METHODOLOGY OF TESTING AND DATA PROCESSING TO PREDICT THE MAIN THERMAL CHARACTERISTICS OF FLAT-PLATE WATER COOLED SOLAR COLLECTORS

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Abstract

Around a year ago, the test station for flat-plate water cooled solar collectors has been put in operation and equipped with all measuring equipment and instrumentation including data acquisition and processing system at the Mechanical Engineering Faculty in Sarajevo.
A short technical description of operational flow diagram including data acquisition system and its "interconnection" with the relevant software interfacing for results evaluation, for the Solar Testing Station, is presented.
Using this station the main thermal characteristics of tested solar collectors have been obtained in accordance with appropriate testing methods given in ASHRAE Standard 93-86 and European standard EN 12975-2. The value of time constant of solar collector and graphics review of functions of thermal efficiency and incident angle modifier, as a final report of this kind of test, is shown and discussed.
This new methodology of testing and data processing will be compared with 1978 ASHRAE methodology. Measurement techniques and the results of the latest tests will be analyzed, and compared with data obtained by 1978 ASHRAE procedure.

Key words: Flat plate solar collector, Thermal efficiency, test station

1. INTRODUCTION

Solar testing station built firstly in mid 80's is reconstructed, enabled to satisfy very strict investigation requirements, by Standard EN 12975-2 and ASHRAE 93-86, and put into operation last year at the Mechanical Engineering Faculty, Sarajevo. Earlier problems connected with very slow achievement of steady state operation is resolved by more modern approach of reconfiguration of distribution lines of the working fluid, as well as by building in more precise heater control, that was able to regulate working fluid temperature within ± 0,1 ^{o}C. The new wind simulator was built in also, enabling maintenance of the required wind velocity above the collector plane. Very precise measurement equipment is acquired, enabling continuous data collection for outside air conditions and incoming solar radiation, as well as measurement of all parameters of the working fluid (temperatures, water flow rate etc.).
Two water cooled flat collectors were tested according to the new Standards. The results of the measured thermal parameters with the relevant comments are presented in the paper. These results are compared with the test results obtained in mid 80's.

2. TEST STATION TECHICAL DESCRIPTION

Basic criteria satisfied during the test station reconstruction were: universal applicability for standard collector modules, autonomy of operation, and solar collector positioning at any solar and/or azimuth angle.

Testing station supporting construction consists of two parts.

- Movable support casing which can rotate in a horizontal plane
- Collector carrying frame with adjustable angle towards horizontal plane

Such a solution of the testing station construction enables investigations by the system "ALTAZIMUTH".

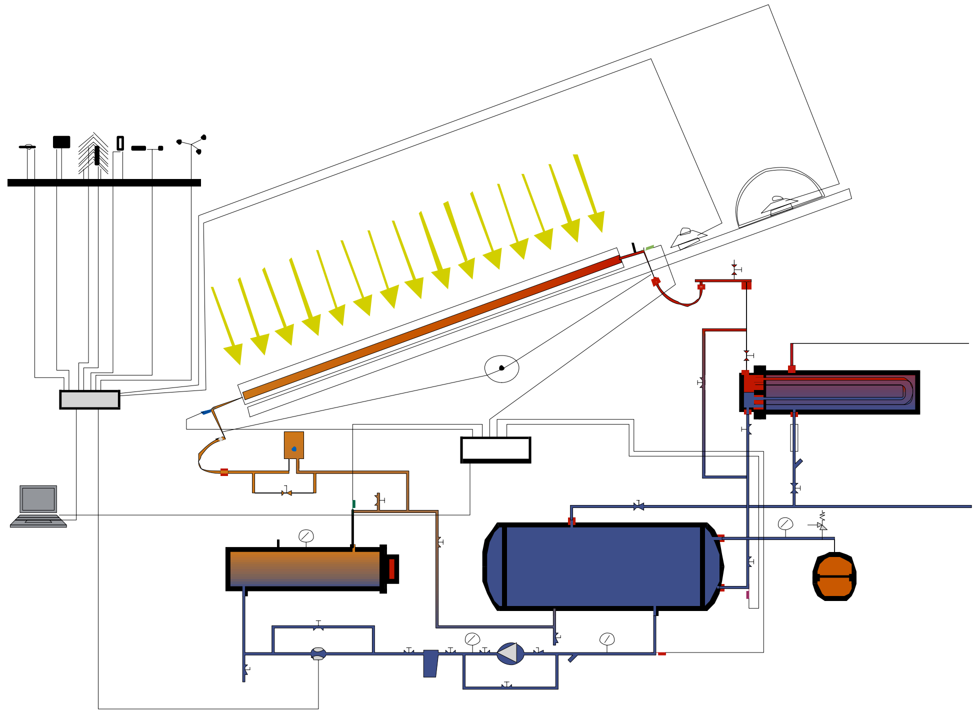


Figure 1: Testing station technological scheme

Inside part of the test station construction is used to place necessary heating/cooling and measuring equipment and other relevant apparatus needed for normal functioning of the closed loop experimental setup. Detailed description of this equipment and its position with relevant piping of distributing lines of the working and cooling medium, including a position of measuring points/instruments, is shown in technological-functional scheme of the testing station, in Figure 1. Closed loop after air venting testing station operates under gage pressure of 1.5 bar. Testing procedure starts by specification of the working medium flow rate. The second quantity to be specified in the measuring procedure is inlet medium (water) temperature, which is to remain constant during one set of measurement.
A rough regulation of this temperature is done by switching on one of three electrical heaters (power 3x2 kW) as needed. A fine regulation is achieved by very precise current flow through heater, by changing its voltage/resistance. This enables the maintenance of the wished working medium temperature within ± 0,1 ^{o}C. Working medium after passing through the solar collector is cooled down in an heat exchanger by the city water (average temperature 11 ^{o}C). All the distribution lines are well insulated. All the regulation procedure is realized by the use of the relevant PC, from one central place inside the room (behind the testing station).

3. BASIC INFORMATION RELATED TO MESUREMENT OF SOLAR COLLECTOR PERFORMANCES ACCORDING TO ASHRAE Standard 93-86 and EN 12975-2

Around the world there exists a number of acceptable/verifiable methods of solar collectors testing. Having this in mind and the fact that we wanted to test the collectors under the real outside weather conditions as prevails in Sarajevo, our attention was directed on two very similar standards: ASHRAE Standard 93-86 and EN 12975-2. In the text to follow, a short description of the basic notions related to measurement solar collector thermal performances is given, as well as, pointing out basic differences between these two standards.

In order to obtain a complete Certificate according to EN 12975-2 Standard it is necessary to make a number of different tests. Thus, some of these tests are related to physical/mechanical quality of the collector in connection with durability and reliability during the normal life time, e.g. testing on inside operating pressure in collector absorber, absorber maximum operating temperature, collector resistance on mechanical loads, etc.
Solar collector thermal performances are related to determination of the collector ability to collect heat of solar radiation and to deliver a useful heat. By this test one determines crucial thermal operating performances of the solar collector:

1. *Instantaneous solar collector efficiency*
2. *Incident angle modificator of solar radiation on the solar collector*
3. *Solar collector time constant*

One may write the governing equation for instantaneous thermal efficiency of the solar collector as follows:

$$\eta = \frac{Q}{A_g \cdot G_t} = F_R(\tau\alpha)_e - F_R U_L \frac{(t_1 - t_a)}{G_t} \tag{1}$$

$$K_{\tau\alpha} = \frac{(\tau\alpha)_e}{(\tau\alpha)_n} \tag{2}$$

The equation (1) represents, in a way, the useful energy obtained at the exit of the collector, when the collector is exposed to real external conditions, for the defined level of a working medium at the collector entrance. In a graphical interpretation of the collector thermal, equation (1) represents a straight line which is cutting of a line length on "y" axis, which corresponds to the product F_R and $(\tau\alpha)_e$, and are obtained experimentally during the collector operation under the conditions, which are very similar to exploitation conditions, implying an incident of solar radiation smaller than 30 ^{o}, towards normal direction on the collector plane.

Incident angle modifier ($K_{\tau\alpha.}$), shown by equation (2), represents a ratio of an effective product of transmission and absorption coefficients at some direct solar radiation incident angle $(\tau\alpha)_e$ and the same product $(\tau\alpha)_n$, but for 0^o incident angle of direct solar radiation.

Since the dependence of the product $(\tau\alpha)_e$ from the incidence angle of the direct solar radiation is a variable quantity, and it changes from the collector to the collector, hence the standard collector testing procedure requires experimental determination of the incident angle modificator for each collector separately.
Solar collector time constant is the first solar collector characteristic to be determined in the process of its certification and/or thermal performances evaluation. Its value represents the solar collector time response, that is, the quality mark of the collector behavior in the transient operation times, irrespective on the cause of this behavior, which may influence on the sudden changes of the collector heat balance. By the definition, it is a time, in which, the exit temperature of the working medium will drop on nearly one third of its value, due to shadow on the upper collector surface, as shown by equation (3).

$$\frac{t_{2,\tau_2} - t_{1,\tau_1}}{t_{2,\tau_1} - t_{1,\tau_1}} = 0.368 \tag{3}$$

$$x = \frac{t_1 - t_a}{G_t} \tag{4}$$

By the graphical interpretation of thermal efficiency function of solar collectors, one of the first steps is determination of variable, ”x”, as a function of measuring quantities for each single test, in an agreement with the equation (4).

Based on at least 16 independent values of the variable “x”, one calculates the thermal efficiency of the solar collector, as shown by the equation (5).

Based on this, the calculated values of “η” are introduced into the relevant diagram. Using standard procedure of regression analyses, the relevant equation of the collector thermal efficiency is obtained. Usually, it is a straight line, or the second order polynomial. It is not allowed to do any extrapolations outside the bordering-measuring points.

$$\eta = \frac{\int_{\tau_1}^{\tau_2} \dot{m} c_f \left(t_2 - t_1\right) d\tau}{A_g \int_{\tau_1}^{\tau_2} G_t d\tau} \tag{5}$$

During each single point test it is necessary to determine-measure the following quantities, with the relevant accuracy: G_t - total solar radiation on the plane coplanar to the solar collector plane; m – mass or volumetric flow rate of the working medium; t_1– collector inlet temperature of the working medium; t_2 – solar collector exit temperature of the working medium; t_a – ambient air temperature; c_f – average value of the specific heat of the working medium.

Testing time for each test point depends on the solar collector time constant, but it is never less than 5 minutes. The time length, required to maintain steady state, before starting each test, is equal to three values of the solar collector time constant, or 15 minutes, whichever is the greater.

In order to have acceptable testing results, the following conditions have to be met:

- The average value of the total solar radiation on the collector plane, during the test duration, must not be less than 790 W/m^2,
- Direct solar radiation incident angle and collector plane normal, must be less than 30º,
- Diffuse radiation part in the total solar radiation must not be greater than 20%,
- Ambient air temperature: $t_a < 30\ ^oC$
- Air velocity, u, measured 50 mm above the solar collector plane : 2.2 < u < 4.5 m/s.

It was pointed out earlier that, in order to determine the solar collector thermal efficiency function, it is necessary to perform 16 independent tests, at 4 temperature levels of the inlet temperature of the working medium. To each inlet temperature correspond 4 single tests at the different day time periods, two before, and two after the local solar noon time, ordered/set symmetrically.

Inlet temperature levels of the working fluid are : **1st**. level: $t_1 \sim t_a$, where, $\eta_1 = \eta_{max}$; **2nd**. level: t_1, where, $\eta_2 = 0{,}7\ \eta_{max}$; **3rd**. level: t_1 , where, $\eta_3 = 0{,}4\ \eta_{max}$; and **4th**. level: t_1 where, $\eta_4 = 0{,}1\ \eta_{max}$.

Water cooled flat solar collectors thermal characteristics testing procedures by ASHRAE 93-86 and EN 12975-2 standards do not have essential differences in the measuring procedures. Some of the differences in EN 12975-2 standard compared to ASHRAE 93-86 standard are:

- Different values of operating temperatures when determining the thermal efficiency function,
- Calculation of instantaneous thermal efficiencies for each single test,
- Argument, x, calculation (in equations (4) and (5)) for calculation of thermal efficiency function (η=f(x)), by using an average working fluid temperature, during the test duration,

- Test time duration and time length to maintain the steady state before each test starting time,
- Different forms of the results presentation.

4. COLLECTOR TESTING AND RESULTS INTERPRETATION

During the time period (August – September) 15, 2003. the measurements were performed, in order to determine thermal performances of two different producers solar collectors. Technical information and data for the relevant collector are shown in the graphs below.

Testing location was the flat roof of the Mechanical Engineering Faculty building, Sarajevo, which allows an ideal exposition of the testing station to the south direction, free of any obstructions, sun reflections, etc.; Geographical location of the measuring location is: Latitude: 43° 52' North; Longitude: 18° 24' East and height above the sea level: 532 m.

<u>Solar collector time constant measurement:</u>

Table 1 is showing basic testing information. Figure 2 is showing temperature changes for both the collectors. Note (Figure 2), water exit temperature decreases, after the collector is shadowed, down to the value obtained by solving equation (3). If the obtained results are compared, one may see that the collector 1 is more inert than collector 2. This drawback comes directly from the greater thermal capacity of the collector type 1.

Table 1

Collector type	Testing time data			Angles				Ambient air state		
	Date	Test start time LT	Test start time LS_oT	δ	β	γ	θ	t_a	Wind velocity	Wind direction
		Hour min	Hour min	[°]	[°]	[°]	[°]	[°C]	m/s	
Type 1	21.08.03	13^{30}	13^{40}	11,8	20	0	27	28,3	0.966	S-W
Type 2	28.08.03	13^{41}	13^{53}	9,2	20	0	29	29,9	0.429	N-W

Table 1 : continued

Collector type	Heat transfer fluid						Solar radiation data				Results	
	$(t_1)_o$	$(t_2)_o$	c_f	ρ	$\dot{V}$	Δp	G_t	G_d	G_b	G_d	**$(t_2)_1$**	**VK**
	[°C]	[°C]	J/kgK	kg/m^3	l/min	bar	W/m^2	W/m^2	W/m^2	%	**[°C]**	**[s]**
Type 1	28,8	35,6	4179	995	2,367	0,12	905	139	766	15,4	**31.1**	**60**
Type 2	30,4	37,3	4179	995	2,085	0,053	831	101	730	12,2	**33.0**	**160**

Based on the interpretation of the obtained values of the collector time constants, one may conclude that all single measurements to determine thermal efficiency of the solar collector and incident angle modifier, may be limited to 5 min (300 s).

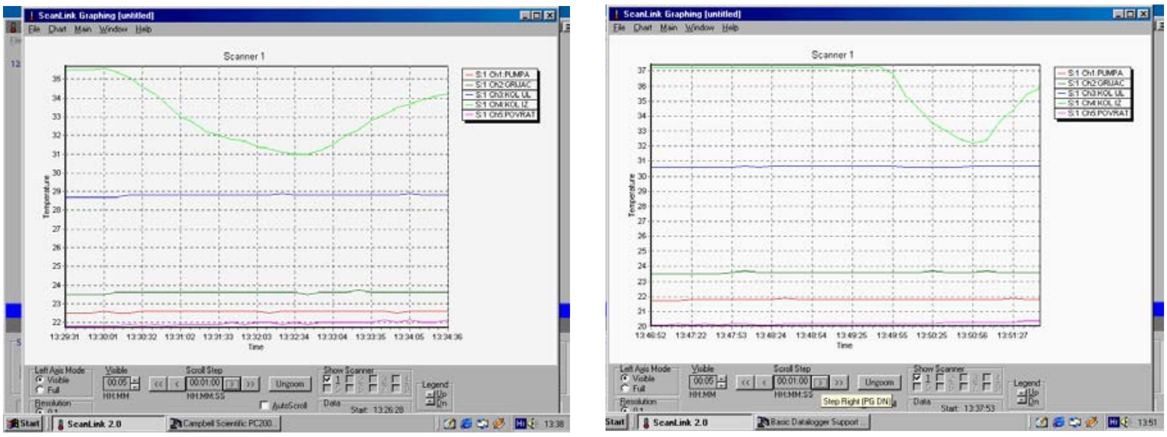
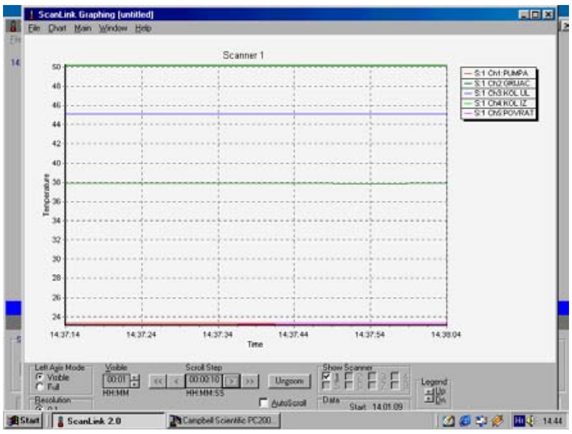


Figure 2. Graphical representation of working fluid temperature changes in the process of the time constant determination for collectors type 1 and type 2

Thermal efficiency function determination

During the testing process all the relevant requirements by the testing Standard were respected. Figure 3 is showing the working fluid temperature changes during one measurement. From this figure, one may see that the temperature lines are horizontal, and from the measuring data one can see that the temperature variation was within limits of 0,1 ^{o}C. Similarly, in Figure 4, and from the relevant measurements data, one may see that the changes of solar radiation intensity were within 32 W/m^2.



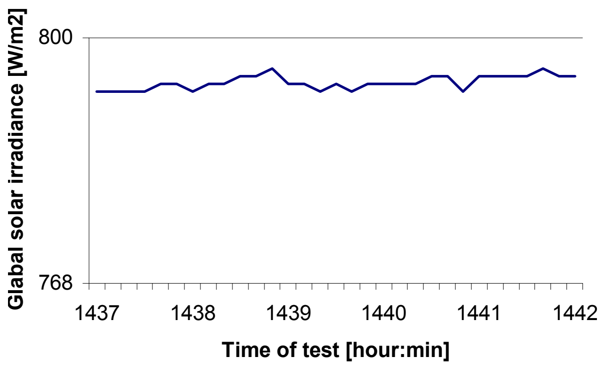


Figure 3: Graphical presentation of steady state achievement during the realization of one single test to determine the solar collector thermal efficiency function

Figure 4: Total solar radiation change during the testing

Table 2 contains the summary survey of all the tests – measurements performed for the collector type 1. Figure 5 is showing graphical representation of the thermal efficiency function for collector type 1. Figure 6 is showing comparative representation of three thermal efficiencies for 2 different collectors. Type 1 of the collector (built 25 years ago) has two curves one from the testing year 1978, and another one from the year 2003. This implies a deterioration of the thermal characteristics of this collector (which was not used in meantime), most probably due to aging, tightness decrease etc. As far as the thermal characteristics of the collector type 2, one may state that its thermal characteristics are much better in the whole testing range of the argument, x.

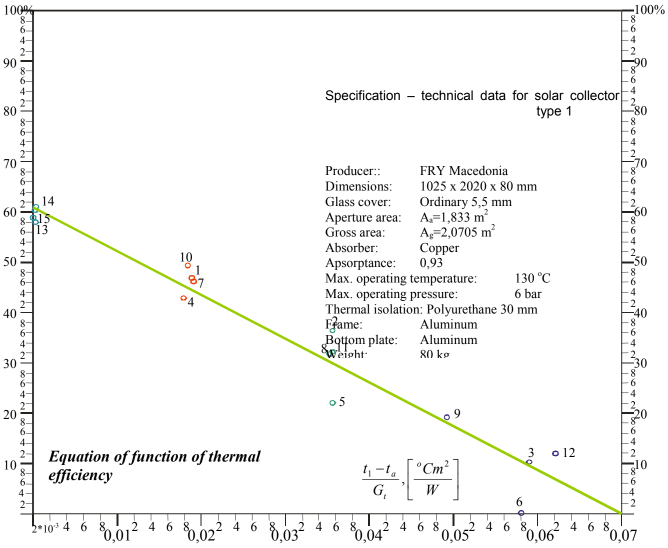


Figure 5: Graphical representation of the thermal efficiency function for collector type 1

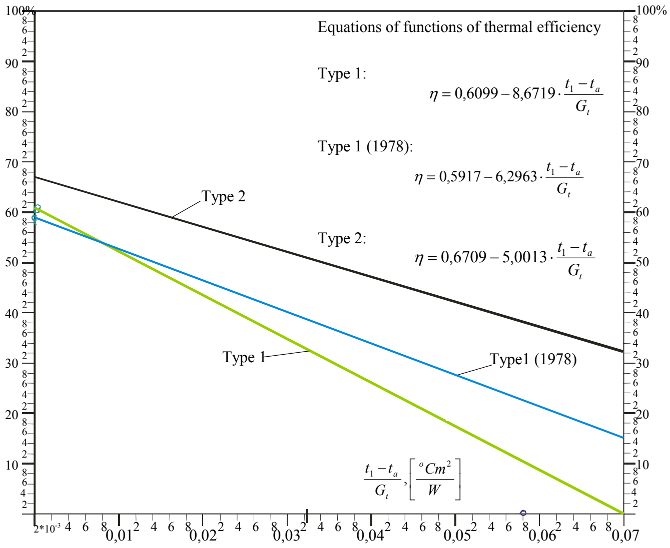


Figure 6: Comparative representation of the thermal efficiency of three different collectors

Table 2: Summary survey of data for testing collector type 1

Temp. range	Test number	Date (all0.8.03)	Testing time, Test start: LT	LS$_o$T	Angles: δ	β	γ	θ	Ambient air state: t_a	Wind velocity	Wind direction	Heat transfer fluid (all Δp = 0.12 bar): t_1	t_2	c_f	ρ	[illegible]	Solar radiation data: G_t	G_d	G_b	G_d	Results: x	η
[°C]			sat min	sat min	[°]	[°]	[°]	[°]	[°C]	m/s		[°C]	[°C]	J/kgK	kg/m³	l/min	W/m²	W/m²	W/m²	%	°Cm²/W	
45	1	14.	1310	1318	14,1	5	0	30	28,5	0,181	N-W	44,9	50	4180	989	2,399	868	157	711	18	0,018894	0,469
60	2	14.	1345	1350	14,1	15	0	30	28,5	1,139	N-W	59,1	63	4185	983	2,427	860	145	715	16,9	0,035581	0,364
80	3	14.	1435	1440	14.1	30	20	30	29	0,129	W	78,1	77	4195	973	2,382	832	143	689	17,2	0,059014	0,103
45	4	14.	1523	1531	14.1	30	45	30	30	0,362	S-W	45,1	49,7	4180	989	2,397	844	143	701	16,9	0,017891	0,435
60	5	14.	1540	1548	14,1	45	45	27	30	0,186	S-W	59,8	62,1	4185	983	2,422	836	161	675	19,3	0,035646	0,221
80	6	14.	1610	1618	14.1	50	60	22	30	0,219	S-W	76,5	76,6	4194	974	2,424	801	143	658	17,8	0,058052	0,010
45	7	17.	1138	1147	13.1	5	0	26	28,5	0,230	S-W	45	50	4180	989	2,420	865	108	757	12,5	0,019075	0,462
60	8	17.	1202	1211	13,1	0	0	30	29	0,336	W	60,3	63,8	4186	982	2,435	887	106	781	12,0	0,035287	0,318
80	9	17.	1242	1251	13.1	5	0	28	30	0,530	N-W	75,2	77,4	4180	989	2,412	918	99	819	10,8	0,049237	0,192
45	10	17.	1348	1357	13.1	20	0	30	29	0,370	S-W	45,1	50,5	4180	989	2,405	875	99	776	11,3	0,0184	0,494
60	11	17.	1415	1424	13,1	30	10	30	30	0,185	S-W	60,2	63,6	4186	982	2,427	848	102	746	12,0	0,035613	0,322
80	12	17.	1449	1458	13.1	30	30	29	30	0,367	N-W	79,4	80,6	4197	972	2,412	795	100	695	12,6	0,062138	0,120
30	13	21.	1048	1058	11.8	5	0	30	23	0,306	N	23,2	28,7	4187	997	2,387	760	112	648	14,7	0,000263	0,580
30	14	21.	1119	1129	11.8	60	0	29	24,8	0,269	N-W	25,1	32,1	4180	996	2,374	912	30	882	3,3	0,000329	0,611
30	15	21.	1241	1251	11.8	30	0	13	28,2	0,654	S	28,2	36,1	4179	995	2,354	1056	38	1018	3,6	0	0,589
30	16	21.	1315	1325	11.8	10	0	29	28,3	0,513	S-W	28,5	35,5	4179	995	2,365	917	146	771	15,9	0,000218	0,604

5. CONCLUSIONS AND RECOMMENDATIONS

- From the information presented one may conclude that the reconstruction of the solar testing station was successful.
- The testing station is equipped with all the necessary instrumentation to determine solar collector thermal characteristics by both the standards, ASHRAE and EU.
- The next step of the activities is a comparison of the investigation results for the solar collectors already tested by the different laboratories, in order to verify the quality and the accuracy of the testing station.

6. REFERENCES

J. A. Duffie, W. A. Beckman: Solar Engineering of Thermal Processes. John Wiley & Sons, New York, 1985.

Method of Testing to Determine the Thermal Performance of Solar Collectors, ASHRAE ANSI/ASHRAE 93-1977.

Methods of Testing to Determine the Thermal Performance of Solar Collectors; ASHRAE, ANSI/ASHRAE 93-1986 (RA 96).

Thermal Solar Systems and Components – Collectors Part 1: General requirements, prEN 12975-1:1997.

Thermal solar systems and components – Collectors Part 2: Test Methods, prEN 12975-2:1997.

E. Kulić, M. Korić: Solar testing station for testing flat-plate water cooled solar collectors, Interklima, Zagreb, April, 26-27, 2001.