Solar Thermal Collector in Facades

Collecting solar thermal energy for heating and cooling purposes

Perla Berenice Cruz Lopez
St. num. 1542109

MSc. Graduation Thesis
Building Technology Department
Faculty of Architecture
TU Delft

General information

Solar Thermal Collector in Facades

Collecting solar thermal energy for heating and cooling purposes

MSc. Graduation thesis

Façade Design
Master track Building Technology
Faculty of Architecture
TU Delft

Student name	Perla Berenice Cruz Lopez
Student number	1542109
Lab coordinator	Ir. A. Bergsma
Main Mentor	Ir. A. Bergsma
Chair	Design of Construction
Second Mentor	Dr. R. Bokel
Chair	Building Physics
External Supervisor	A. Mulder

January 2011.

Preface

Nowadays fully glazed façades are extensive used for their transparency and lightweight appearance. But the downside of this kind of façades comes from the incident solar radiation to which they are exposed, leading to overheating problems. Currently, cooling accounts for most of the energy that is used in buildings and because of this, people are becoming conscious of the need of reducing the use of primary energy in buildings, and thus reduce pollution and excessive costs. *Solar Thermal Collectors in Façades* proposes a way to control and prevent overheating in buildings while it offers a system that can generate thermal energy for heating and cooling purposes. It deals with the idea of using the façade, or part of the façade, as a solar thermal collector for energy generation and daylight control.

A venetian blind, which can be located in front or in between the façade panes, is proposed to do the task of a shading system and solar thermal collector, transferring the collected heat through a thermal network, so that it can be stored and used later for solar heating and cooling purposes. It is proposed that such venetian blind is enabled to track the sun along its path and its shape and materials were adapted to absorb most of solar thermal energy.

The current thesis is divided in seven chapters. Chapter 1 presents the overheating problem commonly found in buildings, the motivation for this research, and the research question and objective are defined. Chapter 2 exposes some selected topics on solar radiation. Chapter 3 reviews the available sun shading systems and analyzes the best option for the purpose of this thesis. Chapters 4 and 5 concerns a review of the heating and cooling methods as well as the technologies used for those methods. Chapter 6 offers an overview on the collector that is going to be research on. Chapter 7 deals with the method for calculating the performance of the proposed collector. Chapter 8 gives general results of the collector performance for diverse cities. Chapter 9 involves two cases of study. Chapter 10 and 11 display the design and materialization of the collector and Finally, Chapter 12 exposes the conclusion and recommendations for such device.

Key Words: Solar thermal collector, energy generating façade, sun shading devices, active solar heating and cooling, façade integration, venetian blinds, sun tracking.

Table of Contents

Figure index

Nomenclature

Radiation Nomenclature

G	Irradiance (W/m2)
H	Irradiation for a day (J/m2)
I	Irradiation for an hour (J/m2)
R	Radiation tilt factor

Subscripts

b	Beam radiation
d	Diffuse radiation
g	Ground reflected radiation
n	Normal
t	Radiation on a tilted plane

Symbols

A	Aperture area (m2)
A_c	Total collector aperture area (m2)
h_c	Convection Heat transfer coefficient (W/m2-K)
h_r	Radiation Heat transfer coefficient (W/m2-K)
h_w	Wind Heat transfer coefficient (W/m2-K)
K	Extinction coefficient
k	Thermal conductivity (W/m-K)
m	Air mass
N	Days in month
n	Refraction index
N_g	Number of glass covers
S	Absorbed solar radiation per unit area (J/m2)
T	Absolute temperature (K)
T_a	Ambient Temperature (°C)
T_{av}	Average collector fluid temperature (°C)
T_b	Local base temperature (°C)
U	Overall heat transfer coefficient (W/m^2-K)
U_b	Inside heat loss coefficient (W/m^2-K)
U_e	Edges heat loss coefficient (W/m^2-K)
U_L	Solar collector overall heat loss coefficient (W/m^2-K)
U_t	Outside heat loss coefficient (W/m^2-K)
V	Wind velocity (m/s)

Greek

α	
β	Collector Slope

δ	Declination angle
ε_g	Emissivity of glass cover
ε_p	Absorber plate admittance
λ	Wavelength
ρ	Albedo
θ	Incidence angle
θ_z	Zenith angle
τ	Transmittance
τ_α	Absorber transmittance
$\tau\alpha$	Transmittance-absorptance product

1 Introduction

The current architectural trend in contemporary office buildings exhibits a transparent and lightweight appearance by the use of glazing in large areas of the façade. However, the façade is not all about appearance, but it should also provide thermal and visual comfort and have the lowest energy consumption possible. This can be achieved if the façade is carefully design to provide effective protection against excessive solar gains, thus careful design of solar control systems is essential.

Nowadays, buildings have an increasing demand on energy. Most of this energy is used to achieve a good thermal comfort in the indoor spaces. Buildings today account for 40% of the world's primary energy consumption and are responsible for about one third of the global CO_2 emissions (Price *et al,* 2006). The energy saving potential is large and the cost efficiency of building-related energy saving is therefore high. Most of this energy reduction could be done by taking appropriate heat-related measures.

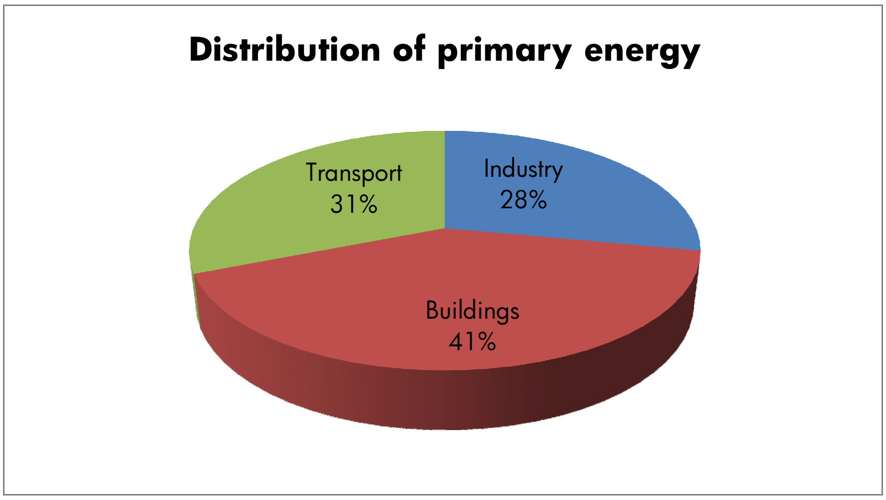


Figure 1. Distribution of energy consumption within the European Union.

In moderate European climates such as those in Germany, about 80% of the total energy consumption in buildings is used for space heating, 12% for warm water production and the rest for electrical appliances and lighting (Eicker, 2009). This enormous heat consumption is primarily caused by low thermal insulation in buildings. In the other hand, in new buildings with low heating requirements, energy consumption in the form of electricity and air-conditioning is becoming more dominant due to the increasingly use of fully-glazed facades and huge internal loads caused by appliances. The use of renewable energy resources for electricity and air-conditioning could make a great contribution in this area.

Cooling and refrigeration account for about 15% of the total electricity consumption worldwide, even more than that used for heating, which causes that the peak loads of electricity in many countries now occur in summer rather than in winter.

By adopting sustainable measures such as façade systems that could preserve, or in best cases, that enable the generation of energy; or the use of passive or active solar cooling methods, these consumption loads can be diminished. Comfort temperatures can be achieved in a cost-effective way, avoiding unnecessary expenses and damage to the environment.

1.1 Objective

Nowadays architecture tends to be mainly made of high-rise buildings. The façades are becoming the greatest surface of a building that is exposed to solar radiation. Therefore, it would be wise to block the solar energy from entering the buildings and collect it for a later use. The challenge is to take the solar energy that strikes the façade and transform it into a specific type of energy that is needed in the building, e.g. activating heating and cooling processes.

This thesis proposes the development of a shading system that additionally works as a solar thermal collector. It was found that for this use, the correlation between the need to block the solar radiation and the requirement for cooling down buildings during summer was beneficial for this system. A venetian blind is selected as departing point for the system, because the operability of this type of sun shading device is easier, as well as the fact that it is already extendedly used. This venetian blind was analyzed and optimized to fulfill sun shading and solar energy collection.

1.2 Motivation

The motivation for developing this thesis was the urgency to decrease the use of fossil energy in buildings for heating and cooling due to two main reasons. During the production of energy from fossil fuels extreme pollution is created. The CO_2 that is produced is, in great extend, the cause of the greenhouse effect and therefore the over warming of the earth. Secondly, this type of energy is not renewable, which means that sooner or later, there will be a shortage of energy if alternative, renewable energy production is not exploited.

In the coming years, there will be enormous efforts to reduce the use of primary energy, especially in buildings that house a significant amount of people, such as apartment and office buildings. It is essential to start by proposing new and relatively simple mechanisms that can assist the reduction of energy use. The objective of this thesis is to propose an effective system that can be used in new buildings or fitted in existing ones with minor modifications.

1.3 Research Question

The following question will be the guide throughout the current research:

What is the best configuration of a venetian blind in order to face the sun, expose the maximum possible surface and resist high temperatures while it collects as much solar thermal energy as possible for active heating and cooling purposes, and still fulfill the function of sun shading device?

1.4 Scope of Research

The current research deals with the exploration of the different aspects that can influence the absorption on a solar collector. Those aspects are analyzed, so that when placed together, they can produce a venetian blind that is also optimal for solar thermal collection. Therefore, the research focuses on finding the configuration that performs better for solar tracking, solar radiation absorption, heat transmittance and sun shading for both automatic and user operability.

This thesis will focus in the analysis and research on the venetian blind, its geometry, performance and connection with the building. It is out of the aim of this research to analyze the entire solar heating and cooling system in the building.

2 Solar radiation

The sun is a hot gaseous matter that has an effective blackbody temperature of 5777K. The sun is in itself a continuous fusion reactor and several of such reactions have been suggested to supply the energy radiated by the sun. The energy that is produced in the center of the sun is then transferred out to the surface and then radiated into the space. The radiation of the energy in the center of the sun is in the x-rays and gamma-rays of the spectrum, and as the temperature drops at larger radial distances, the wavelengths of the radiation increase. Because the sun in made up of many different layers that have different properties and temperatures, it can be said that the sun does not function as a blackbody radiator at a fixed temperature. Instead, the sun emits radiation that is the result of those several layers of gases that emit and absorb radiation at different wavelengths (Duffie, 2006).

2.1 Solar constant and radiation on earth surface

The eccentricity of the earth’s orbit is such that the distance between sun and earth varies approximately 1.7%. At a mean sun-earth distance, sun subtends an angle of 0.5° to the earth, which is so minimal that the radiation emitted by the sun towards the earth results in a nearly fixed intensity of solar radiation outside the atmosphere of the earth (Figure 2).

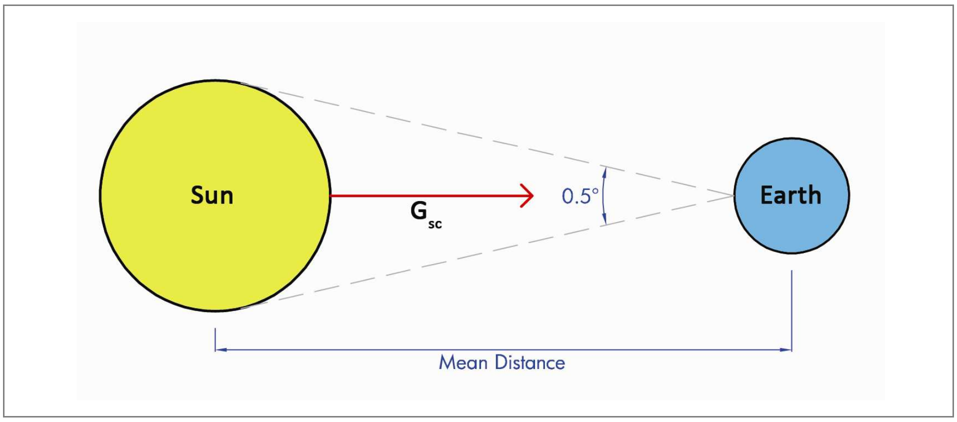


Figure 2. Schematic relationship of the sun and earth distance and radiation.

The **solar constant** G_{sc} is the energy emitted by the sun in a unit of time, which is received in a unit area of surface that is normal to the propagation of the radiation, at mean earth-sun distance, outside of the atmosphere (Duffie, 2006). After many different estimates for measuring the solar constant, The World Radiation Center (WRC) adopted the value of 1367 W/m^2, with an uncertainty of 1%.

Even though the term of solar constant G_{sc} exists, the radiation may vary during the year. There are two main causes of this variation. The first is inherent to the sun and is related with the sunspot activity. These variations have different values depending on the author, but for engineering purposes, the energy emitted by the sun is considered to be fixed. The second variation is caused by the variation on the earth-sun distance throughout the year. This variation is of the order of ±3% and is measured on the normal plane of the radiation on the *n*th day of the year (Figure 3).

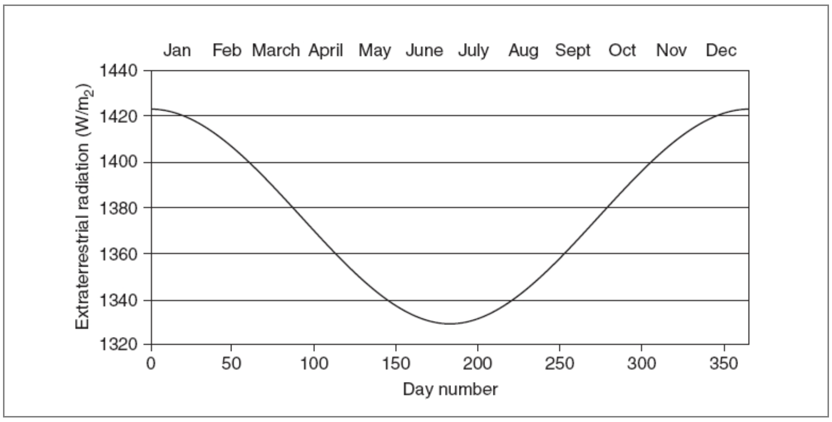


Figure 3. Variation of the extraterrestrial solar radiation throughout the year (Duffie, 2006).

From the total energy in the spectral radiation, the distribution of such energy in different wavelengths was also defined and the WRC made a standard, which is show in Figure 4 (a). For most thermal energy applications, only thermal radiation is important. The spectrum of electromagnetic radiation is divided into wavelength bands. The bands that are important in solar energy and its application are in ultraviolet to near-infrared range, which is from 0.3 to approximately 25 µm. This range also includes the visible spectrum (0.38 and 0.72 µm).

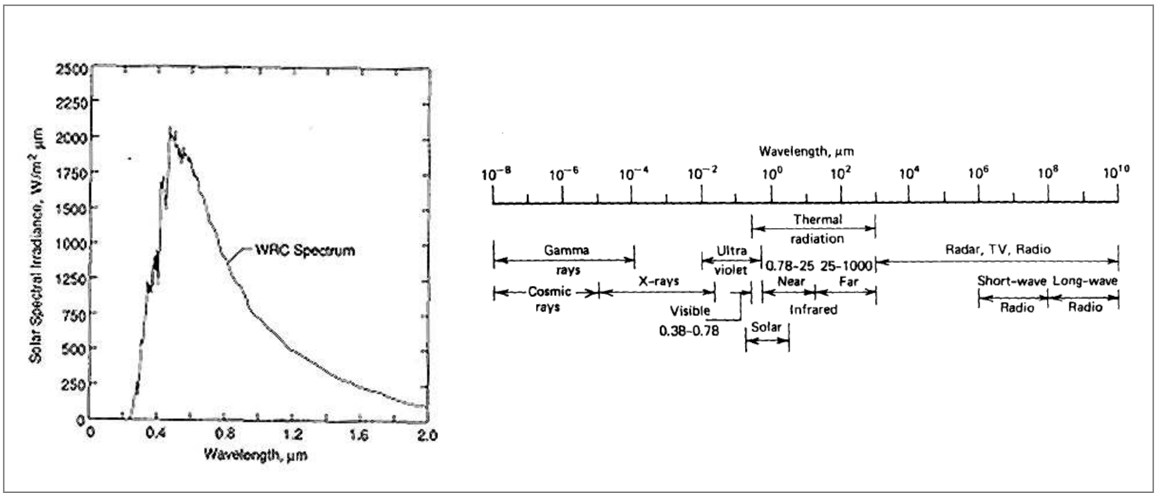


Figure 4. The WRC standard spectral irradiance curve at mean earth-sun distance (Duffie, 2006).

The earth intercepts around 2 billionths of the energy emitted by the sun. This energy is almost 10 000 time the total power generated by man today. Outside atmosphere, the solar constant is received (G_{sc} = 1367W/m^2 = 4.92MJ/m^{2}hr). At noon with a clear sky, the solar energy inside the atmosphere can reach up to 1,000 W/m^2 (approx. 3.6 MJ/m^{2}hr) in a surface perpendicular to the rays.

The radiation is not the same for all the regions in earth, the sunshine levels are determined by the sun's trajectory, hours of sunshine and sky condition. The sun path (sun trajectory) is mainly used to calculate and design devices that interact with the solar radiation to obtain energy of any type. Depending on the path, it can be calculated the amount and direction of the radiation that is expected to fall into a surface. The radiation can also be diminished by the amount of clouds in the sky. As it passes through the clouds, the solar radiation can be absorbed and reflected by dust and droplets of water in the air, and scattered by molecules suspended in the air. Therefore, the radiation is made of beam radiation G_b and diffuse radiation G_d. These two components constitute the global solar radiation G. Additionally to the global solar radiation G, the reflected radiation can be summed up to the radiation that falls on a surface.

3 Sun shading systems

The extended use of glass in façades is leading to overheating inside the building. Façades are subsequently becoming almost transparent for the short-wave solar radiation which is absorbed by the interior walls and slabs. When this energy is radiated from these walls and slabs, it comes as long-wave radiation, making it impossible to escape back to the exterior and heat is accumulated inside, causing high loads of energy for cooling.

For this reason, many sun-shading systems have been developed to diminish the solar gains through windows and facades. The sun shading systems that are currently available are attached to the façade to block the sun. These architectural elements can go from overhangs and wing walls with a fixed position, which protect the buildings for certain hours in the day; to louvers or blinds that can be operated, manually or automatically to adjust the tilt angle towards the direction of the sun or even track the solar path (Figure 5). It has been found that sun shading systems that are placed inside the building are less efficient than those located in façade cavities or in the exterior. Internal blinds allow radiation to trespass the glazing, and once the radiation is inside, it would not escape back. External blinds block radiation from even reaching the glazing, so heat stays out (Zumbotel, 2010). For this reason, only external and cavity blinds will be analyzed. Various sun-shading devices were analyzed in order to see how they perform under different circumstances (Table 1):

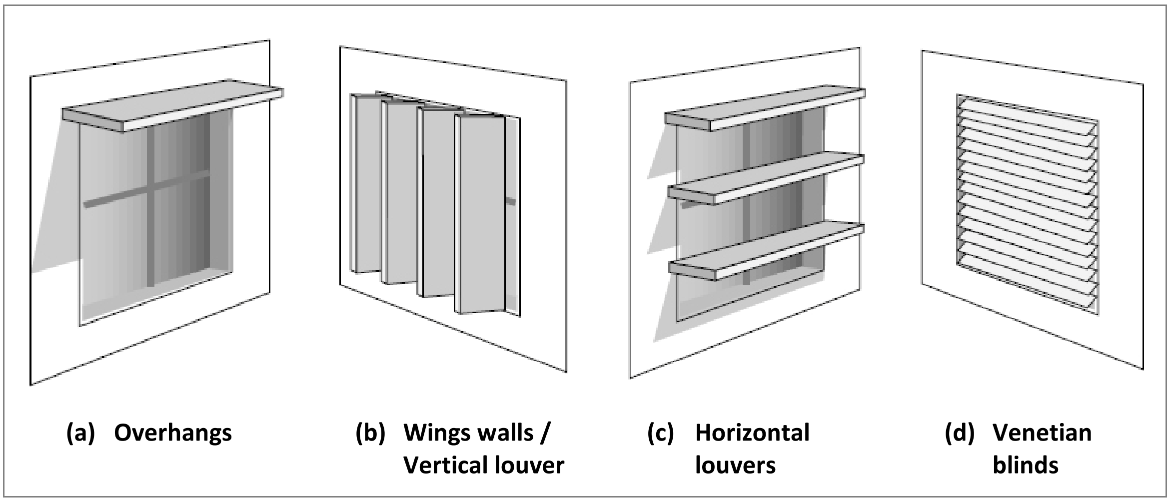


Figure 5. Different sun shading systems .

Device	Does it block the early and late solar radiation?	Does it block mid-day solar radiation?	Is it possible to track the solar path?	Is it possible to be overruled by user?	Is it possible to let daylight in when displayed?	Is it possible to preserve the transparency when not needed?
Overhang	✗	✓	✗	✗	✓	✗
Wing wall	✓	✗	✗	✗	✓	✗
Vertical louvers	✓	Could be	✓	✓	Not for mid-day solar radiation	✗
Horizontal louvers	Could be	✓	✓	✓	Not for early and late solar radiation	✗
Vertical blind	✓	Could be	✓	✓	Not for mid-day solar radiation	✓
Horizontal blind	Could be	✓	✓	✓	Not for early and late solar radiation	✓
Roller blind	✓	✓	✗	✓	✗	✓

Table 1. Different types of sun shading systems and their capabilities.

As seen in Table 1, the best option to choose is a vertical or horizontal (Venetian) blinds that can be retracted when they are not needed or when the user decides to. A second good option would be vertical or horizontal louvers that have the same possibilities as the blinds, when they are considered as part of the architectural design since they cannot be retracted. Overhangs, wing walls and roller blinds are not good options for this type of solar thermal collector device, since they cannot track the solar path for a better thermal collection.

It is of outmost importance to have control over the solar radiation that goes into the rooms when the building is being used. For an office building, during working hours (9:00 – 17:00) the sun is mostly high in the sky; therefore, the horizontal blinds would be more effective for this application. Thus, only the horizontal blinds will be analyzed.

In term of functionality, the sun shading and solar thermal collector should fulfill some requirements in order to perform efficiently:

- Block excessive solar radiation into the building
- Let daylight in

- Prevent glare
- Collect as much solar thermal energy as possible

From an architectural the point of view, there are also some conditions to be fulfilled:

- Keep view to the exterior
- Keep the feeling of transparency of the building
- Avoid the use of electric energy to light the rooms as much as possible
- Keep the texture of the façade (e.g. flat glazed façade) if solar blocking elements are not part of the design

Automatic blinds can fulfill the requirements of solar radiation blocking very precisely, but trouble arise when it comes to the comfort of the user, because some of his/her desires can be contradicting to the solar radiation management. Since both aspects are important, the best solution would be to use an automatic device that can be overruled by the user at any time.

3.1.1 Venetian Blinds

The venetian blinds are a type of sun shading device that has been used since the eighteen century. They comprise a group of slats that hang down from a principal rail and they can be tilt in order to redirect or neglect any kind of sun radiation.

Placing the blinds inside the building can reduce the heat gain in at most in 55%. Venetian blinds evolved as a combination of exterior shading device and operable shading system. The solar gain can now be reduced in 80 or 90% (Eicker, 2009). Due to the environment factors, such as rain or wind, this kind of venetian blinds have been modified for the exterior use, implementing weather-resistant materials, as well as new clamping devices to avoid extreme deterioration.

Working principles

The study of the mechanism for external venetian blinds was considered as departing point for the subsequently development of the solar thermal collector in the form of blinds. Exterior blind has 10 main parts that are listed in Figure 6:

1. Top rail
2. Blind-bearing
3. Slats
4. Bottom rail
5. Ladder cord
6. Lifting tape
7. Lateral guide
8. Tensioning shoe
9. Electric motor
10. Control device

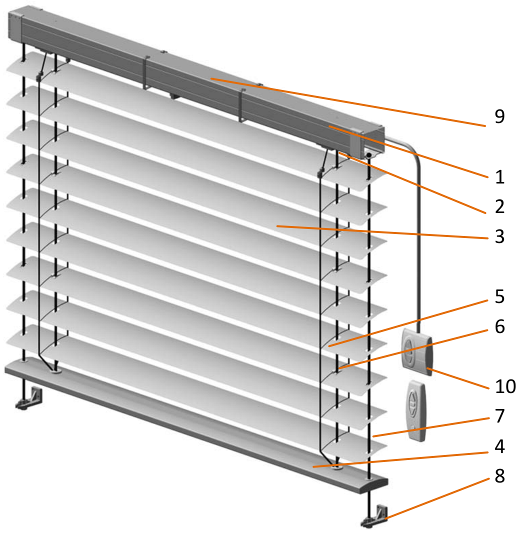
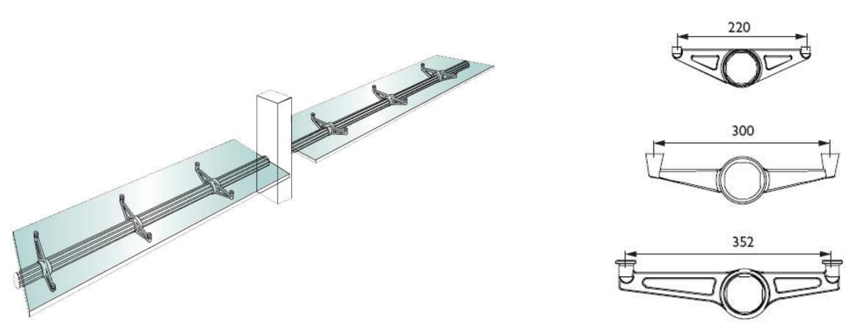


Figure 6. Parts of an external venetian blind (Hella Group, 2009).

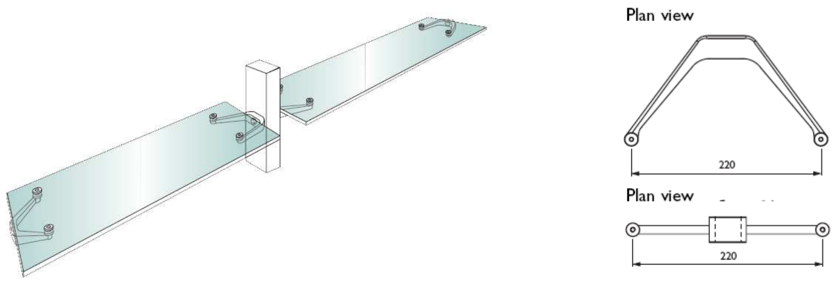
The retractable and the tilting mechanism are done by two sets of cords. For retracting, the lifting tape is pulled up by the mechanism inside the top rail. In this way, the slats can stack together at the top of the system. To tilt, the blinds are equipped with a ladder cord, which is made of two cords that run at each side of the width of the slat. These cords are attached to each other by a third transversal cord, or divider, that runs underneath the slat. When any of the principal cord of this ladder is pulled up, the divider takes an inclined position, which makes the slats to be inclined as well. To avoid the decontrolled movement of the slats when the blind is being deployed or retracted, a guide made out of wire is place through a punched hole in the extremes of each slat.

3.1.2 Louvers

Louvers are also slats that are placed in front of a façade, but in comparison with the venetian blinds, louvers are fixed in a certain place and have larger dimensions. They can also be tilted from closed to open letting daylight in. Some of the carrier systems that are available now in market where analyzed and some characteristics were taken for further design (Figure 7):

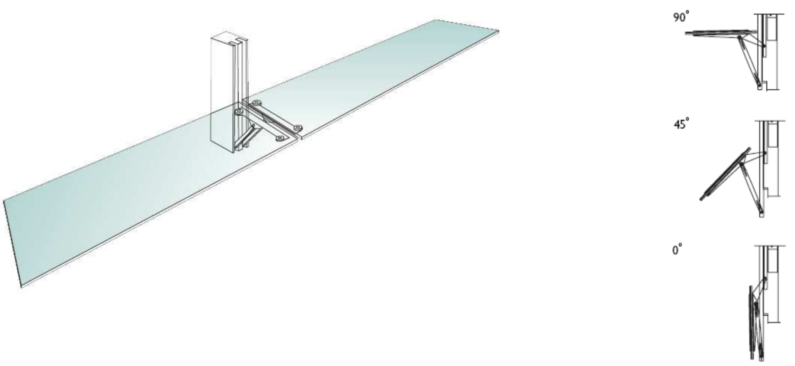


1. Axis is seen from inside
2. Avoids torsion by having an axis
3. Several gripping points
4. Tiltable



1. Clear to the outside
2. Has more torsion
3. Tiltable

1. Carrier is big
2. No torsion
3. Tiltable



1. No elements interrupt view
2. More complex tilt mechanism
3. Tilting is done along the edge

Figure 7. Louver carrier systems (Colt Int. Ltd., 2010).

4 Review on Solar heating and cooling methods

When a decrease of primary energy for heating and cooling is done, it is directly reflected in the general energy consumption of a building. Even though some improvements on the use of renewable energy for various industry sectors, in the building industry some efforts have been made majorly for the conservation of heat inside the buildings, but little has been done for cooling purposes.

Renewable energy for heating and cooling purposes has been described as the *sleeping giant* of renewable energies applications. It has not received as much attention as the renewable energies for transport and electricity, even though it has great potential. Where solar thermal resources exist, heating or cooling technologies can be competitive with those using fossil fuels (International Energy Agency, 2007).

According to the objectives of the current thesis, solar thermal energy is going to be used to enhance the thermal comfort of those buildings which adopt a solar thermal collector in their façade; therefore only solar thermal energy is going to be analyzed. Table 2 shows the different systems that use solar thermal energy to work and what kind of output they give.

Renewable energy source	Technology	Direct heating	Cooling	Electricity
Solar thermal	Passive cooling building designs		✓	
	Passive heating building designs	✓		
	Active thermal heating	✓		
	Active solar cooling	✓	✓	
	Integrated PV-thermal collector	✓		✓
	Concentrating solar heat	✓	✓	✓

Table 2. Energy services from solar thermal energy (International Energy Agency, 2007).

In the case of the researched system, heat collected on the façade is going to be used to power solar heating and cooling processes in a centralized heater or chiller. This use of solar thermal energy is best known as active solar heating and cooling.

4.1 Passive Solar Systems

Passive Solar technologies are means of using sunlight as useful energy without the use of active or mechanical systems. Such systems collect the solar energy and convert it into usable heat to warm up space, mass, water, or to produce convective air flows for ventilation. Heat can even be store to be used in the future. They normally use none or very low amount of conventional energy to enable devices that enhance the solar energy collection.

Passive solar systems can be classified according to the type of use that is given to the solar energy and how the energy is collected. When the energy is intended as an assisting method to heat or cool a space, it is called *passive solar heating* or *passive solar cooling* respectively.

4.1.1 Passive Solar Heating

In passive solar heating, all architectural elements e.g. floors and walls are intended to work as collectors, absorbers and radiators of solar thermal energy for the winter period and reject the heat in summer. For a correct use of passive solar heating instruments, special attention has to be paid to the location of the dwelling, orientation, type of construction, and the placement of glazing and shading elements. Attention has to be paid to the solar path for the altitude of the location in question and the thermodynamic principles in order to design a correct system. There are three configurations that can be used for passive solar heating (Figure 8) (Passive Solar Design, 2010):

Direct solar gain

The direct solar gain system proposes that the walls, floor and ceiling of a dwelling act as thermal energy collectors and absorbers, while the solar radiation is falling directly on them through a glazing which on the south façade (in the case of the northern hemisphere). During night time, the absorbed energy is released to the space through radiation (Figure 8 (a)).

Indirect solar gain

This system uses thermal mass to absorb the energy from the sun. A thermal mass e.g. wall or water tank is placed right behind the glazing on which the sunlight is incident and subsequently absorbed by the thermal mass. The thermal mass releases the heat into the living space during the night through radiation, convection and conduction. There can also exist heat losses during the night due to the short distance between the thermal mass and the glazing (10 cm. approx.). To reduce losses, an insulated glazing unit can be used instead, but the solar energy that goes through the glazing will be diminished. Some vents can be placed in the wall (thermal mass) in order to intensify the convection through the heated zone during the day and have to be closed during night to prevent losses. An example of this system is the trombe wall (Figure 8 (b)).

Isolated solar gain

The heat is moved to the living area using a fluid (water or air) by natural convection. The energy collection is done in a glazed space facing the equator, such as a solarium. This space is separated from the living area with a thermal mass. This solarium can also be used for other living purposes (e.g. as greenhouse). The heat is brought into the living space by means of a convective flow that goes through some vents that are placed at the top and bottom of the wall (thermal mass). At night, the vents should be shut down so that the heat stays inside and prevent thermal losses. The space between the glazing and the thermal wall works as insulating mass (Figure 8 (c)).

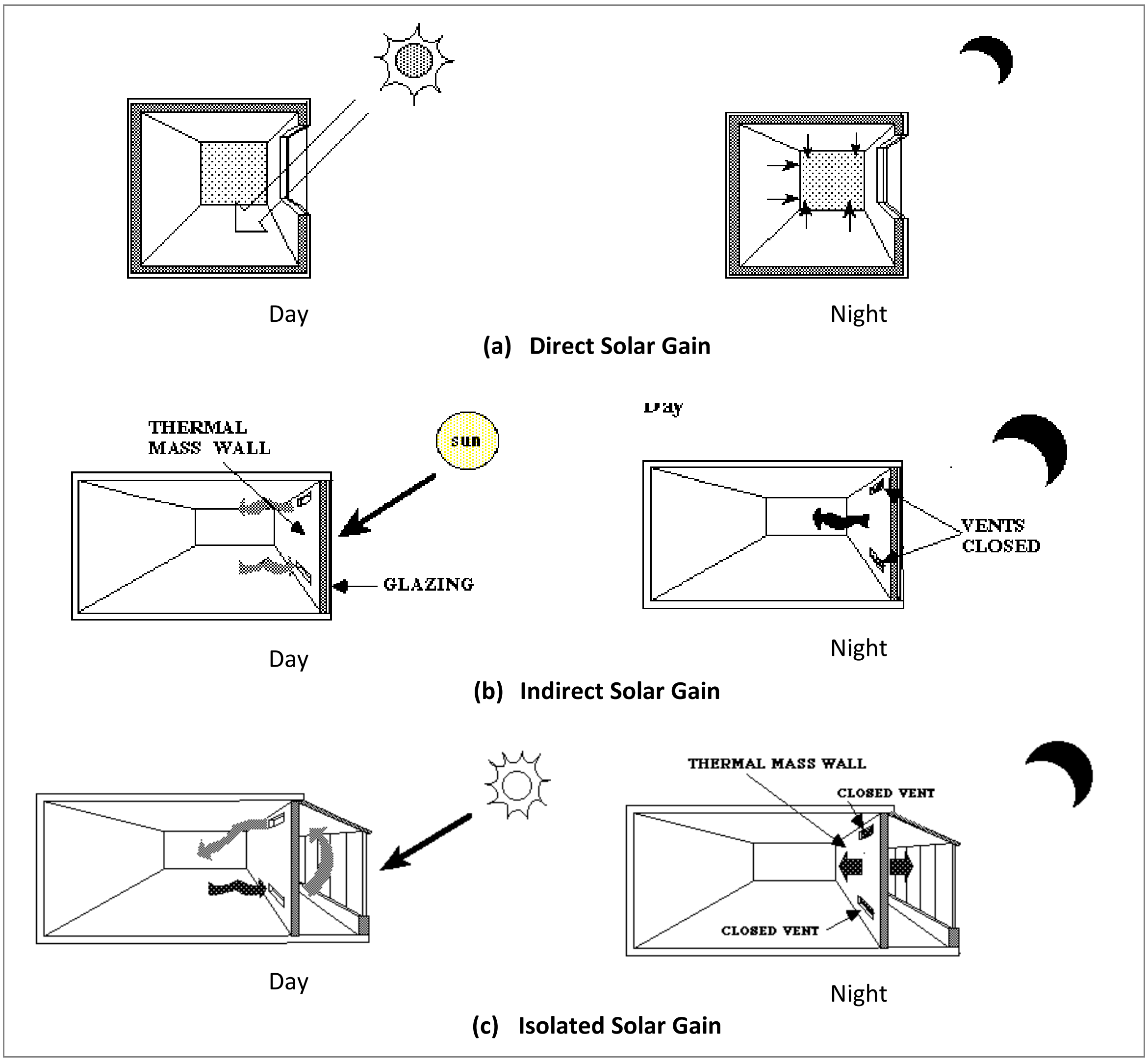


Figure 8. Passive solar heating systems (Passive Solar Design, 2010).

Heat can also be stored for later use. Some storage tanks can be made of solid material, such as concrete slabs or walls, cisterns and ponds. Insulation for these storage devices is of great importance, since heat should be kept as much as possible.

Other decisive aspect for solar energy collection is the type of glazing that is selected. Direct solar gain is significantly increased when insulated and spectrally selective glazing is used. For this uses, glazing that has a coating that inhibits the solar gain are not recommended.

4.1.2 Passive Solar Cooling

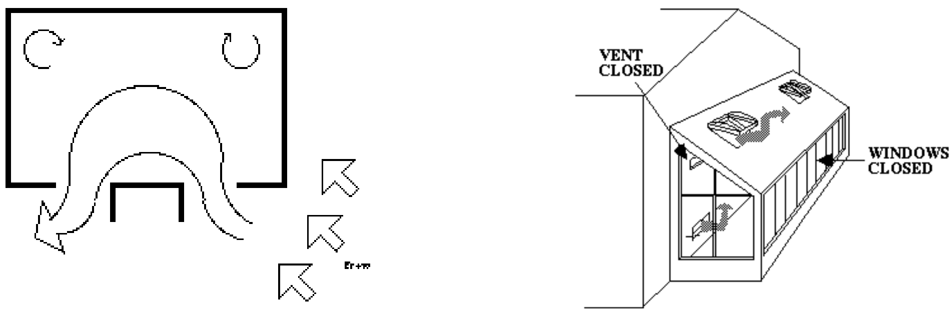
The passive solar cooling methods use a thermosyphon system to redirect excessive heat to the outside of a building by natural convective flows. It can be either by letting fresh air come in or heating up air to drag the excessive heat from the inside (Passive Solar Design, 2010).

Operable windows

Windows can be opened create a current inside a living space. In one side, facing the prevailing wind direction, a window is opened to let fresh air in, and in the opposite façade, a secondary window is opened to let hot air out (cross ventilation). The current of fresh air drags the hot air out with it, cooling down the room (Figure 9 (a)).

Thermal chimney

A thermal chimney is done when a space with an exterior exhaust (e.g. sunroom) is heated up. A bottom vent from the living space to the sunroom should be opened to drag the warm air out. Fresh air is drawn into the house by opening a north facing window. The heated air in the sunroom will create a thermosyphon, dragging the warm air from the living space and exhausting it through the outlet at the top. Thermal chimneys can also be constructed in a narrow space, such as cavities in facades with an insulated glass unit in the inside (Figure 9 (b)).



(a) Operable windows **(b) Thermal chimney**

Figure 9. Passive Solar cooling (Passive Solar Design, 2010).

Another way of preventing overheating in buildings is the use of sun shading systems. These systems can have fixed position (passive system), or can track the sun for a better response on sun path (active system).

4.2 Active Solar Systems

Active solar systems are used to convert solar energy into usable lighting, heating, cooling or as input for other processes that require electricity. In active solar systems, the collection of solar energy is done by means of major mechanical devices, which require a certain amount of energy input. These systems can have significantly higher solar collection, since the internal mechanical and electrical devices are used to enhance the heat transfer.

4.2.1 Active Solar Heating

Active solar heating is majorly done with the use of solar collectors. Usually water or another heat transfer fluid is circulated through a duct and heated from direct solar radiation on the solar collector panel. Various designs of collectors are utilized in order to concentrate the solar radiation on the fluid duct and to maximize solar gains. The amount of heat energy captured per square meter of collector surface area varies but typically it can range from 300 to 800kWh/m^2/yr. The solar energy collected is carried from the circulating fluid either directly to tap water, space conditioning equipment or thermal energy storage tank, from which it can be drawn for use at night or cloudy days.

Space heating systems can use either liquid or air collectors. Liquid-based systems heat water or an antifreeze solution in a hydronic collector, whereas air based systems heat air in an air collector (U.S. Department of Energy, 2010). The energy delivery system may use the same medium or a different one from that used in the collector. Usually systems that use air collectors also use air for storage and delivery of energy. Systems that use liquid collectors may use water or water plus antifreeze for collection, water for storage and water or air for heat delivery, e.g. floor heating systems and air handling unit respectively.

Air-based active solar heating

Air-based heating systems use air as the working fluid for absorbing and transferring the solar energy. Solar air collectors can directly heat a room or can pre-heat the air that passes through a heat recovery ventilator or an air coil of an air-source heat pump. An advantage of air systems is that they do not freeze, and small leaks do not cause significant problems. In the other hand, air is a less efficient heat transfer medium than liquid; therefore, air-based systems operate with lower efficiency (U.S. Department of Energy, 2010).

Glazed flat-plate collector

It is best suited for moderate temperature applications ranging from 30° to 70°C, and for applications that require heat during the winter. It is mainly used for heating dwellings. The glazing of the collector helps to prevent losses, while the solar radiation goes through it and reaches the absorber (Figure 10 (a)).

Unglazed flat-plate collector

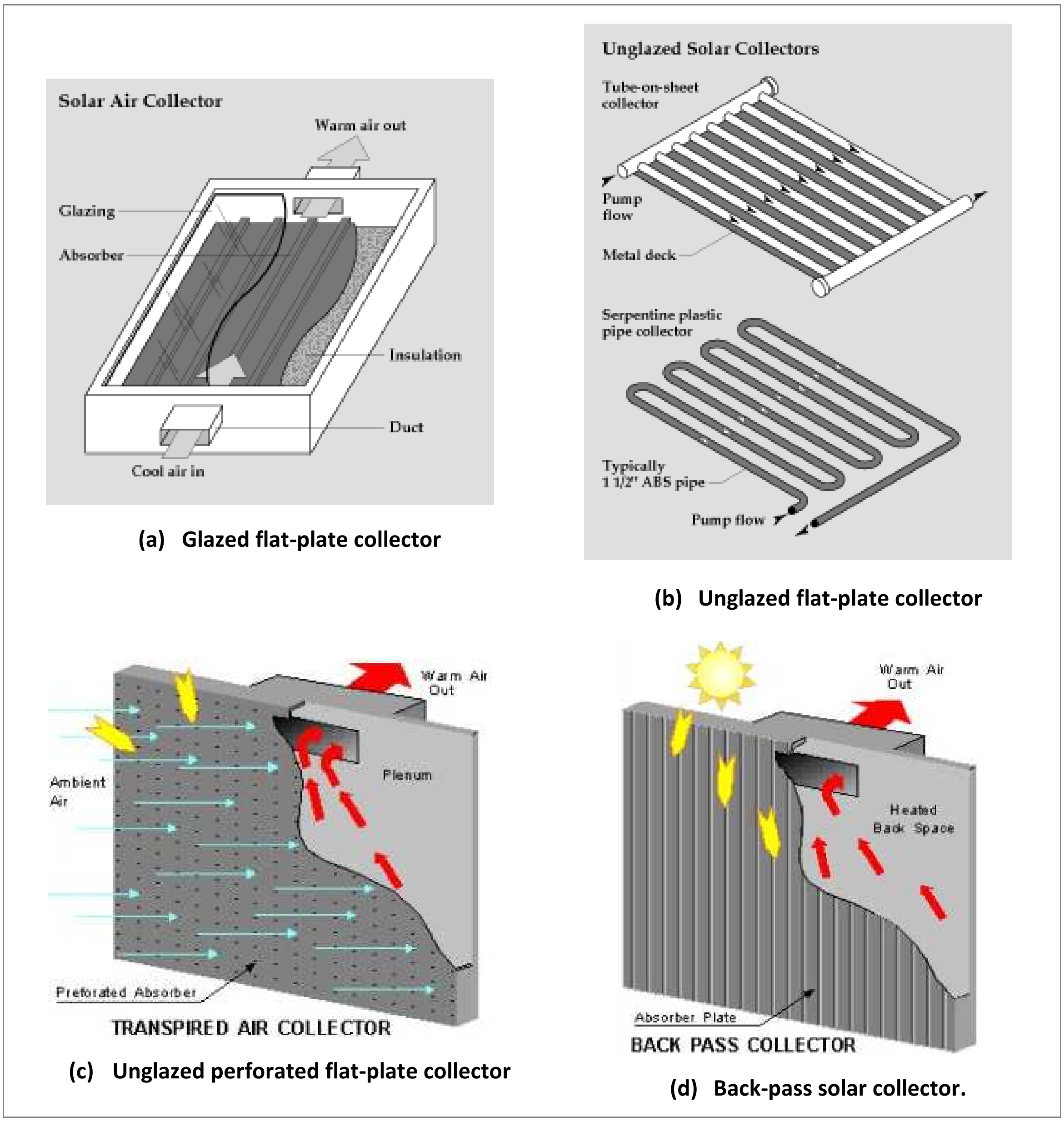
These collectors are suitable for temperatures below 30°C. Because they are not insulated, they can lose part of the absorbed radiation in windy days (Figure 10 (b)).

Unglazed perforated plate collector

It is a collector made of a cladding which is perforated. The cladding collects the heat from solar radiation and then air passes through the holes and gets heated. The air is then drawn to the inside of a building by means of a fan to provide fresh preheated air to the rooms (Figure 10 (c)).

Back-pass solar collector

This collector consists on an absorber or thermal mass material that absorbs the solar radiation. In the back of this collector, air passes by and gets heated by the heat radiated by the thermal mass before it is drawn to the inside of a building (Figure 10 (d)).



(a) **Glazed flat-plate collector**

(b) **Unglazed flat-plate collector**

(c) **Unglazed perforated flat-plate collector**

(d) **Back-pass solar collector.**

Figure 10. Air based solar collectors (Encyclopedia of Alternative Energy and Sustainable Living, 2010).

Liquid-based active solar heating

In this kind of collectors, the working fluid could be water, antifreeze (usually propylene glycol), or other type of liquid that can absorb the solar heat. The liquid is flowing through the high-pressure piping network controlled by a circulating pump. Once the liquid has passed through the collector and it has been heated, it runs into a storage tank or a heat exchanger for immediate use. The flow rate through the collector should be between 0.82 and 1.22 liters per minute per square meter of collector, in the case of using water as the heat transfer fluid (U.S. Department of Energy, 2010).

These solar collectors can be classified as non-concentrators or concentrator depending on how the collected energy is treated. In the non-concentrating type, the collector area is the same as the absorber area, which means that the whole solar thermal collector absorbs the radiation. In the case of concentrators, the radiation that falls on a surface is reflected to a specific point or absorber. The most common non-concentrating collectors are:

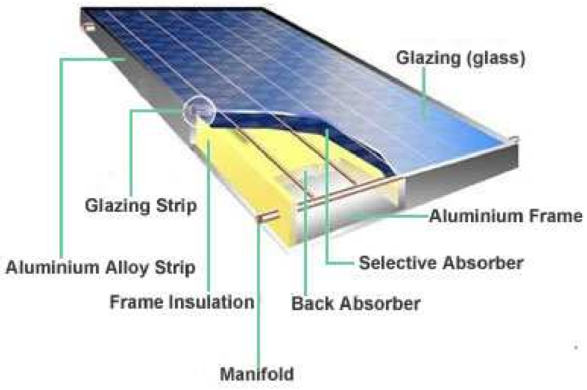
Flat-plate collector

The collector consists of a dark flat-plate absorber; a glazing that enables radiation to go through but reduces heat losses; a heat transport fluid that flows through tubes to remove the heat from the absorber; and an insulation material in the back; all fitted in an aluminum frame.

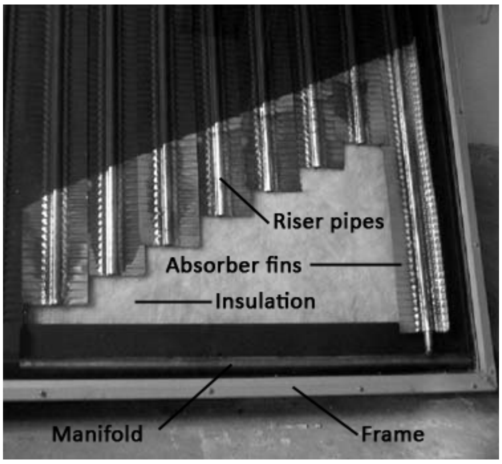
The sunlight passes through the glazing and strikes on the absorber, which is made of a high transmittance material that has a high-absorption coating. Tubes filled with heat-transport fluid (risers) run vertically through the absorber and once the fluid gets heated, it exits the collector and transfers the heat to an insulated water tank to store it by means of a heat exchanger. The risers are connected at both ends to a manifold or header, which works as inlet and outlet of the fluid. The absorber plate can be a single sheet on which all risers are fixed or each riser can be fixed on a separate fin. Each riser can be welded to the absorbing plate or they can be an integral part of the plate.

The glazing prevents convection losses by restraining the air layer that is between the absorber and the glass due to its short thickness, avoiding convective cycles. Radiation is also prevented because glass is almost transparent to shortwave radiation, but not for long wave radiation, creating a greenhouse effect in the interior of the collector.

Attention has to be paid when using collectors that have polymer absorbers because they can melt if stagnation temperature is reached. In the other hand, metal absorbers and tubing can be cracked if not drained on freezing periods (Figure 11).



(a) Pictorial view (Kender Technologies, Inc., 2009).



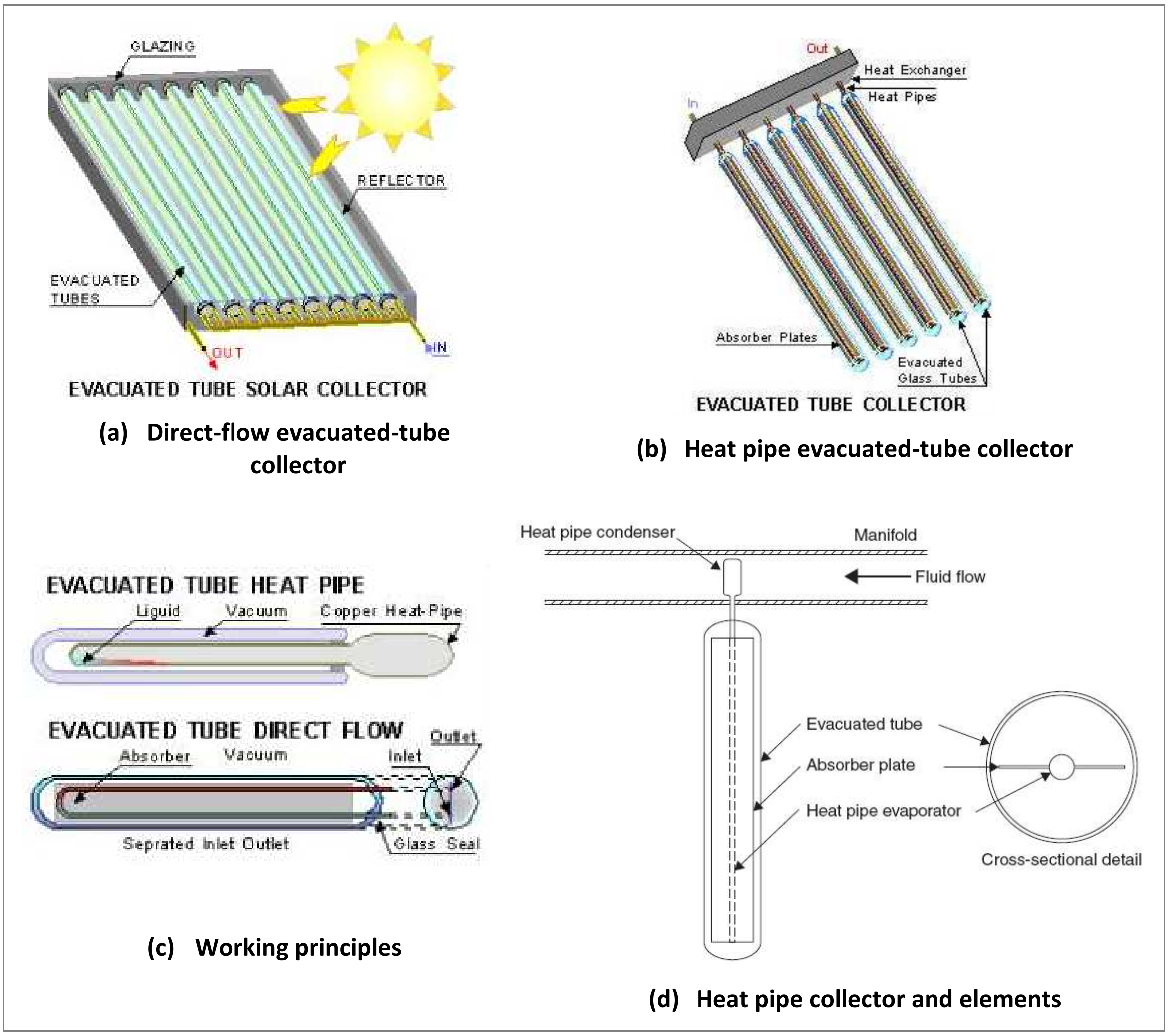
(b) Fins, risers and manifold (Kalogirou, 2009).

Figure 11. Typical flat-plate collector

Evacuated-tube collector

This collector uses liquid-vapor phase change materials to transfer heat at high efficiency. They consist of parallel rows of evacuated glass tubes that feature a fin attached to a pipe inside, which takes the heat out of the collector. The vacuum reduces the heat loss through conduction and convection; therefore they can reach higher temperatures that those of the flat plate. They can reach temperatures in the range of 70°C to 177°C, under the right set of circumstances. This kind of collectors withdraws the energy from the light, and not from the environment, making it possible to perform well in cold climates. The advantage of this collector is that the circular profile of the tube will always be perpendicular to the sun rays, and therefore, the energy collected is almost constant throughout the day time.

There are two types of evacuated-tube collectors: Direct-flow and heat pipe. The direct-flow evacuated-tube collector has a flat or curved aluminum fin attached to a metal or glass pipe. This fin is covered with a selective coating that absorbs radiation. The heat-transfer fluid runs constantly through the pipes and takes the heat from the fins. The heat pipe evacuated-tube collector consists of a heat pipe to which is attached a black copper absorber fin inside a vacuum tube. The heat pipe contains a small amount of fluid (e.g. methanol) that undergoes an evaporative-condensing cycle. In this cycle, solar heat evaporates the liquid and the vapor travels to the condenser region, where it condenses and releases it latent heat. The condensed fluid returns to the collector for the process to be repeated. (Encyclopedia of Alternative Energy and Sustainable Living, 2010); (Figure 12 (c) and (d)).



(a) Direct-flow evacuated-tube collector

(b) Heat pipe evacuated-tube collector

(c) Working principles

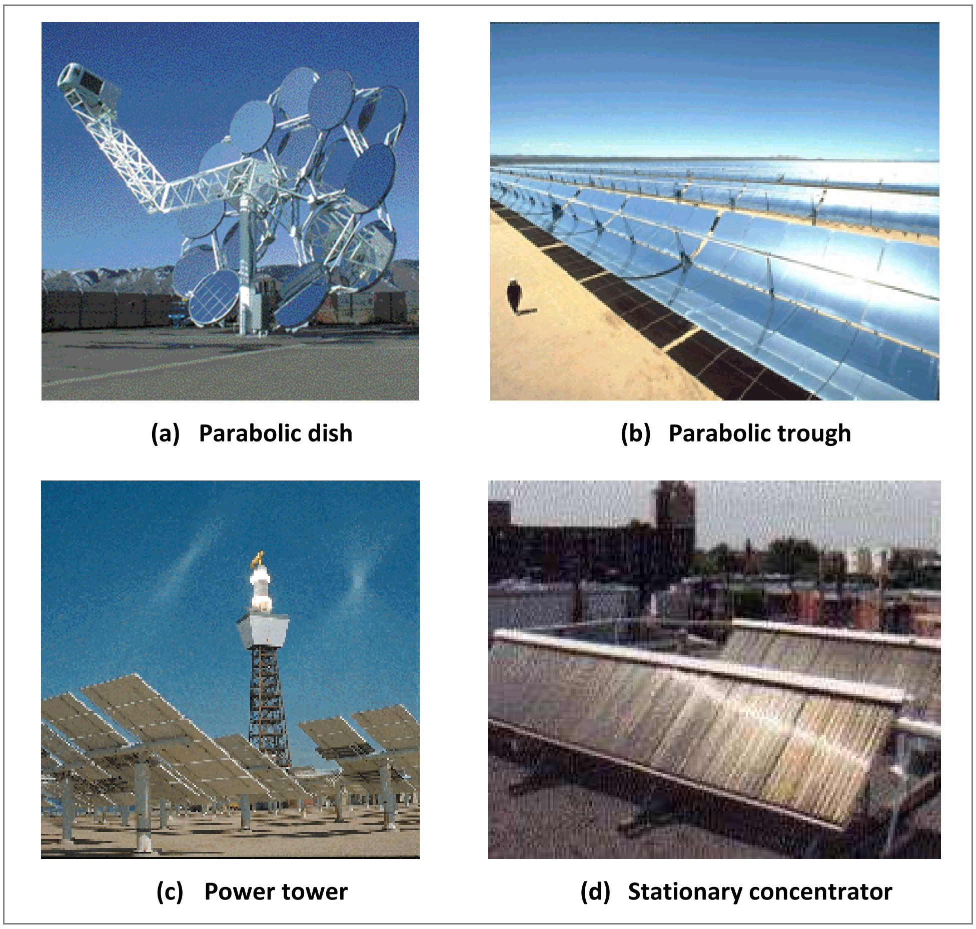
(d) Heat pipe collector and elements

Figure 12. Evacuated-tube collectors and their elements (Encyclopedia of Alternative Energy and Sustainable Living, 2010).

Concentrating collector

A concentrating collector uses reflective surfaces to re-direct the radiation into a small area, where it is absorbed. Concentrators can increase the total energy incident to the absorber hundreds of times. Thus it is used for applications where high temperatures are needed e.g. steam production or generation of electricity. The main types of concentrators are (Figure 13):

- Parabolic dish collectors
- Parabolic trough collectors
- Power towers
- Stationary concentrating collector



(a) Parabolic dish **(b) Parabolic trough**

(c) Power tower **(d) Stationary concentrator**

Figure 13. Concentrating collectors (Encyclopedia of Alternative Energy and Sustainable Living, 2010).

4.2.2 Active solar cooling

Because of the increasing energy consumption derived from cooling purposes, the most important area to work on is the cooling technology. To reduce the primary energy consumption of chillers, thermal cooling systems offer interesting alternatives especially for energy that comes from solar thermal collectors.

The main technologies for thermal cooling are close-cycle absorption and adsorption machines, which use either liquids or solids respectively for the sorption process. In both cases, the useful cold is produced through the evaporation of the refrigerant. For air-based cooling systems, desiccant cooling cycles are useful, as they directly condition the inlet air to the building.

An advantage of solar-assisted cooling technologies is that peak cooling demands often correlate with peak solar radiation which makes them suitable for inexpensive cooling production.

Absorption cooling

In this kind of cooling systems, ammonia is commonly used as refrigerant. The system works on the principle that water can absorb gas ammonia to form a highly concentrated solution. When the solution is heated in the generator, the gas ammonia comes off. The gas is then cooled down and liquefied in the condenser. Afterwards, the liquid passes to the evaporator, where the liquid ammonia becomes gas again and cools down the evaporator as it does so. Finally, the gas ammonia dissolves in water forming again the concentrated solution in the absorber and returns back to the generator where the cycle starts again (Figure 14).

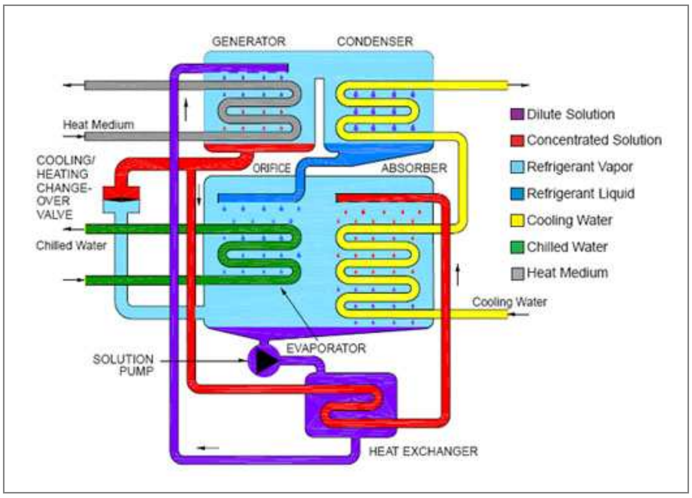


Figure 14. Absorption cooling system. (Encyclopedia of Alternative Energy and Sustainable Living, 2010)

Desiccant cooling

This technology is an open-heat driven cycle. It uses a desiccant wheel and a thermal wheel in tandem to cool and dehumidify the air. This cycle can be driven by natural gas, waste heat or heat from solar energy. Air coming in is dehumidified as it goes through the desiccant wheel. Air passes through a heat recovery wheel (thermal wheel) to extract the excessive heat. Afterwards, the air is humidified and thus further cooled, according to preset supply values. When the air is coming out, it is then humidified to its saturation point, so that it can take all the heat from the thermal wheel and to restore afterwards the desiccant wheel (Figure 15).

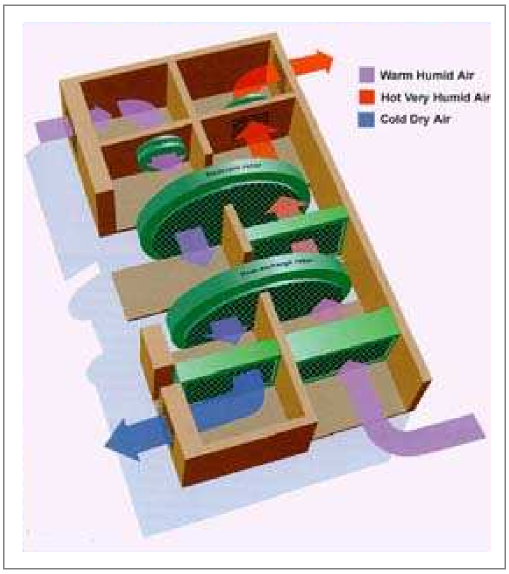


Figure 15. Desiccant cooling system. (Encyclopedia of Alternative Energy and Sustainable Living, 2010)

5 Heat transmittance devices

After the reviewing various systems, it was decided that the range of temperature for the blind collector would be up to 120°C. This means that a low-temperature type of collector should be used in this application. Some important characteristics of low-temperature collectors that are consider to be relevant for the development of the Venetian blind solar thermal collector are pointed out next:

Flat plate collector:

- The absorber plate can be divided into smaller pieces. This can relate somehow to the size of a slat of a venetian blind.
- Glazing prevents heat losses on glazed collectors, but in unglazed collectors, overheating is rapidly dissipated.
- The absorber plate is coated with a selective absorber layer.

Evacuated tube collector:

- Uses heat pipes instead of water risers to increase the heat transmission to the manifold.
- It has a dry connection between the heat pipe head and the manifold.

Solar concentrators:

- Solar tracking mechanisms

Because the collector to be developed will take the characteristics listed above, it was found important to do a deeper research on heat pipes and how heat can be transmitted to another fluid (for the case of the manifold).

5.1 Heat Pipe

A heat pipe is another type of heat transfer mechanism that employs the thermal conductivity and the change of phase to do the transfer. It is a pipe made of a high transmittance material, mostly cooper. Heat pipes have an extremely effective high thermal conductivity. While solid conductors such as aluminum, copper, graphite and diamond have thermal conductivities ranging from 250 W/mK to 1,500 W/mK, heat pipes have effective thermal conductivities that range from 5,000 W/mK to 200,000 W/mK (Thermacore, 2010). The heat pipe has its beginnings on the thermosyphon. It is helpful to describe the operation of the latter before going deep into the heat pipe.

A thermosyphon is a tube that contains a small quantity of water. This tube is evacuated and then sealed. The lower end of the tube is heated causing the water to vaporize. This vapor rises to the cold end where it condenses. The condensate returns to the hot end by gravity. Because the latent heat of evaporation is large, a high quantity of heat can be transported through even when with small temperature differences between the two ends of the tube. Thus, the structure will also have a high effective thermal conductance. The first limitation found for the thermosyphon is that the evaporator region should always be at the lowest point, so that the condensate can return by gravitational force.

The basic heat pipe differs from the thermosyphon in that a wick (inside porous layer), constructed for example from a few layers of fine gauze, is incorporated to the inside walls of a pipe, and capillary forces return the condensate to the evaporator. This enables the evaporator to be located in any position and orientation (Reay, 2006). Besides the wick, a heat pipe is filled with a refrigerant which could be water or some other liquid. Because a heat pipe is vacuum and completely sealed, the boiling point of water can be lowered so that it can work even with small temperature differences (Figure 16).

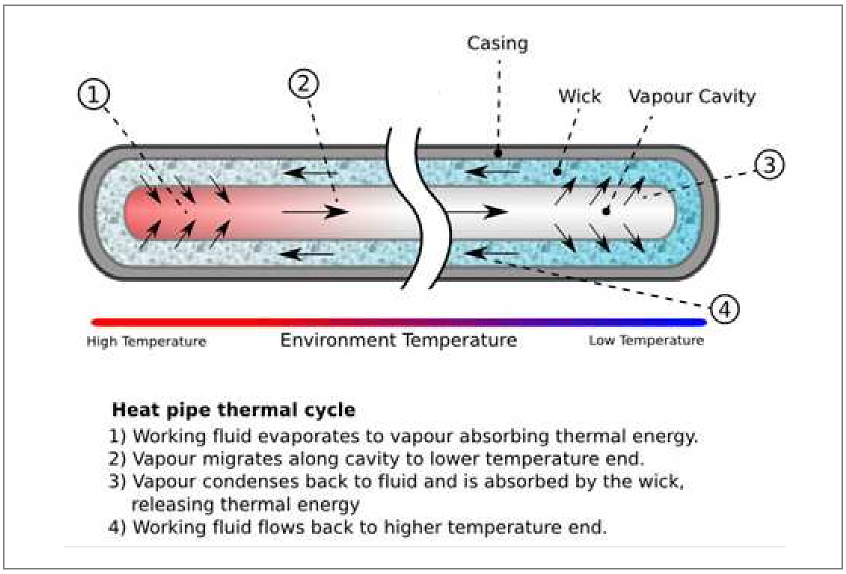


Figure 16. Heat pipe. (Encyclopedia of Alternative Energy and Sustainable Living, 2010)

Besides the basic heat pipe condensate return, there are also other methods to return the condensate to the evaporator. Those methods are listed in Table 3:

Technique	Method
Gravity	Thermal siphon
Capillary force	Standard heat pipe
	Loop heat pipe
Centripetal force	Rotating heat pipe
Electro-kinetic force	Electrohydrodynamic heat pipe
	Electro-osmotic heat pipe
Magnetic forces	Magnetohydrodynamic heat pipe
	Magnetic fluid heat pipe
Osmotic forces	Osmotic heat pipe
Bubble pump	Inverse thermal siphon

Table 3. Methods of condensate return

In a longitudinal section, a heat pipe is made up of an evaporator section and a condenser section. If external geometrical requirements make it necessary, a further adiabatic section can be included to separate the evaporator and the condenser (Figure 17(a)). The cross-section of a heat pipe consists of the container wall, the wick structure and the vapor space (Figure 17 (b)).

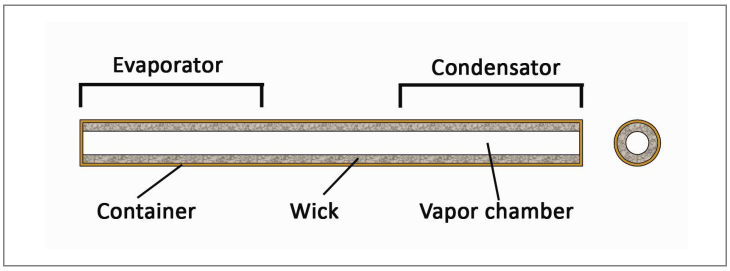


Figure 17. The main regions of the heat pipe.

A heat pipe has several characteristics that make it very suitable for heat transfer:

- Very high effective thermal conductance
- The ability to act as a thermal flux transformer
- It is an isothermal surface of low thermal impedance

Also special forms of heat pipe can be designed having the following characteristics:

- Different geometries
- Variable thermal impedance
- Loop heat pipes
- Thermal diodes and switches
- Bending and flattening

5.1.1 Operation of heat pipes

The overall thermal resistance of a heat pipe should be low, and it is defined by:

$$R = \frac{T_{hot} - T_{cold}}{\dot{Q}}$$

(Eq. 1)

Flow is induced due to a pressure difference between the evaporator and the condenser. In order for the heat pipe to operate, the maximum capillary pumping pressure, $\Delta P_{c,max}$ must be greater that the total pressure drop in the pipe. This pressure drop is made up of three components:

- The pressure drop ΔP_1 required to return the liquid from the condenser to the evaporator.
- The pressure drop ΔP_v necessary to cause the vapor to flow from the evaporator to the condenser
- The pressure due to the gravitational head, ΔP_g which may be zero, positive or negative, depending on the inclination of the heat pipe.

Therefore, for a correct operation:

$$\Delta P_{c,max} \geq \Delta P_1 + \Delta P_v + \Delta P_g$$

(Eq. 2)

If this condition is not met, the wick will dry out in the evaporator region and the heat pipe will not operate. The maximum allowable heat flux for which (Eq. 2 holds is referred to as the capillary limit. In other words, the capillary limit is the rate at which the heat pipe working fluid travels from the heat pipe condenser to the evaporator through the wick. Typically, the capillary limit will determine the maximum heat flux over much of the operating range; however, there are also some conditions that limit the heat flux.

During start-up and with certain high-temperature liquid metal heat pipes, the vapor velocity may reach sonic values. This is done because the difference in pressures can be high between evaporator and condenser; therefore the sonic velocity sets a limit on the heat pipe performance. At velocities approaching sonic, compressibility effects must be taken into account for the vapor pressure drop.

The viscous or vapor pressure limit is also generally the most important at start-up. At low temperature, the vapor pressure of the fluid in the evaporator is very low, the maximum difference in vapor pressure is insufficient to overcome viscous and gravitational forces, preventing a satisfactory operation.

At high fluxes, the vapor velocity necessarily increases; if this velocity is sufficient to entrain liquid returning to the evaporator, then the performance will decline, hence the existence of an entrainment limit that is defined as the friction between vapor and liquid travelling in opposite directions.

Finally a boiling limit is encounter when the temperature difference becomes excessive due to a critical value of heat flux; therefore the liquid vaporizes from the added heat.

5.1.2 Components of a heat pipe

Working fluid

The first consideration for the selection of the working fluid is to identify its operating vapor temperature range. There might be several possible working fluids for that temperature range; therefore some requirements must be taken into account:

- Compatibility with wick and wall materials

- Good thermal stability
- Wettability[1] of wick and wall materials
- Vapor pressures not too high or low over the operating temperature range
- High latent heat
- High thermal conductivity
- Low liquid and vapor viscosities
- High surface tension
- Acceptable freezing or pouring point

A table enlisting different working fluids and their temperature range can be found in Appendix 3. It is important to note that heat pipes are not functional when the temperature of the heat pipe is lower than the freezing point of the heat pipe working fluid. Freezing and thawing of heat pipes is a design issue, which may destroy the sealed joint of a heat pipe when placed vertically.

The wick or capillary structure

The first purpose of the wick is to generate capillary pressure to transport the working fluid from the condenser to the evaporator, thus, the selection of a wick material depends mostly on the properties of the working fluid. It must also be able to distribute the liquid around the evaporator section to any areas where the heat is likely to be received by the heat pipe. Often to fulfill these two functions, two types of wick are required, particularly where the condensate has to return over a distance larger than 1 m, in 0 gravity.

The maximum capillary head generated by a wick increases with decreasing pore size, while the wick permeability, which is also desired, increases with increasing the pore size. Low-performance wicks in horizontal and gravity assisted heat pipes should permit maximum liquid flow rate by having a large pore size.

The thickness of the wick must be optimized as well. The heat transport capability of the heat pipe is raised by increasing the wick thickness. However, the increased radial thermal resistance of the wick created by this would work against the increased transport capability and would lower the maximum evaporator heat flux.

There are many different wick forms available, meshes and twills are the most common. They can be found in a wide range of pore sizes and materials e.g. stainless steel, nickel, copper and aluminum. There are also homogenous wicks made of metal foams and felts
A table showing radial heat fluxes for some workings fluids and wick materials can be found in Appendix 3.

[1] It refers to a fluid that when in contact with solid surfaces it experiences attraction forces "wetting" the solid, and therefore, allowing capillarity (e.g. water).

The container

The function of the container is to isolate the working fluid from the outside environment, therefore it has to be leak-proof and maintain the pressure across its walls at the same time that it enables the heat transfer. The selection of the material for the container depends on various factors:

- Compatibility with working fluid and surrounding environment
- Strength to support its own weight and that of the wick and the fluid
- Good thermal conductivity
- Ease of fabrication, weldability and machineability
- Non Porous
- Wettability

5.1.3 Manufacturing of heat pipes

Out of all the materials available, copper, aluminum and stainless steel are the most common materials for producing heat pipes. Tubes of any of these materials readily available and can be obtained in a wide variety of diameter. Even though commercial copper can be used, it is preferred to use the oxygen-free high-conductivity cooper.

There are three types of wick that are commonly used: Wire mesh, sintered wick and grooved wick. The most common is indeed the woven wire mesh, which can be made of many materials, but stainless steel, monel and copper are extendedly used due to the capacity of having small pore sizes. Stainless steel meshes are the most easy to handle.

For fixing a mesh wick in a pipe, several methods can be used. If the mesh has inherent springiness it can be rolled and fitted to the inside of the tube. The springiness will keep it against the heat pipe wall. Some meshes can also be diffusion bonded to the pipe, giving a stronger and permanent attachment to the wall of the pipe. Another way to fit the mesh inside is to spot weld the wick. This is only possible with the pipe is big enough to accommodate an electrode inside while welding (Figure 18 (a)).

For a sintered wick, the process involves bonding together a large number of particles in the form of packed metal powder. Therefore, the pore size can be easily selected. The simplest way to make a wick by sintering is to sinter the powder in the final container tube; the advantage of this process is that the wick is also sintered to the tube, creating a strong bond. First, a temporary mandrel is placed in the center of the heat pipe tube, and then the metal powder is poured in the space between the tube and the mandrel. After sintering, the mandrel is removed and the heat pipe in re-sintered in order to bond the part that was in contact with the mandrel (Figure 18 (b)).

Finally, the groove wick is normally used in aerospace engineering. It is made of an extrusion of a tube with groves already made in the interior wall (Figure 18 (c)).

Figure 18. Different wick on heat pipes (Frosty Tech, 2010).

5.2 Heat Storage

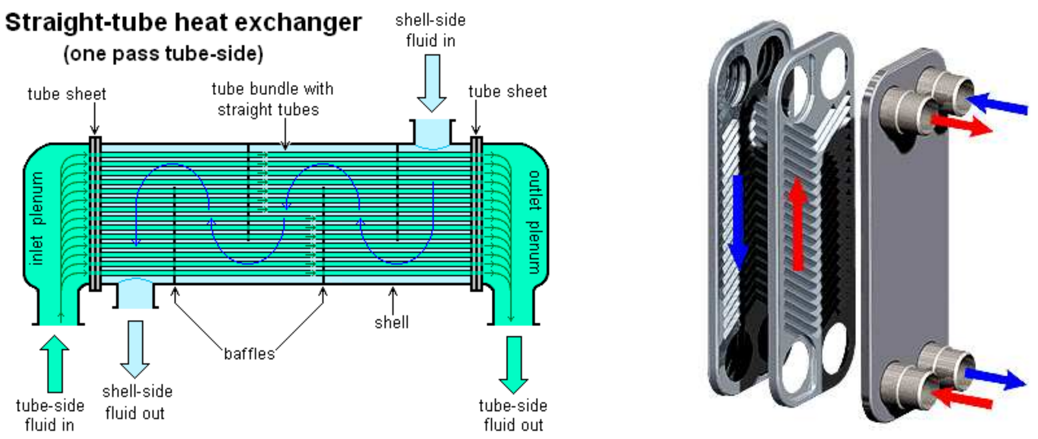
The thermal energy storage refers to the accumulation of heat in a reservoir for a later use. Normally, the thermal storage maintains temperature above the ambient, but it can also be kept at lower temperatures. Thermal energy storages store heat from the active solar collectors in an insulted repository for a later use. Most active solar heating systems have storages with a capacity of few hours to a day heat collected. The use of seasonal thermal stores is increasing, so that the summer collected heat can be used for winter space heating. It has been calculated that one cubic meter of water can store 334 MJ.

5.3 Heat exchange

5.3.1 Heat exchanger

It is a device that is used to transfer heat from a fluid to another. It enables the heat transfer between two different media, even though the fluids are physically separated. There are different types of heat exchangers depending on the fluids that are used and the way the exchange is done. The most common heat exchangers are the shell and tube and the plate exchangers.

The shell and tube heat exchanger consist of a series of tubes that contain fluid that are immersed in a shell or chamber that contains another fluid. Either fluid can dissipate or obtain heat in order to transfer it to the other fluid (Figure 19 (a)). Plate heat exchanger is integrated by multiple, thin, slightly-separated plates that have very large surface areas and fluid flows through for heat transfer. This type of heat exchanger could be better for those applications where there is not much space available (Figure 19(b)).



(a) Shell and tube heat exchanger **(b) Plate heat exchanger**

Figure 19. Heat Exchangers (Wikipedia under *heat exchangers*, 2010).

5.3.2 Manifold heat exchanger

A manifold heat exchanger is a method to supply cold fluid to a set of smaller pipes or collect heat from the set of pipes and carry it through the main current. The fluid inside the manifold and the pipes can be in direct or indirect physical contact. When the fluid is in direct contact, it comes through a manifold of cold fluid, circulates through the pipes, taking heat out from the system in its way and exists through a second manifold (Figure 20 (a)).This type of manifold in normally used in the flat plate collectors. When the fluids have no physical contact, the pipes containing the hot fluid will transfer the heat to the manifold fluid through the walls of the pipes, which are in contact with the manifold fluid (Figure 20 (b)). This type of manifold is usually found on evacuated tube collectors that use heat pipes.

(a1) Direct heat transfer manifold (Reuk, 2006).

(b1) Indirect heat transfer manifold.

(a2) Direct heat transfer manifold in flat plate collector (Radiant Floor Company, 2009).

(b2) Indirect heat transfer manifold in evacuated tube collector (Hadi Solar, 2010).

Figure 20. Manifold heat exchanger.

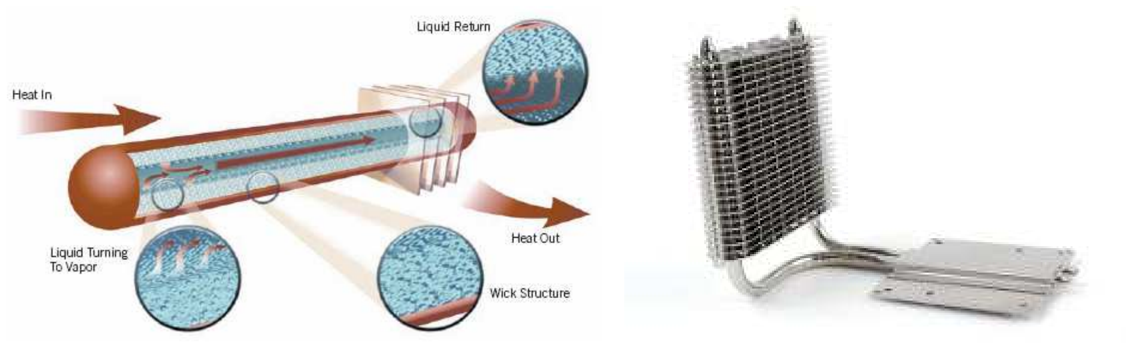
5.3.3 Heat sink

A heat sink is a component that transfers heat generated on a solid material to another medium. Heat sinks are intended to increase the amount of surface from which the heat is given away or received, in order to have a better heat transfer. Normally heat sinks are used in electronics applications such as computers and graphic processors to reduce its temperature.
The heat transfer on a heat sink is done by two effects: conduction via the surrounding fluid and by thermal radiation. The surface of the heat sink influences the emissivity, if the surfaces are shiny or metallic, only a small part of the heat is absorbed by the heat sink and therefore little is given out. Matte black absorbs heat better and therefore heat is given away easier. The most common types of heat sinks are the pin and fin heat sinks (Figure 21).

(a) Pin heat sink. **(b) Straight fin heat sink.** **(c) Flared fin heat sink.**

Figure 21. Different types of Heat Sinks (Wikipedia under *heat sink*, 2011).

Heat sinks can be attached to almost any thermal device that need heat dissipation. In some electronic applications, a heat sink is attached to the condenser of the heat pipes that drive the heat from the processor to the outside (Figure 22). In the case of the Venetian Blind Solar Thermal Collector, a heat sink will be used to transmit heat from the heat pipe to the manifold in the retractable slats.



(a) Pictorial view of heat pipe with heat sink at condenser. **(b) Heat sink and heat pipe for an electronic device.**

Figure 22. Heat pipe attached to heat sink. (Power Electronics Technology, 2011).

6 System overview

After researching the various devices that are available, a final idea of collector was developed. The system overview shows the working principles of the thermal collector and how it is connected to the overall system for heating and cooling.

6.1 Venetian Blind Solar Thermal Collector

With the addition of the Venetian Blind and the characteristics taken from the solar collectors mentioned above, the basic idea of the Venetian Blind Solar Thermal Collector (VBSTC) is outlined. Similar to a flat-plate collector, a VBSTC has an absorber surface and a riser that takes the heat out from the collector (Figure 23). The main parts of the VBSTC are next described as well as the name that will be used to refer to them throughout the thesis.

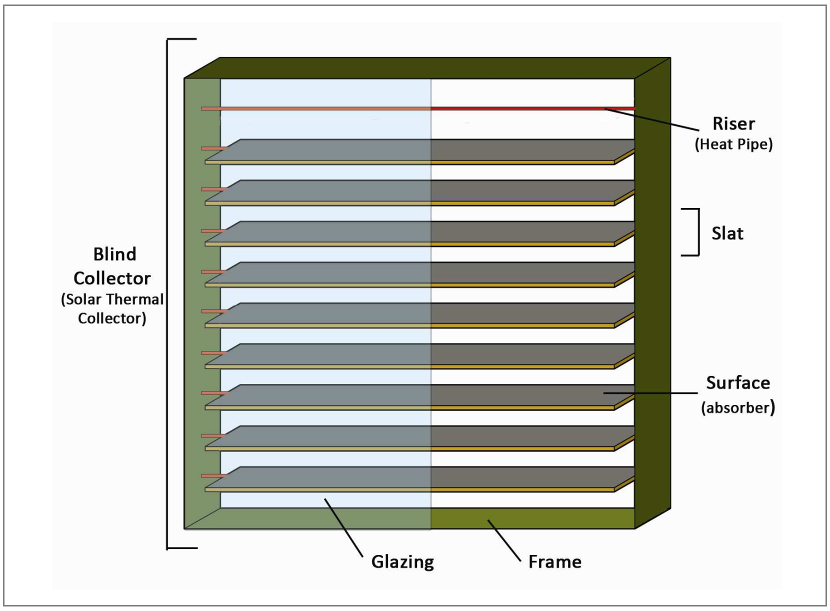


Figure 23. Parts of a Venetian Blind Solar Thermal Collector.

Blind collector

This is the generic name that will be used throughout the thesis to refer to a Venetian Blind Solar Thermal Collector. A blind collector comprises the absorber surfaces, risers, frame and glazing (if used).

Slat

A slat is each of the lamellas of fins that form a blind. In a regular Venetian Blind, the slats are rotated in order to adjust the amount of light that enters a room. For the blind collector, besides the light adjustment, the slats are rotated to track the sun path to maximize the radiation incident on them. They also work as substrate for the absorber surface or coating.

Absorber Surface

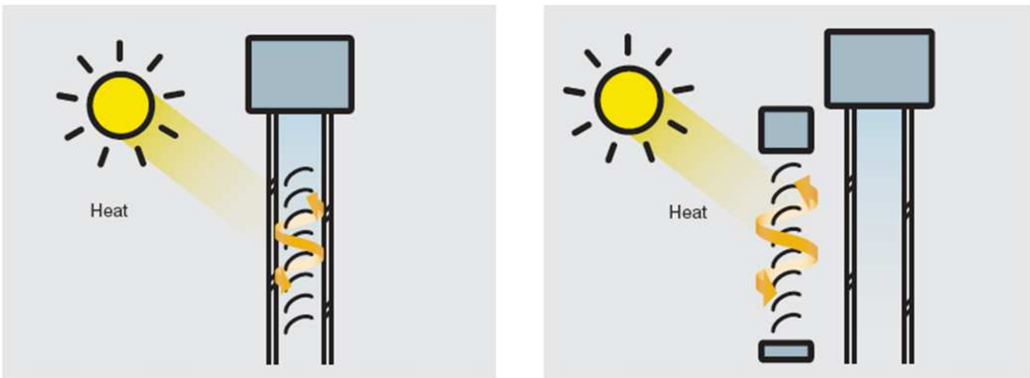
It is the surface that will always be facing towards the sun. This surface absorbs the radiation and then transmits it to the slat. In the case of the current thesis, the surface is a selective coating that is applied to the slat (substrate) and has an absorption coefficient of 0.95 of all solar radiation that is incident at normal. Such selective coating will be described in dept later on.

Heat Pipe

Even though a heat pipe works in a closed loop, it can be consider as a riser because it withdraws the heat from the slat and carries it to the main network that gathers heat from all blind collectors.

Glazing

The glazing is the layer place in front of the slats of a blind collector to protect them from weathering. Regular flat-plate collectors may or may not have a glazing layer. For this research, both options are going to be analyzed, using a different façade setup for each one. In double skin façades, the blind collector can be placed within the cavity, so that the external skin can also function as glazing for the blind collectors. This type of placement will be specified as *cavity blind collector* (Figure 24 (a)). For all types of facades, the blind collector may be placed in front of the façade, and it that case, the blind collector will be identified as *external blind collector* (Figure 24 (b)).



(a) Cavity blind collector **(b) External Blind Collector**

Figure 24. Blind collector placed inside the cavity and in front of the façade (Zumbotel, 2010).

6.2 Overall system

The overall heat management system is divided into three parts (Figure 26). The first part comprises the collection of solar thermal energy through the blind collector. This section is a closed loop mechanism driven by the slats that have a high absorbing coating and are connected to a heat pipe (riser) underneath. The heat pipe takes the heat from the slat and drives it to the antifreeze network (second section) (Figure 25). This heat pipe should be insulated in order to prevent heat losses before the heat reaches the second section of the system.

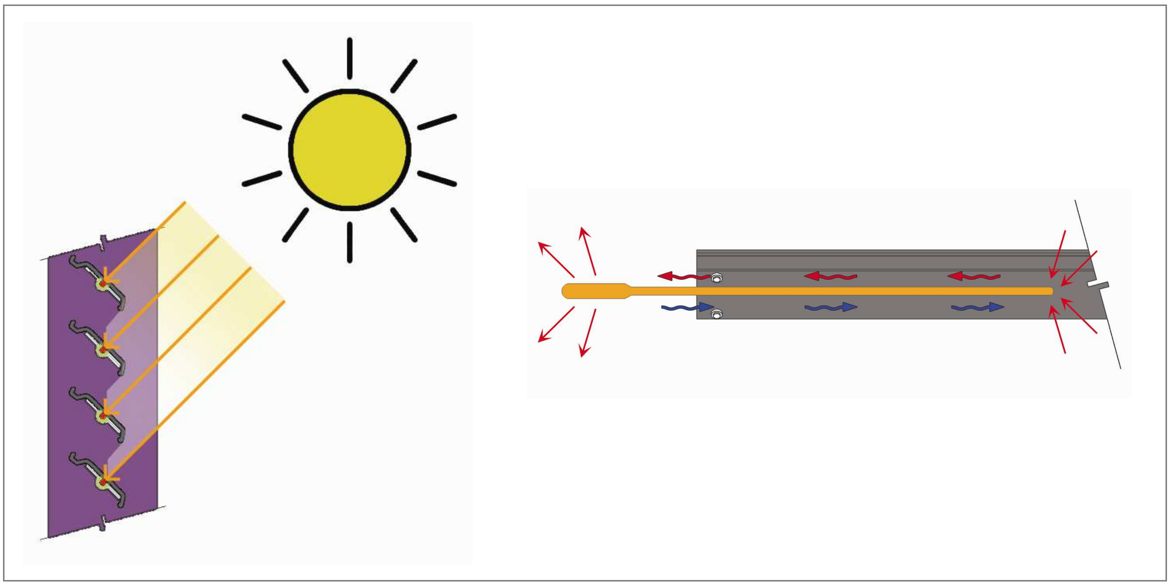


Figure 25. First part of the system: Collection of solar thermal energy through slats in a venetian blind.

The second section consists of a series of tubes that run antifreeze in a close loop scheme, and works as a heat transmittance medium from the blind collector until the final destination (antifreeze network) (Figure 26). The antifreeze network starts with the manifold that receives the heat from the heat pipe, and gives it out through a heat exchanger which is in contact with the third phase of the system. The antifreeze solution is made of propylene glycol and is stored in an antifreeze reservoir from where it is pumped into the façade at the bottom and drives the heat out from the blind collector, exiting on an opposite point at the top of the façade panel. The antifreeze is then driven to a heat exchanger into a storage tank, where it loses all the heat that it carries; and finally it returns back to the antifreeze reservoir.

The third part consists of a solar heating or cooling cycle that produces conditioned air for the rooms inside the building. These systems need a source of heat to work which is provided by the antifreeze solution in the second section.

For the objectives of this paper, only the first part of the system and its connection to the second one is going to be developed in detail.

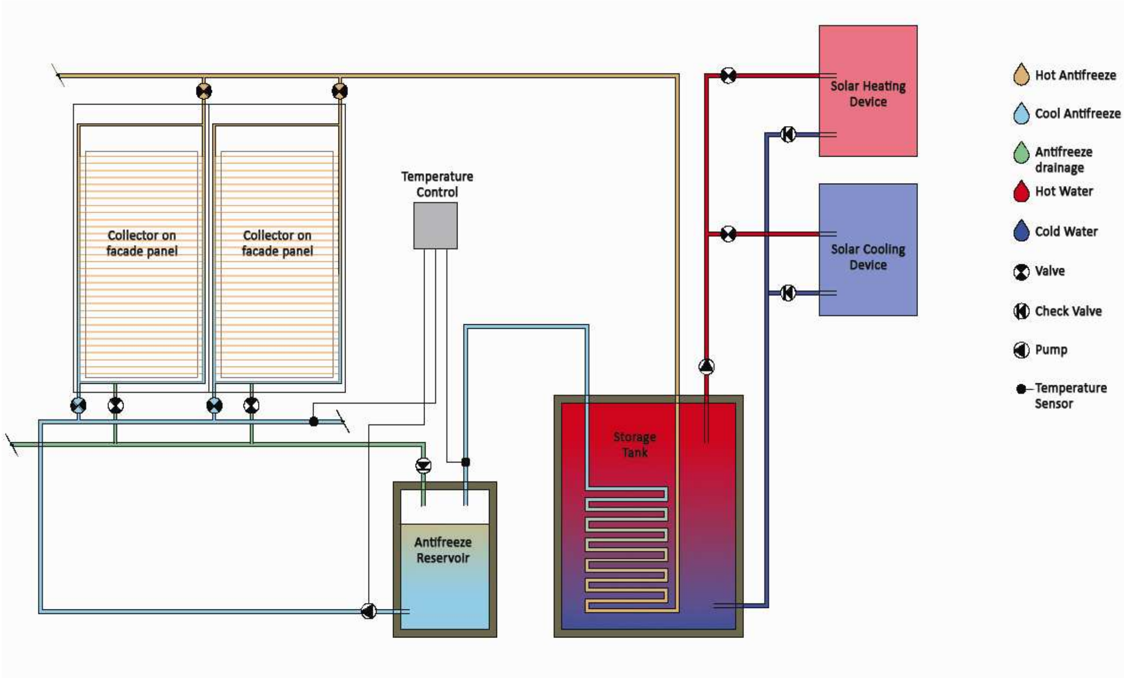


Figure 26. Solar thermal collection and cooling/heating systems interconnected.

During daytime, the collectors absorb solar radiation and the system conveys the heat to the storage tank using antifreeze. As the building requires heat, it is taken from the storage tank. The control of the overall solar energy system is done by differential temperature controllers. These controllers can act as switches for pumps in case of freezing or overheating.

Depending on the conditions of a particular building at a certain time, the system will have five basic modes of operation:

Solar energy	Heat	Storage tank	Action
Available	Not required	Depleted	Heat is stored in the tank
Available	Required	Depleted	Energy is used to supply demand
Not available	Required	Heated	Stored energy is used to supply demand
Not available	Required	Depleted	Auxiliary energy has to be used
Available	Not required	Fully heated	Energy is discarded by dissipation, moving blinds inwards and opening relief valves

Table 4. Modes of operation for a blind collector.

6.3 Scenarios for research

In order to determine the best configuration for the blinds, some scenarios were defined so that their performance can be evaluated and then compared to each other. The blind collectors will be evaluated depending on the façade they are on. In each facade a calculation will be done for four different solar tracking modes: solar tracking with hourly angle adjustment; solar tracking with daily angle adjustment; solar tracking with monthly angle adjustment; and fixed angle throughout the year. For each of the scenarios mentioned, the possibility to differentiate the blinds from external blinds or cavity blinds is also going to be taken into account.

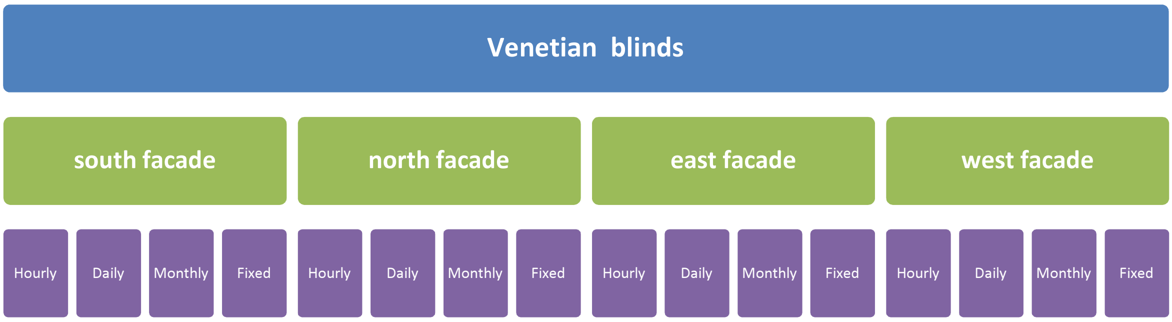


Figure 27. Blind scenarios to be analyzed.

In the other hand, the blind collector can also have two different degrees of movement independently from the way they track the sun. They can be fixed in front of the façade panel or they can be retractable, leaving a clear and unblocked view to the outside. Figure 28 shows a scheme of two blind collectors. Figure 28 (a) is a blind that tilts but is fixed in its spot, while Figure 23 (b) shows a blind that tilts and also retracts to clear up the façade.

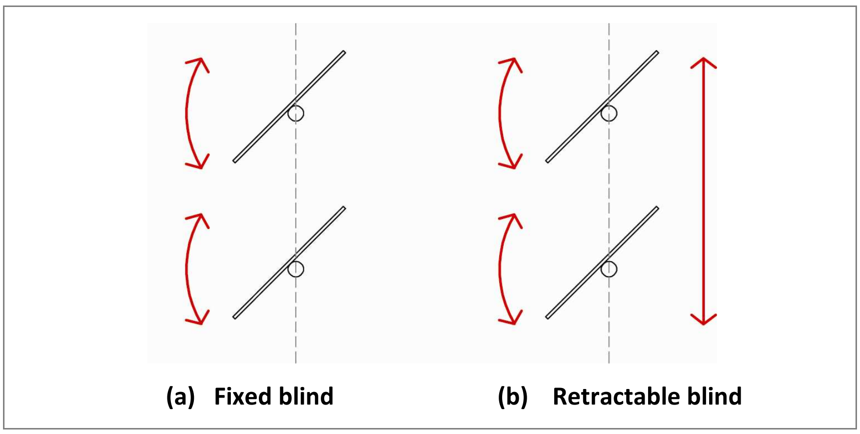


Figure 28. Degrees of movement of blinds.

Both degrees of movement have some advantages and disadvantages. The blind with a fixed location has a better heat collection because is exposed to solar radiation at all times, but the view to the outside is diminished. The retractable blind allows a better view to the outside and a better natural light income. The down fall for this blind is the lower radiation collection and a complex mechanism to work properly.

6.4 Selection of Cities

In order to propose a solution that best meets the condition for different latitudes, seven different cities were chosen as representative. The latitude between the cities varies approximately in 10°. Those cities are listed below:

Latitude around	City	Country	Latitude	Longitude
0°	Singapore	Singapore	1°17' N	103°51'E
10°	Caracas	Venezuela	10°30'N	66°56'W
20°	Mexico City	Mexico	19°41'N	99°13'W
30°	Shanghai	China	31°10'N	121°28'E
40°	New York	USA	40°43'N	74°00'E
50°	Amsterdam	Netherlands	52°22'N	4°54'E
60°	Helsinki	Finland	60°12'N	24°56'E

Table 5. Cities to analyze and their latitude.

For those cities, the sun position was defined for each day and hour of a year, according to the latitude and the declination of the sun at each particular hour. See Appendix 1 for sun path diagrams.

7 Absorbed solar radiation: Calculation method

The main objective of the analysis is to obtain an impression on how different configurations of blind collectors can assist the energy demand of a building. The calculation will detect how much solar radiation can be absorbed and transmitted as useful energy. In order to do so, a series of steps have to be done:

1. *Solar radiation data*
   Solar radiation data has to be acquired. Hourly data is needed in order to get a better examination of the radiation absorption in blind collectors, especially for those that track the sun hourly.

2. *Sun path and direction of radiation*
   The elevation and azimuth of the sun should be calculated for each hour of the year to determine the direction from which the radiation will strike the blind collector.

3. *Surface alignment and solar tracking*
   After the direction of the radiation is know, the absorber surfaces have to be aligned towards this direction to enhance the solar radiation absorption. The angle of alignment is then calculated.

4. *Radiation on sloped surfaces*
   The amount of global radiation falling on a sloped surface is defined from that falling on a horizontal surface.

5. *Shadow casting on surfaces*
   Because the slats of a Venetian blind are displayed one on top of another, shading between each other is created, reducing the total absorption of the blind collector. Therefore the amount of shaded area in the slats should be found geometrically.

6. *Absorption coefficient*
   Because the absorption of a material depends on the angle of incidence of the radiation, the shading, the absorption coefficient for beam, diffuse and reflected radiation is calculated according the angle of alignment of the surfaces.

7. *Absorption of radiation in external blinds*
   Absorption of radiation is determined from solar radiation data, according to the angle of incidence of the radiation, angle of the surface and coefficient of absorption.

8. *Absorption of radiation in cavity blinds*
   This calculation of the absorption takes into account the reduction of radiation due to glazing.

9. *Thermal losses from the slats*
   The temperature of the slats is defined and subsequently the thermal losses in steady state are calculated for both types of blind collectors.

10. *Useful energy*
    The net energy, which is the energy that is going to be transmitted to the antifreeze network, is calculated for both blind situations.

After the energy comparison was done for each city, two of the cities were selected for further analysis. This analysis includes:

11. *Standard room*
    A standard room will be defined, so that all the further analysis can be directly related to a specific room setup.

12. *Energy loads*
    The heat loads of the standard room are defined for both selected cities. This will give an idea of the amount of energy needed for heating and cooling.

13. *Auxiliary solar energy*
    The amount of energy generated by the blind collector will be compared to the energy loads from the room, in order to know the percentage of energy input that the blind if offering per square meter.

14. *Natural lighting*
    An optimization of the blind will be done in order to let daylight inside the room, during office hours.

7.1 Terminology and symbols

Most of the calculations done in this thesis are based on equations taken from (Duffie, 2006). For a better understanding of those calculations, the definitions of the terminology and symbols of those equations that are shown next were taken from that author in order to be consistent with the equations.

Air mass m: Ratio of the mass of atmosphere through which beam radiation passes to the mass it would pass through if the sun were at the zenith. Thus at sea level, $m = 1$ when the sun is at zenith, and $m = 2$ for a zenith angle θ_z of 60°. For zenith angles from 0° to 70° at sea level, to a close approximation, m

$$m = {}^{1}/_{\cos\theta_z}$$

(Eq. 3)

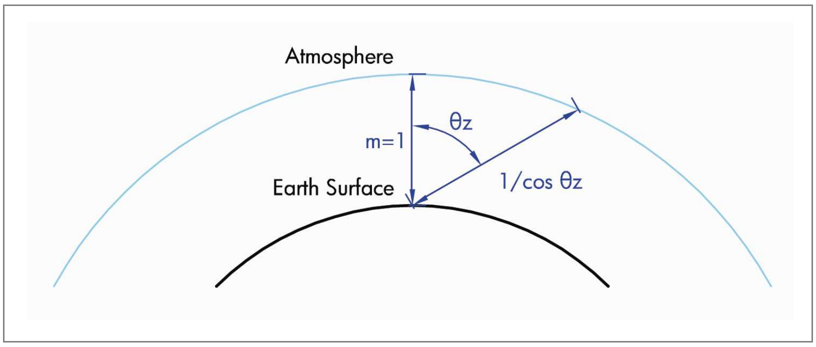


Figure 29. Air mass for a certain point in earth surface.

Beam Radiation: Solar radiation received from the sun without having been scattered by the atmosphere. (Beam radiation is often referred to as direct solar radiation. Here the term beam is used to avoid confusion between direct and diffuse subscripts).

Diffuse Radiation: Solar radiation received from the sun after its direction has been changed by scattering by the atmosphere.

Total Solar Radiation: The sum of the beam and the diffuse solar radiation on a surface (The total solar radiation is sometimes used to indicate quantities integrated over a wavelength of the solar spectrum). The most common measurements of solar radiation are total radiation on a horizontal surface, often referred as global radiation on a surface.

Irradiance, W/m^2: Rate at which radiant energy is incident on a surface, per unit area of surface. The symbol G is used for solar irradiance, with appropriate subscripts for beam b, diffuse d, or spectral radiation s.

Irradiation or Radiant Exposure, J/m^2: The incident energy per unit area on a surface, found by integration of irradiance over a specific time, usually an hour or a day. Insolation is a term applying specifically to solar energy radiation. The symbol H is used for insolation for a day. The symbol I is used for insolation for an hour (or period of time specified). The symbols H and I can represent beam, diffuse or total and can be on surfaces of any orientation.
Subscripts in G, H and I are as follows:

o refers to radiation above earth's atmosphere, referred to as extraterrestrial radiation.
b and ***d*** refer to beam and diffuse radiation respectively.
T and ***n*** refer to radiation on a tilted plane and on a plane normal to the direction on the propagation. If neither T nor n appear, the radiation is on a horizontal plane.

Radiosity or **Radiant Exitance**, W/m^2: The rate at which radiant energy leaves a surface, per unit area, by combined emission, reflection, and transmission.

Emissive Power or **Radiant Self-Exitance**, W/m^2: The rate at which radiant energy leaves a surface per unit area, by emission only.

Solar Time: Time based on the apparent angular motion of the sun across the sky; with solar noon the time the sun crosses the meridian of the observer. Solar time is the time used in all of the sun–angle relationships. It does not coincide with the local time, it is necessary to convert standard time to solar time by applying corrections.

Geometric relations between solar radiation and the plane of any particular orientation can be described in terms of several angles, which are indicated next:

$\boldsymbol{\varphi}$ **Latitude**: the angular location north or south of the equator, being north positive; $-90° \le \varphi \le 90°$.

δ **Declination**: the angular position of the sun at solar noon with respect to the plane of the equator, being north positive; -23.45° ≤ δ ≤ 23.45°.

β **Slope**: the angle between the plane of the surface in question and the horizontal; 0 ≤ β ≤ 180°. (β > 90° means that the surface has a downward facing component).

γ **Surface azimuth angle**: the deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, with zero due south, east negative , and west positive; -180° ≤ γ ≤ 180°.

ω **Hour angle**: the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour, morning negative, afternoon positive.

θ **Angle of incidence**: the angle between the beam radiation on a surface and the normal to that surface.

θ_z **Zenith angle:** the angle between the vertical and the line to the sun.

α_s **Solar altitude angle**: the angle between the horizontal and the line to the sun; it is component of the zenith angle.

γ_s **Solar azimuth angle**: the angular displacement from south of the projection of beam radiation on the horizontal plane. Displacements east of south are negative and west of south are positive.

7.2 Solar Radiation Data

Extraterrestrial radiation is weakened in the atmosphere by absorption and reflection and partly converted by dispersion into diffuse radiation. The relative air mass *m* which solar radiation has to pass through also determines the amount of radiation absorbed or scattered.

In order to know the amount of solar radiation, it is not very wise to base calculations on the attenuation of the extraterrestrial radiation by the atmosphere i.e. turbidity factors, because according to Duffie (2006), it results in extremely inaccurate radiation values. Instead, to predict the performance of solar processes, measurements of solar radiation from previous years are used.

Normally the available radiation data accounts for beam and diffuse solar radiation on a horizontal surface per hour, which is normally used in simulation of normal processes. Daily data is also commonly available and hourly radiation can be estimated form this data. Monthly solar radiation is also available, but it is not recommended to be used due to nonlinearities of the solar processes, which are not taken into account in the monthly data.

The solar data can come in different forms. It can be instantaneous measurements (irradiance W/m^2) or integrated over a period of time (irradiation MJ/m^2). It is important to be aware of the time period of the measurements, the type of radiation measured (beam, diffuse or global), the receiving surface orientation and the period over which they are averaged if they are.

Most radiation data is measured on horizontal surfaces. Two types of data are widely available: Monthly average daily total radiation on a horizontal surface *H*; and hourly total radiation on a horizontal surface *I*.

For this research, the irradiation data (MJ/m^2) for each hour (*I*) of the year was taken from METEONORM 5.1 software. METEONORM is specialized software for calculating the irradiance, incident irradiation in an hour, monthly average daily radiation and monthly radiation on horizontal and inclined surfaces, through interpolating values from different meteorological stations around the world.

The irradiation data taken from METEONORM is already divided into beam radiation I_b, diffuse radiation I_d and global radiation *I*, so no calculations were done to calculate each one of them. Radiation will be given in MJ/m^2, since it makes easier to sum up the energy.

7.3 Sun path and direction of radiation

For any technical application of solar energy, it is of great importance to know the position of the sun in the sky dome in order to know the direction and incidence angle of the solar radiation that falls on the solar collector. The compilation of the sun positions throughout the year is known as the sun path and it is given by the solar altitude angle α_s which describes how high the sun appears in the sky; and the solar azimuth angle γ_s, which tells the coordinate quadrant in which the sun is located in a horizontal plane. Both angles are measured in a spherical coordinate system.

The solar altitude angle α_s is formed by the vector between the observer and the sun, and the horizontal plane in which the observer is standing. The solar azimuth angle γ_s, refers to the angle formed by the projection of such vector on a horizontal plane and the south (for north hemisphere) or north (for the south hemisphere) (Figure 30).

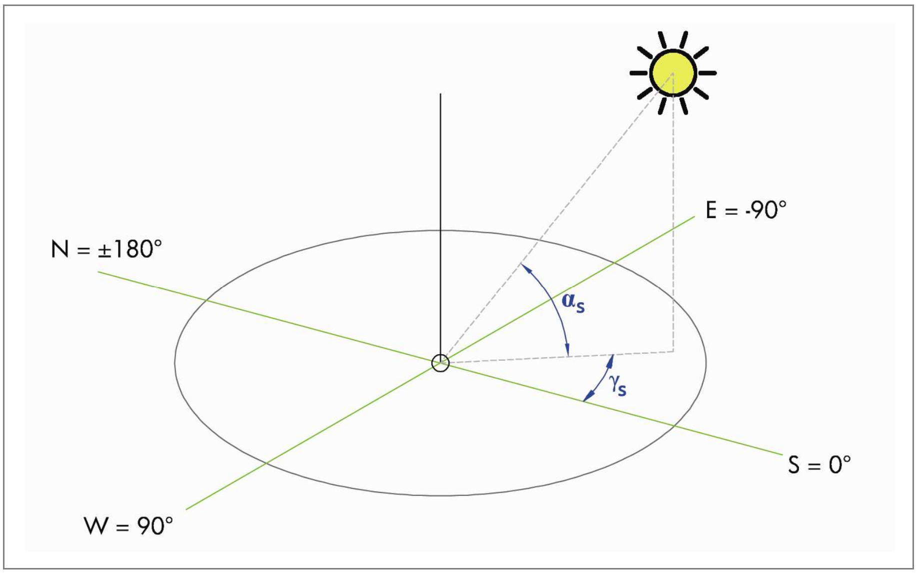


Figure 30. Solar altitude angle α_s and Solar azimuth angle γ_s.

7.3.1 Solar Altitude Angle α_s

Even though the sun remains still, the apparent path that it follows and its elevation throughout the day varies depending on the place of the earth where it is being observed due to the rotation and translation of the earth. The solar altitude angle α_s therefore, depends on the latitude of the place of interest, the day of the year, the declination of the sun and the hour of the day.

Latitude φ

The latitude φ of a place is the angle distance north or south from the equator. The furthest the place from the equator is, the lower the solar altitude angle would be. For the purpose of this thesis, latitudes on north are positive and latitudes on south are negative.

Number of day n

The number of day in the year relates to position of the earth relative to the sun while translating in its orbit. The number of day of the year *n* can be obtained easily using the *Table of Recommended average days for months and values of n*, shown in Table 6, from Klein (1977).

Month	n for i th Day of the Month	For the average Day of the Month		
		Date	n Day of the year	δ Declination
January	i	17	17	-20.9
February	31 + i	16	47	-13.0
March	59 + i	16	75	-2.4
April	90 + i	15	105	9.4
May	120 + i	15	135	18.8
June	151 + i	11	162	23.1
July	181 + i	17	198	21.2
August	212 + i	16	228	13.5
September	243 + i	15	258	2.2
October	273 + i	15	288	-9.6
November	304 + i	14	318	-18.9
December	334 + i	10	344	-23.0

Table 6. Recommended Average Days for Months and Values of n by Months.

Declination δ

The declination of the sun δ is the angle between the rays of the sun and the plane of the earth's equator at solar noon. Because the Earth has an axial tilt of approximately 23.45°, at the solstices, the angle between the rays of the sun and the plane of the earth's equator reaches the value of 23.45°. The declination of the sun is a function of time which varies over the seasons depending on the translation of the earth. The maximum declination that can be obtained is in the equinoxes and is (±) 23.45° (Figure 31). The declination is about 0.5° per day and it can be obtained from the equation proposed by Copper (1969). Declinations towards the north are positive and those towards south are negative.

$$\delta = 23.45 \sin\left(360 \frac{284 + n}{365}\right)$$

(Eq. 4)

Where: *n* is the number of day in the year.

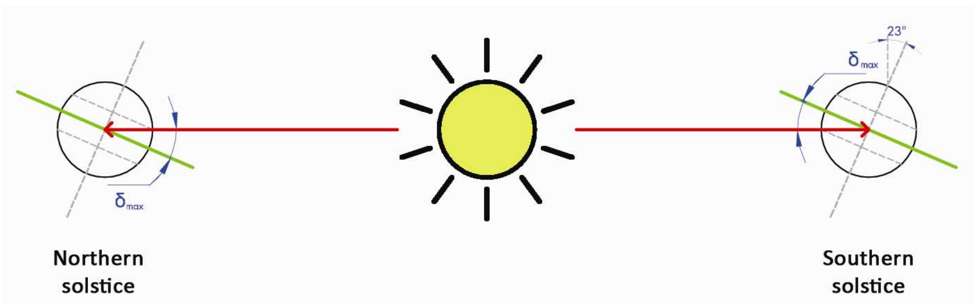


Figure 31. Declination angle of the rays of the sun and the earth's Equator.

Hour angle ω

The hour angle ω is the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis. Each hour accounts for a 15° angle. In this thesis, morning location of the sun will be considered negative and those in the afternoon positive, while noon is considered as $\omega = 0°$.

Zenith angle θz

Finally the zenith angle θ_z is the angle between the vertical and the vector from the observer to the sun (Figure 32). The sum of the zenith angle θ_z and the solar altitude angle α_s is equal to 90°. The zenith angle can be obtained from:

$$\cos\theta_z = \cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta$$

(Eq. 5)

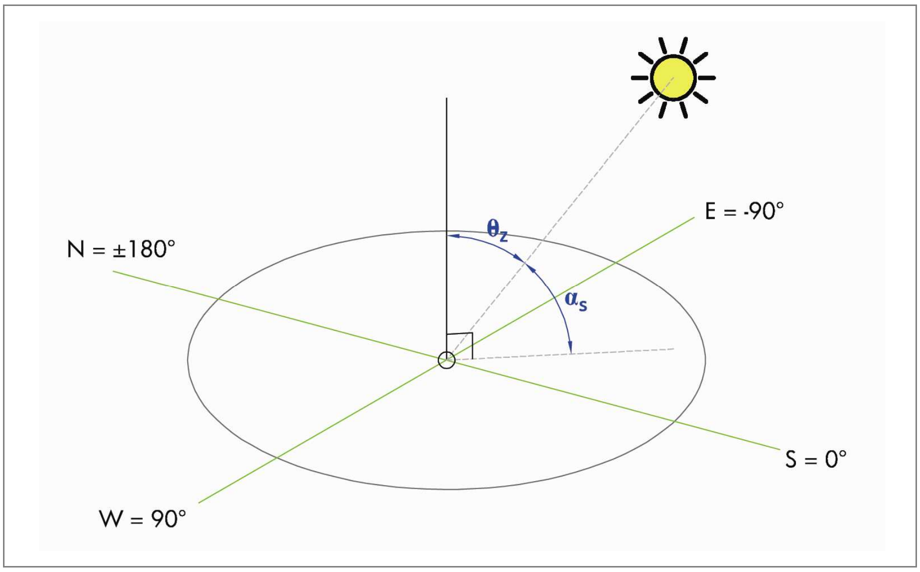


Figure 32. Zenith angle θ_z.

Thus, the altitude angle α_s is given by:

$$\alpha_s = 90° - \theta_z$$

(Eq. 6)

7.3.2 Solar Azimuth Angle γ_s

Because of the rotation of the earth the sun rises from east and sets in west, and during the day the sun has an apparent path in the sky dome. The angular displacement from south of the projection of beam radiation on the horizontal plane is the azimuth of the sun for that particular time.

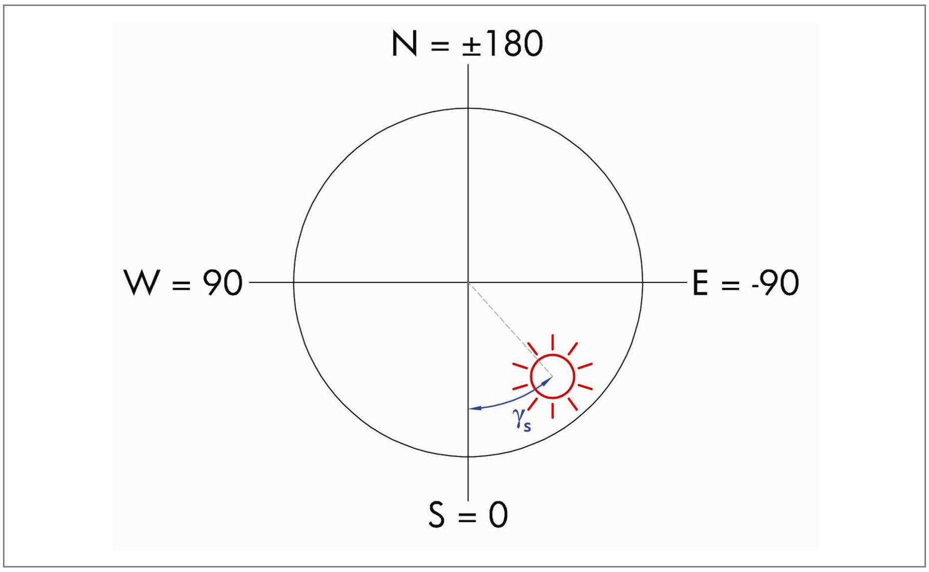


Figure 33. Solar Azimuth Angle γ_s seen from top view.

The solar azimuth angle γ_s can have values that range from 180° to -180°. Departing from south (0°), displacements towards east are negative and those toward west are positive. To calculate γ_s, it is important to know in which quadrant the sun will be. This is determined by the relationship of the hour angle ω, to the hour angle ω_{ew}, when the sun is due west or east. The solar azimuth angle γ_s is therefore calculated as follows:

$$\gamma_s = C_1 C_2 \gamma'_s + C_3 \left(\frac{1 - C_1 C_2}{2}\right) 180$$

(Eq. 7)

Where

$$\sin \gamma'_s = \frac{\sin \omega \cos \delta}{\sin \theta_z}$$

(Eq. 8)

Or

$$\tan \gamma'_s = \frac{\sin \omega}{\sin \varphi \cos \omega - \cos \varphi \tan \delta}$$

(Eq. 9)

$$C_1 = \begin{cases} 1\ if|\omega| < \omega_{ew} \\ -1\ \ otherwise \end{cases}$$

(Eq. 10)

$$C_2 = \begin{cases} 1\ if\varphi|\varphi - \delta| \geq 0 \\ -1\ \ otherwise \end{cases}$$

(Eq. 11)

$$C_3 = \begin{cases} 1\ if\omega \geq 0 \\ -1\ \ otherwise \end{cases}$$

(Eq. 12)

$$\cos\omega_{ew} = \tan\delta / \tan\varphi$$

(Eq. 13)

C1, C2 and C3 are the constants which determine the quadrant in which the sun is located. C1 is relationship between the hour angle ω, to the hour angle ω_{ew}, when the sun is due east or west and determines the location of the sun in east or west. Constant C2 is the relation from altitude φ and declination δ; this determines the location of the sun in north or south. C3 determines whether the sun is at noon or not.

7.4 Surface Alignment and Solar Tracking

To design a solar thermal collector that is optimal for the location, the tilt angle and geometry of the collector has to be determined according to the local solar geometry. In some solar collectors a form of tracking mechanism is used to enable the collector to follow the sun. The main objective for collectors that track the sun is to minimize the angle of incidence θ of the solar radiation on surfaces, so that reflection can be reduced and absorption can be as large as possible.

The tracking mechanism requires the collector absorber surface to be aligned towards the direction of the sun. Tracking surfaces are classified depending on their movement. They can track the sun rotating about a single axis or two axes. The most common tracking mechanisms are those that rotate about an axis that is oriented horizontally east-west, horizontally north-south and vertical or parallel to the earth axis, but there are also double-axis collectors that can move in almost any orientation and give a full track of the sun (Figure 34).

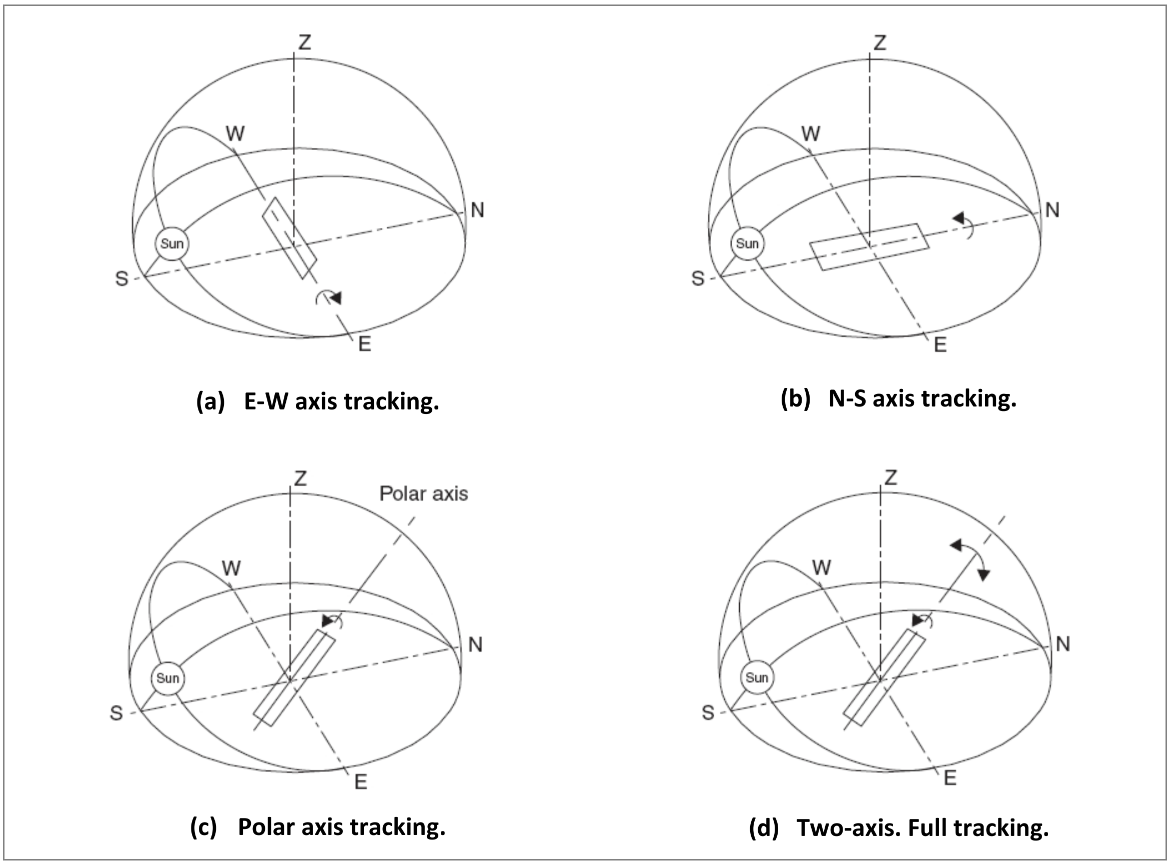


Figure 34. Various models of solar tracking (Kalogirou, 2009).

In the case of this thesis research, two of these tracking mechanisms will be used. The surfaces of the slats that will absorb radiation will be rotating about an east -west axis (Figure 34 (a)) to track the sun when placed on the north and south façades; and a horizontal north-south axis (Figure 34 (b)) for the east and west façades.

For each façade, four blind collectors with a different frequency of angle adjustment to track the sun will be analyzed for a later comparison: Hourly angle adjustment, daily angle adjustment, monthly angle adjustment and a permanent fixed angle. This means that the collector will have a different slope angle β every time an angle adjustment occurs in order to reduce the incident angle θ (Figure 35). So for every type of angle adjustment, the incident angle θ, the slope angle β and the direction on which the collector surface will be facing (surface azimuth γ).

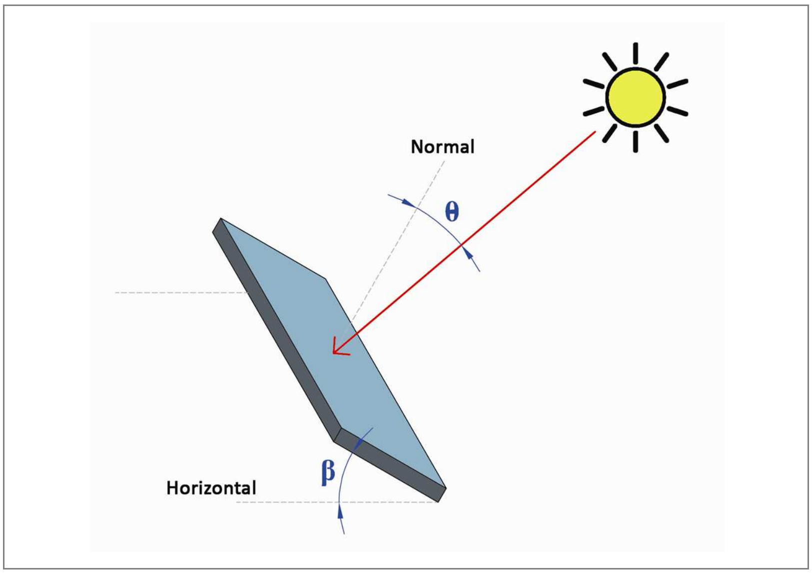


Figure 35. Angle of incidence θ of radiation on a surface and slope angle β of collector.

7.4.1 Solar Tracking with an Hourly Angle adjustment

For hourly angle adjustment of the slope of the collector, the solar altitude angle and the solar azimuth for every hour are necessary to update the alignment of the collector and the direction in which it will be facing.

North and South façades

For blind collectors that are placed on the north or south façades (east-west axis tracking) with an hourly angle adjustment, the angle of incidence θ of the solar radiation on the collector surface can be estimated by:

$$\cos\theta = (1 - cos^2\delta\ sin^2\omega)^{1/2}$$

(Eq. 14)

The slope of the collector is then defined by:

$$\tan\beta = \tan\theta_z|\cos\gamma_s|$$

(Eq. 15)

To define whether a slat of the blind collector will be facing south or north, the slat surface azimuth angle γ should be identified. The surface azimuth angle γ expresses the direction in which a collector surface would be facing according to the tracking of the sun. It uses the same notation as the solar azimuth angle γ_s being south = 0°. When the solar azimuth angle γ_s is between -90° and 90° (radiation striking on the south façade), a collector with an east-west axis tracking will have a surface azimuth angle γ = 0° (facing south). In the other hand, when the solar azimuth angle is γ_s > |90°| (radiation striking on the north façade) the surface azimuth angle γ = 180° (facing north).

In Figure 36, it can be seen the change in slope angle β for the hourly angle adjustment tracking for selected days in Mexico City. Positive angles correspond to slats on South facades; negative angles are corresponding to North façade slats.

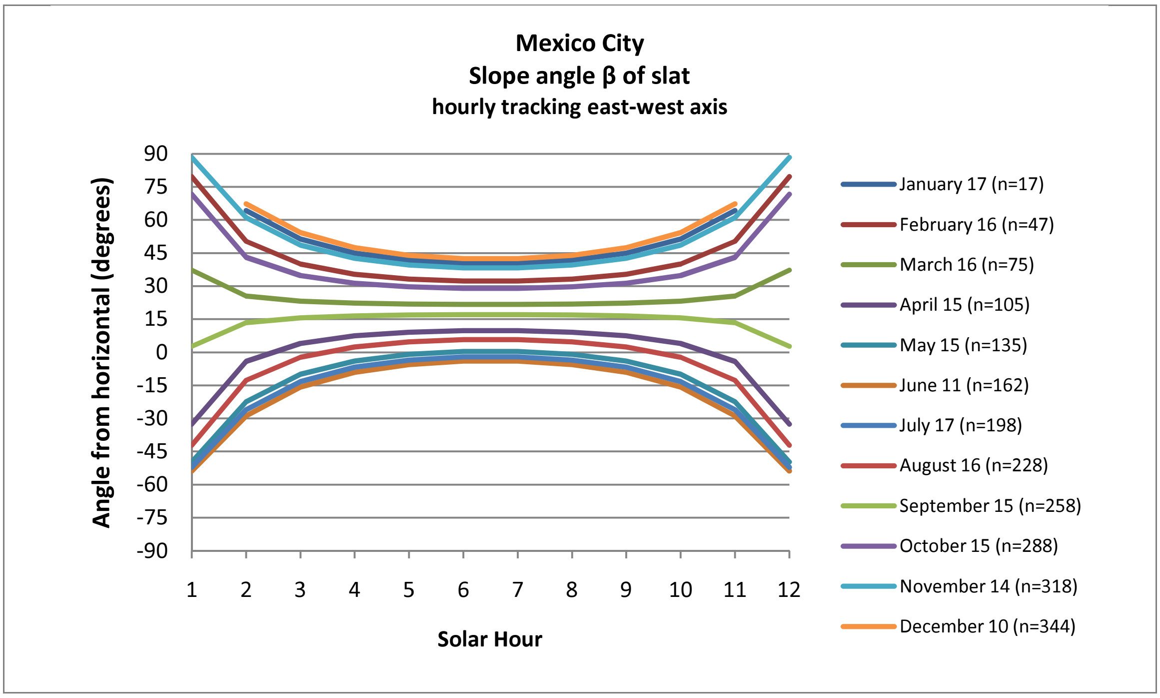


Figure 36. Slope angle for hourly angle adjustment for Mexico City.

East and West façades

For blind collectors that are placed on east or west façades (north-south axis tracking), with an hourly angle adjustment, the angle of incidence θ is defined as follows:

$$\cos\theta = (cos^2\theta_z + cos^2\delta\ sin^2\omega)^{1/2}$$

(Eq. 16)

The slope of the collector is given by:

$$\tan\beta = \tan\theta_z |\cos(\gamma - \gamma_s)|$$

(Eq. 17)

To define the surface azimuth angle γ, the following relations are used:

$$If\ \gamma_s < 0°\ then\ \gamma = -90°$$

$$If\ \gamma_s > 0°\ then\ \gamma = 90°$$

(Eq. 18)

This means that if the solar azimuth angle γ_s is negative, the collector will be facing east; and if the solar azimuth angle γ_s is positive, the collector will be facing west.

7.4.2 Solar Tracking with a Daily Angle adjustment

When a daily angle adjustment is used, the slope angle β of the collector remains constant during the day. The optimal slope angle in this case would be the one that enables beam radiation to be normal to the collector surface at noon each day (Duffie, 2006).

North and South façades

For the collectors that rotate about a horizontal east-west axis with a daily angle adjustment, the angle of incidence θ is given by:

$$\cos\theta = sin^2\delta + cos^2\delta\cos\omega$$

(Eq. 19)

And the slope angle of such surface is given by:

$$\beta = |\varphi - \delta|$$

(Eq. 20)

The slope angle β is completely dependent on the maximum solar altitude of that day at noon, which is related to the declination δ for a certain day in the year.

The surface azimuth angle γ is also given by the declination of the sun δ in relation to the latitude φ of the place. If the declination of the sun is smaller than the latitude, it means that the solar radiation is striking the south façade. In the other hand, if the declination is greater than the latitude, it means that the solar radiation is striking the north façade.

$$If\ (\varphi - \delta) > 0°\ then\ \gamma = 0°$$
$$If\ (\varphi - \delta) < 0°\ then\ \gamma = 180°$$

(Eq. 21)

East and West façades

For blind collectors that are placed on east or west façades (north-south axis tracking), with a daily angle adjustment, the angle of incidence θ is defined by the general equation. This equation relates the angle of incidence with the angles of the solar geometry, surface slope and azimuth:

$$\cos\theta = \sin\delta\sin\varphi\cos\beta - \sin\delta\cos\varphi\sin\beta\cos\gamma + \cos\delta\cos\varphi\cos\beta\cos\omega + \cos\delta\sin\varphi\sin\beta\cos\gamma\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega$$

(Eq. 22)

The slope angle β for slats that track the sun daily in east and west facade is determined by finding the mean profile angle of the sun for the particular surface azimuth (See section 7.6.1 Solar Profile Angle). This means that for the east façade, the average of all profile angles α_p has to be obtained and therefore the slope angle β would be given then by:

$$\beta = 90 - \overline{\alpha_p}$$

(Eq. 23)

7.4.3 Solar Tracking with a Monthly Angle adjustment

For this type of tracking, an angle that can be optimal for the entire month should be used. This slope angle is based on the recommended average day of the month from the *Table of Recommended average days for months and values of n* (Table 6).

To find the slope angle β, (Eq. 20) is applied to the recommended average day of the month. This angle will be the same for all days of the same month. For the surface azimuth angle γ, (Eq. 21) is also used for this type of angle adjustment on the average day of the month.

To obtain the angle of incidence θ of the radiation on the collector surface the general equation can be used (Eq. 22). The incidence angle can also be defined by (Eq. 24) when the zenith angle θ_z is known:

$$\cos\theta = \cos\theta_z\cos\beta + \sin\theta_z\sin\beta\cos(\gamma_s - \gamma)$$

(Eq. 24)

East and West façades

The incident angle θ for slats that adjust monthly on east and west facades can be found by using (Eq. 22).

In order to know the monthly slope angle β, (Eq. 23) is used on the recommended average day of the month, and then it is applied to all days in that specific month.

7.4.4 Fixed- angle surfaces

South façade

The slope angle β for fixed slats is determined according to the latitude of the place where they are going to be placed[2]. For south facades, the slats should be oriented towards the equator and their optimum slope angle is equal to the latitude of the location φ, with an angle variation of 5° to 10° depending on the main intended application. If the application is for solar cooling, the optimum slope angle $\beta = (\varphi - 10°)$, in this way the radiation coming from the high altitude of the sun during summer can be collected. If the collector is mainly used for space heating, then the optimal angle $\beta = (\varphi + 10°)$ to improve the collection of low solar radiation during winter. But if annual performance if intended, the optimal slope angle $\beta = (\varphi \pm 5°)$, to have relatively better performance during winter or summer (Kalogirou, 2009).

North façade

In the case of the north façade, the slope angle β of the slats was defined first by identifying if at certain period of the year, the solar radiation at noon is being received from the north. If the latitude angle φ is lower than the maximum declination angle of the sun δ (23.45°), then the solar radiation will come from the north during summer equinox. In that case, the slope angle $\beta = (\varphi – 23.45°)$.

East and West façades

For east and west facades, the slope angle β of the slats is determined by finding the mean profile angle of the sun from the horizon to the zenith. This angle would be 45°, and therefore, the slope angle β would be 45° as well.

7.4.5 Collection of radiation on each facade

Because the amount of radiation falling on each façade is going to be analyzed, the surface azimuth γ for all the different types angle adjustments was defined hourly in the calculations. In this way, in the early morning, when sun rises from the east, the radiation will be collected on the east façade, and as soon as the solar azimuth goes from negative to positive, the west façade will start collecting the radiation. Same happens for the north and south façades during the day (Figure 37).

Another important consideration for the calculation is that the slope angle β of the slats is considered to be β=0° if no solar radiation is falling on the façade in which the slat is placed. For the hourly angle adjustment mechanism this means that as soon as the sun is not radiating

[2] The slope angle calculation described is intended for façades located in the northern hemisphere.

in that particular façade, the slats will move to horizontal. For daily angle adjustment, if no radiation is falling on the façade during the day, β =0°. On monthly angle adjustment, if no radiation is falling on the façade during the month, β =0°. If this is false, (Eq. 20) remains valid.

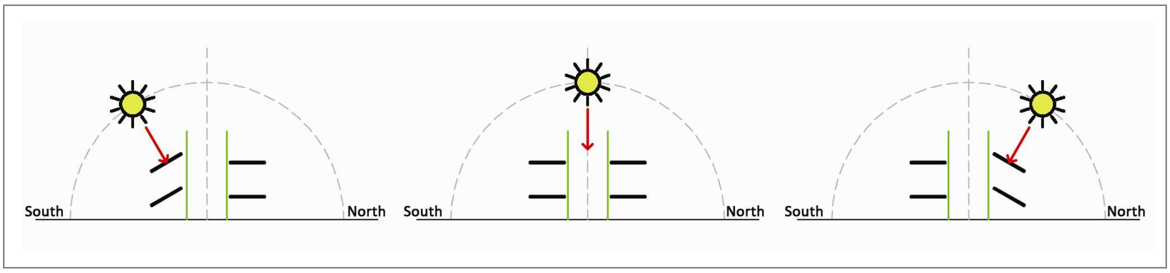


Figure 37. Slope angle β of slats when no solar radiation is falling on a particular façade.

7.5 Radiation on Sloped Surfaces

Because the beam and diffuse radiation have different angles on incidence on the façade, they are treated separately and then added together to come to a total radiation on sloped surfaces. For both, the amount of radiation that falls on a slope surface has to be determined from that calling on a horizontal plane.

7.5.1 Ratio of beam radiation on sloped surfaces to that on horizontal surfaces R_b

Since most of the solar data is given as total radiation for hours or days on a horizontal surface, it is necessary to calculate an hourly radiation on a tilted surface from measurements on horizontal planes. For most engineering purposes, beam and diffuse radiation on tilted planes are required for performance calculation. The ratio of beam radiation on a tilted surface to beam radiation on a horizontal surface at any time is called the geometric factor R_b. It is determined by:

$$R_b = \frac{G_{b,T}}{G_b} = \frac{G_{b,n} \cos\theta}{G_{b,n} \cos\theta_z} = \frac{\cos\theta}{\cos\theta_z}$$

(Eq. 25)

Where: $G_{b,T}$ is the beam irradiance on the tilted surface
G_b is beam irradiance on the horizontal surface

7.5.2 Total radiation on sloped surfaces I_T

In order to know the radiation that is falling onto a sloped surface, the direction from which the beam and diffuse radiation reach the surface in question must be known. The direction from which the diffuse radiation is received depends on the conditions of the sky, such as the distribution of the light in the sky dome, the cloudiness and the atmospheric clarity, which are highly variable.

Some authors identify that the diffuse radiation is composed of three parts: The isotropic part, received uniformly from the entire sky dome; the circumsolar diffuse, which is the solar radiation scattered and is concentrated in the part of the sky that is around the sun; and finally the horizon brightening, that is concentrated near the horizon. Figure 38 shows these three components.

When diffuse radiation strikes a surface, some of it comes from reflected radiation from the ground and other surfaces around. The angle in which the diffuse radiation is distributed is in some degree dependant on the ground reflectance called albedo ρ_g.

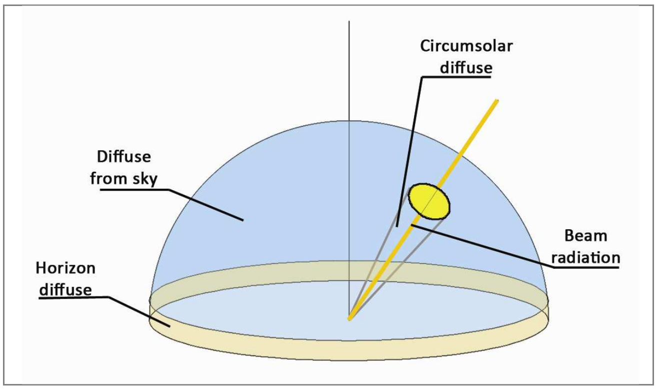


Figure 38. Distribution of diffuse radiation over the sky dome.

The incident solar radiation can then be determined by the sum of the different radiations: beam radiation, the three components of diffuse radiation and the reflected radiation. After the Incident solar radiation on the tilted surface I_T has been determined, the ratio of total radiation on the tilted surface to that on the horizontal surface can be determined.

To calculate the incident solar radiation on a tilted surface, there are several methods available. The Isotropic sky method assumes that the diffuse radiation and the ground-reflected radiation are isotropic. The Anisotropic sky method makes a differentiation between circumsolar radiation, diffuse radiation, horizon brightening and ground reflection in order to calculate more accurate the incident radiation. Because the results from the two methods lead to a very slight difference, the Isotropic sky method will be used to calculate the radiation in the absorber surfaces. This method gives more conservative results, which can be useful to the research to depict a less favorable absorption condition.

7.5.3 Calculation of radiation on sloped surfaces. Isotropic sky method.

This method assumes that the diffused and ground-reflected radiation is isotropic. With this assumption, the diffused radiation is treated the same regardless the orientation. In this method, the radiation on the tilted surface is considered to have three components: beam radiation, isotropic diffuse radiation and solar radiation diffusely reflected from the ground.

To determine the amount or diffuse and reflected radiation that fall on the surface, the view factor from the surface to the sky should be determined. The view factor describes the range directions that the surface can get. A surface which is tilted at slope angle β from the horizontal has a view factor to the sky of $F_{c-s} = (1 + \cos\beta)/2$; a view factor to the ground of $F_{c-g} = (1 - \cos\beta)/2$; and if the surroundings have a diffuse reflectance of ρ_g, the reflected radiation from the surroundings on the surface will be $I\rho_g(1 - \cos\beta)/2$. Therefore the total solar radiation on the tilted surface for an hour is expressed as:

$$I_T = I_b R_b + I_d\left(\frac{1 + \cos\beta}{2}\right) + I\rho_g\left(\frac{1 - \cos\beta}{2}\right)$$

(Eq. 26)

Where:

$I_b R_b$ Accounts for the beam radiation that is incident to the tilted surface.

$I_d\left(\frac{1+\cos\beta}{2}\right)$ Accounts for the isotropic diffuse radiation with the view factor from the surface to the sky.

$I\rho_g\left(\frac{1-\cos\beta}{2}\right)$ Accounts for the ground reflected radiation with the view factor from the surface to the ground.

7.6 Shadow casting on surfaces

It is important to determine the shadow that can be produced on slats because it affects the amount of radiation that the surface of the slat can collect. Even though shadows can be produce by a great number of objects, calculating the shadows coming from external objects cannot be predicted, therefore only the shadows that are produced within the slats will be taken into account. In order to know the shadows on the slats, the solar profile angle and the geometry of the slats should be defined.

7.6.1 Solar profile angle α_p

An important angle to take into account is the profile angle α_p of beam radiation on a receiver plane *R* that has an azimuth angle of γ. The profile angle is the projection of the solar altitude angle on a vertical plane which is perpendicular to the plane in question. Because the slats are aligned to the façade, they can only track the sun as it goes up and down, and they are not facing perpendicular the sun. As the solar altitude angle α_s of the sun is projected on a plane normal to the surface creating the profile angle α_p, it is to this angle to which the slats react to. On Figure 39, the profile angle α_p would be the angle on which a horizontal plane *D* has to be rotated about axis E-F, so that it can include the solar altitude angle α_s. When the sun is perpendicular to the surface, both the solar altitude angle α_s and the profile angle α_p are the same. The profile angle can be calculated from:

$$\tan \alpha_p = \frac{\tan \alpha_s}{\cos(\gamma_s - \gamma)}$$

(Eq. 27)

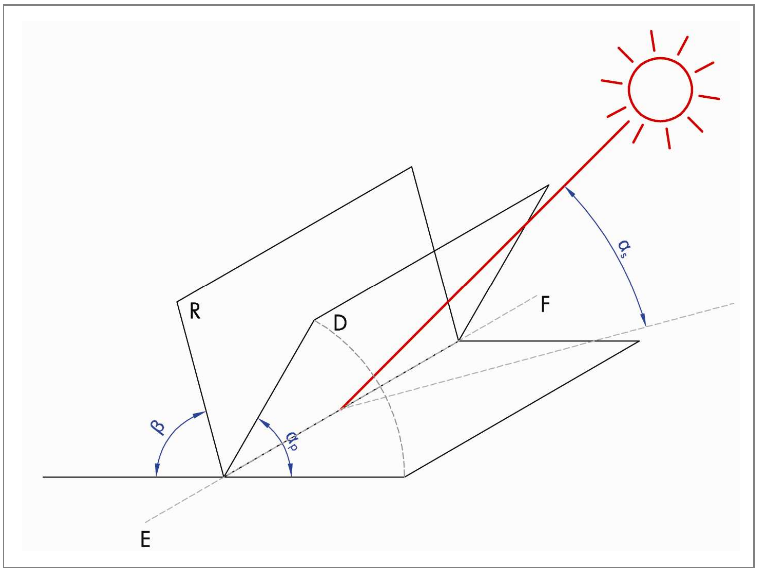


Figure 39. The solar altitude angle α_s, and the profile angle α_p, for surface R

7.6.2 Shadow casting and geometry

There could be various elements that produce shadows on the slats, including surrounding elements (e.g. trees or buildings), collectors from adjoining rows on an array, and overhangs and wing walls, among others. In the case of this research, only the shading caused by adjoining slats will be calculated.

Taking as an example a flat-plate collector array which is fixed on the ground (Figure 40), it can be seen that as long as the profile angle α_p (here the angle of the beam with respect to the horizontal) is equal or greater than the angle ABC, no point in the back row will be shaded by the front row. If the profile angle α_p, at a point in time, is smaller than angle ABC (e.g. angle AB'C'), the back row will be blocked from beam radiation from point B' to the bottom, causing shading.

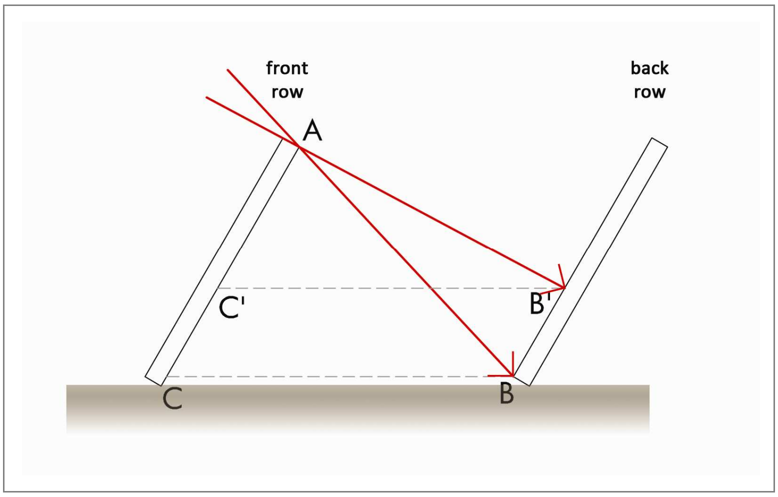


Figure 40. Section of two rows flat-plate collectors fixed on the ground.

Applying this to a stack of slats placed one on top of the other, it can be seen on Figure 41 that the profile angle should be smaller than angle ABC so that no point in the bottom slat is shaded. If the profile angle at a certain point in time is greater than angle ABC (e.g. angle AB'C'), the collector will be shaded from point B' to the back.

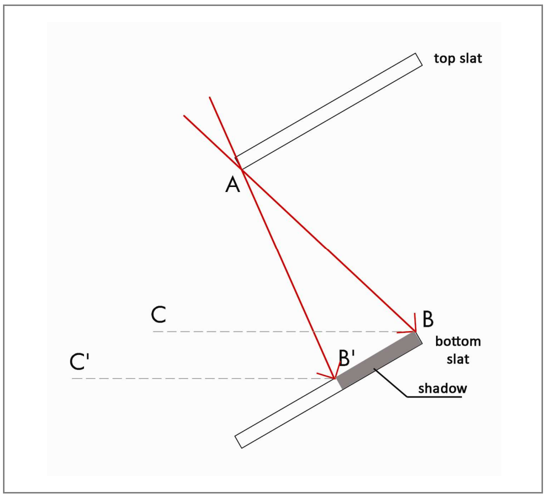


Figure 41. Section of two rows of collectors in a stack array.

The percentage of the shaded area in relation with the full dimension of the slat would represent how much heat is blocked from being absorbed, or how much material is not receiving heat. Even though the shaded part does not receive heat, heat is transmitted by conduction to this area and heat losses are present.

The amount of shading can be calculated trigonometrically by determining the height of the triangle formed by the points ABD shown in Figure 42(a). The height is shown as segment AB', which is perpendicular to the slat surface and is given by:

$$\overline{AB'} = D_p \sin \alpha_v$$

(Eq. 28)

$$\alpha_v = 90° - \beta$$

(Eq. 29)

Where: α_v is the angle formed by the vertical and the edge of the slat,
β is the slope angle of the surface,
D_p is the distance between slats,

Then the length of the segment B'D and BB' are calculated by:

$$\overline{B'D} = D_p \cos \alpha_v$$

(Eq. 30)

$$\overline{BB'} = \frac{\overline{AB'}}{\tan(\alpha_p + \beta)}$$

(Eq. 31)

The width of the slat that is shaded is defined by the total width *W* minus the length of the segments B'D and BB':

$$W_s = W - (B'D + BB')$$

(Eq. 32)

In the case where the profile angle is greater than angle AB'C' (Figure 42(b)), segment BB' is defined by:

$$\overline{BB'} = \frac{\overline{AB'}}{\tan\left(180 - (\alpha_p + \beta)\right)}$$

(Eq. 33)

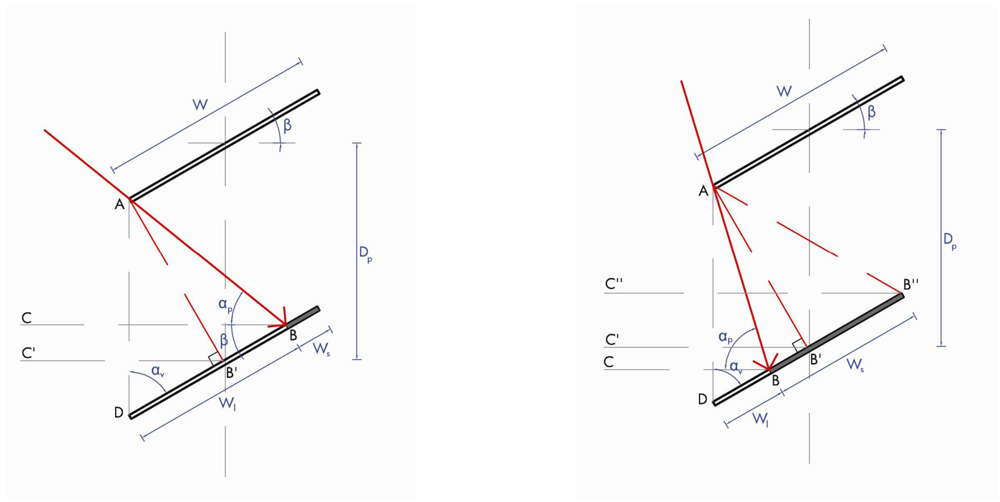
And the width of the slat that is shaded is calculated as:

$$W_s = W - (B'D - BB')$$

(Eq. 34)

Where: W is the width of the slat
α_p is the profile angle

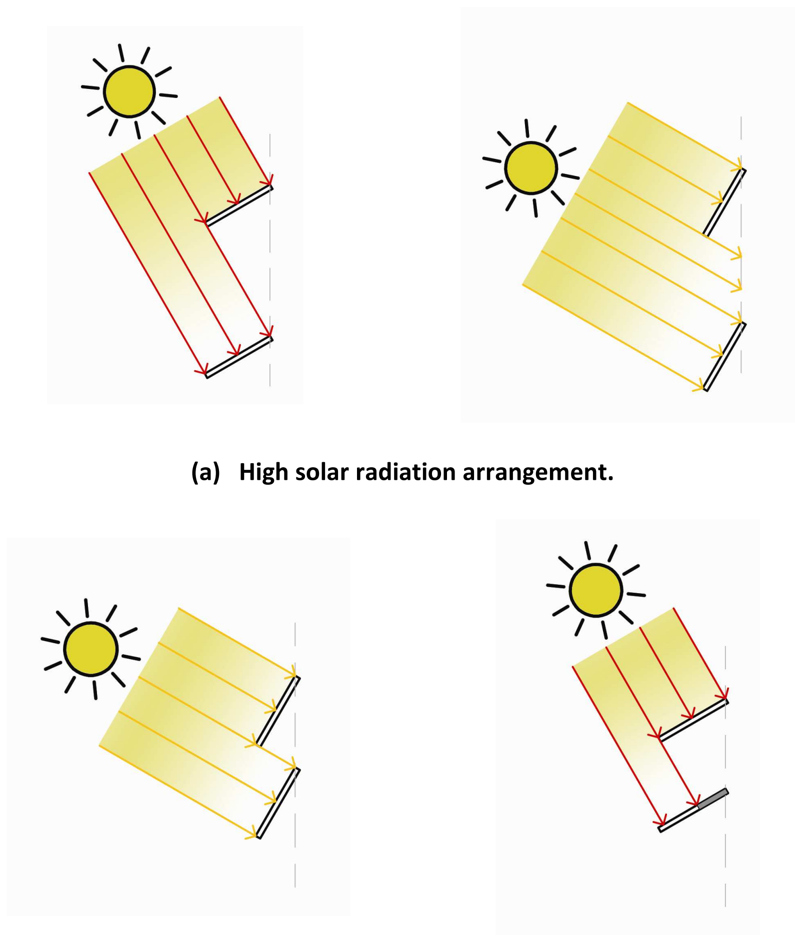
Note that the smallest profile angle of the solar radiation that the slat can block from entering into the room is angle AB"C", smaller angles will not produce shading on the slat.



(a) Profile angles smaller than normal **(b) Profile angles greater than normal**

Figure 42. Geometry of shading on fixed slats.

For slats that track the sun, the surface is normal to the profile angle α_p at all times. Knowing the profile angle will result on knowing the angle in which the slat will move, and therefore the shadow that may be casted. Shadow can be avoided by increasing the distance between slats, so that the top slat does not shade the one in the bottom in high solar angles. With this, two trails for slat offsetting arise: If the slats are offset in such distance that the highest solar angle does not produce a shadow between them, a space between slats is created and the lower solar radiation would not be completely blocked and therefore it would not be absorbed (Figure 43 (a)). This gap between slats can also produce glare in the room inside, diminishing the quality of the sun shading system (venetian blind). In the other hand, if the offset is done in reference with the lowest solar radiation to be blocked and absorbed, when the solar radiation comes from a high angle, shading will be produced between slats (Figure 43 (b)).



(a) High solar radiation arrangement.

(b) Low solar radiation arrangement.

Figure 43. Offset of slats according to solar elevation.

The decision on what is best to use depends on the climate and the latitude where the thermal solar collector blind is going to be used. For latitudes where the sun is normally on a high elevation angle, it would be wise to use a solar collector that is offset according to the high angles, while for latitudes where the sun is mostly in a low elevation angle, the collector that catches low-angled radiation is more convenient.

7.7 Absorption Coefficient

Solar collectors must have high absorptance for solar radiation. They also undergo heat losses by a combination of mechanism, including thermal radiation from the absorbing surface. It is desirable that this long-wave radiation is kept as minimal as possible. To achieve so, usually a selective surface or coating id used to improve the efficiency of collectors. This selective surface absorbs most of the solar radiation incident to the surface and keeps heat loss from radiation as low as possible.

7.7.1 Angular Dependence of solar absorptance in coatings

The directional absorptance for blackened surfaces is a function of the incident angle θ of the radiation falling on them. For selective coatings, the absortance is normally given for radiation with an incident angle θ = 0°. The absorptance for other incident angles is generally not available. In Figure 44, it can be seen that the absorption decreases when the incident angle is greater. It is suggested that the surfaces with a selective coating may exhibit the same behavior (Pettit, 1976). Therefore a polynomial approximation to fit the curve in Figure 44 for different incident angles is given by:

$$\frac{\alpha}{\alpha_n} = 1 + 2.0345 \times 10^{-3}(\theta_e) - 1.99 \times 10^{-4}(\theta_e)^2 + 5.324 \times 10^{-6}(\theta_e)^3 - 4.799 \times 10^{-8}(\theta_e)^4$$

(Eq. 35)

Where: θ_e is the effective incidence angle in degrees.

α_n is the absorptance at normal incidence angle. This can be found from the properties of the absorber (coating).

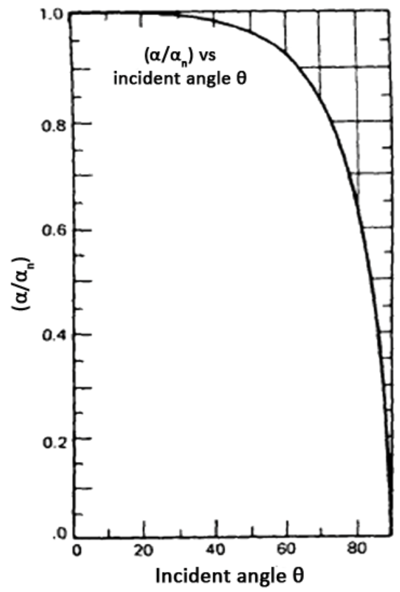


Figure 44. Ratio of solar absortance to solar absortance at normal incident for a flat black surface (Duffie, 2006).

The variation of absorptance for black paint is shown in Table 7 for incidence angles from 0° to 90°. The absorptance for diffuse radiation for such paint is approximately 0.90 (Kalogirou, 2009).

Angle of incidence (°)	Absorptance
0-30	0.96
30-40	0.95
40-50	0.93
50-60	0.91
60-70	0.88
70-80	0.81
80-90	0.66

Table 7. Angular Variation of Absorptance for Black Paint.

7.8 Absorption of radiation in external blind collector

According to the previous section, the absorptance of the selective coating depends on the angle of incidence θ of the radiation. In order to calculate the solar radiation on a tilted surface, the absorptance coefficient (α) has to be calculated for beam, diffuse and reflected radiation according to (Eq. 35).

In the case of beam radiation, the angle of incidence θ is used as the effective incident angle θ_e shown in (Eq. 35). For the effective incidence angle for diffuse radiation, $\theta_{e,d}$, and ground-reflected radiation, θ_{eg}, the following equations can be used:

$$\theta_{e,d} = 59.68 - 0.1388\beta + 0.001497\beta^2$$

(Eq. 36)

$$\theta_{e,g} = 90 - 0.5788\beta + 0.002693\beta^2$$

(Eq. 37)

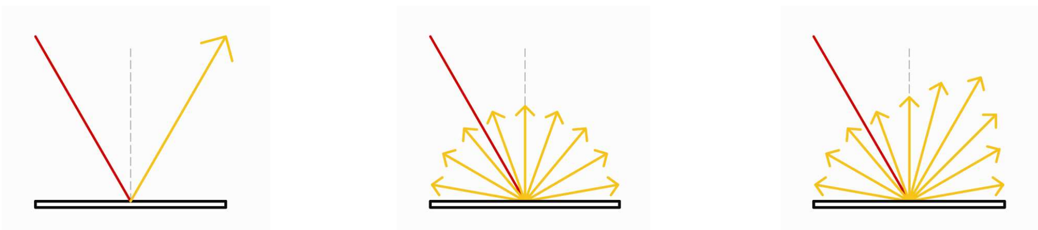
From (Eq. 35), the absorptance coefficient for beam $(\alpha)_b$, difusse $(\alpha)_d$ and reflected $(\alpha)_g$ radiation can be defined.

In order to know the final absorbed radiation, (Eq. 26) from the isotropic sky method is used. Each term is multiplied by their respectively coefficient of absorption.

7.9 Absorption of radiation in cavity blind collector

7.9.1 Reflectance of surfaces

When radiation strikes a surface, two types of reflection can happen. Specular reflection happens when an incident ray strikes an ideal (smooth) surface and the angle of reflection is equal to the angle of incidence θ. Diffuse reflection occurs when the ray strikes a surface and it gives an isotropic and homogeneous reflection in all directions. Ordinary (real) surfaces have anisotropic or irregular reflections which different in every direction (Figure 45). In general, the magnitude of the reflected intensity in a particular direction for a given surface depends on the wavelength and the spatial distribution of the incident radiation. For engineering calculations, the reflection that is achieved by highly polished surfaces could approach to specular behavior; and machined, painted or treated surfaces are assumed to be diffuse.



(a) Ideal **(b) Diffuse** **(c) Real**

Figure 45. Surface Reflection

In order to know the amount of radiation that is reflected from the glazing of the façades, it is important to know the incident angle θ of the radiation. Even if the sun is shining, no beam radiation will strike the façades if the sun position is in an opposite azimuth quadrant to that of the façade.

For south façades, radiation will be incident is the solar azimuth angle γ_s is between -90° and 90°. Radiation will be incident on east façades if the solar azimuth angle γ_s is between -180° and 0° and between 0° and 180° for west façades. North façades will have direct radiation when the solar azimuth angle γ_s >|90°| (Figure 46). Note that the standard notation is used to define the solar azimuth angle γ_s (south γ_s=0°, towards east negative, towards west positive).

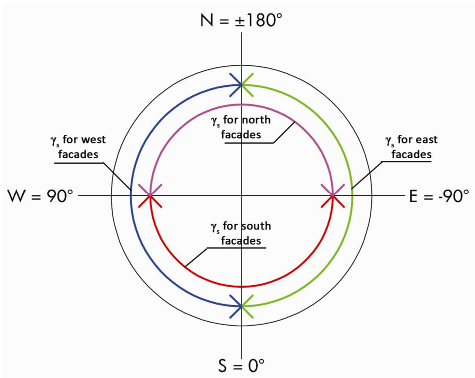


Figure 46. Incidence of radiation in façades.

From Figure 46 it can be observed that according to the solar azimuth angle γ_s, radiation from the sun will be incident in two façades most of the times. For solar thermal collection purposes this means that solar thermal energy can be collected in two façades at any moment.

According to the incident angle, the coefficient of transmission of the glazing can be calculated. In this case, the data was taken from WIS software for a clear pane of glass of 6 mm (Table 8).

Angle	Solar direct transmittance	Solar direct reflectance	Absorption
90	0.000	1.000	0.000
80	0.414	0.546	0.040
70	0.673	0.288	0.039
60	0.798	0.164	0.038
50	0.853	0.111	0.036
40	0.876	0.090	0.034
30	0.885	0.082	0.033
20	0.888	0.080	0.032
10	0.889	0.080	0.031
0	0.889	0.080	0.031
Diffusive	0.809	0.156	0.035

Table 8. Reflectance of clear glass of 6mm (SGG Diamant 6mm).

7.9.2 Radiation on glass

Glass is to a certain degree transparent to radiation at certain wavelengths. This property depends on the wavelength of the incident radiation, the type of surface, the direction of the incident ray, the electromagnetic field associated with the wave and the refraction index of both media.

When radiation strikes the surface of a transparent plate at an incidence angle θ_1, part of the radiation is reflected in an angle equal to θ_1 and the remainder is refracted. Refraction is caused when the beam passes through the interface of two media with different density. It causes the transmitted beam to bend at angle θ_2, toward the perpendicular to the surface of higher density (Figure 47). The angle of refraction θ_2 can be calculated by:

$$n = \frac{n_2}{n_1} = \frac{\sin\theta_1}{\sin\theta_2}$$

(Eq. 38)

Where: *n* is the ratio of refraction index for the two media

n_1 and n_2 are the refraction indices of the media

Typical value of refraction index is n = 1 for air, n = 1.526 for glass and n = 1.33 for water.

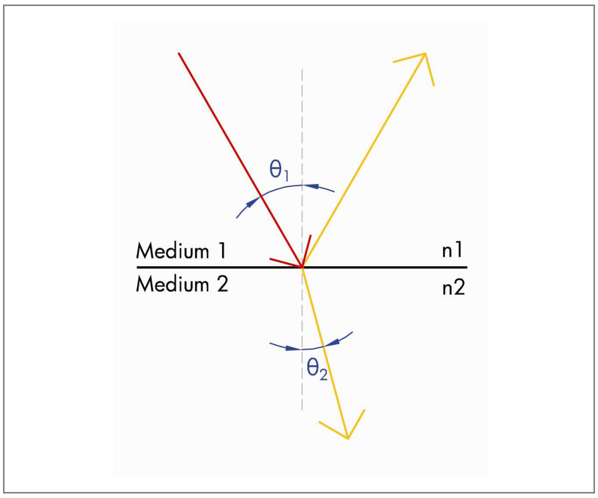


Figure 47. Incident and refraction angles for a ray that passes through different media.

Radiation is also made up by parallel and perpendicular components depending on the way they propagate. When one of the components is suppressed or is dominating, it is said that the light is polarized. The perpendicular and parallel components of unpolarized radiation are found as follows:

$$r_{\perp} = \frac{\sin^2(\theta_2 - \theta_1)}{\sin^2(\theta_2 + \theta_1)}$$

(Eq. 39)

$$r_{\parallel} = \frac{\tan^2(\theta_2 - \theta_1)}{\tan^2(\theta_2 + \theta_1)}$$

(Eq. 40)

When a beam of thermal radiation is incident on the surface of a transparent body, part of it is reflected, part is absorbed and part is transmitted through the body. These phenomena are called reflectance ρ, absorptance α and transmittance τ, respectively, and are related by the following equation:

$$\rho + \alpha + \tau = 1$$

(Eq. 41)

The transmittance can be calculated taking only into account the absorption losses. This helps to determine the radiation that when through the glass, reduced by absorption and finally reaches the absorber surface. The transmittance without absorption losses τ_{α}, can be calculated from:

$$\tau_{\alpha} = e^{\left(-\frac{KL}{\cos\theta_2}\right)}$$

(Eq. 42)

Where: *K* is the extinction coefficient, that can range from 4m-1 for low-quality glass, to 32m-1 for high-quality glass,
L is the thickness of the glass cover.

When the initial radiation is known, the transmittance, reflectance and absorptance of a single glazing can be calculated considering both reflection and absorption losses. They can be found by the following equations. These expressions are for perpendicular components of polarization, but they can be used as well for parallel components.

$$\tau_{\perp} = \frac{\tau_{\alpha}(1 - r_{\perp})^2}{1 - (r_{\perp}\tau_{\alpha})^2} = \tau_{\alpha}\frac{1 - r_{\perp}}{1 + r_{\perp}}\left(\frac{1 - r_{\perp}{}^2}{1 - (r_{\perp}\tau_{\alpha})^2}\right)$$

(Eq. 43)

$$\rho_{\perp} = r_{\perp} + \frac{(1 - r_{\perp})^2 \, {\tau_{\alpha}}^2 \, r_{\perp}}{1 - (r_{\perp}\tau_{\alpha})^2} = r_{\perp}(1 + \tau_{\alpha}\tau_{\perp})$$

(Eq. 44)

$$\alpha_{\perp} = (1 - \tau_{\alpha}) \left(\frac{1 - r_{\perp}}{1 - r_{\perp}\tau_{\alpha}} \right)$$

(Eq. 45)

The total transmittance, reflectance and absorptance can be calculated from the average value of the two components of polarization for each one respectively.

$$\tau = \frac{\tau_{\perp} + \tau_{\parallel}}{2}$$

(Eq. 46)

$$\rho = \frac{\rho_{\perp} + \rho_{\parallel}}{2}$$

(Eq. 47)

$$\alpha = \frac{\alpha_{\perp} + \alpha_{\parallel}}{2}$$

(Eq. 48)

7.9.3 Absorbed Solar Radiation

In order to predict the radiation that would be absorbed by the collector with a glazing cover, the incident radiation that falls on a tilted surface or facade should be known first. The incident radiation, as described before, has three components: beam, diffuse and ground reflected radiation. Using the isotropic model, (Eq. 26) can be used to calculate the absorbed radiation, S, by multiplying each term (beam, diffuse and reflected radiation) with the appropriate transmittance-absorptance product ($\tau\alpha$).This term describes the amount of radiation that was transmitted through the glazing and the portion of it that ultimately is going to be absorbed in the absorber surface.

$$S = I_b R_b (\tau\alpha)_b + I_d (\tau\alpha)_d \left(\frac{1 + \cos\beta}{2} \right) + I\rho_g (\tau\alpha)_g \left(\frac{1 - \cos\beta}{2} \right)$$

(Eq. 49)

The combination of the glazing with the absorber surface is shown in Figure 48, together with the ray tracing of the radiation. From the incident radiation that falls on the glazing, τ is transmitted through the glass and from that radiation, $\tau\alpha$ is absorbed on the slats. $(1-\alpha)\tau$ is reflected back to the glass cover. This reflection is assumed to be diffuse. $(1-\alpha)\tau\rho_d$ is reflected back to the slats. The multiple reflection of diffuse radiation continues so that the fraction of the incident solar radiation ultimately absorbed is:

$$(\tau\alpha) = \tau\alpha\sum_{n=1}^{\infty}[(1-\alpha)\rho_d]^n = \frac{\tau\alpha}{1-(1-\alpha)\rho_d}$$

(Eq. 50)

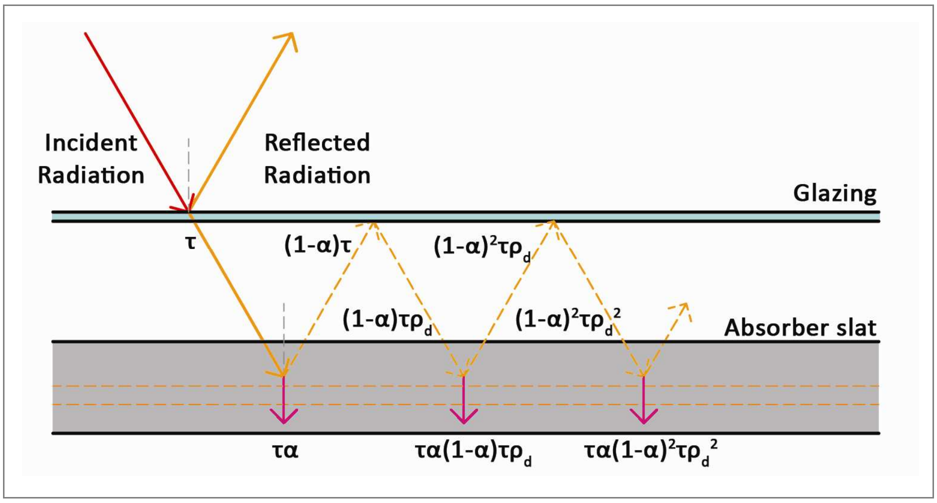


Figure 48. Top view of façade showing radiation transfer between glazing and absorber slats.

For most practical solar collectors, the following approximation of the total absorbed radiation is done:

$$(\tau\alpha) \cong 1.01\tau\alpha$$

(Eq. 51)

To calculate the transmittance τ, (Eq. 46) can be used, while the absorptance coefficient α of the surfaces that are tilted on a determined angle can be obtained from (Eq. 35).

Note that for flat-plate collectors, where β of glazing and absorber is the same, the same effective incident angle for beam, diffuse and ground-reflected radiation can be used for both glazing and absorber. In the case of a blind collector, the glazing is β=90° and the absorber slats can take a different angle. In that case, a particular effective incident angle for beam radiation (θ_G, θ_C), diffuse radiation ($\theta_{e,d,G}$, $\theta_{e,d,C}$) and ground-reflected radiation ($\theta_{e,g,G}$, $\theta_{e,g,C}$) should be calculated separately for glazing and absorber slats using (Eq. 36) and (Eq. 37). Subscripts G and C stand for glazing and collector respectively.

7.10 Heat losses in the slats

7.10.1 Heat losses in external blind collector

For the solar thermal collector that is placed in front of the façade with no weathering protection, the thermal losses occur in the form of long-wave radiation from the collector to the outside and convection dependent on the wind speed.

7.10.2 Heat losses in cavity blind collector

For this type of collector that is located inside a cavity, the heat loss is reduced by the glazing cover. The absorber radiates heat out which is absorbed by the air layer in the cavity and then transferred to the glass. If the absorber has a selective coating, its emittance is relatively small and radiation exchange between the absorber and the outer glazed skin is significantly reduced.

There are several ways to calculate heat losses. The method used here is intended for flat-plate solar collectors. Every layer of the collector toward the outside has a resistance to transport heat. The sum of the resistance of all layers gives the total heat resistance of the system. The inverse of the resistance is the heat transfer coefficient, which gives an idea of how much heat can be lost through the system. Energy losses can be found by:

$$Q_{loss} = \frac{T_s - T_a}{R_L} = U_L A_c (T_s - T_a)$$

(Eq. 52)

Where: T_s is the temperature of the absorber surface
T_a is the temperature of the air
R_L is the overall heat resistance of the system
U_L is the overall heat transfer coefficient

The overall heat transfer coefficient is given by the sum of the heat transfer coefficient all the directions in which the collector can radiate:

$$U_L = U_o + U_i + U_e$$

Where: U_o is the heat transfer coefficient to the outside
U_i is the heat transfer coefficient to the inside
U_e is the heat transfer coefficient from the edges of the collector

In steady state condition, the heat transfer from the absorber surface to the glass and from the glass to the ambient air is the same. The heat transfer between the layers has to be calculated separately, and the temperature of absorber surface, glass and air has to be known in order to know the final heat loss. Because the temperature of the glass is not known, several iterations are needed to get to the final result.

There is an empirical equation developed by Klein (1975), where the heat transfer coefficient can be calculated in a very straight forward evaluation:

$$U_o = \frac{1}{\dfrac{N_g}{\dfrac{C}{T_s}\left(\dfrac{T_s - T_a}{N_g + f}\right)^{0.33} + \dfrac{1}{h_w}}} + \frac{\sigma(T_s^2 + T_a^2)(T_s + T_a)}{\dfrac{1}{\varepsilon_s + 0.05N_g(1-\varepsilon_s)} + \dfrac{2N_g + f - 1}{\varepsilon_g} - N_g}$$

(Eq. 53)

Where: N_g is the number of glazing panes protecting the collector
σ is the Stefan -Boltzmann constant, = 5.67 x 10^{-8} W/m^2-K^4
ε_s is the emittance of the absorber surface
ε_g is the emittance of the glass
h_w is the convection heat transfer coefficient

Constants *f* and *C* are defined by:

$$f = (1 - 0.04h_w + 0.0005h_w^2)(1 + 0.091N_g)$$

(Eq. 54)

$$C = 365.9(1 - 0.00883\beta + .0001298\beta^2)$$

(Eq. 55)

The air convection heat transfer coefficient can be calculated by:

$$h_w = \frac{8.6V^{0.6}}{L^{0.4}}$$

(Eq. 56)

Where: V is the speed of the air
L is the length of the collector

Because the mechanism of heat loss to the inside and to the outside is similar, (Eq. 53) is used for heat radiation in both directions, just modifying the number of glass panes and the wind speed.

Heat losses from the edges are relatively small because they have to be well-insulated so that the manifold can be allocated in that section; therefore they are neglected.

8 General analysis results

In order to produce a graph that could show the general behavior of the solar thermal collection in the blinds, there were some parameters that were used to define the initial geometry of the blinds, the type of glazing and the materials used for collection.

For calculation, the blinds were considered to be 100 mm width and 1000 mm long. The thickness of such blinds is 2 mm. The distance between blinds for shading purposes was considered to be 100 mm, following the low solar radiation arrangement shown in Figure 43 (b). For calculations, the slats are considered to be flat (Figure 49).

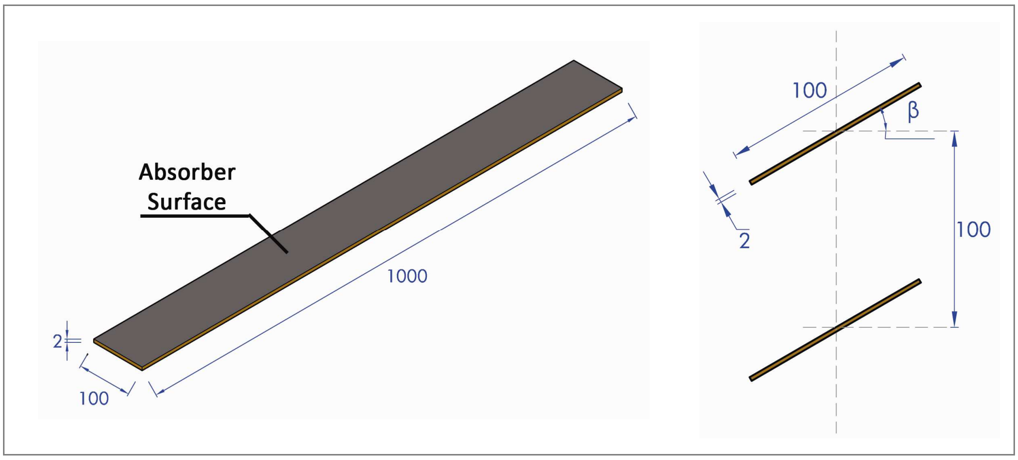


Figure 49. Slat geometry parameters for calculations input.

For absorption calculation, the absorber surface was considered to be a selective surface that has an absorptance of α = 0.95 and an emittance of ε = 0.10. The slat was considered to be made of copper as well as the heat pipe. The heat pipe is considered to be have a contact area with the slat of 10 mm width (Figure 50).

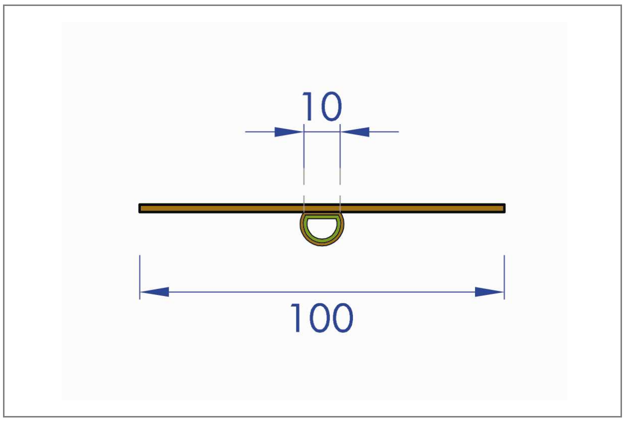
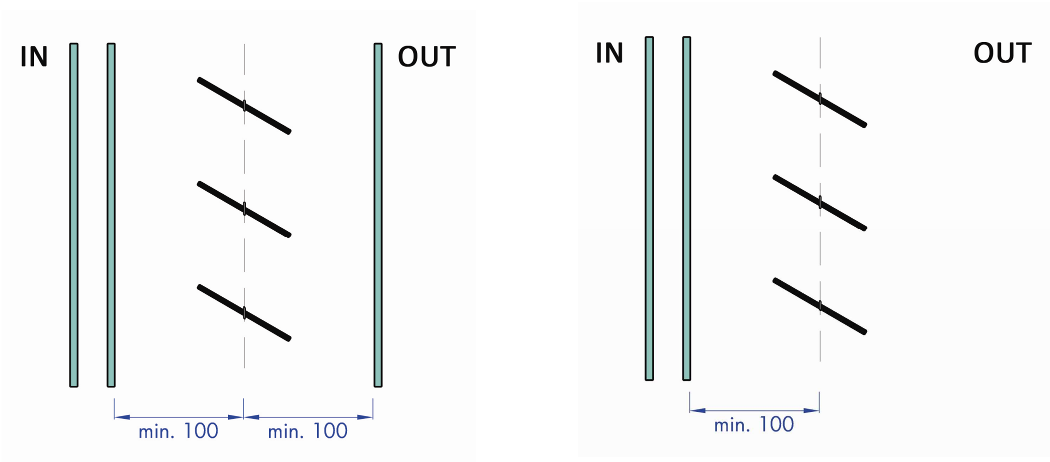


Figure 50. Contact area between slat and heat pipe.

For heat loss calculation, two types of losses were considered, the heat loss to the exterior and the heat loss to the interior room, due to different temperatures caused by the high temperature of the blind collector. For both, the layering of the façade was defined as shown on Figure 51. For the double skin façade, front glazing (exterior glass) was considered to be a 6 mm clear glass with low-iron content for better transmission of radiation. The internal glazing is considered to be a 6-8-6 insulated glazing unit.



(a) Double skin façade for cavity blind collector input

(b) Single skin façade for external blind collector input

Figure 51. Façade layers for absorption and heat loss calculation.

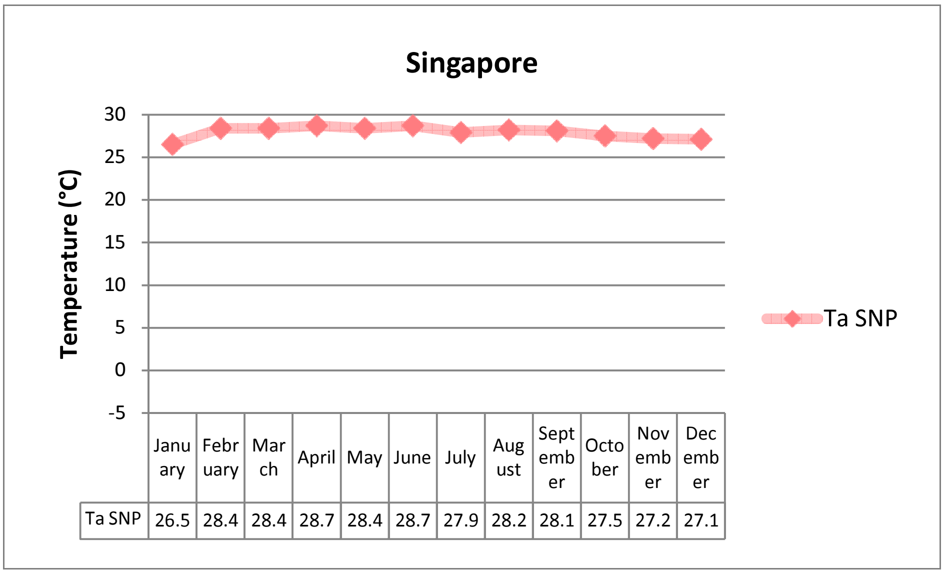
8.1 Results for Each Latitude

The general results for each of the seven cities are presented next. These results are divided into three parts, which are commented for every particular city. The first part corresponds to the absorption per m^2 of the blind collector according to the local radiation. Second part consists of the heat losses that are encountered depending on the configuration of the blind collector. Finally the useful energy is presented.

All calculations were made for two configurations: external blind collector and cavity blind collector. For each of these, the slats are considered to be arranged respectively high solar radiation and low solar radiation according to Figure 43. To refer to each arrangement, the terms *unshaded* and *shaded* are used respectively.

8.1.1 Singapore (1°17'N)

Singapore has a tropical humid climate with monthly average temperatures ranging from 26°C to 29°C. Because of high temperature along the year, energy collected from the blinds would work only for cooling. High air temperatures help reducing heat losses to the outside, so in theory more energy should be possible to be collected.



	January	February	March	April	May	June	July	August	September	October	November	December
Ta SNP	26.5	28.4	28.4	28.7	28.4	28.7	27.9	28.2	28.1	27.5	27.2	27.1

Figure 52. Average monthly temperature for Singapore.

Due to the low latitude of Singapore, the sun path is extended to the north; therefore, almost half of the year radiation is received from the north (Figure 53). For this reason, the north façade was also analyzed in order to compare how much heat can be produced from blinds located there.

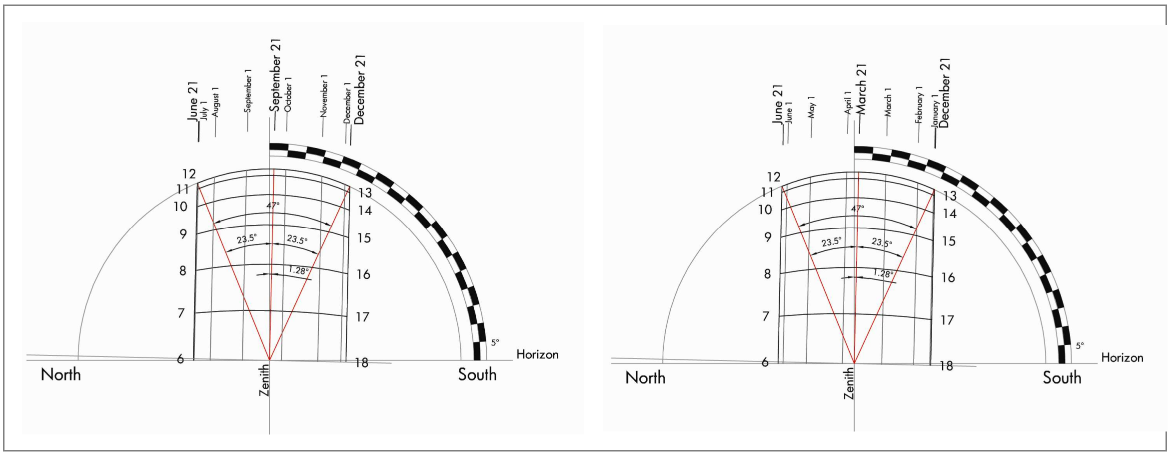


Figure 53. Sun path for Singapore.

South Façade

Because local latitude φ = 1°17’, the sun is normally high in the sky even in equinoxes, where the sun has an altitude of 65.27° during winter and 67.83° during summer (Figure 53). The slats of a collector remain mostly shaded because the sun is coming from directly above, even though a high solar radiation arrangement is used. The more the sun moves toward the vertical, the more shade is encountered. Once the sun has an azimuth γ_s towards the north, the slope of the slats in the south façade will be 0°.In that case, the slats that are not receiving beam radiation will only be collecting diffuse and reflected radiation. For this reason, it can be seen in Figure 54 (a) that both configurations, unshaded and shaded slats are receiving the same amount of radiation during the spring and summer months (April to August). Same phenomenon happen to the slats of cavity blinds (Figure 54 (b)).

In autumn and winter, the south façade is much more susceptible to beam radiation. Here a slight difference between the fixed-angle slats and the tracking slats can be noticed for the case of the unshaded configurations, since tracking systems tend to reduce the angle of incidence of radiation. For the shaded situation, this difference is vanished because of the percentage of shading, which is less for the fixed-angle blind.

North Façade

Similar to the south façade, the north façade receives around 450 MJ/m^2 in the months where the sun is radiation from the north (April to August). The differences between angle adjustment frequencies for tracking are not relevant for external blinds. For shaded blinds, there is a slight difference between hourly adjustment and daily and month, due to the shades that are casted on the slats, but there is not much difference with the fixed-angle slats. So for this façade, it is also recommended to use a fixed-angle blind collector (Figure 55).

East and West Façade

Absorbed Radiation for both east and west façades is equal, since half of the day radiation (morning radiation) is collected in the east façade and the other half (afternoon radiation) is collected in the west façade Figure 56 shows the radiation on the east and west façade. For these two façades, the hourly angle adjustment tracking has a better performance, followed by the hourly and month angle adjustment and finally, fixed-angle blinds normally give less radiation. In order to obtain a reasonable amount of absorbed radiation and keeping simplicity of the blind, it would be recommended to install daily or monthly angle adjustment tracking in these façades; they give a comparatively good amount of radiation, but are much easier to operate.

It also can be seen that even though the radiation collected in the east and west façade is less compared to the radiation on the south façade on the peak months, it is still a great amount of energy.

Figure 54. Absorption per m^2 of absorber surface for South Facade.

Figure 55. Absorption per m² of absorber surface for North Facade.

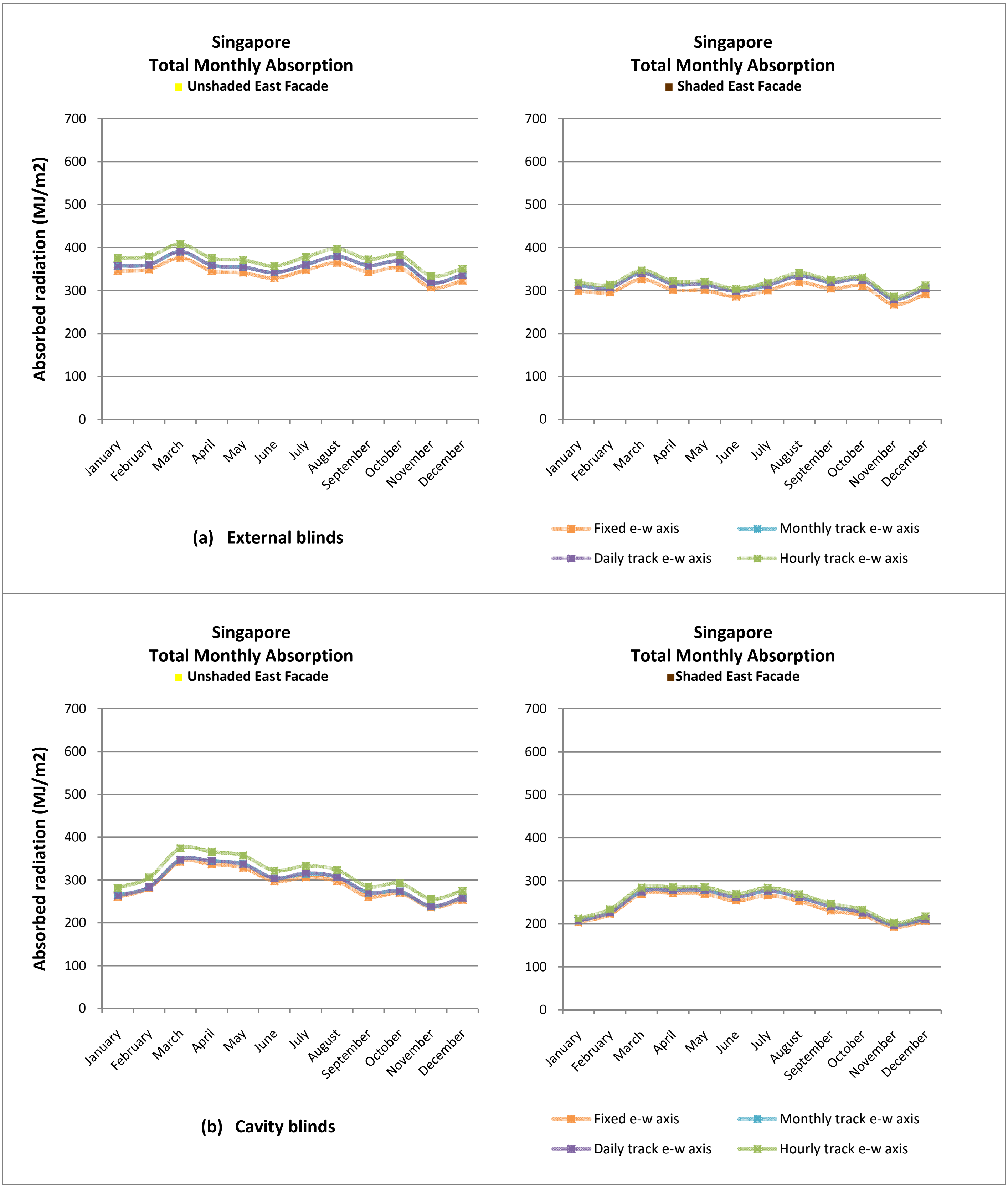


Figure 56. Absorption per m^2 of absorber surface for East and West Facade.

8.1.2 Caracas (10°30'N)

Caracas has a tropical warm climate, with temperatures ranging from 21°C to 24°C throughout the year (Figure 57). Even though the air temperature outside is in the range of a comfortable temperature, in the inside of a building, it can be increased due to equipment, solar radiation and people. Because this increase in temperature, the energy obtained from the blind collector will be only used for cooling purposes.

Because of the low latitude, as in Singapore, the sun path is extended to the north. Almost a quarter of the yearly radiation is received from the north. Because of this reason, it was interesting to analyze the north façade as well (See Appendix 1 for sun path diagram).

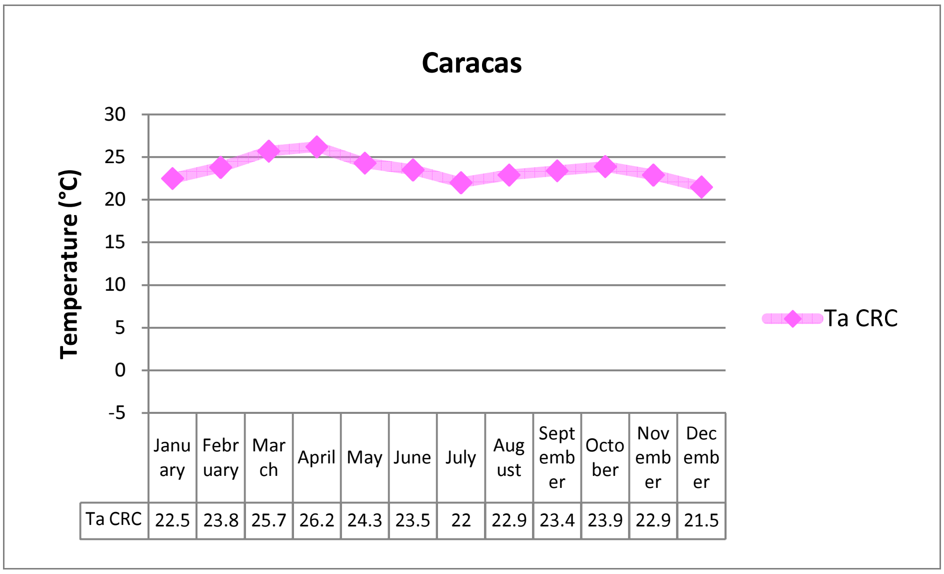


Figure 57. Average monthly temperature for Caracas.

South Façade

From Figure 58 it can be seen that from May to August, the radiation in south façade drops due to the solar azimuth γ_s>|90°C|. Thus collection in the blind, from both shaded and unshaded configurations, just accounts for diffuse and reflected radiation. There is no difference on using different angle adjustments, except for unshaded blinds in winter, where the tracking blinds have better performance than the fixed-angle slats. This low collection does not have any significant disadvantage, because during winter, the temperature drops for few degrees, but to the point where needed heating. So overheating from the sun is less and less cooling is needed. For this façade, it is recommended to use a fixed-angle blind collector.

North Façade

In the North Façade, there is also insignificant difference in the absorbing performance between the systems in the unshaded mode. For the shaded mode, the hourly adjustment and fixed-angle blinds perform slightly better. Therefore, for the ease of operation and installation, it is also recommended to use fixed-angle blinds.

East and West Façade

Absorbed radiation of the east and west façade can also contribute in a great extent to the total absorbed radiation. In the worst case scenario, which would be a blind in a cavity with shading, it can provide approximately 200MJ/m2 each month of the year, which is almost the amount of radiation absorbed in the south façade during the months from May to August (Figure 60).

Figure 58. Absorption per m^2 of absorber surface for South Facade.

Figure 59. Absorption per m^2 of absorber surface for North Facade.

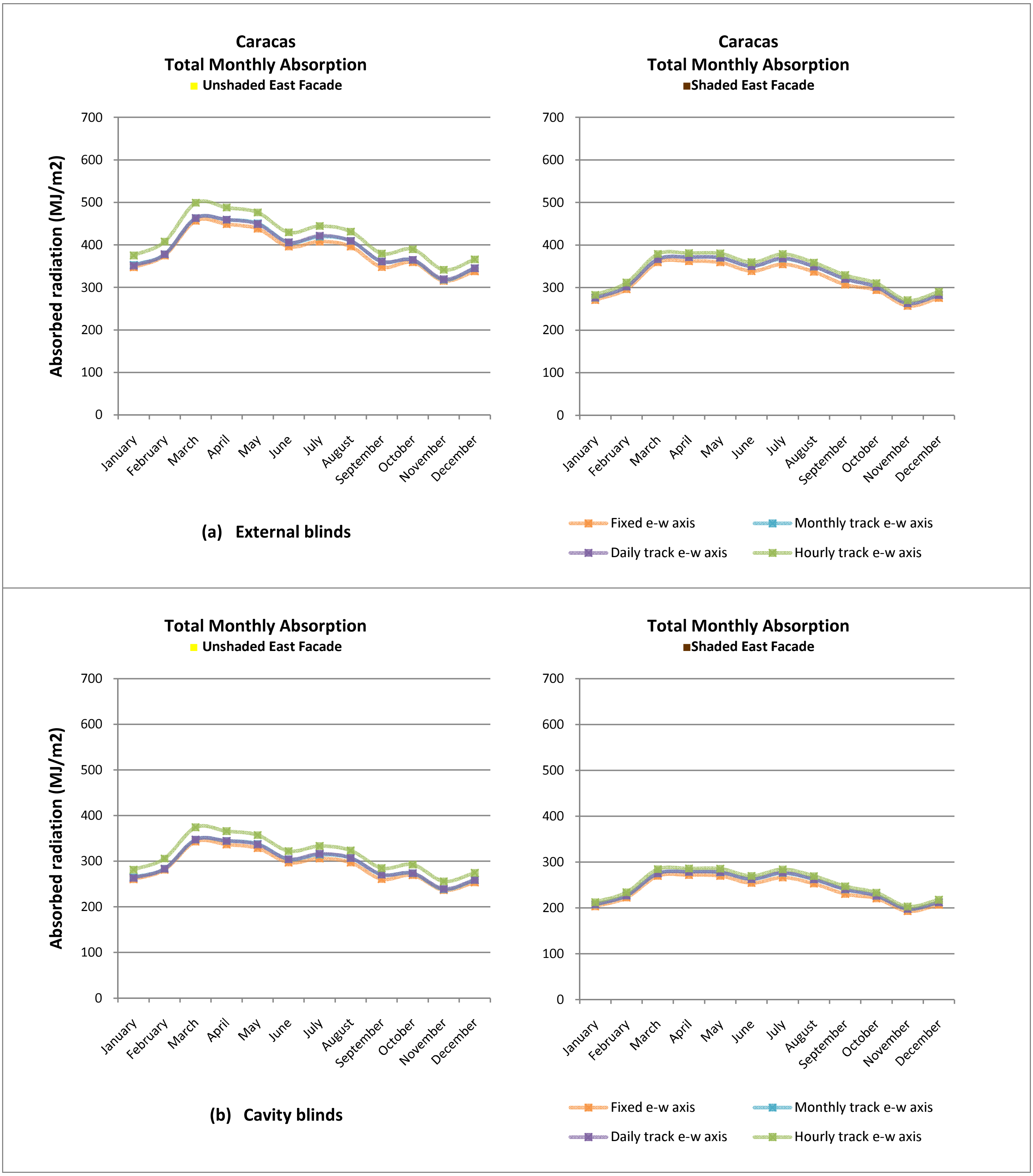


Figure 60. Absorption per m^2 of absorber surface for East and West Facade.

8.1.3 Mexico (19°41’N)

Mexico City has a warm-moderate climate. The temperature monthly average ranges from 13°C to 21°C (Figure 61). Because during winter, temperature is lower that than considered as thermally comfortable inside room, this means that small heat losses can occur during winter, which cause a decrease in the temperature of the interior space. For this reason, it is advised that the solar radiation collected from the blinds be input for both solar heating and cooling.

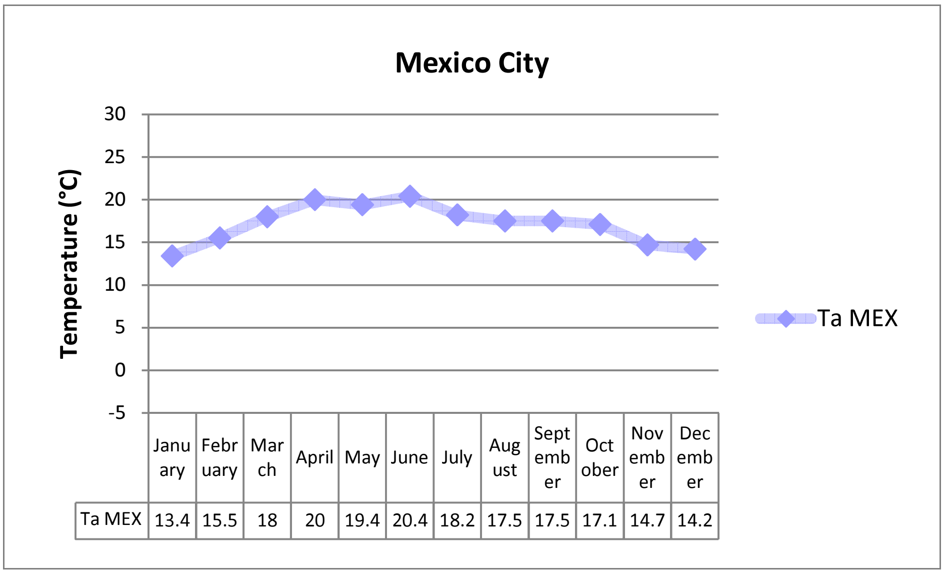


Figure 61. Average monthly temperature for Mexico City.

South Façade

Latitudes similar to that of Mexico City are in the verge of having almost no solar radiation from the north. In the particular case of Mexico City, around 90% of solar radiation is received from the south. Therefore collector located in this façade will be collecting most of the solar radiation.

Fort his façade, the months of low collection are May, June and July. This is due to the high solar altitude that approximates to 90°, so even if the blind is arranged according the high solar radiation, it will keep shaded. This can be seen in Figure 62, where the radiation for unshaded blinds is equal to that of shaded blinds during those months.

The latitude for this city is still small enough that the difference between angle adjustment tracking is still very small, therefore, for this façade it is still recommended to use a fixed-angle blind collector for ease of operation, but also a month angle adjustment would be good to collect as slightly more radiation.

North Façade

The radiation of north façade is decreased in this latitude compared to that of Singapore and Caracas, being most of it due to diffuse and reflected radiation. The difference in performance starts to be more disperse between the types of tracking. It can be seen on Figure 63 that those that have better radiation absorption, for both shaded and unshaded blind, are the hourly angle adjustment tracking and the fixed-angle blind. Therefore any of both is recommended.

East and West Façade

For these façades, the amount of radiation absorbed is considerably good. The shaded cavity blind can provide around 250MJ/m^2 per month. In this façade, it can be seen in Figure 64 that the hourly tracking definitely makes a difference compared to the performance of the other three types of sun tracking, especially for the shaded external blind.

Figure 62. Absorption per m^2 of absorber surface for South Facade.

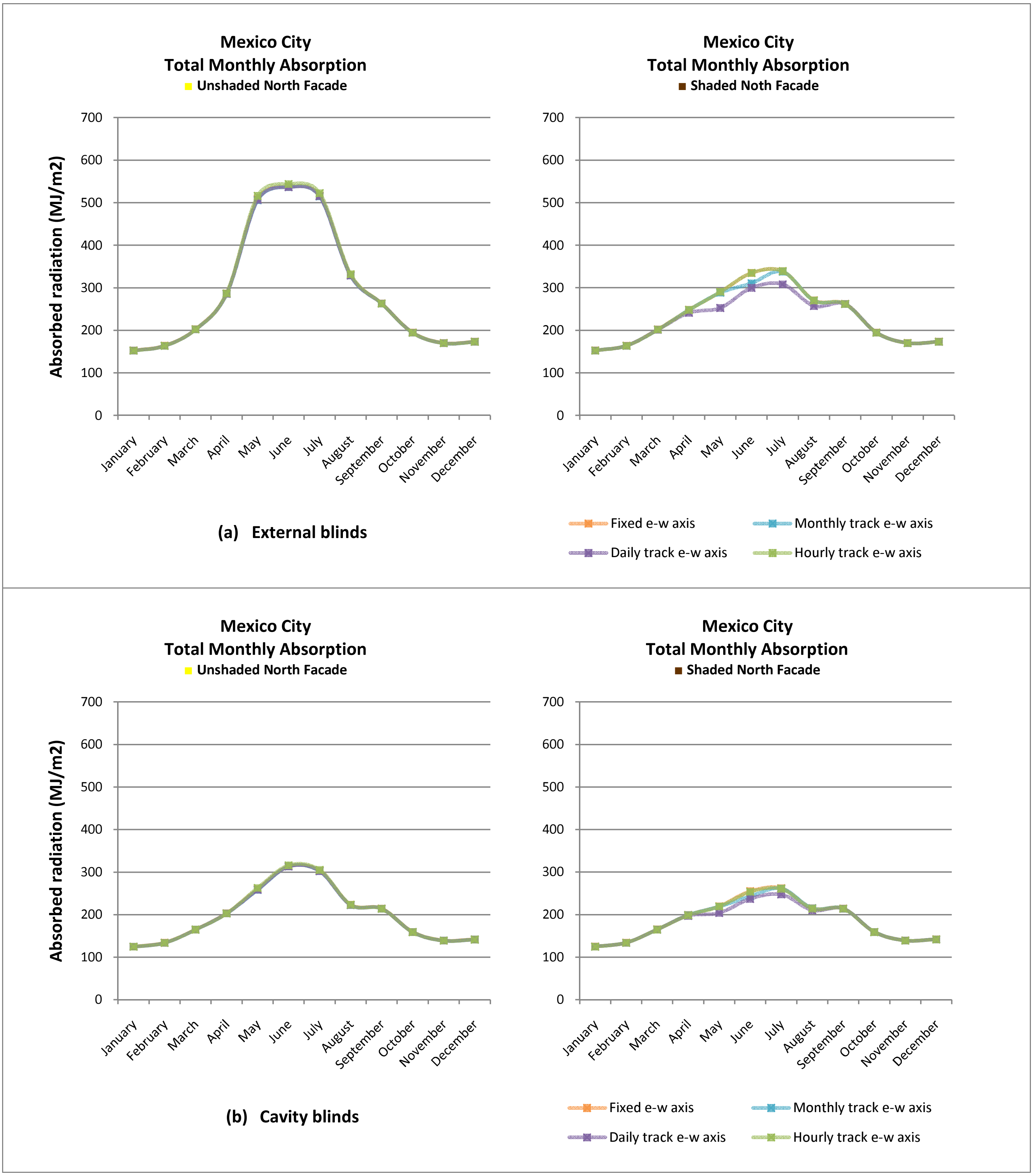


Figure 63. Absorption per m^2 of absorber surface for North Façade.

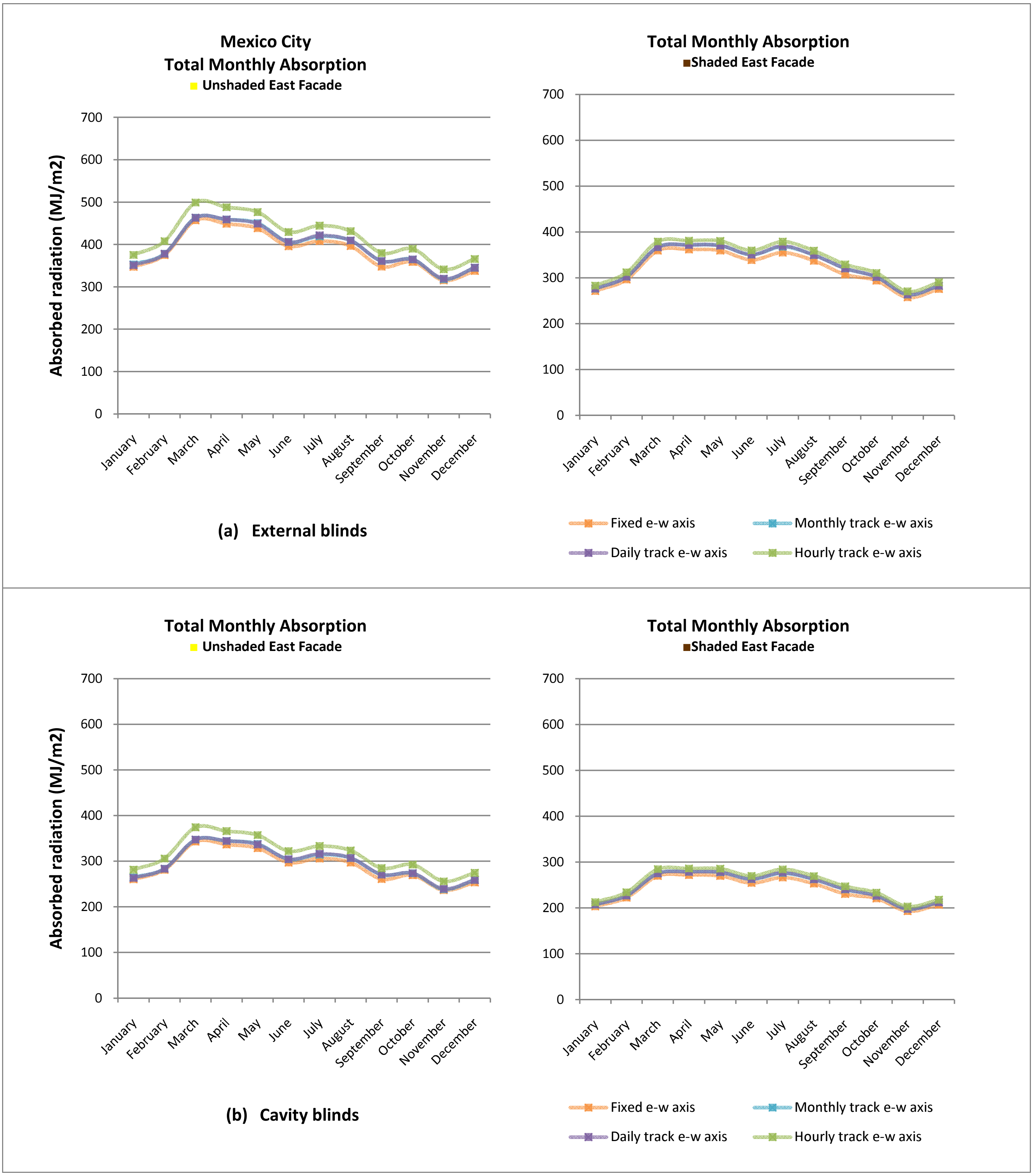
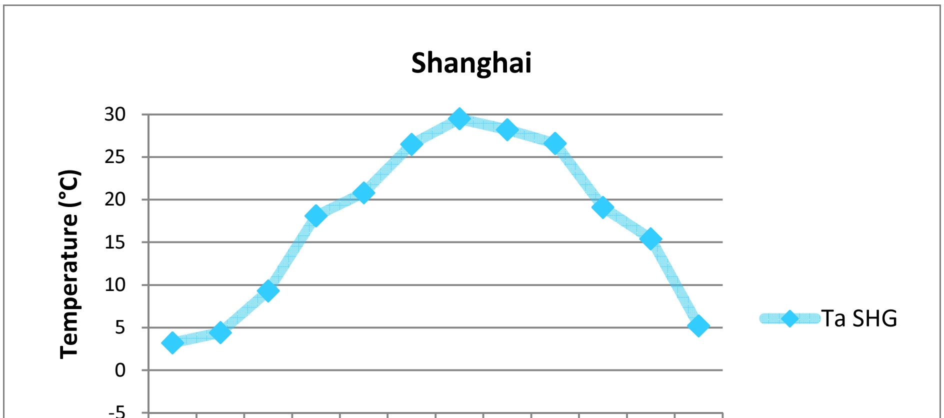


Figure 64. Absorption per m^2 of absorber surface for East and West Façade.

8.1.4 Shanghai (31°10’N)



	January	February	March	April	May	June	July	August	September	October	November	December
Ta SHG	3.2	4.4	9.3	18.1	20.8	26.5	29.5	28.2	26.6	19.1	15.4	5.2

Figure 65. Average monthly temperature for Shanghai.

South Façade

Radiation in the south façade is very variable for this location. It can reach up to 500 MJ/m2 per month during July, but in the winter it only gets around 200 MJ/m2. The tracking blind collectors perform better in Shanghai than the fixed-angle collector. In the months in which the absorption is almost the same for unshaded and shaded configuration is because there is little or none beam radiation falling on the slat and only diffuse and reflected radiation is being collected. That is the case for the months of January and December. For this façade, any kind of tracking blind except for the fixed angle gives equal solar radiation absorption (Figure 66).

North Façade

In the north façade very little to non beam radiation is being collected. Most of the absorption is done for diffuse and reflected radiation. But even with no beam radiation, collection is still considerable, especially when the absorbed radiation of shaded blinds is compared. For this façade, all the types of collector perform equally, therefore, for the sake of simplicity, the fixed-angle blind collector is recommended (Figure 67).

East and West Façade

For the east and west absorption, absorption done by hourly angle adjustment tracking is considerably better that other systems. This radiation is definitely an important part of the radiation that can be collected from the façade (Figure 68).

Figure 66. Absorption per m^2 of absorber surface for South Façade.

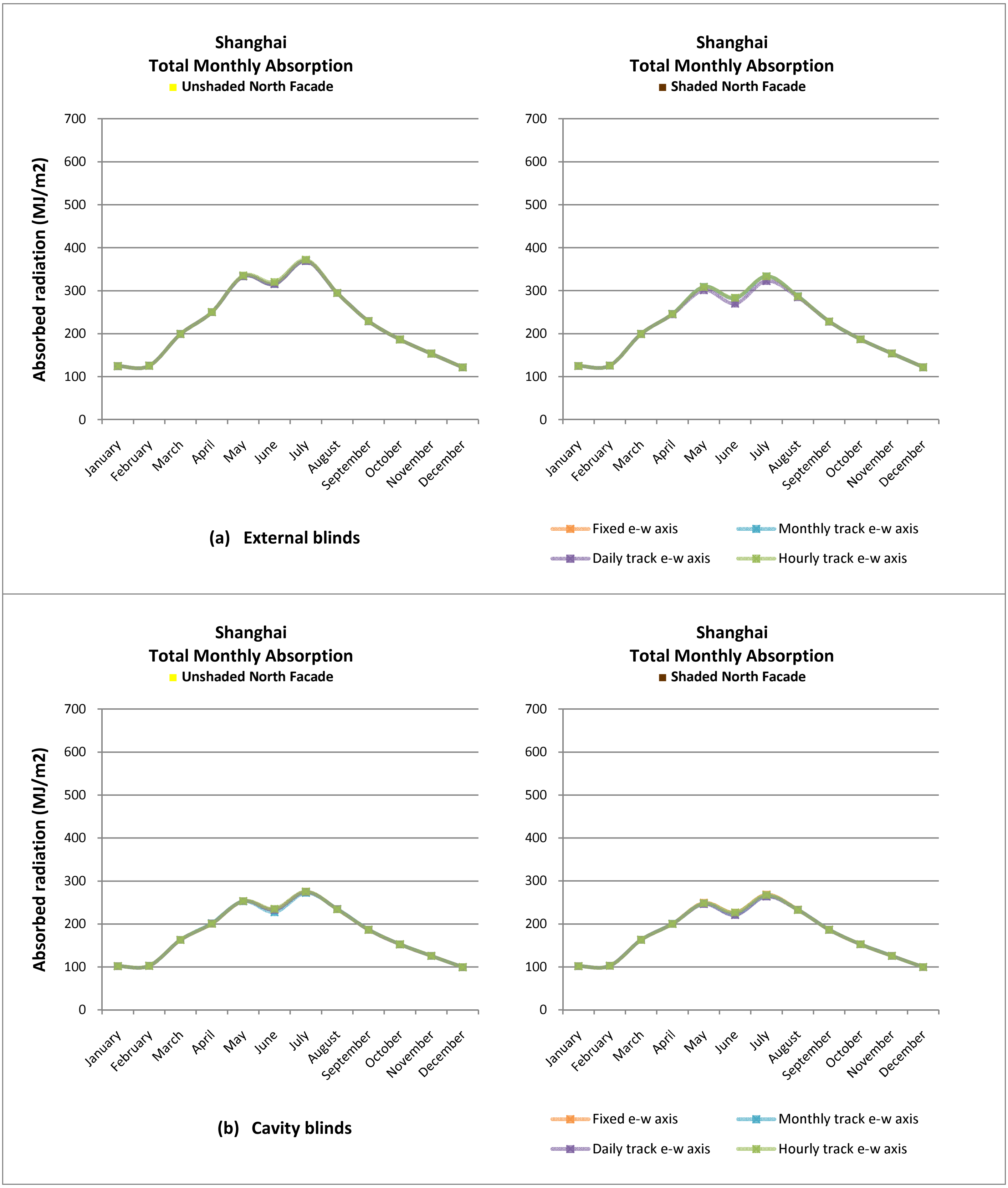


Figure 67. Absorption per m^2 of absorber surface for North Façade.

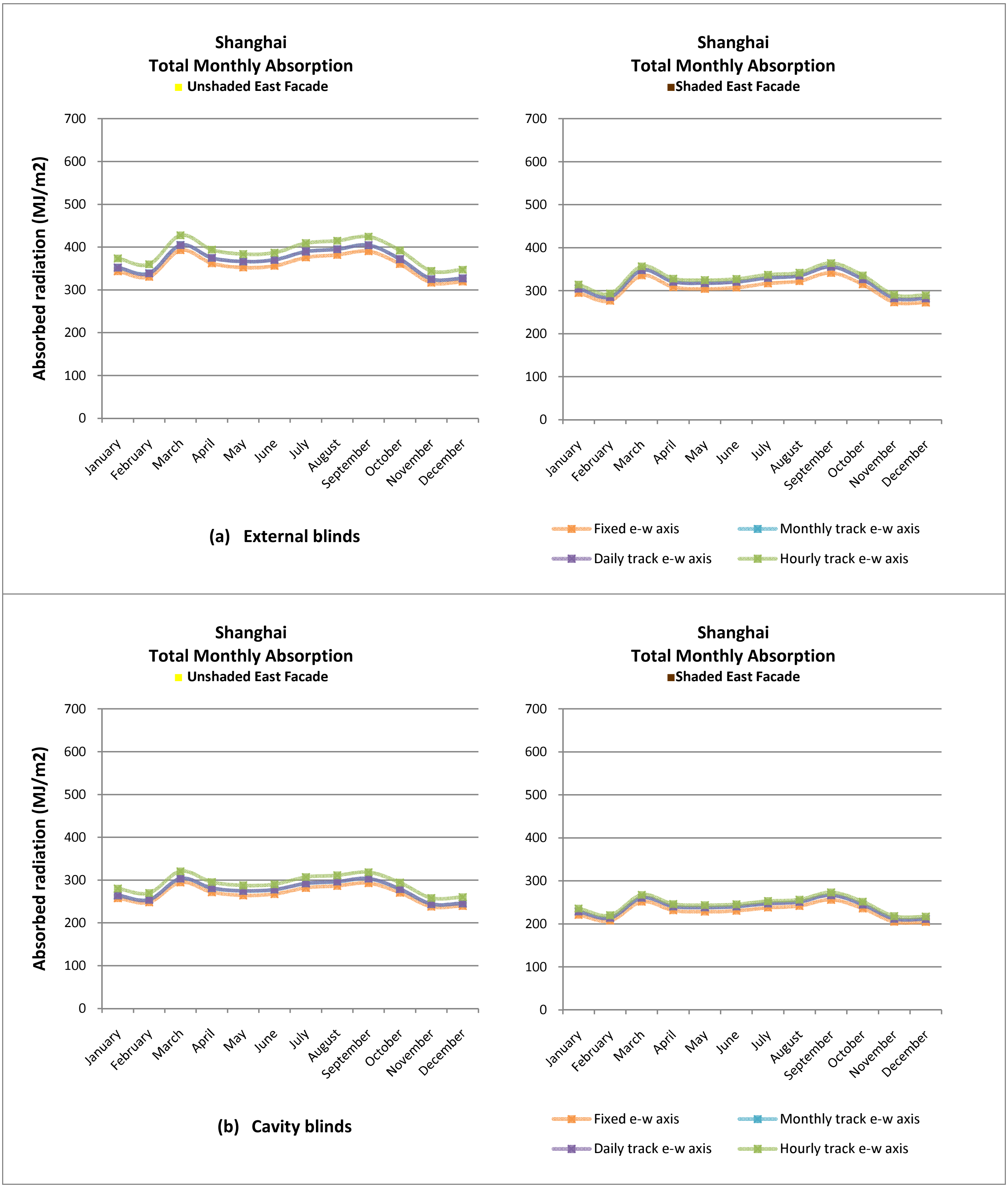


Figure 68. Absorption per m^2 of absorber surface for East and West Façade.

8.1.5 New York (40°43'N)

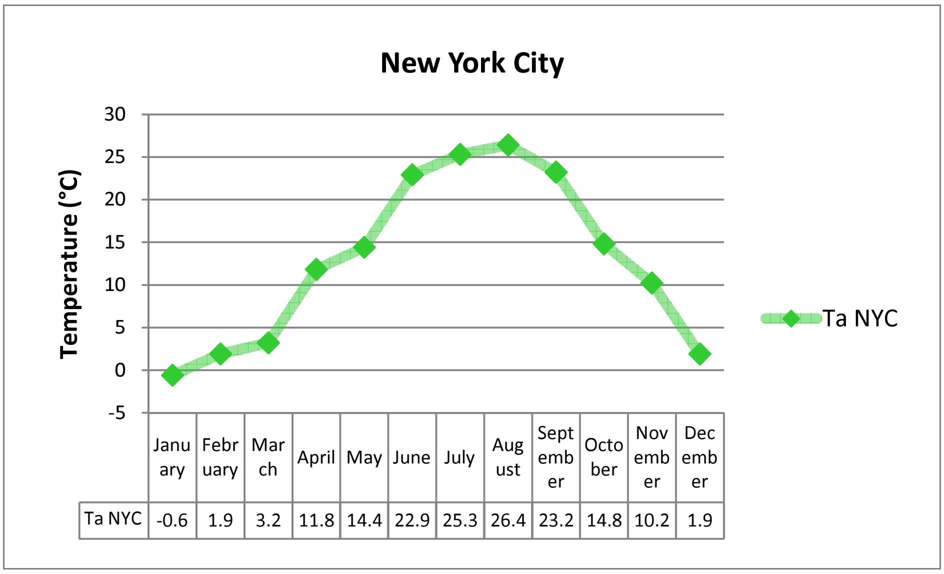


Figure 69. Average monthly temperature for New York City.

South Façade

From this latitude on, the type of tracking becomes important. For the south façade, it can be seen in Figure 70 that the peak absorption occurs during the months from May to August, exactly where the temperature (Figure 69) increases and the demand for cooling is greater. The recommended blind collector for this façade is definitely the hourly angle adjustment, especially for those month is summer.

North Façade

In the north façade, radiation absorption is decreasing compared to lower latitudes. Most of the radiation that is collected is diffuse and reflected radiation. Here, glazing of the cavity plays an important role in the absorption of this façade, decreasing even more the already small amount of radiation (Figure 71). For this façade all types of collector perform at the same rate. Fixed-angle blind collector is recommended if collection is desired to be done.

East and West Façade

The amount of radiation absorbed in the east and west façade is considerable compared to that of south. Hourly angle adjustment is show in Figure 72 to give the best absorption of radiation.

Figure 70. Absorption per m^2 of absorber surface for South Façade.

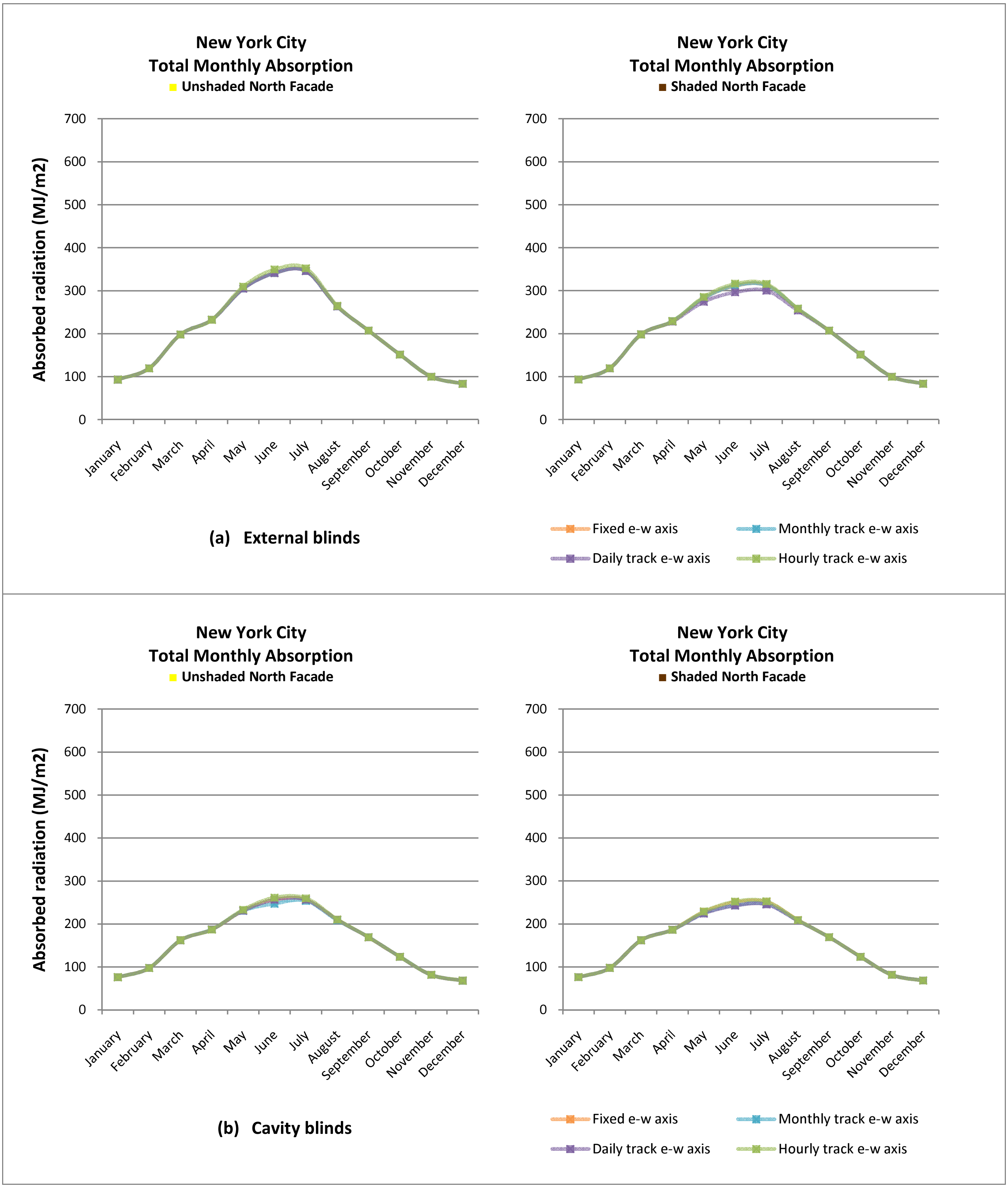


Figure 71. Absorption per m^2 of absorber surface for North Façade.

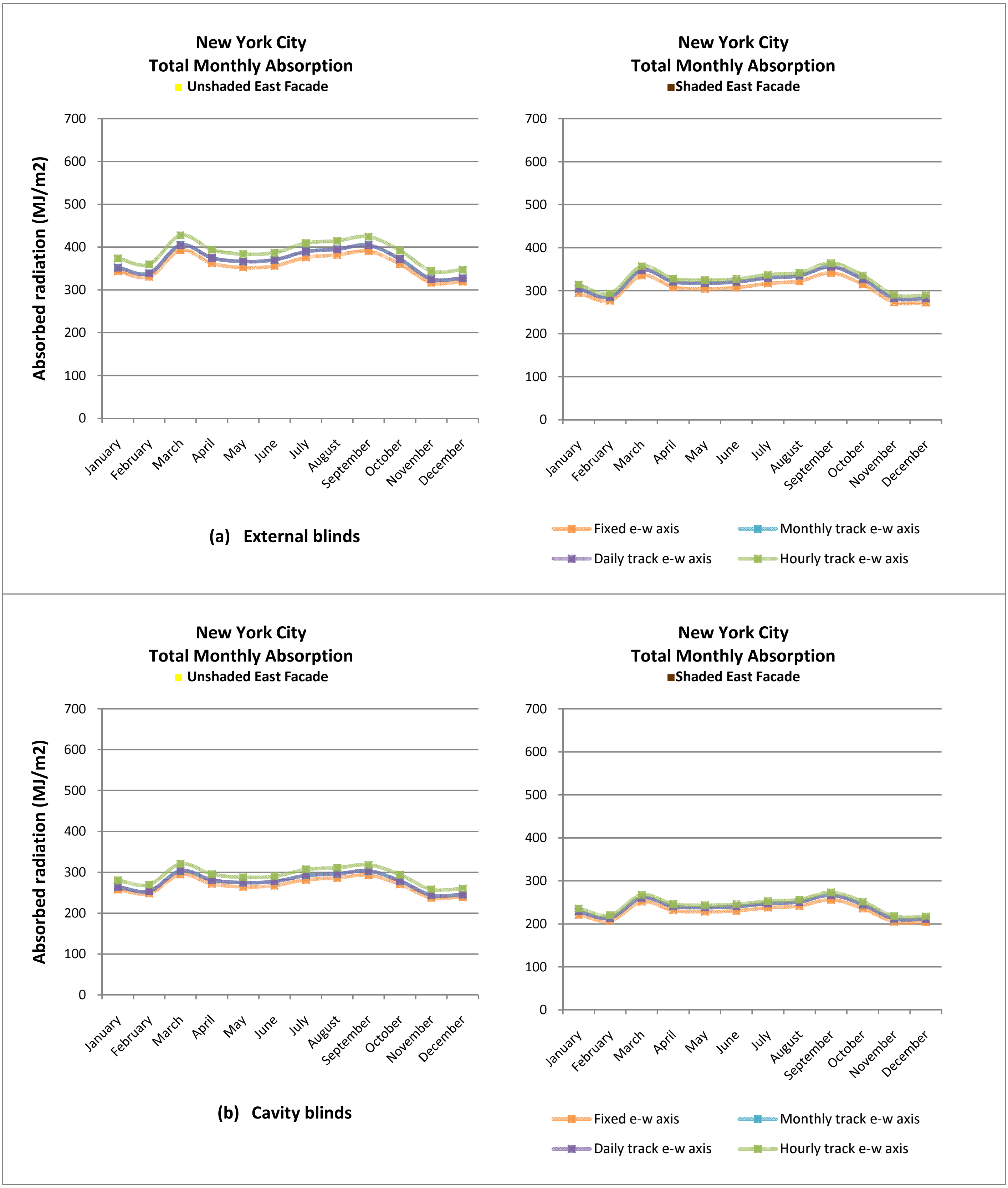


Figure 72. Absorption per m^2 of absorber surface for East and West Façade.

8.1.6 Amsterdam (52°22'N)

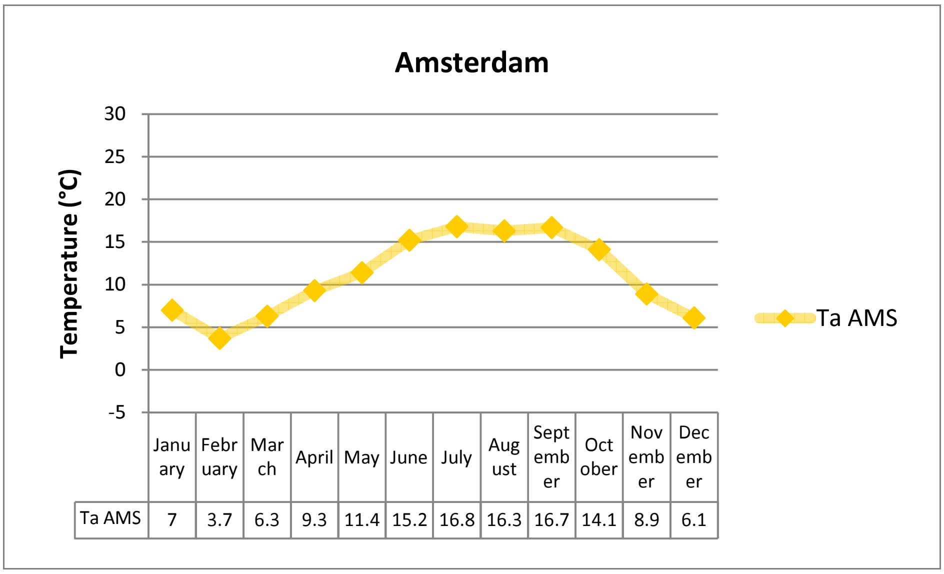


Figure 73. Average monthly temperature for Amsterdam.

South Façade

Radiation in the south façade is the most important collecting source of for this altitude. For those months of winter, the performances of all collectors are equal, but the difference in performance can be encountered from May to August. In Figure 74 it can be seen that hourly angle adjustment is the best option, especially for these months where cooling is needed.

North Façade

North façade is collecting only diffuse and reflected radiation during winter. The amount of radiation collected in not significant compared to the radiation on the south or east and west facades during the same period. During summer, the length of the day is larger and the sun rises from the north-east. Few hours pass by before the sun has a south position, and during these hours, the north façade can absorb radiation. A fixed-angle blind collector can be placed in the north façade with an unshaded position to enhance solar collection. Glare would not be a problem for this façade because the solar radiation is quite low in sunrise and sunset (Figure 75).

East and West Façade

The radiation absorbed in these facades is quite high. It is due to the low solar altitude, which produces less shading on the slats, and therefore greater absorption. As for the south façade, it is recommended to use hourly angle adjustment for the solar tracking, because it gives a better performance of about 50MJ/m^2 compared to the other types of blind collector (Figure 76).

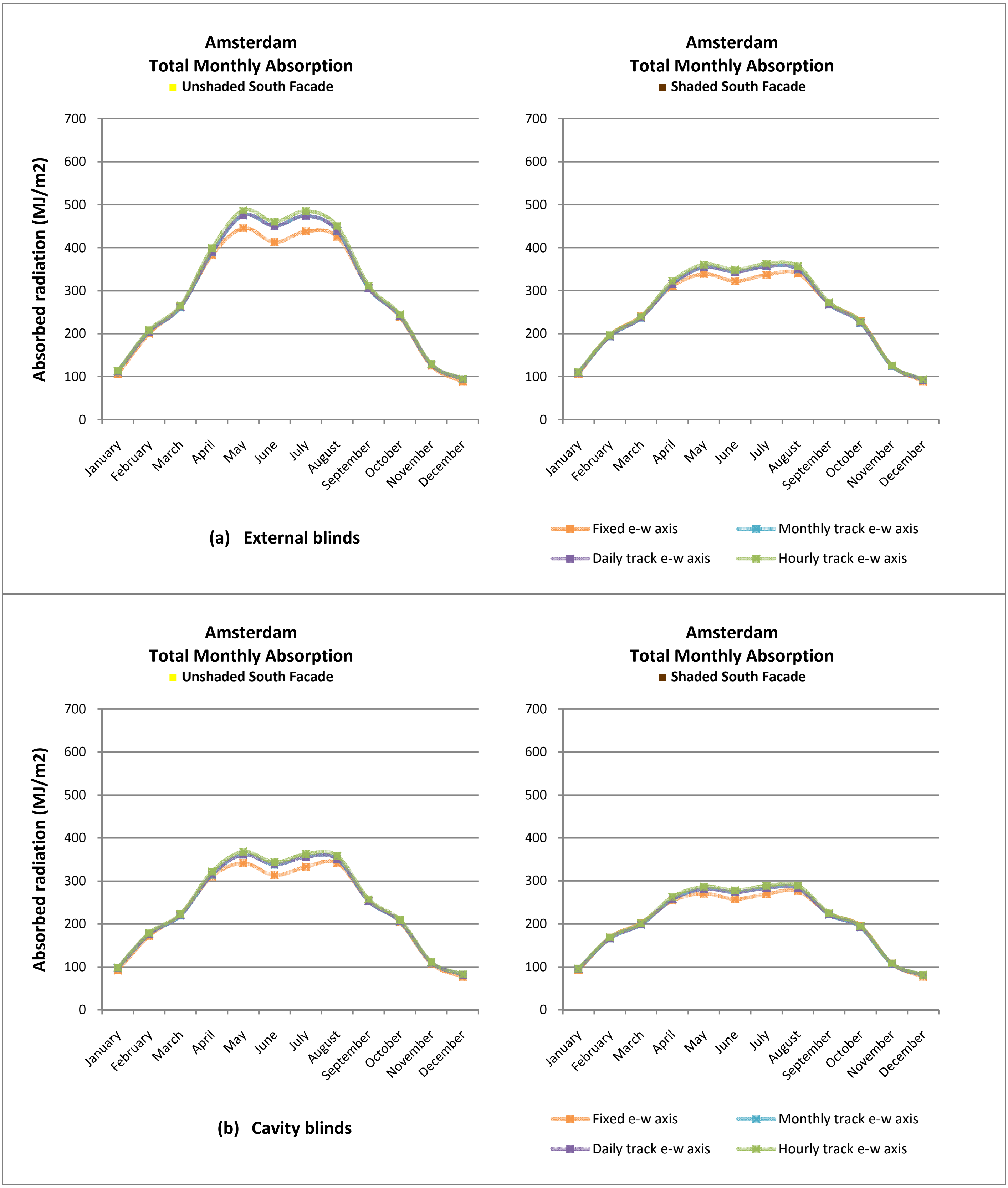


Figure 74. Absorption per m^2 of absorber surface for South Façade.

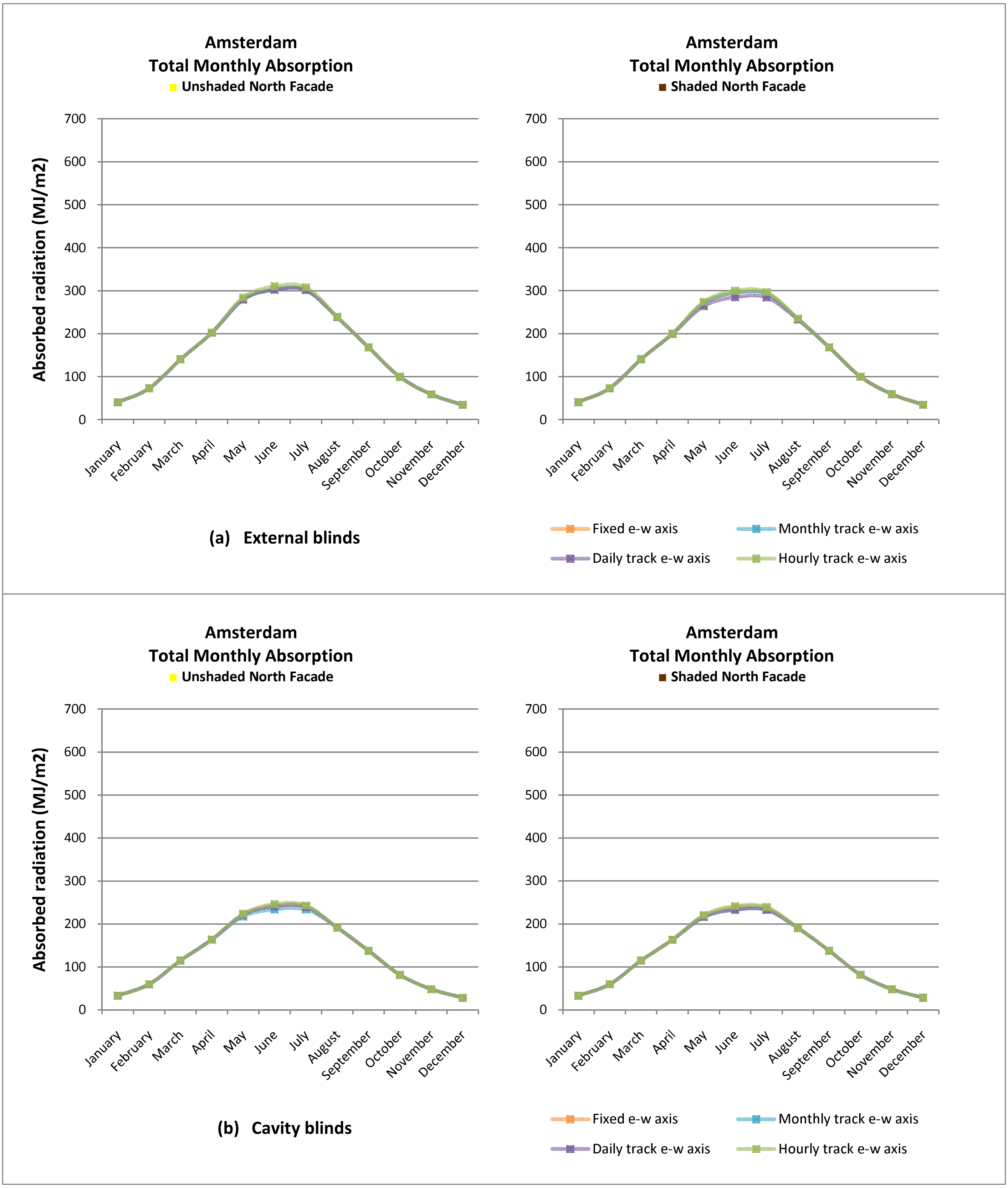


Figure 75. Absorption per m^2 of absorber surface for North Façade.

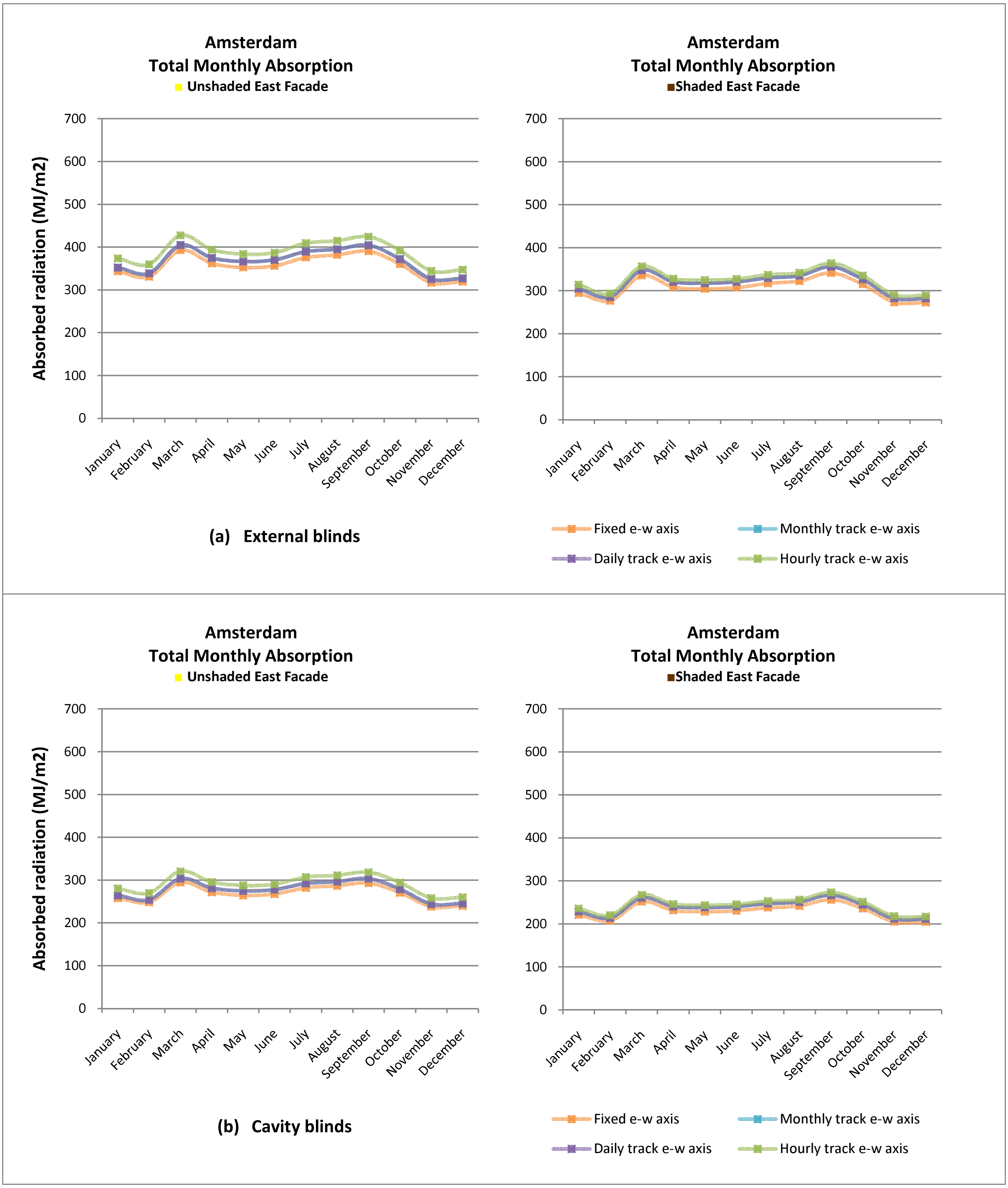


Figure 76. Absorption per m^2 of absorber surface for East and West Façade.

8.1.7 Helsinki (60°12’N)

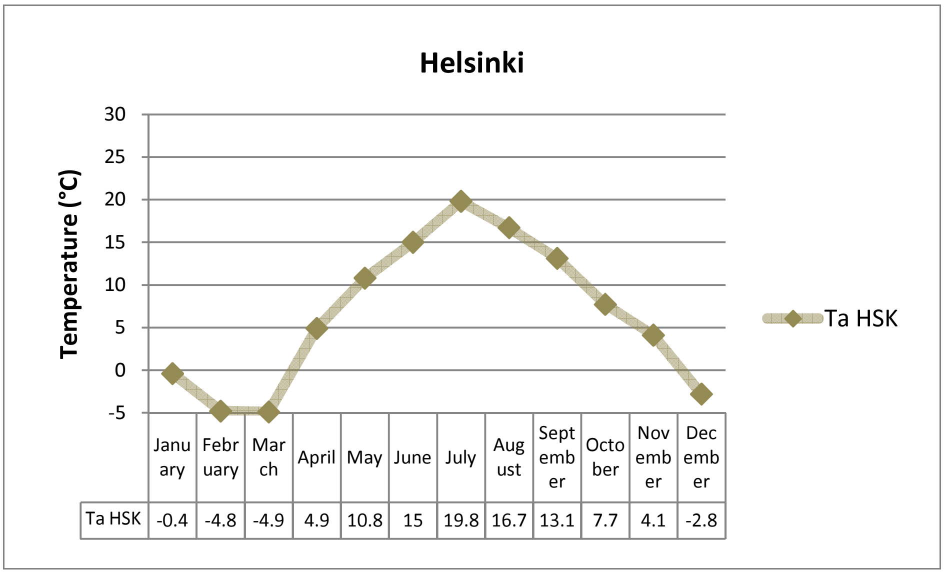


Figure 77. Average monthly temperature for Helsinki.

South Façade

Because the solar path in Helsinki, due to the latitude, high quantities of solar radiation can be absorbed from May to July because the solar altitude is in its highest point, but not to high to produce considerable shading on slats. During winter months, the radiation decreases considerably and therefore the absorption decays to a really low level (50 MJ/m^2). It would be convenient for the case of cities with high latitude to collect as much energy as possible during the summer for a later use in winter (Figure 78). For this façade it is recommended to use an hourly angle adjustment for the solar tracking system.

North Façade

Radiation on the north can be collected due to the fact that the sun path is very inclined towards the south during the summer, so the length of the day is larger, having the sun rise in the north-east. It takes a few hours before the sun goes to a south-east position, and during these hours, absorption can be done in the north facade. Same behavior can be found in the west before sunset (See solar path for Helsinki in Appendix 1).

East and West Facades

It is worth to collect radiation from east and west facades because it can give a high energy input of approximately 300MJ/m$^{2.}$ As seen before, for these façade it is recommended to use an hourly angle adjustment for the solar tracking system as seen in Figure 80.

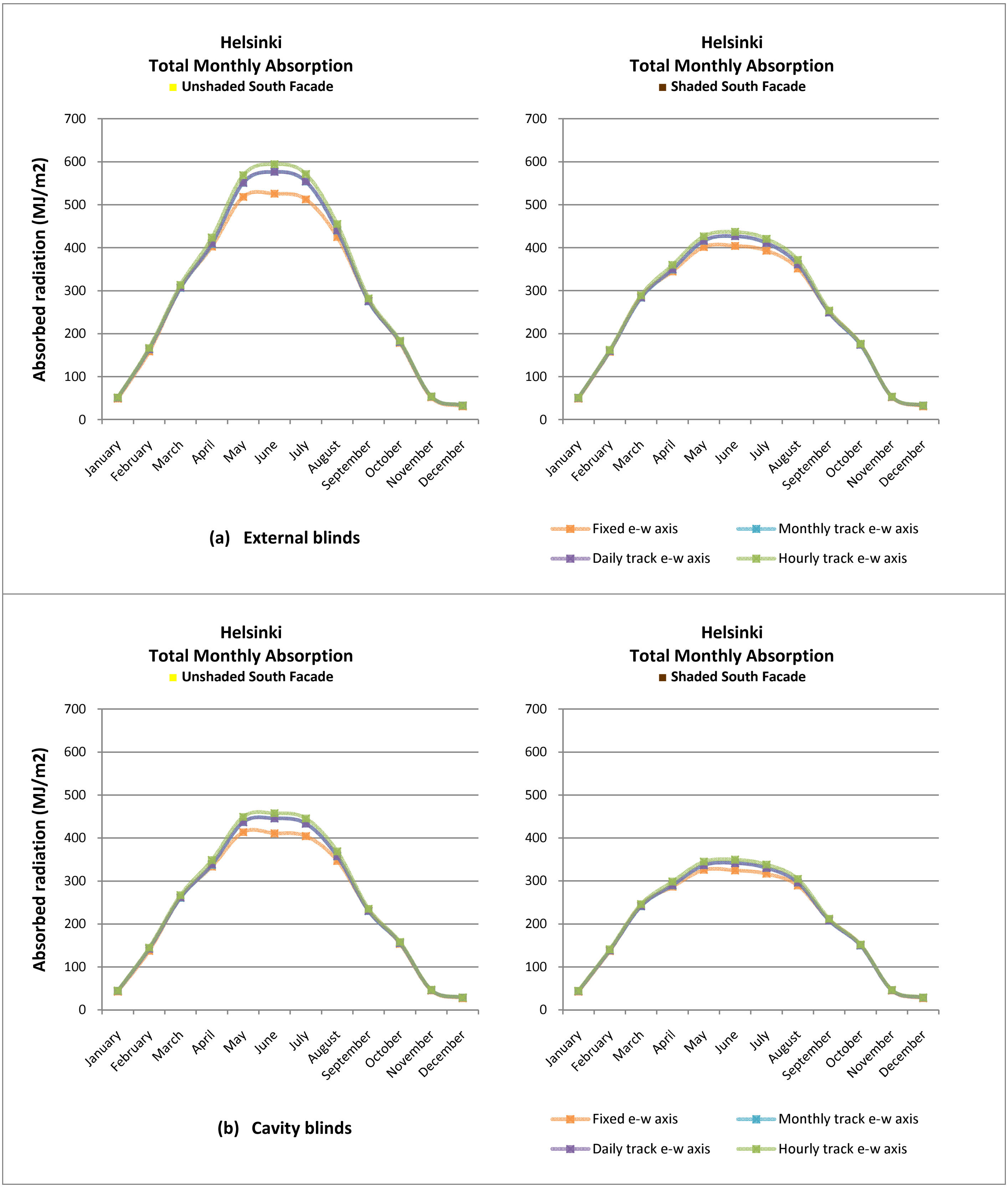


Figure 78. Absorption per m^2 of absorber surface for South Façade.

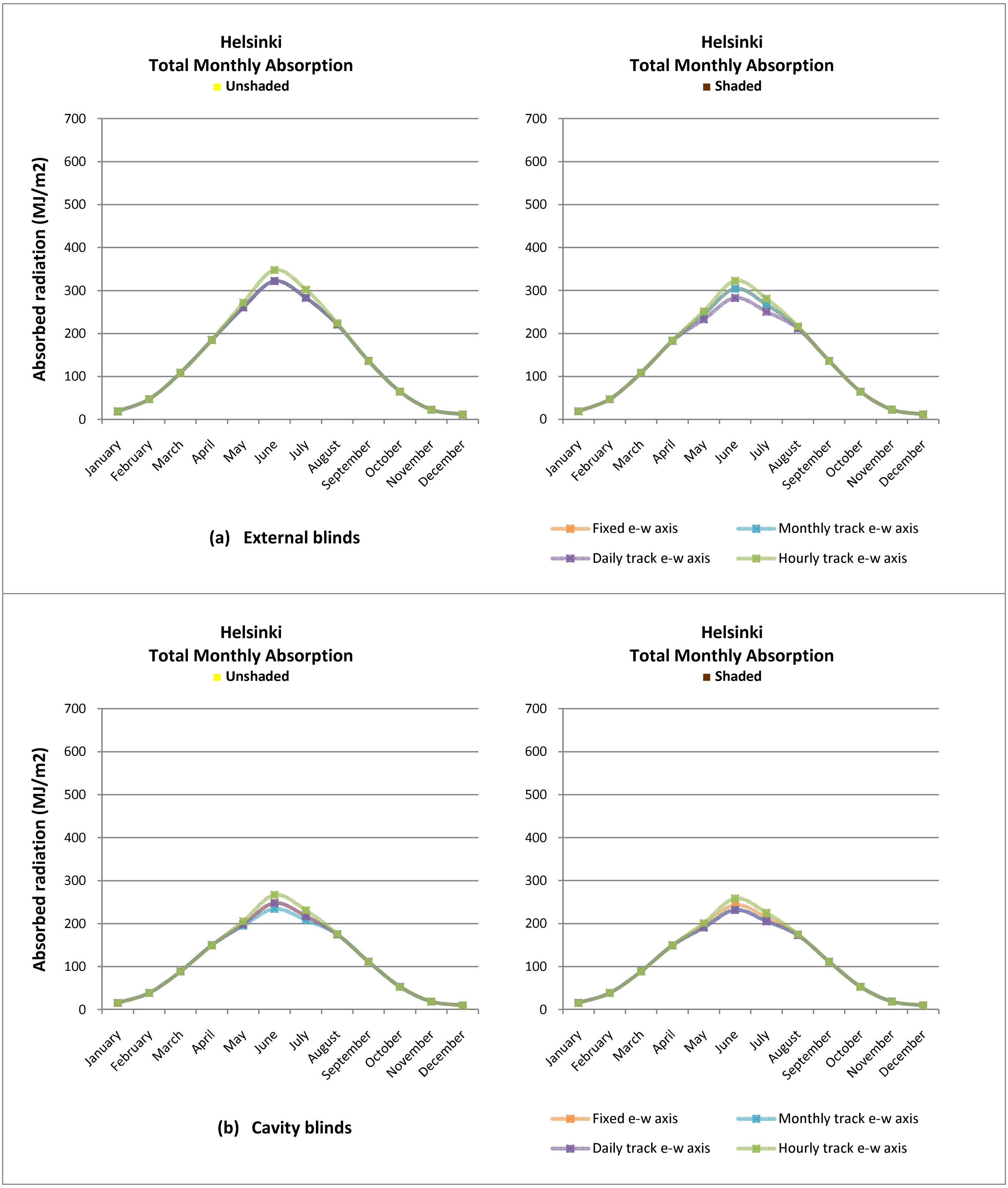


Figure 79. Absorption per m^2 of absorber surface for North Façade.

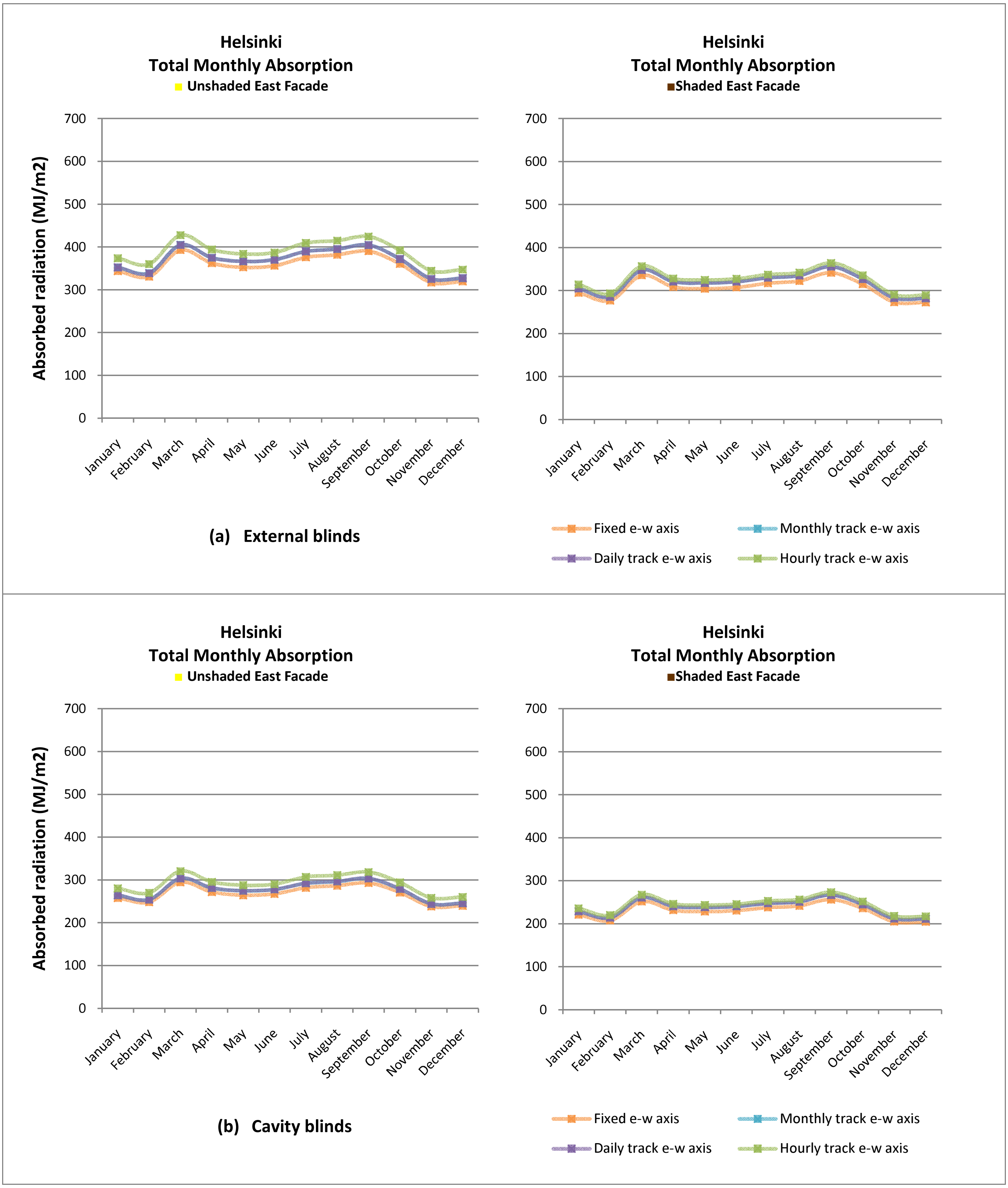


Figure 80. Absorption per m^2 of absorber surface for East and West Façade.

8.2 Summary of results

The difference between the frequencies of angle adjustment for the solar tracking has no significant effect in the solar collection for those latitudes close to the equator. Here, any of the solar tracking systems gives the same output of energy when they are installed according to the low solar radiation arrangement (taking shading into account see Figure 43 (a)), so for sake of economy and ease of installation it is recommended to use the fixed-angle blind collector. As the latitude increases, the frequency of the solar tracking angle adjustment starts having an effect on the amount of radiation collected per square meter. Hourly angle adjustment tracking works better for situations where the sun is normally in a low elevation (Table 9).

City	South Façade	North Façade	East / West Façade
Singapore	Fixed	Fixed	Hourly
Caracas	Fixed	Fixed	Hourly
Mexico City	Fixed	Fixed	Hourly
Shanghai	Any tracking	Fixed/ Not relevant	Hourly
New York City	Hourly	Fixed/ Not relevant	Hourly
Amsterdam	Hourly	Fixed/ Not relevant	Hourly
Helsinki	Hourly	Fixed/ Not relevant	Hourly

Table 9. Recommended solar thermal collector blind for each façade in different locations.

For south façades in low latitudes, the absorption of radiation is considerable during the winter and fall, and decreases during spring and summer due to the lack of beam radiation on the façade, so only diffuse and reflected radiation is collected. In the other hand, radiation in the north façade can be collected during summer, so having a blind collector in the north façade can contribute to the total solar energy output.

For latitudes greater than 30°, most of the radiation is found on the south facades. A frequent angle adjustment mechanism is recommended for these latitudes. Radiation on the north façade is not significant compared to the radiation than is found on south facades. The radiation that is collected in this façade is composed only of diffuse radiation; therefore there is no difference between the absorption on external blinds and cavity blind (without taking into account the heat losses) Therefore the solar collection in this façade can be negligible.

9 Study cases

In the present study cases, a further analysis of the performance of the blind collectors is done by comparing the useful energy that the blinds can deliver to the thermal loads that a specific room needs. After this comparison, a better overview can be obtained on how much of the energy needed in a room can be generated by the blinds. For this task, a standard room was defined in order to compare the thermal load of the room to the amount of energy that can be generated in the façade that comprises that specific work area.

For these study cases, two cities were selected for further analysis: Mexico City and Amsterdam. Mexico City was selected because it was found interesting how this kind of technology, which has a higher impact on cold climates, can be developed and adapted in moderate climates with low latitudes. The selection was also driven by a personal interest in Mexico City.

Amsterdam was selected because from the general analysis it could be inferred that the blind collectors work better in locations with a relatively greater latitude just like that of Amsterdam. Additionally, it is worthy to examine how the blind collector performs in the latitude where this thesis was developed.

9.1 Standard room definition

A standard room is needed in order to calculate and refer the output of the calculation to a defined space. For the case of these case studies, a room with inside dimensions of 10x10 m. is used, with the following characteristics:

- The height of the office room is 2.8 m.
- The area that is covered by each façade is 28 m^2. The total façade area is 112 m^2.
- It is a detached office room
- Glazed in all four facades
- Working space for 16 people (each with own electronic equipment e.g. computers)
- Double glazing unit is used in inner façade skin.

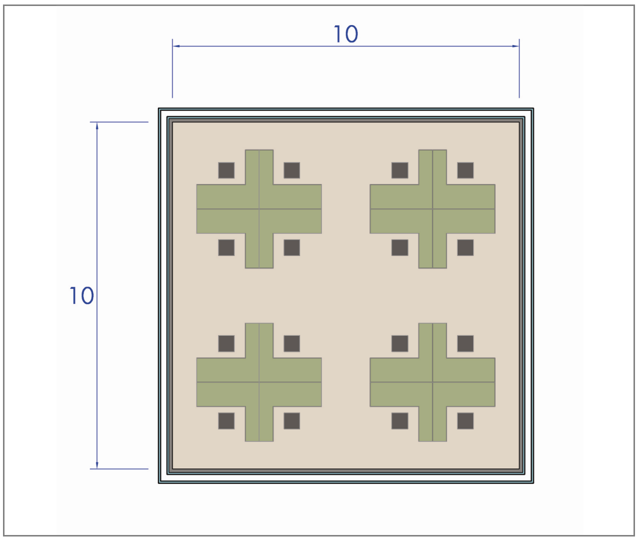


Figure 81. Plan view of standard room.

9.2 Type of Solar Thermal Collector Blind

According to the results of the calculations above, the blinds that are going to be taken into account for the current study cases are those corresponding to Mexico City and Amsterdam, shown in Table 9. For Mexico City, the energy output of the fixed solar thermal collector blind will be used for the current case. For Amsterdam, the hourly adjustment solar thermal collector blind will be used for further study.

9.3 Thermal load estimation

In order to know how much energy is needed to maintain a desired temperature in a room, the thermal load of that room has to be defined. The thermal load is an estimation of the amount of energy that is required to heat or cool a building, according to the indoor temperature compared to a balance temperature T_b. The balance temperature is given by ASHRAE, and is an approximate temperature at which thermal comfort can be met. In order to calculate the thermal loads of a building, the heat gains, the building heat transfer, and the outdoor air temperature have to be known.

9.3.1 Heat Gain in buildings

Heat gain is the rate at which energy is transferred or generated within the space and consists of sensible and latent heat. These gains normally occur in the following forms:

- Solar radiation passing through glazed surfaces of buildings
- Heat transfer through conduction, convection and radiation from inner surfaces into the space
- Sensible heat convection and radiation from internal objects
- Ventilation and infiltration of heated air
- Latent heat gains that are generated within the space

9.3.2 Building Heat Transfer

Each building has a particular construction layering which gives a certain amount of resistance for heat losses to the exterior. Heat can be transferred through the building (e.g. through walls, slabs, windows) all modes: convection, conduction and radiation. The rate at which a building transfer heat to the outside is determined by:

$$Q = \frac{A \times \Delta T_{total}}{R_{total}} = UA \times \Delta T_{total}$$

(Eq. 57)

Where: ΔT_{total} : total temperature difference between inside and outside air (K)
A: area of the building element perpendicular to the heat flow direction (m^2)
R_{total}: total thermal resistance across the building element (m^2-K/W)

The total thermal resistance of a building element (e.g. a wall) made of different layers in the summation of the resistance of each particular layer. The air indoor and outdoor also have a certain resistance to give and take the heat, so they also have to be considered in the total resistance of air to air calculation, that is, heat transfer that goes from inside air to outside air. For conduction within a layer of material, the thermal resistance per unit area of a material is given by:

$$R = \frac{x}{k}$$

(Eq. 58)

Where: *x*: thickness of the layer of material (m)
k: thermal conductivity of the material (W/m-K)

For the resistance of the air (indoor and outdoor), the thermal resistance per unit area is given for a combination of convection and radiation, which is determined by the inverse of the convection and radiation heat transfer coefficient *h* (W/m2-K):

$$R = \frac{1}{h}$$

(Eq. 59)

Normally, the convection and radiation heat transfer coefficient for indoor air is 7.5 W/mK. For the outdoor air, the heat transfer coefficient is 25 W/mK. Outdoor air heat transfer coefficient is larger than that of indoor air due to the velocity of wind.

Therefore, in a construction with a single layer construction, the total heat resistance R_{total} would be given by:

$$R_{total} = R_i + R_w + R_o = \frac{1}{h_i} + \frac{x}{k} + \frac{1}{h_o}$$

(Eq. 60)

Where: R_i is the resistance of the indoor air
R_w is the resistance of the construction layer
R_o is the resistance of the outdoor air

In other terms, the heat that is carried out from the construction is given by the overall heat transfer coefficient, also known as the U-value, which is determined by:

$$U = \frac{1}{R_{total}} = \frac{1}{R_i + R_w + R_o} = \frac{1}{\frac{1}{h_i} + \frac{x}{k} + \frac{1}{h_o}}$$

(Eq. 61)

For constructions with a layer of air, heat resistance coefficient depends on the width of the cavity. Convection will not develop in a very narrow cavity, which would decrease the heat losses, but the narrower the cavity, the more heat transfer by conduction is found. Therefore, heat resistances for cavities are very difficult to calculate by hand. For this reason, some values are given in accordance to NPR 2068 for cavities that have horizontal heat flow:

Thickness of cavity (mm)	Heat resistance for horizontal flow
0	0.00
5	0.11
7	0.13
10	0.15
15	0.17
25	0.18
50	0.18
100	0.18
300	0.18

Table 10. Heat resistance of layers of air in cavity.

9.3.3 Thermal load Calculation

The thermal load is the rate at which energy must be removed or added from a space in order to preserve the temperature and humidity desired. Normally, it can be thought that the energy received by heat gain is the same amount of energy that has to be removed by cooling at a certain period of time, but the amount of energy can differ mainly because the radiant energy from surfaces and from direct solar radiation is absorbed by the cooler surfaces in the room. Therefore the temperature of the room air will increase until these surfaces radiate the absorbed heat. Cooling load can only be considered when the heat is received by the room air by convection and this occurs when the temperature of the surfaces of the room is higher than that of room air. Therefore, there is a time lag that depends on the heat storage characteristics of the surfaces material, being more significant when the heat capacity is greater. Hence, the peak cooling load can be smaller than the maximum heat gain and it can occur much later than the period of heat gains. This is also possible for the heating loads.

The extraction rate is amount of heat that is removed from a space by cooling and dehumidifying in relation to time. This is equal to the cooling load when space conditions are constant and the equipment is operating. Because the operation of the cooling equipment induces some fluctuations in the temperature of the room air, the heat extraction rate changes over time, and so does the cooling load.

There are several methods to calculate the thermals loads of a building. The heat Method Balance provides dynamic simulations of the buildings load. In this method, all energy flows must be balanced, therefore, a set of energy balance equations for the space and the interior and exterior surfaces of each wall, roof and floor have to be solved simultaneously. The Transfer Function Method is a simplified approach that can provide the loads that are originated from various parts of the building; therefore, determining the heating and cooling loads is easier. This method is based on a series of conduction transfer functions and room transfer functions which are response time series, which relate a current variable to past values of it and other values in periods of 1 h. This method takes into account the thermal load from walls and roofs; partitions, ceilings and floors; glazing, people, lighting and appliances (Kalogirou, 2009).

For the scope of this thesis, the Degree Day Method is used. This method is used to predict the seasonal energy consumption. Each degree that the average outdoor air temperature falls below a balance temperature T_b of 18.6°C represents a Degree Day (DD). The number of degree days in a day is obtained approximately by the difference of T_b and the average outdoor air temperature T_{av} defined as $(T\_max - T\_min)/2$. Therefore, the number of heating degree days is given by:

$$(DD)_h = (T_b - T_{av})$$

(Eq. 62)

The number of heating degree days over a month is obtained by the sum of the daily values from:

$$(DD)_h = \sum_m (T_b - T_{av})$$

(Eq. 63)

Similarly, cooling degree days for a month are obtained by:

$$(DD)_c = \sum_m (T_{av} - T_b)$$

(Eq. 64)

To determine the monthly or seasonal heating load D_h, the following equation is used:

$$D_h = (UA)(DD)_h$$

(Eq. 65)

Where: (UA) represents the heat loss characteristics of the building.

The heat loss characteristics of a building can be found which is given by:

$$(UA) = \frac{Q_h}{T_i - T_o}$$

(Eq. 66)

Where: Q_h is the sensible heat loss (kW)
T_i - T_o design indoor and outdoor temperature difference (°C)

In order to obtain the monthly or seasonal heating load in kJ, (Eq. 65) should be multiplied by 3600 x 24 = 86,400 to convert days into seconds:

$$D_h = \frac{86.4 \times 10^3 Q_h}{T_i - T_o}(DD)_h$$

(Eq. 67)

For cooling, the balance temperature is usually 24.6°C. Similar to (Eq. 67), the monthly or seasonal cooling load in kJ is given by:

$$D_c = \frac{86.4 \times 10^3 Q_c}{T_o - T_i}(DD)_c$$

(Eq. 68)

9.3.4 Thermal loads for study cases

Mexico City

Building Heat transfer

Because there is no standard on what the total heat transfer coefficient (U-value) should be for buildings located in Mexico City, the U-value is going to be calculated in a simple process just to have an idea of the resistance of the building is.

Material	Thickness *x* (m)	Thermal conductivity *k* (W/mK)	Resistance R (m^2K/W)
R_i			0.13
Glass pane	0.006	1.1	0.54
Air Cavity	0.008		0.14
Glass pane	0.006	1.1	0.54
Air cavity for blinds	0.200		0.18
External glass pane	0.006	1.1	0.54
R_o			0.04
Total			2.11

Therefore, U-value for the construction of double skin with a cavity for blinds is (double glazing unit and external skin glass, see Figure 51 (a)):

$$U = \frac{1}{R_{total}} = \frac{1}{2.11} = 0.47\ \mathrm{W/mK}$$

For the single façade construction (only double glazing unit, see Figure 51 (b)), the U-value would be:

$$U = \frac{1}{R_{total}} = \frac{1}{1.35} = 0.74\ \mathrm{W/mK}$$

Taking into account that the area of the façade is 112 m^2, the total heat transfer for double skin façade is:

$$Q = UA \times \Delta T_{total} = 112 \times 0.47 \times (24.6° - 17.2°) = 389.53\text{W}$$

The heat transfer for single skin façade is:

$$Q = UA \times \Delta T_{total} = 112 \times 0.74 \times (24.6° - 17.2°) = 613.31\text{W}$$

Thermal loads

According to the method presented, the Degree Days for each month was calculated. Results are presented in the following table:

Month	Degree Days for heating $(DD)_h$	Degree days for cooling $(DD)_c$
January	105	0
February	64.6	0
March	28.1	0
April	9.85	0.6
May	3.35	0.9
June	6.5	0
July	7	0
August	6.15	0
September	20.1	0
October	30.4	0
November	69.5	0
December	93.5	0

Therefore, the heating load D_h and D_c is found with the help of (Eq. 67) and (Eq. 68). Results are plotted in the following table:

Double Skin Facade		Single Skin Facade	
Heating Load D_h (MJ/month)	Cooling Load D_c (MJ/month)	Heating Load D_h (MJ/month)	Cooling Load D_c (MJ/month)
478	0	752	0
294	0	462	0
128	0	201	0
44.8	2.73	70.5	4.3
15.2	4.09	24	6.44
19.6	0	46.5	0
31.8	0	50.1	0
28	0	44	0
91.2	0	144	0
138	0	217	0
316	0	497	0
425	0	670	0

Amsterdam

Building Heat Transfer

In the case of Amsterdam, the total heat transfer coefficient *U* for buildings is outlined by the local standards. Buildings should have a U-value of 0.37 W/mK for walls, roof and floor. Therefore, this value is going to be used in order to calculate the thermal loads.

Thermal loads

The Degree Days for each month for Amsterdam is shown in the following table:

Month	Degree Days for heating $(DD)_h$	Degree days for cooling $(DD)_c$
January	19010.6	0
February	17234.9	0
March	16576	0
April	12761.4	0
May	7320.38	0
June	4521.1	37.29
July	2355.86	130.53
August	1887.59	190.62
September	4129.5	0
October	8254.85	0
November	14182.8	0
December	17587.1	0

Because for both types of façade the U-value has to be 0.37 W/mK according to the Dutch standards, the heating and cooling loads are the same for both facades. These loads are shown in the following table:

Heating Load D_h (MJ/month)	Cooling Load D_c (MJ/month)
1642.54	0
1489.10	0
1432.17	0
1102.59	0
632.48	0
390.62	0
203.54	0
163.08	0
356.78	0
713.21	0
1225.40	0
1519.53	0

9.4 Auxiliary Energy

The auxiliary energy is the regular energy that has to be supplied into the building to fulfill the comfort temperature in the work room after the useful energy from the solar thermal collector blind has been used.

After calculating the amount of energy required for heating and cooling purposes, it can be compared to the thermal energy that can be generated in the blind collectors according to the output they give from each façade in order to know the amount of auxiliary energy.

For heating, the heat generated on the solar thermal collector blind can be directly supplied to the room. For cooling, the Coefficient of Performance (COP) of the absorption chiller should be taken into account in order to know how much cold can be generated. In the case of the current cases, the COP for cooling will be considered to be of 1.2, which is a very conservative coefficient.

9.4.1 Mexico City

The total useful energy from an external fixed solar thermal collector blind per m^2 is given on the table below.

Month	Useful Energy (MJ/m^2)			
	South Facade	North Facade	East Facade	West Facade
January	90.89	30.53	54.20	54.20
February	79.93	32.78	59.27	59.27
March	70.51	40.39	71.83	71.83
April	56.17	49.66	72.36	72.36
May	48.82	57.92	71.85	71.85
June	55.23	66.94	67.76	67.76
July	58.33	67.78	70.94	70.94
August	53.03	54.12	67.39	67.39
September	61.25	52.47	61.39	61.39
October	71.50	38.94	58.77	58.77
November	80.12	34.04	51.42	51.42
December	90.55	34.68	55.07	55.07

When this useful energy is multiplied by the area of the corresponding façade of the standard room (28 m^2 each façade), and the summed up with the thermal energy generated from the other three façades, the total energy from the Solar Thermal Collector Blinds is found. Figure 82 shows the comparison between the energy demanded by thermal loads and the output energy from the façade for an external blind (single skin façade). It can be seen that during the months of summer, the blinds produce a surplus on thermal energy. This means that this thermal energy should be stored, used for other purpose or dissipated.

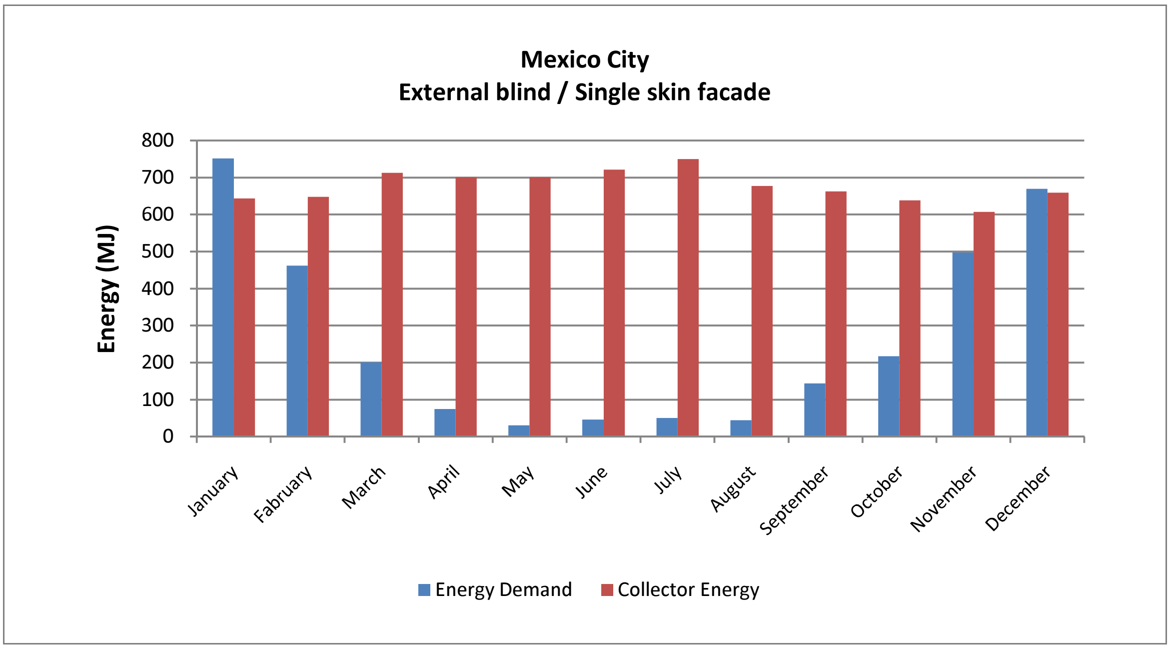


Figure 82. Energy demand and collector energy output for shaded external blinds.

For cavity blinds, the useful energy per m² of collector is given in the following table:

Month	Useful Energy (MJ/m²)			
	South Facade	North Facade	East Facade	West Facade
January	75.95	24.98	40.65	40.65
February	64.10	26.81	44.45	44.45
March	52.04	33.03	53.87	53.87
April	42.18	39.85	54.27	54.27
May	38.85	43.93	53.89	53.89
June	45.35	51.01	50.82	50.82
July	47.89	52.45	53.20	53.20
August	42.00	43.03	50.54	50.54
September	47.77	42.88	46.04	46.04
October	56.56	31.86	44.07	44.07
November	66.34	27.84	38.57	38.57
December	76.16	28.36	41.30	41.30

The comparison of the total useful energy from the solar thermal collector blind and the thermal loads of the standard room with a double skin façade is shown in Figure 83.

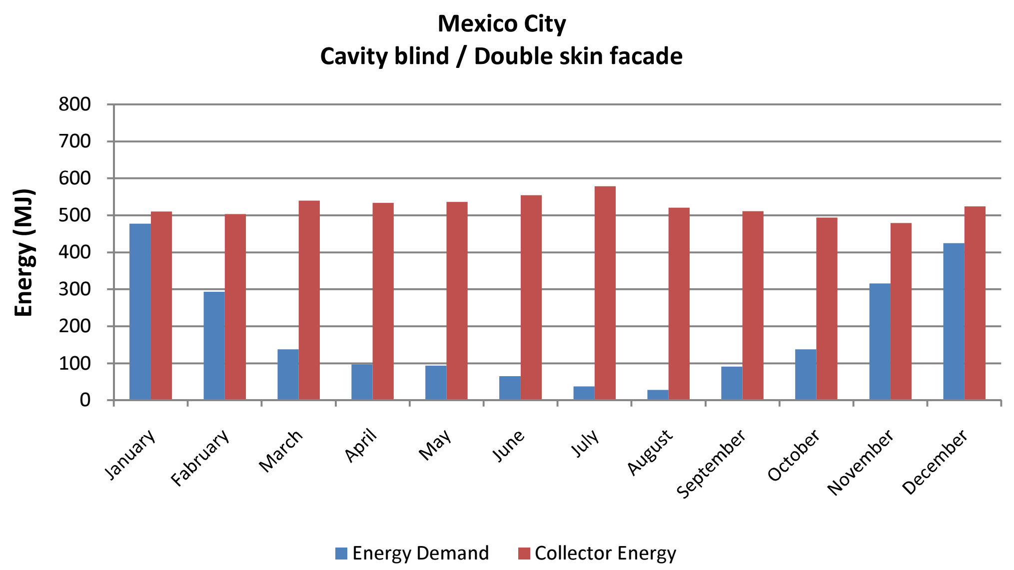


Figure 83. Energy demand and collector energy output for shaded cavity blinds.

9.4.2 Amsterdam

Total useful energy from external blinds per m^2 is shown in the table below.

Month	Useful Energy (MJ/m^2)			
	South Facade	North Facade	East Facade	West Facade
January	22.11	8.07	29.21	29.21
February	39.23	14.57	36.83	36.83
March	48.00	28.07	56.43	56.43
April	64.40	40.06	65.29	65.29
May	72.10	54.76	75.79	75.79
June	69.82	59.92	79.82	79.82
July	72.49	59.35	86.36	86.36
August	71.36	47.00	76.27	76.27
September	54.52	33.57	60.80	60.80
October	45.61	19.91	48.96	48.96
November	25.13	11.80	28.98	28.98
December	18.67	6.87	22.89	22.89

In Figure 85, the comparison of the thermal loads and the collector useful energy can be seen for the standard room with a single skin façade and an external blind. It can be noticed that during the winter months, the heating loads are exceeding by far those that can be provided by the blinds and that during summer, the exceeding collected energy can be stored in order to be used during the winter months.

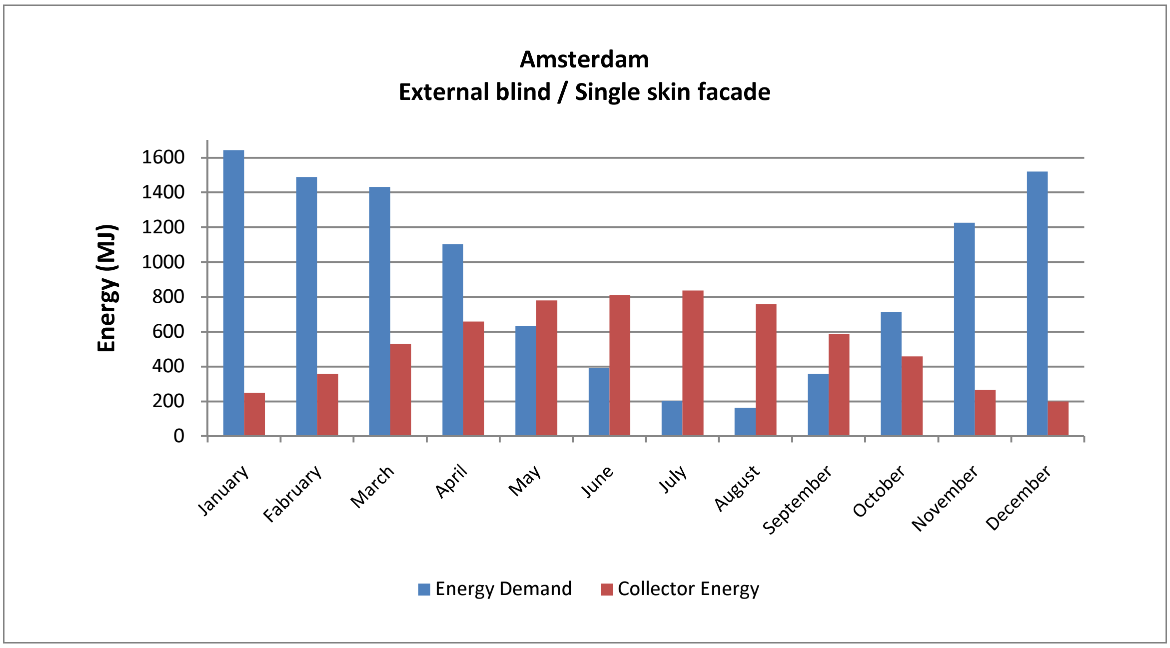


Figure 84. Energy demand and collector energy output for shaded cavity blinds.

Total useful energy from cavity blinds is shown in the following table. This energy is less than that from the external blind because of the reduction of absorption due to the external glazing of the double skin façade.

Month	Useful Energy (MJ/m^2)			
	South Facade	North Facade	East Facade	West Facade
January	19.22	6.60	21.91	21.91
February	33.71	11.92	27.62	27.62
March	40.29	22.96	42.32	42.32
April	52.50	32.62	48.97	48.97
May	57.32	44.09	56.84	56.84
June	55.65	48.30	59.87	59.87
July	57.69	47.82	62.52	62.52
August	57.80	38.16	57.20	57.20
September	45.13	27.46	45.60	45.60
October	38.99	16.29	36.72	36.72
November	21.65	9.65	21.74	21.74
December	16.26	5.62	17.17	17.17

For this type of blind and façade, the effect is similar to that shown on Figure 84, even though the useful energy from blinds is diminished. Only the thermal requirements of four months during the summer can be completely fulfilled, while for the rest of the months auxiliary energy would be needed.

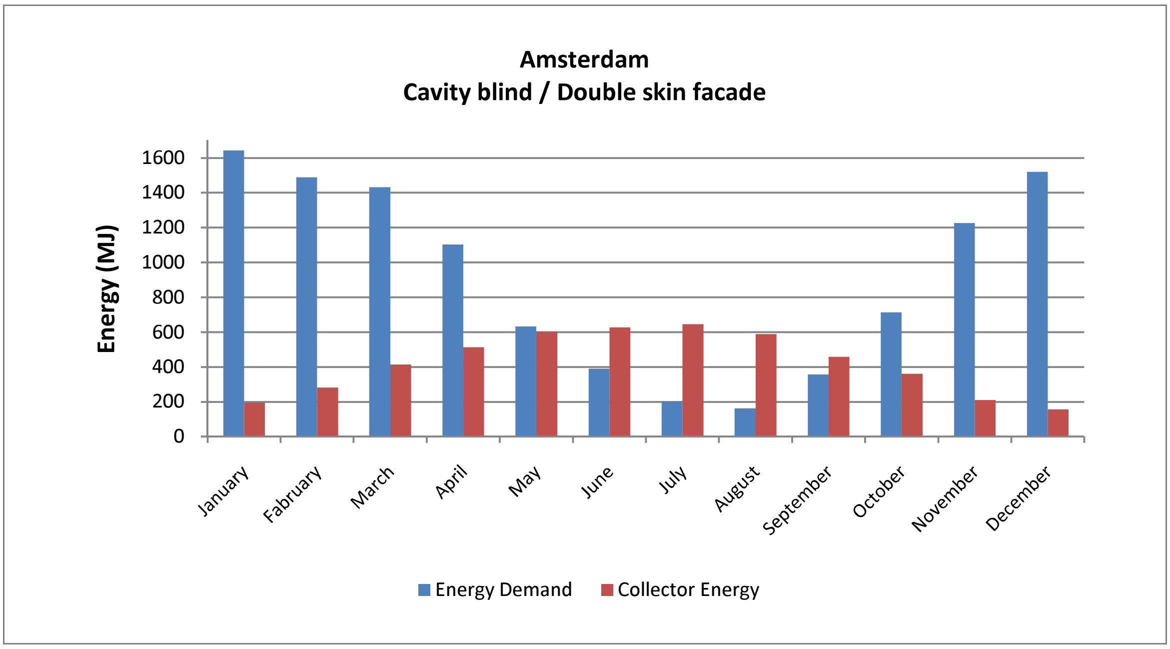


Figure 85. Energy demand and collector energy output for shaded cavity blinds.

9.5 Summary of study cases

For Mexico City, the difference between outdoor temperature and indoor temperature does not vary much throughout the year, and therefore low thermal loads are encountered, and useful energy from the blinds can satisfy the needed energy, using the remaining useful energy for storage or for other type of use.

Thermal loads of the standard room located in Amsterdam are not completely fulfilled. During winter, the outdoor air temperature drops and the heating loads increase significantly. During summer, the outdoor air temperature is closer to that of indoors; therefore low cooling loads are encountered.

Even though some important information about the performance of the blinds is given in the study cases, it is important to note two aspects that play an enormous role in comparing thermal loads against useful energy from the blinds. The Degree Day method uses average outdoor air temperature to calculate the temperature difference from outside and inside. This of course neglects the peaks in air temperature that can be found along the day, which can cause a larger thermal load than that expressed for the average temperature, especially for the climates that have changing weathers. The second aspect is that this method only takes into account the temperature difference between indoor and outdoor air and the heat transfer that occurs through the walls of the room. This method does not take into account the overheating problems that can occur due to office appliances, lighting and people, so according to this method if the outdoor air temperature is not higher that the comfort temperature (18.6° for heating , 24.6° for cooling), no thermal loads will be recorded.

9.6 Natural Lighting

Light synchronizes the human biological clock with day, night and seasonal rhythms. A lack of natural daylight can lead to disorders of the autonomic nervous system, loss of energy, fatigue, a tendency towards self-isolation and metabolic disorders. Conversely, intensive light therapy has been shown to support the healing process.

Current standards and guidelines regarding residential and workplace lighting condemn us to a kind of biological darkness: regular shading devices at work reduce daylight intensity from 100 000 lx outside to 500-1000 lx indoors.

In low latitudes, due to the high altitude of the sun, blinds remain partially opened, letting diffuse daylight inside the room. Beam radiation is not entering the room, but glare can be encountered. In high latitudes, the shading systems are closed during periods of the largest solar gains, darkening the interior and resulting in a need for artificial lighting. Using energy to power artificial lighting is an issue that should be avoided, especially since the total electrical energy for lighting is transformed into heat that must be removed in summer by cooling systems. The radiation equivalent of the sun gives 100 lumen/W. Artificial lighting can only give 50 lumen/W. This simple comparison demonstrates the potential for energy conservation in architecture through improving the daylight utilization.

If the upper slats of the blind are replaced with reflective slats, and arranged with a lower slope angle β, they can redirect the incoming light to light the ceiling and provide a diffuse light in the room. This new arrangement would slightly reduce the solar thermal collection of the blind collector but, in the other hand, it would save energy for lighting (Figure 86). The advantage of this system is that beam radiation and glare is blocked, while daylight is still entering the room.

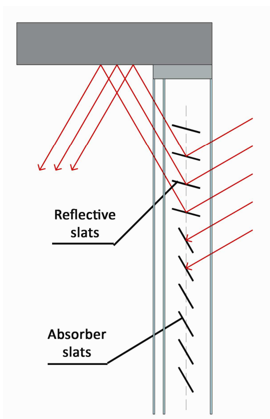
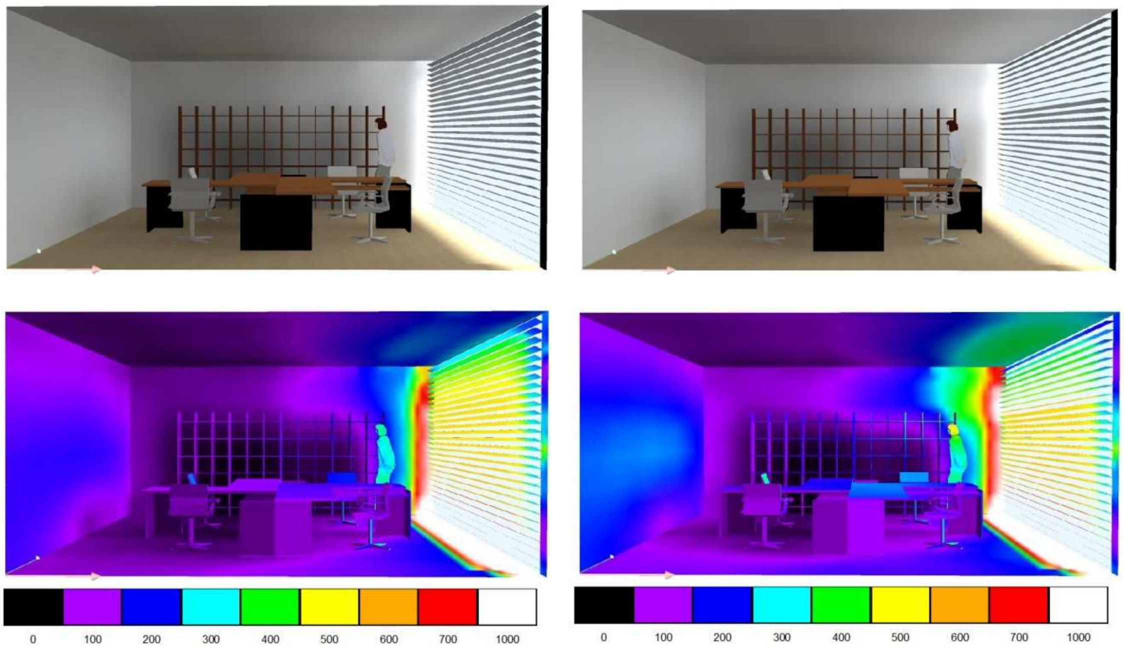


Figure 86. Different angle in upper slats for light income.

According to a calculation made in DIALux, a more opened angle can give more light to the back of the room by reflecting it to the ceiling. In Figure 87 a room located in Mexico City facing south was simulated. The date was set on the average day of June (11th) and the time is half an hour after solar noon. It can be seen that when the top blinds are set in a different angle, light can be reflected in the ceiling, leaving the working surfaces on the desk with a good illuminance level.



(a) Even angled slats. (b) Upper slats in a lower slope angle.

Figure 87. Light reflection for greater illuminance.

10 Venetian Blind Solar Thermal Collector Design

10.1 Solar Thermal Collector Blind Design

According to the summary made after the calculations, and following the study cases, for Mexico City the best blind collector would be that with fixed slope angle. This type of blind collector shows a minimum difference in absorption compared to the other systems and because there is no movement it can be easier and cheaper to install.

For Amsterdam, the hourly angle adjustment blind collector was selected for the south façade and the fixed-angle blind for east and west façade. Even though it was pointed out that the hourly adjustment in east and west facades gives a better performance, energy collection is slightly smaller for the fixed angle blind collector. It was considered that north façade does not receive much radiation, so no blind collector is going to be placed there.

Some working principles for the rest of the blind collectors can be found in Appendix 4.

10.1.1 Requirements and restrictions

After the literature review and the calculations done, some requirements and restrictions arose. First, the blind collector should have the following parts to work properly:

1. Absorbing slats
2. Heat pipe to transfer the heat from slats to network
3. Manifold to collect the heat from the heat pipes
4. Antifreeze inlet and outlet
5. Retracting mechanism
6. Tilting mechanism (for hourly adjusted blind collector)

There are also some restrictions for the blind collector in order to work properly. Some selection of materials and mechanism were selected to resist the working temperatures. In opposition to a normal venetian blind, all mechanisms of the blind collector for retraction and tilting are located in the side rails to prevent damage of the elements from direct solar radiation and to preserve the surface of the slat as clear as possible to enhance the solar thermal collection.

For the ease of reading, the elements of the blind collector will be presented one by one, as well as the description of the characteristics and the design method to reach the final shape and material. At the end, the complete and integrated system for the fixed angle blind collector and the hourly adjusted blind collector will be shown.

10.2 Slats

10.2.1 Material

The slats are the most important element in the solar thermal collector, since the solar radiation is going to be collected and absorbed in it. It has to be made out of a material that absorbs as much radiation as possible, that has a good transmittance coefficient and that resist temperatures up to 120°C according to the calculation. Thermal conductivity of some materials is shown in Table 11. It can be seen that copper, gold and silver are the materials with the highest coefficient of all, but the last two are significantly expensive for the use in such application. Therefore, copper or another material with relatively high thermal conductivity, but less expensive has to be used such as aluminum.

Material	Thermal conductivity W/mK
Gold	318
Silver	429
Copper	401
Aluminum	120 - 180 (alloy)
Stainless steel	12.11 - 45
Concrete	1.7
Glass	1.1
Air	0.025
Mineral Insulation	0.04

Table 11. Heat transmittance coefficient of various materials.

To maximize the collection of solar radiation, a solar selective coating must be applied to the slat in order to have a high absorptance for short-wave radiation, and a low emittance of long-wave radiation. Normally this kind of coating is black color, but various colors coatings have been proposed by several authors mainly for aesthetical reasons. The Acktar solar selective coating makes it possible to absorb up to 98% ± 1% of the incoming thermal energy and transfer it to the slat. It has a thermal emittance of 11% ±2%. This coating can be applied on materials such as aluminum, copper, stainless steel, glass or polymers and can be used in almost any receiver geometry (Acktar advance coatings, 2010). Other resource could be the sputtering selective-coating, which has an absorption <95% and an emittance >5%. The sputtering selective-coating absorber has high resistance to long-term vapor condensation, high corrosive resistance and high operating temperatures. (ThermoTechnologies, 2005).

The sputtering is a physical manufacturing process that involves coating a substratum with metal particles. The manufacturing process takes place in a high vacuum chamber and the coating process involves three stages: stabilizing layer coating, semi-conductor layer coating (radiation absorbent layer) and anti-reflection layer coating. The absorbent layer is made of titanium oxide (TINOx).

Essentially, typical selective surfaces consist of a thin upper layer, which is highly absorbent to shot-wave radiation but relatively transparent to long-wave thermal radiation, deposited on a surface that has a high reflectance and low emittance for long-wave radiation. Coatings are especially important for collectors that operate in a much higher temperature than that of ambient air. Matte black paint can be applied, but it would not be effective with temperatures more than 40°C above ambient.

10.2.2 Shape

The amount of radiation that can be absorbed also depends on the shape of the slat. Depending on how the slat is oriented, the incidence angle can be increased or decrease in order to absorb radiation better. The best configuration would be to have a flat surface that is completely normal to the direction of the solar radiation, because such configuration would ensure that the whole surface is absorbing the same amount of radiation at the same time. In the other hand, an even convex curved surface is always normal to solar radiation, but the surface that is actually being normal is very small compared to the total surface, therefore the solar radiation will strike the rest of the surface and mostly bounce off of it, while just a small part of this radiation would be absorbed. A concave curve has the possibility to redirect the sun to a concentrated collector for better absorption, just like a parabolic trough collector (Figure 88).

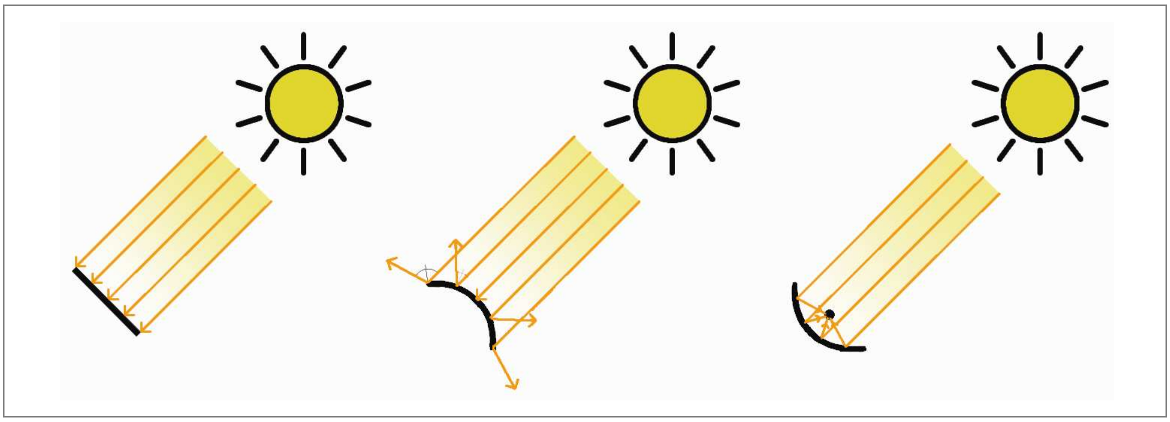


Figure 88. Three different shapes for a slat.

There are three aspects that have to be considered when selecting the correct slat shape:

- The slat has to be able to collect as much solar thermal energy as possible.
- The slat has to be strong and stable enough to resist its own weight with minimum deformation and to tilt without torsion or vibration.
- The shape of the slat has to be such that, when the blind is retracted, the pack of slats is as small as possible in order to reduce the blocking of view to the outside.

For aspect number one, the concave slat would be the one that with redirecting light can concentrate a great amount of radiation. The weak point of this type of shape is that when the blind is manually driven, the incidence angle can be modified and therefore, no collection would be made at all, because all radiation would not be reflected to the concentrator, but somewhere else. A flat slat would be the second best for this purpose, and even if the slat is manually driven, the incidence angle would be changed, but still some of the radiation can be absorbed. The convex shape would be always collecting radiation because it is normal to the solar radiation at all times, but the area is very small.

In aspect number two, because the slats are so long in comparison to their width, and they are only supported in their extremes, it so very likely to suffer from torsion if the tilt mechanism is not properly calibrated in both sides. For all types of slats, it is necessary to modify the profile shape to produce one more resistant against deformation. For the flat slat, it can be done by adding folded edges that can work as beams for the slat, For the curved slats, it can be done by increasing the height of the curve (Figure 89).

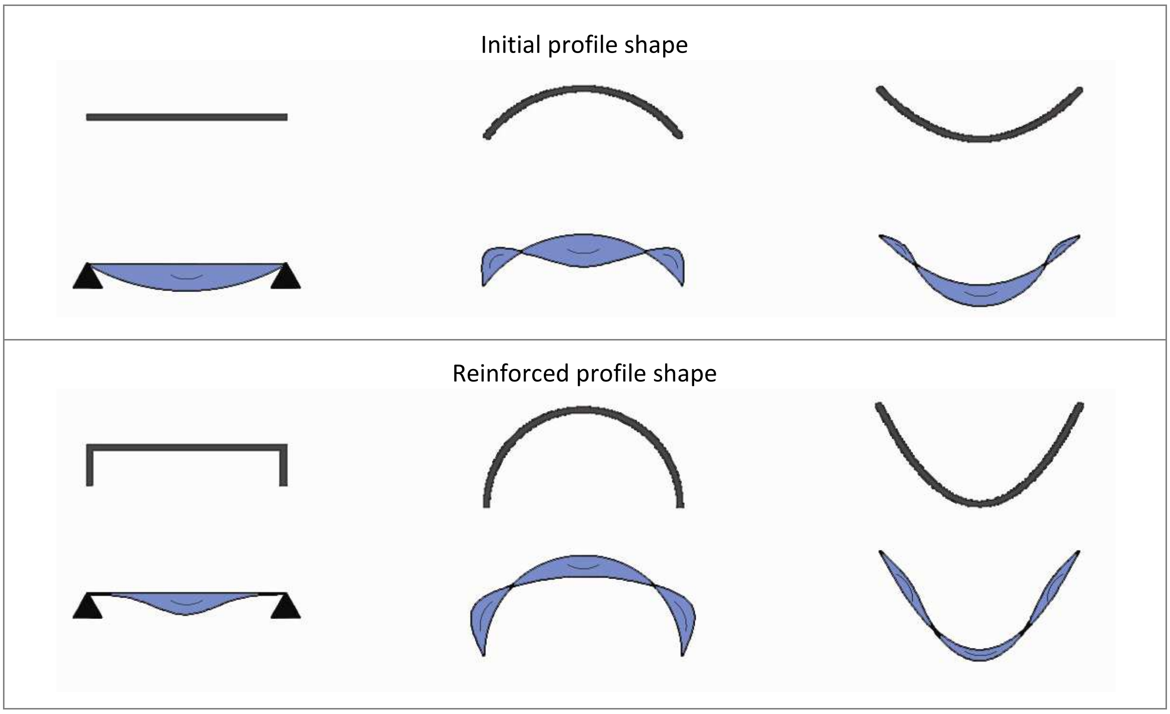


Figure 89. Reinforcement of slat profile shape for less torsion and deformation.

Finally, aspect number three has to do with the elements that the slat should have to work and the location and distance between them. These elements are the heat pipe, insulation and shell. For the flat and convex surface, the heat pipe, insulation and shell can be placed right underneath the slat surface, while for the concave has to have a focal point in which the radiation is going to be redirected, and such focal point has to be placed at a certain distance from the surface, which makes the packing bigger (Figure 90).

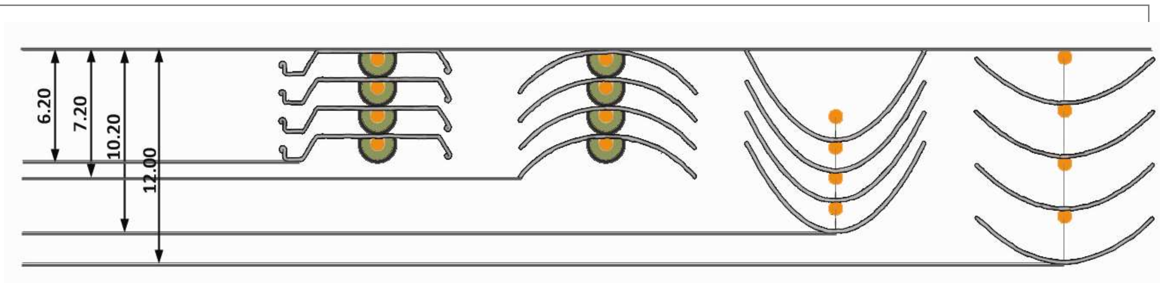


Figure 90. Packing of different slat shapes.

Therefore, the shape that was found to be more convenient for this application was a flat surface slat, which gives a good solar thermal collection, it can be made strong enough and the packing would be smaller.

From a practical approach, the slats of a blind have to work together to give the user a certain degree of lighting in the room, especially for those blinds that tilt. The user may want to open the slats to receive the most daylight, but it can also happen to be a completely darkened room. The shape of the slat has to be able to provide this as well. Figure 91 shows the final shape of a slat. It is flat on top to receive the radiation from the sun; it still preserves the folded edged against deformation, it has the ability to match with the slat above and below to produce a complete dark room, and finally it is made of two layers of cooper or aluminum pressed together to form a cavity in between to allocate a heat pipe.

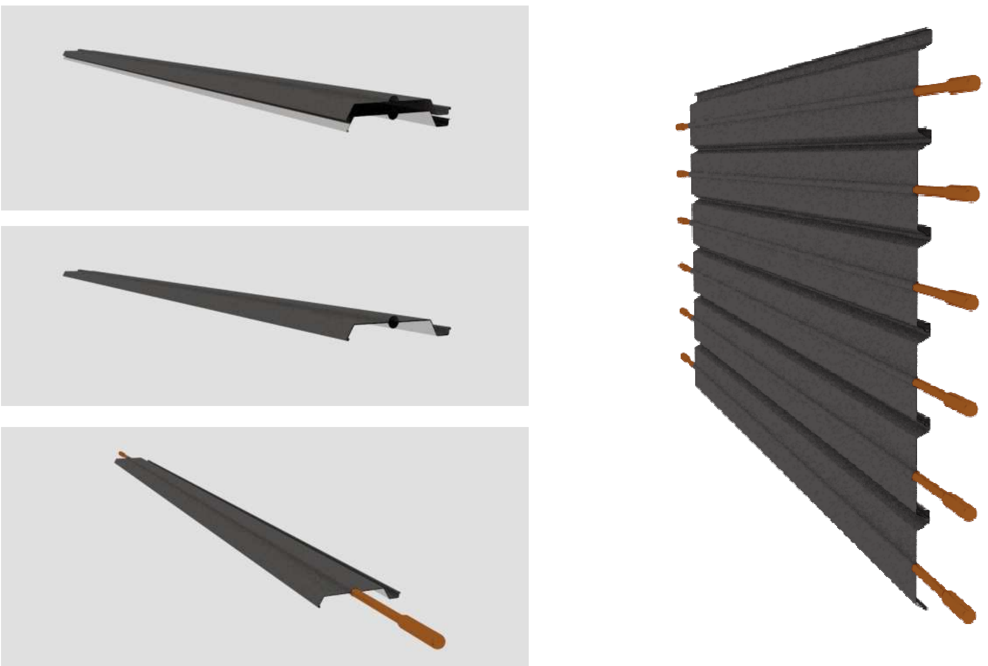


Figure 91. Final slat shape.

10.3 Heat Pipes

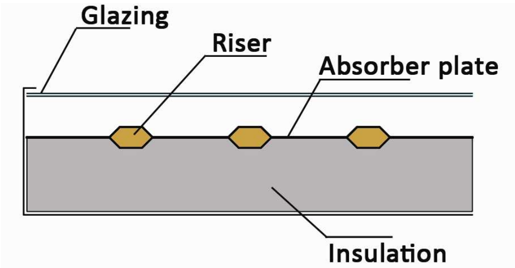
The most common heat pipe is the one that works with capillary forces. It is easier to manufacture and has a high efficiency. Because there is no need to apply external forces of any kind to the standard heat pipe, it is going to be used for this application.

Heat pipes are energy-efficient; light weight, low cost and have the flexibility to be produced in almost any size and shape. The length of the heat pipe will depend on the width of the blind frame and the size of the façade panel. Even if the blind is long, heat pipes have the ability to transport heat over a long distance.

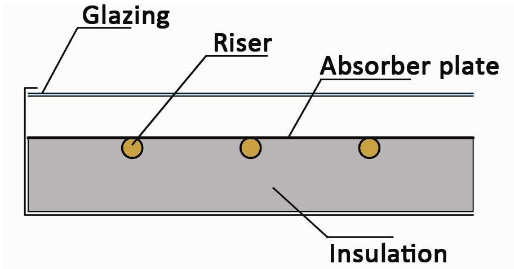
There are different materials for the shell and working fluid, depending on the range of temperature they will be used for. Temperatures on the slat and heat pipe will be high ranging from 60°C on partly cloudy days to even 120° C in clear days. Therefore a heat pipe that withstands this temperature has to be selected. The most common heat pipe working fluid is water and it can work in temperatures ranging from 1°C to 325°C, with shells that can be made of copper, monel, nickel or titanium. This type of heat pipe can be used for blinds that will be allocated inside a cavity, because the temperature in the cavity most of the times will be over 0°C. For blinds that are going to be exposed to the environment, the working fluid can be acetone in a shell made of aluminum or stainless steel, which works in temperatures from -40°C to 125°C. The water-copper heat pipes from Thermacore are guaranteed that they will last over 20 years working in good conditions (See complete table at Appendix 3).

10.3.1 Slat-Heat pipe connection

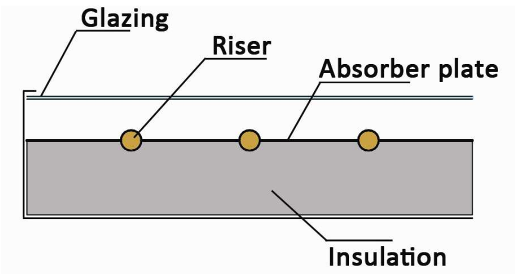
For flat-plate collectors, there are a number of ways to connect the absorber with the risers that carry the heat-transmission fluid. The major problem encountered is to obtain a good thermal bond that can enable the heat transmission, without incurring in excessive costs. Figure 92 (a) shows an integrated riser in the absorber plate, which ensures a good thermal transfer. Normally for this configuration, the absorber plate and risers is made of copper, aluminum or stainless steel. Figure 92 (b) and (c) show risers welded and embedded the absorber plates. There are various ways to fix the risers such as weld, braze, or fasten. Soft weld should be avoided, because in high temperatures it can be melted. Figure 92 (d) shows an extruded rectangular tube that provides a larger contact surface between riser and absorber.



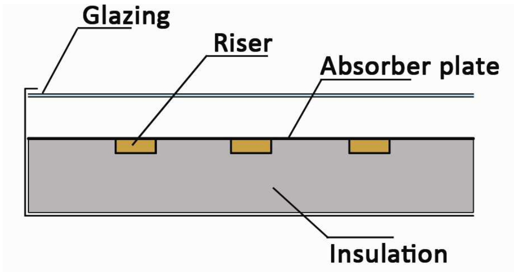
(a) Integrated riser in absorber plate



(b) Welded riser to absorber plate



(c) Embedded riser in absorber plate



(d) Rectangular riser for larger contact surface

Figure 92. Various ways of bonding absorber and risers in a flat plate collector

For the blind collector, it is important that the heat pipe is in contact with the slat as much as possible. This is the reason to integrate to connecting systems into one. As stated before, the slat is made of two layers of copper or aluminum that are pressed together created a void in the center in which the heat pipe will be embedded (Figure 93).

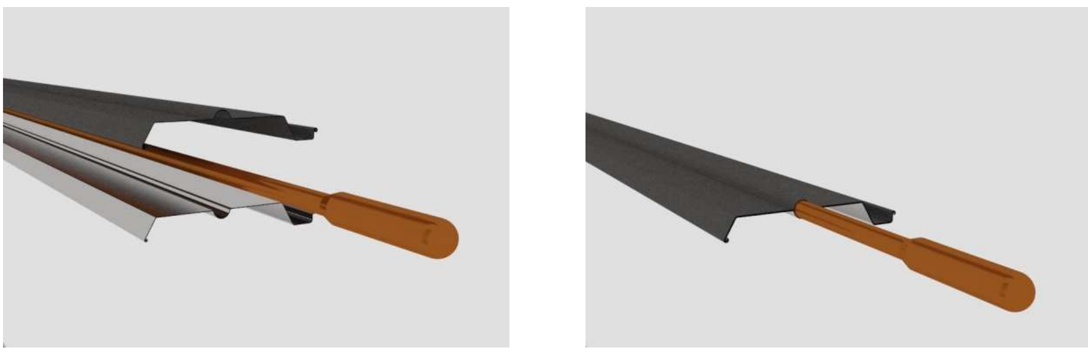


Figure 93. Slat and heat pipe connection.

10.3.2 Insulation

Because the slats and heat pipe will work at high temperatures and space between each slat is relatively limited, an insulation that can withstand this is needed. There are few materials that are currently being used for insulation on thermal collectors: glass fiber, rock fiber and ceramic fiber. Glass and rock fiber are used for applications of low-temperature range that withstand up to 500°C, but after this temperature, they are not fire resistant. Ceramic fiber or aluminum silicate is used in applications that manage temperatures up to 1300°C. Because the blinds will only take temperature up to 100°C, there is no need to use high performance insulation. Therefore mineral wool is going to be used for insulating the heat pipe along the slat.

Mineral wool has a thermal conductivity of 0.04 W/mK. This conductivity increases as the temperature rises. At 650°C, the thermal conductivity is 0.22 W/mK, which still represent a good insulation rate.

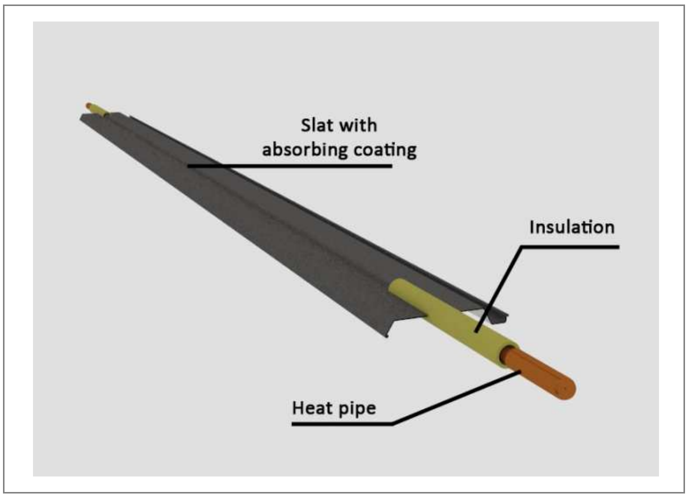


Figure 94. Insulation of heat pipe

10.3.3 Shell

The shell is the protective skin of the heat pipe and insulation. The shell is also the element that is fixed to the frame of tilting/retractable mechanism in order to hold the slat in place. For that reason, the shell should be made of a stiff, durable and light-weight material. This can be fulfilled with some metals like stainless steel or aluminum.

It has to be ensured that the shell does not take any heat from the cavity air, solar radiation, adjoining elements or from the heat pipe via the insulation. To prevent this, a high reflective (or low emissive) material should be used to keep the shell heating up. Polished aluminum, for instance, has an emissivity of 0.04; and polished steel has an emissivity of 0.06 at 27°C. At 527°C, emissivity increases to 0.08 and 0.1 respectively.

Because aluminum is normally anodized for architectural applications, the emissivity decreases to 0.9 at 27°C, and same thing happens with stainless steel. Therefore, when it is not possible to use a high reflective material for the shell, it is possible to coat it with a high-reflective coating, creating a similar phenomenon of reflection. In this case, the shell should be coated in and outside to reflect radiation from any possible direction (Figure 95). There are several high-reflective coatings now in the market such as Sherwin Williams E-Barrier coating, High-reflective coating from Shanghai optics, among others. (See table of emissivity for various material in Appendix 3).

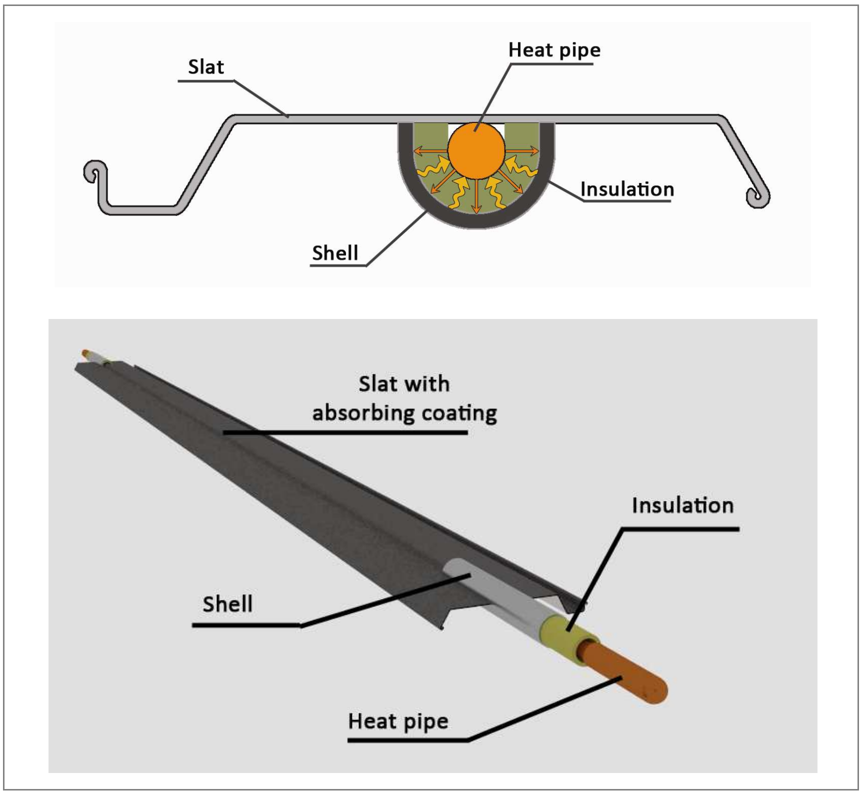


Figure 95. Coating on shell and reflection.

10.4 Retracting mechanism

This mechanism consists of a drive steel chain that hangs from a sprocket at the top of the blind frame. At the bottom of the mechanism, a guide on the drive chain is connected to the bottom slat of the blind. When the sprockets are mechanically rotated, the drive chain is pulled up and so the guide and the bottom slat. The guide drives the chain through the frame in a correct position and prevents movement and noises inside the frame. When the blind is deployed, the chain is pulled down and the guide drags the slats down. At the back edge of the slats, a scissor-like chain is attached to all of the slats so that they can preserve the spacing between them when they are deployed. This scissor-like chain also is effective when retracting the blinds because it folds up, reducing the space necessary to accommodate it (Figure 96).

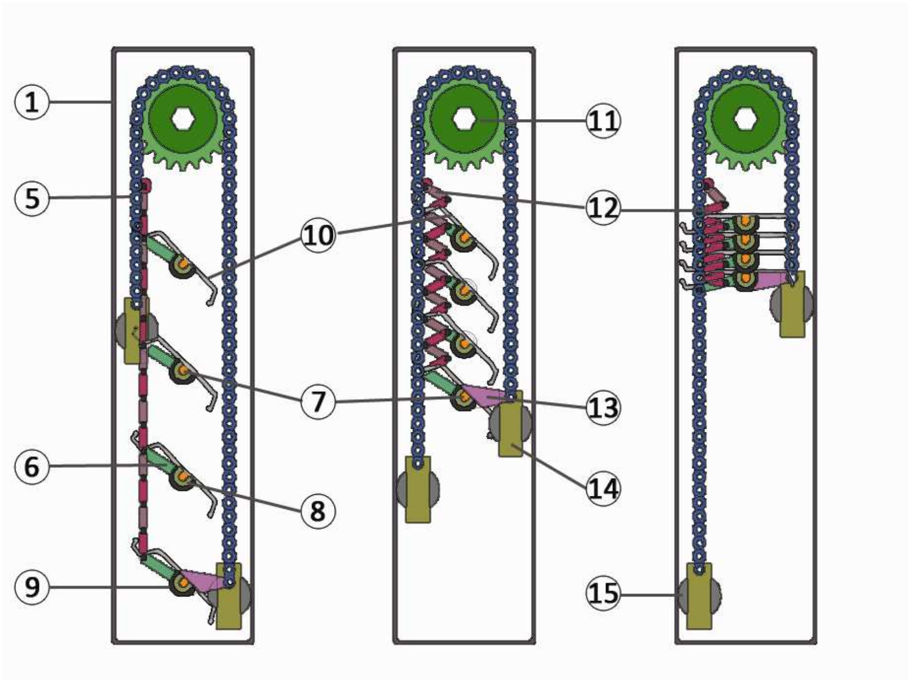


Figure 96. Principle of retracting mechanism for blinds.

1.Frame
5. Lifting chain
6. Angle lever
7. Heat pipe
8. Insulation along the heat pipe
9. Axis shell
10. Slat
11. Sprocket
12. Scissor-like chain
13. Lifting lever
14. Chain guide
15. Guide roller

Because the chain used in the retracting mechanism should roll around the sprocket and will be driving motion to the bottom sprocket from the motor on the top frame, this chain should be a drive chain, often called roller chain. Normally, this type of chains are made of steel and the size and dimensions of the it depends on the source of input power, drive machine type of driven equipment, horse power to be transmitted, revolutions per minute of the sprocket, distance between sprockets, size of the sprocket and tension of the chain. Thus, the size of the chain will be completely dependent of the type, size and weight of the slats to be driven up and down (Figure 100).

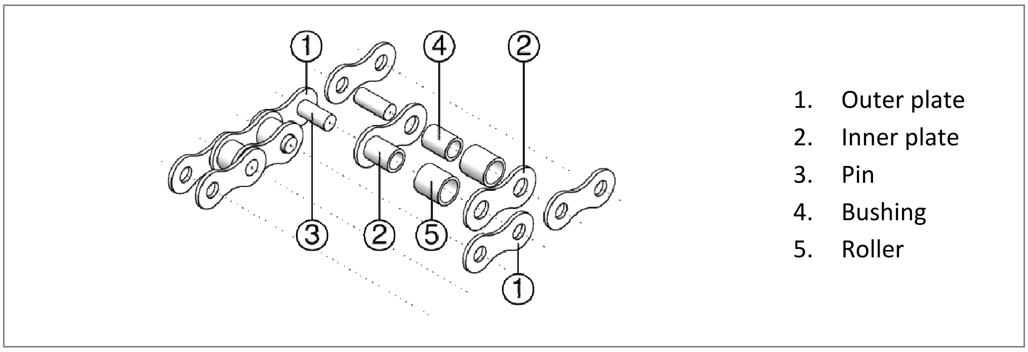


Figure 97. Roller chain.

The final mechanism consists of four sprockets, 2 at the top and 2 at the bottom of the blind and two roller chains that connect the sprockets and drive motion from the single motor located at the bottom of the blind, inside the frame

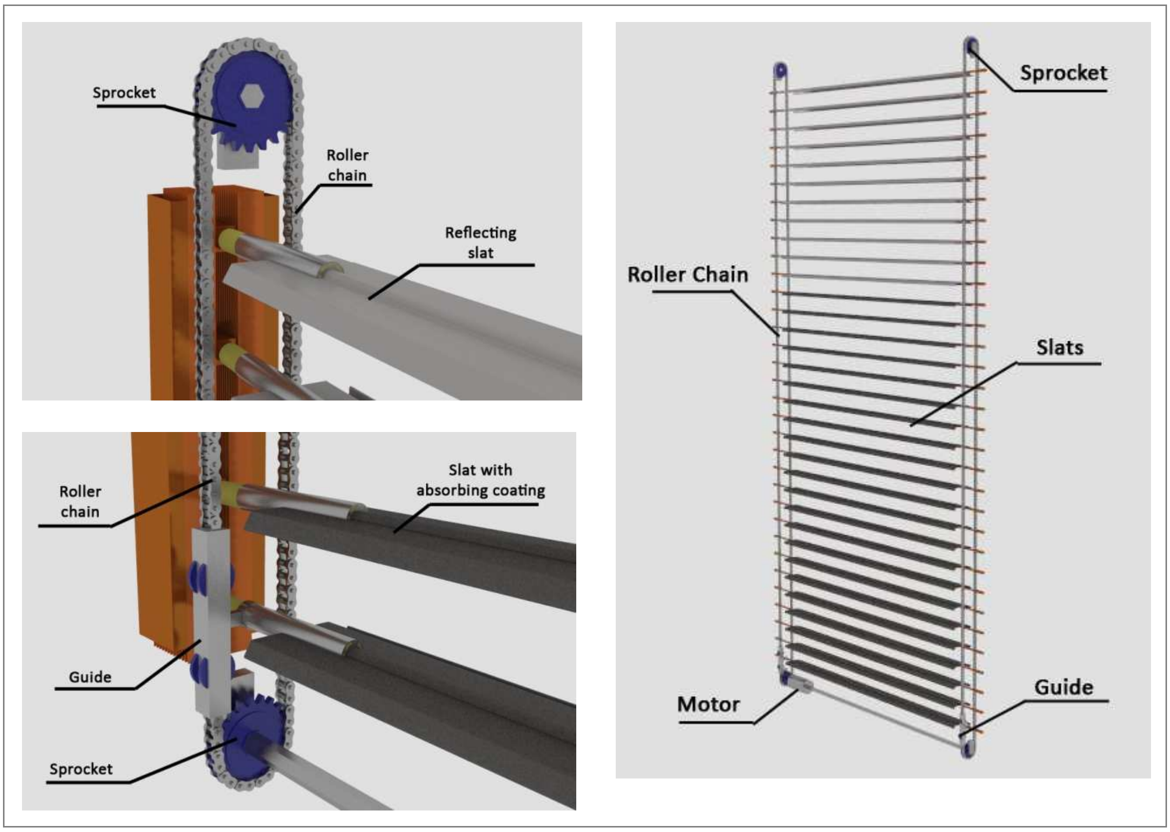


Figure 98. Retracting Mechanism.

10.5 Tilting mechanism

The tilting mechanism for the blind collector is based on a regular tilt mechanism. A steering bar is placed on the top frame from which two tilt chains hang. All slats are connected to a tilt beam, which in turn is connected to the tilt chains at both ends. When the motor tilts the steering bar, one tilt chain is pulled up while the other is driven downwards. This misalignment of the chains produces a change in angle in the tilt beam and as consequence, the slats is also tilted (Figure 99).

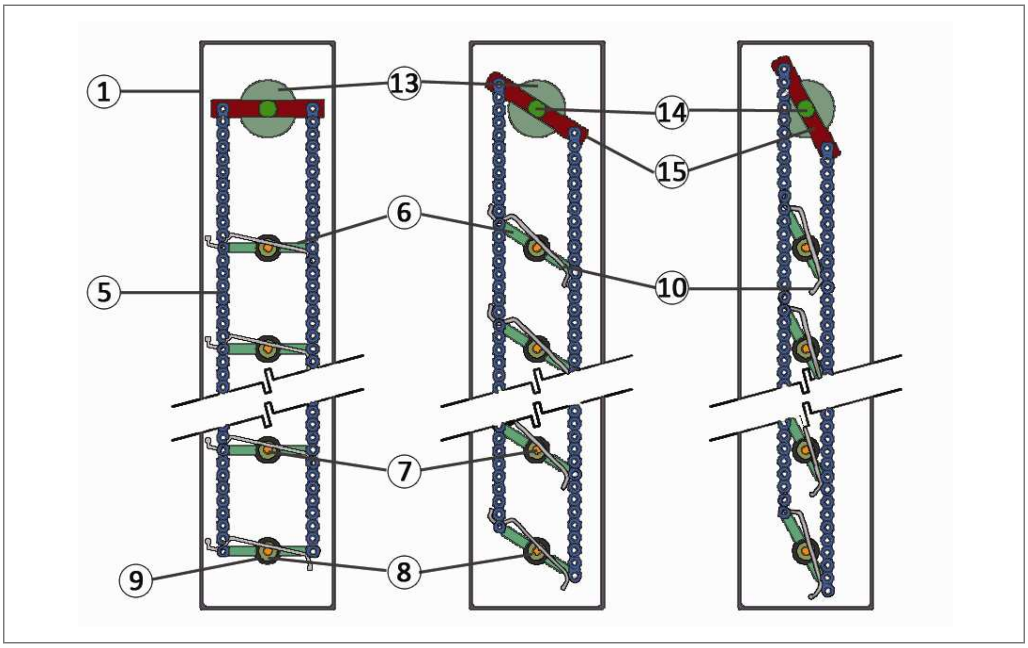


Figure 99. Principle of tilting mechanism for tracking blind.

1. Frame
5. Tilt chain
6. Tilt beam
7. Heat pipe
8. Insulation along the heat pipe
9. Axis shell
10. Slat
13. Tilt motor
14. Tilt axis
15. Tilt steering bar

Since both mechanism (retraction and tilt) have to work together in the tracking blinds, the tilt chains have to be such that they can be compacted in a smaller space when the slats are retracted. In order to fold the tilt chain in a predetermined way, a scissor-like chain was created. This chain consists of bars lineally interconnected. Two chains are running parallel from top to bottom. At each 4 bars, a tilt beam is connected to both chains, creating a ladder. The tilt beam has a semicircular holding device at the midpoint to fasten the shell of the heat pipe (Figure 100). The scissor-like chain has to be strong enough to hold in place the blinds and tilt them. It is proposed to use steel as material in order to resist the weight and deformation better.

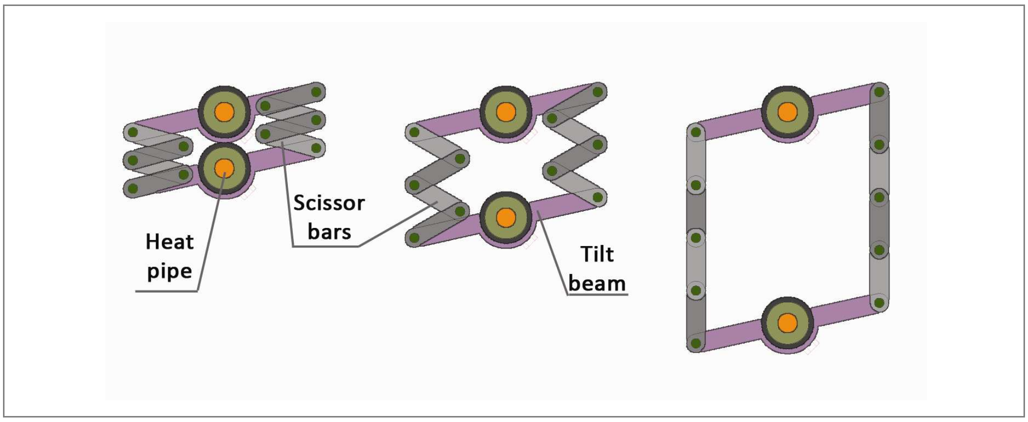


Figure 100. Scissor-like chain for tilting.

The final mechanism consists of two tilting sets, one at each side of the blind. The motor is located at the top frame and drives the steering bars of both sides via an axis bar. The tilt beam is fixed to the cast of the slat in order to tilt it (Figure 101).

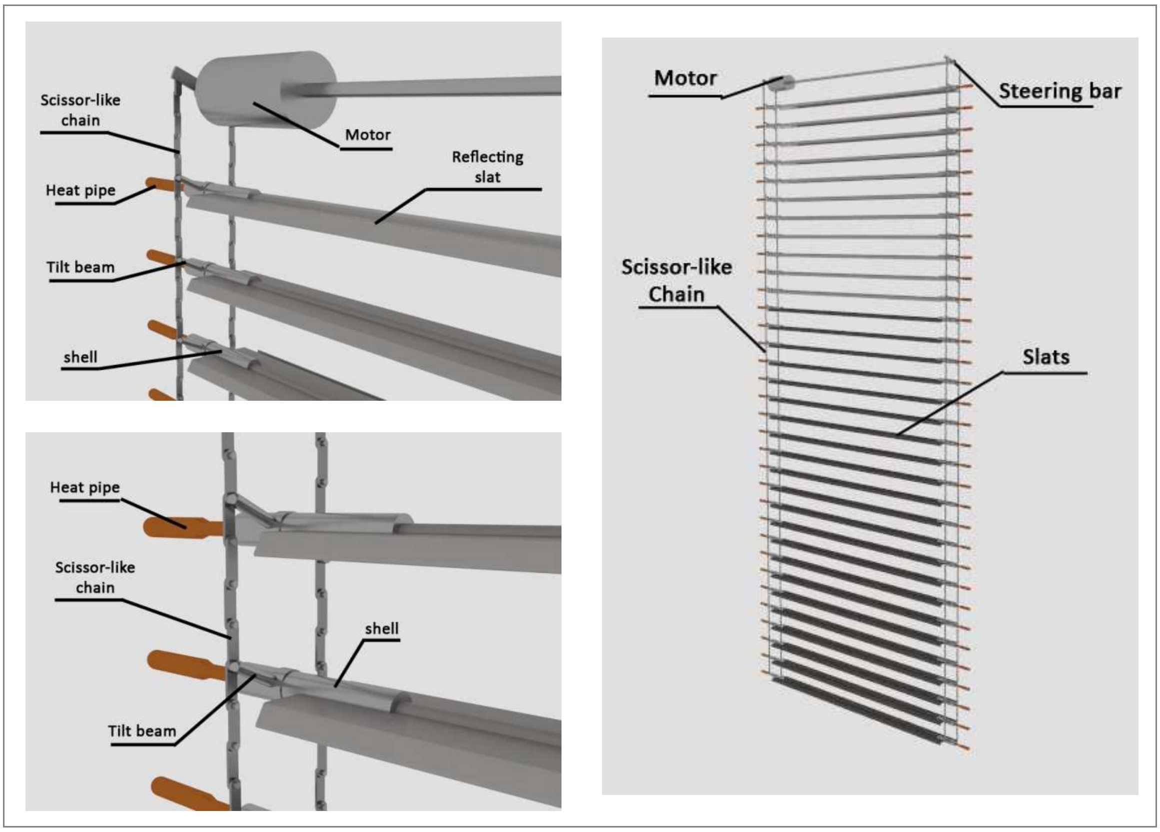
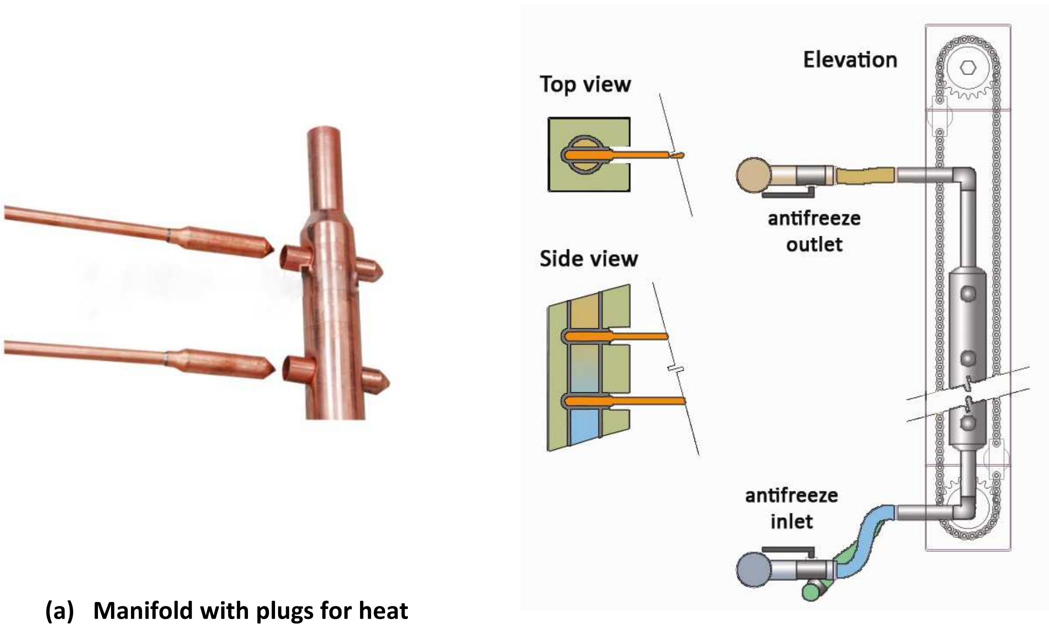


Figure 101. Tilt mechanism

10.6 Manifold

Most of the manifolds for solar thermal collectors are made of copper since it has good thermal transmittance and it can resist high pressure. Both manifolds described in this section are proposed to be made of copper to enable a good transmittance between the head of the heat pipe and the antifreeze solution.

For the blinds that are non-retractable, the heat transfer from the slats to the antifreeze solution is done by means of two manifolds located one at each side of the blind. This manifold consists of a tube with some plugs pierced through the tube and welded to keep them in place and to avoid leaking. In these plugs, the head of the heat pipe is placed into and heat is transferred through direct contact of the antifreeze to the surface of this plugs. This is the most common manifold type, even for other kind of collectors such as evacuated tube collectors (Figure 102).



(a) Manifold with plugs for heat pipes.

(a) Manifold for fixed slats with inlet and outlet.

Figure 102. Principle of manifold for non-retractable blinds.

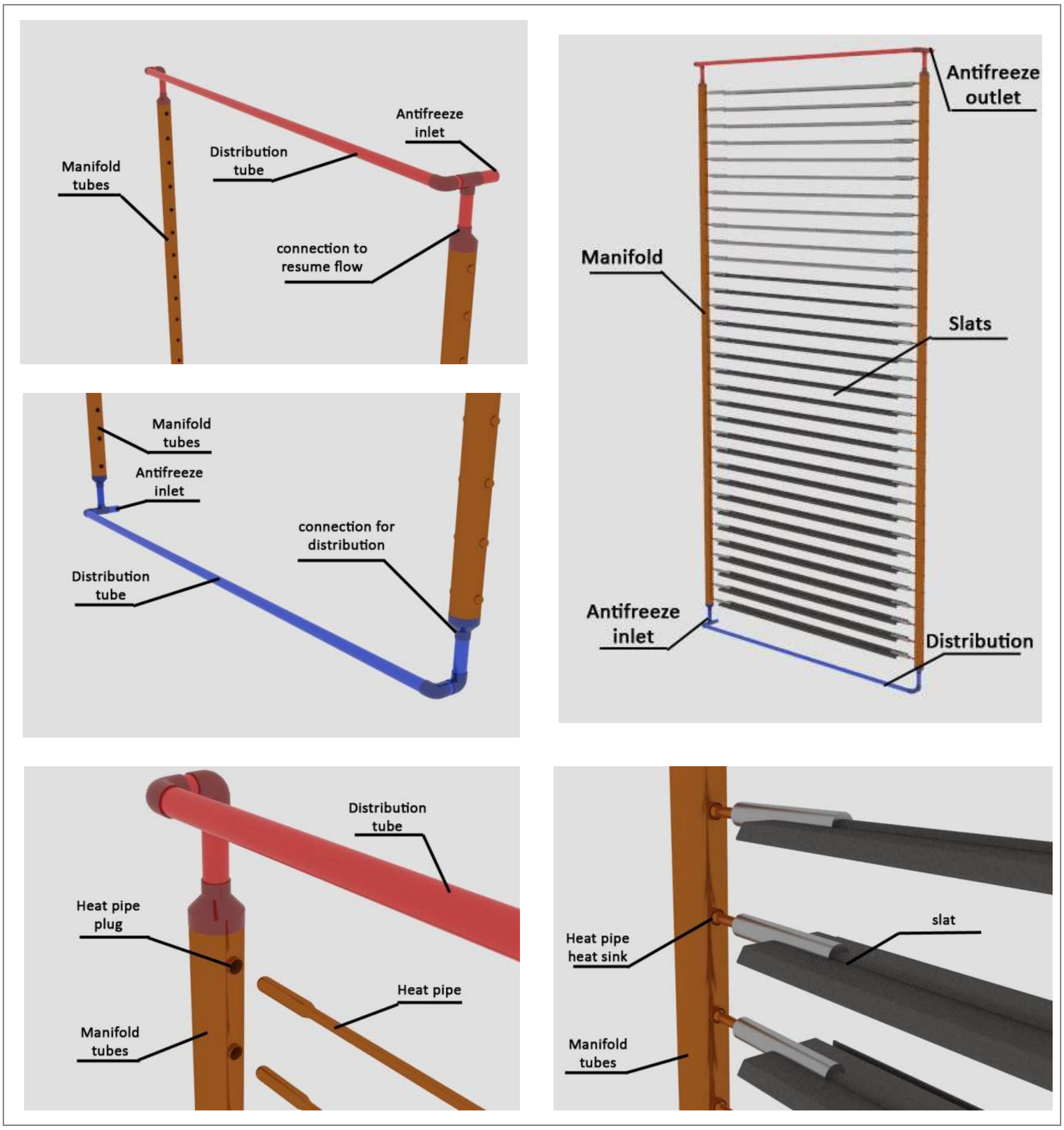


Figure 103. Manifold for fixed angle mechanism.

For the blinds that should be able to move vertically, the connection between the heat pipe and the manifold should be done in a different way. The plug cannot be fixed anymore because the head of the heat pipe should move along the manifold to allow retraction. Therefore the manifold should be divided into two tubes so that a free space is created in between for the head of the heat pipe to move up and down. The manifold is then formed by two flatten tubes that face the heat pipe head along their larger side to increase the surface of contact. These two tubes are connected at the top and at the bottom of the frame so that they resume in just one incoming and out coming tube for antifreeze (Figure 104).

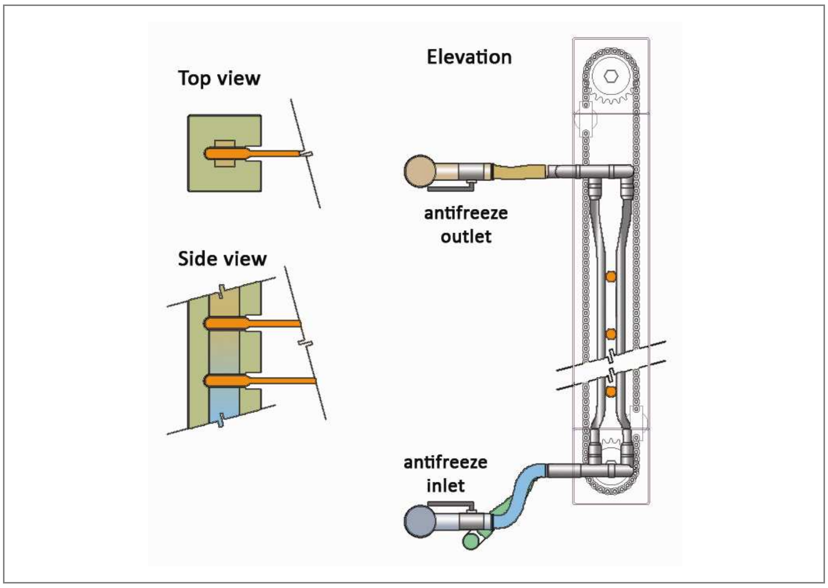


Figure 104. Manifold for retractable blinds. Two flatten tubes run next to the heat pipe heads along the length of the frame.

The final design of the manifold integrates heat sinks in both the manifold and the heat pipe condenser to increase the surface that radiates off and the surface that receives the heat.

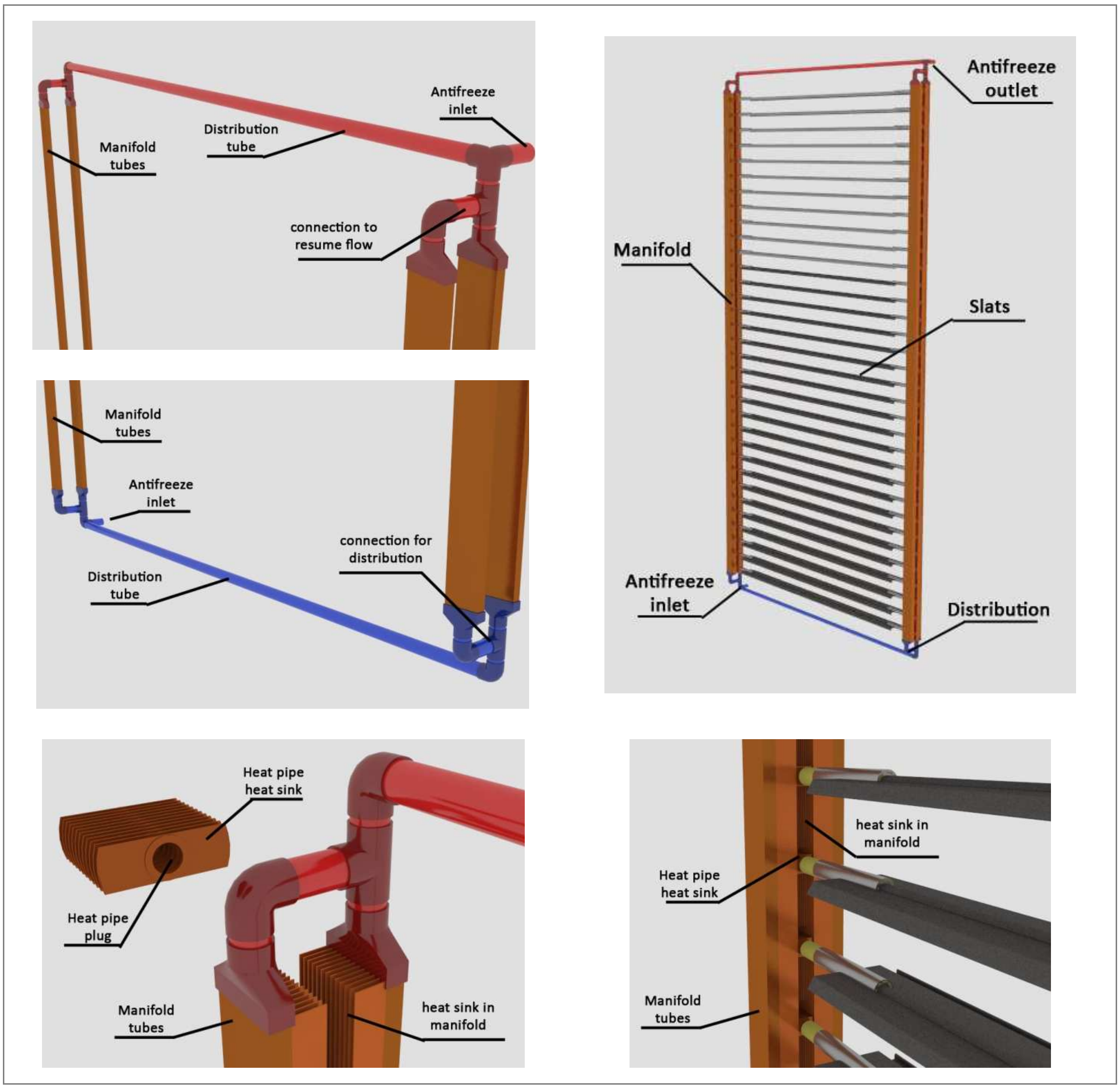


Figure 105. Manifold for retractable mechanism.

10.7 Frame

Since most of the frames for façade are made of aluminum, it was defined that the frame for the blind would be done in the same material to be consistent with the materials that are normally being used in a façade. This frame has to be protected from the inside to prevent heat absorption and from the outside it might take mostly light colors to diminish absorption from direct solar radiation.

10.8 Glazing of façade

The glazing of the façade plays an important role on the system. When placing the solar thermal collector inside a double skin façade cavity, the outer glazing has to be as transparent as possible for radiation to go through and strike the slats, while the inner glazing should work as insulation against the temperature that is going to be generated in the cavity.

Exterior skin glazing

The ideal glazing for solar collectors would have the following properties:

- High temperature capability
- Transmit light very well
- Long life when exposed to UV and high temperatures
- Good impact resistant
- Light weight and easy to work
- Opaque to long-wave radiation to reduce heat loss
- Low cost

Glass has been extensively used in flat-plate collectors because it can transmit up to 90% of the incoming shortwave radiation, and it is virtually opaque to log-wave radiation coming from the absorber. The glass that is normally used for windows is not suitable for its use in collectors due to its high content of iron. Glass with low content of iron has a relatively high transmittance for solar radiation, approximately 85-90% for normal incidence. Tempered glass in mostly used, since non-tempered glass in collectors can crack from the heat. Antireflective coatings and surface texture can improve transmission significantly.

Although glass is almost opaque to long-wave radiation, absorption of that radiation can increase the temperature of the glass, and the heat loss is found through radiation and convection.

There are also plastic films and sheets that can be used as glazing for a collector. They also have high transmittance for short-wave radiation, but because most usable varieties have a transmission band in the middle of the thermal radiation spectrum, they may have long-wave transmittances as high as 40%. In the other hand, plastics are also limited in the temperatures they can take without deteriorating or deforming. Only few plastics can resist to UV radiation for long periods.

Interior skin glazing

The total solar energy transmittance G of glass has two components:

- The total solar radiation transmitted through the glass and

- The radiation that is initially absorbed by the glass and then released into the interior by heat transfer and movement of the air after a time delay

The higher the G-value, the more heat will pass through the glass. The lower the G-value, the less the room will be heated by solar radiation.

Typical G-values:

- Double glazing g = 80%
- Thermal protection glazing g = 50 to 70%
- Solar protection glazing g = 20 to 40%

For the interior glazing pane, different characteristics are required. This pane has to have a low G-value in order to prevent from overheating the room.

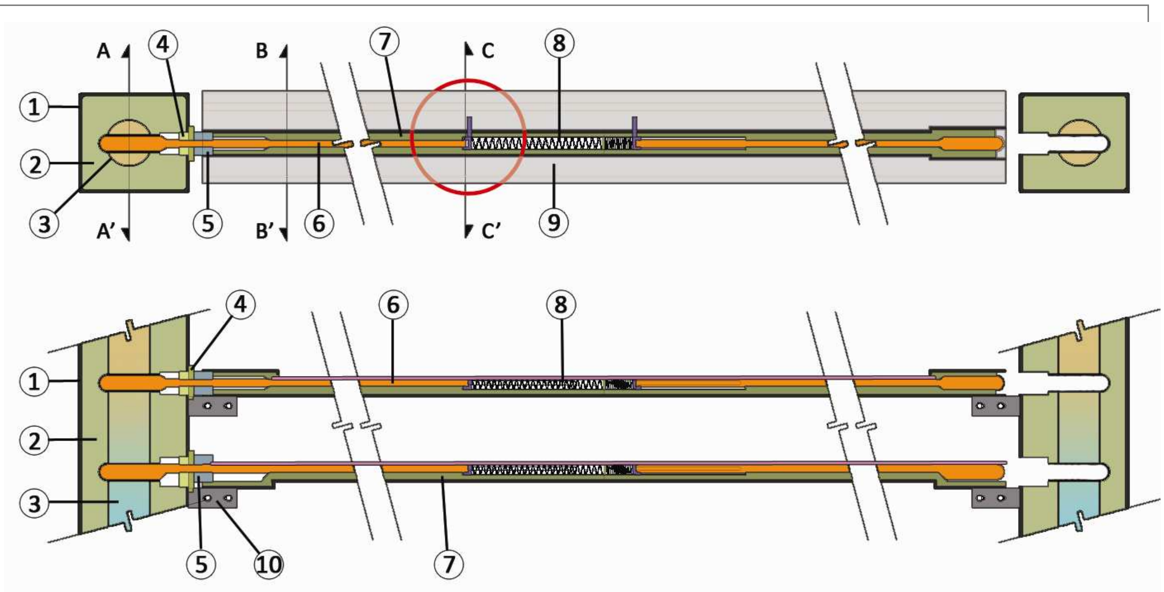
These values might be used for the inner pane of glass, which must be a double insulated glass unit in order to prevent heat transmission from the cavity to the room. It can also be good for the interior pane to be coated with a low-E coating to reject all incoming radiation from the window and reflected back to the blind.

10.9 Fixed angle blind collector

Because the fixed blind does not show any degree of movement, the thermal transfer is the only matter that is taken into account for this blind. The blind, which is previously fixed in a certain defined angle, collects the solar radiation and transfers it to the heat pipe underneath the slat. This heat pipe in turn, has to transfer the heat to a manifold that is located at the frame at each side of the façade panel. Because no movement is encountered, this last connection can be made to fit precisely to the heat pipe head with no danger of friction.

The heat pipe head is inserted in a plug into the manifold piping and it is held in place by means of a spring located in the center of the slat which pushes the heat pipe towards the manifold. Because of such easy connection, each heat pipe and slat can be replaced one by one when needed. In Figure 106 (a) it can be seen at the right side of the slat that when the spring is contracted, the heat pipe is driven inside the slat and therefore, the slat can be removed. (b) Shows two possible ways of allocating the heat pipe inside the slat: The first is done with a conventional heat pipe which produces a bump on the top surface of the slat. The second is done with a heat pipe that has a shifted head so that it can fit inside the slat keeping the superior surface flat.

The spring mechanism works by pushing the heat pipe into the plug and it pulls the heat pipe inside of the slat by means of a lever that compresses the spring (Figure 106 (c)).



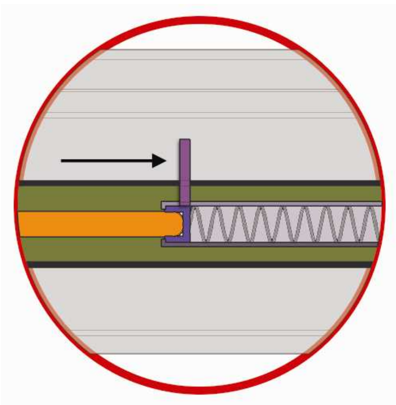


Figure 106. (a) Top view of fixed blind mechanism for heat transfer and mounting. (b) Side view of two different arrangements for allocating the heat pipe inside the slat. (b) Contracting spring detail.

1. Frame of venetian blind
2. Insulation
3. Manifold
4. Cap
5. Heat pipe insulation on the edge
6. Heat pipe
7. Insulation along the heat pipe
8. Spring and spring chamber
9. Slat
10. Fixation point

Figure 107 shows three sections of the fixed angle blind. Section A-A' displays the plug in which the head of the heat pipe is inserted and the flow of antifreeze through the manifold. The heat is transferred to the antifreeze by being in contact to the surface that surrounds the head of the heat pipe which is embedded in the manifold tube. Section B-B' shows the fixing point of the slat to the frame by means of a metallic plate. It also displays the heat pipe and the insulation and shell that protect it from the environment; and the gripping point of the slat to the heat pipe shell. Section C-C' shows the spring lever on the shell of the heat pipe.

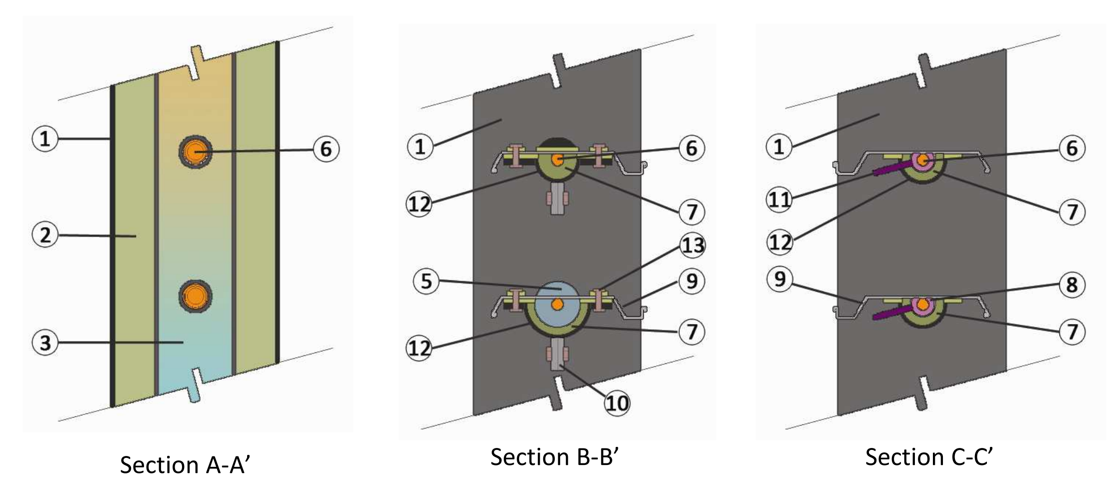


Figure 107. Section A-A': Manifold with heat pipe heads embedded. Section B-B': Two different gripping mechanisms. Section C-C': Spring and lever.

11. Spring lever
12. Axis Shell
13. Slat grip

Two types of fixed-angle blinds can be developed, depending on the mechanisms that are added to it. If a simple blind which is fixed in place is wanted, then the manifold with heat pipe plugs can be used (Figure 108). This blind can be used as louvers in front of the façade.

Figure 108. Fixed-angle blind.

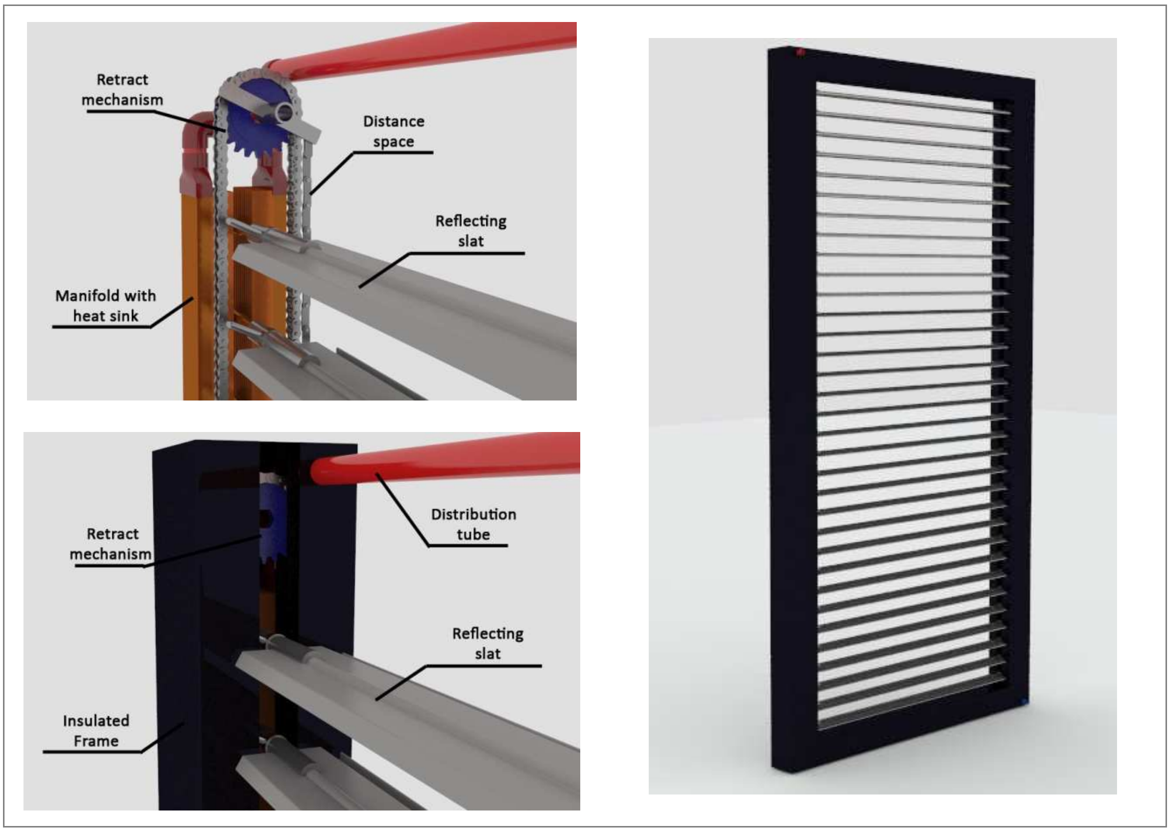


Figure 109. Fixed-angle retractable blind.

10.10 Tiltable and retractable blind

This type of blind requires that the manifold allows the blinds to move vertically; therefore the manifold is made of two parallel tubes that run vertically with a fin heat sink attached to them. In this manifold heat sink a secondary heat sink is fitted. Both heat sinks are not in direct contact but close enough to transfer heat by radiation. The heat pipe is inserted then in se secondary heat sink plug, from where the heat will be dissipated towards the antifreeze.

For ease of maintenance, each slat and heat sink can be replaced individually, using the same spring system shown in Figure 106 (a).

Since this blind has the most degrees of movement, it comprises all mechanisms mentioned above. The tilting is done by means of a scissor-like chain which allows the slat to tilt from -30° to 90°. The retraction is done through the rotation of the sprockets located at each end of the blind. When the blind is to be retracted, the scissor-like chain can be folded, so that it gets compressed into a smaller size. The blind should be lifted in a horizontal position, to enable the mechanism to fold easily.

Figure 110. Tiltable and retractable blind

11 Handling of the blind

11.1 Operability

During some periods of time, the light that comes through the façade and into a room is not enough to reach the levels of luminance required in a room. This problem can occur during the months enclosed by the fall and winter season. These months experience a low elevation of the sun and a short day length. If sun collection was to be done, the blind would probably be almost closed due to the tracking of the sun.

In this aspect a dilemma comes to play on what is better for energy saving: If collection of solar radiation is done, blinds would be closed up, avoiding the entrance of daylight. In the other if daylight is allow to enter, the savings would be on avoid the use of artificial lighting.

It is quite difficult to predict the sky condition for a certain day, and therefore, the blind cannot be set up to start working at a certain time, because there might be not enough radiation to collect and the little daylight that may be available can get blocked.

Because of this, it would be better if the blinds could be automatically driven but with the possibility to be overruled by the users. So when users want modifying the angle to open the slats to get more daylight; it can be possible and the collection can be still done, but in a reduced mode.

When the blinds are running in automatic mode, which means that they are tracking the sun, they can be set up to work in groups of blinds as follows:

Individual blind control

This type of control is used in single-person offices and is normally controlled manually, but can also be automated for a good tracking of solar radiation, sun shading, glare control and redirection of sunlight.

Group blind control

This type of control is intended for sectors or team offices and open-plan offices. The control can be done manually or automated.

Floor blind control system

This control is used for offices that are using a whole floor space, so that the blinds can work together for the whole space.

Façade blind control system

The façade control operates all the blind from a façade. It creates a uniform façade design and can also prevent from reflection from adjacent buildings or light trespassing to neighbor buildings at night.

Building blind control system

It creates a uniform design for all facades of the building. It can create a complete blackout for preventing overheating during weekends and day-long solar collection.

11.2 Maintenance

Even though there is a way to dismount a slat when a part of it is not working properly, it is also possible to remove the entire blind package out of the façade by opening the cavity from inside the room and pulling out the blind frame. In order to do so, the valves shown in Figure 26 of the incoming and out coming antifreeze solution should be shut down and the system must be drained back to the antifreeze reservoir before any dismounting. When shutting the valves down, it is ensured that the rest of the solar thermal collectors of the adjacent façade panel will continue working without any risk or interruption.

11.3 Critical situations

There are some special situations where the solar thermal collector blind should be operated in a different way than expected, which are exposed next:

There could be some times when the solar radiation is intense, the storage tank is fully charged and the energy is not being used. The accumulation of heat in the blind could lead to intense thermal radiation to the indoor air, increasing the temperature of the room behind the blind collector. When this becomes excessive, it can lead to stagnation of the fluids and even failure of the system.

To prevent this, the easiest solution is to turn the slats to face inwards or retract them, in that way, the absorbent coating will be blocked from direct radiation. To prevent stagnation, the antifreeze solution should be drained back to the deposit. It is important to include a ventilation system for the façade cavities that will allocate a blind collector, since the air inside the cavity can also reach high temperatures.

Due to the high temperature that the blinds can reach, it is advised to place the blind collector at least 20 cm from the inner glazing pane, to prevent direct radiation from the blind to the and to promote convective cycles in the area next to the blind.

To prevent freezing of the heat pipe heat transfer fluid on external blinds, a fluid that can take low temperatures should be use instead of regular water heat pipes.

12 Conclusion

The façade in buildings is becoming the most important part of the aesthetics of a building, but it is also an architectural element that determines in great extend the consumption of energy for heating and cooling in a building. It is the greatest surface of a building in which solar radiation falls producing overheating in most of the cases. In order to respond to this problematic and contribute to the reduction of energy consumption, the current thesis proposes an integration of solar thermal collectors into a façade for solar heating and cooling.

Placing an object in front of the façade would directly affect the performance of a building. When direct radiation goes through the façade, the thermal energy is trapped indoors and overheating occurs, besides glare problems. In the other hand, if the sun is completely blocked out it results on the use of artificial light. The proposed way to integrate solar collection in the façade is by blocking the sun partially when it is required, just as regular sun shading devices. Therefore the solar thermal collection was proposed to be integrated in the façade as a solar shading system.

A review on sun shading devices was made and it was found that for an office building, where the working hours go from 9:00 to 17:00, venetian blinds respond better to the blocking of direct solar radiation while letting daylight in. Therefore the shading system selected for this research was venetian blinds.
An analysis on the available solar collectors for low temperatures was carried out and two of them were found to be relevant for this application: Flat plate collector and Evacuated tube collector. From both, some components were taken for a later adaptation into the façade.

For architectural reasons, two different configurations were found to be convenient in order to perform subsequent calculations: External blind collector, which is an unprotected solar collector placed in front of the façade; and a cavity blind collector, which is located in a cavity formed by a double skin façade. After defining a preliminary shape of the *Venetian blind solar collector*, a calculation concerning the absorption of solar radiation was made for different frequency of solar tracking located in seven selected cities. It was found that for cities with latitudes up to 23.45°, the frequency of angle adjustment for solar tracking does not have a great impact in the absorption of solar radiation in south facades. Contrary to this, in high latitude cities (over 23.45°), the most frequently the solar collector angle is adjusted in the south façade the better the absorption, being the hourly angle adjustment more preferable. It was also found that for those cities with latitude smaller that 23.45°, the northern façade has a great impact in the total absorption of radiation that a building can collect, since direct radiation is to be found striking this façade. For the rest of the cities, no beam radiation is found on the north façade, and therefore only diffuse radiation is collected, which accounts for a slight part of the total radiation absorbed. For east and west facades, frequency of adjustment plays a minor role: hourly angle adjustment has a slightly better performance, but it may not be worth the cost of such tracking system for such a small gain in thermal energy.

For further analysis, Mexico City and Amsterdam were selected. In order to find the useful energy that is transmitted the heating or cooling divide, the heat losses were calculated. In this case, the temperature of the blind collector was estimated to reach up to 120°C in Mexico City and 95°C in Amsterdam.

The absorption in external blinds that are placed in front of the façade are greater than those located in the façade cavity, due to the direct incidence of the radiation on the absorptive surface, but in the same way, external blinds have greater heat losses, than cavity blinds, especially in those cities where the outdoor temperature tends to be low (high latitude cities), due to the differential of temperature and the direct contact with the wind. It is recommended for high latitudes cities to allocate the blind collector in the façade cavity.

Because outdoor temperatures in Mexico City do not vary much from the comfort temperature, the thermal loads that are encountered are relatively low compared to those from Amsterdam, where the temperature differential is greater, especially during the winter months. Useful energy can satisfy the needed energy for a standard room in Mexico City, and even show a surplus during the summer. In the other hand, useful energy collected in Amsterdam does not fulfill the thermal requirements and auxiliary energy has to be consumed.

According to the analysis made, a design for each particular case was developed. For Mexico City, the blind collector that performs better is that with a fixed angle, while the hourly adjustment for solar tracking has a better performance in Amsterdam. For both designs, special attention should be paid to the temperature on which they are intended to be used and the configuration within the façade, especially when the solar collector is going to be placed in a cavity with little ventilation.

Having a solar thermal collector in the façade will require more preparation during the construction stage due to the required installation of especial piping and pumps. Aesthetically, Venetian blinds of this type not only produce an impression of texture in front or behind a glass pane, but also it can provide certain degree of design for an architectural composition of the façade. If blinds are controlled room by room, storey by storey or an entire façade, the different display of the blinds and the different tilt angle can create different arrangements that can be interesting to look at during the day or even during night time.

Recommendations

During the calculation of the absorptance of radiation, the effect of shading plays a significant role in the determination of the radiation falling on surfaces. Shading should be calculated for each particular site and façade, especially in urban space, where there are much more elements that can produce shading.

Heat losses are closely related to the air temperature that is found in the site and the configuration of the façade where the blind is going to be placed. It is convenient to do a calculation for each particular case in order to know the size of the absorber and type of piping and pumping depending on the scale and needs of each building. It is also important to calculate the solar path and amount of energy required to avoid over sizing of the system.

The thermal loads of the building define the amount of energy required for heating and cooling. Is it important to do a calculation taking into account the differential of temperatures throughout the day and the office appliances, lighting and people that may contribute to overheating the space for cooling purposes; and the amount of ventilation and characteristics of the building that may increase for heating loads.

It would be better for the sake of the research to produce a prototype of the façade that can be tested in real-life conditions. In this way more tangible data can be collected and the system performance can be understood in a better way.

Bibliography

- Acktar advance coatings. (2010). *Solar Selective Coatings*. Retrieved September 10, 2010, from Acktar advance coatings: http://www.acktar.com/default.asp?catid={1621426A-0F08-4C5B-B69C-8BF955ED0EEA}
- Arpaci, V. S. (1999). *Introduction to Heat Transfer.* Upper Saddle River: Prentice Hall.
- Brown, G. (2001). *Sun, Wind & Light. Architectural Design Strategies.* New York: Wiley.
- Colt Int. Ltd. (2010). *Solar Shading Systems. Architectural Solutions.* Retrieved from Colt International Limited: www.coltgroup.com
- Duffie, J. A. (2006). *Solar engineering of thermal processes.* Hoboken: Wiley.
- Eicker, U. (2009). *Low energy cooling for sustainable buildings.* London: Wiley Publications.
- Encyclopedia of Alternative Energy and Sustainable Living. (2010). *Evacuated Tube Collector*. Retrieved June 2010, from Encyclopedia of Alternative Energy and Sustainable Living: http://www.daviddarling.info/encyclopedia/E/AE_evacuated_tube_collector.html
- Frosty Tech. (2010). *Heatpipe Wick Structures Exposed: Sintered, Groove and Mesh*. Retrieved 2010, from Frosty Tech: http://www.frostytech.com/articleview.cfm?articleID=2466
- Hella Group. (2009). Blind Technical Documentation Booklet.
- International Energy Agency. (2007). *Renewables for Heating and Cooling. Untapped potential.* Paris: International Energy Agency.
- Kalogirou, S. A. (2009). *Solar Energy Engineering. Processes and Systems.* USA: Elsevier.
- Kender Technologies, Inc. (2009). *Basics of Solar Water Heating*. Retrieved 2010, from Total Green Energy Solutions: http://www.totalgreenenergysolutions.com/solarwater.php
- Passive Solar Design. (2010). *Passive Solar Design*. Retrieved September 2010, from http://passivesolar.sustainablesources.com/
- Pettit, R. (1976). Solar Absorptance and Emittance Properties. *J. Vacuum Science and Technology 13, No. 2*, (p. 596).
- Power Electronics Technology. (2011). *Heat-Pipe/Heat-Sink Technology Improves 6-kW Cooling*. Retrieved January 2011, from Power Electronics Technology: http://powerelectronics.com/thermal_management/heatpipes_spreaders/heatpipeheatsink-technology-improves-20091009/
- Reay, D. (2006). *Heat Pipes: Theory, Design and Applications.* Amsterdam: Elsevier.
- Thermacore. (2010). *Heat Pipe Technology: Passive heat transfer for greater efficiency*. Retrieved October 6, 2010, from Thermacore Thermal Management Solutions: http://www.thermacore.com/thermal-basics/heat-pipe-technology.aspx
- ThermoTechnologies. (2005). *ThermoTechnologies. The solar revolution: Security in a changing world*. Retrieved November 04, 2010, from http://thermomax.com/index.php

- U.S. Department of Energy. (2010). *Active Solar Heating*. Retrieved June 14, 2010, from U.S. Department of Energy: http://www.energysavers.gov/your_home/space_heating_cooling/index.cfm/mytopic=12490
- Zumbotel. (2010). *Luxmate blinds control.* Retrieved from Zumbotel: www.zumbotel.com

Appendix 1. Solar path diagrams

Singapore (1°17’N)

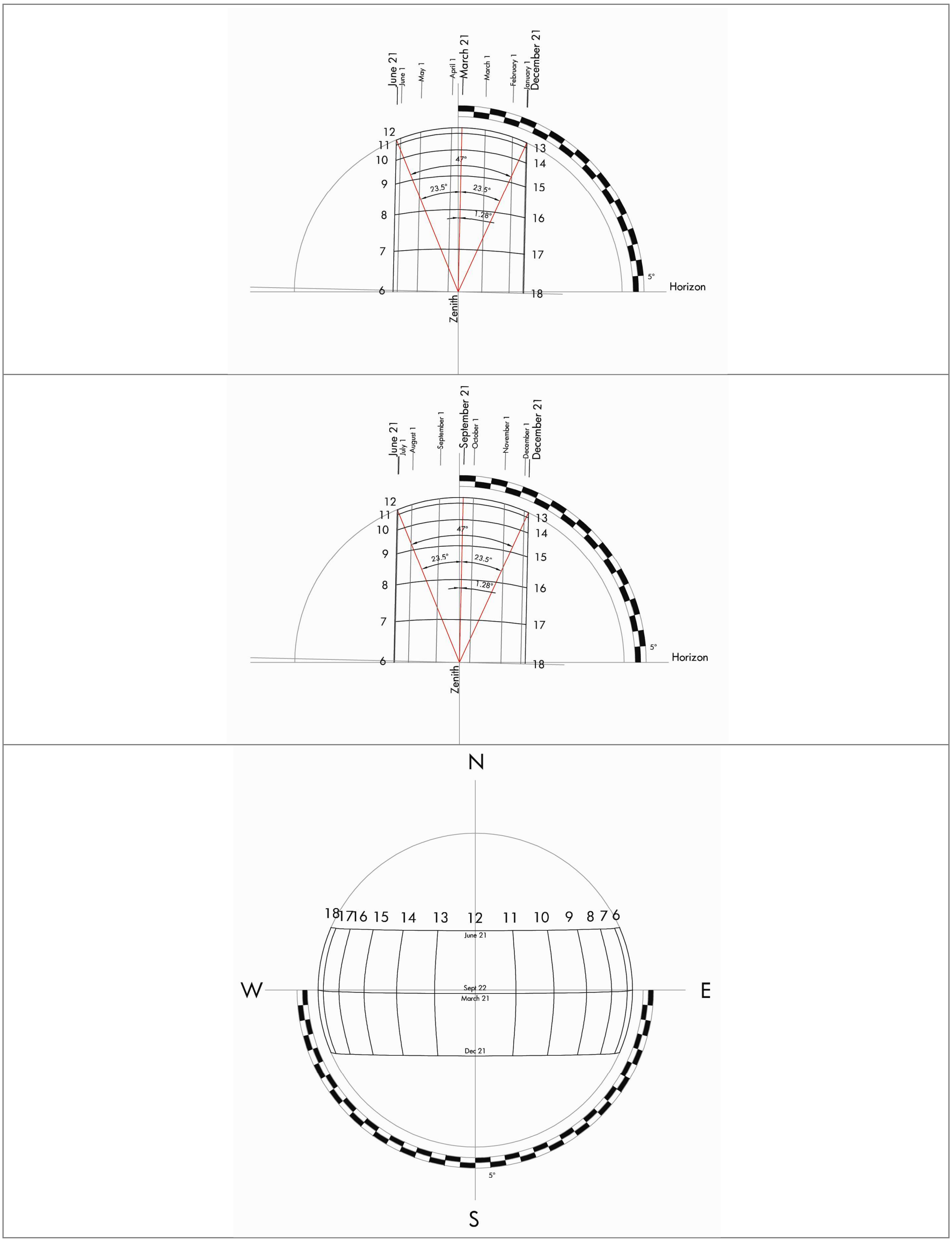


Figure 111. Sun path Singapore (1°17’ N). Orthogonal projection.

Caracas (10°30’N)

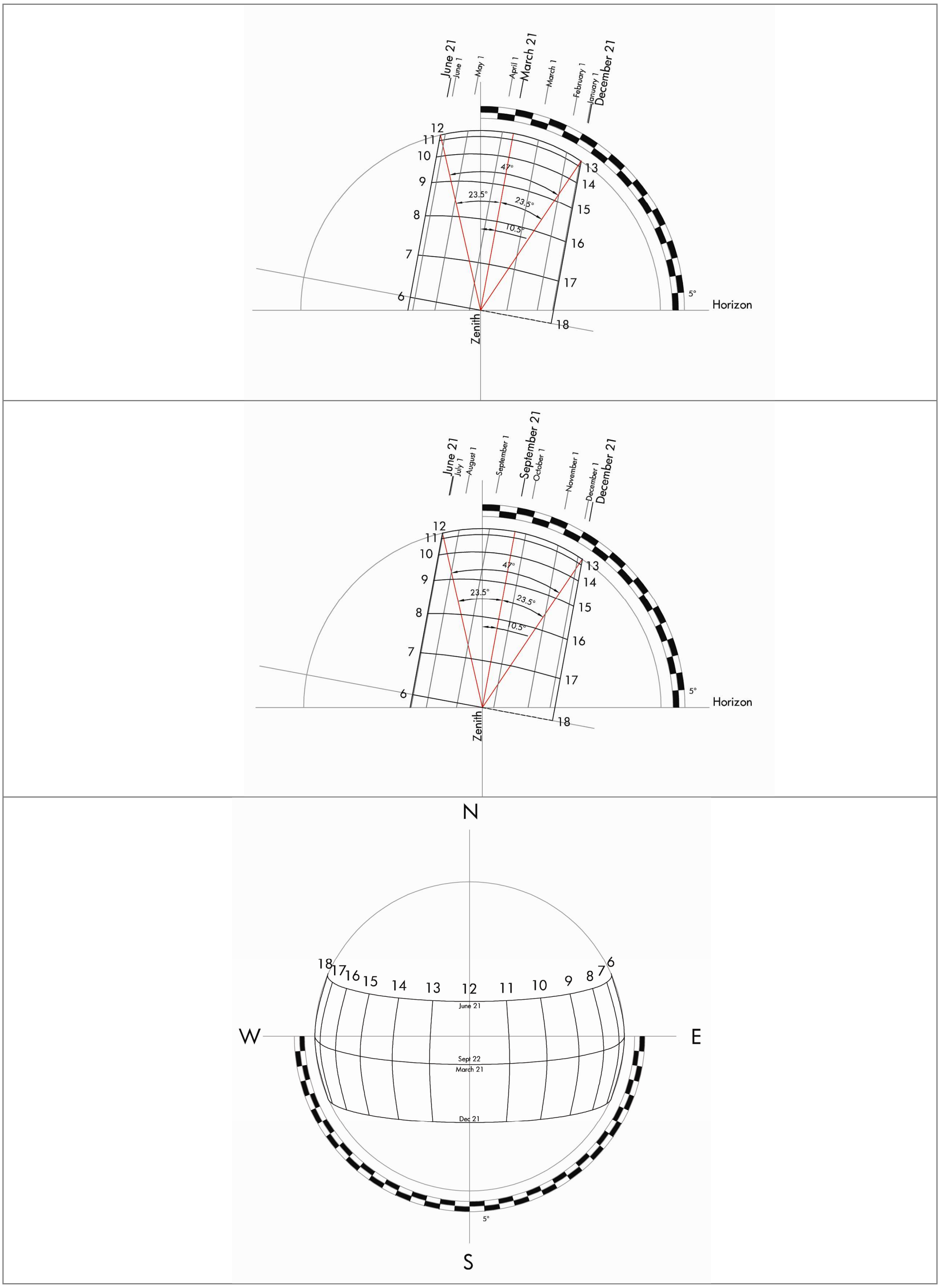


Figure 112. Sun path Caracas (10°30’N). Orthogonal projection.

Mexico (19°41’N)

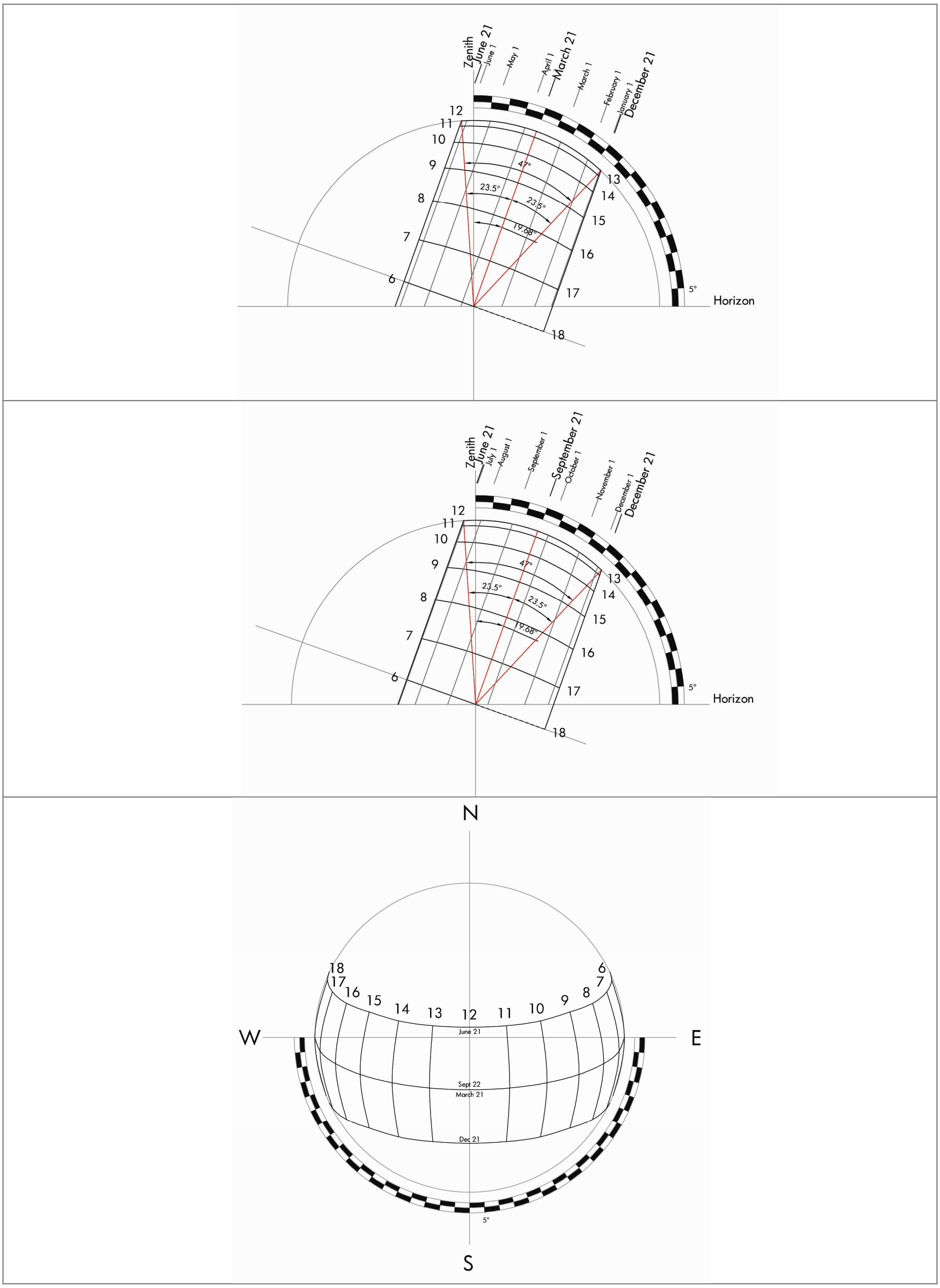


Figure 113. Sun path Mexico (19°41’N). Orthogonal projection.

Shanghai (31°10'N)

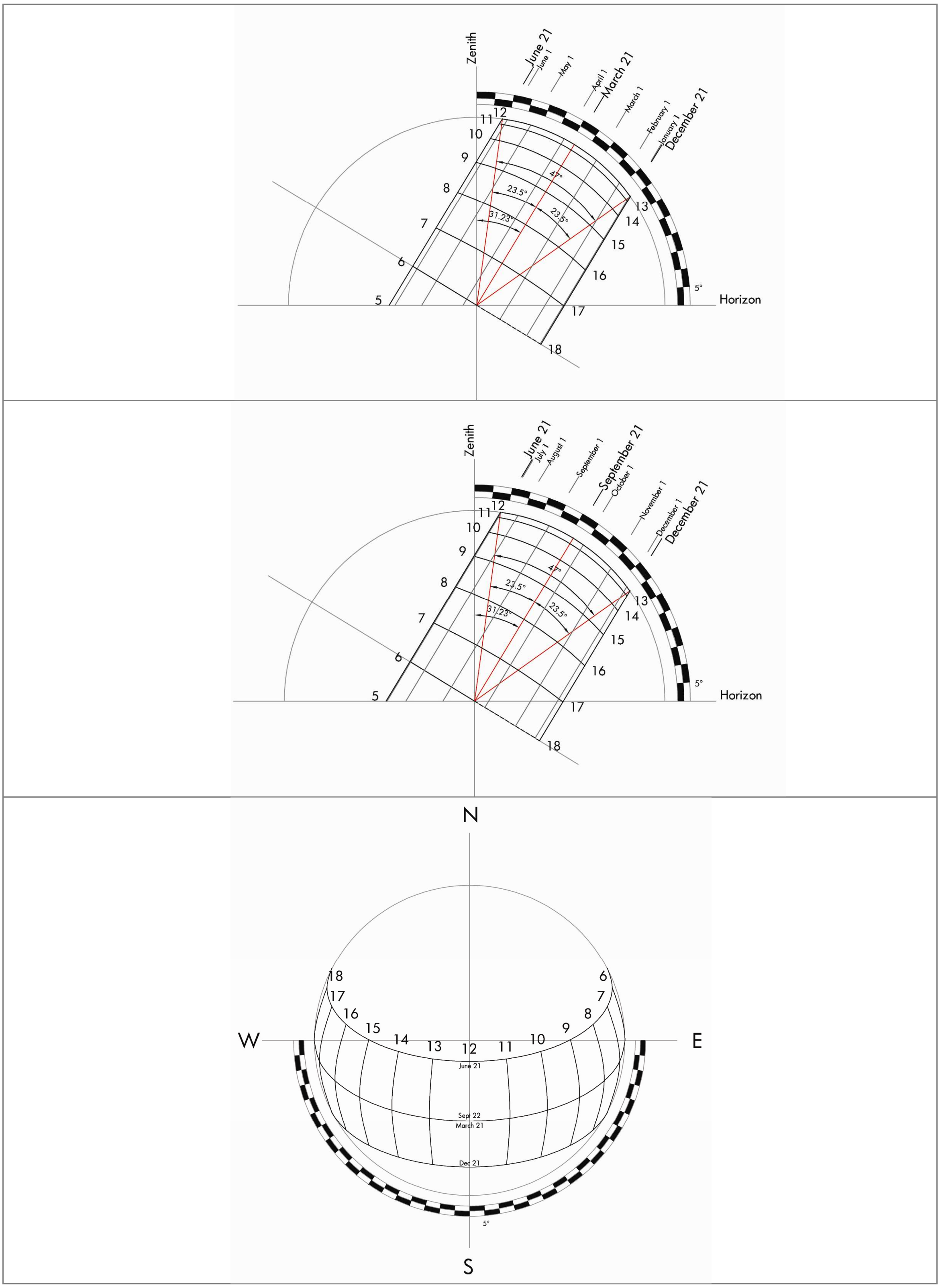


Figure 114. Sun path Shanghai (31°10'N). Orthogonal projection.

New York (40°43'N)

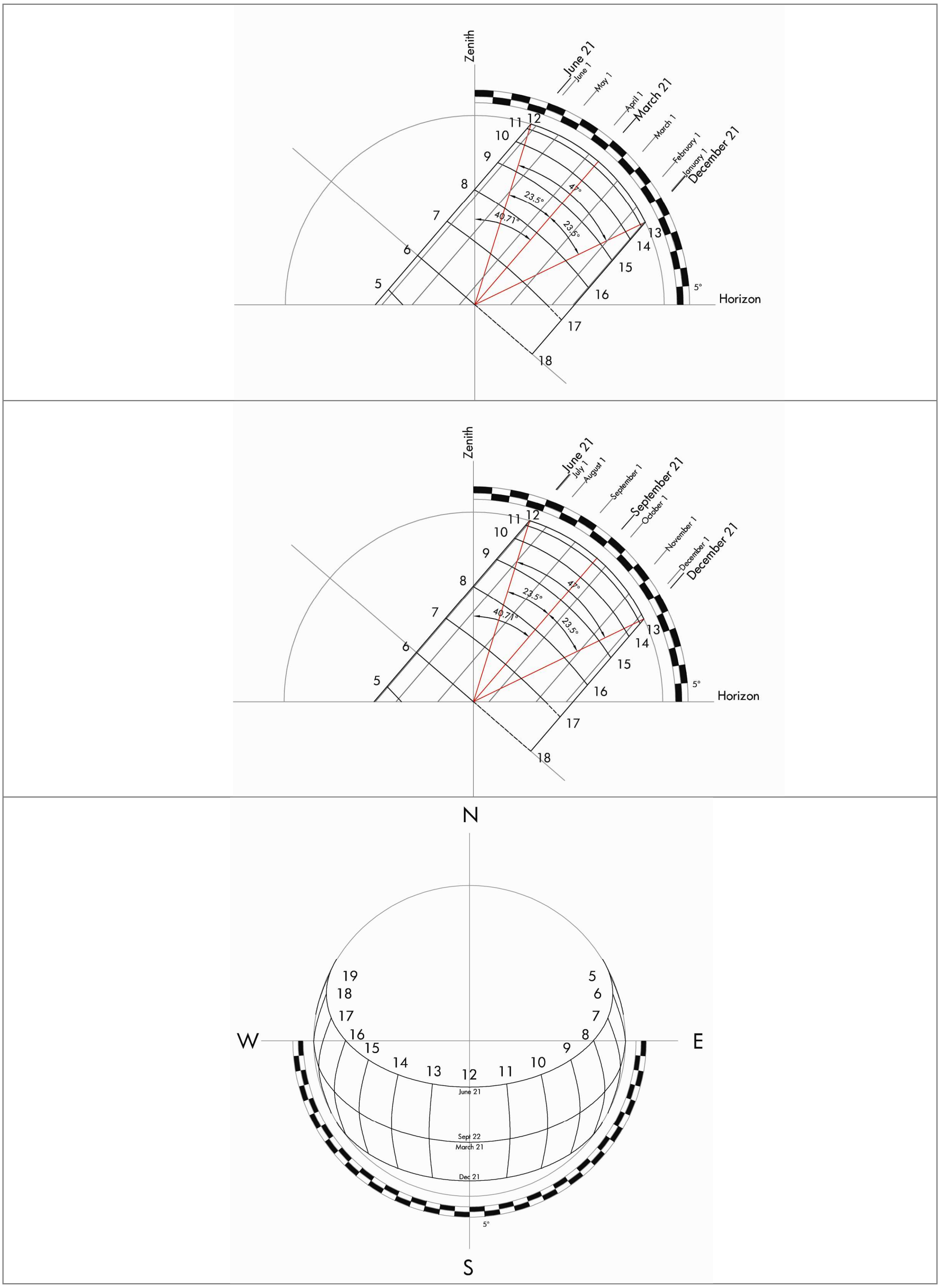


Figure 115. Sun path New York (40°43'N). Orthogonal projection.

Amsterdam (52°22'N)

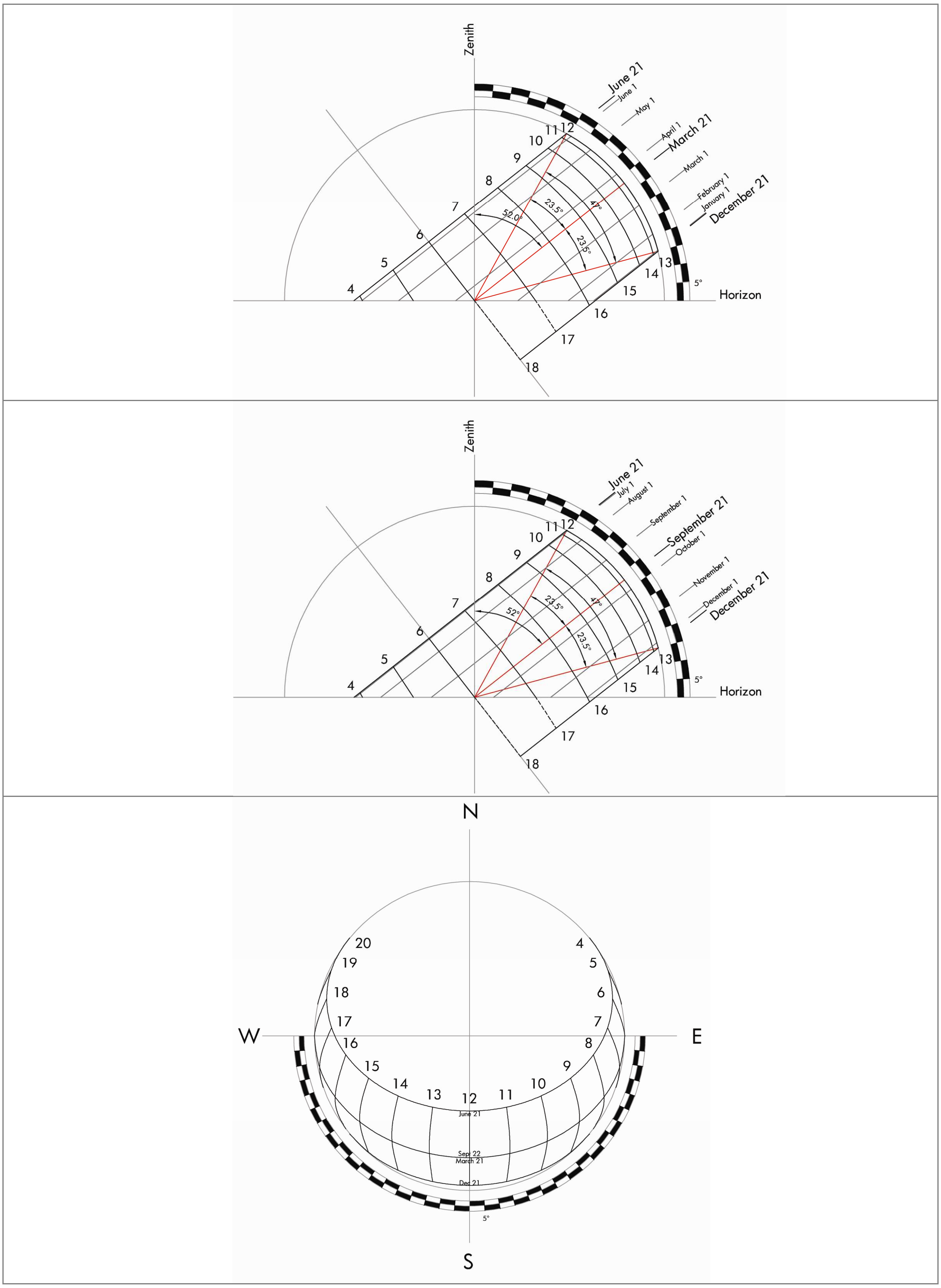


Figure 116. Sun path Amsterdam (52°22'N). Orthogonal projection.

Helsinki (60°12’N)

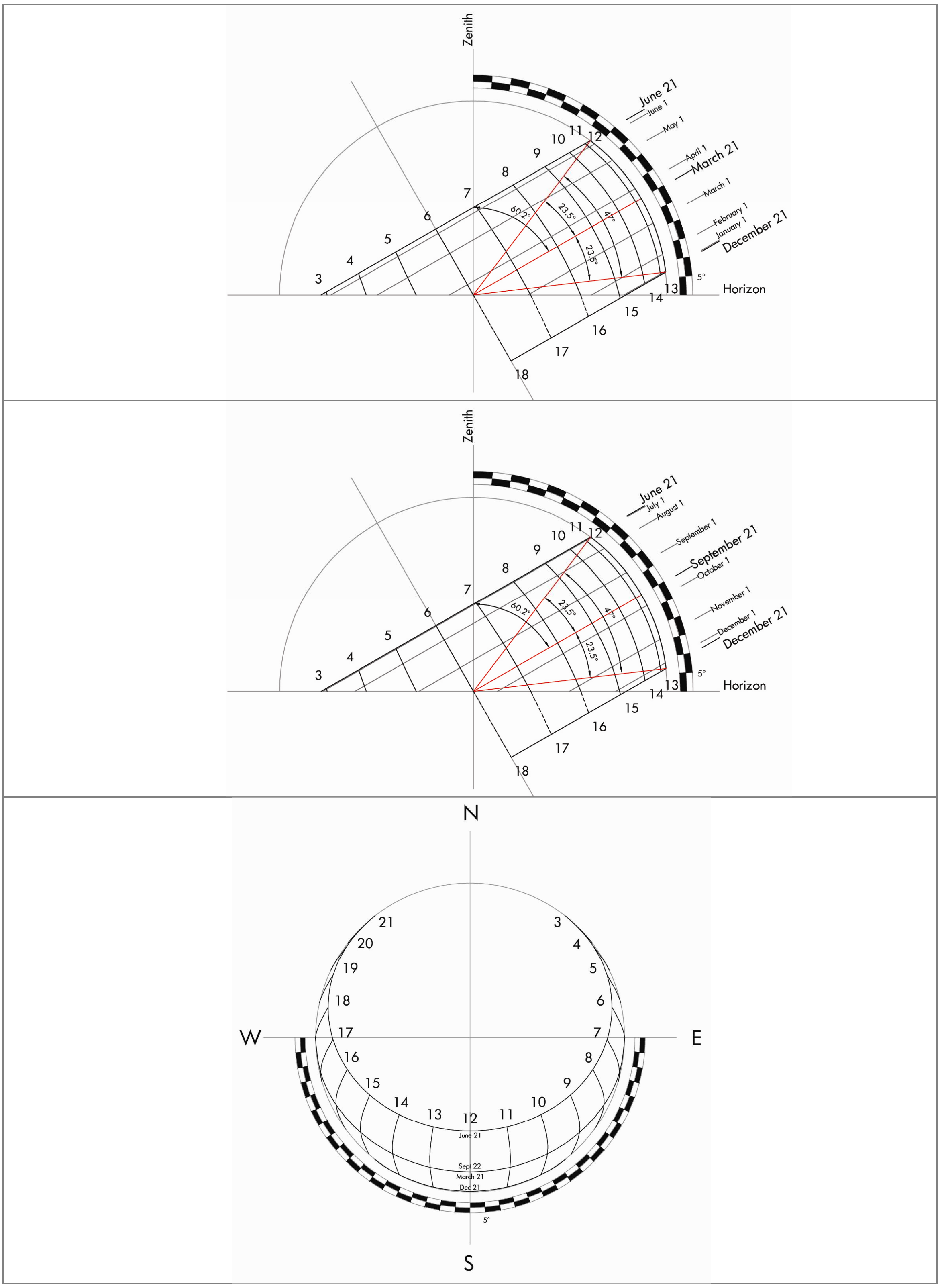
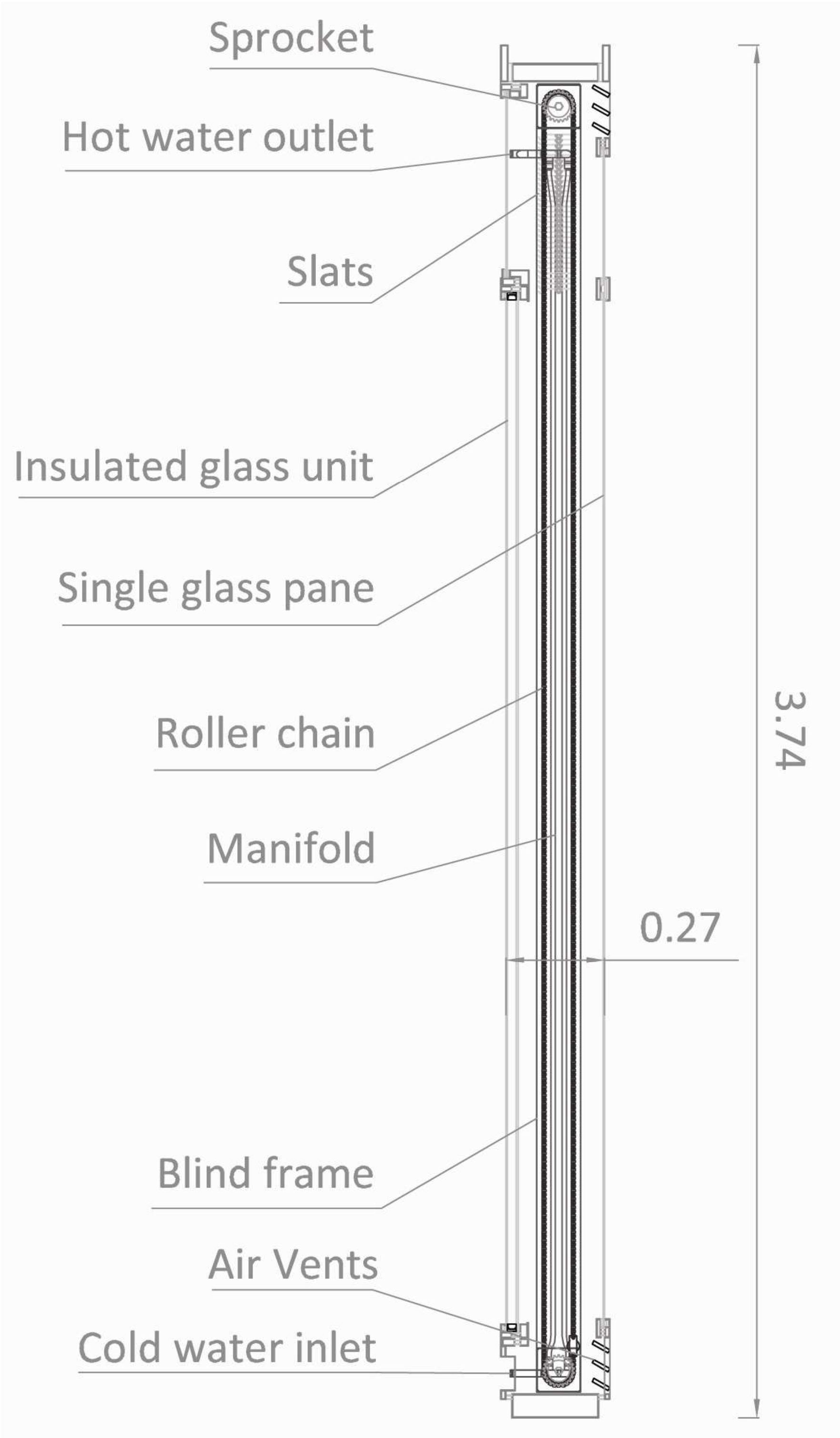


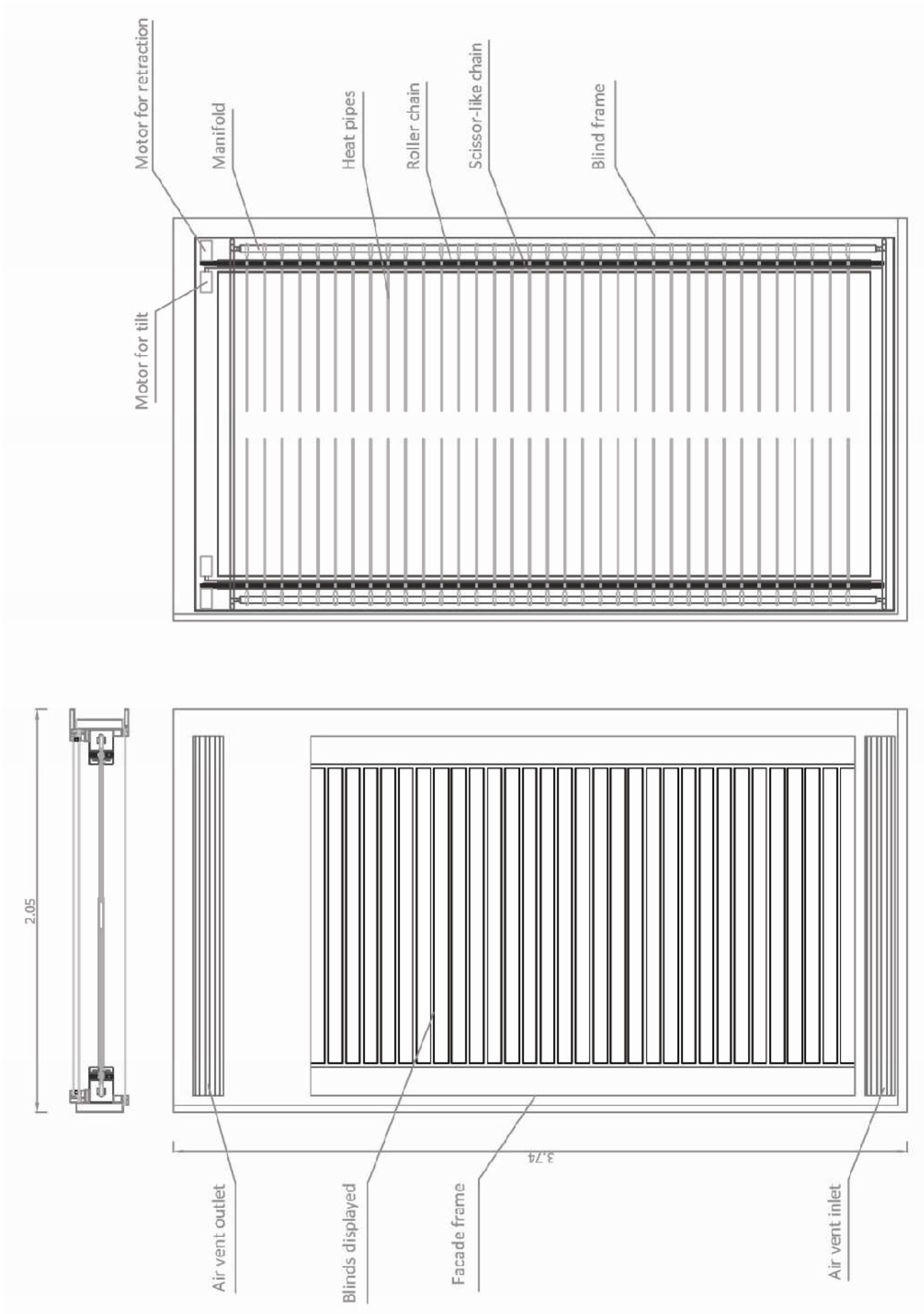
Figure 117. Sun path Helsinki (60°12’N). Orthogonal projection.

Appendix 2

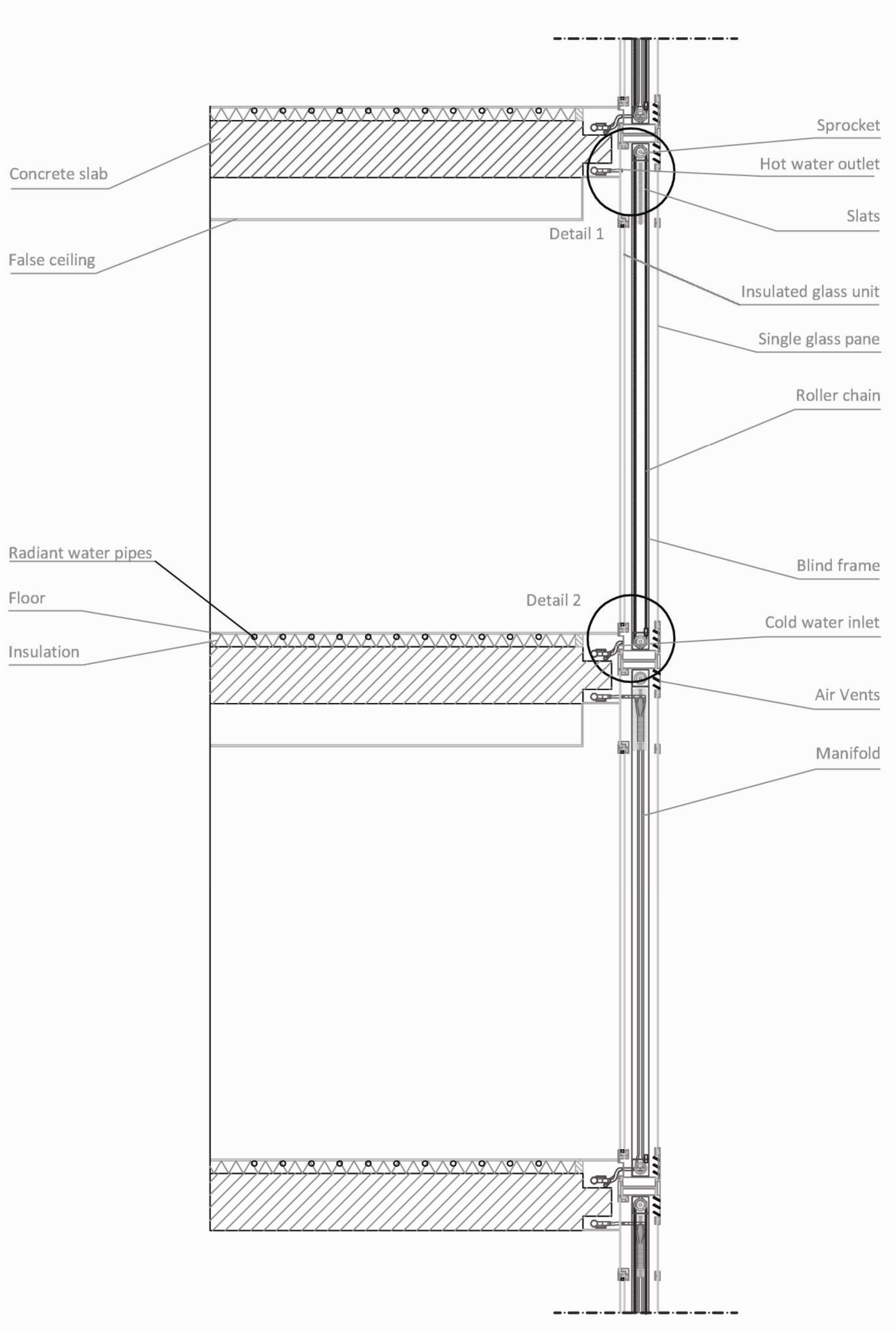
Detailed Drawings



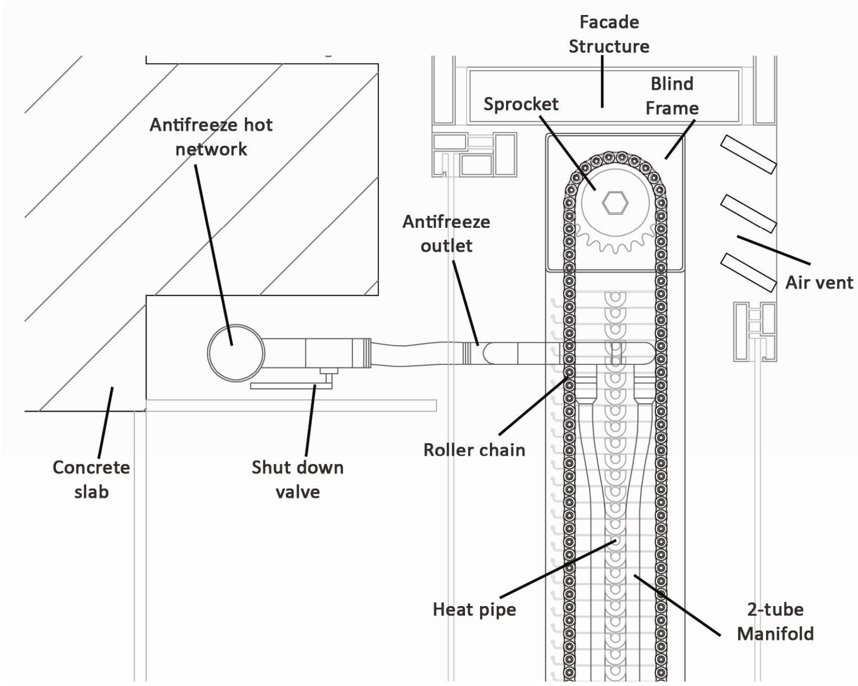
Plan 1. Vertical section of façade panel with solar thermal collector blind embedded.



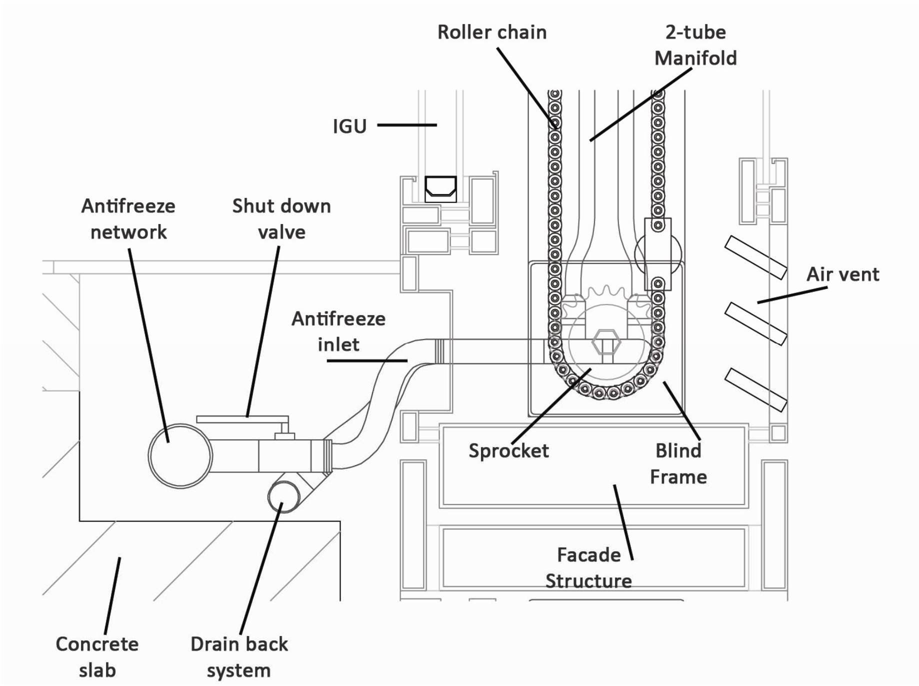
lan 2. Front view of façade panel and frontal section.



Plan 3. Vertical section of facade



Detail 1



Detail 2

Plan 4. Details of façade.

Appendix 3

Heat Pipe working fluids*

Heat Pipe Working Fluid	Operating Temperature Range (°C)	Heat Pipe Shell Material
Low Temperature or Cryogenic Heat Pipe Working Fluids		
Carbon Dioxide	-50 to 30	Aluminum, Stainless Steel, Titanium
Helium	-271 to -269	Stainless Steel, Titanium
Hydrogen	-260 to -230	Stainless Steel
Methane	-180 to -100	Stainless Steel
Neon	-240 to -230	Stainless Steel
Nitrogen	-200 to -160	Stainless Steel
Oxygen	-210 to -130	Aluminum, Titanium
Mid Range Heat Pipe Working Fluids		
Acetone	-48 to 125	Aluminum, Stainless Steel
Ammonia	-75 to 125	Aluminum, Stainless Steel
Ethane	-150 to 25	Aluminum
Methanol	-75 to 120	Copper, Stainless Steel
Methylamine	-90 to 125	Aluminum
Pentane	-125 to 125	Aluminum, Stainless Steel
Propylene	-150 to 60	Aluminum, Stainless Steel
Water	1 to 325	Copper, Monel, Nickel, Titanium
High Temperature Heat Pipe Fluids		
Cesium	350 to 925	Stainless Steel, Inconel, Haynes
NaK	425 to 825	Stainless Steel, Inconel, Haynes
Potassium	400 to 1,025	Stainless Steel, Inconel, Haynes
Sodium	500 to 1,225	Stainless Steel, Inconel, Haynes
Lithium	925 to 1,825	Tungsten, Niobium
Silver	1,625 to 2,025	Tungsten, Molybdenum

* (Thermacore, 2010)

Radial evaporator heat fluxes in heat pipes**

Working fluid	Wick	Vapor temperature (°C)	Radial flux (W/cm^2)
Ammonia	various	20-40	5-15
Methanol	nickel foam	25-30	0.03-0.4
Methanol	Nickel foam	30	0.24-2.6
Methanol	1 x 200 mesh (horiz.)	25	0.09
Water	Various	140-180	25-100

Water	Mesh	90	6.3
Water	100 mesh s/s	90	4.5
Water	Nickel felt	90	6.5
Water	Sintered cooper	60	8.2

** (Reay, 2006)

Emissivity of various materials

Material	300K	500K	800K	1600K
Aluminum				
Smooth, polished	0.04	0.05	0.08	0.19
Smooth, oxidized	0.11	0.12	0.18	
Rough, oxidized	0.2	0.3		
Anodized	0.9	0.7	0.6	0.3
Copper				
Polished	0.04	0.05	0.18	0.17
Oxidized	0.87	0.83	0.77	
Iron and Steel				
Iron, polished	0.06	0.08	0.1	0.2
Iron, oxidized	0.6	0.7	0.8	
Stainless, polished	0.1	0.2		
Stainless, oxidized	0.5-0.8			
Glass	0.95	0.9	0.7	
Brick				
Alumina refractory			0.4	0.33
Red, rough	0.9			
Fireclay	0.9		0.8	0.8
Paints				
Aluminized	0.3-0.6			
Most others	0.9			
Wood	0.8-0.9			

Appendix 4

Blind collector varieties

12.1.1 Tiltable blind with no retraction

The mechanism for this blind consists of a main axis located at the top of the blind frame which rotates and by doing so, tilts a steering plane which is attached to a roller steel chain. This chain is attached to both ends of each slat and pulls up or down the edges of the slats in order to tilt them (Figure 118). Tilt angle can go from -30° to 80°.

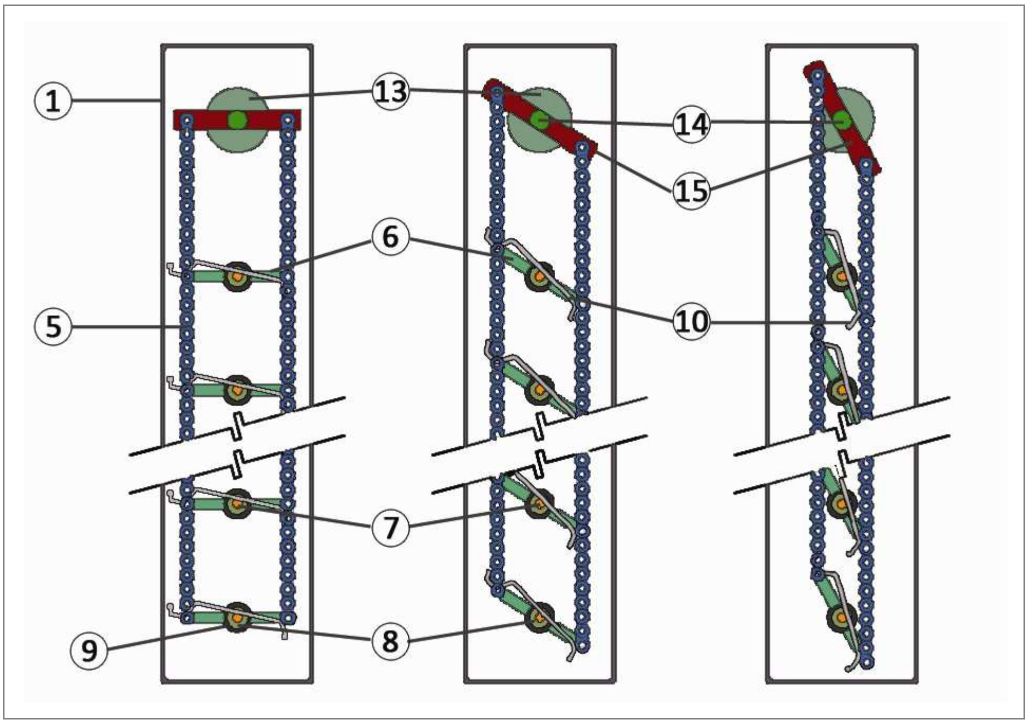


Figure 118. Tilting mechanism for tracking blind.

1. Frame
5. Tilt chain
6. Tilt lever
7. Heat pipe
8. Insulation along the heat pipe
9. Axis shell
10. Slat
13. Tilt motor
14. Tilt axis
15. Tilt steering bar

The heat collection is done in the same way as the previous blind, through the slats with a high absorbing coating and transferred to a heat pipe underneath. The heat pipes are connected into the manifold in a plug that is slightly wider to avoid friction when tilting is done (Figure 119).

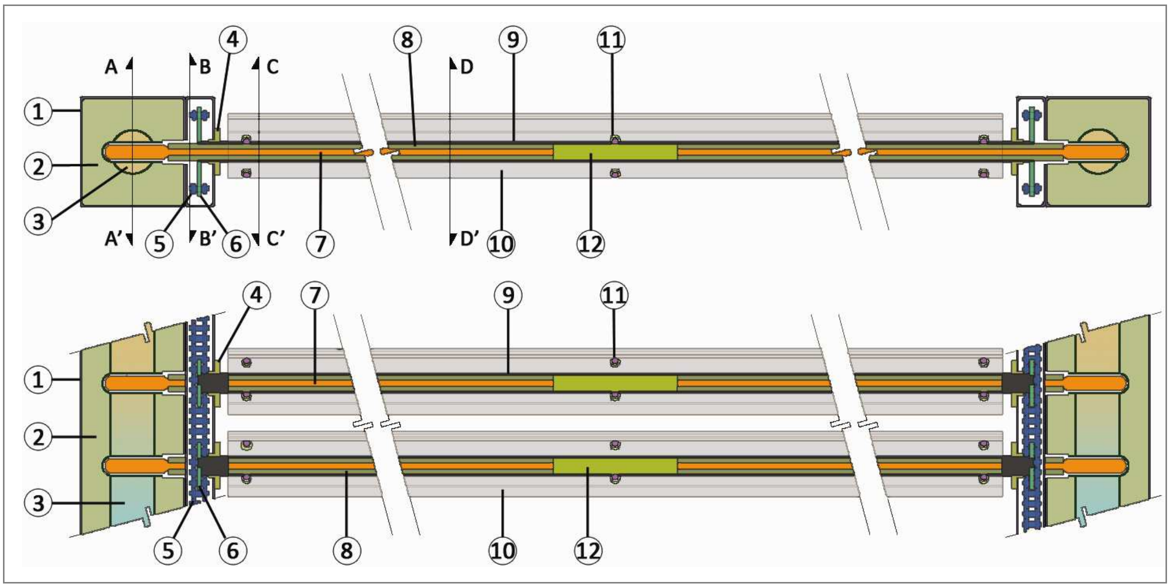


Figure 119. Top and front view of the mechanism for a blind that tilts.

1. Frame
2. Insulation
3. Manifold
4. Cap
5. Tilt chain
6. Tilt lever
7. Heat pipe
8. Insulation along the heat pipe
9. Axis shell
10. Slat
11. Slat grip
12. Insulation fitting

If replacement needs to be done, the slat can be dismounted from the heat pipe shell. To remove the whole slat need to be removed, the heat pipe can be pulled off after the slat has been removed and then the cap from the tilting chain can be removed, and the slat can be screwed off of the chain, releasing all connection point of the slat to the mechanism.