Text by

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From the material to the product: *B-3 Solar protection*

1 Introduction

Textile applications can be used in different ways to establish climate control, for example: by the use of special materials (phase-changing materials) or coatings; by the use of multiple layers of textile; by heating or cooling of the membranes; and by cooling through ventilation of air through the membrane

A membrane can function in different ways. It can be used as solar protection and as thermal and acoustic insulation. Solar protection devices are used to prevent solar heating; for this purpose non-transparent membranes and multiple-layer membranes can be used. The thermal insulation value depends on the thickness of the membranes and the spaces between the membranes. Better insulation can be attained by using transparent insulation or reflecting layers. Membranes in it self provide but little acoustic insulation. Acoustic insulation can be achieved by putting materials such as: rock wool, glass wool, nano-gel or even water, between the multiple layers of membranes.

Heat transfer is nowadays an important issue in the design of buildings. In chapter 1.2 the basic heat transfer principles will be discussed and the relation between theses principles will be made clear in an example.

In chapter 2 the different methods of climate control with regard to membrane constructions can be divided into four categories: transparent or non-transparent membranes on the inside of the construction and transparent or non-transparent membranes on the outside of the construction. Different combination can be made that result in different structures like: air-open, air-tight and transparent membranes and with or without ventilation.

1.1 Definitions

Single-layer textile

Material, woven or knitted into one single layer that is made of fiber or yarn (and has poor acoustic and thermal insulation properties).

Multi-layer textile

Material, woven or knitted in double- or multi-layers that is made of fiber or yarn (and may have acoustic and thermal insulation properties).

ETFE

Ethylene tetrefluorethylene

PVC

Polyvinyl chloride

Multi-layer Insulated Membrane Roof /ETFE cushions

Cushions consisting of two or more layers of ETFE membranes with encapsulated air. The heated air between the layers realizes the thermal and acoustic insulation. The air inside the cushion is heated by solar energy that can be extracted and used to heat the building.

Air-open membrane

Air that can move freely through this kind of membrane.

Air tightness

The resistance of the building envelop to inward or outward air leakage. Low air tightness will result in the increase of energy consumption through air leakage. Therefore, the air tightness is a very important factor in current building design.

Transparent membrane

Membrane through which visible light can pass through.

Ventilation

The use of air as a transport medium for cooling or heating. The air can be preheated between membranes.

Visible light transmittance

The percentage of incoming visible light that passes through a material, weighted by the sensitivity of the human eye. A single pane glass has a visible light transmittance of approximately 0,9.

Solar transmittance

Percentage of incoming solar radiation that passes through a transparent material. A single pane glass has a solar transmittance of approximately 0,8 i.e. 80 percent of the solar radiation is transmitted through the glass.

Blackbody
A theoretical radiation source that absorbs all radiation, thus reflecting and transmitting none.

1.2 Basic heat transfer principles

Heat transfer is important when textiles are used for solar protection. The three main heat transfer principles are discussed in this paragraph: radiation, convection and transmission.

1.2.1 Radiation emission and radiators

A material with a specific temperature acts as a radiation source. The emitted radiation equals the absorbed radiation according to the law of Kirchhoff.

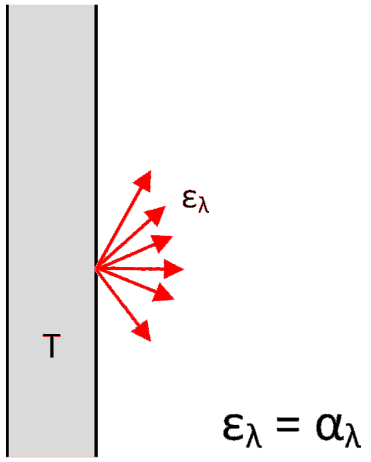


Figure 01 Emitted radiation (ε_λ) by a material.

The emitted radiation differs for every wavelength, forming a spectrum. This spectrum is related to the temperature of a blackbody, a theoretical radiation source, and is defined by the radiation law of Planck.

$$E_{\lambda,T} = 2\pi hc^2 \frac{\lambda^{-5}}{e^{ch/kT\lambda} - 1} \quad [\text{W/m}^3]$$

$E_{\lambda,T}$ = emission for wavelength λ and temperature T		[W/m^3]
λ = wavelength		[m]
T = temperature		[K]
c = Speed of light	299,792,458	[m/s]
k = Boltzmann constant	$5.669 * 10^{-8}$	[W/m^{2}K^4]
h = Planck constant	$6.6260693 \times 10^{-34}$	[Js]

This spectrum can be visualized in an intensity curve. The surface under an intensity curve equals the total emitted radiation of the material and will be larger at a higher temperature. The total emitted thermal radiation is defined by Stefan-Boltzmann's law:

$E_T = \varepsilon_\lambda \times \sigma \times T^4$		[W/m^2]
ε_λ	= emission coefficient for wavelength λ	[-]
σ	= Stefan-Boltzmann's constant = $5{,}669 * 10^{-8}$	[W/m^{2}K^4]
T	= temperature	[K]

There are three manners to describe a radiation source: a black body, a grey body or a selective radiator. [Figure 02]

A black body has an emission coefficient of 1. A black body absorbs all radiation, thus reflecting and transmitting none.
A grey body radiator has an emission coefficient which is lower than 1 and is constant for every wavelength.
A selective radiator has a different emission coefficients for every wavelength which is lower than 1.

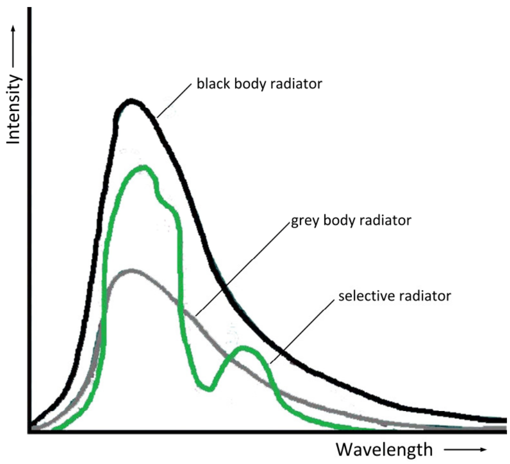


Figure 02 Radiation emission of different radiator; Black Body (black), Grey Body (grey) and a Selective radiatior (green)

Example 1 The sun
The spectrum of the sun is slightly different than the spectrum of a black body with a temperature of 5800K. Besides, the atmosphere filters some light in different wavelengths resulting in gaps in the spectrum. Stefan-Boltzmann's law relates to a perfect black body, implying that the value acquired with this formula gives a greater result than what will occur in reality.

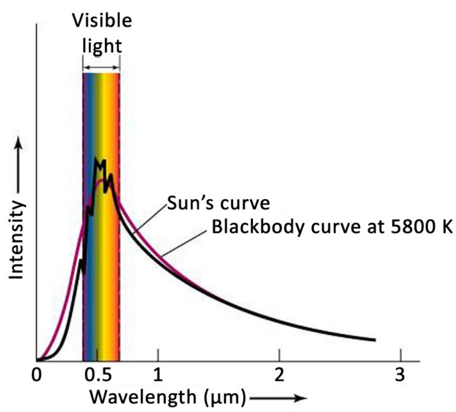


Figure 03 Intensity curve of emitted radiation of the sun and a blackbody with a temperature of 5800K.

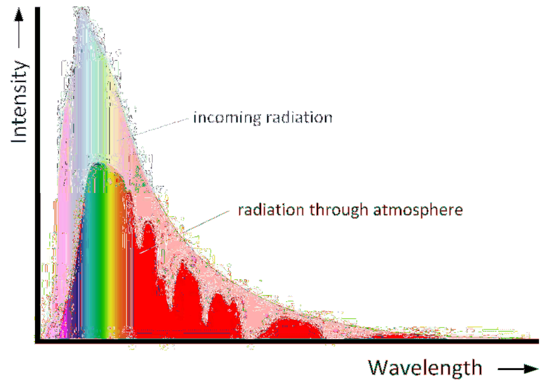


Figure 04 Intensity curve of incoming radiation with the filter effect of the atmosphere

The mean total radiation i.e. direct and diffuse radiation at a vertical surface in the summer in the Netherlands is approximately 400 W/m^2. [W.H. Knoll, E.J. Wagenaar and A.M. van Weele, 2002, Handboek installatietechniek, ISSO, Rotterdam]

Example 2 Materials

Membranes and textiles are no perfect black body emitters because they reflect light. The result is that not all light is absorbed and in case of transparent materials light can pass through the material. The non-transparent membranes and textiles act more like “grey body” radiators and the transparent membranes act more like “selective” radiators. These properties can be used to block the infra red radiation- warmth – and to allow visible light.

Non-transparent

A non-transparent material will absorb and reflect incoming radiation. The material will act as a grey radiator with, in this example, a temperature of 80 ℃ on the inside of the building. Above mentioned is qualitative visualized in figure 05.

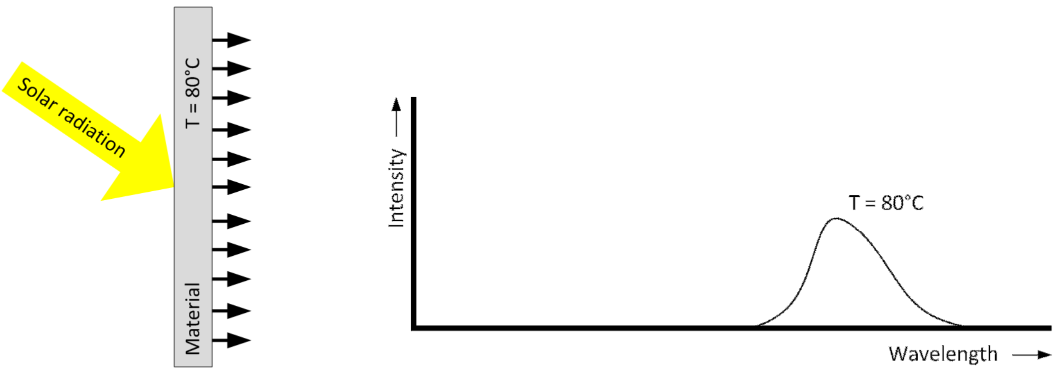


Figure 05 A schematic representation of solar radiation on a nontransparent material and a intensity-wavelength graph of the situation

Transparent

A transparent material will allow solar radiation causing a heat generation, called: passive solar energy. Therefore, one can clearly see the importance of solar protection.

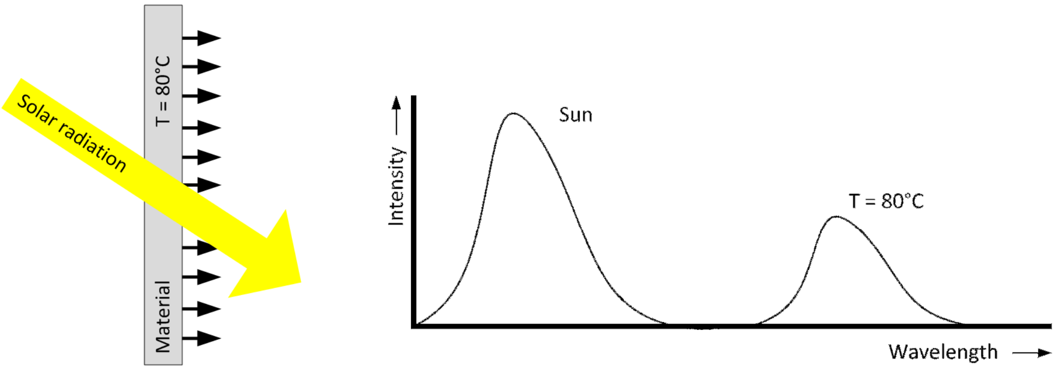


Figure 06 A schematic representation of solar radiation onto a transparent material and an intensity-wavelength graph of the situation

Coatings are important in the radiation heat transfer process because they can provide for selective radiator properties. The reflection and emission is related to surface properties like roughness and color. Rough surfaces reflect less radiation than smooth surfaces. Dark colors have a higher emission coefficient than bright colors. Transparent membranes have a high transmitting coefficient because they allow light to pass through easily.

1.2.2 Radiation

Radiation can be split into the visible spectrum and the invisible spectrum. The visible spectrum is radiation with wavelengths between 0.4 and 0.8 µm. On the one hand, radiation exists with a smaller wavelength, named ultraviolet light and on the other hand, radiation with a larger wavelength, 0.8 to 800 µm, which is defined as infra red light. Radiation heat transfer is mainly caused by infra red radiation because of the larger intensity of these wavelengths in the solar spectrum. [Figure 03 and 04]

Three material properties are important components with regard to the incoming radiation with wavelength λ: absorption α_λ, reflection ρ_λ, transmission τ_λ. The sum of these three components is always 1, representing the amount of incoming radiation. A non-transparent material does not transmit radiation.

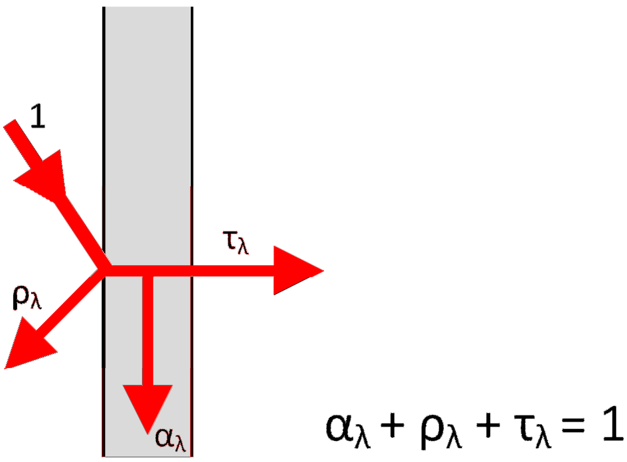


Figure 07 Incoming radiation (1); absorption (α_λ), reflection (ρ_λ), transmission (τ_λ).

Example	Solar radiation falls on a single layer of transparent PVC-membrane.		
Incoming radiation		800 W/m^2	
absorption (α_λ)	20%	160 W/m^2	This will raise the temperature of the membrane
reflection (ρ_λ)	10%	80 W/m^2	
transmission (τ_λ)	70%	560 W/m^2	

1.2.3 Convection

In the case of air flowing over a surface, heat is transferred by convection. This air flow can be driven by mechanical installation or originates by temperature or pressure differences. The energy flow by convection depends on the heat transfer coefficient on the surface, which equals the size of the surface on which contact is made and the difference between the surface temperature and air temperature. The heat transfer coefficient on the surface is related to the dynamic viscosity of the air, the air speed and the property of the airflow, laminar or turbulent. Convection is used in façade construction with multiple layers of textiles to extract the warmth between the different layers.

$Q = \alpha \times A(T_s - T_a)$	[W]
Q = heat current by convection	[W]
α = convection coefficient	[W/m^2K]
A = surface	[m^2]
T_s = surface temperature	[K]
T_a = air temperature	[K]

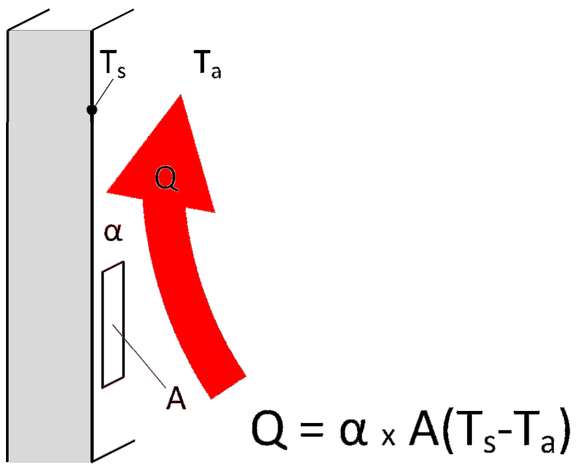


Figure 08 Heat transfer by convection

Example			Convection along a surface in a single membrane construction
$Q = \alpha \times A(T_s - T_a)$		[W]	By solar irradiation the membrane will
α = convection coefficient	7.7	[W/m^2K]	warm up. This causes a higher surface
A = surface	1	[m^2]	temperature.
T_s = surface temperature	80	[℃]	Note: when using multiple layers and an air

T_a = air temperature Q = heat current by convection	20 462	[°C] [W]	cavity the surface temperature will be lower and so will the heat current by convection

1.2.4 Transmission

Heat can be transferred through a material by transmission. The size of the heat current that is generated by heat transmission depends on the heat transmittance properties of the material. The higher the thermal transmittance coefficient (λ), the higher the heat current allowed to pass through the material. A single membrane is not adequate to keep the heat outside or inside the building because of the lack of thickness of the membrane. In case of ETFE cushions the thermal transmittance coefficient of membranes is relatively high compared to the encapsulated air.

$Q = A*(\lambda / d)*(T_2-T_1)$	[W]
Q = heat current by transmission	[W]
A = surface	[m^2]
λ = transmission coefficient	[W/mK]
d = thickness	[m]
T_2 = outside surface temperature	[°C]
T_1 = outside surface temperature	[°C]

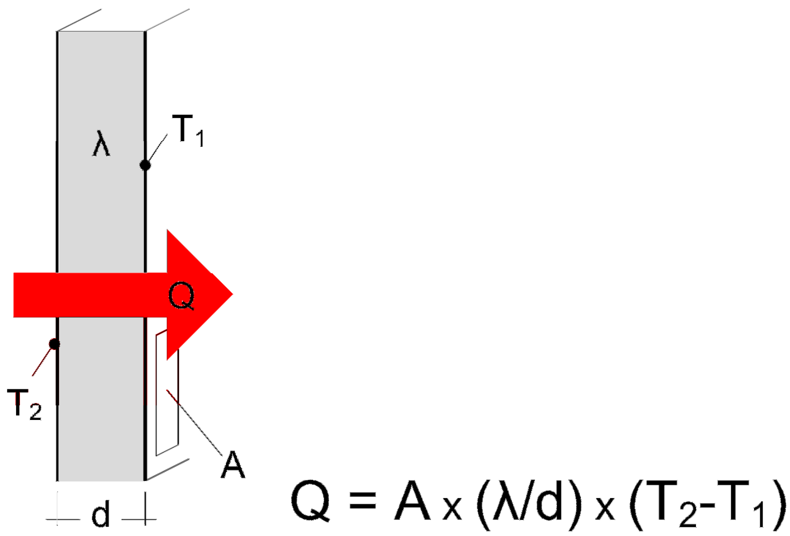
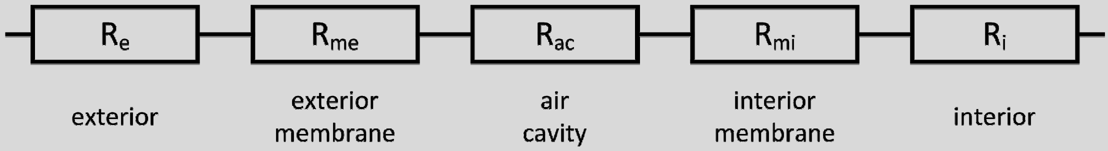


Figure 09 Heat transfer by transmission

Example
The heat transmission through the construction can be visualized as a series of resistances. The external resistance is 0.04 mK/W, the internal resistance is 0.13 mK/W and the resistance of a cavity of approximately 5 centimeters with standing air is 0.17 mK/W. The thermal transmittance coefficient (λ) of PVC is 0.15 W/mK. The thermal resistance of one membrane, with a thickness of 1 mm, is 0.001 / 0.15 = 6.67×10^{-3} mK/W. The scale between the thermal resistances of the membrane and the standing air inside the cavity is 6.67×10^{-3} :

0,17 or 1 : 25. It can be concluded that a single membrane does not have a high thermal resistance compared to the thermal resistance of the air cavity.



$R_j = d_j/\lambda_j$ = thermal resistance [m^2K/W]
d = thickness of membrane [m]
λ = thermal transmittence coefficient [W/mK]
$U = 1/(R_e + R_{me} + R_{ac} + R_{mi} + R_i)$ = thermal transmittence [W/m^2K]

1.2.5 Example concerning radiation, convection and transmission

Non-transparent single layer construction

To clarify the relation between the different heat transfer processes (radiation, convection, transmission) an example is provided of a nontransparent single layer membrane façade construction. The conditions are in the summer in the Netherlands, resulting in the temperature difference along the façade being 10K; outside 30℃ and inside a 20℃ temperature.

Radiation

The mean total solar radiation on a vertical surface in summer in the Netherlands is approximately 400 W/m^2.

Radiation of the surface of the façade can be calculated with the Stefan-Bolzmann law.

$E_T = \varepsilon_\lambda \times \sigma \times T^4$		[W/m^2]
ε_λ	= emission coefficient for wavelength λ = approx. 0.90	[-]
σ	= Stefan-Boltzmann's constant = $5.669 * 10^{-8}$	[W/m^2K^4]
T	= temperature	[K]

A surface with temperatures of 10℃, 20℃ and 60℃ respectively emits 328 W/m^2, 376 W/m^2 and 430 W/m^2.

Convection

Considering a temperature difference of 60K between the air temperature inside and the temperature of the membrane on the surface, the heat flow by convection is 462 W/m^2. A temperature difference of 10 K will result in 77 W/m^2.

Transmission

The thermal resistance of the double layer façade is approximately 0.34 m^2K/W. The temperature difference along the construction is 10 K so the heat current by transmission is approximately 29 W/m^2.

Conclusion

According to the above mentioned it can be concluded that façade design preference is given to a low solar transmittance and a high visible light transmittance. The solar radiation is the most important component in the physical mechanisms of the façade. Therefore, it needs to be blocked to prevent internal overheating in the summer.

The infra red part of the spectrum causes the greatest amount of heat, consequently, this is the part that should be blocked. The visible part depends on transparency of the construction. This part is desired, because of a high demand in architecture for transparency in façade construction.

1.3 Membranes façade construction

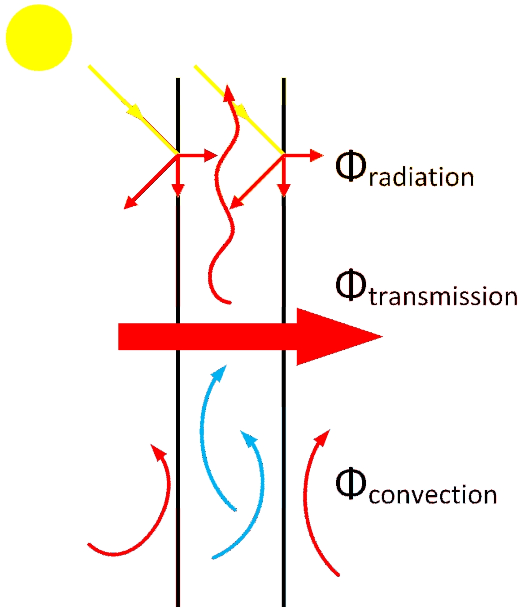


Figure 10 Heat transfer principles and construction

The membrane façade constructions have various properties which are important for the physical functioning of the construction in relation to the three main heat transfer principles as discussed before.

Double layer construction
This construction is made of two layers with a cavity containing standing air in between . The standing air will give a lower heat transfer through the transmission. The cavity can also be ventilated to control the climate.

Transparent membranes
Transparent membranes allow for visible light and infra red light to pass through at a high rate. When applying a transparent membrane on the outside of the construction, the internal heating in the façade construction by solar radiation must be taken into account. Considering that a transparent membrane is applied on the inside of the building, the internal heat production when sunlight hits the construction elements such as: floor and walls, must be taken into account.

Non-transparent membranes
Non transparent membranes block direct sunlight and can, therefore, on the one hand be used as sunscreens. When used on the outside, they prevent the sun from entering the construction. On the other hand, they absorb sunlight so as to gain warmth but, no passive solar heating on the inside of the building is provided for. Applying a non-transparent membrane on the inside of the construction the energy emitting properties of the

membrane must be taken into consideration because the membrane will warm up as a result of solar irradiation.

Semi-transparent construction
The problem with regard to a semi transparent construction is that direct solar radiation causes internal heating. With a solar transmission of 10% in the summer in the Netherlands 100 W/m^2 will directly enter the building causing possible overheating

Airtight membranes
Airtight membranes are impenetrable for air. The airflow through the construction is reduced.

Air open membranes
Air open membranes allow air to move freely. They are used as a windbreaker and as solar shading. Outside air can enter the air cavity.

Ventilated cavity
A ventilated cavity has a forced airflow between the inner and outer layer. This airflow is created with a mechanical installation or by temperature or pressure differences along the construction. The airflow is used to minimize the internal heat production by solar irradiation or to obtain hot air for heating the building by passive solar heat

1.3.1 Examples of building components

2nd skin façade
In the case of second skin façades, the textile surface is on the exterior of the building. A ventilated space is created between the textile surface and the. The textile structure is used for sun protection and is an important element for the architecture of the building. The outside textile surface can be single layered, multi-layered (cushions) and insulated.

Climate façade
Behind the curtain wall-façade a second textile surface is applied/attached? This textile surface is used for sun protection in combination with installations to control the climate of the building.

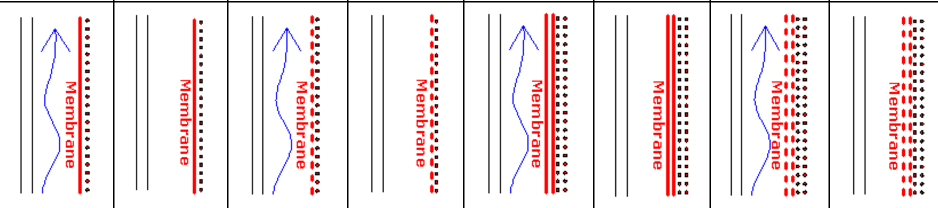
Roofs
There are many examples of textile roofs for permanent buildings. This section will describe the possibilities and effects of single-layered, multi-layered (cushions) and insulated textile structures taken into account: sun protection and climate control of the building.

Shelters
This section will describe the climate control of non-permanent and/or semi-permanent buildings and pavilions, divided in the categories: pre-stressed membranes and inflatable's.

2 Building constructions

2.1 Transparent membrane on the interior

This façade construction type is made of different layers with a transparent membrane on the inside of the construction. A transparent membrane on the inside of the building envelop can be used as an airtight layer.

Position	Inside							
Transparent	Yes							
Layers	Single				Multi			
Air tightness	Yes		No		Yes		No	
Ventilation	Yes	No	Yes	No	Yes	No	Yes	No
Principe								
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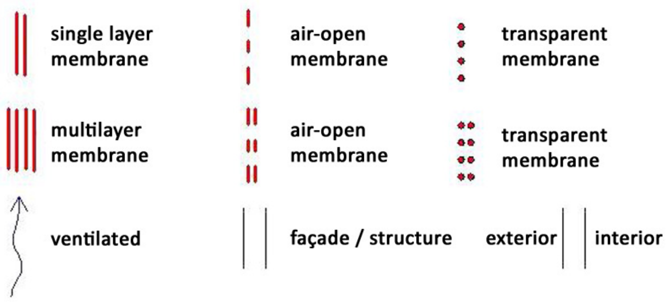
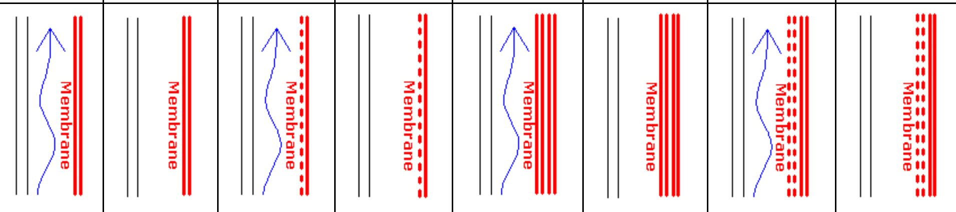
Legend								

*Not available 1: An air open and transparent membrane has no technical function: no shading, no insulation. It can be used for aesthetical purposes only.

**Not available 2: Multiple layers of air open and transparent membranes have no technical function: no shading, no insulation. They can only be used for aesthetical purposes only.

2.2 Non-transparent membrane the interior

A non-transparent membrane on the inside of the construction can be used for solar radiation protection.

Position	Inside							
Transparent	No							
Layers	Single				Multi			
Air tightness	Yes		No		Yes		No	
Ventilation	Yes	No	Yes	No	Yes	No	Yes	No
Principe								
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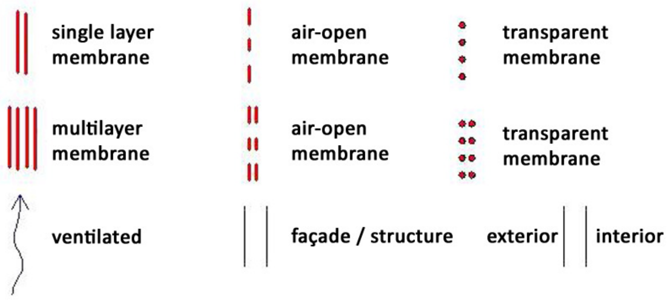
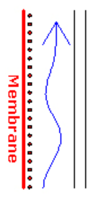
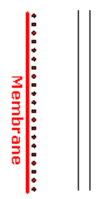
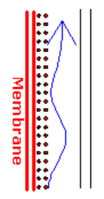
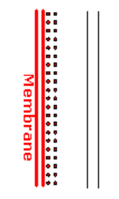
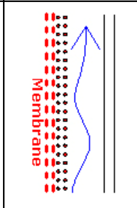
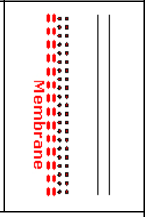
Legend								

2.3 Transparent membrane on the exterior

A transparent membrane can be used for façade construction in which a clear view is important. The use of solar heating is possible, especially combined with ventilation.

Position	Outside							
Transparent	Yes							
Layers	Single				Multi			
Air tightness	Yes		No		Yes		No	
Ventilation	Yes	No	Yes	No	Yes	No	Yes	No
Principle								
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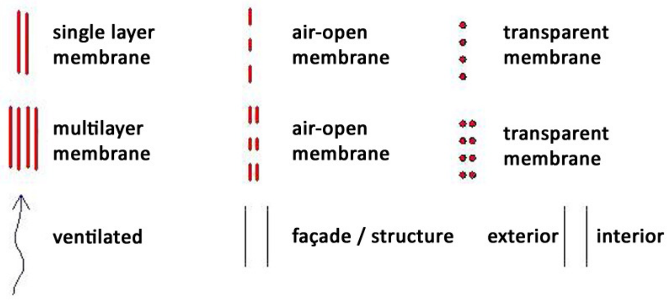
Legend								

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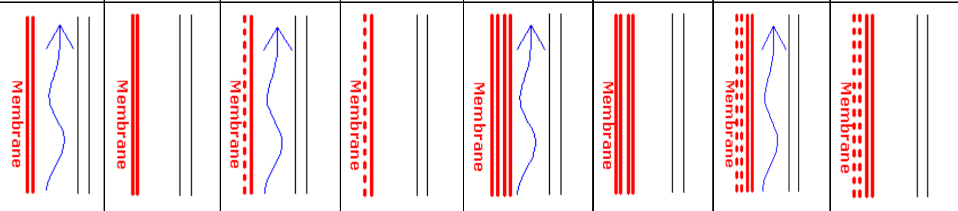
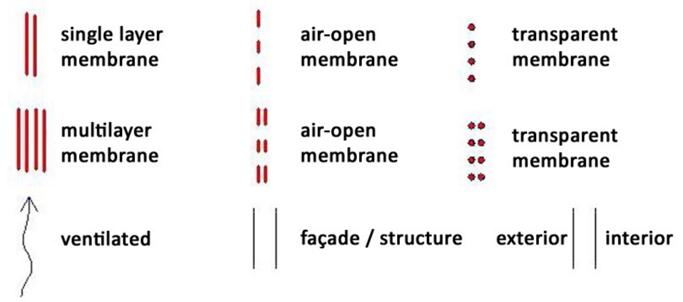
**Not available 2: Multiple layers of air open and transparent membranes have no technical function: no shading, no insulation. They can be used for aesthetical purposes only.

2.4 Non-transparent membrane on the exterior

With a non-transparent membrane on the outside of the construction the solar radiation cannot reach the construction and less heat is produced internally.

Position	Outside							
Transparent	No							
Layers	Single				Multi			
Air tightness	Yes		No		Yes		No	
Ventilation	Yes	No	Yes	No	Yes	No	Yes	No
Principle								
Example					non examples available			
Legend								

3 Example

The following example is part of a research project in building physics of Research Group Product Development at the Department of Architecture, Building and Planning (ABP) at the Eindhoven University of Technology, Eindhoven, the Netherlands. It shows the physical properties of a membrane façade construction.

3.1 Introduction

At the Eindhoven University of Technology a low-cost and flexible building system for dairy cattle has been developed in cooperation with a coalition of leading consultancy companies [Gijsbers, 2005]. This so called Boogstal®, in English: Arched Stable was created within the SlimBouwen© approach for building technology and product development [Lichtenberg, 2005] and was enthusiastically introduced as a pilot project in October of 2006 in Dieteren in the south of The Netherlands. The building has been developed to deliver a stable indoor climate of 0 to 20°C, which is the thermo-neutral zone of dairy cattle.

Figure 11 A & B Pilot project Arched Stable for dairy cattle in Dieteren, The Netherlands

3.1.1 Passive Climate Control

The construction of the stable is made of several steel truss arches. In between, two adjacent arches, a double layered membrane has been placed as roof covering and to create a natural ventilation system which can be adjusted depending on the amount of ventilation needed.

Figure 12 Detail of the roof: truss structure, upper and lower membrane and ventilation openings

The roof is primarily designed to keep the indoor temperature low in case of high outdoor temperatures. Dairy cattle are able to withstand cold temperatures easily; therefore, the building is not insulated. However, dairy cattle are highly sensitive to temperatures above 25 °C, which cause heat stress and lowers the production of milk drastically.

The double layered roof [Figure 13] consists of an outer layer of 55% open windbreak mesh which tempers the wind speed, but more important it blocks the major part of sun radiation. Subsequently, a part of the collected heat in the membranes will flow away through the air buffer in between of the two layers because of convection. Heat from inside the building can get out through the large amount of ventilation openings by buoyancy induced flow (stack effect) and because of air movement at wind speeds over 3 m/s.

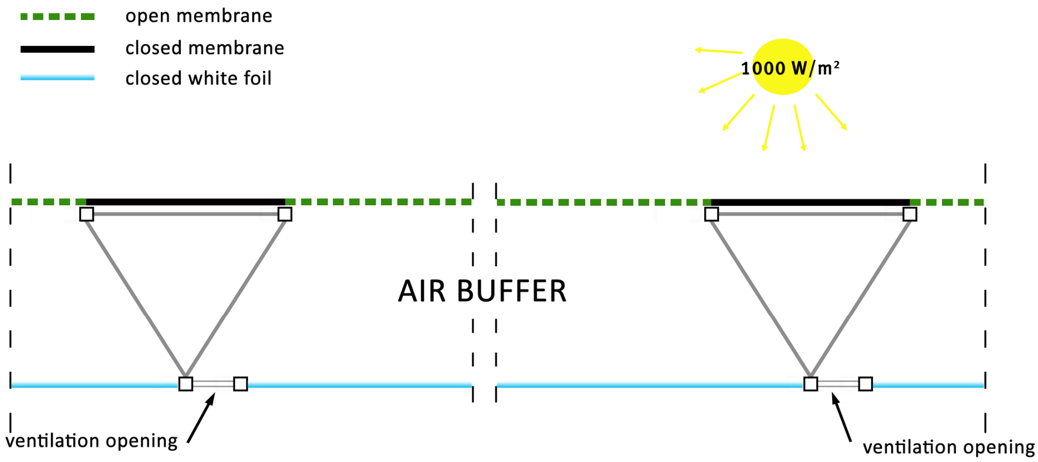


Figure 13 Detail of the roof, on top a windbreak mesh and below a semi transparent foil

The lower layer of white foil keeps rain outside. Underneath the truss elements, which are closed on top, small open strips for ventilation purposes have been attached, which cover the total length of the structural arc This results in a homogenous and sufficient ventilation flow through the building, which is proven by the lack of condensation and the stability of indoor temperature and humidity during the monitoring phase of one year [Gijsbers, et al. 2007]. The white foil prevents direct sunlight from entering the indoor space and creates a diffuse and natural transmission of daylight. As a result, light intensity that is generally comparable to outside conditions on a cloudy day all year round, which is an enormous improvement on indoor comfort compared to traditional housing for dairy cattle.

In comparison to a normal single layered roof without insulation (for example sheets of corrugated iron, fiber-cement corrugated sheeting or a single layer of foil), approximately 75% less heat flow during a sunny day (T_a = 30°C; sun load = 1000 W/m^2) in the inside of the building is attained. The surface temperature of the roofing material is also significantly lower: 85°C in the case of a single layered roof and 35°C in the case of a double layered roof. These numbers result in a large increase of indoor comfort during hot outdoor temperatures.

3.2 References

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