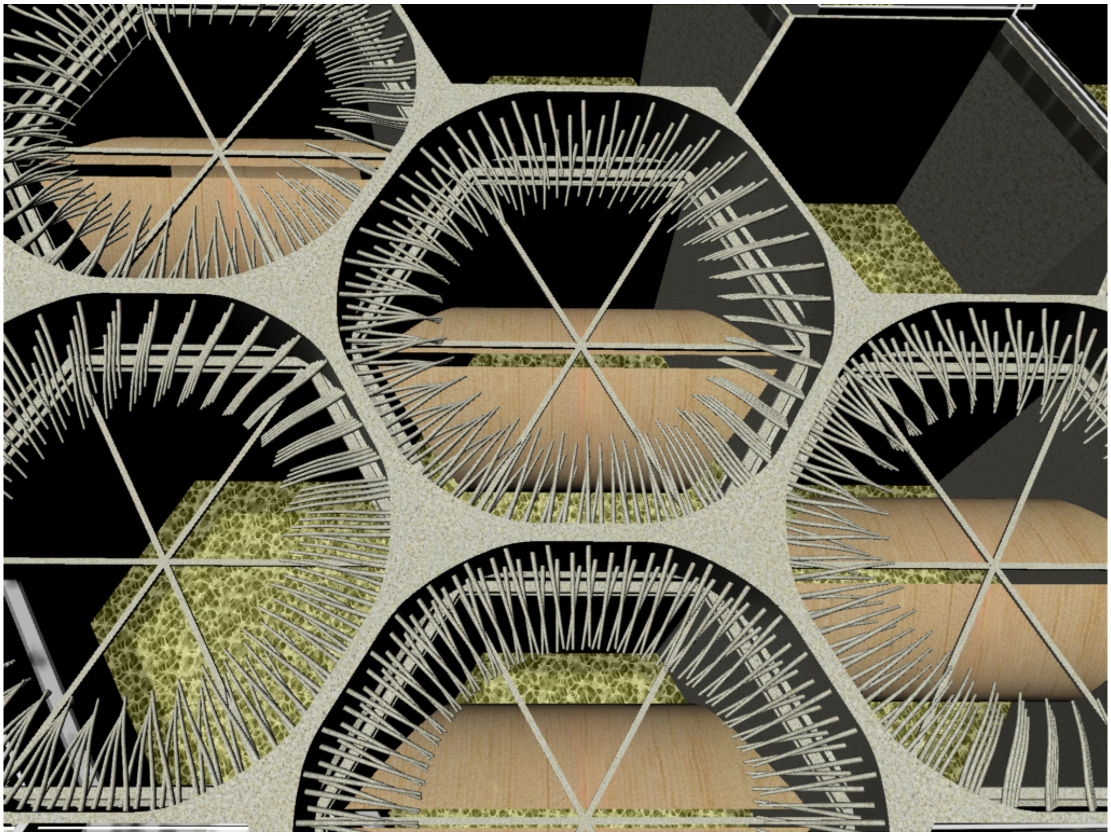




Water irrigation system inside the monobrick.

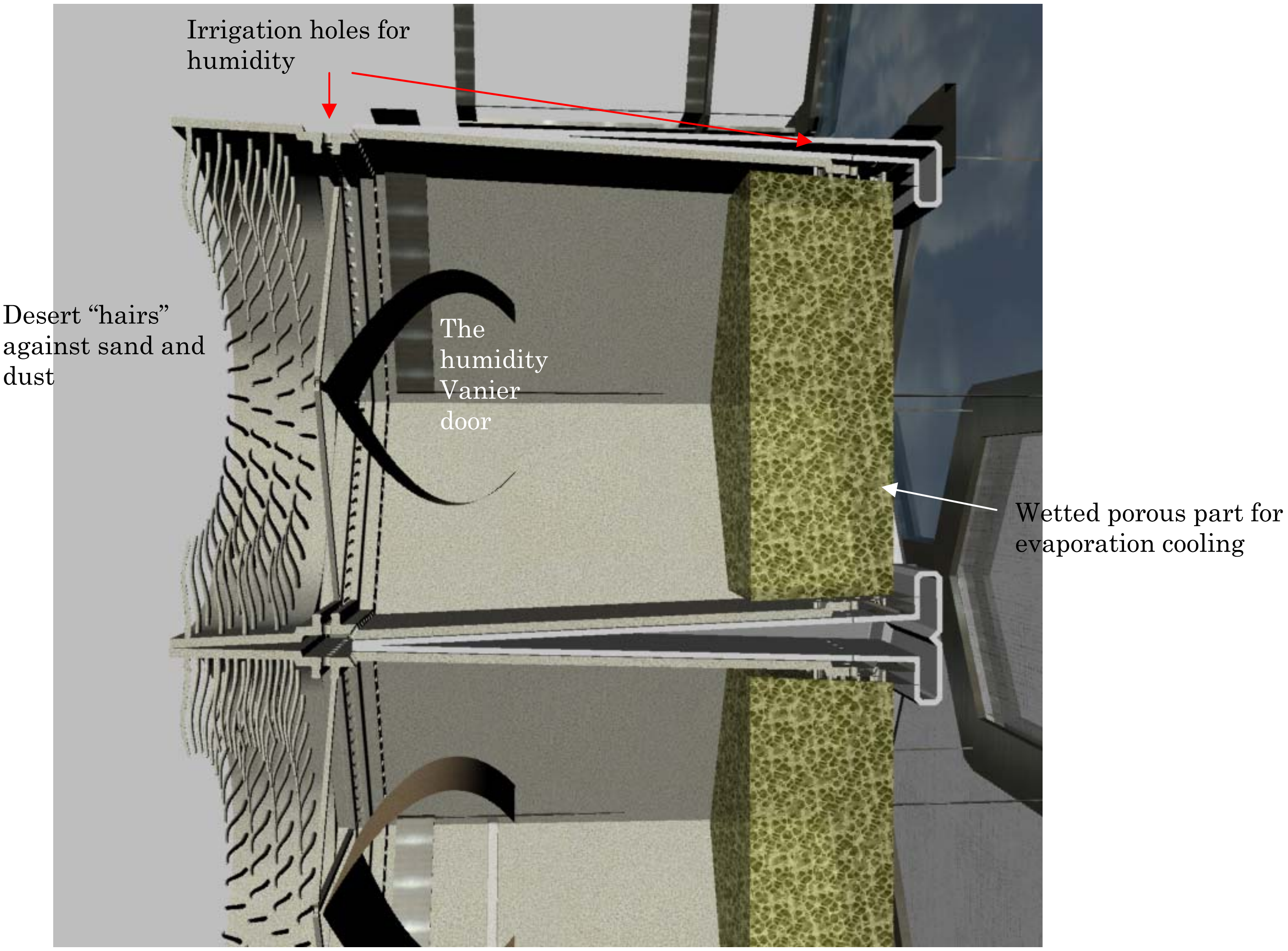




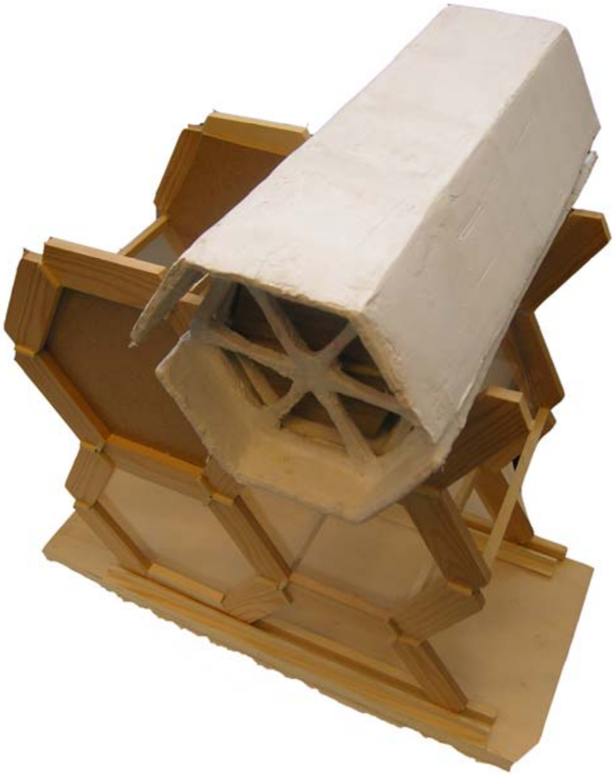


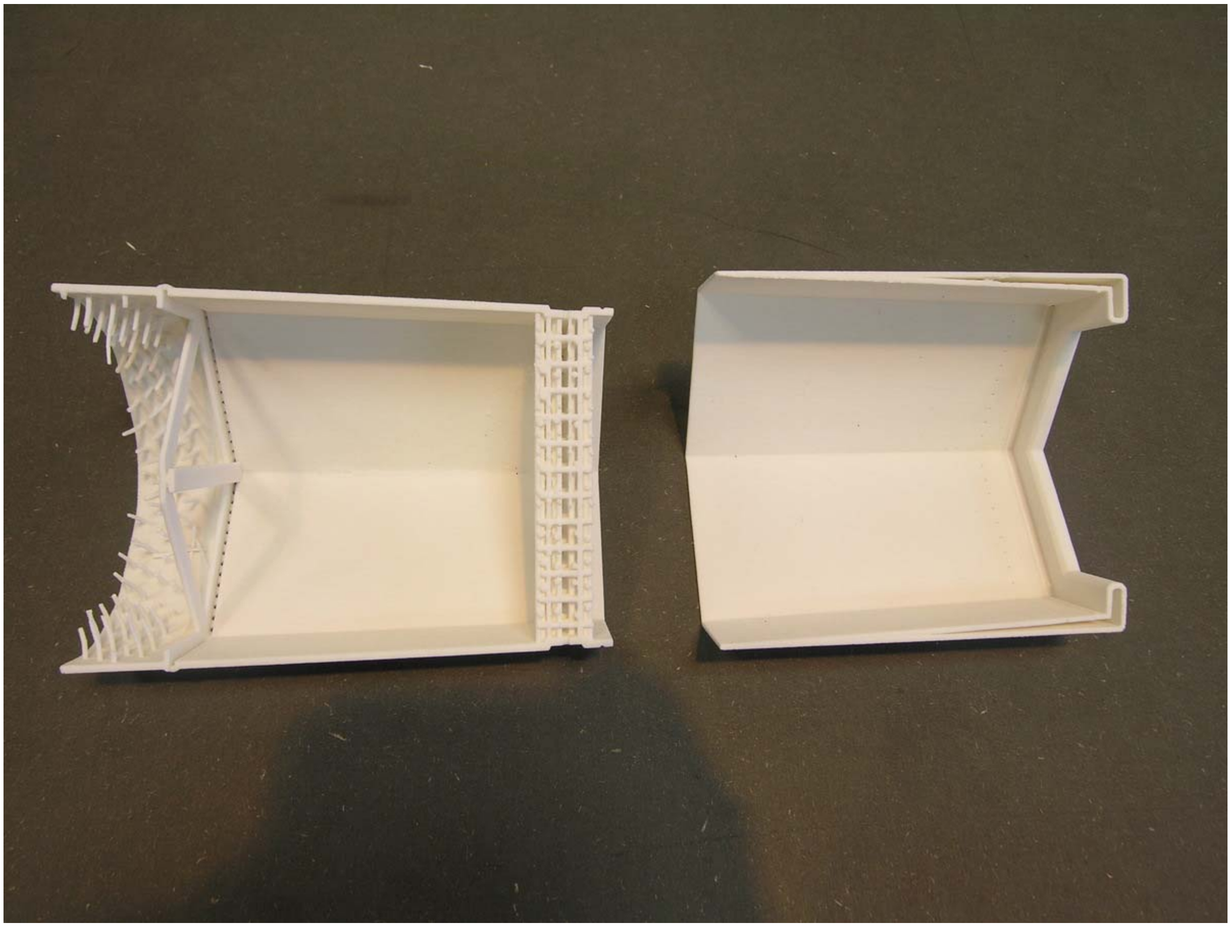
Summery:

The 3d rapid prototype brick has an advantage on direct evaporator systems such as "desert swamp coolers" because of its integrative assembly. The "lego" diversity has many advantages and the amount of cooling needed will influence the overall design. This system is meant to be an envelope for arid dry climates.

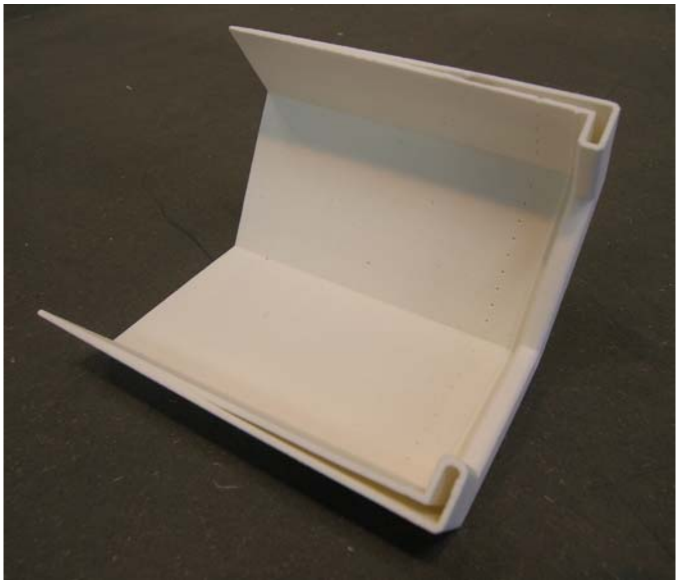


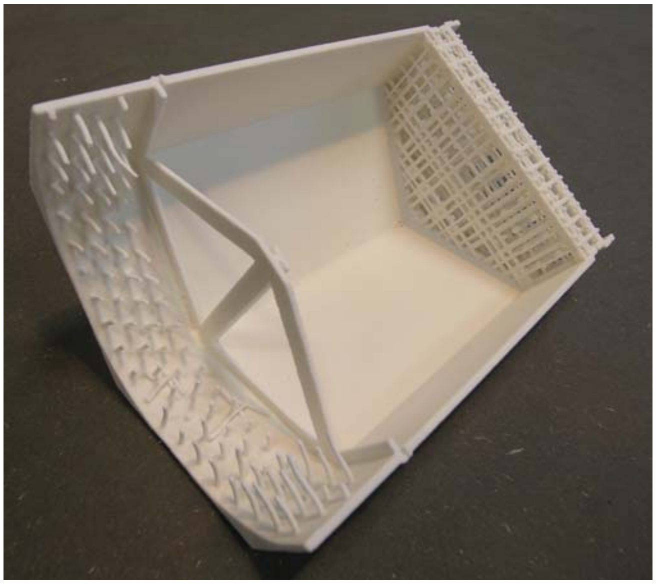
Working models



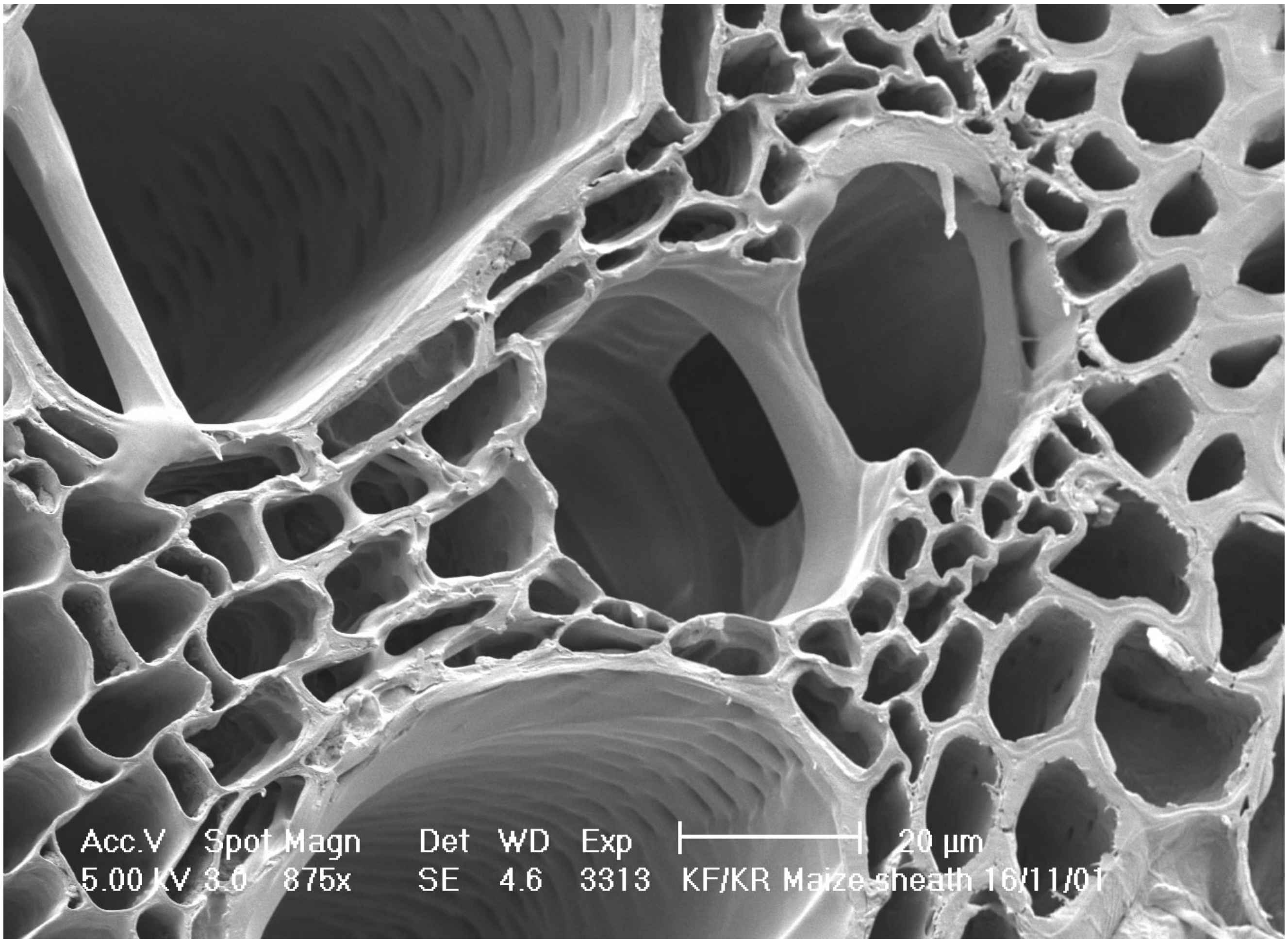


3d print model of a section in brick and monobrick





3.5 Calculations for thermal regulating systems



1- Indirect/direct heat exchanger in a porous clay system
2- Direct cooler –"stoma" brick

Abstract

Two different evaporator coolers are the main focus of this paper the first is an indirect /direct evaporator block made of porous clay. The system should be used in areas were the dry bulb temperature could not be achieved in a semi operating systems.
The second system is a direct evaporator, a 3d printed brick that contains a wetted porous part for evaporative cooling .this direct evaporator cooler should be used in arid regions.
The paper will try to define the potential of such evaporating cooling systems through exploration of different experiments and research that have been conducted in this field.
The paper aims to estimate the cooling performance and thus be a part of a later performed experiment.

Introduction

Evaporative cooling is a physical phenomenon in which evaporation of a liquid, typically into surrounding air, cools an object or a liquid in contact with it. Latent heat describes the amount of heat that is needed to evaporate the liquid; this heat comes from the liquid itself and the surrounding gas and surfaces. When considering water evaporating into air, the wet-bulb temperature, as compared to the air's dry-bulb temperature is a measure of the potential for evaporative cooling. The greater the difference between the two temperatures, the greater the evaporative cooling is.

A simple example of natural evaporative cooling is perspiration, or sweat, which the body secretes in order to cool itself. The amount of heat transfer depends on the evaporation rate, which in turn depends on the humidity of the air and its temperature, which is why one's sweat accumulates more on hot, humid days; the perspiration cannot evaporate.

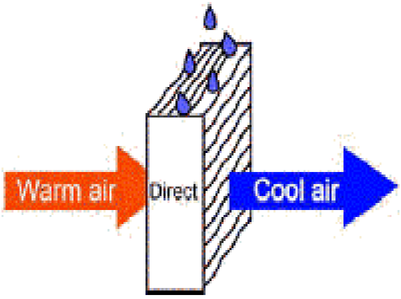
The ancient Egyptians hung wet mats in their doors and windows, and wind blowing through the mats cooled the air—-the first attempt at air conditioning. This basic idea was refined through the centuries: mechanical fans to provide air movement in the 16th century, cooling towers with fans that blew water-cooled air inside factories in the early 19th century, swamp coolers in the 20th century.

Evaporative cooling is a very common form of cooling buildings for thermal comfort since it is relatively cheap and requires less energy than many other forms of cooling. However evaporative cooling requires an abundant water source for evaporation.the next simple examples illustrate direct evaporative cooling. Modern technology has dramatically increased the efficiency and effectiveness of *direct evaporative cooling* and made possible four other types of evaporative cooling: *indirect evaporative cooling*, *indirect/direct evaporative cooling*, *indirect/indirect evaporative cooling*, and *indirect/DX evaporative cooling.*

Direct evaporative cooling

with direct evaporative cooling, outside air is blown through a water-saturated medium (usually cellulose) and cooled by evaporation. The cooled air is circulated by a blower.

Direct evaporative cooling adds moisture to the air stream until the air stream is close to saturation. The dry bulb temperature* is reduced, while the wet bulb temperature** stays the same.



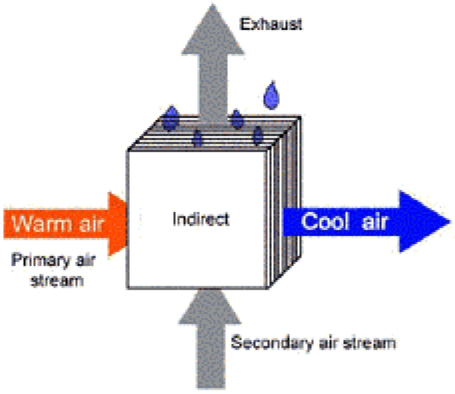
dry bulb: Sensible air temperature (as measured by a thermometer).
***wet bulb*: The lowest air temperature achievable by evaporating water into the air to bring the air to saturation.

Indirect evaporative cooling

with indirect evaporative cooling, a secondary (scavenger) air stream is cooled by water. The cooled secondary air stream goes through a heat exchanger, where it cools the primary air stream. The cooled primary air stream is circulated by a blower.

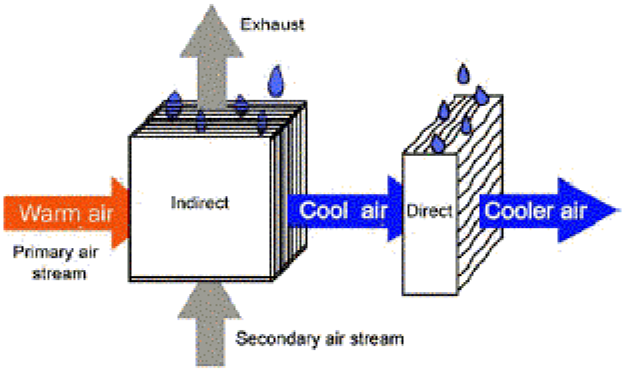
Indirect evaporative cooling does not add moisture to the primary air stream. Both the dry bulb and wet bulb temperatures are reduced.

During the heating season, an indirect system's heat exchanger can preheat outside air if exhaust air is used as the secondary air stream.



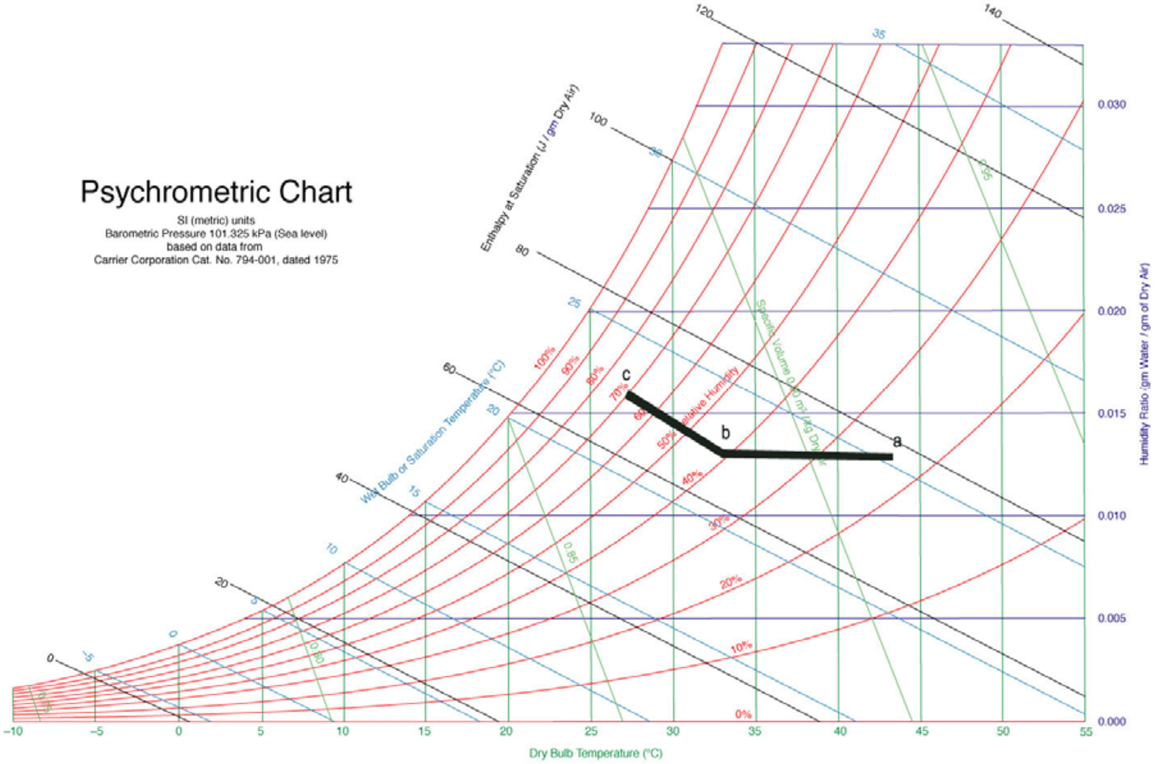
Indirect/direct evaporative cooling

In the first stage of a two-stage cooler, warm air is pre-cooled indirectly without adding humidity (by passing inside a heat exchanger that is cooled by evaporation on the outside). In the direct stage, the pre-cooled air passes through a water-soaked pad and picks up humidity as it cools. Since the air supply is pre-cooled in the first stage, less humidity is needed in the direct stage to reach the desired cooling temperatures



General Performance

Understanding evaporative cooling performance requires an understanding of psychometrics. Evaporative cooling performance is dynamic due to changes in external temperature and humidity level. Under typical operating conditions, an evaporative cooler will nearly always deliver air cooler than 27°Celsius (80°Fahrenheit). A typical residential 'swamp cooler' in good working order should cool air to within 3°C–4°C (6°F–8°F) of the wet-bulb temperature. In practice, it may be difficult to predict the performance from standard weather report information, because weather reports usually contain the dew point and relative humidity, but not the wet bulb temperature.



The air to be cooled at point **a** - sensibly cooled by the indirect evaporate cooling part till point **b** (since the water content of the air does not change line **ab** is parallel to the dry bulb temperature).this then enters the second block part where the result of the direct evaporative cooling reaches point **c**.

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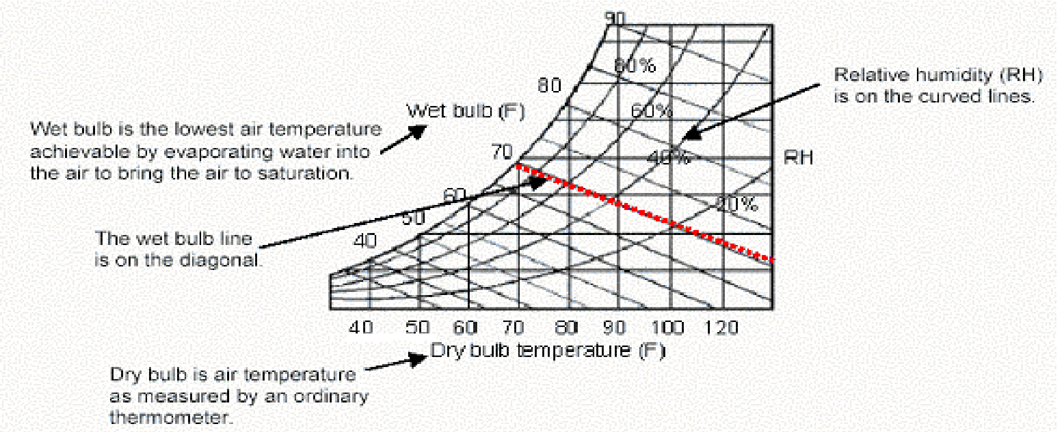


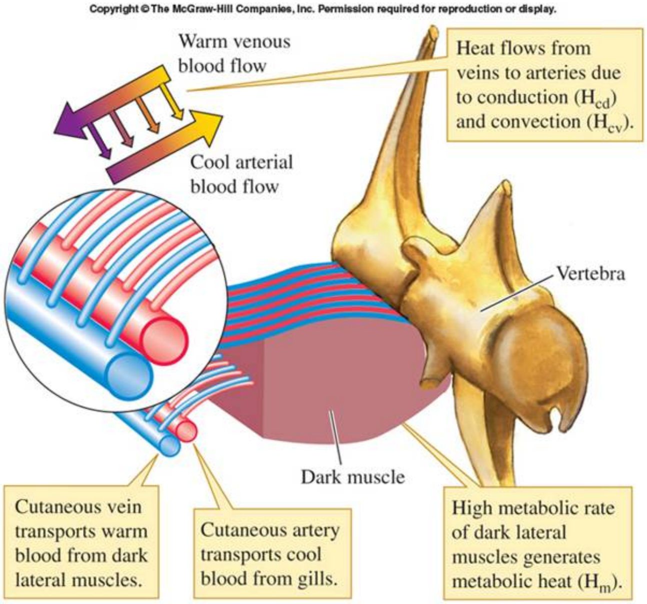
Comparison to air conditioning

Advantages

- **Less expensive to install**
- Estimated cost for installation is 1/8 to 1/2 that of refrigerated air conditioning
- **Less expensive to operate**
- Estimated cost of operation is 1/4 that of refrigerated air.
- Power consumption is limited to the fan and water pump vs. compressors, pumps, and blowers.
- **Ease of Maintenance**
- The only two mechanical parts in most basic evaporative coolers are the fan motor and the water pump, both of which can be repaired for very little and often by a mechanically able homeowner.
- **Ventilation air**
- The constant and high volumetric flow rate of air through the building reduces the **age-of-air** in the building dramatically.
- Evaporative cooling increases humidity, which, in dry climates, may improve the breathability of the air.
- **Health**
- The pad itself acts as a rather effective air filter when properly maintained; it is capable of removing a variety of contaminants in air, including urban ozone caused by pollution, regardless of very dry weather. Refrigeration-based cooling systems lose this ability whenever there is not enough humidity in the air to keep the evaporator wet while providing a constant trickle of condensate that washes out dissolved impurities removed from the air.
- Does not need an air-tight structure for maximum efficiency, so building occupants can open doors and windows.
- Disadvantages
- **Performance**
- High dew point (humidity) conditions decrease the cooling capability of the evaporative cooler.
- No dehumidification. Traditional air conditioners remove moisture from the air, except in very dry locations where recirculation can lead to a buildup of humidity. Evaporative cooling adds moisture, and in dry climates, dryness may improve thermal comfort at higher temperatures.
- **Comfort**
- The air supplied by the evaporative cooler is typically 80–90% relative humidity; very humid air reduces the evaporation rate of moisture from the skin, nose, lungs, and eyes.
- High humidity in air accelerates corrosion, particularly in the presence of dust. This can considerably shorten the life of electronic and other equipment.
- High humidity in air may cause condensation. This can be a problem for some situations (e.g., electrical equipment, computers, paper/books, old wood).
- **Water**
- Evaporative coolers require a constant supply of water to wet the pads.
- Water high in mineral content will leave mineral deposits on the pads and interior of the cooler. Bleed-off and refill (purge pump) systems may reduce this problem.
- The water supply line may need protection against freeze bursting during off-season, winter temperatures. The cooler needs to be drained too, as well as cleaned periodically and the pads replaced.
- **Miscellaneous**
- Asthma patients may need to avoid poorly maintained evaporative coolers.
- A sacrificial anode may be required to prevent excessive evaporative cooler corrosion.

1- Indirect/direct heat exchanger in a porous clay system

This block emerged from a research conducted in the field of bio mimicry. The main aspects of this evaporator were learned from the countercurunt heat exchanger system found in the tuna fish “rete” of the swimming muscles.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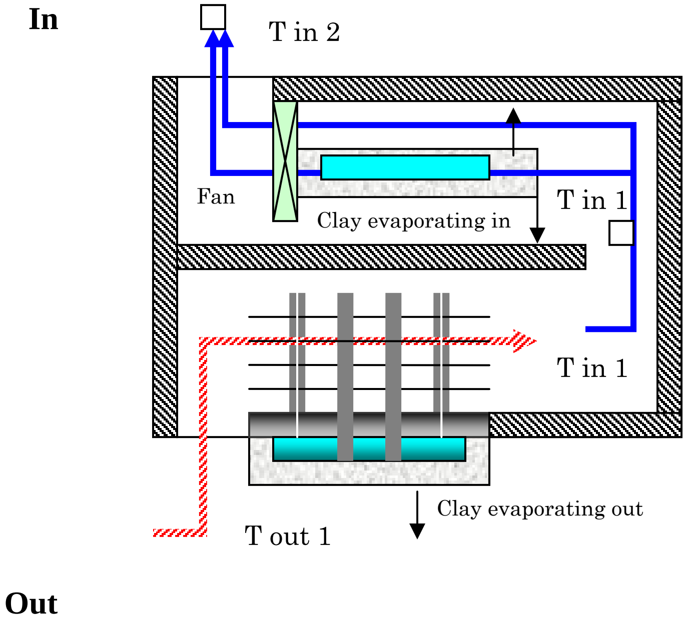
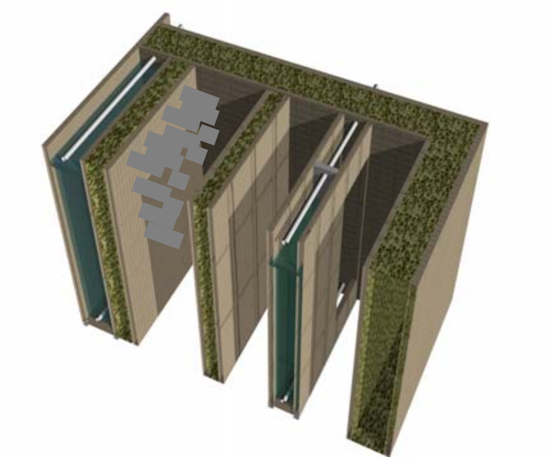
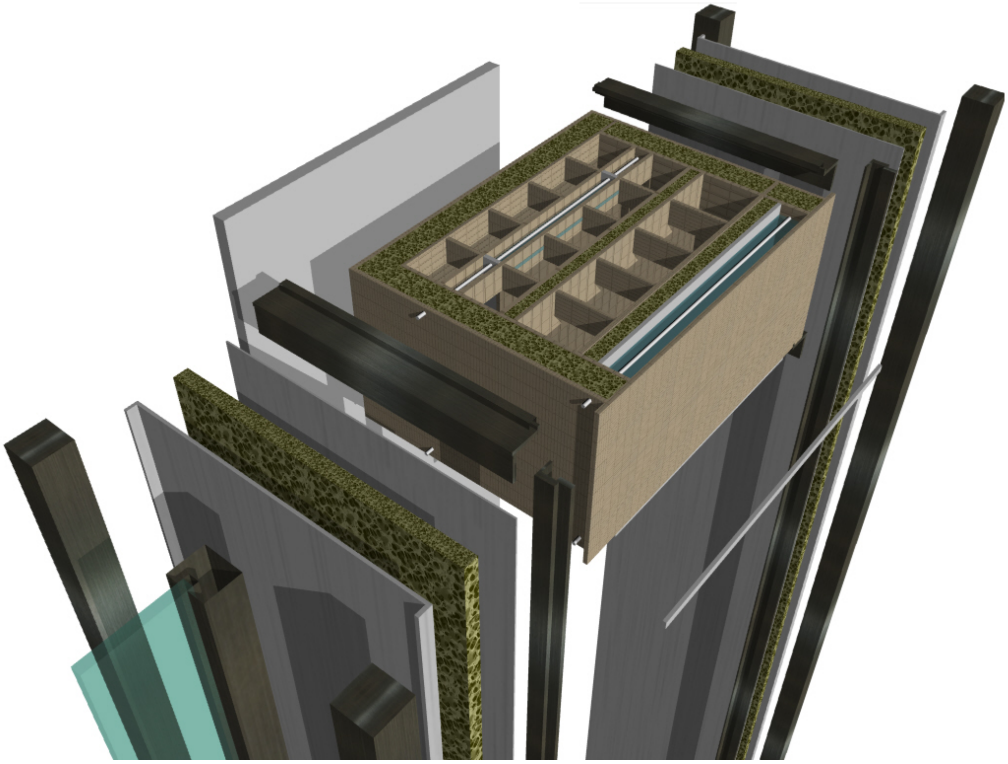
- **Transformation and abstraction from the natural system**:

- **Convection**-Heat exchanges through flows in different directions, depending on the period of year.
- Fluid or gas is pressurized during the different seasons or different times in a day cycle through the tubes.
- Porous material allow sweating
- Indirect-direct evaporator

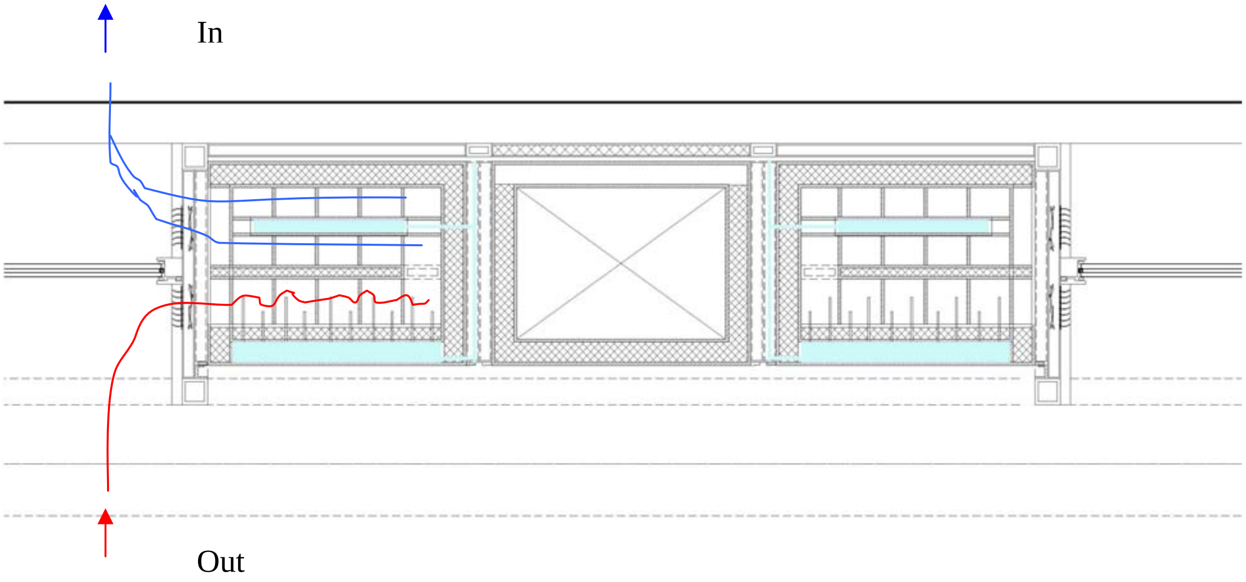
In order to calculate and understand the potential of this complex indirect-direct evaporating cooling system which comprises of two systems connected in a chain configuration. There are many different equations that need to be solved
The first is the heat exchanger build up of heat pipes connected to the clay compartment (where the evaporation is to the outer surroundings)
The second part is the second half of the clay container where water evaporation through the porous clay cools the pre-cooled air before it enters the building. The indirect evaporative cooling process requires no energy input apart from that required for the fan and water pump. The efficiency and the performance of this system are therefore likely to be high.



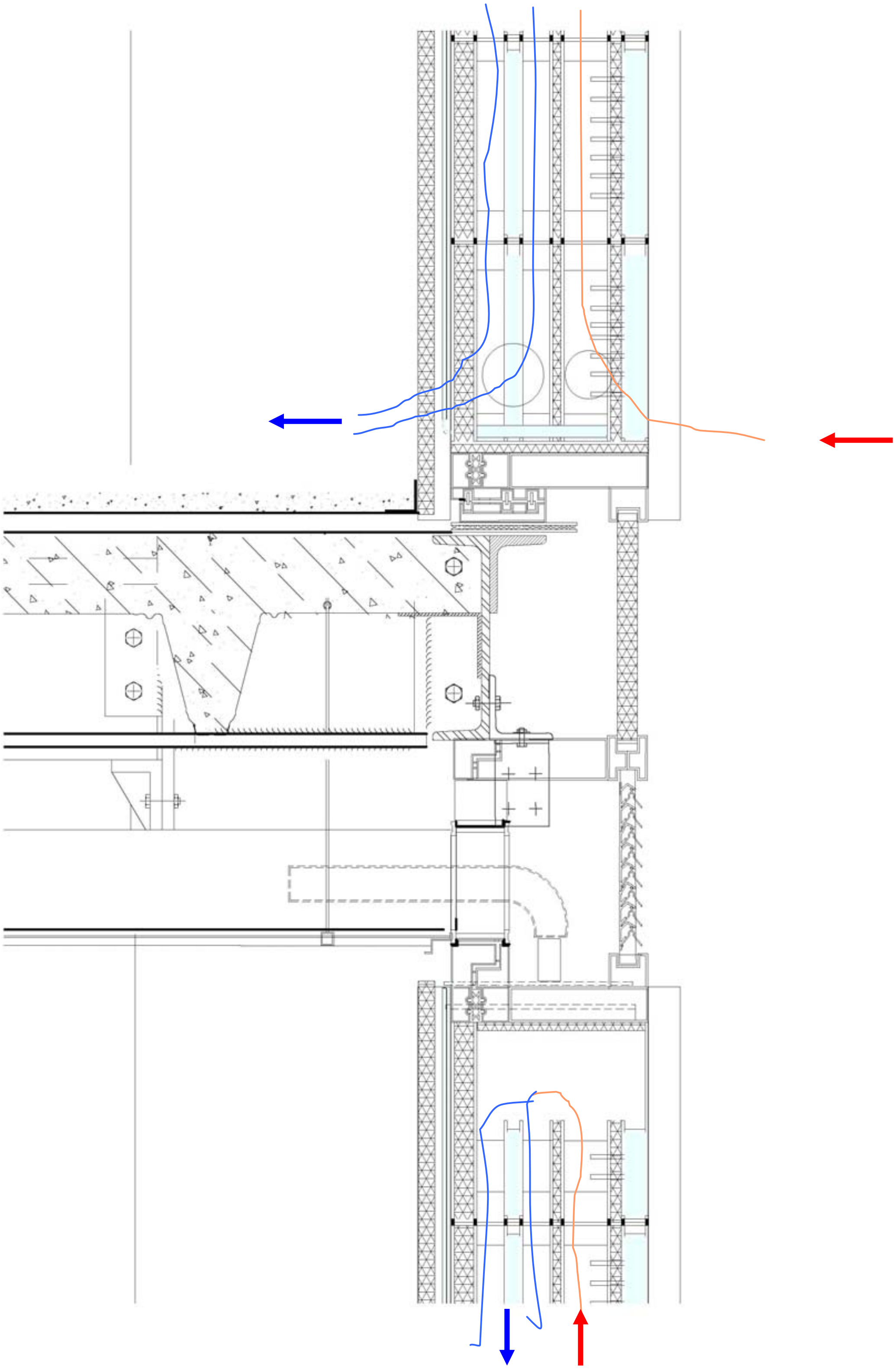




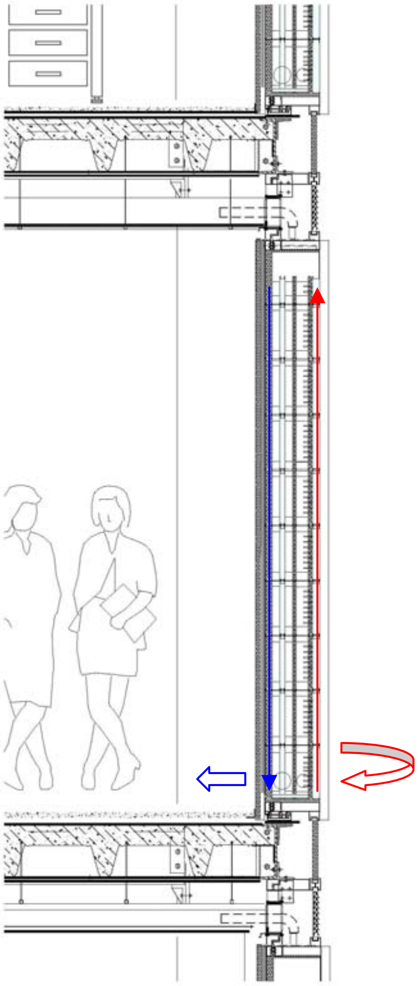
Exploded view- the block and its insulation box

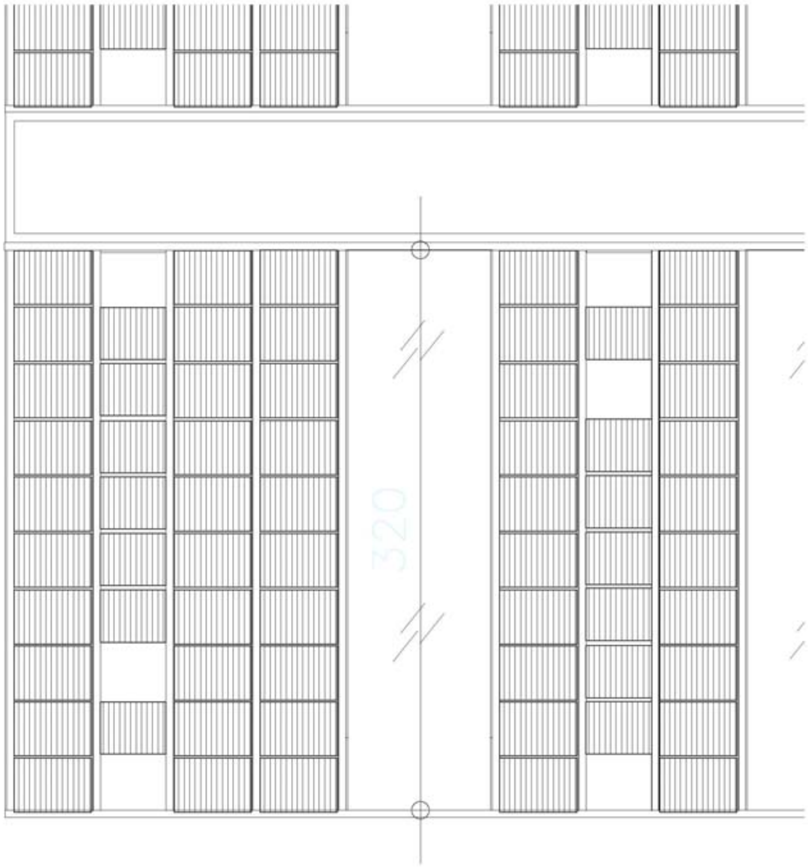


Plan- describing the air movement from outside to inside.



Section- describing the air movement within the block "ducts".





Calculations

The first calculations are for one row of blocks with a surface area of 1.2 m outside and approximation of 3.6m for the inner heat exchange surface-

-assumptions and hypothesis:

-
- Using red terracotta -porous clay –(minimum15 percent porosity.)
- Air passages are thermally isolated
- The top and bottom of the clay container are negligible
- Saturation efficiency of about 70%
- A maximum indoor air velocity up to 1

Region- Asia Jerusalem

Outside temperature is **30.2 °*C*(** *Sources* are from ASHRAE (2001b chapter 27)
Inside humidity ratio- **RH=28%*(*** *Sources* are from ASHRAE (2001b chapter 27)

Material properties:

Material	Thermal conductivity λ W/mK	Density ρ kg/m3	Specific heat capacity c J/kgK
Glass	1.0	2500	750
Water at 25oC	0.6	1000	4181
water vapor	0.0179		1996
Air	0.025	1.23	1008
Carbon dioxide	0.014	1.95	820
ceramic	2	1500	850
Aluminum alloys	160	2800	880
Copper	380	8900	380
Steel	50	7800	450

Some typical heat transfer coefficients include:

- Air - h = 10 to 100 W/(m^2K)
- Water - h = 500 to 10 000 W/(m^2K)

Evaporative heat energy= 2270 k J/kg

The overall heat transfer coefficient can be used to calculate the total heat transfer through a wall or heat exchanger construction. The overall heat transfer coefficient depends on the fluids and their properties on both sides of the wall, and the properties of the wall and the transmission surface.

For practically still fluids - average values for the overall heat transmission coefficient through different combinations of fluids on both sides of the wall and type of wall - can be found in the table below:

Fluid	Transmission Surface	Fluid	Overall Heat Transmission Coefficient	
			(Btu/ft^2 hr ^oF)	*(W/m^2 K)*
Water	Cast Iron	Air or Gas	1.4	7.9
Water	Mild Steel	Air or Gas	2.0	11.3
Water	Copper	Air or Gas	2.3	13.1
Water	Cast Iron	Water	40 - 50	230 - 280
Water	Mild Steel	Water	60 - 70	340 - 400
Water	Copper	Water	60 - 80	340 - 455
Air	Cast Iron	Air	1.0	5.7
Air	Mild Steel	Air	1.4	7.9
Steam	Cast Iron	Air	2.0	11.3
Steam	Mild Steel	Air	2.5	14.2
Steam	Copper	Air	3.0	17
Steam	Cast Iron	Water	160	910

Steam	Mild Steel	Water	185	1050
Steam	Copper	Water	205	1160
Steam	Stainless Steel	Water	120	680

$1\ Btu/ft^2\ hr\ ^oF = 5.678\ W/m^2\ K = 4.882\ kcal/h\ m^2\ ^oC$ - **Unit Converter**

The overall heat transfer coefficient U per unit areain a heat exchanger can be expressed as:

$U = 1 / (1 / h_A + dx_w / k + 1 / h_B)$
(1)

where
U = *the overall heat transfer coefficient* (W/m^2K)
A = *the contact area for each fluid side* (m^2)
k = *the thermal conductivity of the material* (W/mK)
h = *the individual convection heat transfer coefficient for each fluid* (W/m^2K)
dx_w = *the wall thickness* (m)

Decision using U =13$(W/m^2\ K)$ as if the heat tubes are copper heat exchangers that use air to water transmission.

Thermal energy can be stored in a material as sensible heat by raising its temperature.

The heat storage can be calculated as:
$Q = V \rho\ c_p[Tin\text{-}Tout]=mc_p[Tin-Tout]$ (2)
Where
Q = *sensible heat stored in the material* (J)
V = *volume of substance* (m^3)
ρ = *density of substance* (kg/m^3)
m = *mass of substance* (kg)
c_p = *specific heat capacity of the substance* $(J/kg\ ^oC)$
$[Tin - Tout]$= *temperature change* (^oC)

Heat Load:

$Q = c_p\ \rho(air)\ q\ [Tin - Tout]$ (3)

Where
Q = *heat load* (W)
Cp= *specific heat capacity* $(W/m^2\ K)$ = 1008
P=*density* kg/m^3 = $1.2\ kg/m^3$
q = *fresh air flow through the room* (m^3/s) *Then:* $q= nV/3600$
$q=4x65/3600=0.072\ m^3/s$
$[Tin - Tout]$ = *temperature difference* (^oc) = $Tin =30.2$

1.2x1008x0.072x [30.2 − Tout] = Q

The equation for convection can be expressed as:

Q = k A [Tin − T(water)]

(4)

Where

TAP water=*20 ^{o}C,*

Q *= heat transferred per unit time (W)*

A *= heat transfer area of the surface (m^o) 0.4x3=1.2m for outside estimated 3.6 for the heat pipes exchangers*

k *= convective heat transfer coefficient of the process (W/m^{2o}C)* ***switch to U*** =13*(W/m^2 ^{o}C,)*

[Tin − Tout] *= temperature difference between the surface and the bulk fluid (^{o}C)*

13x3.6x (30.2-20) = Q

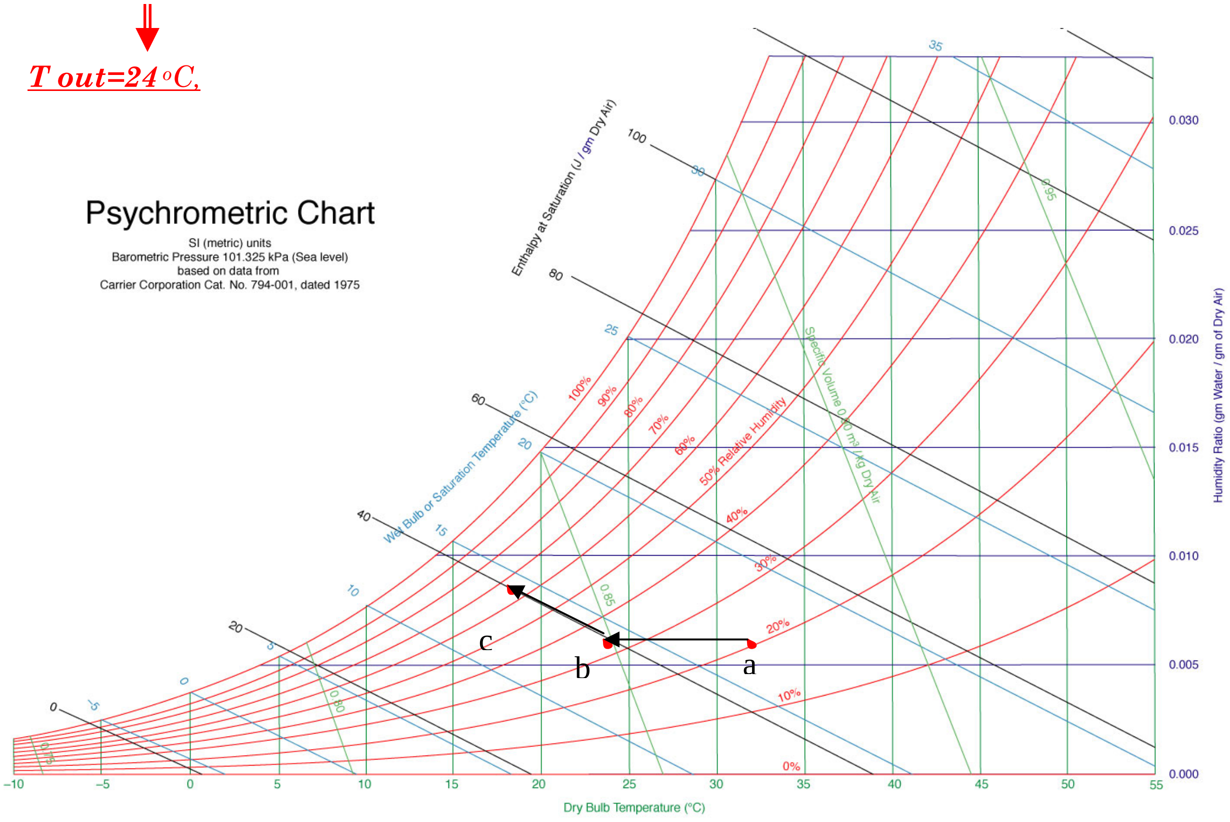
13x3.6x (30.2-20)= 1.2x1008x0.072x [30.2 − T out]

46.8x10.2=87[30.2 − T out]

2153=87 T out

⇓

T out=24 ^{o}C,



Using the psychometric chart

a. **TDB-Jerusalem +30.2** *^{o}C* **RH=28%**

b. **TWB- Jerusalem =24** *^{o}C* **RH =40%**

c. **RH constrained not to exceed 80% the direct part will reach 17** *^{o}C*

Using heat load equation to find the Q- COOLING LOAD after moving through the heat exchange part:

$$Q = c_p \rho \,(air)\, q\, [T_{in} - T_{out}] \qquad (3)$$

Where

Q = *heat load (W)*

C_p= *specific heat capacity (W/m^2 K)* **= 1008**

P=*density kg/m^3* = ***1.2 kg/m^3***

q = *fresh air flow through the room (m^3/s) Then:* **$q = nV/3600$**

$q=4\times65/3600=0.072$ *m^3/s*

[Tin − Tout] = *temperature difference (°c)* = ***Tin =30.2***

$$1.2\times1008\times0.072\times[30.2 - 24] = Q$$

$$\underline{Q = 540\ W}$$

From latent heat:

$$Q = m\,L \qquad (5)$$

$(H\ \ t) = m\,L$; water to gas (evaporation) = 2,270x10^3 J/kg

m / t = *mass flow rate of the product (kg/s)*

$$m/t = 540\ /\ 2{,}270\times10^3$$

$$\underline{m/t = 0.238\times10^{-3}\ kg/s}$$

Flow or Continuous Heating Processes

In heat exchangers the product or fluid flow is continuously heated.

The mean heat transfer rate can be expressed as

$$q = c_p\ [T_{in} - T_{out}]\ m\ /\ t \qquad (6)$$

Where

q = *mean heat transfer rate (kW (kJ/s))*

m / t = *mass flow rate of the product (kg/s)* ***=0.238 x10^{-3}*** *kg/s*

c_p = *specific heat capacity of the product (kJ/kg.°C) - Material Properties and Heat Capacities for several materials* ***water=4181***

[Tin − Tout] = *change in temperature of the fluid (°C) (30.2-20)*

$$q = 4181\times10.2\times0.238\times10^{-3}$$

$$\underline{q = 10.15\ kW}$$

Calculating the Amount of evaporation

If we know the heat transfer rate - the amount of steam can be calculated:

$$m_s = q/\,h_e \qquad (7)$$

where

m_s = *mass of steam (kg/s)*

q = *calculated heat transfer (kW)*

h_e = *evaporation energy of the steam (kJ/kg)*

$m_s = 10.15/2270 = 4.5 \times 10^{-3} (kg/s)$

$4.5 \times 10^{-3} \times 3600 =$

16.2 kg/h

The cooling capacity can be calculated from :

$$Qc = \frac{\rho A(\text{block duct})\, v Cp(\text{air})\, [Tin - Tout]}{A(\text{blocks})}$$

(Elfati Ibrahim ,li shao Saffa B Riffat 2003)

This means the heat transfer rate of the air passage in the container divided by the surface area of the ceramic part that "sweats"

First you need to know the air flow rate inside the block duct. This is influenced by the changing pressures! If un- known the default is 1m/s

$$Qc = \frac{\rho A(\text{block duct})\, v Cp(\text{air})\, [Tin - Tout]}{A(\text{blocks})} \qquad (5)$$

Where

Qc =*cooling capacity (W/m²)*

A =*area (m²)* 0.3x0.2=0.06

P=*density kg/m³* = **1.2 kg/m³**

Cp= *specific heat capacity (W/m² K)* =**1008**

E= *vapour pressure (N/m²)*

T= *temperature (K)*

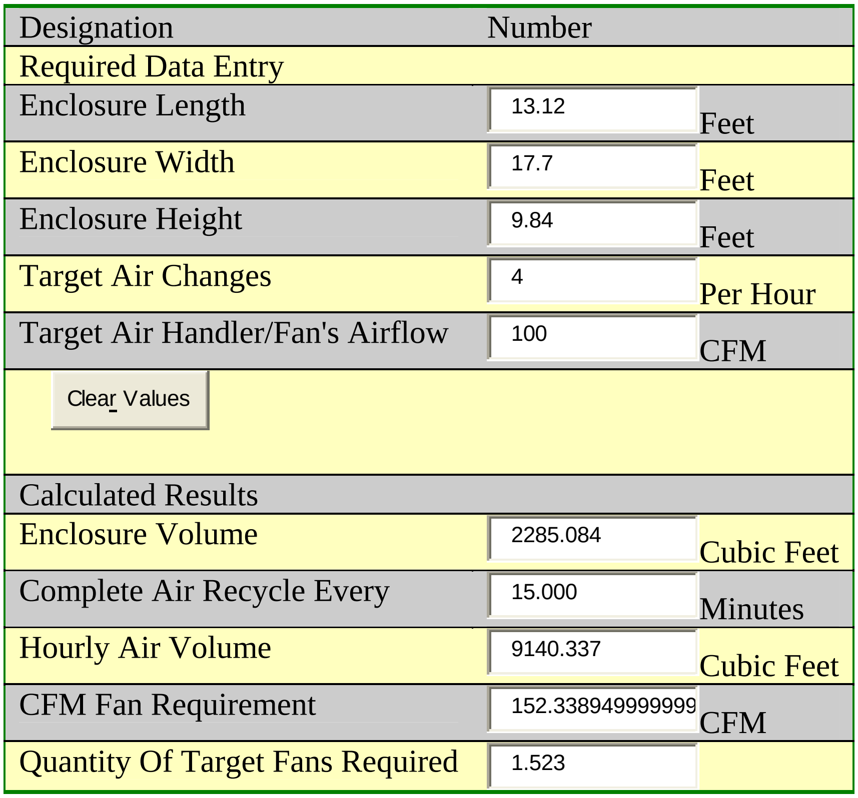
v=*air velocity (m/s)* 1m/s

Area of blocks each block has 2 sides of (0.4m x3 m=1.2 m²) for 4 rows =4.8 m²

$$\boxed{\frac{1.2 \times 0.06 \times 1 \times 1008 \times 13.2}{4.8} = 199\ W/m^2}$$

Energy Efficiency Ratio - *EER*

The Energy Efficiency Ratio - *EER* - is a term generally used to define cooling efficiencies of unitary air-conditioning and heat pump systems.
The efficiency is determined at a single rated condition specified by an appropriate equipment standard and is defined as the ratio of net cooling capacity - or heat removed in *Btu/h* - to the total input rate of electric energy applied - in *watt hour*. The units of *EER* are *Btu/Wh*.



Designation	Number	
Required Data Entry		
Enclosure Length	13.12	Feet
Enclosure Width	17.7	Feet
Enclosure Height	9.84	Feet
Target Air Changes	4	Per Hour
Target Air Handler/Fan's Airflow	100	CFM
Clear Values		
Calculated Results		
Enclosure Volume	2285.084	Cubic Feet
Complete Air Recycle Every	15.000	Minutes
Hourly Air Volume	9140.337	Cubic Feet
CFM Fan Requirement	152.338949999999	CFM
Quantity Of Target Fans Required	1.523	

$$EER = E_c / P_a$$

(7)

Where

EER = *energy efficient ratio (Btu/Wh)*
E_c = *net cooling capacity (Btu/h)*
P_a = *applied energy (Watts)*

Heat Load for one row of blocks

$$Q = c_p \rho \text{ (air) } q\ [Tin - Tout]$$

(3)

Where

Q = *heat load (W)*
Cp= *specific heat capacity* ($W/m^2 K$) = **1008**

P**=density kg/m^3 =* ***1.2 kg/m^3
q** = fresh air flow through the room (m^3/s) Then:* ***q= nV/3600
***q=4x65/3600=0.072** m^3/s*
[Tin − Tout]** = temperature difference (°c) =* ***Tin =30.2

1.2x1008x0.072x [30.2 − 24] = Q ***Q= 540 W***

1 watt is approximately 3.413 BTU/h.

540 x3.413=
1843 BTU/h

Applied fans and water pumps need about 40 w(2 small silent fans that totally give 150 cfm)
EER = E_c / P_a

For one row of blocks there are 4 of these in one office

$$\frac{1843}{40} = 46 \text{ Btu/Wh}$$

- Higher than 10 *EER* - = efficient system

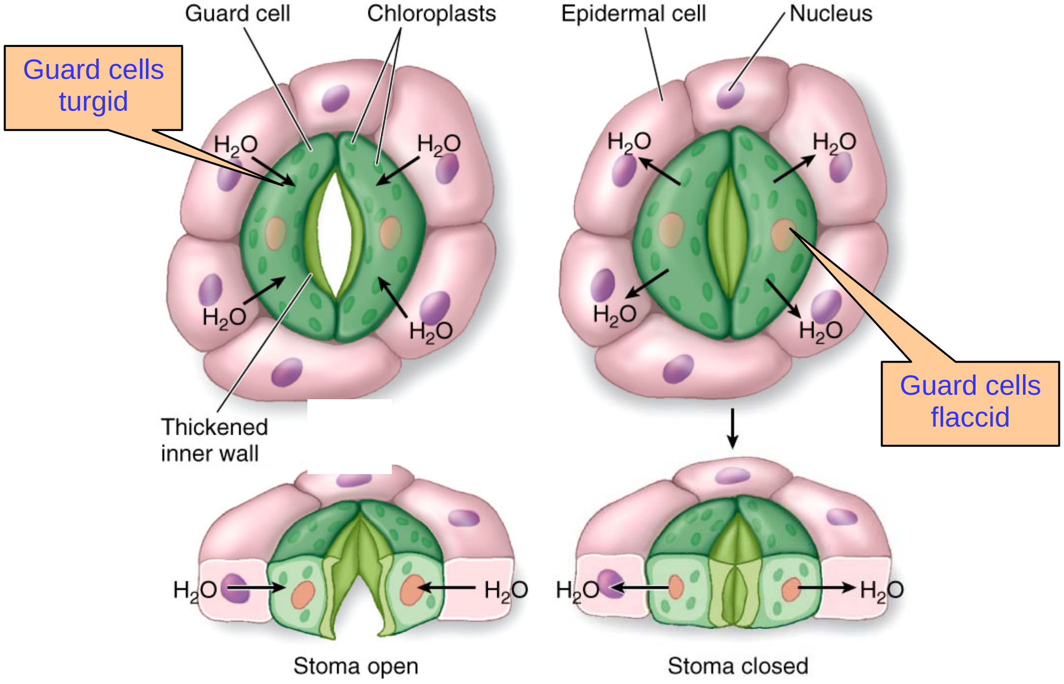
Energy performance:

Based on different mechanical investigations the calculations and from literature review several main assumptions can be made:

- A combination of an indirect direct cooling produces final temperatures raging from 0.3K below the ambient TWB (for an ambient RH of 80%) to 2.6 K below TWB(for an ambient RH of 9%)but produces a final RH generally grater than 90% which is unacceptably high.
- If the direct step is restricted not to exceed 80%, temperatures do not exceed 25C.and the effectiveness is as high as 116.
- In humid climates a better approach is to enhance the evaporative cooling capacity by using liquid desiccants. This together with restricted humidity can provide comfortable conditions all the time anywhere.
- The evaporative cooling systems need big amounts of water which are usually expensive especially in arid climates nevertheless in most of the world evaporative cooling is used to cool steam turbines that produce electricity. Electricity that could be minimized in these cooling systems.
- The efficiencies of a combined evaporative cooler saves a lot of yearly energy use (up to 95 %in a modular house or classroom in semi arid regions.
- Less operating costs
- Less polluting
- High indoor air quality

2- Direct cooler –"stoma" brick

This block emerged from a research conducted in the field of bio mimicry. The main aspects of this evaporator were learned from the "stoma" guard cells in plants .



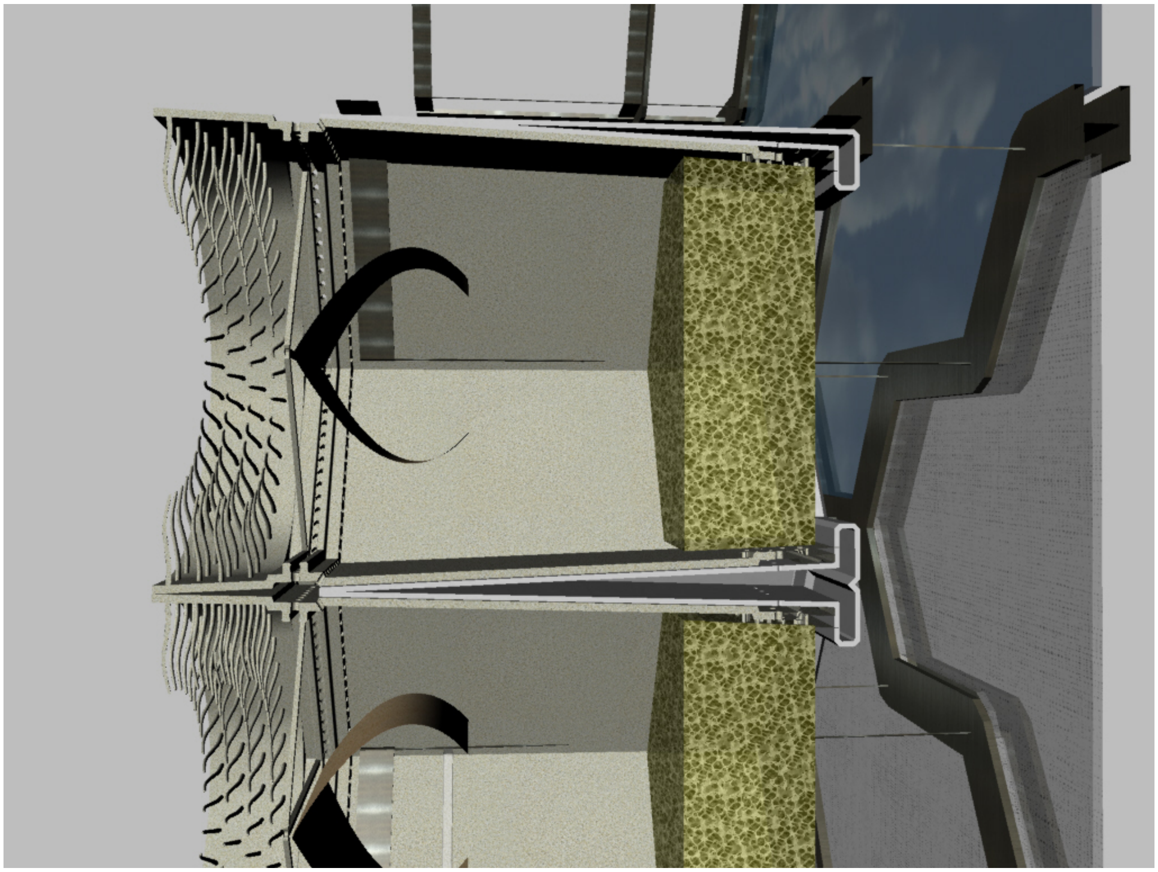
- **Transformation and abstraction from the natural system**:

- Open-close cells
- Cooling through evaporation.
- Wet "sponge" cool air circulated through it
- **Evaporation-**Heat exchanges through a net of Opening/closing diaphragm.
- Passive direct cooling with water irrigation system
- Material-a 3d print of a porous sponge.
- Hairs block dust/sand in arid regions

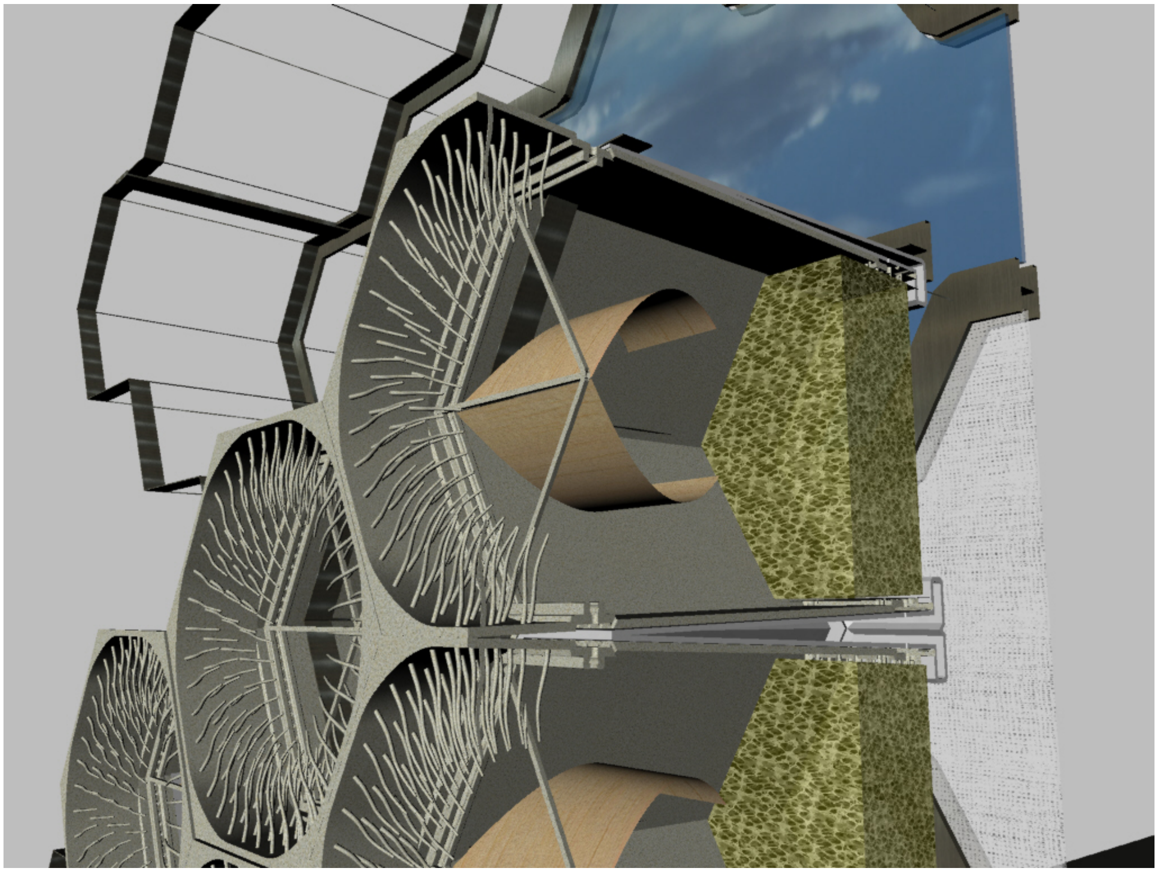
Direct evaporative cooling

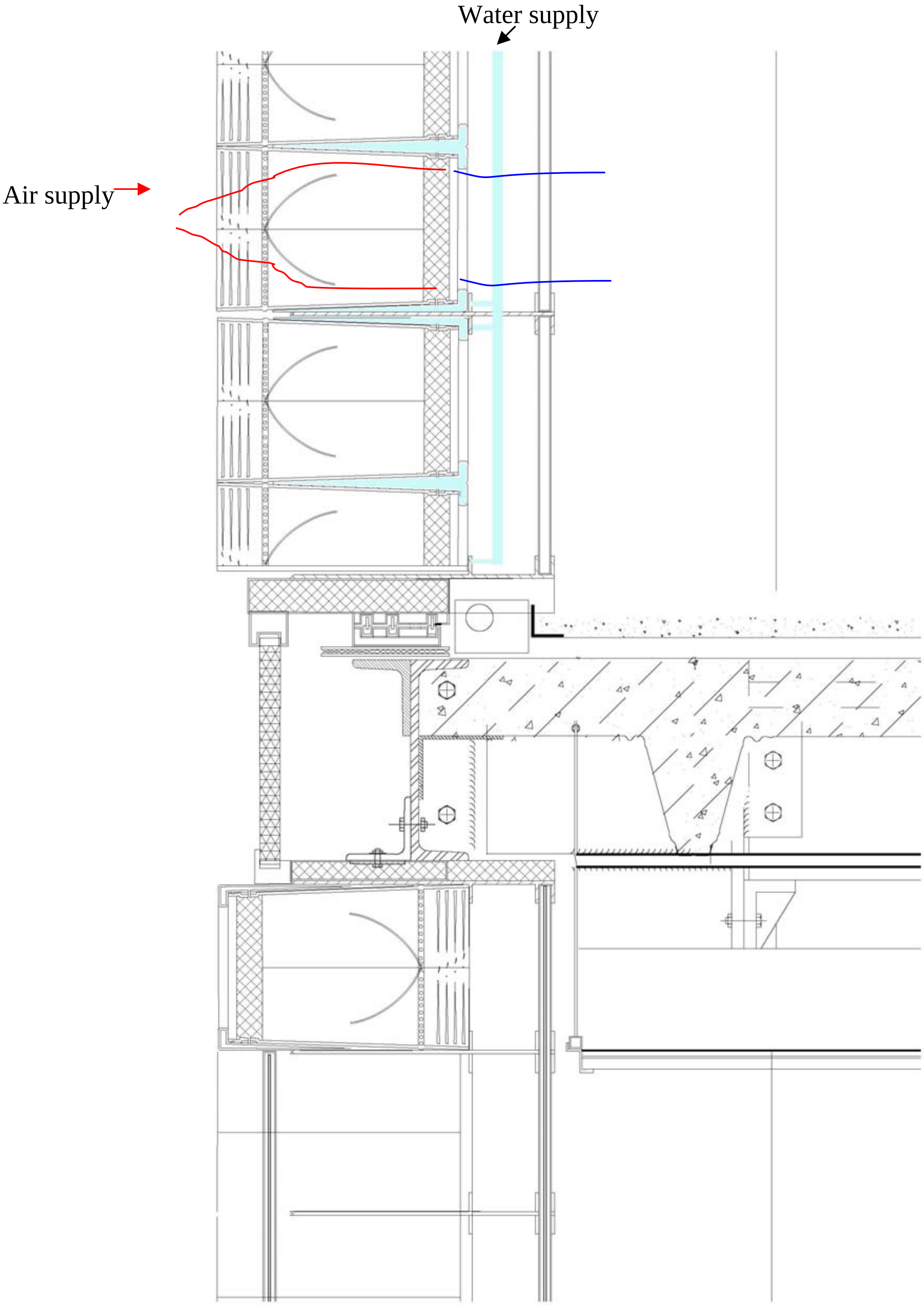
with direct evaporative cooling, outside air is blown through a water-saturated medium (usually cellulose) and cooled by evaporation.

Direct evaporative cooling adds moisture to the air stream until the air stream is close to saturation. The dry bulb temperature* is reduced, while the wet bulb temperature** stays the same.



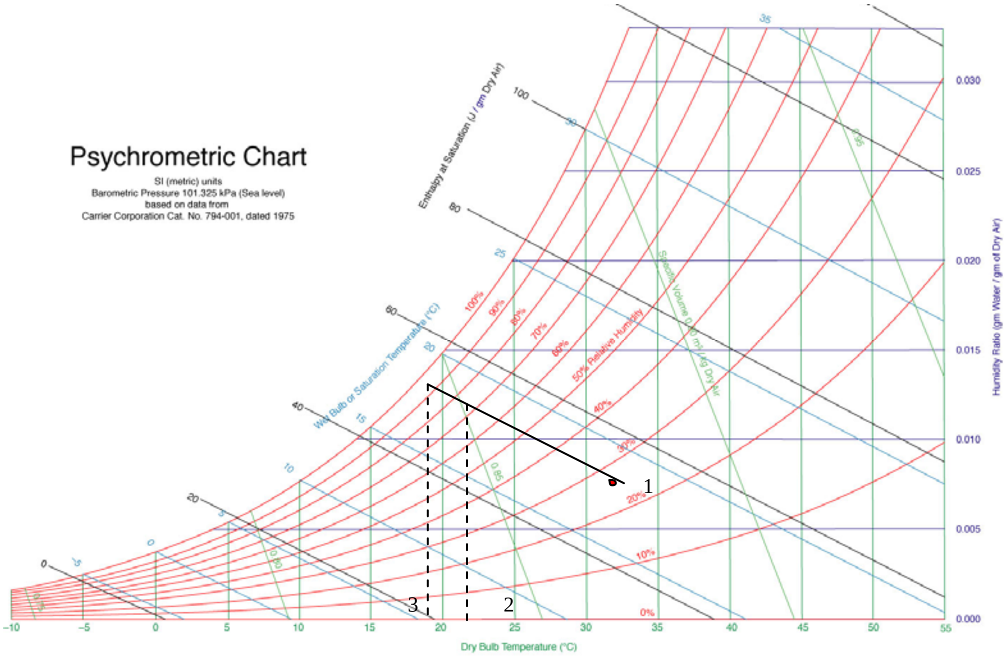
3d sections with the porous wetted part (in green)





Section- describing the air/ water movements within the brick.

Calculations



Region- Asia Jerusalem

Outside temperature is **30.2 ᵒC(** *Sources* are from ASHRAE (2001b chapter 27)
Inside humidity ratio- **RH=28%(** *Sources* are from ASHRAE (2001b chapter 27)

Using the psychometric chart

1. **TDB-Jerusalem +30.2 ᵒC RH=28%**
2. **when RHconstrained not to exceed 75% t final=22 ᵒC**
3. **RH not constrained t final=19 ᵒC**

Energy performance:

- Efficient in dry arid climate
- a direct cooling can produce a final RH generally grater than 90% which is unacceptably high.
- If the direct step is restricted not to exceed 80%, temperatures Under typical operating conditions, will nearly always deliver air cooler than 27°Celsius (80°Fahrenheit). A typical residential 'swamp cooler' in good working order should cool air to within 3°C–4°C (6°F–8°F) of the wet-bulb temperature.
- The evaporative cooling systems need big amounts of water 4-6 litters an hour which are usually expensive especially in arid climates nevertheless in most of the world evaporative cooling is used to cool steam turbines that produce electricity. Electricity that could be minimized in these cooling systems.
- The efficiencies of a direct evaporative cooler saves a lot of yearly energy use (up to 70 %in a modular house or classroom in semi arid regions.
- Less operating costs
- Less polluting
- High indoor air quality

Appendix 1- Evaporative cooling in different climates

As explained in this paper evaporation of water can cool air in contact with it down to the wet bulb temperature. The WB temperature depends on the absolute humidity and the DB temperature of the air. TDB x TWB is always less than TDB (unless the air is saturated in which the two are equal).the difference in TWB and TDB is grater the lower the absolute humidity is!

There are temperate regions and climates that have a lower absolute humidity (because of their lower initial TDB).In these places, although the cooling effect is less than in dry arid regions, a lower final temperature can be achieved through evaporation.

The following tables compare different cities in several climatic zones in an extreme ambient condition, In order to evaluate the potential for a direct-indirect evaporative façade.

Table 1 dry bulb temperature exceeded 1% of the time, average wet bulb corresponding to these conditions, and the corresponding relative humidity. Also given are the temperature and RH that would be achieved by a direct, indirect and a combined evaporative cooler with an effectiveness of o.85 and 0.65 and a combined effectiveness respectively. The final temperature and the overall effectiveness (EF) are given with an RH that is once not constrained and the second time constrained not to exceed 80% humidity.

location	Ambient conditions			Direct cooling		Indirect cooling		Indirect+direct evaporator			
								Free RH		RH< 80%	
	Tdb	Twb	RH	Tf	RH	Tf	RH	Tf	RH	Tf	EF
Canada Toronto	28.7	20.9	49	22.1	90	23.6	67	20	94	21.7	89
USA Miami	32.2	25.1	56	26.2	91	27.6	73	24.5	95	26.6	78
USA Las Vegas	40.9	18.6	8	21.9	73	26.4	19	15.4	80	15.6	113
USA New York	31.5	22.8	47	24.1	89	25.8	66	21.9	94	23.7	89
Latin America Mexico city	27.9	13.7	16	15.8	79	18.7	29	11.2	85	11.7	113
Latin America Buenos Aires	32.1	22.3	42	23.8	88	25.7	62	21.2	93	22.9	94
Europe Athens	33	20.1	29	22	84	24.6	48	18.5	90	19.7	103
Europe Paris	28	19.4	44	20.7	88	22.4	62	18.3	93	19.8	94
Europe Berlin	27.91	18.1	38	19.6	87	21.5	55	16.8	91	18.1	100
Africa Cairo	36.2	20.5	23	22.9	81	26	41	18.5	87	19.5	106
Africa Harare	29.1	16.3	25	18.2	82	20.8	41	14.3	88	15.2	108
Asia Tokyo	31.2	25.1	61	26	92	27.2	77	24.5	96	26.8	72
Asia Beijing	32.9	21.8	37	23.5	86	25.7	57	20.5	92	22	97
Asia Jerusalem	30.2	17.7	28	19.6	83	22.1	45	15.9	89	16.9	106
Australia Sydney	29.4	19.7	40	21.2	87	23.1	58	18.5	92	19.9	97

Table 2 wet bulb temperature exceeded 1% of the time, average dry bulb corresponding to these conditions, and the corresponding relative humidity. Also given are the temperature and RH that would be achieved by a direct, indirect and a combined evaporative cooler with an effectiveness of o.85 and 0.65 and a combined effectiveness respectively.
The final temperature and the overall effectiveness (EF) are given with an RH that is once not constrained and the second time constrained not to exceed 80% humidity.

location	Ambient conditions			Direct cooling		Indirect cooling		Indirect+direct evaporator			
								Free RH		RH< 80%	
	Twb	Tdb	RH	Tf	RH	Tf	RH	Tf	RH	Tf	EF
Canada Toronto	22.2	26.9	66	22.9	94	23.8	80	21.7	96	23.9	64
USA Miami	26.1	30.3	71	26.7	95	27.6	84	25.7	97	28.3	48
USA Las Vegas	21.22	30.4	44	22.6	88	24.4	62	20.1	93	21.8	93
USA New York	24.2	29.3	65	25	93	26	80	23.7	96	26	64
Latin America Mexico city	16.1	23	49	17.1	90	18.5	64	15.1	93	16.5	93
Latin America Buenos Aires	23.8	28.9	65	24.6	93	25.6	79	23.3	96	25.5	65
Europe Athens	22.9	29.2	58	23.8	92	25.1	74	22.2	95	24.3	77
Europe Paris	20.3	25.9	60	21.1	92	22.3	75	19.6	95	21.6	77
Europe Berlin	19.2	25.9	53	20.2	91	21.5	69	18.3	94	20.1	86
Africa Cairo	23.6	30.4	56	24.6	91	26	73	22.9	95	25	79
Africa Harare	19.6	24.2	65	20.3	93	21.2	78	19	96	21	69
Asia Tokyo	26.1	30.1	73	26.7	95	27.5	84	25.8	97	28.3	44
Asia Beijing	25.4	29	75	25.9	95	26.7	86	25.1	97	27.6	38
Asia Jerusalem	20.5	26.3	59	21.4	92	22.5	74	19.8	95	21.7	78
Australia Sydney	22.3	26.2	71	22.9	95	23.7	83	21.9	97	24.2	52

The following tables (*taken from a handbook on low energy buildings and district –energy systems L.D.Danny H arvey2006) Sources* are from ASHRAE (2001b chapter 27)

BOX 6.2 Determination of the output of direct, indirect, and indirect–direct evaporative coolers

The outputs of direct and indirect evaporative coolers given in Tables 6.7 and 6.8 were computed from the equations given below, using the ambient drybulb temperature (T_{db}) and wet-bulb temperature (T_{wb}) given in these tables as inputs. All equations are taken from ASHRAE (2001b, Chapter 6), except where indicated otherwise.

Given T_{db} and T_{wb}, the saturation vapour pressures $e_s(T_{db})$ and $e_s(T_{wb})$ in Pa are computed using:

$$\ln e_s(T) = C_1/T + C_2 + C_3T + C_4T^2 + C_5T^3 + C_6 \ln T \tag{B6.2.1}$$

where $C_1 = -5.8002206 \times 10^3$, $C_2 = 1.3914993$, $C_3 = -4.8640239 \times 10^{-2}$, $C_4 = 4.1764768 \times 10^{-5}$, $C_5 = -1.4452093 \times 10^{-8}$, $C_6 = 6.5459673$. Next, the saturation humidity mixing ratios $W_s(T_{dp})$ and $W_s(T_{wb})$ (kg water vapour/kg dry air) are computed using:

$$W_s(T) = 0.62198 \frac{e_s(T)}{P_a - e_s(T)} \tag{B6.2.2}$$

where P_a is the atmospheric pressure (taken to be 101350Pa). The mixing ratio W, degree of saturation μ, and relative humidity RH are computed from:

$$W(T) = \frac{(2501 - 2.381T_{wb})W_s(T_{wb}) - 1.006(T - T_{wb})}{2501 + 1.805T - 4.186T_{wb}} \tag{B6.2.3}$$

$$\mu = \frac{W(T_{db})}{W_s(T_{db})} \tag{B6.2.4}$$

and

$$RH = \frac{\mu}{1 - (1 - \mu)e_s(T_{db})/P_a} \tag{B6.2.5}$$

respectively (temperature inputs to Equation (B6.2.3) are in °C).

During direct evaporation cooling, the air parcel follows a path along a line joining the points (T_{db}, $W(T_{db})$) and (T_{wb}, $W(T_{wb})$) on the psychrometic chart. The proportion of the distance between the points that is travelled is equal to the effectiveness of direct evaporative cooling, η_{dir}.

Thus, the final temperature and mixing ratio are given by:

$$T_f = T_{db} - \eta_{dir}(T_{db} - T_{wb}) \tag{B6.2.6}$$

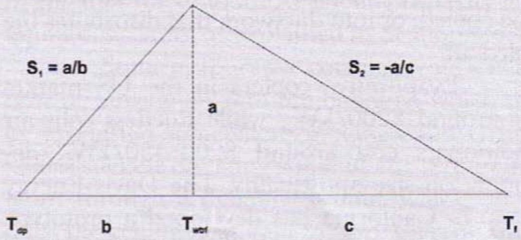
and

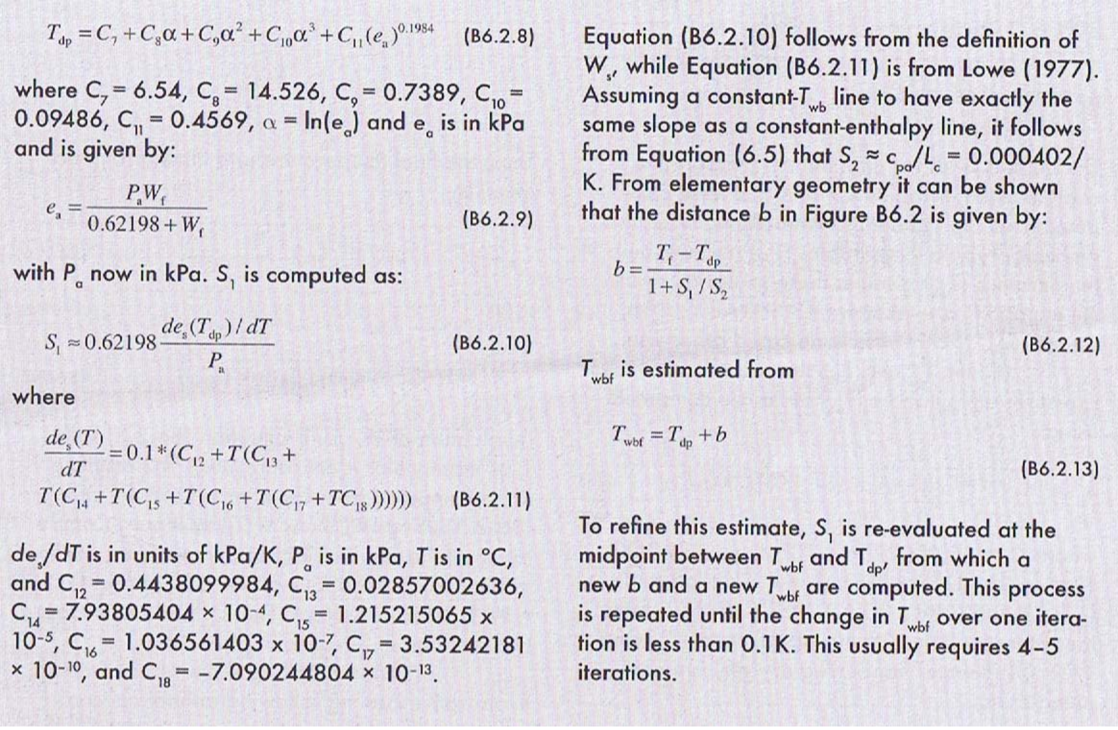
$$W_f = W(T_{db}) - \eta_{dir}(W(T_{db}) - W(T_{wb})) \tag{B6.2.7}$$

(evaluation of W_f using Equation (B6.2.3) with T_f as input yields identical results). The resulting RH is computed from Equations (B6.2.4), and (B6.2.5) using $W(T_f)$ and $e_s(T_f)$ as inputs. Computation of the result of indirect evaporation cooling is identical to the above procedure, except that $W_f = W(T_{db})$ and the effectiveness of indirect evaporation cooling, η_{ind}, is used in place of η_{dir}.

In order to calculate the result of direct evaporative cooling following an indirect cooling stage, T_{wb} of the airstream emerging from the indirect evaporative stage (T_{wbf}) must be known and used in place of the original T_{wb} (along with T_f from the indirect stage in place of the original T_{db}) in the algorithm given above for direct evaporative cooling. T_{wbf} can be estimated as the temperature at the intersection of the lines formed by the slope of W_s versus T evaluated at the dewpoint temperature (T_{dp}) and the constant-T_{wf} line passing through T_f (this makes use of the fact that T_{wb} lies at the intersection of the constant-T_{wf} line and the W_s curve, as seen from Figure 6.3). These are the lines with slope magnitudes S_1 and S_2 in Figure B6.2. T_{dp} (°C) is computed from:

Figure B6.2 Finding the wet-bulb temperature (T_{wbf}), given the final drybulb temperature (T_f) and the dewpoint temperature (T_{dp}).





$$T_{\mathrm{dp}} = C_7 + C_8\alpha + C_9\alpha^2 + C_{10}\alpha^3 + C_{11}(e_{\mathrm{a}})^{0.1984} \qquad \text{(B6.2.8)}$$

where C_7 = 6.54, C_8 = 14.526, C_9 = 0.7389, C_{10} = 0.09486, C_{11} = 0.4569, $\alpha = \ln(e_a)$ and e_a is in kPa and is given by:

$$e_{\mathrm{a}} = \frac{P_{\mathrm{a}} W_{\mathrm{f}}}{0.62198 + W_{\mathrm{f}}} \qquad \text{(B6.2.9)}$$

with P_a now in kPa. S_1 is computed as:

$$S_1 \approx 0.62198 \frac{de_{\mathrm{s}}(T_{\mathrm{dp}})/dT}{P_{\mathrm{a}}} \qquad \text{(B6.2.10)}$$

where

$$\frac{de_{\mathrm{s}}(T)}{dT} = 0.1*(C_{12} + T(C_{13} + T(C_{14} + T(C_{15} + T(C_{16} + T(C_{17} + TC_{18})))))) \qquad \text{(B6.2.11)}$$

de_s/dT is in units of kPa/K, P_a is in kPa, T is in °C, and C_{12} = 0.4438099984, C_{13} = 0.02857002636, $C_{14} = 7.93805404 \times 10^{-4}$, $C_{15} = 1.215215065 \times 10^{-5}$, $C_{16} = 1.036561403 \times 10^{-7}$, $C_{17} = 3.53242181 \times 10^{-10}$, and $C_{18} = -7.090244804 \times 10^{-13}$.

Equation (B6.2.10) follows from the definition of W_s, while Equation (B6.2.11) is from Lowe (1977). Assuming a constant-T_{wb} line to have exactly the same slope as a constant-enthalpy line, it follows from Equation (6.5) that $S_2 \approx c_{pa}/L_c$ = 0.000402/K. From elementary geometry it can be shown that the distance b in Figure B6.2 is given by:

$$b = \frac{T_{\mathrm{f}} - T_{\mathrm{dp}}}{1 + S_1/S_2} \qquad \text{(B6.2.12)}$$

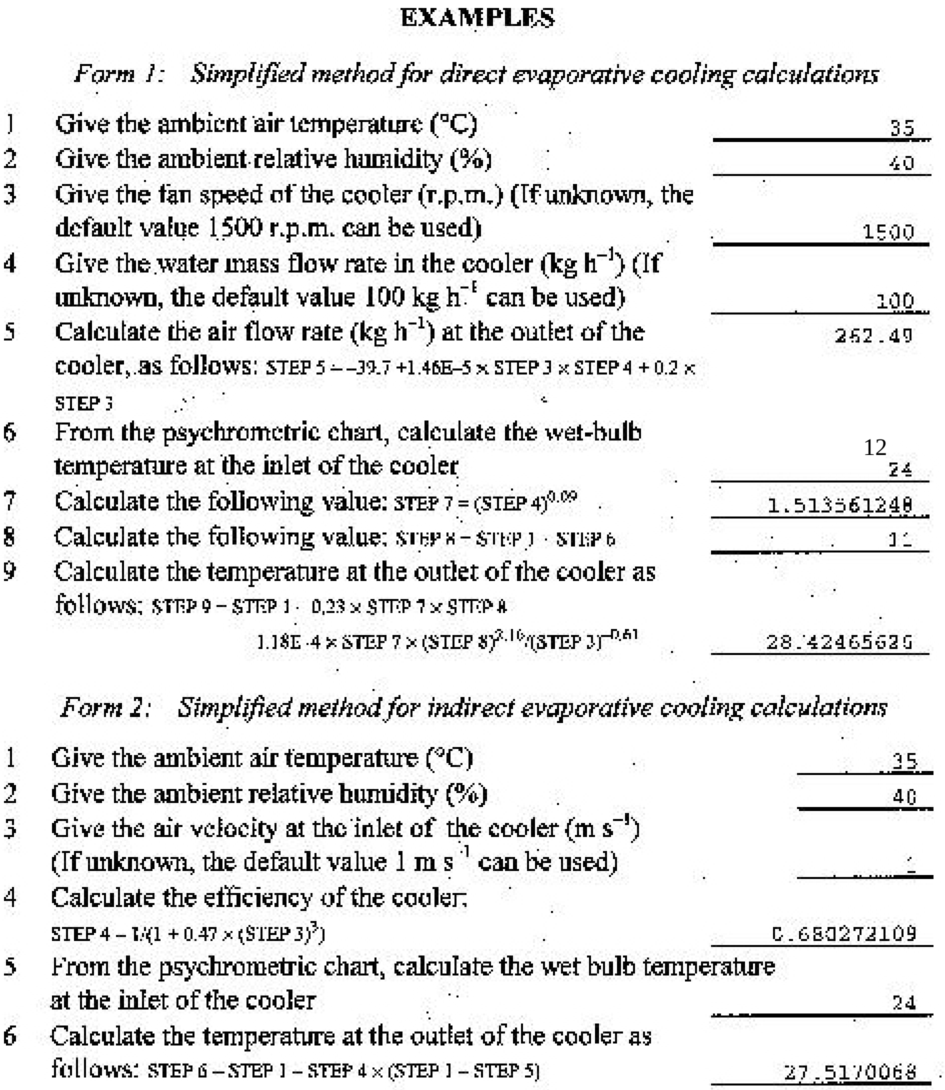
T_{wbf} is estimated from

$$T_{\mathrm{wbf}} = T_{\mathrm{dp}} + b \qquad \text{(B6.2.13)}$$

To refine this estimate, S_1 is re-evaluated at the midpoint between T_{wbf} and T_{dp}, from which a new b and a new T_{wbf} are computed. This process is repeated until the change in T_{wbf} over one iteration is less than 0.1K. This usually requires 4–5 iterations.

Appendix 2

first example- Davis Energy Group **DEVELOPMENT OF AN IMPROVED TWO-STAGE EVAPORATIVE COOLING SYSTEM**



EXAMPLES

Form 1: Simplified method for direct evaporative cooling calculations

1 Give the ambient air temperature (°C) 35
2 Give the ambient relative humidity (%) 40
3 Give the fan speed of the cooler (r.p.m.) (If unknown, the default value 1500 r.p.m. can be used) 1500
4 Give the water mass flow rate in the cooler ($kg\ h^{-1}$) (If unknown, the default value 100 $kg\ h^{-1}$ can be used) 100
5 Calculate the air flow rate ($kg\ h^{-1}$) at the outlet of the cooler, as follows: STEP 5 = –39.7 + 1.46E–5 × STEP 3 × STEP 4 + 0.2 × STEP 3 262.49
6 From the psychrometric chart, calculate the wet-bulb temperature at the inlet of the cooler 12 24
7 Calculate the following value: STEP 7 = $(\text{STEP 4})^{0.09}$ 1.513561248
8 Calculate the following value: STEP 8 = STEP 1 – STEP 6 11
9 Calculate the temperature at the outlet of the cooler as follows: STEP 9 = STEP 1 – 0.23 × STEP 7 × STEP 8 1.18E–4 × STEP 7 × $(\text{STEP 8})^{2.16}/(\text{STEP 3})^{-0.61}$ 28.142465625

Form 2: Simplified method for indirect evaporative cooling calculations

1 Give the ambient air temperature (°C) 35
2 Give the ambient relative humidity (%) 40
3 Give the air velocity at the inlet of the cooler ($m\ s^{-1}$) (If unknown, the default value 1 $m\ s^{-1}$ can be used) 1
4 Calculate the efficiency of the cooler: STEP 4 = $1/(1 + 0.47 \times (\text{STEP 3})^{3})$ 0.680272109
5 From the psychrometric chart, calculate the wet bulb temperature at the inlet of the cooler 24
6 Calculate the temperature at the outlet of the cooler as follows: STEP 6 = STEP 1 – STEP 4 × (STEP 1 – STEP 5) 27.5170068

Second example- Davis Energy Group **DEVELOPMENT OF AN IMPROVED TWO-STAGE EVAPORATIVE COOLING SYSTEM**

Simulated Installation>>		**Ductless**		
	High Speed	**Medium Speed**	**Low Speed**	**Ducted High Speed Low Speed**
Fan Power, Watts	498	266	58	445 110
Total Power, Watts	521	289	81	468 133
Supply cfm	1551	1251	750	1250 750
Secondary cfm	622	478	250	800 490
Entering Air Dry Bulb, °F	104.7	103.7	104.3	103.1 106.5
Entering Air Wet Bulb, °F	70.8	71.1	73.0	73.3 74.3
Between stage Dry Bulb, °F	87.0	85.0	84.5	80.5 82.9
Leaving Air Dry Bulb, °F	67.8	67.8	68.8	68.7 69.1
Leaving Air Wet Bulb, °F	65.0	65.3	67.2	66.6 67.5
Indirect Effectiveness, %	52.2	57.2	63.3	75.7 73.3
Direct Effectiveness, %	87.1	87.4	91.0	84.8 89.6
Total Effectiveness, %	108.9	110.1	113.6	115.3 116.2
Capacity, Btu/hr	20,660	17,155	11,128	19,257 11,770
Capacity, tons	1.72	1.43	0.93	1.60 0.98
EER	40	59	136	41 88

Table 1. Results of IDEC Testing

$\boldsymbol{Qc} = \dot{Q} \times \rho \times c_p \times (TAR_{DB} - TAO_{DB} + EFF_{tot} \times (TAO_{DB} - TAO_{WB}))$,

Where

Qc is the system capacity, $\dot{Q}$ is the airflow rate, ρ is air density, *cp* is the specific heat of air, *EFFtot* is the system effectiveness, and *TARDB*, *TAODB,* and *TAOWB* are the indoor dry bulb temperature, outdoor dry bulb temperature, and outdoor wet bulb temperature, respectively. To calculate the results in Table 1 we used Sacramento design conditions: 101°F DB/70°F WB, and an indoor temperature of 80°F.

EER, or energy efficiency ratio, is the ratio of the system capacity (in Btu per hour) to energy consumption (in Watt-hours, or Wh). Vapour compression cooling systems of comparable capacity typically have EER values of approximately 10.

4. Discussion and evaluation

The existing literature and the present results suggest that there is a high potential for the" stoma brick façade and the heat exchange block façade.
Learning from nature and adopting its knowledge in architectonic systems has not been explored enough and should lead the way for new inventions in this field.
Direct responses to environment influences without additional electronic or mechanical control as a passive alternative in a sustainable way are the future. This change that hasn't been explored enough could eventually lead to new concepts and models.
In order to achieve a responsive adaptable element there is a need to
--Use energy as an integrated flow within a material and not as an outer source.
--Use material not as a raw detailing substance but a performative structure with inherent capacity towards responsiveness, Directionality and differentiation of dimensions.
--Use structure not just by its structural capacity and appearance, but as an opportunity to provide different orientation and exposures. (*Michel Hansel, Achim Menges, 2008*).

There are many facets of this study which could be extended in future work, and contribute to a more complete answer to the main research question. The logical next step will be to include simulations and physical tests in order to contribute to a full coherent understanding of the systems potential. A further interesting goal, again inspired from natures performance, would be to test the system's response to different particular occasions(e.g. different climatic changes, wind rain etc') .The use of a realistic scenario in a simulation would allow the investigation of a range of parameters and demonstrate the structure's specific performance.

5. Conclution

Mimicking nature has a huge potential to accomplish the new approach for a sustainable architecture. It is clear today more than ever that a shift from the old way of building our environment should take place. The integrative way of using passive or low energy consuming systems integrated as a hole together with form material and construction is one of the ways to treat such big issues.
The starting point of this research involved the biological paradigm and its abstraction and transformation to the built environment.
The main research question addressed the innovative techniques of design, that can be developed and eventually applied to construct and sustain man-made structures which are adaptive and integrative.
The objective of the thesis was to study the potential impact of natural systems on human construction methods, and enrich new engineers and architectural design methodologies. The methodology was recommended as a model for the study of thermoregulation in building envelopes (Lidia badarnah 2008).The project started from the observation of systems and ended in the calculations for evaluating the proposed architectural systems. The multidisciplinary study of the complex natural structures, where biological phenomena's of different systems solve thermoregulation issues are wisely embedded in the ending design phase.

It seams that both- Indirect/direct heat exchanger made of a porous clay block and a 3d printed direct cooler –"stoma" brick have a high potential of sufficient cooling capacity.

A well defined experiment is needed in order to evaluate how good it really is compared to alternative direct in-direct evaporative coolers.

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