



Design and Performance Evaluation of a Solar Flat Plate Collector for Water Heating Applications

Zaydaan van der Velde

*Department of Electrical and Computer Engineering, Coral Reef School of Systems Management, Mauritius
zaydaan.van.der.velde@crssm-mu.net*

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Abstract

This methodology paper presents the design and performance-evaluation procedure for a glazed solar flat-plate collector intended for domestic and low-temperature water-heating applications. The proposed collector uses a blackened metallic absorber, copper riser tubes, a transparent glass cover, rear insulation, a 100 L storage tank, and a controlled water-circulation loop. The evaluation method combines an energy balance with outdoor measurements of solar irradiance, ambient temperature, collector inlet and outlet temperatures, and mass flow rate. Useful heat gain is determined from the water temperature rise, while instantaneous collector efficiency is calculated relative to incident solar energy. The design also permits the conventional efficiency relation between reduced temperature difference and efficiency to be obtained. A representative data set is included only to demonstrate the analysis procedure; it is not presented as a substitute for actual site measurements. Under the illustrative test conditions, useful heat gain and efficiency increased with irradiance and remained strongest near solar noon, while efficiency declined as the collector operating temperature rose above ambient. The proposed methodology is simple, reproducible, and suitable for evaluating design choices, flow rate, heat losses, and storage performance in flat-plate solar water-heating systems.

Introduction

Solar water heating is one of the most direct applications of solar thermal energy because the required delivery temperatures for domestic water are generally within the operating range of non-concentrating collectors. A flat-plate collector absorbs both beam and diffuse solar radiation, converts the radiation into heat at an absorber surface, and transfers the heat to a circulating fluid. Kalogirou (2004) described flat-plate collectors as mature devices for low- and medium-temperature thermal applications and emphasized that optical absorption, heat transfer to the fluid, and reduction of top, bottom, and edge losses govern useful performance. Tian and Zhao (2013) similarly identified non-

concentrating collectors and thermal storage as core elements of practical solar-thermal systems.

Despite the simplicity of the device, collector performance depends strongly on absorber material and coating, glazing, insulation, tube arrangement, fluid flow rate, inlet temperature, ambient conditions, wind, and solar irradiance. Farahat, Sarhaddi, and Ajam (2009) showed through energy and exergy optimization that collector geometry, mass flow rate, inlet temperature, and overall loss coefficient are interdependent design variables. Experimental evidence also demonstrates that collector efficiency should not be treated as a fixed number. Zambolin and Del Col (2010) reported that measured flat-plate performance varies with

operating conditions and the chosen steady-state or daily test procedure, while Chen et al. (2012) demonstrated a measurable dependence of efficiency on flow rate.

For water-heating applications, an appropriate methodology must therefore connect physical design to controlled thermal measurements. The present work proposes a compact experimental design and calculation procedure for a glazed flat-plate collector coupled to an insulated storage tank. The objectives are to specify the collector and instrumentation, define a repeatable outdoor test method, quantify useful heat gain and instantaneous efficiency, examine the influence of irradiance and temperature lift, and provide a transparent results format that can later be populated with measured data. The emphasis is methodology rather than claiming a new experimental data set.

Literature Review

Kalogirou (2004) provided a broad technical review of solar thermal collectors and established the energy-balance basis widely used for evaluating flat-plate devices. The review explains that radiation absorbed by the plate is partitioned into useful heat transferred to the working fluid and thermal losses to the surroundings. This framework supports the use of useful heat gain and efficiency as the principal response variables in collector testing.

Farahat et al. (2009) extended performance analysis by combining energy and exergy considerations. Their optimization study showed that absorber area, tube dimensions, mass flow rate, fluid temperatures, and overall heat-loss coefficient all affect collector performance. The study supports designing the experimental plan around variables that can be physically controlled or measured rather than evaluating efficiency without reference to operating temperature and flow.

Hobbi and Siddiqui (2009) experimentally investigated passive heat-transfer enhancement devices inside a flat-plate collector. They found that devices intended to increase turbulence did not necessarily improve thermal performance because buoyancy effects could dominate the flow. This result is important for methodology design: modifications should be evaluated experimentally rather than assumed to be beneficial from forced-convection reasoning alone.

Zambolin and Del Col (2010) compared a glazed flat-plate collector with an evacuated-tube collector under stationary standard and daily

conditions. Their work reinforced the need to control inlet temperature and environmental variables and to evaluate efficiency over a useful operating range. Huang et al. (2010) tested a thermosyphon flat-plate solar water heater using a mantle heat exchanger and reported mean daily efficiency up to about 50%, while also showing that introducing a heat exchanger can penalize collector performance by raising the collector-loop temperature.

Taherian et al. (2011) combined dynamic simulation with outdoor measurements for a closed thermosyphon flat-plate system and obtained good agreement between predicted and experimental behavior. Their work showed that inlet and outlet temperature, absorber temperature, glazing temperature, irradiance, and ambient conditions are useful validation variables. Ayompe et al. (2011) monitored domestic-scale flat-plate and evacuated-tube systems for a year and reported an annual average collector efficiency of 46.1% for the flat-plate system under the studied temperate-climate conditions. This long-term result illustrates why short-term peak efficiency should not be interpreted as annual system performance.

Chen et al. (2012) tested flat-plate collectors at several volume flow rates and observed higher start efficiencies at higher flow rates, highlighting the need to report the selected flow condition. Tian and Zhao (2013) reviewed collector and storage developments and emphasized optical optimization, heat-loss reduction, and heat-transfer enhancement. Finally, Ayompe and Duffy (2013) analyzed a complete flat-plate solar water-heating system over one year and reported a 45.6% annual collector efficiency, a 37.8% system efficiency, and measurable pipe losses. Wang et al. (2015) reviewed solar water-heating research through 2015 and identified component sizing, performance simulation, laboratory measurement, dynamic on-site evaluation, and energy/economic assessment as continuing research priorities. Together, these studies justify a methodology that separately measures collector heat gain, collector efficiency, storage behavior, and distribution losses.

Methodology

1. Collector design and test rig

The proposed test rig consists of a single-glazed flat-plate collector, a thermally insulated hot-water storage tank, a small circulation pump, a flow-control valve, a flow meter, and temperature and irradiance sensors. The absorber plate is bonded to parallel copper risers

connected to upper and lower headers. A transparent cover reduces convective losses while transmitting solar radiation, and mineral-wool insulation reduces heat loss from the rear and edges. For reproducibility, the collector is

mounted facing the equator and tilted approximately at the local latitude; the illustrative configuration uses a 30° tilt. The storage tank is placed close to the collector to minimize pipe losses.

Table 1. Proposed design and measurement specifications

Item	Proposed specification	Purpose / measurement
Collector aperture	1.50 m ² ; 1.5 m × 1.0 m	Incident solar-energy area
Absorber	1.0 mm aluminum; high-absorptance black coating	Solar absorption and lateral conduction
Flow tubes	Copper; 8 risers, 10 mm OD; 22 mm headers	Transfer heat to circulating water
Glazing / air gap	4 mm low-iron glass; 25 mm gap	Transmit radiation and reduce top loss
Insulation	50 mm mineral wool at back and insulated edges	Reduce conductive heat loss
Storage tank	100 L insulated tank	Store useful thermal energy
Nominal flow rate	0.020 kg/s water	Controlled test condition
Sensors	Pyranometer; Pt100/thermocouples; flow meter	Measure G, T _a , T _{in} , T _{out} and mass flow

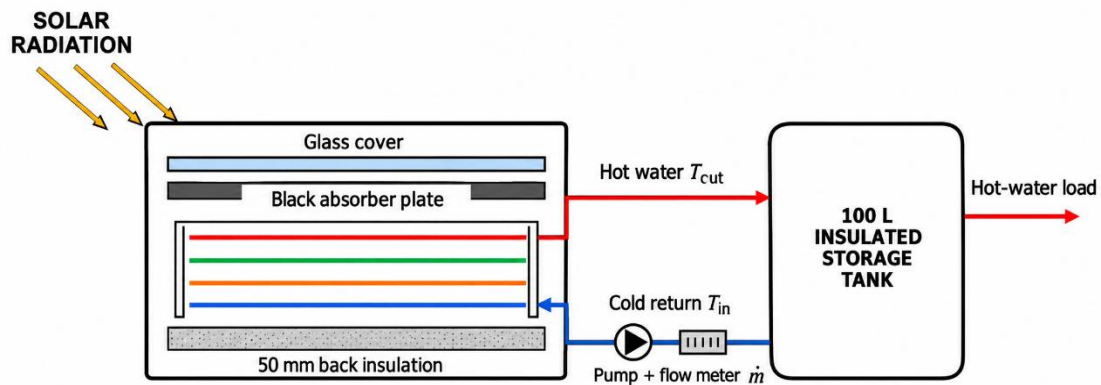


Figure 1. Proposed flat-plate solar water-heating collector and measurement arrangement.

2. Experimental procedure

Testing is carried out outdoors on clear or predominantly clear days. Before data collection, the system is filled, air is removed from the loop, sensor readings are checked, and the flow rate is adjusted to 0.020 kg/s. Measurements of global irradiance on the collector plane (G), ambient temperature (T_a), collector inlet temperature (T_{in}), outlet temperature (T_{out}), and mass flow rate are recorded at 5-min intervals from morning through the post-noon period. For a performance point to be accepted, flow should be stable and irradiance should not fluctuate sharply during the averaging interval. The storage tank is initially mixed or brought to a known starting temperature so that day-to-day comparisons are meaningful.

At each interval, readings are averaged over a short steady period and the collector temperature rise is calculated. The experiment

should be repeated for at least three days with comparable sky conditions. If the effect of flow rate is studied, only one factor is changed at a time, for example 0.010, 0.020, and 0.030 kg/s, while keeping collector geometry and measurement practice unchanged. Calibration or manufacturer accuracy should be documented for every instrument, and uncertainty in calculated efficiency should be estimated from the combined uncertainty in temperature difference, flow rate, irradiance, and area.

3. Performance calculations

The instantaneous useful heat gain transferred to water is calculated from the measured fluid temperature rise:

$$Q_u = \dot{m} C_p (T_{out} - T_{in})$$

where Q_u is useful heat gain (W), $\dot{m}$ is water mass flow rate (kg/s), C_p is the specific heat of water (approximately 4180 J/kg·K in the test range),

and $T_{\text{out}} - T_{\text{in}}$ is the collector temperature rise. Instantaneous thermal efficiency is then:

$$\eta = Q_u / (A_c G)$$

where A_c is collector aperture area (m^2) and G is irradiance on the collector plane (W/m^2). To compare performance at different operating temperatures, the measured data may also be regressed using the conventional linear form:

$$\eta = F^R(\tau\alpha) - F^R U^L [(T_{\text{in}} - T_a)/G]$$

The intercept represents effective optical performance, while the slope reflects thermal losses. The energy stored in the tank over a test period can be estimated from $Q_s = M C_p (T_{\text{final}} - T_{\text{initial}})$, after accounting for hot-water draw-off and tank losses when applicable. These equations follow the thermal-performance

framework used in established flat-plate collector studies (Kalogirou, 2004; Zambolin & Del Col, 2010; Ayompe & Duffy, 2013).

Results

Table 2 demonstrates how the proposed calculations would be reported using a representative data set. The values are intentionally illustrative and should be replaced by measured readings when the test rig is operated. At constant nominal flow, useful heat gain increases strongly from the morning toward solar noon because both irradiance and the water temperature rise increase. The computed efficiency reaches approximately 61–63% around the strongest irradiance period and then declines as irradiance falls and the collector remains thermally elevated above ambient.

Table 2. Representative performance-calculation example (illustrative data)

Time	G (W/m^2)	T _a (°C)	T _{in} (°C)	T _{out} (°C)	ΔT (K)	Q _u (W)	η (%)
09:00	510	25.5	28.0	32.6	4.6	385	50.3
10:00	665	27.0	30.0	37.3	7.3	610	61.2
11:00	795	28.5	33.0	41.8	8.8	736	61.7
12:00	860	30.0	36.0	45.7	9.7	811	62.9
13:00	820	31.5	39.0	48.1	9.1	761	61.9
14:00	690	32.0	41.0	47.9	6.9	577	55.7
15:00	520	31.0	41.5	46.1	4.6	385	49.4

The pattern is consistent with the established behavior of glazed flat-plate collectors: efficiency decreases when the temperature difference between the collector and ambient becomes large relative to available solar irradiance. Chen et al. (2012) showed that flow rate also alters measured collector efficiency, so the selected mass flow rate must be reported with every efficiency result. The representative midday efficiencies are higher than the annual average values reported by Ayompe et al. (2011) and Ayompe and Duffy (2013), which is expected because annual values include low-radiation periods, cold starts, pipe losses, standby losses, and variable weather. Huang et al. (2010) likewise demonstrated that system components such as heat exchangers can reduce the net performance of the collector loop.

For a real experiment, the principal outputs should include the daily energy gain, peak outlet temperature, mean collector efficiency, storage-tank temperature rise, and an efficiency-versus-reduced-temperature plot. Repeated tests should be averaged and accompanied by uncertainty bounds. If design alternatives are compared, a statistically meaningful comparison should use the same irradiance range, inlet-temperature range, and flow condition. The analysis should

distinguish collector efficiency from whole-system efficiency because tank, piping, and control losses can materially reduce delivered hot-water energy (Ayompe & Duffy, 2013).

Conclusion and Discussion

A complete methodology has been developed for designing and evaluating a glazed flat-plate solar collector for water heating. The design combines a 1.50 m^2 absorber, copper flow passages, glass glazing, rear insulation, controlled water circulation, and a 100 L insulated storage tank. The evaluation procedure measures irradiance, ambient temperature, inlet and outlet water temperatures, and mass flow rate, then converts these measurements into useful heat gain and instantaneous efficiency. This approach is consistent with pre-2015 collector literature, which shows that optical properties, heat-loss coefficient, operating temperature, flow rate, heat exchangers, and system losses all influence measured performance. The illustrative results show the expected operating trend: useful heat gain rises with increasing solar irradiance, reaches its maximum near solar noon, and decreases later in the day. Efficiency is highest when strong radiation coincides with a moderate

collector-to-ambient temperature difference. As the water and absorber become hotter, thermal losses increase and efficiency can decline even when outlet temperature remains high. Therefore, outlet temperature alone should not be used as the criterion for judging collector quality. For experimental implementation, the most important requirements are calibrated instrumentation, stable flow, repeated outdoor tests, consistent inlet conditions, and explicit uncertainty analysis. Future work can compare absorber coatings, tube spacing, glazing options, flow rates, and storage volumes using the same method. The representative values in this paper should be replaced by actual measurements before the work is submitted as an experimental research paper. With that substitution, the proposed methodology provides a practical basis for assessing thermal performance and identifying design improvements for domestic and low-temperature solar water-heating applications.

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