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Performance and operational effectiveness of evacuated flat plate solar collectors compared with conventional thermal, PVT and PV panels

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HIGHLIGHTS

- A high vacuum increases efficiency and reduces heat losses.
- Test results were in good agreement with theoretical models.
- 50% higher efficiency than conventional panels or tubes at $T_M = 100\,^{\circ}\mathrm{C}$, $G = 1000\,\mathrm{W/m^2}$.
- 104% increase over conventional flat plate in predicted heat to district main operating at 85 °C.
- PVT panels are more effective than organic Rankine cycles for low temperature heat and power.

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ABSTRACT

The concept of an evacuated flat plate (EFP) collector was proposed over 40 years ago but, despite its professed advantages, very few manufacturers have developed commercial versions. This situation suggests both technical difficulties in manufacturing a competitively-priced sealed for life panel and a lack of awareness of the benefits of such panels.

This paper demonstrates an evacuated flat plate simulation that closely models experimental efficiency measurements. Having established the validity of the model, it compares published data for a commercial EFP collector with predictions for an optimal design to investigate whether any further efficiency improvement might be possible. The optimised design is then evaluated against alternative solar energy devices by modelling a number of possible applications. These comparisons should inform choices about solar options for delivering heat: EFP collectors are well-suited to some of these applications.

Evacuated flat plate collectors are a possible alternative to concentrating collectors for Organic Rankine Cycle power generation. The annual output for all the modelled collectors was found to be a quadratic function of delivery temperature: this enabled a novel optimisation of ORC source temperature. Predictions for concentrating and non-concentrating ORC plant are compared with a PV/thermal alternative. The ORC output is significantly less than a PV panel would achieve; applications needing both heat and power are better served by PVT panels. This is an original and novel result.

1. Introduction

1.1. Evacuated flat plate solar thermal collectors

Non-concentrating solar thermal collectors for low temperature applications such as domestic solar hot water (DSHW) conventionally adopt either a flat plate (FP) or evacuated tube (ET) format. Evacuated tube collectors can also be used for medium-temperature applications such as industrial process heat.

Of the UK's primary energy consumption approximately 26% is used for space heating [1]. The EU requirement for process heat in the 80–240 °C range has been estimated as 300 TWh per annum [2] and process heat is 38% of the US total energy use [3]. High efficiency solar thermal technologies can contribute to the decarbonising of these sectors.

Evacuated flat plate (EFP) solar thermal collectors are anticipated to

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Nomenclature

A_A	frontal area of absorber (m^2)
A_g	collector gross area (m^2)
C	effective heat capacity of absorber (J/m^2 K)
E_u	useful heat to absorber per time step (J/m^2)
E_1	annual heat output for absorber at temperature T_1 (Wh/m^2)
$E_{eq,Th}$	thermal equivalent of combined annual energy output (Wh/m^2)
G	total (beam + diffuse) irradiance (W/m^2) measured perpendicular to collector
G_{clear}	predicted irradiance, clear conditions (W/m^2)
G_E	effective irradiance, with beam component perpendicular to plate (W/m^2)
G_v	irradiance reference value (W/m^2)
I_{sc}	solar irradiance above atmosphere (W/m^2)
$\dot{Q}_u$	useful heat output (W/m^2)
$\dot{Q}_1$	heat output with absorber at temperature T_1 (W/m^2)
T_a	ambient temperature (°C)
T_g	cover glass temperature (°C)
T_p	plate mean surface temperature (°C)
T_{env}	environment radiative (sky) temperature (°C)
T_{HM}	heating main temperature (°C)
T_M	mean temperature difference $T_p - T_a$ (°C)
T_1, T_2	absolute temperatures of heat transferred into and out of a heat engine cycle (K)
$T_{1,opt}$	heat delivery temperature that maximises value of energy produced (K)
U_L	overall heat loss coefficient (W/m^2 K)
a,b,c	curve fit coefficients for heat output
a_0,a_1,k	standard atmosphere constants for mid-latitude climate
f	ratio of ORC to Carnot efficiency (second law efficiency)
f_d	fraction of radiation that is diffuse
h_i,h_o	heat transfer coefficient (W/m^2 K) to inward or outward-facing glass surface
k_τ	weather clearness index
q_{abs}	rate of heat absorption in glass (W/m^2)
t	time (seconds)
v	energy cost ratio, electricity:heat
$\alpha_1,\alpha_2,\alpha_3$	coefficients of efficiency polynomial
ε_{eg}	effective emissivity, environment to glass
ε_{pg}	effective emissivity, plate to glass
η_A	efficiency based on absorber area
η_g	efficiency based on gross area
η_{ORC}	Organic Rankine Cycle efficiency
$\eta_0,\tau\alpha$	transmission-absorbance product
λ	rate constant for exponential temperature step decay
μ	cycle profitability parameter $(v-1)f$
σ	Stefan-Boltzmann constant
τ_b,τ_d	beam and diffuse transmission coefficients for clear atmosphere

Subscripts and superscripts

‘	linearised parameters

Abbreviations

CHP	combined heat and power
DSHW	domestic solar hot water
EFP	evacuated flat plate collector
ET	evacuated tube collector
FP	flat plate collector (non-evacuated)
ORC	Organic Rankine cycle
PTC	parabolic trough collector
PV	photo-voltaic panel
PVD	physical vapour deposition
PVT	photo-voltaic/thermal panel
RTD	resistance temperature detector
TVP	evacuated flat plate collector by *TVP Solar*

combine the high fill factor, ease of cleaning and visual aesthetics of FP collectors with the low heat loss coefficient of ET collectors. They consist of a flat absorber contained within an evacuated enclosure with a top glass cover. An array of pins supports the glass cover against atmospheric pressure loading. Such collectors can achieve high operational temperatures suitable for many industrial applications and also operate efficiently in low irradiance conditions, a valuable feature for solar thermal collectors in the UK and at high latitudes. Unlike concentrating collectors, EFP collectors do not track the Sun; they can therefore be integrated into the building envelope, as the roof or fascia, where they can provide efficiency gains through building insulation [4,5]. The use of a façade to generate heat may also be valuable [6].

Two different designs of EFP collectors were built, each using a flooded panel absorber but with different enclosures. The test results are summarised here to demonstrate the accuracy of a simulation model: more comprehensive test details are given in Moss et al. [7]. Further simulations, of an improved design, have demonstrated the advantages for DSHW heating under typical UK irradiance conditions and assessed the potential use of an organic Rankine cycle for power generation.

1.2. Recent developments in thermal collectors

Much research has taken place over the past 20 years to improve efficiency in conventional solar collectors. Suman et al. [8] provides a detailed overview of solar collector technology and configurations whilst Colangelo et al. [9] reviews research into flat plate collectors over the past decade.

Collector efficiency is often characterised as $\eta = \tau\alpha - \frac{U_L T_M}{G}$ where T_M is the difference between absorber and ambient temperatures. An ideal high-efficiency collector would combine a transmission-absorbance product $\tau\alpha \approx 1$ with a low heat loss coefficient U_L and operate under high irradiance levels G. The optimisation of $\tau\alpha$ involves spectrally selective coatings and absorption media. Selvakumar and Barshilia [10] has reviewed the use of PVD coatings for medium and high temperature solar thermal applications. Colangelo et al. [11] tested the viability of nanofluids as selective absorbers. Anti-reflection coatings on the cover glass improve optical transmission: Caër et al. [12] developed a sol-gel technique for reducing the refractive index of SiO_2 to create a durable anti-reflection coating.

The absorber temperature is a key parameter in determining the choice of solar collector. Domestic solar hot water (DSHW) applications only require temperatures of order 70 °C but more novel applications such as industrial process heat, combined heat and power (CHP) or refrigeration require higher temperatures. Freeman et al. [13] investigated the suitability of thermal collectors for small scale CHP. Absorption refrigeration systems require heat at 70–120 °C [14]. Alobaid et al. [15] compared the merits of thermal collectors and PV panels to power solar cooling systems.

High temperature applications such as thermal power stations typically use concentrating collectors [16,17]: these minimise the efficiency penalty at high T_M by effectively increasing the irradiance intensity G. The insensitivity to diffuse radiation, complexities of the tracking and the need for regular mirror cleaning mean that they tend