HI-SMART: HIGHER EDUCATION PACKAGE FOR NEARLY ZERO ENERGY AND SMART BUILDING DESIGN

MODULE #4

CHAPTER 2: SOLAR THERMAL ENERGY UTILISATION

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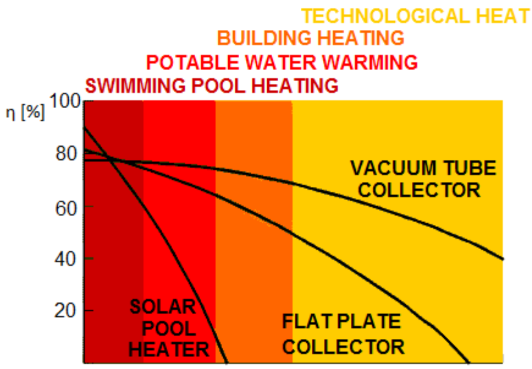
4.2.1 INTRODUCTION

Energy efficiency has become one of the key targets of building service design over the past years, as the building sector's enormous savings potential have been revealed. Solar radiation is a stable and predictable source of energy, and for its exploitation countless companies offer a wide range of technical equipment. Hungary's geographical and climate properties make it possible to reach considerable amount of energy out of solar radiation, yet meteorological conditions can influence the part of the year we should concentrate on. Based on the type of the heat consumer, different build-ups of solar collectors are to be chosen. Their construction defines the optimal application field; this connection is explained with the collector's efficiency curves. Yet not widely known products of the solar thermal industry are solar air heaters. Their simple structure makes them a reliable element of a heating system, suitable not only for building services, but also for agricultural use. Many system alternatives are provided to make use of the warm air produced by the collectors. [1]

4.2.2 THERMAL PROCESSES IN SOLAR COLLECTORS

Offering an option for heating costs savings as well as energy independence, solar thermal technology has become more and more wide-spread over the past decades in Europe. Techniques have been developed for transferring the sunlight's energy into valuable heat used for a wide range of purposes. Depending on the temperature level required, different collector constructions are used. The appropriate choice of device defines the efficiency of the system, underlining the importance of reliable design. To see how very much a collector's efficiency depends on its construction under various operational properties, Figure 4.2.1 shows the efficiency characteristics. [1]



$$\Omega = \frac{T_{Coll,mid} - T_{amb}}{E_{glob,K}} \qquad \left[\frac{K \cdot m^2}{W}\right]$$

Figure 4.2.1: Efficiency curves of solar thermal collectors

As seen in Figure 4.2.1, collector efficiency is a function of the temperature difference between the collector's mean temperature ($T_{Coll,mid}$) and the ambient air temperature (T_{amb}), divided by the solar radiation intensity (E_{glob}). The higher temperature is required at constant ambient air temperature, the bigger the difference will be between the collector's mean temperature and the ambient air temperature.

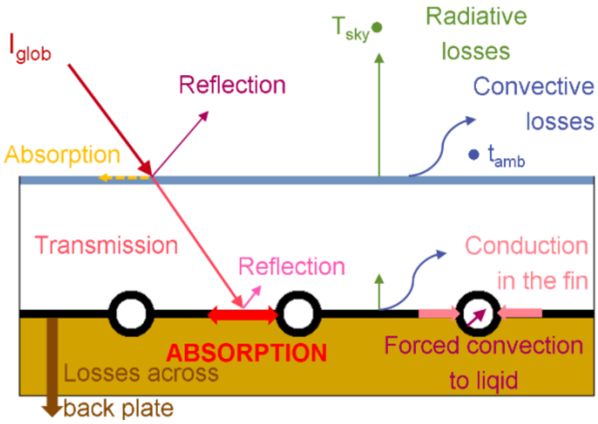


Figure 4.2.2: Thermal processes in a flat-plate collector

During operation, a solar collector's efficiency is reduced by optical and thermal losses. The thermal processes in the flat plate collector can be seen in Figure 4.2.2. Due to absorption, reflection and transmission processes inside a collector, not the entire solar radiation arriving onto the collector surface will be transformed into heat we can directly use. The radiation is partially absorbed and reflected by transparent glazing. Yet most of the radiation reaches the absorber, where it is absorbed and transformed into heat. A part of the radiation reaching the absorber is reflected. As there is a difference in temperature between the absorber and the ambiance, the absorber will cool down. To minimise this effect, insulation is applied in the collector's structure. The higher temperature a collector is expected to produce, the better insulation is required. To reduce the heat loss through the collector's glazing often two panes of glass are used. Thermal losses are convective to the ambience (t_{amb}) and radiative to the surroundings and the sky (T_{sky}) It is easy to see that although more sheets provide better insulation, they increase the optical loss at the same time. Therefore, heating systems with solar collectors must be purpose-built with the suitable type of collector selected for the specific use. [1]

4.2.3 SOLAR COLLECTOR CONSTRUCTIONS

As seen in Figure 4.2.1, the highest values of collector efficiency can be reached by solar pool heaters. They completely lack of transparent glazing which results in minimal optical loss. Metal or plastic pipelines of matt black colour forming the collector surface are exposed to direct sunlight. The water of a swimming pool can circulate in this pipeline directly. As no high temperatures are necessary, the thermal loss remains still low in lack of insulation. With rising temperature difference between collector and ambience the collector's efficiency will drop significantly, as Figure 4.2.1 shows. [1]

Figure 4.2.3: Solar pool heater [2]

Flat plate collectors are very widespread throughout Europe. They offer a solution for many applications in building service engineering. Their structures are insulated and transparent glazing is built in to minimise the absorber's front face heat losses. These provide a higher optical loss compared to solar pool heaters, but the decrease in its efficiency with rising temperature difference between collector and ambience is less intense. Flat plate collectors can produce high enough temperatures to supply heat for domestic hot water warming and also for building heating systems. Yet the lower temperature is required, the higher the collector's efficiency will remain, as Figure 4.2.1 shows. Designing low temperature floor heating systems instead of a system with radiators will enable the collectors to reach higher efficiency. [1]

Figure 4.2.4: Flat plate collector construction [3]

Yet there are many cases when especially high temperatures are to be provided by a solar heating system. Besides residential applications, hot water is necessary for numerous industrial purposes. For example, some German breweries produce their beer using solar energy for the brewing process. In order to ensure higher temperature produced by solar collector, cutting edge insulation is required to keep the collector's operational temperature high. In vacuum tube collectors the absorbers are insulated with evacuated space around. This makes them the most efficient of all when there is a big difference between the collector's operational temperature and the ambient temperature. The two most common collector types using evacuated tubes are heat pipe and Sydney pipe collectors. [1]

Figure 4.2.5: Vacuum tube collector with heat pipes [4]

Figure 4.2.5 shows the build-up of a vacuum tube collector based on the heat pipe principle. It uses the phase change of an evaporating and condensing process medium in order to transfer heat at very low temperature differences. At one end of the heat pipe the heat of the absorber plate evaporates the process medium which gains the heat of vaporization. The vapour rises to the colder end of the heat pipe where it condenses, transferring its heat of condensation to the heating system. The condensate flows back to the other end, and the process can repeat itself. [1]

In direct flow vacuum tube solar collectors, the heat transfer medium circulates directly in the coaxial absorber pipes inside evacuated tubes.

Figure 4.2.6: Vacuum-tube collectors (Sydney tube) with U pipes and CPC mirrors [5]

The Sydney tube, which was developed based on the idea of a thermos bottle, is a double-walled tube evacuated between the two walls. The inner glass wall of the tube is coated with the absorber layer, which can be heated up to 350 °C. As seen in Figure 4.2.7, a so-called Compound Parabolic Concentrator (CPC) reflector directs the radiation onto the absorber surface, making use of the solar radiation falling in between two tubes.

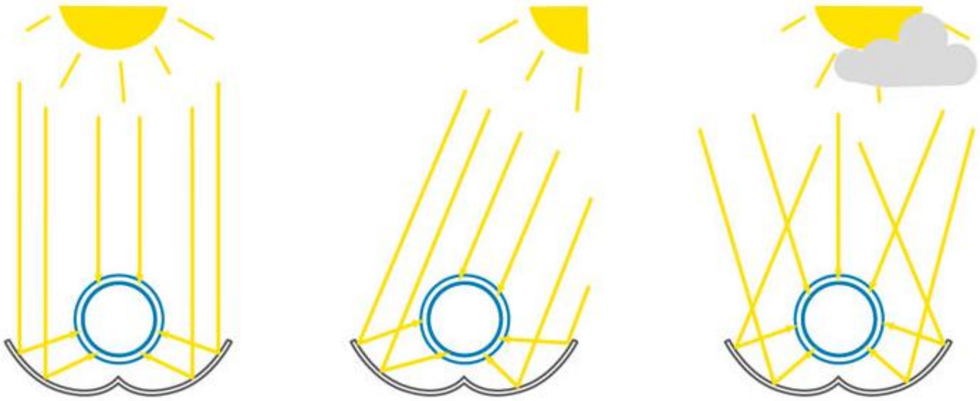


Figure 4.2.7: CPC mirror operational principle [5]

Knowing that a solar thermal system always produces heat when the sun shines, regardless of the actual needs, it is crucial to know our system's behaviour during the periods with solar radiation but without heat demand. In this case the temperature in the collector will rise up to the highest value, when the gain in energy and the heat loss find balance. This operating condition is called stagnation. On a collector's efficiency curve (see Figure 4.2.1) this is the intersection point with the horizontal axis. As all the heat gain leaves the collector as heat loss, the efficiency is 0 % and the temperature difference on the horizontal axis defines the maximum a collector can reach over ambient temperature. Endurance of longer stagnation periods and a trouble-free setback to normal operation are requirements of a well-designed system. For this reason, stagnation periods must be taken into consideration during system design. Simulation programs can help us find out the approximate length of stagnation periods in certain conditions. The temperature a collector reaches in stagnation is usually above the boiling temperature of the heat transfer liquid, so safety devices i.e. expansion vessels and overpressure valves must be dimensioned for these conditions.

Figure 4.2.8: Degradation of water-glycol mixture after a longer exposition to high temperature (>170 °C) [4]

Not only extremely high, but also extremely low temperatures can lead to the malfunction of a system. In winter time the lack of sunshine and low ambient temperature can pose the threat of freezing inside the solar primary circuit. That is why a frost protection agent, usually Propylene-glycol is added to the liquid. This non-toxic, biodegradable organic material of low flammability builds approximately a 40 % part of the heat transfer medium's volume. Due to efficient insulation applied on collectors, solar thermal systems can reach very high temperatures in stagnation periods. The molecules of glycol crack over temperatures of 170 °C, resulting in solid sediments, which can seriously damage the system. This is why a yearly inspection of the heat transfer medium is recommended for installations with longer stagnation periods calculated. Another way to prevent stagnation-related damages is doing without frost protection agent. This can be realised only in systems with vacuum tube collectors which ensure adequate heat insulation. In this case only external joints and pipeline sections are in danger of frost. To avoid frost in these sections, temperature is monitored at critical points. When it reaches a defined minimum value, which is still over 0 °C, warm water flows back from the heating system into the collectors to prevent damage. Uninterruptible power supply guarantees this function even in the case of an eventual electricity cut. Water heat transfer medium without glycol ensures no damage of heat transfer medium in longer stagnation periods which can be favourable for systems predominantly used for building heating.

In general, we can see that the differences in collector construction are various ways of absorber design, as well as insulation techniques against ambience. The physical process remains the same in all cases: solar radiation warms up the absorber which transfers its heat to the heat consumers via the heat transfer medium.

4.2.4 SOLAR AIR HEATERS

The previously outlined overview of solar thermal equipment would not be complete without solar air heaters. These devices are wide-spread in North America and are getting more and more popular on the European continent as well. Having seen the advantages of water as heat transfer medium, it might sound rather unusual to use air for the same purpose.

Although air's lower specific heat capacity can cause some initial doubts, numerous advantages show the justification of solar air heaters.

Considering the aforementioned methods to avoid damage in solar collectors with liquid heat transfer medium caused by too high or too low temperature, we can say that these problems do not even exist with solar air heaters. Air does not freeze in winter, neither does it cause any malfunction during stagnation. The following paragraphs show that the simple construction of solar air heaters makes them a reliable source of renewable energy, suitable not only for ventilation systems, but also for special applications.

The construction of solar air heaters is manufacturer-specific. Basically, two categories can be defined: modular collectors and unglazed collectors with perforated absorber.

MODULAR SOLAR AIR HEATERS

Figure 4.2.9 shows the build-up of a modular solar air heater equipped with a solar-powered fan. They are available as ready units, which can be connected to each other to ensure the power required.

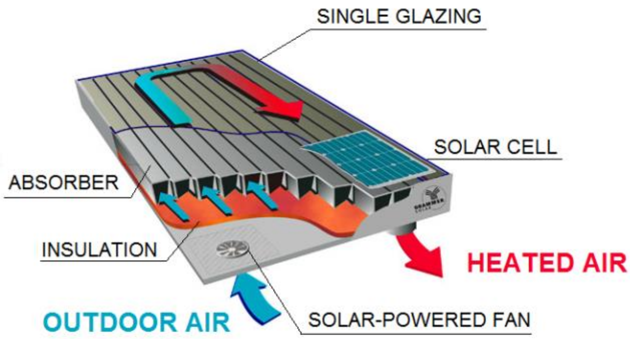


Figure 4.2.9: Modular, glazed solar air heater [6]

The construction of the absorber might vary by manufacturer. In order to provide optimal heat transfer, its surface can be plain, equipped with fins, or even porous. The air can flow on one or both sides of the absorber, or even in absorber canals, as seen in Figure 4.2.9. Considering that the fan's power demand is also included in the efficiency of the solar air heating system, it is important to keep the collector's pressure drop low.

Many modular solar air heaters (like the one in Figure 4.2.9) are equipped with a solar-powered fan, providing an independent operation from public power services. Owners of summer houses can make a good use of this function, as the building structure can be kept dry, tempered over the winter, even when electricity has been switched off. Figure 4.2.10 shows an installation on a wooden cottage near Lake Balaton, Hungary.

Figure 4.2.10: Modular solar air heater on a cottage at Lake Balaton, Hungary

Based on the system's assembly, modular solar air heaters can warm up both fresh outdoor air and indoor air. Heating outside air includes the problem of rising heat demand of the space with rising volume flow. When circulating indoor air through the collector instead, this problem can be eliminated, as in this case the space's heat demand remains independent from the air's volume flow.

UNGLAZED, TRANSPIRED SOLAR AIR HEATERS

Unglazed, transpired solar air heaters are of simpler construction, compared to modular solar air heaters. As Figure 4.2.11 shows, a dark, perforated metal shield is fixed onto a building's façade in a given distance. This metal shield is the absorber.

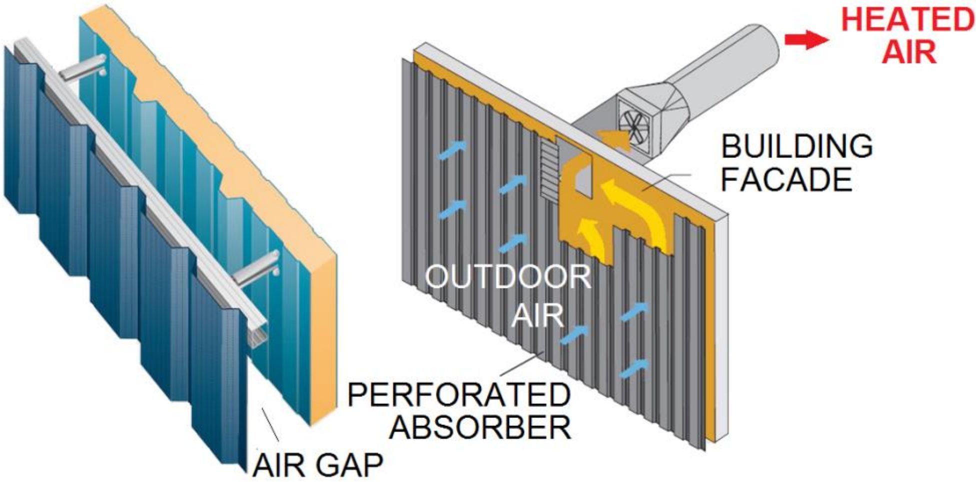


Figure 4.2.11: Construction and operational principle of a transpired solar collector [7][8]

Fresh outdoor air transpires the absorber, rises in the gap and finally a fan forwards it to the building's ventilation system. As seen before, a solar collector's efficiency is limited by optical and thermal losses. Unglazed solar air heaters have the advantage of having minimal optical losses due to the lack of transparent cover, just as previously described for solar pool heaters. They also reach high efficiency at lower operational temperatures, as the temperature difference is little, resulting in low thermal losses, too.

Based on the construction of unglazed, transpired solar air heaters, they can only warm up outdoor air. A thin layer of warm air develops at the outside of the absorber, which is being sucked in through the perforations. While rising up in the gap between absorber and building façade, the air gets heated further. This means, that both sides of the absorber takes an active part in the heat transfer process. Furthermore, the convectional losses of the building envelope can be regained on the surfaces where the air heaters are installed.

C. PVT HYBRID COLLECTORS

The PV-modules nowadays wide-spread both in private households and in industry transform only 15 % of the solar radiation reaching their surface into electricity. The rest warms up the module and diminishes its electric performance. As seen in Figure 4.2.12, a 10 Kelvin drop in the PV module's temperature increases its performance by 3 % .

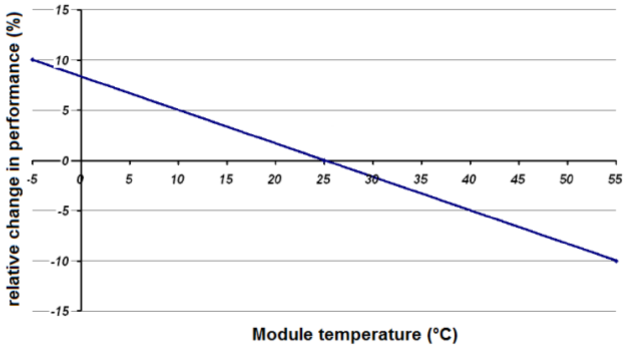


Figure 4.2.12: Temperature dependency of PV power output [6]

The valorisation of the waste heat increases the efficiency and the operational reliability of the PV module and offers an alternative support for the heating system. This can be realised with installing PVT hybrid collectors.

Figure 4.2.13: PVT collectors installed on the roof of a swimming pool [6]

Air streams in the canals behind the PV modules and receives the waste heat from them. PV modules can be combined with unglazed, transpired absorbers, too.

D. SUITABILITY OF SOLAR AIR HEATERS TO DIFFERENT BUILDING TYPES

The efficiency of a solar air heating system depends very much on the type and use of the building in which it is installed. Influencing factors are internal heat loads, passive solar gain, as well as heat and fresh air demand. Low internal heat load and solar gain are advantageous with a possible high fresh air demand, so that the benefits of the solar air heating system can be realized within a short time.

In residential buildings, especially in low-energy ones, mechanical ventilation supplies the necessary amount of fresh air. The ventilation system can be supplemented with solar air heaters, in order to reduce the heating costs, first of all, if no heat recovery unit was previously installed.

In office buildings both the internal heat load, as well as the solar gain can be high, due to the heat emission of the employees and the high glazing rate of the facades. This is why office buildings do not ensure optimal conditions for solar air heaters. Systems heating fresh outside air can directly reach high efficiency due to the high fresh air demand of employees.

Industrial buildings ensure optimal conditions for the operation of solar air heaters. The high spaces usually have a low glazing rate, resulting in low heat gains. Production processes often demand a high rate of fresh air in ventilation, providing good use of a solar air heater system.

E. SYSTEM SOLUTIONS FOR SOLAR AIR HEATERS IN BUILDING SERVICES

Warm air produced with solar air heaters can not only be directly led into an occupied space, but it can be combined with various system elements, making use of the heat for different applications. In fact, in many cases it is strictly necessary to insert a thermal storage unit into the system, in order to balance the time shift between solar radiation and heat demand. In this paragraph an overview is given about possible system solutions.

Radiant heating dates back to the time of the Roman Empire, when a so-called hypocaust was used in thermal baths and some public homes. A hollowed space was built underneath the rooms, in which a woodstove's exhaust fumes streamed. The fumes rose up inside a double wall and left the building structure through a chimney. It lasted long to reach the adequate surface temperature after the start of combustion, and the ancient heating system was not easy to control. Yet this technology did not disappear without trace, modern-age hypocaust structures can be combined with solar air heating systems. In cooperation with an architect, a special building structure must be designed, in which the solar heated air streams in a hollowed structure under the floor or even in the walls.

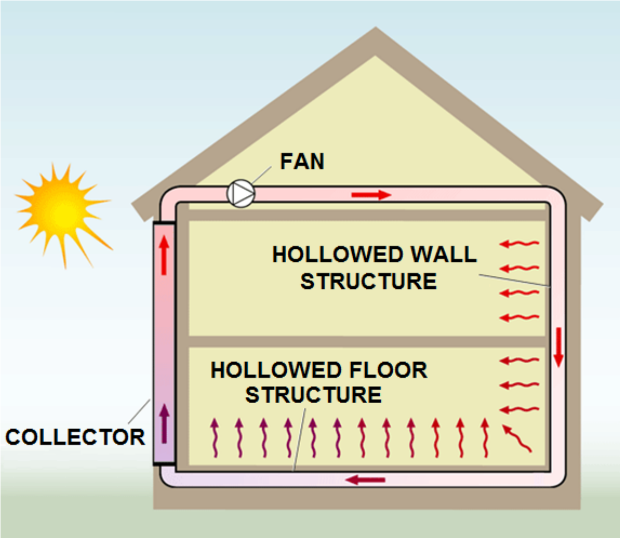


Figure 4.2.14: Hypocaust heating scheme with solar air heating [9]

The solar-heated air can either circulate closed loop, as shown in Figure 4.2.14, but it can also be led into the room as supply air after its way in the hollowed structure. In the latter case the cleanliness of the flow passage is of high importance. The structure must be designed in the way that the air flow can develop across the whole profile without any blind areas. As the surfaces get slightly warmed up, hypocaust heating provides a high comfort inside. Moreover, the building structure behaves as a heat storage mass, which is very advantageous for solar thermal systems.

In case no hypocaust heating can be built, thermal energy storage can be realised by using a pebble bed thermal energy storage unit. When the air is directed to stream through the pebble bed, it can be charged with surplus heat, or discharged when necessary.

It is important to remark that the specific heat capacity of pebble is lower than that of water. That is why 2.5-3 times of the volume is needed to store the same amount of energy with pebble than with water.

Surplus heat produced with solar air heaters can be also used for domestic hot water heating, when an air-to-water heat exchanger is installed into the air duct. Based on the actual demand on hot air and water an electronic system decides about the air rate between ventilation and water heating.

Unglazed, transpired solar air heaters can be used for a free cooling system when installed onto low slope roofs. Based on the principle of nocturnal radiation, the absorber plates can cool by 10 °C below ambient temperature on a clear night. From then on the whole process is the same as when heating in winter, just the direction of the heat transfer is the opposite. Warm air transpires the colder collectors and transfers its heat to the surface. Finally, the cool air is led into the building, lowering or even displacing conventional air conditioning from sunset to sunrise. Moreover, the collector surface provides shading for the roof, reducing daytime heat gains normally received through the roof.

Hot air is used in several agricultural processes, such as crop drying, but it is required in every case when buildings are equipped with mechanical ventilation. Building ventilation requires heat in a wider period of time than space heating, because due to the low heat capacity of air, nonstationary occurrences such as thermal storage of the building structure cannot be taken in account. Whenever the outdoor temperature is lower than the supply air temperature, heating is required using possibly renewable energy sources. Transitional periods, like spring and autumn offer a great deal of solar energy, which can shorten the period when heating systems rely on conventional heat producers. The heat demand of ventilation can be covered with solar energy using solar air heaters, which heat up airflow directly, without the use of water as a heat transfer medium.

Solar air heating is an effective way of providing a building with renewable energy, at low capital costs. Transpired solar collectors, which are common in North America and are getting more and more widespread in Europe too, represent a remarkable segment of the solar air heating market. They can be used in building ventilation, for crop drying and in stock-raising too. Large halls, such as many industrial and agricultural buildings have often low glazing ratio which does not enable them to utilise passive solar gains in their energy households. Their vast facades however can be used for the installation of the transpired solar collector, which consists of a dark, trapezoidal perforated plate, fixed onto the external side of the building wall in a certain distance, creating an air gap. This gap is sealed from the sides, so air can enter it only through the perforations of the absorber plate. Air handling units withdraw fresh air from the air gap, or through a bypass when no air heating is needed. The transpiration of the absorber plate enables the plate to warm up by up to 40 K, reducing the primary energy demand of the drying process.

Depending on the nominal transpiration of the transpired solar collector (TSC) over one m^2 of area, different operational strategies can be determined. High volume flow systems provide lower temperature rise, but they enable the collector to reach high efficiency due to low heat losses from the absorber. Low volume flow systems reach higher temperature rise but the collector efficiency stays lower.

One could think that in the lack of transparent glazing, the TSC has remarkable thermal losses due to convection to the exterior. According to Kutscher et al. [10], assuming homogenous suction on the surface of the absorber, one can state that the suction stabilizes the boundary layers on the external side of the absorber, reducing the effect of convective losses solely to the collector edges. This means that the heat of the external boundary layer is being utilised by the system before losses would occur. Therefore, for large collector surfaces the convective losses are negligible and wind losses remain small, too. Kutscher et al. [10] describe that to ensure little impact of wind:

- the suction face velocity should be preferably 0.04-0.05 m/s, but at least 0.02 m/s,
- at least 25 Pa pressure drop is to be obtained across the perforated plate, and
- the wall should be designed to have uniform flow through itself.

The flow rate through the surface of the TSC has to be kept between 18-180 $m^3/(h \cdot m^2)$ to ensure stable operation. Three air heating strategies can be defined by choosing the appropriate airflow:

- high temperature rise in the range of 18-54 $m^3/(h \cdot m^2)$
- standard operation in the range of 54-108 $m^3/(h \cdot m^2)$
- high air volume in the range of 108-180 $m^3/(h \cdot m^2)$

High-flow TSC systems perform much better than low flow ones, as the efficiency can reach its highest values when high flow is cooling the absorber, utilising the most of its heat, reducing all kinds of thermal losses. In Figure 4.2.15 one can see that for a given wind speed the collector efficiency only depends on the air flow rate, which underlines the negligible impact of convective losses depending on ambient temperature.

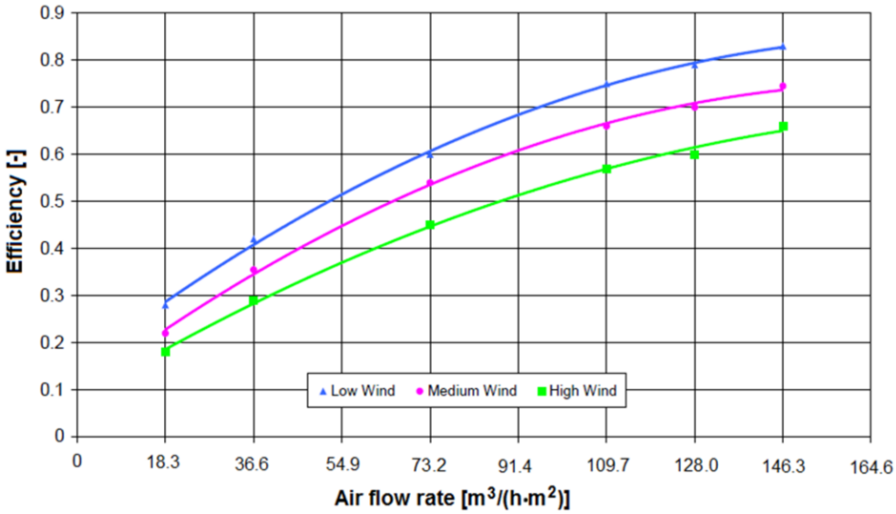


Figure 4.2.15: TSC efficiency as a function of the transpiration rate [11]

With rising transpiration rate the heat exchange effectiveness drops, as the air cannot reach as high temperatures as if lower heat flow would transpire the plate. Temperature rise as a function of solar radiation with transpiration rate and wind speed as parameters is illustrated in Figure 4.2.16.

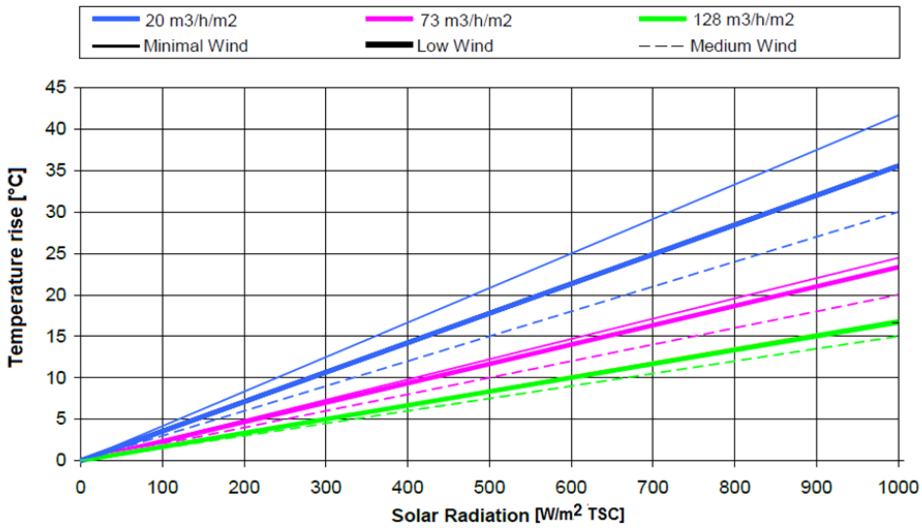


Figure 4.2.16: TSC temperature rise as a function of solar radiation [11]

Transpired solar collectors are available in glazed and unglazed constructions. Glazing reduces the convective losses that would occur between the absorber plate and the ambience, but creates additional optical losses. The choice of the glazing depends on the operational and ambient temperatures. In case high temperature rise is necessary, or the installation is to be set in cold environment, a two-stage transpired solar collector can be applied. This consists of a first stage of a conventional TSC, after which at a higher section of the collector a second perforated absorber is transpired behind a polycarbonate glazing. This enables the airflow to reach higher temperatures or resist to colder environment.

The following case study shows transpired solar collector performance for a reference building of the size of 90×60×11.8 metre equipped with an unglazed TSC. It has 10 m height and a variable length to be able to show effects of collector area as a parameter. Ventilation airflow rate was fixed to change the internal air volume once in an hour, resulting in 63720 m^3/h. This airflow is entirely drawn through the collector in the months with heating demand, so that the TSC can contribute in the air heating process. The airflow is considered to be fix, and the TSC absorber size has been changed as a parameter, changing the TSC transpiration rate at the same time. When there is no heating demand, the TSC is bypassed and therefore these months were not taken into consideration during the calculation. Heating period is different for every location, as for the demonstration of performance cities with very different climate have been chosen. For the months without heating need, the TSC is assumed to be bypassed. The evaluation has been carried out using RETScreen software.

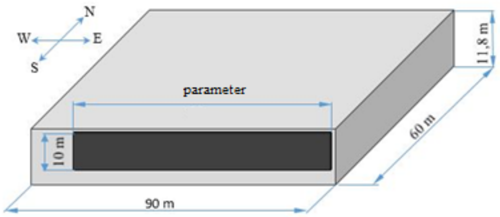


Figure 4.2.17: Reference industrial building

The larger the TSC area is chosen, more heat is delivered annually, but the growth becomes less. This is because the lower collector efficiency of too large absorber areas for a certain airflow. Below 18 $m^3/(h \cdot m^2)$ the airflow drawn through the collector cannot transpire the entire plate, leaving some areas dead zones. The heat transfer between the flow streaming with too low velocity stays inadequate to take the heat of the plate and the operation of the collector turns insufficient. Therefore, TSC systems must not be overdimensioned, meaning the rate of transpiration must be between 18-180 $m^3/(h \cdot m^2)$. As for the locations, one can observe that the best results are obtained in the city of Erzurum, in the east of Turkey, where long and cold winters come with high numbers of sunny hours and high intensity of solar radiation, enabling the TSC to utilise the produced heat. Less sunny locations can benefit less from the TSC, obviously. In Figure 4.2.18 one can observe that a location with high solar radiation intensity, such as Málaga in the south of Spain can benefit little from the transpired solar collector. This is because this case study considered the ventilation air heating of the reference building. In Málaga the heating season is so short that only a small part of the available solar energy can be utilised. Different would be the situation, if instead of building heating, a solar crop drying facility would be equipped with a TSC system. That would make high savings in the south of Spain, too.

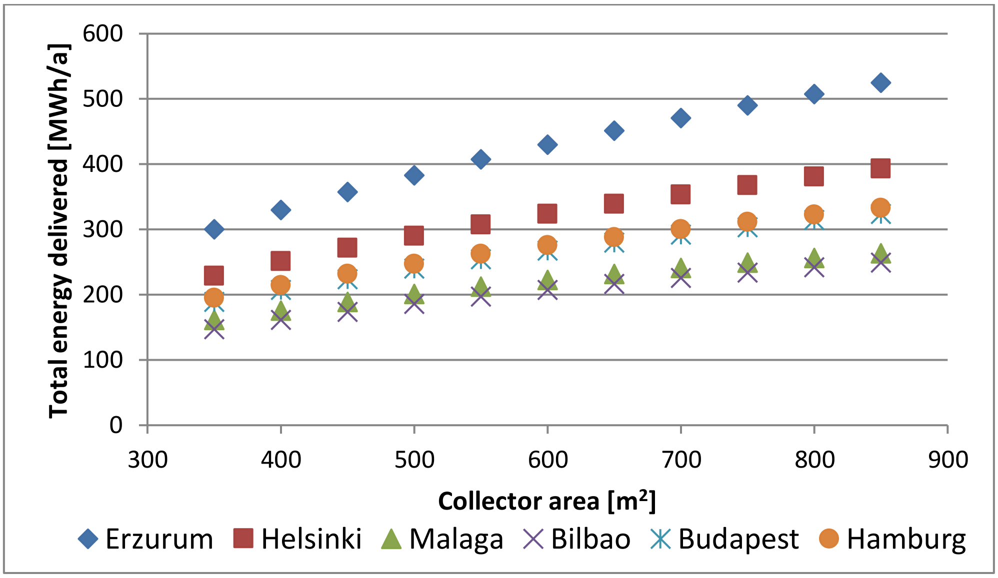


Figure 4.2.18: Total energy delivered as a function of the collector area

In Figure 4.2.19 the area specific annual energy is shown for the same cities. It can be seen that if the transpiration rate remains constant and the area of the TSC rises, one m^2 of the collector will produce less, because the heat transfer coefficient between the absorber plate and the transpiring airflow will drop, the collector plate remains warmer, resulting in higher losses.

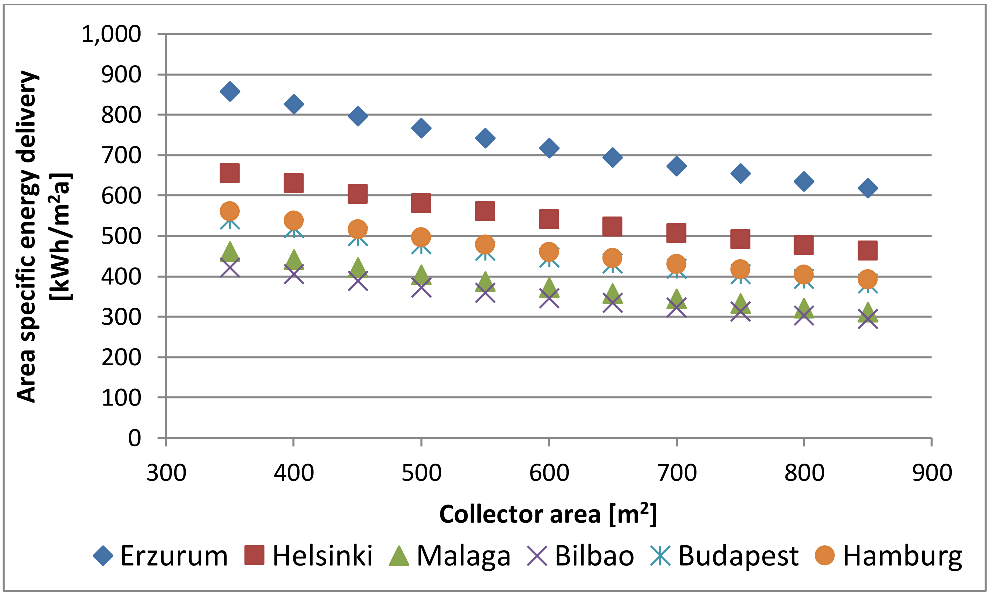


Figure 4.2.19: Annual specific energy delivery as a function of the collector area

F. TRANSPIRED SOLAR COLLECTORS IN AGRICULTURE

As previously mentioned, besides the ventilation air preheating of various agricultural buildings, the transpired solar collector can be effectively used in crop drying processes. In this sector, yearly 300-900 PJ energy could be saved with offsetting conventional fuel-fired mechanical driers with solar thermal technologies. [12] Solar air heating is applicable first of all in driers which operate at a lower temperature below 50 °C. According to the report of Task 29 "Solar Crop Drying" of the International Energy Agency's Solar Heating and Cooling Programme, solar thermal applications in crop drying would be feasible in many large scale applications, but often obstacles are not merely technical. Awareness has to be risen about the available cost effective technologies, quality technical information is to be provided about the systems, and local personnel is to be trained to operate, monitor and optimise a solar drying system. For reliable feasibility studies before the design and setup of a solar air heater, the operation of drying system itself has to be optimised, which process should be based on measurements and evaluations of at least one whole drying season. Problems and uncertainties can originate from the available weather and cost data. Therefore, it is also recommended to collect weather data at the location of the project for a year before setting up a solar air heater. [12] Feasibility tools, such as RETScreen and SWift are available for the evaluation of a transpired solar collector system, calculating system performance in monthly steps based on the typical meteorological year of the chosen location. In the course of Task 29 of IEA SHC, good practices have been realised at several agricultural companies, some of which are presented below to reflect on the applicability of transpired solar collectors in drying technologies.

In Ordbend, California a TSC system of 864 m^2 collector area has been installed for walnut drying purposes. For drying walnuts large volume-flow of air is required heated to lower temperature in order to reduce the moisture content slowly to less than 8%. Walnuts are dried in autumn, when ambient temperatures are around 25 °C at the location of the plant and around 43 °C is needed for the drying process. The transpired solar collector provides 11044 m^3/h solar heated air for the drier. If the actual performance is too high, the dryer can be bypassed to release excess heat. Similarly, it can be provided by conventional heating if the TSC does not produce enough heat due to low solar radiation. With the use of the transpired solar collector, the plant saves 1510 GJ energy and 92 t CO_2 each drying season. [13]

Figure 4.2.20: Roof-mounted transpired solar collectors at a large walnut production & processing facility in Ordbend, California [13]

Walnuts are dried at a low temperature too, with a maximum of 43 °C, reducing their moisture content from 35 % to 10 %. The drying period is in September and October each year.

Figure 4.2.21: Roof mounted transpired solar collector system and the multi-bin walnut drier [14]

A 300 m^2 transpired solar collector has been installed on the roof of the drying facility (Figure 4.2.21), heating up 42475 m^3/h airflow. The saving is 325 GJ of energy every drying season. Figure 4.2.22 shows the configuration of the solar drier.

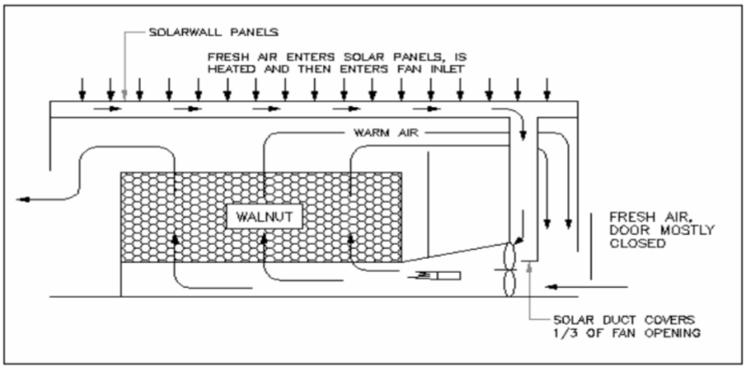


Figure 4.2.22: Operational principle of the solar walnut drier [14]

A coir pith drying facility has been equipped with a 421 m^2 TSC in India. With 60 $m^3/(h \cdot m^2)$ transpiration rate 20 K temperature rise is reached which preheats the fluidised bed driers used in the process. After the solar preheating, conventional burners further elevate the drying air temperature to 105 °C. By the use to the TSC, 14 % of the fuel can be displaces and the payback of the solar thermal system is no more than 2 years. Coir pith is a by-product manufactured from coconut shells, which is used as a soil additive. It holds twelve times its weight in water and holds moisture eight times longer than conventional soil. Furthermore, it can absorb oil, too. During its production procedure, first the raw product has to be soaked in water to remove sodium. The first step of the drying procedure is in a mechanical press, where moisture content can be reduced to 70 %. The fluidised bed drier further dries the coir pith to 20 % moisture content. [12]

One of Panama's largest coffee producers applies 900 m^2 area of transpired solar collectors for coffee drying. Coffee is dried in two stages, first in mechanical driers, then it is further heated in storage silos. The transpired solar collectors provide 33980 m^3/h solar heated airflow for the diurnal drying process, while at night the heat is covered by conventional wood firing. [15]

For a cooperative drying facility owned collectively by over 500 local coffee producers in Guanacaste, Costa Rica a 860 m^2 transpired solar collector provides hot airflow for the drying process. Coffee is dried in a pre-drying silo where its moisture content is reduced from 60 % to 35 %. After this the produce is dried in rotating drums to reach a final humidity of 12 %. The transpired solar collector provides hot air for both stages. [16]

Transpired solar collectors can be efficiently used in broiler and other animal barns too. Poultry require 32 °C in the brooding period and 22 °C when chicks are bigger, meaning there is heating demand in 10 out of the 12 months of the year. TSC can reduce heating related primary energy consumption by up to 30 %. Several further advantages of transpired solar collectors of animal barns have been reported: the increased indoor air quality resulted in a decreased mortality rate among poultry, and indoor cold drafts have been eliminated due to the second shield of the TSC mounted on the barn, acting as an additional baffle. [17]

In applications where solar energy is meant to provide both heat and electricity, transpired solar collectors can be integrated in various ways. PV/T collectors enable to utilise excess heat of the PV panels, increasing their efficiency and integrating the heat into ventilation or drying systems. [18] Transpired solar collector updraft towers, which consist of photovoltaic panels and transpired solar collectors, also generate both heat and electricity, making use of solar energy in 60-80 % daytime. [19][20]

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