Efficiency of flat-plate solar collector

PREFACE

Thermal solar collectors are devices that intercept incoming sun radiation and transform it into a heat which is transfered to medium, such as water, air or solar fluid (glycol/water mixture).

Solar heat can be used:

- to supply heating system,
- to heat up domestic water,
- for heating swimming pools,
- as heat for industrial processes.

The most common solar collectors are:

- flat-plate collectors,
- evacuated-tube solar collectors,
- concentrating solar collectors,
- unglazed solar collectors (heating swimming pools).

FLAT-PLATE COLLECTOR CONSTRUCTION

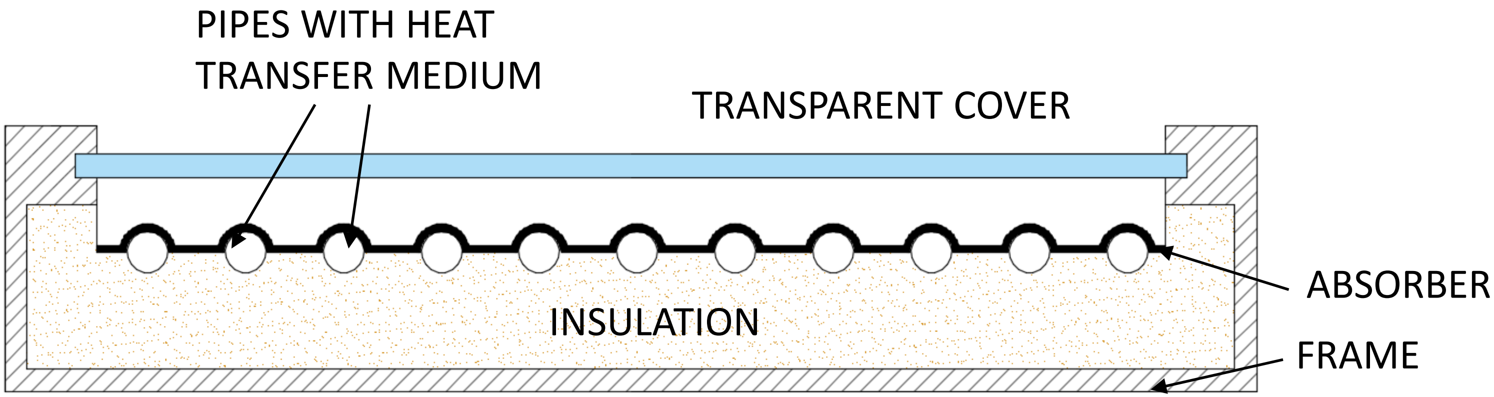


Fig. 1. Sketch of flat solar collector (Source: personal collection)

- **transparent cover** – usually made from solar safety glass; it transmits a great amount of the short-wave light spectrum and prevents the heat losses of collector; cover protects the collector against adverse wheather conditions and mechanical damage,
- **frame** – housing typically made from light-weight material such as aluminum and galvanized steel, fiberglass-reinforced plastic,

Flat-plate collector construction

- **system of pipes** – made of cooper or aluminium and integrated with absorber strip, filled with medium that collect the produced heat from absorber,
- **absorber** – composed of copper or aluminum sheet, collects the solar energy and converts it into heat; the absorber is covered with a selective layer that has the property of high absorption of solar radiation (around 90–95%) and at the same time low emission of infrared radiation (around 5–10%); the absorption layer may be based on black chrome or on oxides of titanium and silicon,
- **insulation** – covers the back of the absorber and the side walls, made from material resistant to high operating temperatures of low heat conduction coefficient, low density and water absorption (mineral wool, polyurethane foam, glass wool, rock wool, fibreglass); insulation ensures low heat losses to the environment.

SOLAR COLLECTOR EFFICIENCY

The **solar energy collection efficiency** is defined as the quotient of usable thermal energy leaving the collector versus usable solar energy falling on the aperture area. If solar irradiance equals 1000 W/m^2 and collector produces at the same time 750 W/m^2, its efficiency equals 75%.

$$\eta_h = \frac{Q_u}{A \cdot E} \qquad (1)$$

where:

Q_u – rate of (useful) energy output [W],

A – aperture area of the collector [m^2],

E – solar irradiance falling on collector aperture [W/m^2].

SOLAR COLLECTOR EFFICIENCY

The useful energy Q_u for the solar collector is the rate of thermal energy leaving the collector, that is the rate of the heat energy being added to fluid passing through the collector:

$$Q_u = \dot{m}_w \cdot c_p \cdot \left(T_{out\ I^\circ} - T_{in\ I^\circ}\right) \quad [W] \qquad (2)$$

where:

m_w – mass flow rate of heat transfer fluid [kg/s]

c_p – specific heat of heat transfer fluid, 4180 J/(kg·K),

$T_{out\ I^\circ}$ – temperature of heat transfer fluid leaving the absorber [˚C],

$T_{in\ I^\circ}$ – temperature of heat transfer fluid entering the absorber [˚C].

SOLAR COLLECTOR EFFICIENCY

Efficiency of solar collector is variable at the time and depends on many parameters:

- collector construction (flat-plate, evacuated tube),
- type of insulation,
- type of cover,
- absorber construction and material,
- solar irradiance,
- heat transfer medium flow,
- temperature of the collector.

The higher difference between ambient and absorber surface temperature, the lower efficiency. Decrease of medium flow causes the increase of its output temperature and lower efficiency of solar collector. Increase of operating temperature of heat transfer medium increases heat losses and decreases its efficiency. For this reason it is recommended to use solar collectors with low-temperature heating systems.

SOLAR COLLECTOR EFFICIENCY

The constant parameter that describes each solar collector is **optical efficiency η_0**. This is the maximum efficiency of particular type of solar collector if there is no heat losses to environment (no difference between ambient and absorber surface temperature). Optical efficiency η_0 indicates the ratio of the solar rays being absorbed to the solar rays penetrating the transparent cover of the collector (transmission). It depends on the rate of transmission of the cover and the absorption rate of the absorber. Higher value of optical efficiency, better ratio of solar energy tranformation to heat energy.

SOLAR COLLECTOR EFFICIENCY

When solar collector operates, the heat losses to environment appear, so the efficiency of collector decreases and can be determined from formula:

$$\eta = \eta_o - \frac{a_1 \cdot (T_{I^\circ} - T_a)}{E} - \frac{a_2 \cdot (T_{I^\circ} - T_a)^2}{E} \qquad (3)$$

where: a_1 – 1st order heat loss coefficient [W/m²K],
a_2 - 2st order heat loss coefficient [W/m²K²],
T_a – temperature of the ambient air [°C],
T_{I° – mean collector fluid temperature [°C]:

$$T_{I^\circ} = \frac{T_{in\,I^\circ} + T_{out\,I^\circ}}{2} \quad [K] \qquad (4)$$

T_{inI° – input collector fluid temperature [°C],
T_{outI° – output collector fluid temperature [°C].

SOLAR COLLECTOR EFFICIENCY

The higher values of heat loss coefficients a_1 and a_2, the lower solar collector efficiency.

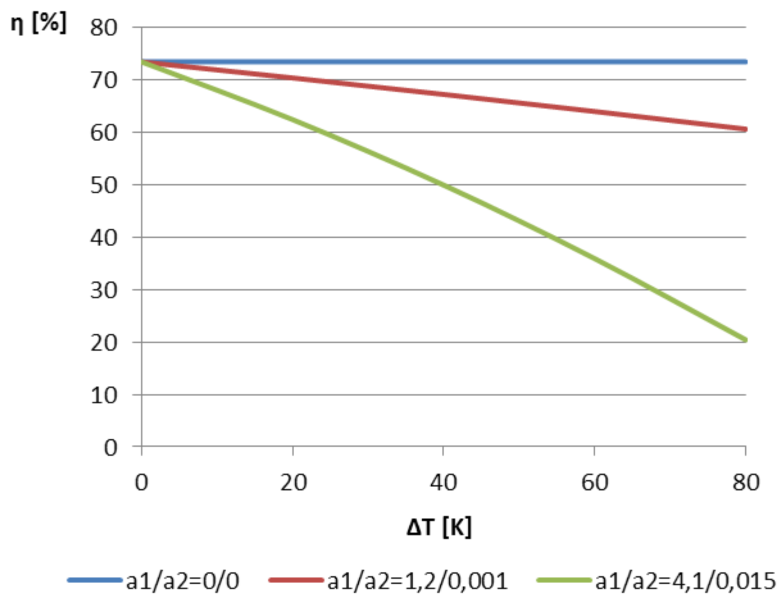


Fig. 2. Relation between solar collector efficiency and heat loss coefficients for variable temperature difference ΔT between temperature of the ambient air and mean collector fluid temperaturę (Source: personal collection)

Solar collector efficiency

The relation between solar collector efficiencies is presented in figure.

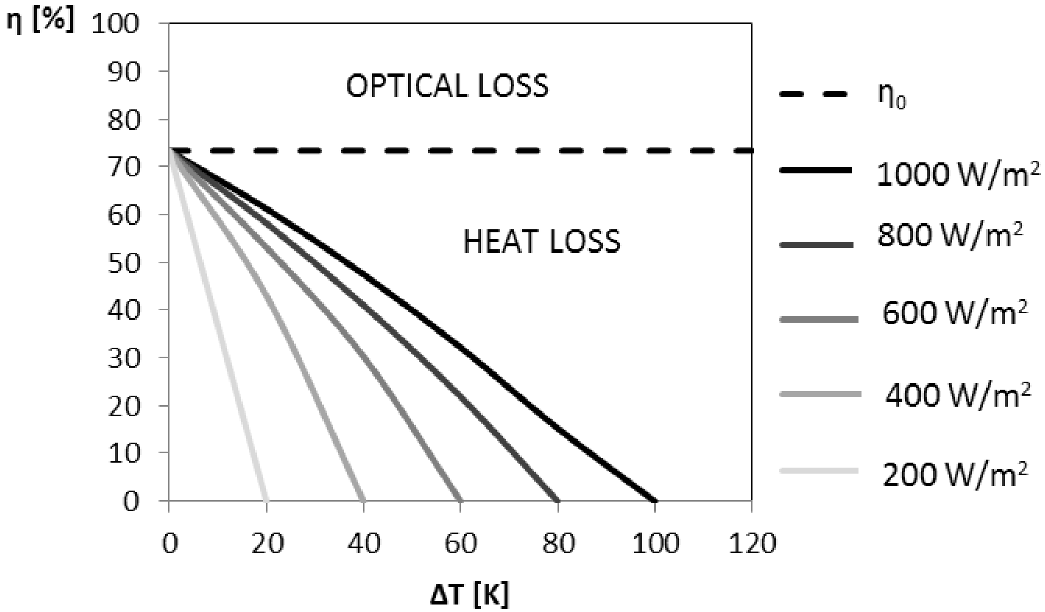


Fig. 3. Relation between optical solar collector efficiency and operational efficiency for variable temperature difference ΔT between temperature of the ambient air and mean collector fluid temperaturę (Source: personal collection)

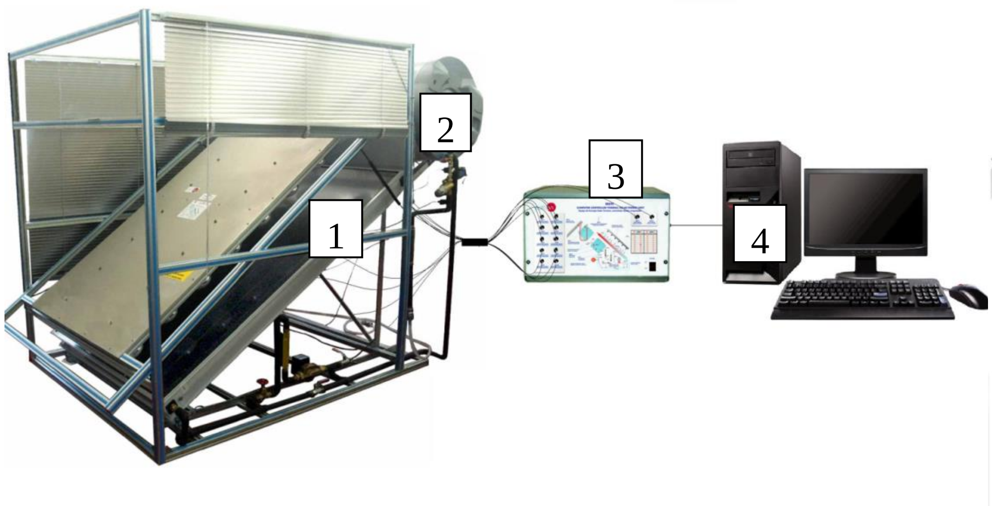
HEAT CHARACTERISTIC OF SOLAR COLLECTOR

- Hottel-Whillier-Bliss curve: relation between operational efficiency of solar collector and reduced temperature difference (the difference between mean heat transfer medium temperature and ambient temperature related to solar irradiance),

$$T_r = \frac{\left(T_{I^\circ} - T_a\right)}{E} \quad \left[\frac{m^2 \cdot K}{W}\right] \qquad (5)$$

- relation between operational efficiency and difference between absorber temperature and ambient temperature,
- relation between operational efficiency and difference between mean heat transfer medium temperature and ambient temperature.

SCHEME OF LABORATORY STATION



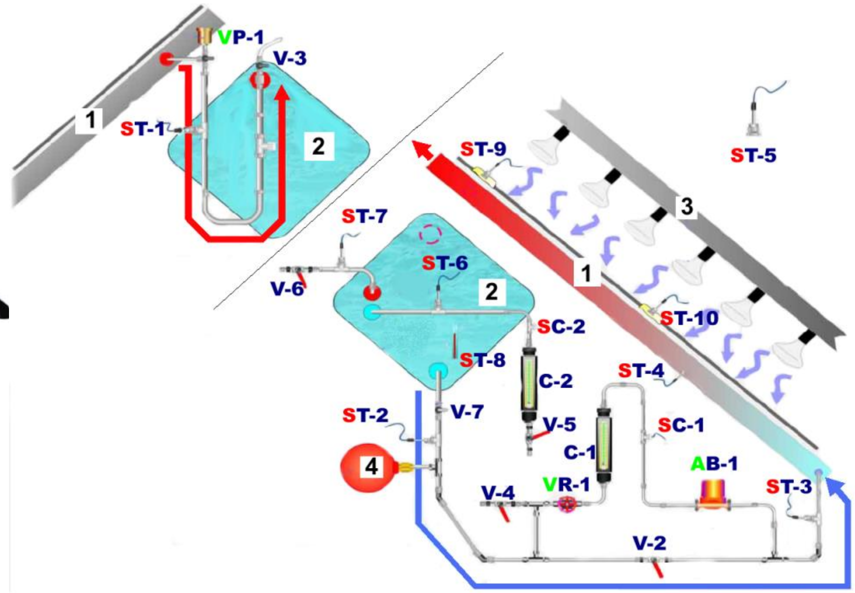


Fig. 4. Scheme of a laboratory station:
1 - water heat solar collector,
2 – accumulation tank,
3 – control unit,
4 – PC
(Source: Edibon materials)

INSTRUCTION MANUAL

Part 1. Measurement of solar collector operational parameters

1. Open the valve V-6 on a water outlet from the accumulation tank (secondary circuit II°).
2. Set the water flow in secondary circuit II°, given by lecturer, with the use of the valve V-5 (sensor SC-2).
3. Close the valve V-2 on a primary circuit I°.
4. Open the control valve VR-1, located near the circulation pump, on a primary circuit I° and open the rotameter valve.
5. Set the water flow in primary circuit I°, given by lecturer, with the use of rotameter (SC-1).
6. Turn on a line of lights given by lecturer (single or double line).
7. Write down in printed table following parameters:

- the temperature and flow in primary circuit I° (ST-2, ST-1, rotameter),
- the temperature in secondary circuit II° (ST-6, ST-7),
- the ambient temperature (ST-5).

INSTRUCTION MANUAL

Part 1. Measurement of solar collector work parameters

Parameter		Sensor	Unit	Time [min]									
				0	5	10	15	20	25	30	40	50	60
$T_{in\ I^{\circ}}$	temperature of fluid entering the absorber	ST-2	[°C]										
$T_{out\ I^{\circ}}$	temperature of fluid leaving the absorber	ST-1	[°C]										
T_a	temperature of the ambient air	ST-5	[°C]										
$T_{in\ II^{\circ}}$	temperature of fluid entering the heat tank	ST-6	[°C]										
$T_{out\ II^{\circ}}$	temperature of fluid leaving the heat tank	ST-7	[°C]										
$Q_{I^{\circ}}$	heat transfer fluid flow	SC-1	[l/h]										

8. Repeat all measurements in the intervals given by the lecturer until the work of the collector is stabilized.
9. Fill in the table in MsExcel file.

INSTRUCTION MANUAL

Part 2. Determination of average lamp irradiance reaching the surface of solar collector

1. Measure the lamp irradiance in points given by the lecturer, with the use of solar irradiance meter.
2. Write down the results in a printed table.

Top of the collector										
No	**2**	**4**	**6**					**18**	**20**	**22**
2				0	0	0	0			
4				0	0	0	0			
6				0	0	0	0			
8				0	0	0	0			
10				0	0	0	0			
12				0	0	0	0			
14				0	0	0	0			
16				0	0	0	0			
18				0	0	0	0			
20				0	0	0	0			
22				0	0	0	0			
24				0	0	0	0			
26				0	0	0	0			
28				0	0	0	0			
30				0	0	0	0			
32				0	0	0	0			
34				0	0	0	0			
Bottom of the collector										

Instruction manual

Part 3. Results

1. Fill in the table in MsExcel file to get the results.
2. Write the conclusions:
   A. Describe the relation between heat efficiency, collector efficiency and temperature difference $T_{I°} - T_a$
   B. Explain the differences between those two characteristics
   C. Describe the relation between $|T_{inII°} - T_{outII°}|$ and time

Prepared by
Anna Werner-Juszczuk

Bialystok University of Technology