TOWARDS A UNIFIED STANDARD FOR SOLAR AIR HEATING COLLECTORS

Gerhard Stryi-Hipp, Korbinian Kramer, Jens Richter, Christoph Thoma,

Stefan Fortuin, Stefan Mehnert and Christian Welz

Fraunhofer Institute for Solar Energy Systems ISE, Freiburg (Germany)

1. Introduction

Although solar air heating collectors have some significant advantages in comparison to liquid heating collectors, currently they have only a market share of less than 1% of the solar collector world market. The main advantages of using air as heat transfer medium are the absence of stagnation and freezing problems and a reduced tightness requirement. This makes it for instance easier to integrate solar air heating collectors into façades. Different air heating collector types available range from non-covered open-loop collectors for space heating support at low temperatures, to high performance evacuated tube collectors with high efficiencies at increased temperatures. An important barrier for a broader use of solar air heating collectors is the lack of common standards for testing to ascertain quality and performance. The Fraunhofer Institute for Solar Energy Systems ISE is currently working on the development of testing standards for covered and non-covered air collectors, the development of simulation tools to calculate solar gains of solar air heating systems as well as the improvement of solar air heating collector technology. This work is done in co-operation with industry within the project 'Luko-E', which is co-funded by the German ministry for the environment. In the following the status of the work is described.

2. Technology Overview

Different air heating collector concepts exist, which are used in different niche markets. Currently their applications are limited to: direct use of the heated air in space heating, solar assisted air drying applications, and for low temperature heat use which involves a heat exchanger to a secondary water-based heat transfer medium and storage loop (Stryi-Hipp, 2010). Non-covered air heating collectors are mainly used in North America in large façades of commercial and public buildings to support space heating. Covered air heating collectors are mainly used in Europe for space heating support in commercial and other large buildings as well as for some process heating purposes, e.g. the drying of malt at the Brauerei Lammsbräu in Germany. In addition, autonomous solar air heating collector units, with typical 2 m^2 collector area and an integrated PV solar driven ventilator, are used to heat air in small buildings like weekend houses.

2.1. Air Heating Collector Construction and Flow Patterns

Air collector development focuses on improvements in the heat transfer construction due to the low thermal capacity of air and the much lower heat transfer coefficient between absorber and air, than when using liquid heat transfer media. An improved heat transfer coefficient can be realized by increasing the surface area that is in direct contact with the air, or 'intensifying' the contact itself e.g. by letting the air flow through holes in a sheet absorber, so called perforated absorber, or by using voluminous absorber.

Unlike with water heating collectors it is not necessary to use hermetically sealed channel structures for air heating collectors. Air as heat transfer medium thus allows for higher flexibility in the construction, such as the position of the absorber. Many different absorber geometries and collector flow designs can be realized. Figure 1 shows different absorber-flow designs of air heating collectors. A1-A3 and B1-B3 are covered; A4 and B4 are non-covered constructions. Row 'A' shows the perforated transparent cover or perforated absorbers through which the air is passed to improve the heat transfer coefficient. A1 and A4 configurations take in fresh outside air through these holes and are sometimes called 'transpired'. The row 'B' shows covered and non-covered air collectors where the air flows between the cover and the absorber, behind the absorber, or on both sides of the absorber. A possible channel or fin structure attached to the absorber, which increases the absorber-air contact area, is not shown.

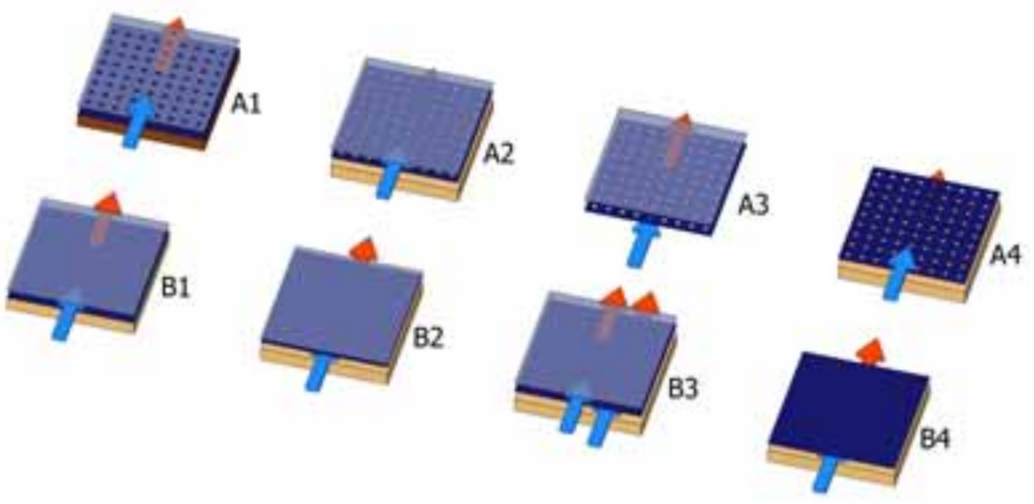


Fig.1: Different types of covered and non-covered air heating cover-absorber constructions

A solar air heating collector system is called ‘open’ loop, if it sucks in fresh air from the outside, heats up the air, and removes it for direct use. In contrast, ‘closed’ loop air collector systems circulate the air through the system and the collector and transfer the heat via a heat exchanger to the point of usage. ‘Closed’ loop systems are able to provide higher outlet temperatures, because the inlet temperature can be higher than the ambient air. If an air collector sucks in the air via an intake manifold it can operate in an ‘open’ or ‘closed’ loop. If the ambient air is sucked in through holes in collector it can be only operated in an open loop system and is therefore called ‘open loop collector’.

Open loop collectors are typically used in façades to preheat the ambient air, which is sucked in through the collector and used in the building. Since the collector operates only at low temperature differences to the ambient and even a small temperature increase of the ambient air is useable, the efficiency of open loop collectors can be high. However, the amount of solar thermal energy, which can be moved into the building, is limited due to the low heat capacity of the air and the low temperature increase in the collector. Therefore the solar fraction of such an open loop system is usually rather small. Since the system can be constructed simple it can be realized very cost effectively.

Closed loop collectors are usually covered collectors and operate at a higher temperature, through to temperatures reaching the level of process heat, where air collectors can use their advantage of having less stagnation problems in comparison to water collectors. For high efficiency and high temperature applications an evacuated tube air heating collector for temperatures up to 120°C was developed at Fraunhofer ISE (Schüle and Siems, 2009).

However, in addition to a good heat transfer it is important to optimize the collector design in order to achieve a low pressure drop to limit the use of electricity for running the ventilator for the forced air circulation.

2.2 Tools for simulation and calculation of air collectors

To calculate the economic performance and convince the potential customer of a solar air heating system it is necessary to simulate the solar yield of the solar air heating system at a specific site and under the specific conditions. For solar liquid heating collectors several well-known and evaluated simulation programs are available. For the air heating systems only two commercial tools are available, which in addition only cover part of the solar air collectors on the market.

The free program ‘RETscreen’ is made available by the Ministry of Natural Resources Canada (NRCan) (RETscreen, 2011). The program, using spreadsheet calculations, calculates system yields for non-covered transpired air collectors. A selection can be made between ventilation air heating and process air heating. The results include values for life-cycle costs, greenhouse gas emission reductions and evaluated energy production.

The second program ‘TSol’ (Pro Version 5) is available from Dr. Valentin EnergieSoftware GmbH and can calculate two system configurations (Valentin, 2011). One is for domestic air heating, the other for domestic air heating in combination with solar domestic hot water heating. TSol provides a choice between fresh air (‘open’) and recirculating (‘closed’ loop) air. The results include the system efficiency, greenhouse gas emission reductions and savings of natural gas.

For predicting the gains of a solar air heating system in detail and optimizing the technology and the design of solar air collector systems, a more detailed simulation tool verified with reliable test data of the solar air collectors is necessary. Fraunhofer ISE is developing a solar air collector Type for the simulation tool TRNSYS in order to model different solar air heating collectors and systems. A yield calculation is also important because it is required for getting subsidies for solar thermal collectors in Germany.

2.3 Benefits and Drawbacks of Air Heating Collectors

To increase the market performance of solar air heating collectors and systems, constructions and applications must be identified where their benefits are relevant and the influence of their drawbacks is minimized or avoided. A general overview is given in Tab. 1.

Tab. 1: Benefits and drawbacks of air heating collectors

Benefits	Drawbacks
• No freezing, nor stagnation problems • Possibly simpler and cheaper systems • Very efficient preheating of fresh air for buildings possible • No problems from leaks, no damage, no environmental or health hazard risk from spilled heat transfer medium (use in façades is possible)	• Low heat capacity of air, thus high air volume rates and larger channels are necessary • Poor heat transfer absorber – air • Closed loop systems: - Additional losses in the air-water heat exchanger - Second solar circuit required (air circuit and water circuit) • Open loop systems - Limited/low temperature range - Fan noise and open air ducts

Today, the solar air collector market mainly increases in niches, where they are already cost effective. This is often the case for non-covered solar air façades for example in large utility buildings such as warehouses in North America which are already using air for space heating and which often have large façades, which receive a lot of sunshine in winter time. In some applications in central Europe, covered solar air heating collectors are competitive with liquid heating collectors. In addition, new applications are under development due to a growing share of buildings with controlled air systems in Europe where new market opportunities for solar air collector systems are expected.

The following market niches for solar air heating collectors can be distinguished in Europe:

- Common single/two family houses with domestic hot water (DHW) only or combined systems for DHW and space heating support.
- Current, still niche, applications in: multi-family houses, heating of non-residential/utility buildings, process heat applications.
- Future applications in, for example, high solar fraction houses (>50% solar fraction)

2.4 Examples of the Application of Air Heating Collectors

Solar air heating collectors can be used in different ways. Figure 1 shows simple systems where solar heated air is used directly for space heating. In this case the façade mounted air collector heats up inside air (a) or outside air (b, c and d) and releases the hot air directly into the building. In this case the building itself is the only means for storing the heat. It is also possible to pass the heated air through a storage facility with high thermal mass to increase heat storage capacity and separate it from the building.

In some collectors a small PV panel is integrated which provides the electricity for the ventilator that drives the air flow through the collector. Since the PV panel produces electricity proportional to the solar irradiation and thus the heat produced, there is no additional controller necessary and an independent operation of the collector is possible.

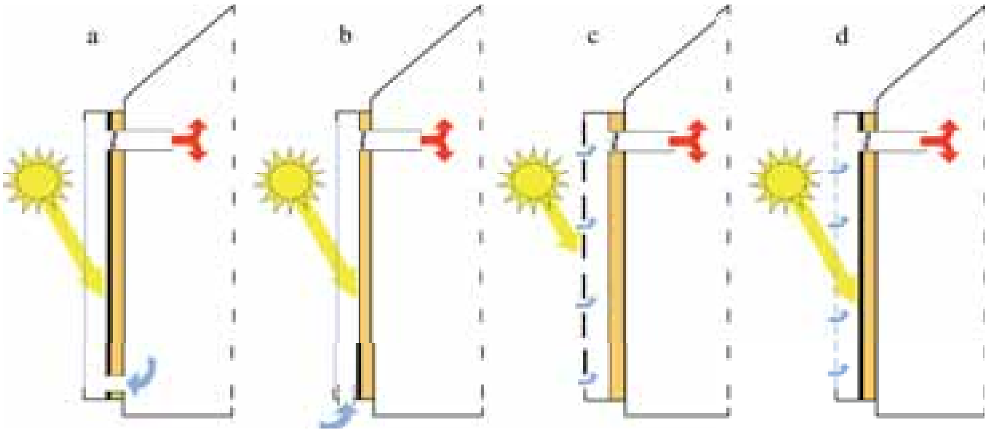


Figure 1: Examples of the use of façade mounted solar air heating collectors with direct use of heated air: recirculating inside air (a), or taking in ambient air through a single inlet (b), a perforated absorber (c) or a perforated transparent cover (d).

Figure 2 shows a solar 'combi'-system for combined domestic hot water and space heating applications. The solar air heating collector is typically installed on the roof. A three way valve at the air intake may allow for sucking in outside-air and the direct use of the solar heated air in the building. Alternatively, inside air can be sucked into the collector, heated up, and blown back into the building.

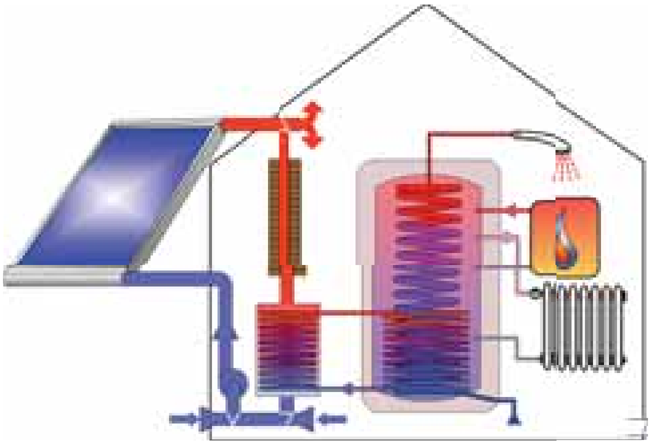


Fig. 2: Examples options for a solar 'combi'-system using an air heating solar collector.

For direct use of the heated air throughout the building, the distribution via air channels that are large in comparison to pipes of the water heating circuit is necessary. Alternatively, a so called hypocaust heat storage system can be installed, here the heated air flows through channels in walls and floors, which take up the heat and slowly release it into the building. If there is no immediate need for direct heating in the building, the heat can stored in a conventional water storage tank via an air-water heat exchanger.

3. Testing Standards

Common testing standards are a basic requirement to develop a market since only then can the quality of the components be certified, the performance measured, the solar yield be calculated accurately, and the performance of the components be compared. All these, more objective figures help with further improvements and creating a vital and constructive competition. However, the currently available testing standards do not sufficiently cover solar air heating collectors yet, at least not from the European point of view.

The oldest and most well-known air heating collector standard is the ANSI-ASHRAE 93, which was first published in 1977. This standard is periodically revised and updated by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, the last time in 2010. The ANSI-ASHRAE 93 provides a good basis for measuring the performance of solar air heating collectors. However, durability and reliability tests are not included. Since 2010, the TestLab for Solar Thermal Systems at the Fraunhofer ISE is accredited for this standard.

Currently, no European testing standard for solar air heating collectors is available. The existing solar collector testing standard EN 12975 from 2006 does not cover solar air heating collector technologies. In Germany, solar collectors need a Solar Keymark certification, based on the test according EN 12975, to be eligible for subsidies. However, since there is no test according EN-standards available yet, as an interim solution solar air heating collectors tested according EN 12975 in the relevant parts, are accepted for subsidies as long as no new framework is established. This has caused and will likely cause more problems among manufacturers competing with slightly different solar air heating technologies, some of which can be tested, certified and subsidised, and some which cannot.

To remedy this situation, and to create a uniform system of test standards, a draft extension to the EN 12975 standard for covered solar air heating collectors was developed by Fraunhofer ISE and proposed to the standardization committees in the end of 2010. The text is based on the ANSI ASHRAE 93 standard, but was further developed. Since the beginning of 2011, the draft is in the comment phase and expected to be finally approved as a part of the new EN 12975 standard in spring 2012.

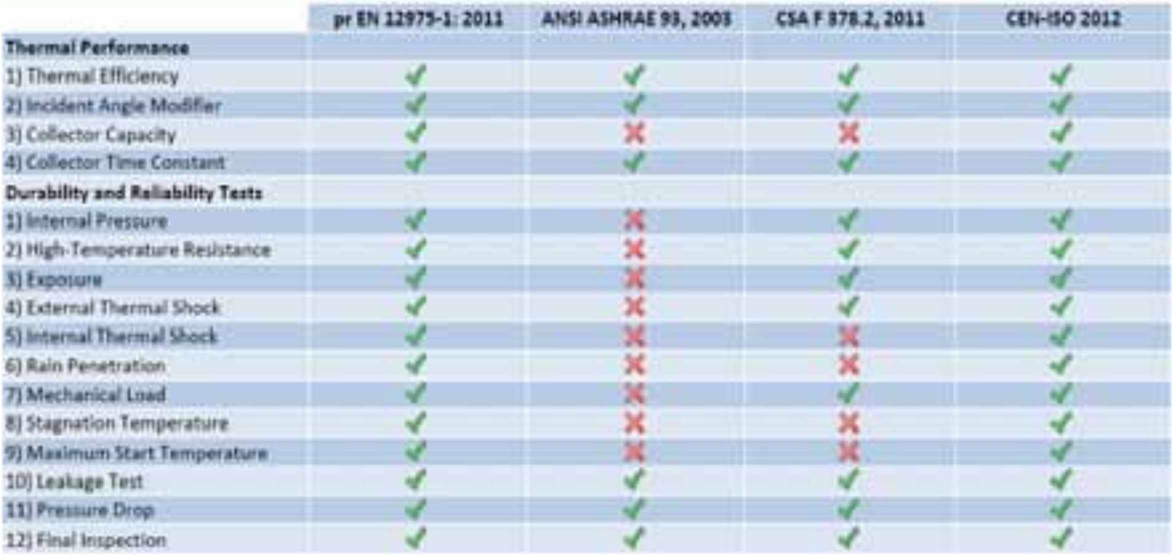
In a lot of aspects, solar air heating collectors can be tested in the same way as water heating collectors. The rainwater penetration, exposure, high-temperature resistance, external thermal shock, mechanical load and stagnation temperature tests as well as the final inspection can be applied in the same way as for water heating collectors.

However, some durability and reliability tests have to be modified for solar air heating collectors. The thermal performance test, the determination of the IAM (Incident Angle Modifier) and collector capacity, the internal thermal shock test and the internal pressure test must be adapted.

The pressure drop test is for water heating collectors optional, but for air heating collectors it should be mandatory. Unlike water heating collectors an air heating collector is usually not fully air tight. Therefore the classical tightness test is not appropriate. Since the leakage rate has a strong influence on the collector performance, it must be taken into account in the performance evaluation and thus has to be measured. In addition, the determination of the maximum start temperature is mandatory for solar air heating collectors, but not considered relevant for water heating collectors.

In parallel to the European activities, the CSA F378.2 standard for solar air heating collectors was developed and published in Canada in 2011 for the comment phase. It is also based mainly on the ANSI ASHRAE 93 standard, but with added several functional test details, similar to the European EN 12975 standard. An overview, which tests are covered by the three standards is given in Tab. 2. The CSA F378.2 standard supports the convergence of the "American" and "European" method and is intended to come into force in 2011.

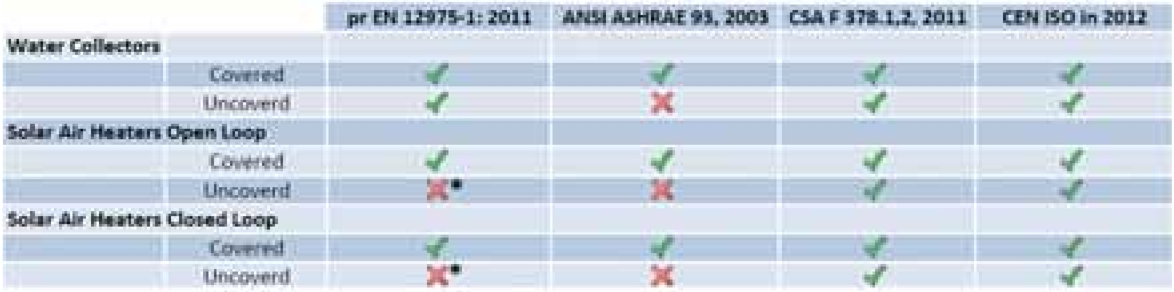
Tab. 2: Standards and tests for solar air heating collectors



	pr EN 12975-1: 2011	ANSI ASHRAE 93, 2003	CSA F 378.2, 2011	CEN-ISO 2012
Thermal Performance				
1) Thermal Efficiency	✓	✓	✓	✓
2) Incident Angle Modifier	✓	✓	✓	✓
3) Collector Capacity	✓	✗	✗	✓
4) Collector Time Constant	✓	✓	✓	✓
Durability and Reliability Tests				
1) Internal Pressure	✓	✗	✓	✓
2) High-Temperature Resistance	✓	✗	✓	✓
3) Exposure	✓	✗	✓	✓
4) External Thermal Shock	✓	✗	✓	✓
5) Internal Thermal Shock	✓	✗	✗	✓
6) Rain Penetration	✓	✗	✗	✓
7) Mechanical Load	✓	✗	✓	✓
8) Stagnation Temperature	✓	✗	✗	✓
9) Maximum Start Temperature	✓	✗	✗	✓
10) Leakage Test	✓	✓	✓	✓
11) Pressure Drop	✓	✓	✓	✓
12) Final Inspection	✓	✓	✓	✓

The extension for air heating collector draft of EN 12975 is limited to covered collectors, since the test methods for non-covered air heating collectors is not fully developed yet. However, Fraunhofer ISE is working on a subsequent draft extension, which shall be presented to the standardization committees by the end of 2011. Which collector types are catered for by which standard is presented in Tab. 3.

Tab. 3: Solar collector types, which are covered by the different standards



		pr EN 12975-1: 2011	ANSI ASHRAE 93, 2003	CSA F 378.1,2, 2011	CEN ISO in 2012
Water Collectors					
	Covered	✓	✓	✓	✓
	Uncoverd	✓	✗	✓	✓
Solar Air Heaters Open Loop					
	Covered	✓	✓	✓	✓
	Uncoverd	✗*	✗	✓	✓
Solar Air Heaters Closed Loop					
	Covered	✓	✓	✓	✓
	Uncoverd	✗*	✗	✓	✓

In Tab 2 and 3, also the CEN-ISO 2012 standard is mentioned as a goal for a worldwide, unified solar air heating standard. Some important steps to achieve this goal have already been described. The installment of a joint working group of ISO and CEN under the Vienna agreement is expected in August 2011. A unified CEN-ISO standard for solar air heating collectors is ready to be published for comments and could even be approved in 2012. Fraunhofer ISE is supporting this process actively with the development of the missing parts of the standard.

4. Conditions for the Air Heating Collector Performance Test

To measure the collector performance with high accuracy and repeatability is a must for further developing the solar system market. As mentioned before, only a well-defined performance test makes collectors performance comparable, allows the calculation of the yield of solar systems and stimulates constructive competition and innovations. In addition, it is a requisite for gaining a deeper understanding of the technology and the research work to improve the technology.

Requirements for testing do not only include methodology and a precise test equipment, but also of definitions of what must be measured under which conditions and the way in which results must be presented. This chapter describes some of the latter. The solar air heating collectors have some peculiarities which require some differences in their performance tests from the performance test of liquid heating collectors. The most important ones are presented in the following.

The results of this work were the basis for the draft of the standard extension for covered solar air heating collectors, which is currently in the comment phase of EN 12975. Since testing of non-covered air heating collectors has additional challenges, e.g. the stronger influence of the wind speed, only covered air heating collectors are considered in the following. However, Fraunhofer ISE is developing test methods and a draft standard for non-covered air heating collectors by end of 2012.

For covered solar liquid heating collectors the following performance model for the instantaneous efficiency is broadly used:

$$\eta = \eta_0 - a_1 \frac{T_m - T_a}{G} - a_2 \frac{(T_m - T_a)^2}{G} \quad \text{(eq. 1)}$$

With the maximum efficiency:

$$\eta_0 = F' \cdot (\tau\alpha)_{eff} \quad \text{(eq. 2),}$$

And the medium temperature of the heat transfer medium:

$$T_m = \frac{1}{2}(T_{in} + T_{out}) \quad \text{(eq. 3)}$$

With the ambient temperature (T_a), the inlet and outlet temperature of the heat transfer medium (T_{in}, T_{out}), the transmission of the cover (τ), the absorption of the absorber (α), the collector efficiency factor (F') and the solar radiation (G). The collector efficiency is determined with the parameters: η_0, a_1, a_2.

4.1 Mass flow dependency

The most important difference between solar collectors with liquid and with air as heat transfer medium is the much lower heat transfer coefficient between absorber and the heat transfer medium air, resulting in a significantly reduced collector efficiency factor (F') for air heating collectors. As a consequence, the temperature difference between absorber (T_{abs}) and the mean temperature of the heat transfer medium (T_m) is much higher for air heating than for liquid heating collectors. A lower efficiency factor (F') leads as well to higher values of the collector parameters (a_1, a_2), because for the same mean operating temperature of the medium(T_m) the absorber temperature (T_{abs}) will be higher and therefore the thermal losses too.

For covered liquid collectors the collector parameter η_0, a_1, a_2 are considered constant regarding the mass flow $(\dot{m})$ of the heat transfer medium (liquid). Although this simplification is tested to be acceptable for liquid based collectors, it is not for acceptable air heating collectors. Therefore equation 1 is rewritten for covered air collectors as:

$$\eta_{covered\ air\ coll}\ (G, T_m, T_a, \dot{m}) = \eta_0(\dot{m}) - a_1(\dot{m})\frac{T_m - T_a}{G} - a_2(\dot{m})\frac{(T_m - T_a)^2}{G} \quad \text{(eq. 4)}$$

Therefore, the performance curve of air heating collectors must state the mass flow used in the tests.

For a better understanding of the dependency of the collector efficiency on the mass flow, simulations and measurements for covered air heating collectors have been carried out. A 1x2 m² flat plate air heating collector with under-finned and under-flown absorber (similar to B2 in Fig. 1) was mathematically modelled to investigate this issue and other physical phenomena. The 2 m long finned flow channel runs parallel to the length of the collector. The one channel in the middle of the collector was divided into a number of equal length segments. Each segment was modelled by seven temperature nodes interacting with each other through heat exchange phenomena. After simulating the first segment at stationary conditions, its outlet air temperature was used as inlet temperature of the second segment, and so on until the last. Thermal effects at the collector edges were neglected.

In addition to the simulation, measurements on different covered flat solar air heating collectors were carried out at the TestLab Solar Thermal Systems of Fraunhofer ISE, after the test stand was improved in order to achieve a similar accuracy in temperature measurements and mass and heat flow as for measurements on liquid heating collectors.

The collector performance curve was simulated for different mass flow rates with the model described. Figure 3 shows the dependence of the collector performance curve on the mass flow. The curves for the laminar flow range (mass flow m_pkt = 60 kg h^{-1}, blue graph), for the transition zone (m_pkt = 200 kg h^{-1}, red graph) and for the turbulent range (m_pkt = 600 kg h^{-1}, green graph) are presented. Since a 2 m^2 collector is simulated, the mass flow corresponds to 30, 100 and 300 kg h^{-1} m^{-2}.

As expected, the efficiency increases with increasing mass flow $(\dot{m})$, since the heat transfer from the absorber to the heat transfer air improves with increasing mass flow. The lower the mass flow is, the more the absorber temperature (T_{abs}) remains above the mean air temperature (T_m), due to the lower heat transfer coefficient. But with a higher absorber temperature (T_{abs}) the heat losses are higher and therefore the efficiency is lower.

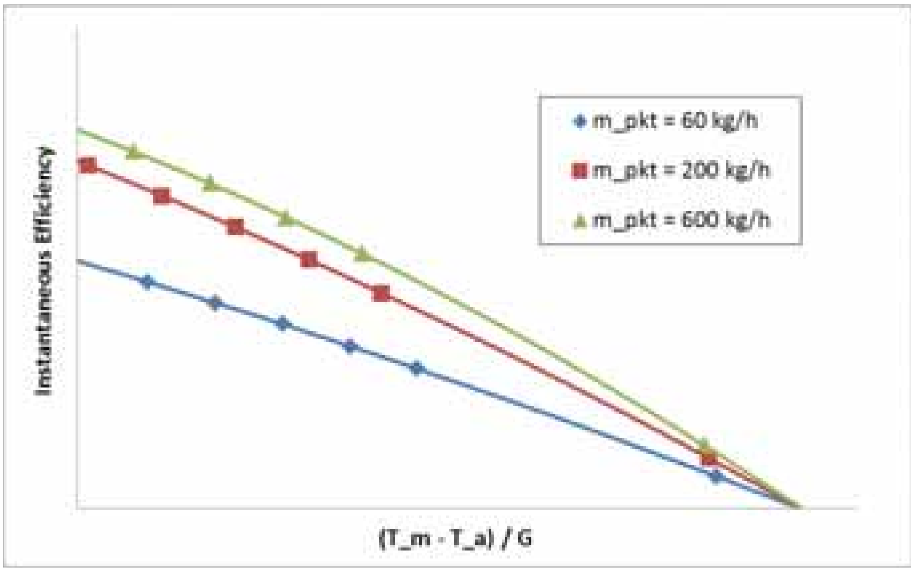


Fig. 2: Simulated performance curves of an 2 m^2 flat air heating collector for three mass flow rates (60, 200 and 600 kg h^{-1})

Figure 3 shows that the performance curves of an air heating collector strongly depend on the air mass flow rate. It is recommended to measure the collector performance for three different mass flow values.

Fig. 5 shows from measurements, how the collector outlet temperature (T_{air}(out)) and the absorber temperature (T_{abs}(out)) close to the outlet depend on the air mass flow rate ($\dot{m}$). In addition, the dependency of the useful thermal power (Q_{flow}(out)) on the air mass flow is shown. The measurements were taken with an almost constant inlet temperature (T_{air}(in)) and a constant irradiation (G) of 993 W/m^2. Both the absorber and air temperatures decrease with increasing mass flow ($\dot{m}$), their difference increases up to a mass flow rate of about 350 kg/h and then decreases (not shown in a separate line). However, the difference between Tabs (out) and T_{air} (mean), shown in figure 4 as well, decreases continuously.

The following phenomena influence the difference between the absorber and the air temperature at the collector outlet: With increasing mass flow:

- the heat transfer between absorber and medium air improves and therefore the temperature difference decreases;
- the residence time of the air within the collector decreases;
- the useful thermal power removed increases, thus the overall thermal losses decrease.

With other thing being equal, the useful thermal power ($\dot{Q}_{out}$) is proportional to the mass flow ($\dot{m}$), due to:

$\dot{Q}_{out} = \dot{m}c(T_{out} - T_{in})$ (eq. 5),

where (c) is the heat capacity of the medium.

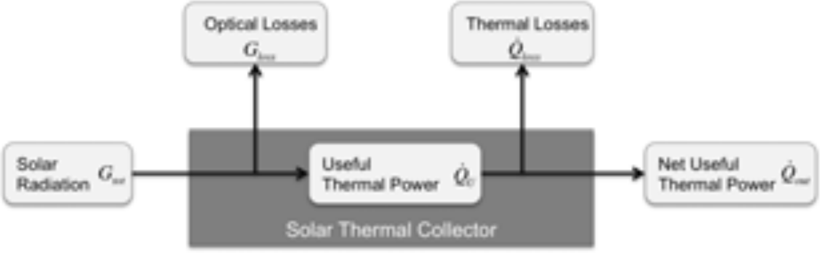


Fig. 4: Definition of the radiation and thermal energy flow through a solar thermal collector

At low mass flow rates also the useful thermal power which can be removed is low. The principal energy flow through a collector is shown in figure 4. With solar radiation on the collector, the absorber temperature rises to the point, where the sum of the thermal losses ($\dot{Q}_{loss}$) and the net useful thermal power ($\dot{Q}_{out}$) is equal to the irradiation (G_{tot}) minus the optical radiation losses (G_{loss}), since the thermal losses mainly depend on the temperature difference between the absorber and the ambient:

$G_{tot} = G_{loss} + \dot{Q}_{loss} + \dot{Q}_{out}$ (eq. 6).

The net useful thermal power ($\dot{Q}_{out}$) depending on the mass flow is shown in 5, named Q_{flow}(out) and normalized to the lowest measured value at 40 kg/h (right axis). Since the irradiation is stays same the net useful thermal power is equal to the efficiency and is thus growing within the mass flow range shown.

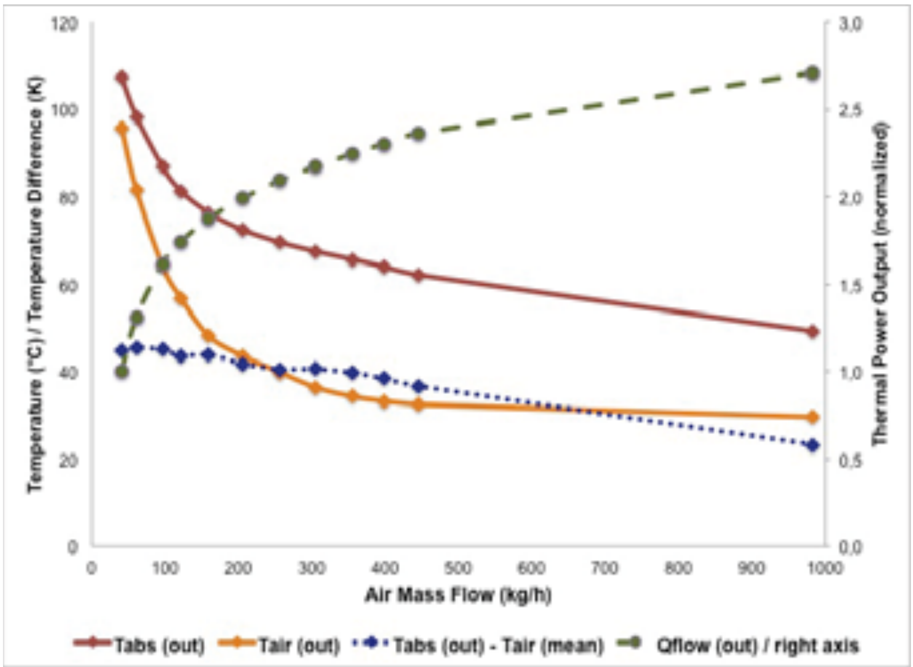


Fig. 5: Measured temperatures of absorber and air at the outlet of the collector, difference between absorber temperature at the outlet and the air mean temperature as well as the net useful thermal power (normalized, right axis) and their dependency on the mass flow

Figure 5 indicates that with increasing air mass flow the efficiency of the collector increases towards an asymptote and also the temperature difference between the absorber and mean temperature of the heat transfer air is continuously decreasing with the increasing air mass flow. It seems it is better to run an air heating collector with rather higher air mass flow rates to increase the efficiency. However, the growing energy demand for the ventilator must be taken into account and an operational optimum must be found.

At low mass flow rates between 40 and 200 kg/h the temperature and power curves are very sensitive to the mass flow rate. This range corresponds with specific mass flow rates between 20 and 100 kg/h.m^2 and the air mass flow is in installed air heating systems typically in the range of 60 to 150 kg/h.m^2 according to manufacturer’s specifications. Thus the influence of the mass flow rate must be considered carefully for air heating collectors.

Further the collector efficiency factor (F’) was determined by simulations for various mass flow rates in order to determine its influence. Figure 6 shows a very strong increase for mass flow rate up to 200 kg/h (specific: 100kg/h.m^2). This underlines the high sensitivity of the efficiency in this mass flow range.

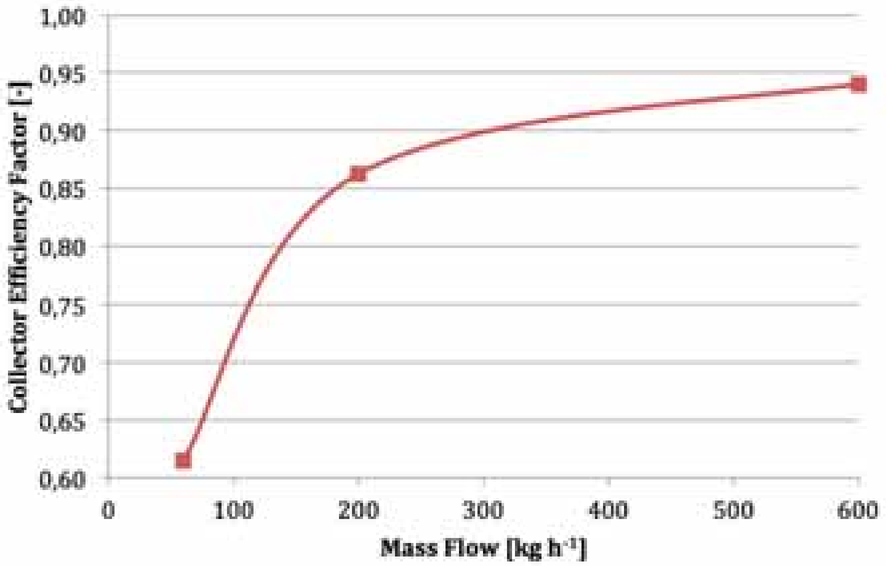


Fig. 6: Simulated dependency of the collector efficiency factor (F’) on the mass flow

The collector efficiency factor (F’) reflects the heat transfer coefficient between the absorber and the heat transfer medium in the maximum thermal efficiency ($\eta_0(\dot{m})$) in equation 4, but it also occurs in the heat losses factors ($a_1(\dot{m})$, $a_2(\dot{m})$). In the first case the collector efficiency factor increases with increasing mass flow by increasing the heat transfer coefficient between absorber and heat medium, in the second case it increases due to the decreasing absorber temperature and therefore lower losses for a given temperature difference (T_m-T_a).

Since at the collector stagnation point the mass flow is zero per definition, and thus the net useful thermal power ($\dot{Q}_{out}$) is zero. The full power of incoming radiation resulting in a useful thermal power is then dissipated through thermal losses. The losses are mass flow independent because mass flow is zero at this point. When efficiency curves for different mass flow rates are extrapolated they thus all pass through the same stagnation point.

4.2 Reference temperature for the performance curve

For the use of the collector efficiency curve it is important to define in the standard the reference temperature for which the performance curve is presented, i.e. the temperature used on the x-axis besides the ambient temperature. For liquid heating collectors the reference temperature is the mean temperature (T_m) of the liquid as described in equation 1. For air collectors two different solutions are already in use. The American ANSI-ASHRAE 93 and the Canadian CSA F378.2 standards are using the inlet air temperature (T_{in}) as reference temperature. In contrary, the IEA-Task 19 recommends the outlet air temperature (T_{out}) as reference temperature for presenting the performance curve. The reasons for these different approaches include the following.

In America mainly non-covered open loop air heating collectors are in use. Therefore the inlet air temperature is equal with the ambient temperature and the temperature increase in the collector is rather small. Then it is much easier to take measurements by using the inlet air temperature as reference temperature. The IEA task 19 presumably focused more on covered air heating collectors and took into account the big temperature difference between the absorber and the heat transfer medium air. Since the temperature profile of the air by flowing through the collector is not exactly known and the outlet air temperature is closer to the absorber temperature than the mean air temperature, and the temperature difference between the absorber to the ambient is physically the relevant parameter for calculating the thermal losses, the outlet temperature was recommended there.

There are four aspects which should be taken into account when making a decision on which reference temperature to use:

1. How is the measurement of the performance curve influenced by the reference temperature?
2. How is the performance curve be used for comparison between solar thermal collectors?
3. How does the reference temperature influence the quality of the performance curve?
4. How is the performance curve be used for simulations of solar air heating systems?

Regarding aspect 1: When an open loop collector is measured, the inlet air temperature is equal to the ambient temperature. Since the mean and the outlet temperatures are fixed for a given radiation and mass flow it wouldn’t matter, which temperature is chosen as reference. However, since open loop collectors only have one efficiency value for a given mass flow and irradiation, this efficiency value must be presented for the same value of the reference temperature for all collectors. However, it needs more effort to do the measurement for the same mean or outlet temperature for all collectors, because the mean and the outlet temperature depend on the efficiency of the collector. The desired mean or outlet temperature must be set during the measurement by changing the inlet temperature. Although, it is much easier to reference the performance of open loop collectors with the inlet air temperature, it is also possible to use the mean and or the outlet temperature.

In the case of closed loop collectors an efficiency curve can be measured by varying the inlet temperature. Therefore no restrictions apply here to which reference temperature can be used.

Regarding aspect 2: The main reason to unify the collector performance standards is to be able to compare performances independent of the construction or heat transfer medium applied. Since for liquid heating collectors, in by far the most cases, the mean temperature of the fluid is used as the reference temperature, a direct comparison via mean temperature of the air as reference in air heating collector performance is possible.

Regarding aspect 3: The thermal losses of a collector depend mainly on the mean temperature of the absorber. The performance of a solar collector, according to equation 1 and 4, depends on the temperature difference between T_m and the ambient temperature T_a. To determine the mean temperature, the inlet and the outlet temperature need to be measured. For the same mean temperature many inlet temperatures are possible, by adjusting the mass flow rate to achieve the appropriate an outlet temperature. The same applies for the outlet temperature. This means, if the inlet or the outlet temperature were to be used only as the reference temperature without defining the other temperatures, the result would not be sufficiently defined.

Regarding aspect 4: Simulation models calculate the outlet temperature of the collector for a given inlet temperature using the efficiency of the collector. If the inlet temperature only would be used in the reference temperature the efficiency would be independent from the temperature difference between inlet and outlet temperature, this is physically not possible. This is the same argument as in aspect 3.

Therefore, only the mean temperature can be used as reference temperature for well-defined measurements of the performance curve. This is the reason, why the mean temperature is proposed as reference temperature for air heating collectors in the draft for the EN 12975. When the difference between inlet and outlet temperature is limited and the measurement conditions do not vary much, which is the case when measuring non-covered open loop collectors, also the inlet temperature could be used by proxy.

Based on this, the following question is: how the mean temperature can be determined. The temperature difference between absorber and air as heat transfer is usually high and an asymptotic profile for both is shown in the results of the simulations of the air and absorber temperatures along the collector channel, shown in figure 7. Also the heat transfer coefficient for each segment is shown. By approximation the temperature increase of the air in the collector is close to a linear increase from the inlet to the outlet except for the 'run-in'. This result was also be validated by measurements. Due to this it was determined that the mean temperature can be calculated in the same way for air heating collectors as for liquid heating collectors, i.e. as the arithmetic average of inlet and outlet temperature as it is described in equation 3.

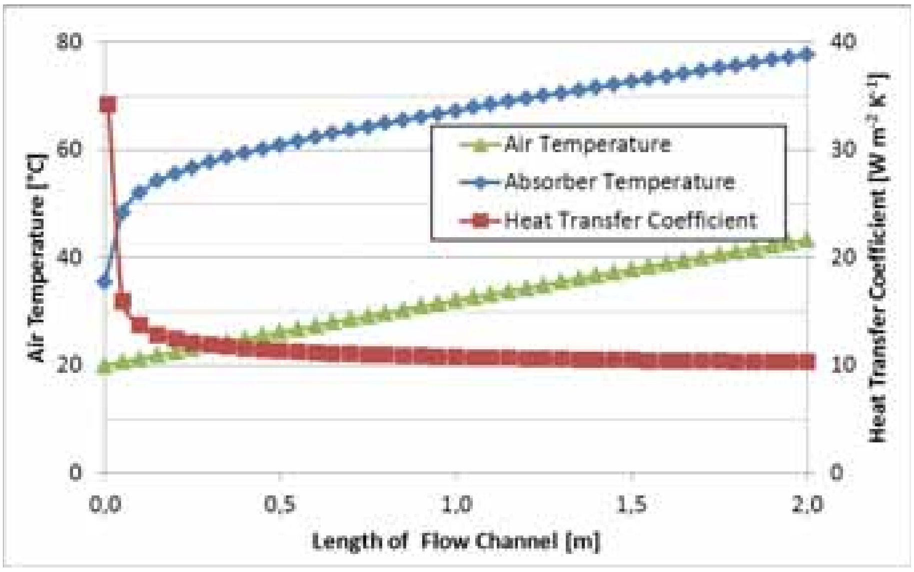


Fig. 7: Simulated temperature of the heat transfer air and the absorber as well as the heat transfer coefficient

Summary

Solar air heating technology has some advantages in comparison to liquid heating collectors, but their market share is less than 1% of the world market. In America mainly non-covered façade air heating collectors are used, in Europe covered air heating collectors are common. One of the main barriers for further deployment of air heating collectors is the missing common standards for performance and quality tests.

Within the project "Luko-E", Fraunhofer ISE improved its performance test stand to accommodate performance measurements with a high accuracy and repeatability for solar air heating collectors and worked out a draft text for the extension of the European solar collector standard EN 12975 to cover solar air heating collectors. This draft is currently in the comment phase.

Besides many details, two basic decisions were made. The dependency of the performance of air heating collectors is reflected in the proposal to measure three performance curves for three different mass flow rates. In addition it is recommended to adopt the mean temperature of the heat transfer medium, calculated as the arithmetic average of the inlet and outlet temperature of the collector, as the collector reference temperature for the performance curve. In this paper it is shown why this mean temperature is physically the only relevant reference temperature for the air heating collector measurements.

Aknowlegement

The authors thank the German ministry for environment (BMU) and the project agency (PTJ) as well as the industrial partners for their support of the work within the project "Luko-E".

References

Stryi-Hipp, G., 2010. Neue Perspektiven für Luftkollektorsysteme. Solarthermie-Symposium, May 2010, Bad Staffelstein, Germany

Thoma, C., Kramer, K., Cerezo, J. D., 2010. Temperature Measurements in Air Ducts – An Optimized Method for Solar Air Heaters, Eurosun, Graz.

ANSI/ASHRAE, 1993.American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1991, ANSI/ASHRAE 93-1986 (RA 91): Methods of Testing to Determine the Thermal Performance of Solar Collectors, USA

IEA Task 19, 1999. Arsenal Research, Department of Renewable Energy, Hubert Fechner, October 1999, Solar Air Systems – Investigations on Series Produced Solar Air Collectors, Austria

Schüle, K., Siems, T., 2009. Vakuumröhren-Luftkollektor für hohe solare Deckungsgrade, published in: Erneuerbare Energie 2009-01, AEE Intec, Austria

RETScreen, 2011. RETScreen Clean Energy Project Analysis Software, www.retscreen.net

Valentin, 2011. T*Sol pro, The Dynamic Simulation Program for the Design and Optimization of Solar Thermal Systems, Valentin Software Inc., http://valentin-software.com/xcartgold/T-SOL-Professional.html