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Current Developments in Flat-Plate Vacuum Solar Thermal Collectors

Farid Arya, Trevor Hyde, Paul Henshall, Phillip Eames, Roger Moss, Stan Shire

Abstract**—**Vacuum flat plate solar thermal collectors offer several advantages over other collectors namely the excellent optical and thermal characteristics they exhibit due to a combination of their wide surface area and high vacuum thermal insulation. These characteristics can offer a variety of applications for industrial process heat as well as for building integration as they are much thinner than conventional collectors making installation possible in limited spaces. However, many technical challenges which need to be addressed to enable wide scale adoption of the technology still remain. This paper will discuss the challenges, expectations and requirements for the flat-plate vacuum solar collector development. In addition, it will provide an overview of work undertaken in Ulster University, Loughborough University, and the University of Warwick on flat-plate vacuum solar thermal collectors. Finally, this paper will present a detailed experimental investigation on the development of a vacuum panel with a novel sealing method which will be used to accommodate a novel slim hydroformed solar absorber.

Keywords**—**Hot box calorimeter, infrared thermography, solar thermal collector, vacuum insulation.

I. Introduction

THE analysis of industrial and domestic energy usage indicates that temperature processes in the range of 20 °C – 200 °C are used in nearly all industrial and domestic sectors. In principle, there is a potential to use solar thermal energy in these lower temperature processes which can reduce the environmental impact of burning fossil fuels [1]. There are different ways of utilising solar thermal energy, for example domestic water heating, space heating and cooling, industrial process heat, thermal power systems, etc. Therefore, solar energy systems can be used for a wide range of applications and have the potential to provide significant benefits. Various types of solar thermal collectors may be used including flat-plate, compound parabolic, evacuated tube, parabolic trough, Fresnel lens, parabolic dish and heliostat field collectors. Among these, flat plate and evacuated tube collectors are of a particular interest for domestic use.

Flat-plate solar thermal collector technology when coupled with vacuum enclosures has the potential to supply clean energy efficiently for use in applications including residential water and space heating [2]. An evacuated flat panel design would be more architecturally elegant than tubular collectors and have a better fill factor, yet be thinner and more efficient than conventional flat panels [3]. Creating a vacuum space around a flat solar absorber thereby taking advantage of its high thermal insulation properties has been investigated by several researchers [4]-[7]. The concept of an evacuated flat-plate collector was commercially realised some years ago. Since no humidity and condensation problems occur in evacuated collector envelopes they have the advantage of a longer lifetime compared to non-evacuated collectors [5]. The use of a moderate vacuum 0.1 mbar – 50 mbar in flat-plate collectors can suppress convection heat losses from the absorber; however, heat transfer due to gas conduction still exists. An evacuated flat-plate solar collector was proposed and simulated in 1970s [4]. It was shown that a pressure of 1 mbar – 33 mbar eliminated convective heat transfer from the absorber to the surrounding glass panes for a separation of 150 mm between the glass panes and the absorber. A vacuum enclosure pressure of less than 0.001 mbar is required to fully suppress both convection and gas conduction and maximize collector thermal performance which is especially important in cold climates or applications requiring high temperatures such as process heat [8]. Evacuated flat plate solar collectors progressed to the point where it was possible to deliver steam at temperatures of up to 150 ºC at efficiencies of nearly 50% [5].

There are a number of challenges in the fabrication of evacuated flat plate solar collectors. The first principle challenge is to create a hermetic seal around the periphery of the glass panes which is sufficiently strong to withstand stresses induced by the atmospheric pressure and the thermal expansion and contraction over its life time. The second challenge is to maintain the separation of the glass panes under the influence of atmospheric pressure. Finally, a careful inlet and outlet port design is required to minimize the heat loss.

II. Fabrication Process

A. Fabrication of Vacuum Panel

A novel method of creating a hermetic seal between glass and a metal such as aluminium or stainless steel has been developed and used in Ulster and Loughborough University to fabricate flat vacuum panels suitable for solar applications. The hermetic seal is created with a metal alloy such as indium or Cerasolzer 217 using an ultrasonic soldering technique; the method is described in detail at [6], [8]. Prototypes of slim flat vacuum panels, 0.4 m × 0.4 m, suitable for use in solar thermal collectors, as shown in Fig. 1, were fabricated and

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their thermal transmittance characterized using a guarded hot box calorimeter. An overall heat transfer coefficient of 0.86 $Wm^{-2}K^{-1}$ in the central panel region was achieved.

The wide vacuum space enables the integration of a wide solar absorber as schematically shown in Fig. 2. The vacuum space provides a high level of thermal insulation around the solar absorber which reduces heat losses from the absorber due to conduction and convection thereby increasing the efficiency of the solar collector. To minimise the radiative heat losses from the collector, glass with low emittance coatings (0.16 emittance) was used for the vacuum envelope. The separation of the panes, which would otherwise touch under the influence of atmospheric pressure, was maintained by an array of stainless steel (grade 304L) support pillars. The pillars were 6 mm in diameter and 10.2 mm high and spaced at 50 mm intervals on a regular square Cartesian grid.

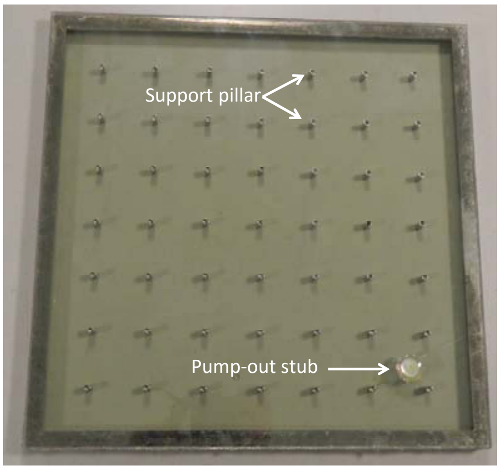

Fig. 1 Prototype of a slim flat vacuum panel. Pump-out port is used to pump down the panel

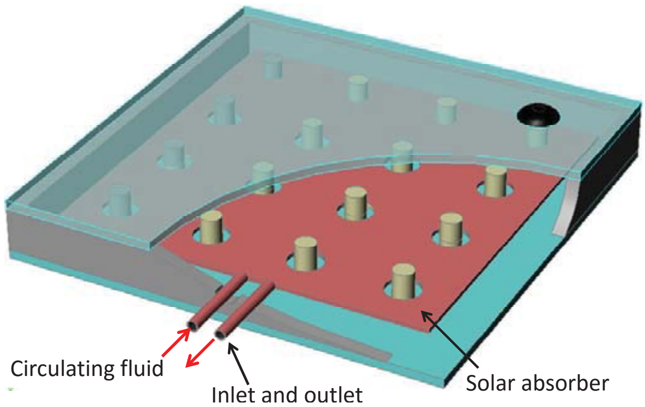

Fig. 2 Schematic diagram of a flat vacuum panel

B. Fluid Inlet and Outlet Port Design

Any contact between the solar absorber integrated in a vacuum panel and the edge spacer or the covering glass panes can contribute to heat transfer from the absorber to the vacuum envelope. Integration of a solar absorber inevitably creates a number of such contacts. To maintain the separation of the absorber from the covering glass panes, a number of support pillars made of low thermal conductivity materials such as glass and ceramic are used. However, the contact points between the fluid inlet and outlet tubes and the surrounding edge spacer could have a significant effect on the heat loss from the absorber. To overcome this the inlet and outlet, ports were designed using co-centric tubes as illustrated in Figs. 3 and 4 [9]. Since the space between the inner and outer co-centric tubes is linked to the space between the glass panes, evacuation of the envelope results in evacuation between the tubes.

To further reduce heat loss, the connection between the inner and outer tubes in the co-centric tubes can be easily insulated by using the conventional insulation materials such as glass wools.

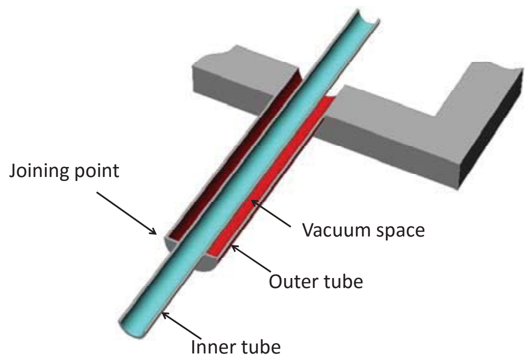

Fig. 3 Schematic diagram of co-centric tube inlet and outlet port design

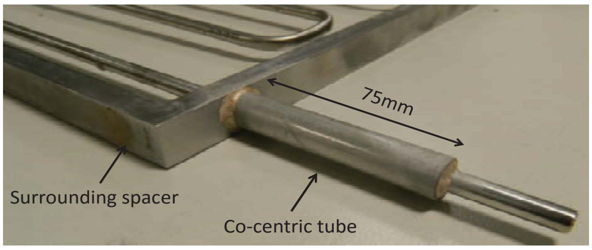

Fig. 4 Co-centric tube inlet and outlet port design

A flat evacuated glass panel, 0.3 m ×0.3 m, was designed and fabricated incorporating a simple tubular solar absorber. Co-centric inlet and outlet tubes were used for thermal fluid transfer through the edge spacer to the absorber. The assembly was tested by using infrared thermography, and its thermal response was analysed.

By circulating hot water through the absorber, a temperature difference is created between the absorber and the vacuum envelope. The heat flux through any contact points between the absorber and the vacuum envelope was detected as shown in Figs. 5 and 6. To investigate the effect of the thermal insulation provided by the high vacuum in the envelope, the collector was tested under both atmospheric and vacuum pressures. Figs. 5 and 6 clearly demonstrate the difference between an evacuated and non-evacuated collector. Both images were taken 30 minutes after hot water circulation commenced. The non-evacuated collector (Fig. 5) had a greater heat loss in comparison to the evacuated collector (Fig. 6) which had a vacuum pressure of 7.2×10^{-5} mbar. The co-centric inlet and outlet tubes exhibit excellent insulation in the evacuated collector whilst their performance is poor in non-evacuated collector. The co-centric tube design for the inlet and outlet ports can be used in any flat plate vacuum collector.

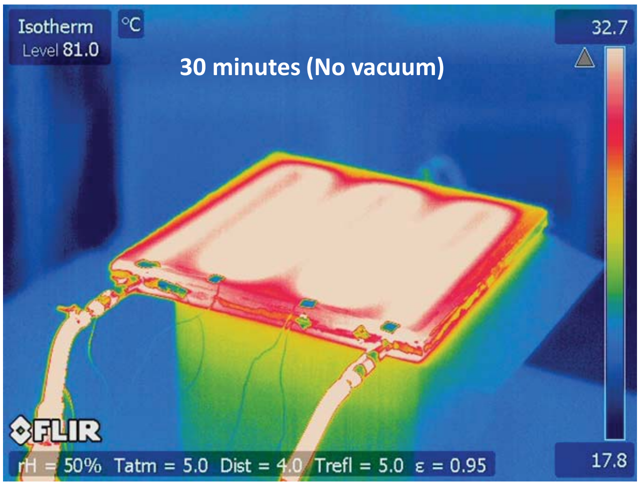

Fig. 5 Non-evacuated solar collector, the picture was taken in 30 minutes of circulating hot water

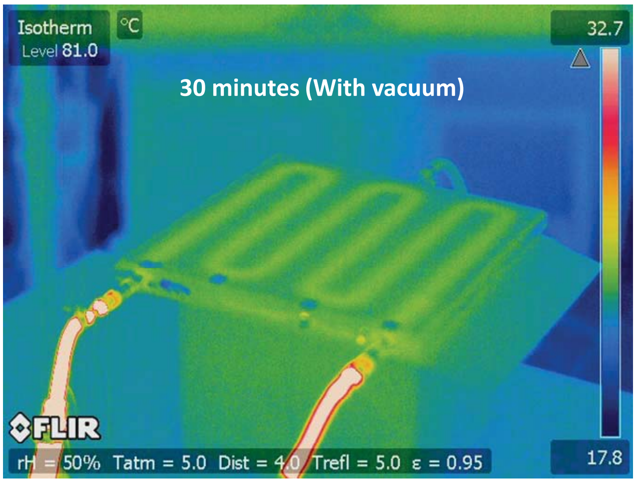

Fig. 6 Evacuated solar collector, the picture was taken in 30 minutes of circulating hot water

C. Heat Transfer in a Vacuum Panel

Heat flow between the glass panes of flat vacuum panels remote from the edge seal can occur due to radiation between the internal surfaces, conduction and convection through residual gas in the evacuated gap and conduction through the support pillars. An infrared thermography technique was used to investigate the effectiveness of the vacuum space in minimizing heat loss from the absorber. In order to take an infra-red image of a flat vacuum panel, a temperature difference of about 20 °C is created between the two sides of the panel. Fig. 7 shows the infra-red image of the panel which clearly depicts increased heat flow through the pillars and the edge seal in comparison to the central region of the panel which indicates a high level of vacuum in the panel [10].

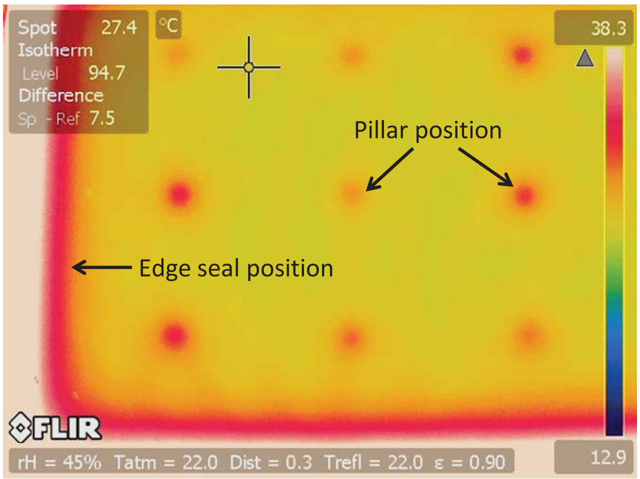

Fig. 7 IR-image of a flat vacuum panel

Creating a temperature difference between the two sides of the vacuum panel during thermal transmittance testing in a hot box calorimeter and during infra-red thermography imposes differential thermal expansion stresses in the panels [8]. The tests in this study did not impact negatively on the integrity of the edge seal; however, further work is required to determine the stress limits the panel can withstand.

D. Current Development

Prototypes of flat vacuum panels suitable for use in solar thermal collectors were fabricated, schematically shown in Fig. 8. The vacuum panel consists of two 4 mm thick glass panes sealed around their periphery to a profiled stainless steel spacer creating a cavity between the glass panes which is to be evacuated. The glass panes, 0.55 m × 0.55 m, were low iron toughened glass, while the spacer was fabricated by folding 1.2 mm thick stainless steel sheet (304L grade) in the form of a U-channel. The edge sealing process was undertaken in a conventional oven at a temperature of about 220 °C. The seal was hermetic and created with Cerasolzer 217 using an ultrasonic soldering technique. Using ultrasonic soldering to create hermetic seals in ultra-high vacuum applications is described in detail in [11], [12]. The separation of the panes which would otherwise touch under the influence of atmospheric pressure is maintained by an array of stainless steel (grade 304L) support pillars. The pillars are 25.2 mm high and 6 mm in diameter and spaced at 60 mm intervals on a regular square Cartesian grid.

After formation of the edge seal, the collector is connected to a turbo molecular vacuum pump via a pump-out port through the edge spacer. A completed prototype of a vacuum panel is shown in Fig. 9. To add strength to the bond between the glass panes and the edge spacer additional metal brackets were used as schematically shown in Fig. 10. An epoxy was used to bond the metal bracket to the panel. The epoxy was not in contact with the internal vacuum environment which would otherwise outgass and degrade the vacuum pressure.

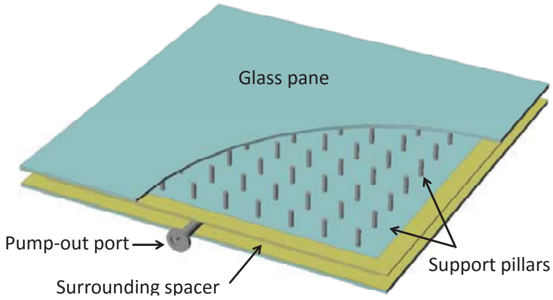

Fig. 8 Schematic diagram of a flat vacuum panel

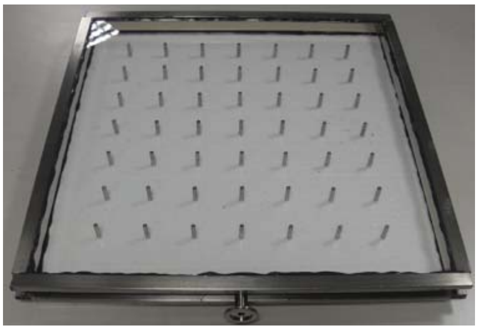

Fig. 9 Fabricated flat vacuum panel

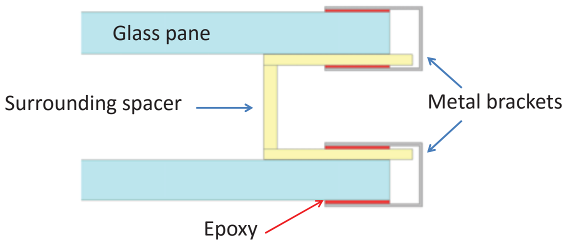

Fig. 10 Metal bracket and epoxy used to support the bond between glass and surrounding spacer

A slim flat solar absorber has been designed and fabricated using a hydroforming technique at the University of Warwick. A method of maintaining a gap between the solar absorber, the glass panes and the surrounding spacer has been developed to avoid thermal bridges. The absorber is plated with black chrome to increase its absorption efficiency, and integrated in a vacuum panel fabricated at Ulster University. The detailed fabrication process for the solar collector and the characterization test results will be reported in further work. The flat-plate solar collector, as shown in Fig. 11, was evacuated to a pressure of 8.3 × 10^{-5} mbar, which would indicate that there are no substantial leaks in the panel or in the solar absorber.

III. Discussion and Conclusion

In this paper, important considerations for the development of flat-plate solar collector technology has been reviewed and ongoing relevant work at Ulster University, Loughborough University and the University of Warwick has been outlined.

A novel sealing method has been developed and used in the fabrication of vacuum panels. The seal was created with a metal alloy, Cerasolzer 217, and applied by using ultrasonic soldering techniques. A profiled stainless steel edge spacer was designed, and prototypes of flat vacuum panel were fabricated.

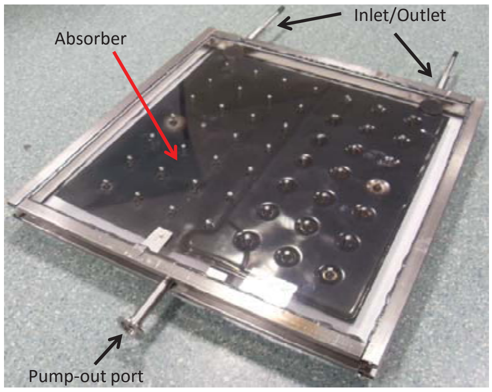

Fig. 11 Slim flat-plate solar absorber integrated in a flat vacuum panel

A flat plat solar absorber was integrated in a vacuum panel and the panel was evacuated to a pressure of 8.3 × 10^{-5} mbar indicating there were no leaks in the panel or in the absorber. A fluid inlet and outlet port design using co-centric evacuated tubes was developed at Ulster and used in the collector. The thermal insulation provided by the vacuum space in the vacuum envelope will minimize the heat loss from the absorber resulting in an increase in the efficiency of the solar collector.

Initial tests showed the edge seal was hermetic and mechanically robust to withstand stresses induced by atmospheric pressure and thermal expansion and contraction. Accelerated ageing tests are required to evaluate the durability of the edge seal.

The features of this design enable the collector to be constructed with a low-profile that would have significant appeal to householders for domestic applications and has greatly enhanced potential for building integration.

This research presents a reproducible fabrication method which has the potential to be exploited in a flat vacuum solar panel production line for flat vacuum panels.

Acknowledgment

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