THERMAL INSULATION LABORATORY
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PERFORMANCE OF UNCOVERED SOLAR COLLECTOR

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CONTENTS

SUMMARY

This report is one of the final reports of contract no. 2592-84-12. ED ISP DK "Performance and durability of Solar Components and Small Solar Systems". The contract is carried out within the framework of the European Solar Collector Testing Programme.

SUMMARY

Testing of efficiency or energy output of uncovered solar collectors of the fully wetted type was investigated.

A model for the energy output of that type of collectors was set up based on the temperature of the absorber surface. In the model the following coefficients have to be inserted: the absorptance of the absorber, the emissivity of the absorber, the convective heat loss coefficient at different air velocities. In order to use the model the relation between the fluid temperature and the absorber temperature has to be known.

The test procedure therefore consists of measurements of 1) the absorptance and the emissivity of the absorber 2) the convective heat loss coefficient and its variation with the air velocity 3) the heat transfer coefficient between the absorber and the fluid.

The two last quantities can be found from heat loss tests.

For a typical uncovered collector the coefficients were measured and a comparison between the measured and the calculated energy output was performed both indoors with a solar simulator and outdoors.

In general there was quite good agreement and the influence of the thermal radiation did not seem to be a problem. The major problem or difficulties are in measuring the convective heat loss coefficient and use it because the relation between the meteorological wind velocity and the air velocity at the absorber surface is not well known.

1. INTRODUCTION

Uncovered solar collectors consist of an absorber and sometimes a frame in order to mount it on the roof but with no cover, insulation or casing. The absorber is typically made of black plastic and due to low thermal conductivity no fins are used - the absorber is fully wetted. The absorber can be made of metal and then a tube with fins can be used, but that type is not treated in this report.

The uncovered collectors are typically used for heating of swimming-pools or other low temperature applications. Coupled to heat pumps the collectors will often be operated at temperatures below the dew-point temperature of the ambiant air and in this way the condensation heat will be used. Only dry operation of the uncovered collectors is dealt with in this report.

The efficiency of uncovered collectors is much more influenced by the air velocity at the absorber surface and the thermal radiation exchange with the surroundings than the efficiency of glazed collectors. Therefore testing of uncovered collectors in solar simulators may produce unrealistic data. The influence of the thermal radiation from the surroundings in solar simulators therefore has to be measured and corrected for. The variation of efficiency with air velocity at the absorber surface also has to be measured and in some way incorporated in the presentation of the efficiency. Due to this a special version of the efficiency test procedure has to be set up for uncovered collectors.

2. MODELS OF EFFICIENCY AND ENERGY OUTPUT

For glazed collectors the mean fluid temperature is used as the characteristic temperature of the collector. For uncovered collectors the temperature difference between the fluid and the ambiant air for typical operating conditions is small (0-10^{o}C). Therefore, the temperature difference between the absorber surface and the fluid has a relative great influence on the heat loss.

In the glazed collector this is taken into account by the collector efficiency factor, F', but this is not really applicable for an uncovered collector because heat is lost directly from the absorber both to the ambiant air (by convection) and the surroundings (by thermal radiation).

Instead of introducing equivalent air temperatures it is much more clear to use the following model based on the absorber temperature. As the expression is simpler for the energy output than for the efficiency the first is used.

Energy output = absorbed energy
minus heat loss due to convection at the absorber top
minus heat loss due to radiation at the absorber top
minus heat loss due to convection at the absorber back
minus heat loss due to radiation at the absorber back.

(2.1) $$q_u = \alpha G - h_{tc}(T_{pt} - T_{at}) - \varepsilon_{pt}\sigma(T_{pt}^4 - T_{st}^4) - h_{bc}(T_{pb} - T_{ab}) - (\sigma/(1/\varepsilon_{pb} + 1/\varepsilon_{sb} - 1))(T_{pb}^4 - T_{sb}^4)$$

q_u is the energy output, W/m^2

α is the solar absorptance of the absorber

G is the solar irradiance, W/m^2

T_{pt} is the temperature of the absorberplate at the top, K

T_{pb} is the temperature of the absorberplate at the back, K

T_{at} is the temperature of the air at the top, K

T_{ab} is the temperature of the air at the back, K

T_{st} is the temperature of the surroundings at the top, K

T_{sb} is the temperature of the surroundings at the back, K

h_{tc} is the convective heat transfer coefficient at the top, W/m^2K

h_{bc} is the convective heat transfer coefficient at the back, W/m^2K

ε_{pt} is the emittance of the absorberplate at the top

ε_{pb} is the emittance of the absorberplate at the back

ε_{sb} is the emittance of the surroundings at the back

σ is Stefan-Boltzmans constant.

The surroundings are treated as if they were an absolute black body with a certain temperature.

The model is based on the assumption that the collector is placed on the roof in such a way that there is a gab between the absorber and the roof. If the collector is insulated at the back or mounted with the absorber in contact with the roof the convective and radiative heat loss from the back should be replaced by a heat loss due to conduction.

(2.2) $$q_u = \alpha G - h_{tc}(T_{pt} - T_{at}) - \varepsilon_{pt}\sigma(T_{pt}^4 - T_{st}^4) - h_c(T_{pb} - T_b)$$

h_c is the heat loss coefficient due to conduction, W/m^2K

T_b is the temperature of the material to which the heat is lost, K.

In most cases T_{pb} will be equal to the average fluid temperature.

As the model is based on plate temperatures it is necessary to set up a relation between the plate temperatures and the fluid temperature. In the fully wetted absorber only conduction in the absorber material and convection in the fluid are of importance. For a fixed flowrate the resistance will therefore be almost constant.

(2.3) $$\alpha G - h_{tc}(T_{pt} - T_{at}) - \varepsilon_{pt}\sigma(T_{pt}^4 - T_{st}^4) = h_{it}(T_{pt} - T_m)$$

(2.4) $$h_{bc}(T_{pb} - T_{ab}) + (\sigma/(1/\varepsilon_{pb} + 1/\varepsilon_{sb} - 1))(T_{pb}^4 - T_{sb}^4) =$$
$$h_{ib}(T_m - T_{pb})$$

(2.5) $$h_c(T_{pb} - T_b) = h_{ib}(T_m - T_{pb})$$

h_{it} h_{ib} is the heat transfer coefficient between the fluid and the topside and back of the absorberplate, W/m^2K

T_m is the average fluid temperature, K

All temperatures of the fluid and the absorber are mean values in the flow direction. Typically the internal heat transfer coefficients at the top and back will be equal and for the insulated back the heat loss will be so small that the plate temperature at the back is equal to the fluid temperature.

3. EXPERIMENTS

The thermal performance of the collector is characterized by the model if the following collector dependent properties are known: $\alpha, \varepsilon_{pt}, \varepsilon_{pb}, h_{it}, h_{ib}, h_{tc}, h_{bc}$. How these properties can be found is described in the following.

3.1 MEASURING OF THE COEFFICIENTS IN THE MODEL

The emissivity of the absorberplate topside and back, ε_{pt} and ε_{pb} are only dependent of the material of the absorberplate. Standard values of emissivity of the material can be used or the emissivity can be measured on samples.

For the collector used in this work an emissivity of 0.92 is given by the manufacturer (Fafco). So we have

(3.1.1) $\varepsilon_{pt} = \varepsilon_{pb} = 0.92$

The absorbtance of the absorberplate can also be obtained as a material property. But this should only be used if the surface of the absorber is plane. The Fafco-collector has a surface which is not plane and the absorptance can, therefore, be higher than for the material itself due to absorption of reflected radiation.

The absorptance of the absorberplate has been measured with a small pyranometer which is first used to measure the incoming radiation on the absorber and next turned around and used to measure the reflected radiation. The instrument is type S-15-SO-3 manufactured by Sensors Inc. and the diameter of the sensor is about 10mm. The shading effect of the pyronometer is therefore neglectable if the pyronometer is placed several centimeters in front of the absorber. The result obtained using this method and instrument in the solar simulator facility gave the following result:

(3.1.2) $\alpha = 0.98$

The absorptance given by the manufacturer is 0.97 but it is not clear whether this is based on a plane sample of the material or on the absorberplate.

The heat transfer coefficient between the fluid and the absorber surface will be the same for the top and back in this case because the absorber is symmetrical. There may be a difference in the convective heat transfer of the fluid due to the opposite directions of heat transport but it is neglected. The heat transfer coefficient between the fluid and the absorber surface has been measured in the following way. The absorber was mounted on the test rig in the solar simulator facility with insulated back so only heat transfer at the topside is of importance. The absorber was exposed to solar radiation and the energy output was measured. The temperature of the absorber surface was measured with a radiation thermometer, type KT 16 manufactured by Heimann. In this way the temperature can be measured without influencing the absorption and the heat transfer. The surface temperature was measured at the lower, middle and upper part of the collector. The fluid temperature was measured at the inlet and the outlet. In this way the mean temperature difference between the absorber surface and the fluid was measured. The measurements were also carried out in heat loss situations. The detailed results are shown in Annex A. The reduced results are shown in table 3.1.1. In this the following "new" symbols are used.

m/A,	fluid mass flow per unit area, kg $s^{-1}m^{-2}$
q_l ,	heat loss, Wm^{-2}
T_i ,	fluid inlet temperature ^oC
T_e ,	fluid outlet temperature, ^oC
T_{pl},	temperature of the lower part of the absorber, ^oC
T_{pm},	temperature of the middle part of the absorber, ^oC
T_{pu},	temperature of the upper part of the absorber, ^oC
ΔT_{fp},	average temperature difference between the fluid and the absorberplate.
u_s	air velocity along the absorber surface, m s^{-1}

Situation	m/A	q_u, q_l	T_i	T_e	T_{pl}	T_{pm}	T_{pu}	ΔT_{fp}	h_{it}	u_s	Time
	kg/m^2s	W/m^2	^oC	^oC	^oC	^oC	^oC	^oC	$W/m^2{}^oC$	m/s	DD.MM.-HH.MM.
Solar irradiated	0.056	948	17.6	21.6	23	24	27	4.7	202	7	20.8-11.48
- -	0.057	942	18.8	22.8	23	25	26	3.9	242	1	20.8-13.12
- -	0.056	939	19.3	23.3	24.5	25.5	29	5.0	188	0	20.8-13.44
- -	0.030	905	19.3	26.5	24	27	30	4.1	221	1	20.8-15.10
- -	0.058	531	39.6	41.8	42.5	44	45	3.1	171	1	21.8-11.48
Heat loss	0.047	538	37.7	35.0	31	32.5		3.9	140	0	13.8-14.27
- -	0.016	454	37.8	31.0	29	32		2.2	206	0	13.8-15.31

Table 3.1.1. Measurements of the heat transfer coefficient between the fluid and the absorber surface.

The heat transfer coefficient between the fluid and the absorber surface is not expected to be measured very accurately. The accuracy of the radiation thermometer is 1^oC. Therefore, the accuracy of h_{it} is about 20% in the actual situation. In all actual running situations the absorber surface can be calculated from the temperature of the fluid and the energy output with an error smaller than 1^oC. Based on table 3.1.1. a value of 200 $W/m^{2o}C$ is suggested to be used for h_{it} and h_{ib}.

The convective heat transfer coefficient at the top can be found from measurements of the heat loss. The absorber was insulated at the back and cross-stream ventilators were used to create different velocities at the top. The temperature of the absorber surface was not measured but found from the water temperature using the relation between the heat loss and the heat transfer coefficient between the water and the absorber surface.

The complete results of the heat loss measurements are given in Annex B. The reduced results are shown in table 3.1.2. The temperature of the surroundings, T_{st}, is not measured directly but the temperature of the air coming out of the wind simulator is used. From a single measurement with the pyrgeometer this assumption looks all-right but in future work the temperature of the surroundings should be measured with the pyrgeometer.

The heat loss due to conduction through the back insulation, q_c, is calculated from the following equation:

(3.1.3) $$q_c = h_c(T_m - T_b)$$

The value used for h_c is calculated to 0.7 $Wm^{-2}C^{-1}$. The temperature of the absorber surface at the back is assumed to be equal to the mean fluid temperature. This can be done as the heat loss at the back is relatively small.

The absorberplate temperature, T_{pt}, is calculated from the mean fluid temperature, T_m, using a value of h_{it} of 200 $Wm^{-2o}C^{-1}$.

(3.1.4) $$T_{pt} = T_m - (q_l - q_c)/h_{it}$$

u_s	T_{at}	T_b	T_{st}	T_m	q_1	T_{pt}	q_{rt}	q_c	q_{tc}	h_{tc}	Time
ms^{-1}	^oC	^oC	^oC	^oC	Wm^{-2}	^oC	Wm^{-2}	Wm^{-2}	Wm^{-2}	$Wm^{-2}{}^oC^{-1}$	DD.MM-HH.HH
0.5	24.4	24.1	23	41.6	203	40.6	104	12	87	5.4	28.5 -09.56
1.0	25.3	25.3	24	41.4	271	40.0	95	11	165	11.3	28.5 -12.36
1.9	23.5	23.7	23	41.1	365	39.3	96	12	257	16.3	24.5 -14.15
2.9	25.2	25.1	24	40.9	427	38.8	87	11	329	24.2	28.5 -15.10
4.0	21.2	23.1	20	40.3	576	37.4	100	12	464	28.7	29.5 -10.01
5.0	21.8	22.6	21	40.2	662	36.9	91	12	559	37.1	29.5 -11.42
6.5	20.8	21.3	20	40.1	764	36.3	93	13	658	42.5	29.5 -12.56
0.2	21.0	21.5	19	31.6	107	31.1	67	7	33	3.3	24.5 -09.11
1.1	20.4	21.8	19	31.5	175	30.6	64	7	104	10.2	24.5 -11.31
1.9	22.6	23.3	22	31.6	180	30.7	49	6	125	15.5	24.5 -13.08
3.1	21.5	23.4	21	32.4	261	31.1	56	6	199	20.7	24.5 -14.52
4.0	23.3	24.2	23	32.4	266	31.1	46	6	214	27.5	23.5 -13.05
5.1	23.9	24.3	23	31.5	259	30.2	40	5	214	34.0	23.5 -11.16
6.5	23.2	24.0	23	31.3	313	29.7	43	5	265	40.8	23.5 -09.49

Table 3.1.2. Results of heat loss measurements.

The radiation loss at the top is calculated from the expression:

(3.1.5) $q_{rt} = \varepsilon_p \sigma (T_{pt}^4 - T_{st}^4)$

Finally the convective heat loss coefficient is found from the expression:

(3.1.6) $h_{tc} = (q_l - q_{rt} - q_c)/(T_{pt} - T_{at})$

The convective heat loss coefficient is then by regression found to vary with the air velocity in the following way:

(3.1.7) $h_{tc} = 10.1 u_s^{0.75}$ [W m^{-2} $^oC^{-1}$]
where the units for u_s must be m s^{-1}

The convective heat loss coefficient is also plotted versus the air velocity on figure 3.1.1.

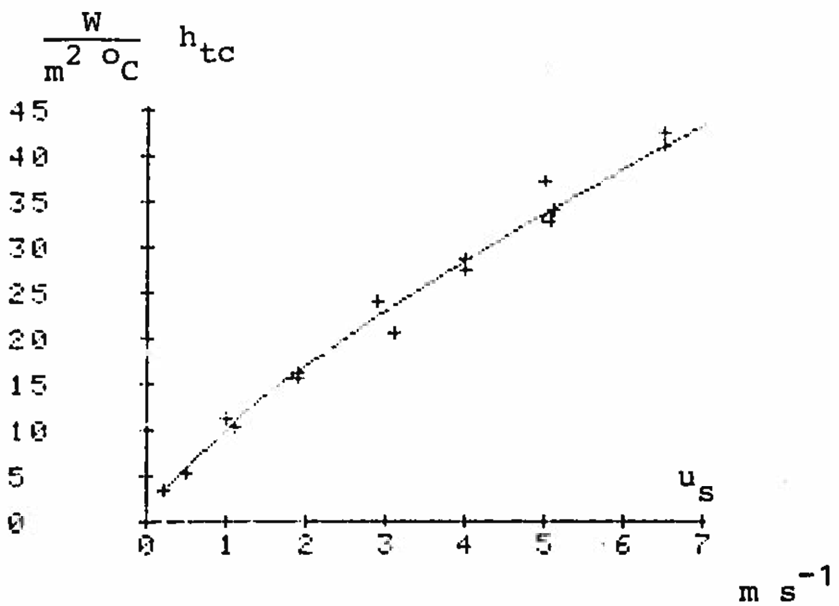

Figure 3.1.1. The convective heat loss coefficient versus the air velocity.

We now have all the coefficients to be used in equation 2.2., and we have the relation between the absorber temperature and the fluid temperature

(3.1.8) $$q_u = 0.98G - 10.1\, u_s^{0.75}\, (T_{pt} - T_{at}) - 0.92\; 5.67\; 10^{-8} (T_{pt}^4 - T_{st}^4) - 0.7 (T_m - T_b) \quad [W\, m^{-2}]$$

(3.1.9) $$T_{pt} = T_m + (q_u + 0.7(T_m - T_b))/200$$

In the equations it is assumed that the back of the absorber has a temperature equal to that of the fluid.

For a given set of climatic data and for given fluid temperature, the equations can be solved by iteration and the energy output calculated.

The convective heat loss to the surroundings behind the absorber was not measured. The reason was that depending on the roof cladding the thickness of the gab between roof and collector and the structure used for fixing the collector you will have different values of the convective heat loss coefficients. Many experiments will be necessary to cover all possibilities and the results are of no fundamental importance to this work.

3.2 COMPARISON BETWEEN MEASURED AND CALCULATED ENERGY OUTPUT

To see if the model and the measurements of the coefficients to be used with it were working well a number of tests using the solar simulator were performed.

The detailed results are shown in Annex A and C. The reduced results are shown in table 3.2.1. A comparison with the model is made and the error is calculated.

G	u_s	T_a	T_b	T_{st}	T_m	$q_{u,test}$	T_{pt}	αG	$-q_{rt}$	$-q_c$	$-q_{tc}$	$q_{u,model}$	error	Time
Wm^{-2}	ms^{-1}	^oC	^oC	^oC	^oC	Wm^{-2}	^oC	Wm^{-2}	Wm^{-2}	Wm^{-2}	Wm^{-2}		%	DD.MM-HH.MM
INDOORS:														
932	0.2	27.7	24.5	31	21.3	951	26.1	913	28	2	5	948	-0.3	20.8 -13.44
932	0.5	23.7	24.6	-	19.6	949	24.3	913	38	4	-2	953	0.4	20.8 -11.48
932	1	23.8	24.4	-	20.8	939	25.5	913	31	3	-17	930	-1.0	20.8 -13.12
919	0.2	29.9	26.2	-	30.4	894	34.9	901	-23	-3	-16	859	-3.9	2.8 -15.08
928	1.9	24.6	26.5	-	27.4	823	31.5	909	- 3	-1	-46	859	4.4	13.6 -13.23
930	5.0	25.2	26.2	-	26.1	774	30.0	911	6	0	-162	755	-2.5	12.6 -14.44
948	4.8	24.7	26.2	-	24.5	849	28.7	929	13	1	-131	812	-4.4	30.4 -15.25
935	6.3	24.9	26.0	-	24.8	811	28.9	916	12	1	-161	768	-5.3	2.5 -12.42
919	0.2	29.0	25.6	-	40.1	767	43.9	901	-81	-10	-45	765	-0.2	6.5 -12.03
907	1.3	27.5	27.0	-	36.5	717	40.1	889	-56	-7	-155	671	-6.4	9.5 -14.23
921	1.8	26.3	26.3	-	36.2	691	39.7	903	-53	-7	-210	633	-8.3	9.5 -10.49
937	2.9	26.4	27.0	-	36.1	613	39.2	918	-50	-6	-287	575	-6.2	8.5 -15.09
932	4.1	25.8	26.5	-	36.2	529	38.8	913	-48	-7	-378	480	-9.3	7.5 -12.35
914	4.7	26.4	27.3	-	35.5	515	38.1	896	-43	-6	-377	470	-6.8	7.5 -15.11
940	6.9	26.5	27.2	-	35.2	466	37.5	921	-39	-6	-473	403	-13.5	8.5 -10.54
924	0.4	27.5	24.3	-	48.6	608	51.6	906	-134	-17	-122	633	4.1	13.5 -11.18
908	1.2	26.6	26.0	-	45.2	557	48.0	890	-108	-9	-248	525	-5.7	10.5 -14.29
919	1.9	27.4	26.3	-	47.7	436	49.9	901	-122	-14	-368	397	-8.9	13.5 -13.27
920	2.8	26.9	27.3	-	47.4	324	49.0	902	-115	-14	-483	290	-10.5	13.5 -15.57
OUTDOORS:														
971	1	20.9	18.6	3	19.9	844	24.1	952	-104	-1	-32	815	-3.4	20.5 -13.41
994	6.5	18.9	18.1	3	19.6	767	23.4	974	-100	0	-184	690	-10.0	20.5 -13.09
965	0.7	23.4	22.2	4	26.2	784	30.1	946	-132	-3	-52	759	-3.2	21.5 -13.02
410	0.7	20.8	18.6	1	24.3	221	25.4	402	-120	-4	-36	242	-9.5	21.5 - 9.08
880	6.5	22.2	21.3	7	20.1	762	23.9	862	-85	1	-70	708	-7.1	14.5 -13.06

Table 3.2.1 Comparison between the energy output measured and predicted by the model.

In the situation where the absorber surface temperature is close to the air temperature or where the air velocity is very low there is a very good agreement between the measured and the calculated energy output. In the situation where the convective heat loss is important the model comes out with energy outputs which are too small. The reason may be found in the uncertainty of estimating the absorber surface temperature, T_{pt}. When measuring the heat transfer coefficient between the absorber surface and the fluid the accuracy of the measurements of the absorber surface temperature was about 1^oC. The value of T_{pt} given in table 3.2.1 is based on this and may therefore also have an error of 1^oC. Such an error will influence the radiative heat loss by about 6 W/m^2 and the convective heat loss by 3-40 W/m^2 corresponding to air velocities of 0.5-7 m/s.

The air velocity used is the average of 15 measurements covering the whole absorber. The variation from top to bottom (close to the ventilator) is typically about 50% of the average air velocity. The velocity is measured 5 cm above the absorber surface with a hot wire anemometer. That is where the maximum velocity is in the air stream produced by the ventilators. Therefore, quite some uncertainty can be expected in the air velocity data.

The convective heat loss coefficient for different air velocities could also be found from tests with the solar simulator and the data in table 3.2.1 would give smaller values of the heat loss coefficient. There is no reason to believe that there should be a systematic error in obtaining the convective heat loss coefficients from heat loss measurements instead of efficiency measurements. The overall accuracy is best in the heat loss measurements and it is, therefore, preferred to use these.

The outdoor results do not differ from the indoor results even if the sky temperature is different.

In general the model seems to be acceptable and the influence of the thermal radiation in the solar simulator tests is not a serious problem. The error arising when using the solar simulator compared to outdoor operation is relatively small and corrections can be applied.

The uncertainty in the convective heat loss is the major problem. First it is rather difficult to measure and secondly it is very dependent on the air velocity along the absorber surface. Thirdly it is a great problem to find the air velocity along the absorber surface from the available wind velocity. This is also true for the air temperature. In big areas of swimming pool collectors the air temperature close to the absorbers could very well be some degrees higher than the meteorological air temperature.

The work reported in this report is not enough to draw conclusions. The method or test procedure described and illustrated in this report and especially in Annex D should be tried by different laboratories on different collectors and perhaps it could be develloped further to be usable for all types of uncovered collectors.

NOMENCLATURE

G	solar irradiance, $W\ m^{-2}$
G_d	diffuse solar irradiance, $W\ m^{-2}$
h_{bc}	convective heat transfer coefficient at the back, $W\ m^{-2}\ k^{-1}$
h_c	heat loss coefficient due to conduction, $W\ m^{-2}\ k^{-1}$
h_{it} h_{ib}	heat transfer coefficient between the fluid and the topside and back of the absorber plate, $W\ m^{-2}\ k^{-1}$
h_{tc}	convective heat transfer coefficient at the top, $W\ m^{-2}\ k^{-1}$
m	fluid mass flow, $kg\ s^{-1}$
m/A	fluid mass flow per unit area, $kg\ s^{-1}\ m^{-2}$
q_c	heat loss due to conduction through the back insulation, $W\ m^{-2}$
q_l	heat loss, $W\ m^{-2}$
q_{rt}	heat loss due to radiation at the absorber top, $W\ m^{-2}$
q_{tc}	heat loss due to convection at the absorber top, $W\ m^{-2}$
q_u	energy output, W/m^2
T_{ab}	temperature of the air at the back, K
T_{at}	temperature of the air at the top, K
T_b	temperature of the material to which the heat is lost, K
T_i	fluid inlet temperature, ^oC
T_m	average fluid temperature, K
T_e	fluid outlet temperature, ^oC
T_{pb}	temperature of the absorberplate at the back, K
T_{pl}	temperature of the lower part of the absorber, ^oC
T_{pm}	temperature of the middle part of the absorber, ^oC
T_{pt}	temperature of the absorberplate at the top, K
T_{pu}	temperature of the upper part of the absorber, ^oC
T_{sb}	temperature of the surroundings at the back, K
T_{st}	temperature of the surroundings at the top, K

T^*	average fluid temperature minus air temperature divided by the solar irradiance, $K\ m^2\ W^{-1}$
α	solar absorptance of the absorber
σ	Stefan-Boltzmans constant
ε_{pb}	emittance of the absorberplate at the back
ε_{pt}	emittance of the absorberplate at the top
ε_{sb}	emittance of the surroundings at the back
ΔT_{fp}	average temperature difference between the fluid and the absorberplate

ANNEX A: Measurements of heat transfer coefficients between the top absorber surface and the fluid.

3.2 INSTANTANEOUS EFFICIENCY: MEASURED AND DERIVED DATA

Solar Simulator

indoor : x
outdoor:

Fluid: Water c_f $Jkg^{-1}K^{-1}$. TILT 67.5^{o}

DATE	LT	G	G_d/G	T_a	u_s	T_i	(T_e-T_i)	T_m	m	T*	η
D-M-Yr	Hrs-Mins	Wm^{-2}	%	^{o}C	ms^{-1}	^{o}C	K	^{o}C	$kg\ s^{-1}$	Km^2W^{-1}	-
20-8-85	11-48	932	0	23.7	7	17.5	4.04	25.7	0.1568	-0.0045	1.023
	11-53	-	-	23.8	-	17.6	4.02	25.8	0.1568	-0.0045	1.019
	11-58	-	-	23.7	-	17.6	4.01	25.7	0.1566	-0.0044	1.017
	12-03	-	-	23.3	-	17.7	3.97	23.3	0.1571	-0.0038	1.009
20-8-85	13-12	932	-	23.7	1	18.8	3.97	20.8	0.1577	-0.0032	1.011
	13-17	-	-	23.8	-	18.8	3.97	20.8	0.1575	-0.0032	1.011
	13-22	-	-	23.8	-	18.8	3.97	20.8	0.1568	-0.0033	1.003
	13-27	-	-	23.8	-	18.8	3.94	20.8	0.1577	-0.0032	1.004
20-8-85	13-44	932	-	27.5	0	19.2	4.03	21.2	0.1576	-0.0068	1.026
	13-49	-	-	27.6	-	19.2	4.03	21.2	0.1573	-0.0068	1.024
	13-54	-	-	27.8	-	19.3	4.03	21.3	0.1548	-0.0069	1.008
	13-59	-	-	27.8	-	19.4	4.01	21.4	0.1580	-0.0069	1.024
20-8-85	15-10	932	-	24.4	1	19.3	7.17	22.9	0.0836	-0.0016	0.968
	15-15	-	-	24.4	-	19.3	7.20	22.9	0.0835	-0.0017	0.971
	15-20	-	-	24.5	-	19.3	7.20	22.9	0.0831	-0.0017	0.967
21-8-85	11-48	926	-	24.3	1	39.6	2.21	40.7	0.1616	0.0177	0.579
	11-53	-	-	24.3	-	39.6	2.21	40.7	0.1619	0.0177	0.582
	11-58	-	-	24.2	-	39.6	2.18	40.7	0.1618	0.0178	0.573
	12-03	-	-	24.3	-	39.6	2.19	40.7	0.1619	0.0177	0.575

Aperture Area: 2.78 m^2

4.3 HEAT LOSSES: MEASURED AND DERIVED DATA

indoor : x
outdoor:

FLUID: Water c_f $Jkg^{-1}K^{-1}$ TILT: 67.5^o

Date	LT	T_a	u_s	T_i	(T_i-T_e)	T_m	m	$(T_m-T_a)_1$	Q_1	U
D-M-Yr	Hrs-Mins	^oC	ms^{-1}	^oC	K	^oC	kgs^{-1}	K	W	$Wm^{-2}K^{-1}$
13-08-85	14-27	22.7	0	37.7	2.76	36.3	0.1305	13.7	1507.6	39.61
-	14-32	22.5	-	37.7	2.74	36.4	0.1304	13.7	1496.2	39.30
-	14-37	22.4	-	37.7	2.75	36.4	0.1303	13.6	1496.1	39.54
13-08-85	15-31	22.5	-	37.8	6.78	34.4	0.0445	11.9	1262.5	38.27
-	15-36	22.5	-	37.8	6.79	34.4	0.0445	11.9	1263.6	38.27
-	15-41	22.5	-	37.8	6.80	34.4	0.0444	11.9	1262.5	38.31
-	15-46	22.6	-	37.8	6.80	34.4	0.0444	11.8	1262.0	38.37

Aperture Area: 2.78 m^2

ANNEX B: Measurements of the heat loss coefficient at different air velocities.

4.3 HEAT LOSSES: MEASURED AND DERIVED DATA

indoor : x
outdoor:

FLUID: Water C_f $Jkg^{-1}K^{-1}$ TILT: 67.5°.

Date	LT	T_a	u_s	T_i	(T_i-T_e)	T_m	m	$(T_m-T_a)_1$	Q_1	U
D-M-Yr	Hrs-Mins	°C	ms^{-1}	°C	K	°C	kgs^{-1}	K	W	$Wm^{-2}K^{-1}$
5-28	09-56	24.4	"0"	42.0	0.74	41.6	0.1785	17.2	552.2	11.52
	10-01	24.4		42.0	0.76	41.6	0.1784	17.2	564.8	11.81
	10-09	24.3		42.0	0.76	41.5	0.1782	17.3	564.2	11.74
	10-04	24.4		42.0	0.75	41.6	0.1827	17.2	576.2	12.06
5-28	12-36	25.2	1.0±0.5	41.9	1.02	41.4	0.1782	16.2	756.7	16.77
	12-41	25.3		41.9	1.01	41.4	0.1787	16.1	753.8	16.79
	12-46	25.3		41.9	1.01	41.4	0.1787	16.1	752.0	16.76
	12-53	25.4		41.9	1.00	41.4	0.1786	16.0	748.3	16.83
5-24	14-15	23.4	1.9±0.9	41.8	1.34	41.1	0.1814	17.7	1012.6	20.59
	14-20	23.5		41.8	1.34	41.1	0.1810	17.7	1016.8	20.71
	14-25	23.5		41.8	1.34	41.1	0.1808	17.6	1013.9	20.71
	14-30	23.6		41.8	1.34	41.1	0.1815	17.6	1013.2	20.75

Aperture Area: 2.78 m^2

4.3 HEAT LOSSES: MEASURED AND DERIVED DATA

indoor : x
outdoor:

FLUID: Water C_f $Jkg^{-1}K^{-1}$ TILT: 67.5^o

Date	LT	T_a	u_s	T_i	(T_i-T_e)	T_m	m	$(T_m-T_a)_1$	Q_1	U
D-M-Yr	Hrs-Mins	^oC	ms^{-1}	^oC	K	^oC	kgs^{-1}	K	W	$Wm^{-2}K^{-1}$
5-28	15-10	25.2	2.9±1.1	41.7	1.59	40.9	0.1790	15.7	1186.8	27.19
	15-15	25.2		41.7	1.58	40.9	0.1785	15.8	1178.3	26.90
	15-20	25.0		41.7	1.59	40.9	0.1786	15.8	1187.6	26.96
	15-27	25.2		41.7	1.60	40.9	0.1791	15.8	1195.1	27.27
5-29	10-01	21.1	4.0±1.8	41.4	2.18	40.3	0.1767	19.1	1610.4	30.25
	10-06	21.2		41.4	2.16	40.3	0.1776	19.1	1606.3	30.25
	10-11	21.2		41.4	2.16	40.3	0.1769	19.1	1595.5	30.08
	10-16	21.2		41.4	2.16	40.3	0.1771	19.1	1598.2	30.10
5-29	11-42	21.8	5.0±2.2	41.4	2.48	40.2	0.1772	18.4	1839.8	35.88
	11-47	21.9		41.4	2.46	40.2	0.1780	18.3	1828.6	36.02
	11-52	21.8		41.4	2.48	40.2	0.1783	18.4	1845.1	36.15
	11-57	21.6		41.4	2.49	40.2	0.1777	18.6	1849.7	35.73

Aperture Area: 2.78 m^2

4.3 HEAT LOSSES: MEASURED AND DERIVED DATA

indoor : x

outdoor:

FLUID c_f $Jkg^{-1}K^{-1}$ TILT: 67.5

Date	LT	T_a	u_s	T_i	(T_i-T_e)	T_m	m	$(T_m-T_a)_1$	Q_1	U
D-M-Yr	Hrs-Mins	^oC	ms^{-1}	^oC	K	^oC	kgs^{-1}	K	W	$Wm^{-2}K^{-1}$
5-29	12-56	20.7	6.5±3.0	41.5	2.88	40.1	0.1777	19.4	2136.1	39.64
	13-01	21.0		41.5	2.84	40.1	0.1779	19.1	2108.6	39.68
	13-08	21.2		41.5	2.83	40.1	0.1782	18.9	2105.2	39.97
	13-13	20.4		41.5	2.89	40.1	0.1780	19.7	2146.2	39.27
5-24	09-11	21.0	0.16±0.13	31.8	0.39	31.6	0.1794	10.6	294.7	9.97
	09-16	21.0		31.8	0.40	31.6	0.1791	10.7	296.1	9.96
	09-21	20.9		31.8	0.40	31.6	0.1788	10.7	298.5	10.02
	09-26	20.9		31.8	0.39	31.6	0.1799	10.7	296.7	9.96

Aperture Area: 2.78 m^2

4.3 HEAT LOSSES: MEASURED AND DERIVED DATA

indoor : x

outdoor:

FLUID: c_f 4182 $Jkg^{-1}K^{-1}$ TILT: 67.5

Date	LT	T_a	u_s	T_i	(T_i-T_e)	T_m	m	$(T_m-T_a)_1$	Q_1	U
D-M-Yr	Hrs-Mins	^oC	ms^{-1}	^oC	K	^oC	kgs^{-1}	K	W	$Wm^{-2}K^{-1}$
5-24	11-31	20.3	1.1±0.6	31.8	0.64	31.5	0.1796	11.2	482.6	15.53
	11-38	20.3		31.8	0.65	31.5	0.1795	11.2	486.3	15.61
	11-43	20.4		31.8	0.65	31.5	0.1799	11.1	488.1	15.79
	11-48	20.4		31.8	0.65	31.5	0.1802	11.1	487.7	15.76
5-23	14-52	21.5	3.1±1.5	32.9	0.96	32.4	0.1828	10.9	730.5	24.15
	14-57	21.4		32.9	0.98	32.4	0.1825	11.0	749.1	24.57
	15-02	21.5		32.8	0.93	32.3	0.1817	10.9	709.1	23.35
	15-07	21.6		32.9	0.94	32.4	0.1820	10.8	711.6	23.63
5-24	13-08	22.5	1.9±0.9	31.9	0.67	31.6	0.1797	9.0	500.9	19.92
	13-15	22.6		31.9	0.66	31.6	0.1800	8.9	499.7	20.15
	13-20	22.6		31.9	0.66	31.6	0.1795	8.9	493.7	19.98
	13-25	22.7		31.9	0.68	31.6	0.1794	8.9	506.7	20.49

Aperture Area: 2.78 m^2

4.3 HEAT LOSSES: MEASURED AND DERIVED DATA

indoor : x
outdoor

FLUID: C_f 4182 $Jkg^{-1}K^{-1}$ TILT: 67.5

Date	LT	T_a	u_s	T_i	(T_i-T_e)	T_m	m	$(T_m-T_a)_1$	Q_1	U
D-M-Yr	Hrs-Mins	^oC	ms^{-1}	^oC	K	^oC	kgs^{-1}	K	W	$Wm^{-2}K^{-1}$
5-23	13-05	23.4	4.0±1.5	32.9	0.97	32.4	0.1827	9.1	739.2	29.32
	13-10	23.4		32.9	0.98	32.4	0.1822	9.1	747.1	29.54
	13-15	23.3		32.9	0.96	32.4	0.1823	9.2	735.1	28.81
	13-20	23.3		32.9	0.97	32.4	0.1823	9.2	739.9	29.03
5-23	09-49	23.2	6.5±3.0	31.9	1.16	31.3	0.1813	8.2	875.6	38.53
	09-54	23.2		31.9	1.14	31.3	0.1811	8.1	861.7	38.05
	09-59	23.2		31.9	1.15	31.3	0.1809	8.1	867.7	38.37
	10-04	23.2		31.9	1.15	31.3	0.1817	8.1	873.8	38.69
5-23	11-16	23.9	5.1±2.1	32.0	0.94	31.5	0.1822	7.6	718.7	33.98
	11-21	23.9		32.0	0.96	31.5	0.1818	7.6	731.9	34.51
	11-26	23.9		32.0	0.94	31.5	0.1820	7.6	714.8	33.91
	11-31	23.9		32.0	0.94	31.5	0.1815	7.6	712.0	33.62

Aperture Area: 2.78 m^2

ANNEX C: Measurements of energy output indoors and outdoors.

3.2 INSTANTANEOUS EFFICIENCY: MEASURED AND DERIVED DATA

Solar Simulator

FLUID: Water C_f $Jkg^{-1}K^{-1}$ TILT: 67.5^o

Date	LT	G		T_a	u_s	T_i	(T_e-T_i)	T_m	m	T^*	η
D-M-Yr	Hrs-Mins	Wm^{-2}	G_d/G	^oC	ms^{-1}	^oC	K	^oC	kgs^{-1}	Km^2W^{-1}	-%
5-02	15-08	919	0	29.9	"0"	28.8	3.16	30.4	0.1879	0.0006	97.3
	15-13	919	-	29.9		28.8	3.17	30.4	0.1877	0.0005	97.3
	15-18	919	-	29.9		28.7	3.17	30.3	0.1877	0.0005	97.4
	15-23	919	-	29.8		28.7	3.18	30.3	0.1871	0.0005	97.3
5-06	12-03	919	-	28.9	"0"	37.7	2.71	40.1	0.1880	0.0110	23.4
	12-10	919	-	28.9		37.7	2.70	40.1	0.1887	0.0110	83.2
	12-15	919	-	29.1		37.7	2.71	40.1	0.1888	0.0108	83.8
	12-20	919	-	29.2		37.7	2.72	40.1	0.1883	0.0108	83.6
5-09	14-23	907	-	27.5	1.3±1.2	35.2	2.56	36.5	0.1865	0.0100	79.2
	14-28	907	-	27.4		35.2	2.55	36.5	0.1867	0.0101	79.0
	14-33	907		27.4		35.2	2.56	36.5	0.1865	0.0100	79.0
	14-38	907	-	27.5		35.3	2.55	36.6	0.1864	0.0100	78.6
5-09	10-49	921	-	26.3	1.8±1.0	35.0	2.44	36.2	0.1862	0.0107	74.3
	10-54	921	-	26.3		35.0	2.45	36.2	0.1868	0.0107	74.6
	10-59	921	-	26.3		35.0	2.47	36.2	0.1863	0.0107	75.2
	11-04	921	-	26.3		34.9	2.48	36.1	0.1868	0.0107	75.6

Aperture Area 2.78 m^2

3.2 INSTANTANEOUS EFFICIENCY: MEASURED AND DERIVED DATA

Solar Simulator

FLUID: Water C_f $Jkg^{-1}K^{-1}$ TILT: 67.5^o

Date	LT	G	G_d/G	T_a	u_s	T_i	(T_e-T_i)	T_m	m	T*	η
D-M-Yr	Hrs-Mins	Wm^{-2}	%	^oC	ms^{-1}	^oC	K	^oC	kgs^{-1}	Km^2W^{-1}	-%
5-08	15-09	937	0	26.2	2.9±1.1	34.9	2.18	36.0	0.1872	0.0105	65.5
	15-14	937	-	26.4		35.0	2.17	36.1	0.1867	0.0103	65.0
	15-19	937	-	26.4		35.0	2.18	36.1	0.1867	0.0103	65.3
	15-24	937	-	26.5		35.0	2.19	36.1	0.1866	0.0103	65.5
5-07	12-35	932	-	25.7	4.1±1.9	35.3	1.87	36.2	0.1873	0.0114	56.6
	12-42	932	-	25.7		35.3	1.88	36.2	0.1872	0.0112	56.7
	12-47	932	-	25.8		35.3	1.89	36.2	0.1867	0.0112	57.0
	12-52	932	-	25.8		35.3	1.87	36.2	0.1877	0.0112	56.5
4-30	15-25	948	-	24.6	4.8±1.8	23.0	3.02	24.5	0.1869	-0.0001	89.5
	15-30	948	-	24.7		23.0	3.02	24.5	0.1872	-0.0002	89.8
	15-37	948	-	24.7		23.0	3.01	24.5	0.1877	-0.0002	89.6
	15-42	948	-	24.7		23.0	3.00	24.5	0.1877	-0.0002	89.4
5-02	12-42	935	-	24.9	6.3±2.3	23.5	2.86	24.9	0.1882	0.0000	86.6
	12-48	935	-	25.0		23.4	2.87	24.8	0.1881	-0.0001	86.9
	12-53	935	-	24.8		23.4	2.86	24.8	0.1877	0.0001	86.3
	12-58	935	-	25.0		23.4	2.84	24.8	0.1877	-0.0002	86.9

Aperture Area 2.78 m^2

3.2 INSTANTANEOUS EFFICIENCY: MEASURED AND DERIVED DATA

Solar simulator

FLUID Water C_f $Jkg^{-1}K^{-1}$ TILT 67.5^o

Date	LT	G	G_d/G	T_a	u_s	T_i	(T_e-T_i)	T_m	m	T*	η
D-M-YR	Hrs-Mins	Wm^{-2}	%	^oC	ms^{-1}	^oC	K	^oC	kgs^{-1}	Km^2W^{-1}	-%
5-07	15-11	914	36.1	26.5	4.7±1.45	34.6	1.83	35.5	0.1867	0.0099	56.1
	15-16	914	36.1	26.3		34.6	1.82	35.5	0.1868	0.0101	56.0
	15-21	914	36.1	26.4		34.6	1.83	35.5	0.1875	0.1000	56.4
	15-26	914	36.1	26.5		34.6	1.83	35.5	0.1865	0.0099	56.3
5-08	10-54	940	35.7	26.5	6.9±2.65	34.4	1.66	35.2	0.1861	0.0092	49.4
	10-59	940	35.7	26.5		34.4	1.67	35.2	0.1863	0.0093	49.8
	11-04	940	35.7	26.6		34.4	1.67	35.2	0.1866	0.0092	49.7
	11-09	940	35.7	26.5		34.4	1.66	35.2	0.1862	0.0093	49.5
5-13	11-18	924	49.3	27.4	0.4±0.2	47.5	2.17	48.6	0.1861	0.0229	65.8
	11-23	924	49.3	27.6		47.5	2.18	48.6	0.1861	0.0227	65.9
	11-28	924	49.3	27.5		47.5	2.18	48.6	0.1863	0.0228	66.0
	11-33	924	49.3	27.6		47.5	2.17	48.6	0.1859	0.0227	65.6
5-10					1.2±0.8						
	14-29	908	45.8	26.9		44.2	2.00	45.2	0.1868	0.0201	61.7
	14-34	908	45.8	26.2		44.2	1.98	45.2	0.1864	0.0208	61.1
	14-39	908	45.8	26.6		44.2	1.97	45.2	0.1873	0.0205	61.2
5-13	13-27	919	48.2	27.2	1.9±0.7	46.9	1.53	47.7	0.1929	0.0223	48.3
	13-32	919	48.2	27.4		46.9	1.54	47.7	0.1864	0.0222	46.9
	13-37	919	48.2	27.5		46.9	1.54	47.7	0.1859	0.0220	46.9
	13-42	919	48.3	27.5		47.0	1.55	47.8	0.1866	0.0220	47.4

Aperture Area:

3.2 INSTANTANEOUS EFFICIENCY: MEASURED AND DERIVED DATA

Solar simulator

FLUID: Water C_f $Jkg^{-1}K^{-1}$ TILT: 67.5^o

Date	LT	G	G_d/G	T_a	u_s	T_i	(T_e-T_i)	T_m	m	T*	η
D-M-Yr	Hrs-Mins	Wm^{-2}	%	^oC	ms^{-1}	^oC	K	^oC	kgs^{-1}	Km^2W^{-1}	-%
5-13	15-57	920	0	26.9	2.8±1.4	46.9	1.17	47.5	0.1870	0.0223	35.7
	16-02	920	-	27.0		46.8	1.16	47.4	0.1875	0.0222	35.7
	16-07	920	-	26.8		46.8	1.14	47.4	0.1873	0.0224	34.7
	16-12	920	-	26.8		46.8	1.14	47.4	0.1871	0.0223	34.8
13-6-85	13-23	928	0	24.6	1.9	25.8	3.27	27.4	0.1670	0.0031	88.7
	13-28	928	-	24.6	-	25.8	3.27	27.4	0.1672	0.0030	88.6
	13-33	928	-	24.6	-	25.8	3.28	27.4	0.1674	0.0030	88.9
	13-39	928	-	24.7	-	25.8	3.28	27.4	0.1666	0.0030	88.7
12-6-85	14-44	930	0	25.1	5.0	24.6	3.01	26.1	0.1700	0.0011	82.8
	14-49	930	-	25.2	-	24.6	3.03	26.1	0.1702	0.0010	83.4
	14-54	930	-	25.2	-	24.6	3.02	26.1	0.1704	0.0010	83.2
	14-59	930	-	25.1	-	24.6	3.02	26.1	0.1706	0.0010	83.4

Aperture Area: $2.78\ m^2$

3.2 INSTANTANEOUS EFFICIENCY: MEASURED AND DERIVED DATA

LATITUDE: 55.5

COLLECTOR AZIMUTH: 0

FLUID: Water C_f $Jkg^{-1}K^{-1}$ TILT: 45^o

OUTDOORS

Date	LT	G	G_d/G	T_a	u_s	T_i	(T_e-T_i)	T_m	m	T*	η
D-M-Yr	Hrs-Mins	Wm^{-2}	%	^oC	ms^{-1}	^oC	K	^oC	kgs^{-1}	km^2W^{-1}	-%
14-5-85	13-06	877		21.8	6.5	18.7	2.72	20.1	0.1831		85.5
	13-12	878		22.0	-	18.7	2.74	20.1	0.1834		86.2
	13-17	880		22.4		18.7	2.78	20.1	0.1828		86.8
	13-22	885		22.6		18.8	2.82	20.2	0.1827		87.7
20-5-85	13-09	991		18.9	6.5	18.7	2.78	20.1	0.1822		76.9
	13-14	994		19.0	-	18.2	2.82	19.6	0.1820		77.9
	13-19	994		18.6	-	18.0	2.79	19.4	0.1817		77.0
	13-24	993		19.2	-	17.9	2.79	19.3	0.1821		77.1
20-5-85	13-41	977		20.6	1	18.3	3.04	19.8	0.1830		85.7
	13-46	975		20.9	-	18.4	3.06	19.9	0.1832		86.6
	13-51	968		21.1	-	18.5	3.05	20.0	0.1831		86.8
	13-56	964		21.2	-	18.5	3.06	20.0	0.1836		87.9
21-5-85	9-08	410		20.8	0.7	23.9	0.80	24.3	0.1840		53.9
21-5-85	13-02	960		22.8	0.7	24.8	2.83	26.2	0.1837		81.4
	13-07	963		23.5	-	24.8	2.83	26.2	0.1839		81.3
	13-12	967		23.6	-	24.8	2.83	26.2	0.1839		80.9
	13-17	966		23.7	-	24.9	2.86	26.3	0.1840		82.0

Aperture Area 2.78 m^2

ANNEX D: Proposal for a test procedure for uncovered fully wetted solar collectors.

PROPOSAL FOR A TEST PROCEDURE FOR UNCOVERED FULLY WETTED SOLAR COLLECTORS.

This proposal is only to be used for solar collectors without cover and with a fully wetted absorber. Only dry operation of the collector is considered.

Model of energy output

(D.1) $$q_u = \alpha G - h_{tc}(T_{pt} - T_{at}) - \varepsilon_{pt}\sigma(T_{pt}^4 - T_{st}^4) - h_{bc}(T_{pb} - T_{ab}) - (\sigma/(1/\varepsilon_{pb} + 1/\varepsilon_{sb} - 1))(T_{pb}^4 - T_{sb}^4)$$

q_u is the energy output, W/m^2

α is the solar absorptance of the absorber

G is the solar irradiance, W/m^2

T_{pt} is the temperature of the absorberplate at the top, K

T_{pb} is the temperature of the absorberplate at the back, K

T_{at} is the temperature of the air at the top, K

T_{ab} is the temperature of the air at the back, K

T_{st} is the temperature of the surroundings at the top, K

T_{sb} is the temperature of the surroundings at the back, K

h_{tc} is the convective heat transfer coefficient at the top, W/m^2K

h_{bc} is the convective heat transfer coefficient at the back, W/m^2K

ε_{pt} is the emittance of the absorberplate at the top

ε_{pb} is the emittance of the absorberplate at the back

ε_{sb} is the emittance of the surroundings at the back

σ is Stefan-Boltzmans constant.

Test prodecure

The absorptance and emissivity are measured according to existing standards or recommendations. The convective heat loss coefficient at the top of the collector is measured in the following way. The collector is insulated at the back and air is blown along the top surface. The heat loss is measured for different air velocities. During the heat loss measurements the following temperatures are measured, the fluid inlet and outlet temperature, the average collector surface temperature, the average air temperature at the top of the collector, the air temperature at the back of the collector and the black-body temperature of the surroundings in front of the collector. The heat loss coefficient of the back insulation h_c is calculated.

The heat loss coefficient at different air velocities are found from the equation:

(D.2) $$h_{tc} = (q_{loss} - \varepsilon_{pt}\sigma(T_{pt}^4 - T_{st}^4) - h_c(T_m - T_b))/(T_{pt} - T_{at})$$

where q_{loss} is the heat loss per unit area, Wm^{-2}. From the same results the heat transfer coefficient from the absorber surface to the fluid can be found using the following equation:

(D.3) $$h_{it} = (q_{loss} - h_c(T_m - T_b))/(T_m - T_{pt})$$

Both h_{tc} and h_{it} can also be found from solar simulator tests and that should be done if the collector is sensible to the direction of the heat flow.

At the back of the collector h_{bc} and h_{ib} can be found in similar ways but h_{ib} will typically be equal to h_{it} and it may therefore not be measured. The convective heat loss coefficient at the back will typically be the same as at the top but the air velocity will of course be different and will be much influenced by the way in which the collector is mounted on the roof. All testing of the convective heat transfer coefficients may therefore be left out.

Instrumentation

In addition to instruments typically used in collector testing the following instruments are needed for testing uncovered collectors according to the procedure described above.

The temperature of the absorber surface can be measured with radiation thermometers. The sensor should be held in such a way that the heat transfer due to heat loss or solar irradiance is not disturbed. An example of a radiation thermometer is shown in figure D.1. For collectors with a non-uniform temperature distribution at the surface it may be easier to use a thermovision equipment. That technique should only be used in heat loss situations and for non-selective absorbers in order to avoid the influence of reflected thermal radiation.

Thermal radiation from the surfaces in front of the collector can be measured with a pyrgeometer. The Eppley pyrgeometer is shown in figure D.2; it can even be used in solar irradiated situations and is therefore necessary in solar simulator tests.

In measurements without solar irradiance the thermal radiation from the absorber and from the surroundings can be measured with a single instrument and that is the indoor climate analyzer, type 1213 manufactured by Brüel & Kjær. Shown in figure D.3.

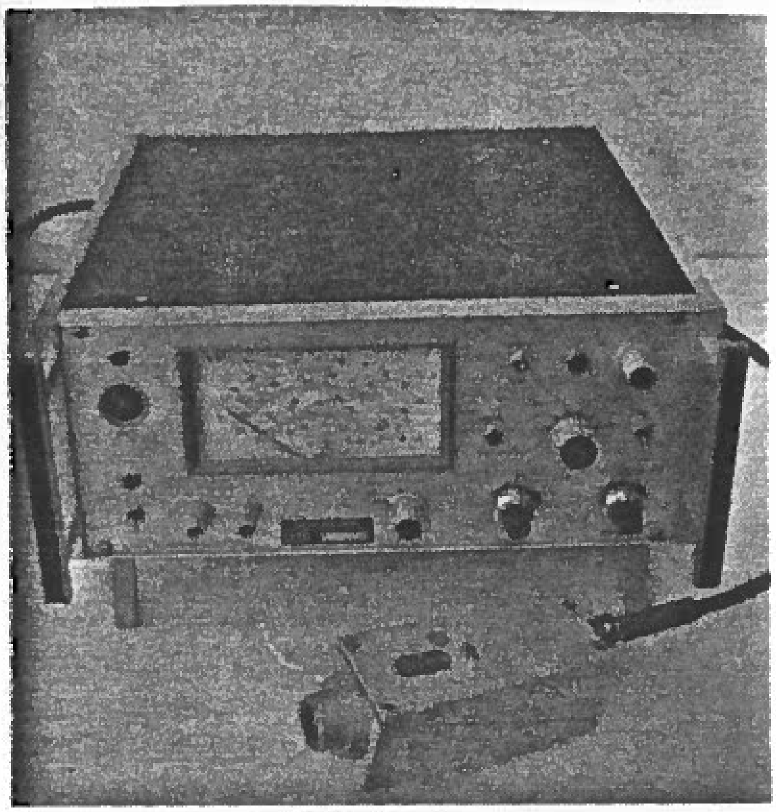

Figure D.1. Radiation thermometer, Heimann KT16.

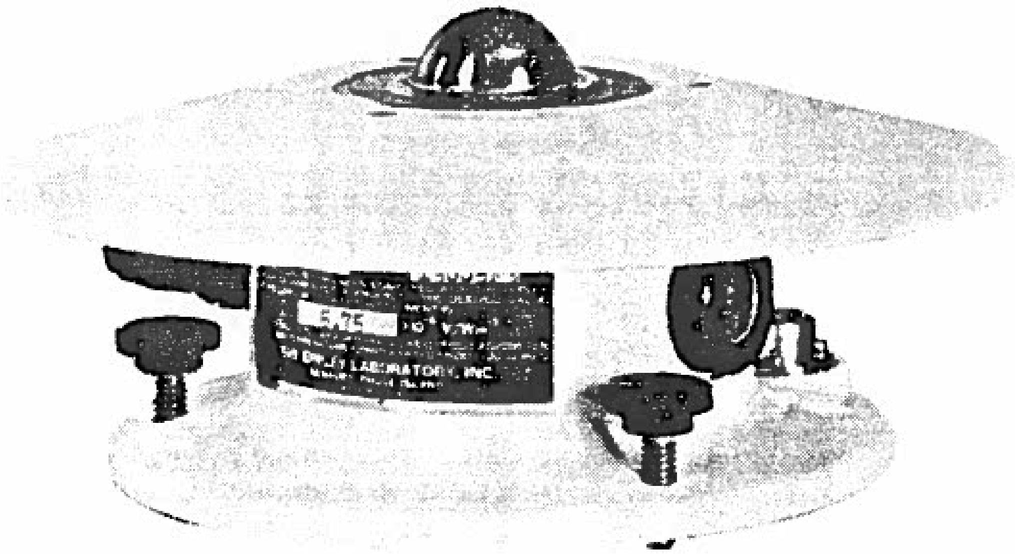

Figure D.2. Infrared radiometer or pyrgeometer, Eppley PIR.

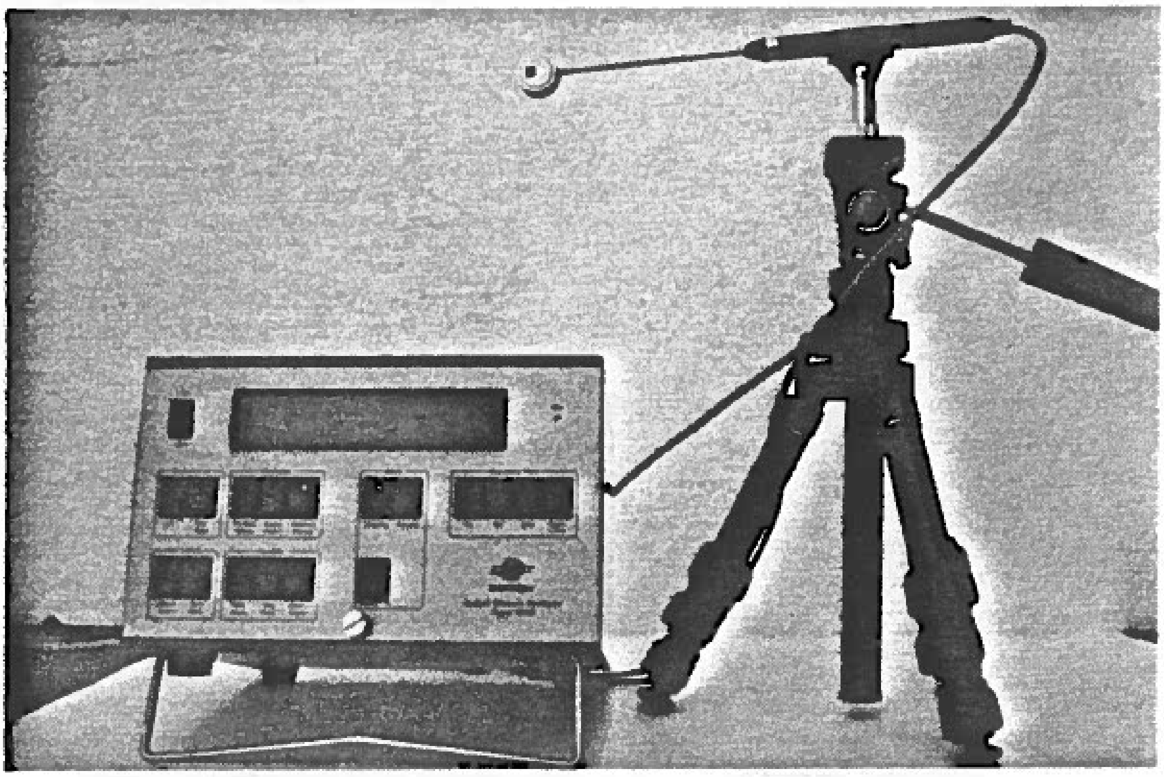

Figure D.3. Indoor climate analyzer, Brüel & Kjær 1213.