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Simulator testing of evacuated flat plate solar collectors for industrial heat and building integration

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ABSTRACT

The concept of an evacuated flat plate collector was proposed over 40 years ago but, despite its professed advantages, very few manufacturers have developed commercial versions. This paper demonstrates the reduction in heat loss coefficient and increase in efficiency resulting from evacuating a flat plate collector: it is hoped that these results will stimulate interest in the concept. Evacuated tubes are now mass-produced in large numbers; evacuated flat plate collectors could in principle replace these tubes if the technical difficulties in creating extended metal-glass seals can be overcome. The experimental experiences described here should indicate targets for future research.

Two different designs of evacuated flat plate solar thermal collector, each with a 0.5 × 0.5 m flooded panel black chrome plated absorber, were tested under a solar simulator. The cover glasses were supported by an array of 6 mm diameter pillars. Inlet and outlet temperatures were monitored via PT100 RTDs and glass temperatures were measured using thermocouples. Inlet temperature was controlled by a fluid circulator connected to a header tank with a Coriolis mass flow meter to measure fluid flow rate. Testing was conducted indoors with and without the use of a fan to cool the top cover glass. The test conditions spanned the range $200 < G < 1000$ W/m^2, $0 \leqslant T_M \leqslant 52$ °C.

Evacuating the enclosure reduced the measured heat loss coefficient by 3.7 W/m^2 K: this was a close match to predictions and corresponds to an increase in aperture efficiency from 0.3 to 0.6 at $T_M/G = 0.06$ m^2 K/W. The poor efficiency under non-evacuated conditions was due to the black chrome absorber coating being less selective than commercial panel coatings.

The solder seals were developed from experience with vacuum glazing but the increased gap led to reliability issues. A vacuum pump maintained the enclosures under a high vacuum (< 0.1 Pa) during testing. The enclosure based on a thin rear metal tray proved to be more effectively sealed than the more rigid enclosure with glass on both sides: the latter developed leaks as the front to rear temperature difference increased. The biggest challenge in the manufacture of evacuated flat plate collectors is to ensure a long-term hermetic seal such that no pumping is required.

1. Introduction

1.1. Evacuated flat plate solar thermal collectors

Evacuated flat plate (EFP) solar thermal collectors are anticipated to combine the high fill factor, ease of cleaning and visual aesthetics of flat plate collectors with the low heat loss coefficient of evacuated tubes. An array of ribs or pillars is required to support the glass cover against atmospheric pressure loading.

Such collectors can operate efficiently in low illumination conditions and moreover achieve "medium" to "high" delivery temperatures for industrial applications, a field that has recently attracted interest. The global potential for industrial use of solar heat is estimated as 180GW (ETSAP, 2015). The EU requirement for process heat in the 80–240 °C range has been estimated as 300 TWh per annum (Kalogirou, 2014) whilst in the United States process heat accounts for 38% of the total energy use (Riggs et al., 2017). Freeman et al. (2015) investigated the suitability of thermal collectors for small scale combined heat and power. Alobaid et al. (2017) compare the merits of thermal collectors and PV panels to power solar cooling systems. Absorption refrigeration systems are potentially a major market and require heat at 70–120 °C (Nkwetta and Smythe, 2012). Unlike concentrating collectors, EFP

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Nomenclature

A_A	frontal area of absorber
G	total (beam + diffuse) illumination (W/m^2) perpendicular to collector
T_a	ambient temperature
T_g	cover glass temperature
T_p	plate mean surface temperature
T_M	mean temperature difference T_p−T_a
T_M^*	scaled temperature difference T_M/G
U_L	overall heat loss coefficient (W/m^2 K)
c	specific heat of coolant (J/kg K)
c_g	specific heat capacity of glass (J/kg K)
d	absorber-glass gap (m)
h	heat transfer coefficient (W/m^2 K)
k	metal conductivity (W/m K)
$\dot{m}$	fluid mass flow rate
p	enclosure internal pressure (Pa)
r	radius (m) for radial conduction
w	glass mass/unit area (kg/m^2)
t_g	glass time constant (s)
η_A	efficiency based on absorber area
η_0,$\tau\alpha$	transmission-absorbance product

collectors can absorb diffuse light and operate without tracking the Sun.

The flat covers on EFP collectors are more attractive than bundles of evacuated tubes and, combined with the high efficiency, make them suitable for integration into roofs or building facias. The vacuum provides effective insulation between front and back covers in addition to its primary role in minimising heat loss from the absorber: evacuated collectors can therefore replace conventional insulation or vacuum-insulated panels (Alam et al., 2017). The use of a façade to generate heat may also be valuable (O'Hegarty et al., 2017; Leone and Beccali, 2016). Moss et al. (2018a) used a simulation based on weather data to show that evacuated flat plate collectors could be more efficient than other forms of solar collector for temperatures up to 210 °C.

There are currently two manufacturers of EFP collectors, SRB and TVP.

The SRB design (Benvenuti and Ruzinov, 2010) uses a long, thin format (64 cm wide, up to 3 m long) with an internal metal framework. The glass covers (front and back) are supported by longitudinal ribs; the absorber uses copper strips that sit between the ribs and are welded to a stainless tube. The edges of the glass are plasma-sprayed with a metal coating to facilitate soldering to the frame. The TVP design (Abbate, 2012; TVP datasheet) uses low melting point frit glass to seal the cover glass to a NiFe alloy edge spacer with a stainless steel back cover. The similarity in expansion coefficients between glass and this 48% nickel alloy avoids the shear stress peaks described by Henshall et al. (2014). The glass is supported by pillars passing through holes in the absorber.

Many proprietary details of these commercial collector designs are undocumented. The present investigation into theoretical and practical aspects of EFP collectors is intended to provide definitive data to guide future evacuated flat plate collector designs. The results presented here are novel in that they are the first published dataset to be accompanied by full construction details for the collectors.

Two different designs of experimental EFP collector were built, each using a flooded panel absorber but with different enclosures.

1.2. Collector efficiency research

Much research has taken place over the past 20 years to improve efficiency in conventional solar collectors.

Colangelo et al. (2016) reviews research into flat plate collectors over the past decade. An experimental comparison of flat plates and evacuated tubes is also given by Zambolin and Col (2010). There have been investigations into anti-reflection coatings (Helsch and Deubener, 2012; Caër et al., 2013) and heat transfer augmentation (Martın et al., 2011; Sharma and Diaz, 2011; Moss et al., 2017). Suman et al. (2015) provides a detailed overview of solar collector technology and configurations.

Collector efficiency is often characterised as $\eta = \tau\alpha - \frac{U_L T_M}{G}$. High temperature applications such as thermal power stations typically use concentrating collectors (Bouvier et al., 2016; Purohit and Purohit, 2017): these minimise the efficiency penalty at high T_M by effectively increasing the illumination intensity G.

An alternative approach for obtaining high efficiency at elevated T_M is to reduce the heat loss coefficient U_L. The radiative contribution to U_L is minimised using spectrally selective coatings and absorption media (reviewed by Kennedy, 2002); such coatings are now well developed.

In contrast, various approaches have been suggested to lessen the conduction component: this is a more intractable problem. Benz and Beikircher (1999) examined the possibility of using a low pressure (1–10 kPa) to inhibit convection together with krypton to reduce the conductivity. Buttinger et al. (2010) arranged a set of narrow concentrating trough collectors under a single cover glass. The internal pressure was reduced to 30 Pa to inhibit convective heat transfer. Beikircher et al. (2015) used a wide air gap to reduce conduction together with multiple intermediate glass or plastic films to inhibit convection. Ehrmann and Reineke-Koch (2012) used a double glazed cover glass. Brunold (SPF) describes a prototype collector using stacked 7 mm diameter glass capillary tubes as a thick transparent insulating layer that inhibits convection.

The use of a vacuum to eliminate conduction losses in a flat plate collector has been studied by Benz and Beikircher (1999) and Benvenuti and Ruzinov (2010), Benvenuti (2013a, 2013b). Under high vacuum conditions the molecular mean free path can exceed the typical separation d of components within the collector: the effective conductivity is then less than the nominal value. At pressure p and absolute temperature T the conductivity scaling multiplier k_p is a function of the Knudsen number Kn (Beikircher et al., 1996):

$$\mathrm{Kn} = \frac{0.008313}{\left(1 + \frac{116}{T}\right)pd}, \quad k_p = \frac{k_{\mathrm{nominal}}}{1 + 3.75\mathrm{Kn}}$$

At a typical temperature of 320 K, $pd = 0.00255$ Pa·m is predicted to reduce the conductivity k_p to 10% of its normal level k_{nominal}. This is equivalent to 2.55 Pa for a 1 mm gap or 0.255 Pa for a 10 mm gap. Below this level of pd the effective conductivity is approximately proportional to pd (Collins et al., 1995), and the conductive heat loss will be proportional to $\frac{k}{d} \propto \frac{pd}{d} \propto p$.

The practical implementation requires low-outgassing materials (Moss et al., 2018b) and hermetic sealing of all joints. Commonly used flat plate collector materials such as flexible sealants are unsuitable for high vacuum conditions and the mechanical and thermal properties of alternative, vacuum-compatible materials introduce a number of design challenges.

2. Manufacture and instrumentation of evacuated collectors

2.1. Enclosure styles

Two styles of collector have been developed (Fig. 1): they share a common absorber design, mounted in different enclosures. In each case an array of pillars supports the cover glass against the atmospheric pressure load.

The "tray" style of enclosure uses a stainless steel tray with a single cover glass on the front (Henshall et al., 2014). This concept is intended