

A comparison of three different collectors for process heat applications

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ABSTRACT

In general vacuum tube collectors are used in solar process heat systems. Another possibility is to use transparent insulated flat plate collectors. A critical point however, is that most of the common transparent insulating materials can not withstand high temperatures because they consist of plastics. Thus, temperature resistive collector covers combining a high transmissivity with a low U-value are required. One possibility is to use capillaries made of glass instead of plastics.

Measurement results ¹ of collector efficiency and incident angle modifier will be presented as well as calculated energy gains for three different collectors: a vacuum tube collector (Giordano Ind., France), a CPC vacuum tube collector (microtherm Energietechnik, Germany) and a new flat plate collector using glass capillary as transparent insulation (SET, Germany).

1. INTRODUCTION

In Switzerland, and similarly in most industrial countries, 25% of the total industrial energy demand is needed for thermal process heat applications in the range up to 300°C². More than half (57%) of this energy is used to produce heat below 150°C.

In the future this 'lower temperature' part of process heat could be enlarged at the expense of the 'medium temperature' range (i.e. 150°C - 300°C). For example, many drying applications can be shifted toward a lower temperature level just by extending drying time. Doing this, in most cases, even the quality of the dried ware is improved.

For solar applications to be practical, this shift towards a lower temperature level is very important. Whereas expensive high concentrating solar systems are needed to generate quantities of steam or oil with temperatures of several hundred degree Celsius, temperatures below 150°C can be produced by high efficiency 'standard' collectors without or with just low concentration of the solar radiation. However, the expression 'standard' has to be considered more detailed:

The higher the temperatures needed the more important is the minimisation of the collector U-value. It is in the nature of the things that this minimisation of the U-value is walking hand in hand with an increasing stagnation temperature. Collectors which can be used in thermal process heat applications (up to 150°C), reach stagnation temperatures of more than 300°C. Therefore, all elements of the collector, such as absorber-coating, insulation materials etc. have to be able to withstand high temperatures.

For a long time vacuum tube collectors were the only choice for this application. As the name suggests, vacuum tubes achieve the required low U-value by evacuating the space remaining between the (hot) absorber and the (cold) 'collector envelope'. Thus, heat conductance of the air is suppressed as well as heat losses due to convection inside the collector. The remaining heat losses are in the order of 1 W/m²K - 2 W/m²K. They mainly originate in the exchange of thermal radiation between the absorber and the surrounding glass-tube and in piping losses. Since no insulation materials are used to suppress absorber losses no problems occur with the temperature stability of such materials.

For flat plate collectors it is a different situation. In addition to thermal radiation losses the air inside the collector, usually at atmospheric pressure, is transferring energy mainly by convection as well as by conduction. Therefore the collector itself has to be insulated against the surroundings. Whereas the rear of the collector can be easily insulated with a variety of temperature and humidity resistant opaque materials available on the market, the front of the collector is more problematic since it is exposed to solar radiation. Transparent insulation materials (TIM) combining high transmittance for solar radiation with low heat conductance are required.

During the last years great strides were made in this field. But most of the available TIM's are still not a good choice for high efficiency, high temperature flat plate collectors. Either they cannot withstand high temperatures because they are made of plastics (most honeycomb and capillary materials) or they are hygroscopic and cannot withstand the humidity inside the collector (aerogels etc.). Thus, efforts were made to realise TIM modules which consist of glass capillaries instead of plastics.

In this paper measurement results of the collector efficiency and the incident angle modifier (IAM) will be presented for an experimental flat plate collector with a glass capillary transparent insulation. As a comparison, measurement results for a vacuum tube collector and a vacuum tube collector with a compound parabolic concentrator (CPC) are shown. Furthermore, calculated gross heat outputs based on the measured collector data for these three collectors are presented.

2. DESCRIPTION OF THE TEST

2.1. Test performance

Thermal performance tests for the collectors were done according to ISO 9806-1.2³. This Standard contains methods for conducting tests outdoors under natural solar irradiance and for conducting tests indoors under simulated solar irradiance. The measurements were made on an outdoor testfacility. As the only difference to the ISO 9806-1.2 wind speed is in the range of 0 to 1.5 m/s instead of 2 m/s to 4 m/s as the ISO Standard demands.

With the exception of the flat plate collector two collectors of each type were mounted in series on a solar tracker. Therefore the conditions for the measurements were comparable. In addition to the determination of the efficiency the incident angle modifier was measured.

To correct the influence of seasonal deviation on the efficiency two reference collectors (flat plate and vacuum tube collector) are used.

2.2. Definition of the reference area

According to the ISO Standard the collector efficiency can be based either on the absorber area A_A or on the gross area A_G :

- Absorber area : The maximum projected area of an absorber where the solar radiation is admitted.
- Gross area : The maximum projected area of a complete solar collector module, exclusive of integral means of mounting and connecting fluid conduits.

2.3. Nomenclature

c_0	Algebraical Constant	-
c_1	Algebraical Constant	$W / (m^2K)$
c_2	Algebraical Constant	$W / (m^2K^2)$
c_p	Specific heat capacity of heat transfer fluid	$J / (kgK)$
x	Characteristical variable	$(m^2K) / W$
F'	Collector efficiency factor	-
A_A	Absorber area	m^2
A_G	Gross area	m^2
G_K	Global irradiance in the collector plane	W/m^2
K	Incident angle modifier	-
T_i	Collector inlet temperature	$^{\circ}C$
T_e	Collector outlet temperature	$^{\circ}C$
T_m	Mean temperature of heat transfer fluid	$^{\circ}C$
T_a	Ambient air temperature	$^{\circ}C$
Q	Useful power extracted from collector	W
U_L	Overall heat loss coefficient of collector	W/m^2K
V	Volume flow rate	m^3/h
V	Ratio of absorber area to gross area	-
$(\tau\alpha)_e$	Effective transmittance-absorption product	-
ρ	Specific density of heat transfer fluid	kg/m^3
η	Collector efficiency	-
η_0	Collector efficiency at $x = 0$	-

2.4. Basic equations

The following equations describe the thermal performance of a solar collector under steady state conditions:

$$Q / A_A = F' (\tau\alpha)_e G_K - F' U_L (T_m - T_a) \quad (1)$$

Or expressed in terms of measured parameters:

$$Q / A_A = V \rho c_p (T_e - T_i) / A_A$$

The thermal efficiency is given by:

$$\eta = Q / (A_A G_K) = F' (\tau\alpha)_e - F' U_L ((T_m - T_a) / G_K)$$

$$\eta = V \rho c_p (T_e - T_i) / (A_A G_K)$$

In reality the heat loss coefficient U_L is not a constant but is a function of the temperature of the absorber plate and the ambient temperature. Therefore we have to obtain the following approach:

$$F' U_L = c_1 + c_2 (T_m - T_a) \quad (2)$$

With the use of (2) equation (1) becomes:

$$Q / A_A = F' (\tau\alpha)_e G_K - c_1 (T_m - T_a) - c_2 (T_m - T_a)^2$$

Therefore the efficiency results in:

$$\eta = F' (\tau\alpha)_e - c_1 (T_m - T_a) / G_K - c_2 (T_m - T_a)^2 / G_K$$

and with $c_0 = F' (\tau\alpha)_e$ and $x = (T_m - T_a) / G_K$

$$\eta = c_0 - c_1 x - c_2 G_K x^2$$

Determination of the Incident Angle Modifier :

The incident angle modifier describes the ratio of the efficiency measured at actual admitted irradiance to vertical admitted irradiance.

$$K = \eta / \eta_0$$

3. DESCRIPTION OF THE COLLECTORS

3.1. Vacuum tube collector ⁴

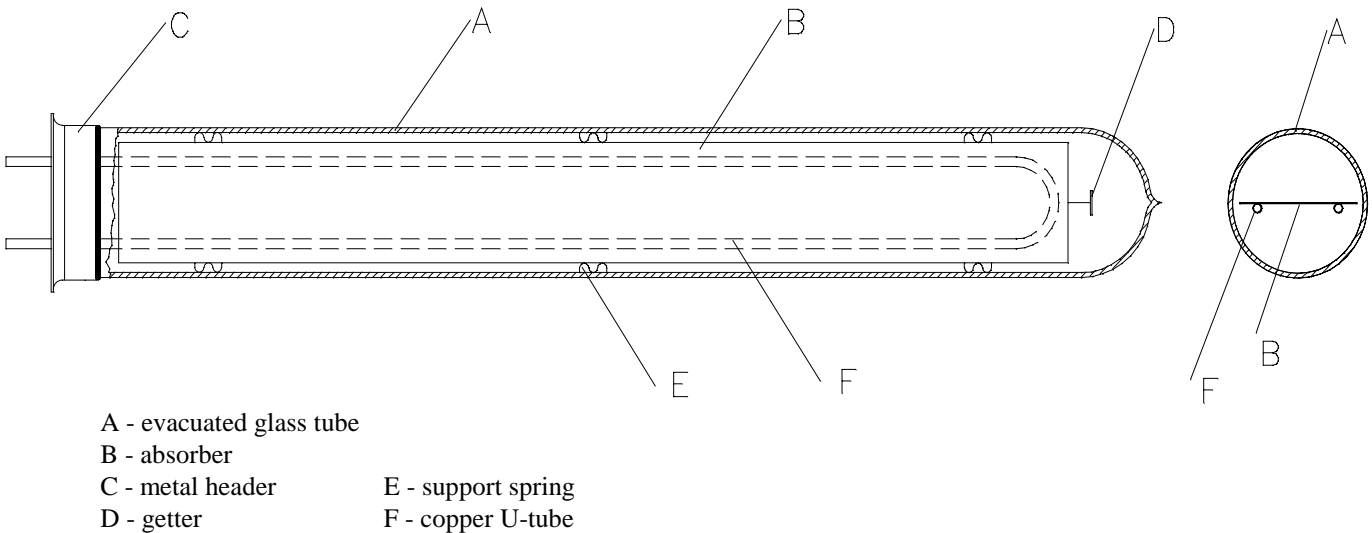


Fig. 3.1: Vacuum tube collector (CORTEC 2; Giordano Industries)

The collector presented in this category is a typical 'Corning' collector. In this case it is the CORTEC 2, produced by Jacques Giordano Industries in France. There are two modules available, one consists of six vacuum tubes and the other of nine tubes. The module tested at our institute has six tubes. The collectors gross area is 1.912 m² and its weight is 42 kg. A tube with a length of 2.5 m and a diameter of 0.1 m is made of borosilicate glass. Long narrow flat absorbers, which are made of black-chrome coated copper (manufacturer values: $\alpha = 0.9$, $\epsilon = 0.05$) are mounted inside the glass-tubes (see fig. 3.1). The heat transfer fluid flows in a copper U-tube which is welded to the absorber. Thus, the inlet and outlet are at the same end of the evacuated tube. Due to the stainless steel membrane used for the in- and outlet, just one glass-to-metal seal is required. Units of three tubes fitted in series are connected via an insulated manifold at the end of the collector.

3.2. Vacuum tube collector with CPC ⁵

This collector, which is assembled by the German microtherm Energietechnik GmbH, comprises of six vacuum tubes produced by Shiroky (Japan). The heat transfer medium flows parallelly through the individual tubes which are connected via an insulated manifold. In

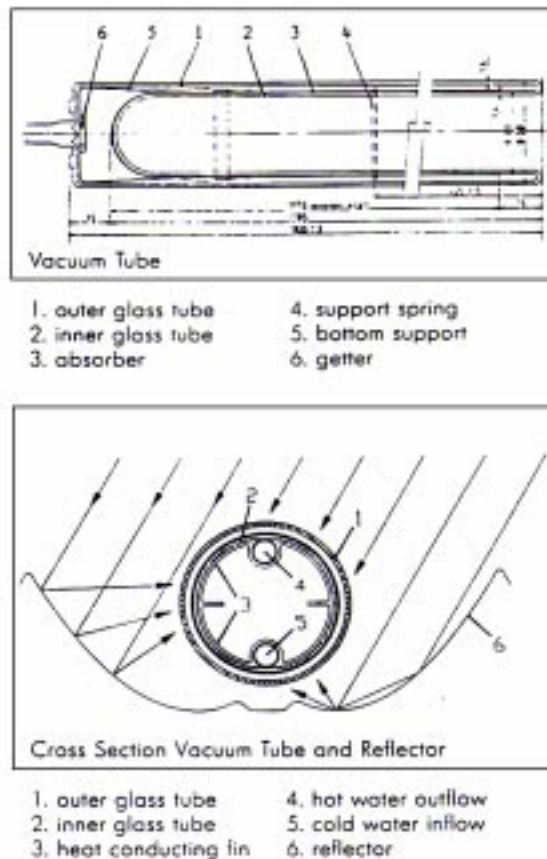


Fig. 3.2: Vacuum tube collector with CPC (SK-6; microtherm Energietechnik GmbH)

order to design larger collector arrays the modules can be linked to one another. The collector has a gross area of 1.191 m² and a weight of 17 kg.

The main component of this collector, i.e. the vacuum tube, was developed by the University of Sydney. It consists of two borosilicate glass-tubes, an inner tube is melted to an outer tube, in a similar way as a thermos flask (see fig. 3.2). The space between the tubes is evacuated to 10⁻⁶ bar. The inner glass tube is selectively coated and serves as the absorber. The manufacturer states that the optical properties of the absorber are $\alpha = 0.93$ and $\epsilon = 0.035$. The heat is transferred through the glass onto an aluminium sheet passing it on to a copper U-tube through which the heat transfer fluid circulates. The advantage of this tube is, that no metal-glass-seal is needed.

Another component of the collector is the reflector made of weatherproof anodised aluminium. The manufacturer states that the reflectivity is 85%. By means of the reflector a disadvantage of vacuum tube collectors is diminished: the low fraction of the absorber area to the collector gross area, which is typically around 0.6.

3.3. Transparent insulated flat plate collector ⁶

The collector described in this section is a prototype collector, developed and constructed by Solar-Energie-Technik (SET) in Germany. At first glance it looks like a standard flat plate collector - but with about twice the thickness. This is due to the special cover used: a transparent insulation material which consists of glass capillaries. These capillaries (produced by Schott Glas in Germany) have a length of 100 mm, a diameter of 7 mm and a wallthickness of 0.1 mm. Approximately 40000 of them, standing close together, are packed between two sheets of glass (see fig. 3.3). The upper pane of glass is needed for weather protection, the lower one is needed just to keep the upper ends of the capillaries in contact with the upper glass plate.

The rear of the collector is insulated by a plate of aluminium coated polyurethane with a thickness of 55 mm and a high temperature resistant mat of micro glass fibers (30 mm). The absorber is placed in the remaining air gap of 30 mm between the back insulation and the transparent front insulation. This leads to a distance of 25 mm from the absorber to the TI module.

The price of this experimental collector cannot be given yet. However, due to the similarity of this collector with a standard flat plate collector of SET the costs will comprise of the flat plate collector costs plus the cost of the glass capillary module.

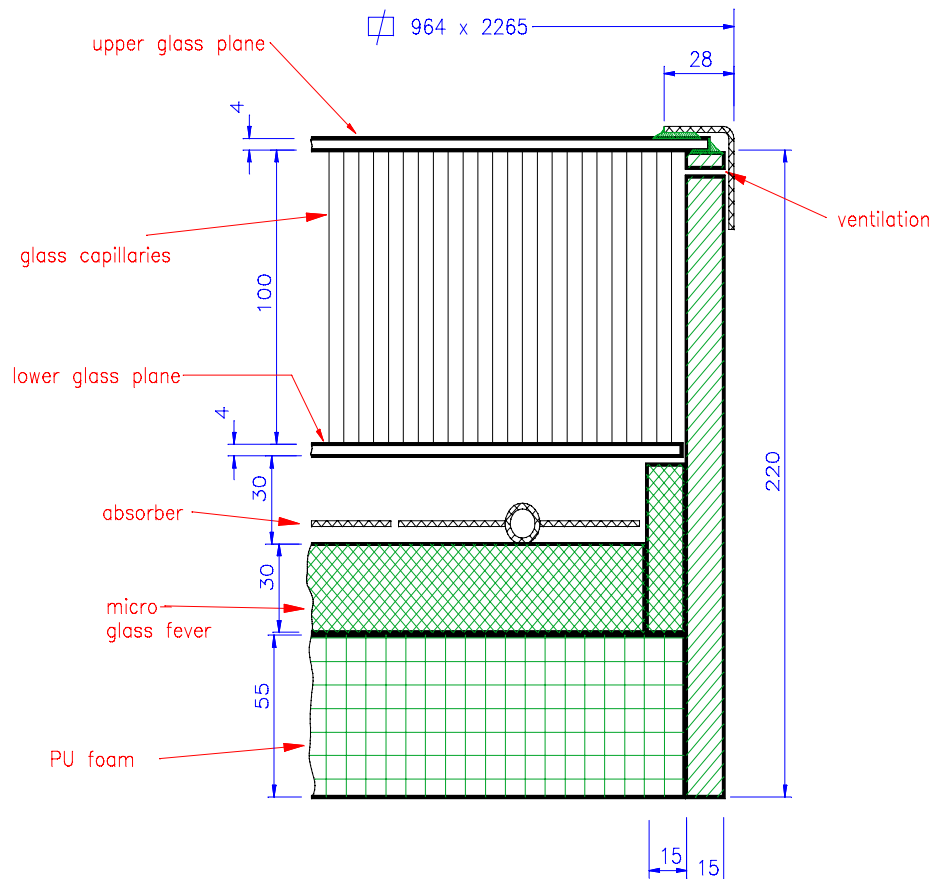


Fig. 3.3: Transparent insulated flat plate collector (prototype, Solar-Energie-Technik)

3.4. Summary of collector data

In the following table technical data of the three tested collectors are summarised. All values which are given by the manufacturer are indicated by a ^{*}. Note that the price is given per m² of absorber area.

	<i>vacuum tube</i>	<i>vacuum tube (CPC)</i>	<i>flat plate (TIM)</i>
manufacturer	J. Giordano Ind.	microtherm	SET
gross area [m ²]	1.912	1.191	2.183
absorber area [m ²]	1.117	1.053 ¹⁾	1.740
weight [kg]	42 [*]	17 [*]	78 [*]
absorber type	black-chrome on copper	metal carbide on copper on glass	black-chrome on nickel on copper
absorptance α [1]	0.90 [*]	0.93 [*]	0.96 [*]
emittance ϵ [1]	0.05 [*]	0.035 [*]	0.12 [*]
insulation	vacuum, 10 ⁻⁶ bar [*]	vacuum, 10 ⁻⁶ bar [*]	glass capillaries
price [SFr/m ²]	2415.- [*]	1396.- [*]	not given

¹⁾ see section 4.1

Tab. 3.1: Summary of collector data

4. COLLECTOR TEST RESULTS

4.1. Collector efficiency

With respect to the ISO 9806-1.2 Standard 'Thermal Performance Tests for Solar Collectors', the collector efficiency η can be based on the absorber plate area A_A as well as on the collector gross area A_G (see section 2.) To get information about the quality of the components used in the collector (such as absorber, cover etc.) the efficiency η_A , based on the absorber area is more powerful. However, for the design of a solar energy system it might be more convenient if η is based on the collectors gross area (i.e. η_G), especially when a large collector area is needed as it is the case with industrial process heat systems. Therefore, in the following both efficiency functions are given, η_A as well as η_G .

The values used to determine the efficiencies are all given in table 3.1. The 'absorber area' specified for the microtherm collector however needs a more detailed explanation. This vacuum tube module is equipped with a CPC. Due to the concentration of the solar radiation, the collector efficiency could become greater than 1 if its physical absorber area is taken as a reference. But it is more realistic to use the area of the concentrator as reference. In this case, the maximum possible efficiency will become 1 if all components of the collector are ideal (i.e. with no losses). Thus, the value given in table 3.1 actually is the area of the CPC rather than the absorber area.

The upper diagram of figure 4.1. shows the collector efficiency functions for the three collectors based on the absorber area A_A , whereas in the lower diagram the efficiencies are based on the gross area A_G . The functions shown are a result of a least square fit of the measured values (typically with $x = 0$ to 0.15 (m²K)/W) with a second order polynomial. This takes into account, that the heat loss coefficient U_L of a collector is a function of temperature.

The resulting fit coefficients, namely c_0 , c_1 and c_2 , are listed in table 4.1. Furthermore, collector efficiencies $\eta(T_m - T_a)$ and heat loss coefficients $U_L(T_m - T_a)$ are given for three different temperature differences (collector mean temperature T_m - ambient temperature T_a) under 800 W/m² insolation in the collector plane.

A comparison of the collector efficiencies based on the absorber area to the efficiencies based on the collector gross area shows the advantage of the transparent insulated flat plate collector, which is given by its relation of A_A/A_G . Actually this collector

shows the highest η_G for x values up to $0.05 \text{ (m}^2\text{K)/W}$, i.e. for high insolation or low temperatures. However, in this range single glazed flat plate collectors can even perform better. This is due to the fact that for this conditions a high transmittance - absorptance product ($\tau\alpha$) is of more importance than a low heat loss coefficient.

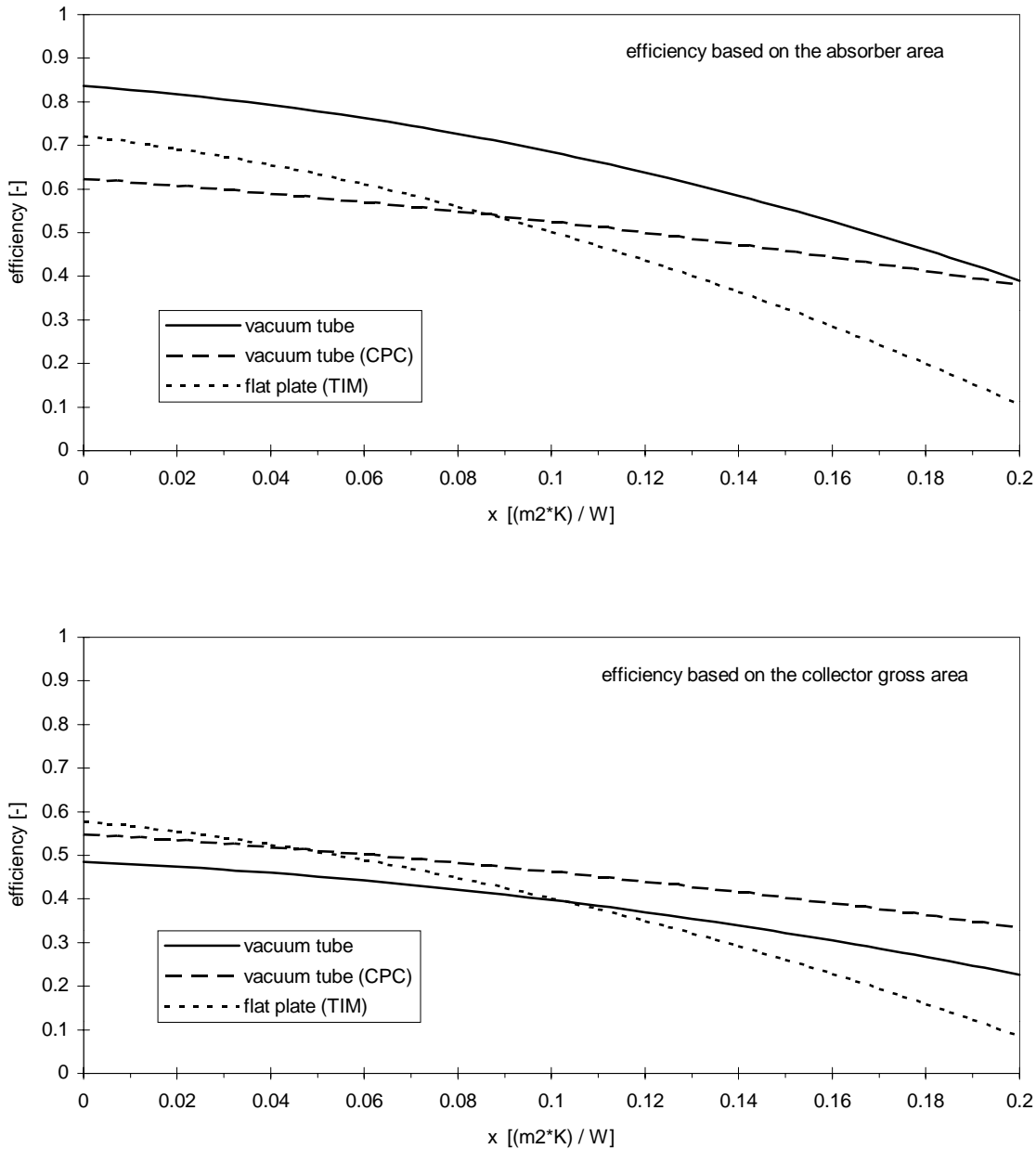


Fig. 4.1: Measured collector efficiencies

For x values above $0.1 \text{ (m}^2\text{K)/W}$, i.e. in the range of high temperatures or low insolation, the transparent insulated collector cannot approach the efficiencies given by the vacuum tube collectors, independent on which area the efficiency is based. This result is not in good agreement with the results of a flat plat collector using honeycomb structured transparent insulation, published by Rommel et. al.⁷

The low slope of the efficiency curve of the vacuum tube with CPC is due to two facts: On the one hand, the absorber has a very low emittance of 0.035. On the other hand the tubular geometry of the absorber provides for a small emitting area. The CORTEC collector shows the best efficiency of the three collectors, based on the absorber area. For an insolation of 800 W/m² and a temperature difference of 120°C (i.e. at $x = 0.15 \text{ (m}^2\text{K)/W}$) its efficiency still exceeds 55%. Actually this is the highest η_A we have measured until now. However, with respect to the collector area, the microtherm collector seems to be the better choice for high temperatures applications.

values based on area:	<i>vacuum tube</i>		<i>vacuum tube (CPC)</i>		<i>flat plate (TIM)</i>	
	A_A	A_G	A_A ¹⁾	A_G	A_A	A_G
c_0 [-]	0.836	0.485	0.622	0.547	0.721	0.576
c_1 [W/(m ² K)]	0.790	0.458	0.740	0.651	1.32	1.06
c_2 [W/(m ² K ²)]	0.009	0.005	0.003	0.003	0.011	0.009
$\eta(50K)$ [-]	0.759	0.440	0.566	0.499	0.604	0.483
$U_L(50K)$ [W/(m ² K)]	1.69	0.980	1.04	0.915	2.42	1.94
$\eta(100K)$ [-]	0.625	0.362	0.492	0.433	0.419	0.335
$U_L(100K)$ [W/(m ² K)]	2.59	1.50	1.34	1.18	3.52	2.82
$\eta(150K)$ [-]	0.435	0.252	0.399	0.351	0.164	0.131
$U_L(150K)$ [W/(m ² K)]	3.49	2.02	1.64	1.44	4.62	3.70

¹⁾ see text

Tab. 4.1: Summary of the collector test results

4.2. Incident angle modifier

Due to the dependence of $(\tau\alpha)$ on the angle of incidence of radiation on the collectors surface, another important property is given: the incident angle modifier (IAM) K (see section 2.). For most collectors, such as standard flat plate, K is a function of just the angle θ between the collector normal and the direction of the incident radiation. However, the collectors considered in this work, are optically nonsymmetric. Therefore, the biaxial incident angle modifiers K_l and K_t has been measured and are defined as follows:

K_l is the IAM referred to the angle varying between the collector normal and its longitudinal axis,

K_t is referred to the angle given by the normal direction and the transverse direction.

For a vacuum tubular collector, the longitudinal direction is determined by the axis of the tubes, while it is given by the length for a flat plate collector.

Strictly speaking, the collectors IAM cannot be measured with the same test as is used to measure the collector efficiency. This is due to the fact, that the incident radiation not only consists of beam radiation, but also consists of a variable component of diffuse and ground-reflected radiation, where no angle of incidence is defined. However, all collector tests are made under 'clear sky' conditions, with a ratio of global to diffuse radiation typically below 15%. This leads to IAM data which are indicative of the effects of the angle of incidence of pure beam radiation.

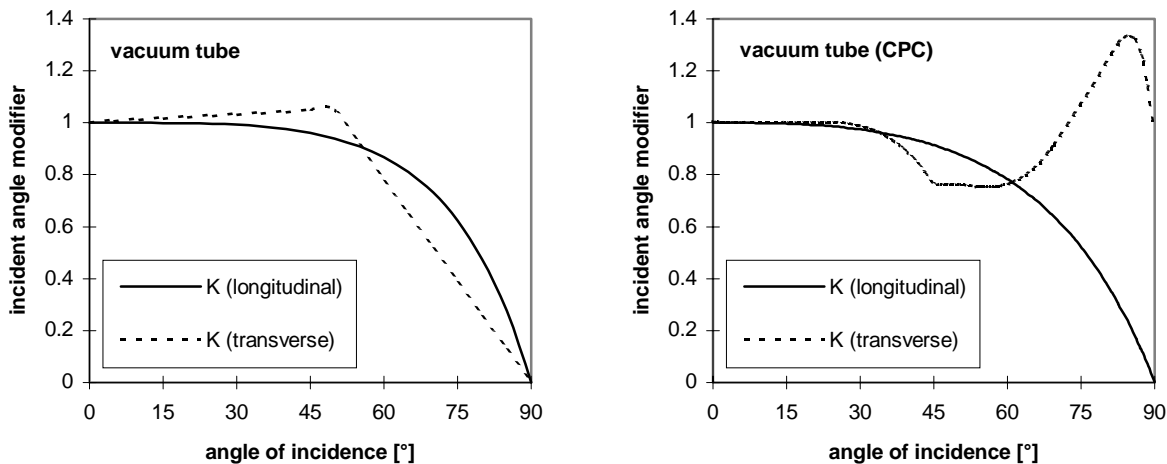
The incident angle modifiers for the three collectors are shown in figure 4.2. The curves K_l and K_t given for the vacuum tube collector (CORTEC) are typical for this collector type. Both of these can be described by an analytical expression⁸ which is determined by only one measurement. This measurement must be taken at an incident angle of 50°. The same statement can be made for the longitudinal IAM K_l of the vacuum tube collector with CPC.

A similar analytical function for the remaining incident angle modifiers is not available yet; neither for K_t of the vacuum tube with CPC nor for K_l and K_t of the transparent insulated flat plate collector. This is due to the fact that there is not the same amount of measurements available as it is for standard flat plate and vacuum tube collectors. Therefore, the corresponding curves given in figure 4.2 are a result of measurements over the whole angular range in the case of the microtherm collector, and measured up to an angle of incidence of 60° in case of the collector of SET.

The increasing of the incident angle modifier K_t of the vacuum tube in the range from 0 to 50° is a typical effect of the geometry of this collector. With increasing the angle of incidence the absorber receives more and more radiation reflected from the neighbour tube. After reaching a maximum value around 50° , each tube starts to shade the neighboured absorber and the IAM drops rapidly.

The somewhat strange looking shape of the transverse IAM K_t of the microtherm collector is due to its tubular absorber in combination with a compound parabolic concentrator. However, the measured curve shows good agreement with theory⁹. The longitudinal IAM K_l of both vacuum tube collectors, the one with as well as the one without concentrator, are both dominated by the cosine law.

Due to absorption inside the transparent insulation, the collector of SET shows incident angle modifiers which are up to 0.1 below the IAM of a single glazed standard flat plate collector. It is remarkable, that the longitudinal and the transverse IAM of this collector are almost the same. A much more pronounced difference was expected because the collector frame is very wide and casts a shadow over the absorber. Thus, in the transverse direction, already 10% of the absorber are shaded by the collector frame at an angle of incidence around 30° . Probably it is caused by reflections inside the glass capillaries that this shading effect is reduced.



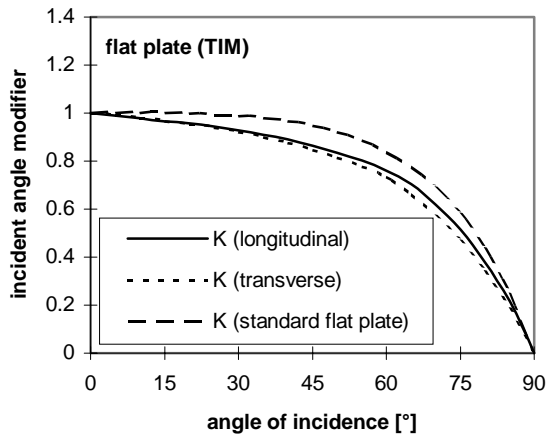


Fig. 4.2: Incident angle modifier functions for the tested collectors

5. SIMULATION RESULTS

Based on the measured results calculations of the gross heat output of the different collectors were done. The calculations were made using the 'BWE92'⁸ computer program. The original version of this program uses different analytical expressions to describe the IAM function(s) of different collector types (see also section 4.2). However, some of the incident angle modifiers of the collectors presented in this paper are not yet implemented in the program code. Therefore, a part of the program has been rewritten, making it possible to run a simulation even with such strange looking incident angle modifiers as K_t in the case of microtherm collector.

The program does not calculate dynamically as in the case of programs such as TRNSYS¹⁰ or POLYSUN¹¹. Therefore, the thermal capacity of the collector does not affect the calculated gross heat output. However, it can be shown that the uncertainty which is due to this simplification is neglectable as long as the input meteo data are at least of hourly time steps, while the gross heat output is for a period of a month or longer⁸.

Collector gross heat outputs are given for absorber mean temperatures of 50°C, 100°C 150°C and 200°C. These values, sketched in figure 5.1, are related to the absorber area (diagram 5.1.a) and to the gross area (diagram 5.1.b) of the collector, respectively. In all cases the collector slope (i.e. the angle between ground and collector plane) is 45°. Due to the optical nonsymmetry of the collectors, there are basically two possibilities how the collector can be installed. The longitudinal or main axis can be either in north - south direction or in east - west direction. However, the annual gross heat output of even the microtherm collector shows a variation of much less than 5% by changing its orientation. Therefore, the results discussed here are restricted to the north - south orientation for all three collectors.

As already discussed, the results are computed by using the 'BWE92' program. All calculations are based on hourly data of the global and diffuse radiation in the horizontal and the ambient temperature measured during the years 1963 to 1970 in Kloten, Switzerland. Therefore, the resulting gross heat outputs are values averaged over a period of eight years.

As can be seen in figure 5.1.b all three collectors have a similar gross heat output for a collector mean temperature of 50°C. However, with increasing temperature the output of the transparent insulated flat plate collector is getting smaller and smaller in comparison with the outputs of the two vacuum tubes. For temperatures of 150°C and above the output of the SET collector becomes less than the half than that of the vacuum tubes.

The effect of a very low U-value as the microtherm collector reveals can be seen as well in figure 5.1.a and b, respectively. For high operating temperatures this collector delivers the best results again. This is independent of the reference area which the gross heat output is based on.

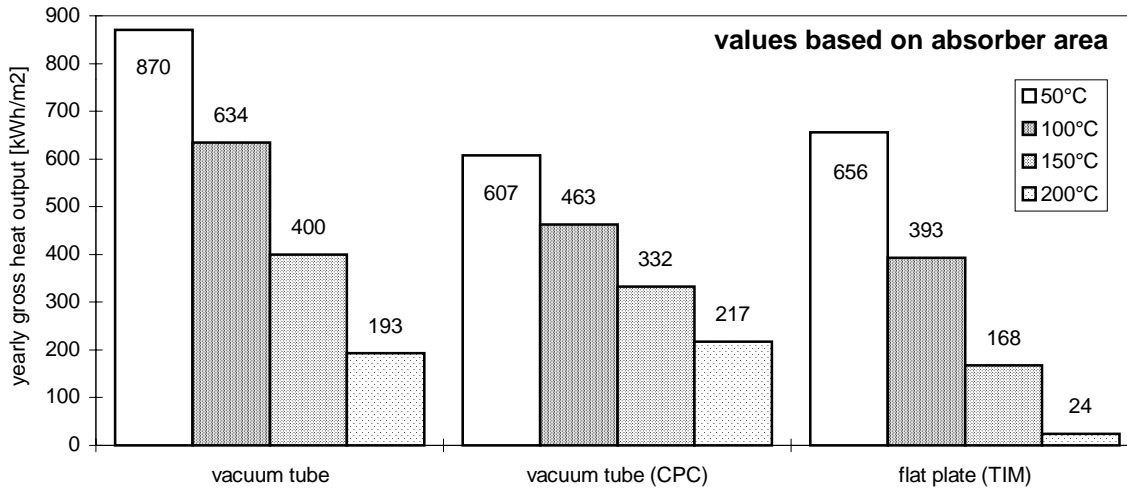


Fig. 5.1.a: Calculated annual gross heat output with respect to the absorber area. Global insolation in collector plane is 1247 kWh/m^2 . Weather data of Kloten, Switzerland.

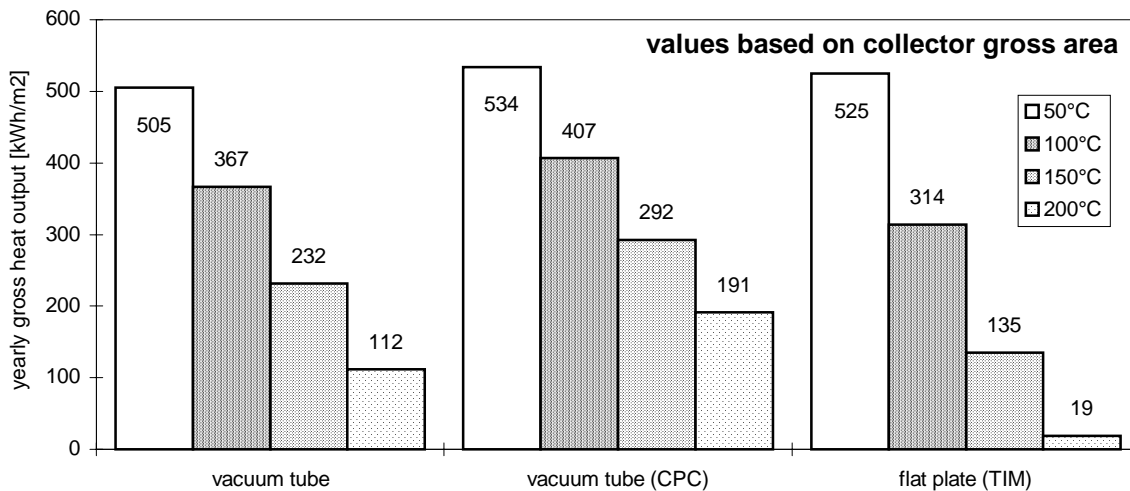


Fig. 5.1.b: Calculated annual gross heat output with respect to the collector gross area. Global insolation in collector plane is 1247 kWh/m^2 . Weather data of Kloten, Switzerland.

6. CONCLUSIONS

A comparison of the test and simulation results of the three collectors shows that for the use in high temperature applications vacuum tubes are superior to the transparent insulated flat plate collector. Only in the low temperature range, the efficiency of the SET experimental collector exceeds the efficiencies measured for the vacuum tubes. But in this temperature range standard flat plate collectors are still the best solution.

After two weeks of outdoor testing on one of our trackers, the transparent insulated flat plate collector shows condensation on the inner side of the outermost glass plane. Actually, for this collector condensation always occurs after a rainfall. Consequently transmittance decreases and heat losses increase. This suggests that the construction of the collector is not yet optimised.

The microtherm vacuum tube with CPC is profitable in operating temperatures of 150°C and above, whereas the CORTEC tube is suited to a range of 100°C to 150°C (in case that minimising collector area is not important). A combination of a CPC with an adapted CORTEC vacuum tube could yield interesting results. The deterioration of the reflectance of the CPC, which is exposed to the weather, has to be monitored over the next years.

As for most applications, costs are an important factor. Since the price for the SET collector was not available cost analyses of the gross heat output could not be made. As the results indicate, an improved transparent insulated flat plate collector could enter into competition with vacuum tube collectors in the temperature range up to 100°C or 150°C. But to do so, its costs has to be clearly below the costs of vacuum tubes. This goal only can be achieved, if the production of the glass capillary module is simplified drastically.

In the future, other competitors to vacuum tube collectors will probably appear on the market. These might be other improved transparent insulated flat plate collectors as the bifacial absorber collector¹². Furthermore, a high vacuum flat plate collector, developed by R. Graf et. al.¹³, is tested at our institute right now. This new collector promises to combine the low U-value of a vacuum tube with the high relation of absorber area to gross area of a flat plate collector.

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