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A non-tracking concentrating collector for solar thermal applications

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HIGHLIGHTS

- A non-tracking solar collector of novel design is tested outdoor in SE Asia.
- A novel performance parameter, the power concentration factor, is introduced.
- The header pipe has a new "wet" connection giving enhanced efficiency.
- The collector is superior to a commercially-available non-concentrating collector.

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ABSTRACT

We report the development of a solar thermal collector module based on our proposed design (Ratismith et.al., 2014) of a large acceptance-angle multiple-parabolic trough which surrounds a standard evacuated cylindrical tube containing a planar absorber plate. The concentrator accepts diffuse solar radiation with an intercept factor of near 100% and so is suitable particularly for tropical climates. The module incorporates a novel direct metal-to-water contact resulting in an improved efficiency of heat transfer to the working liquid. Comparison with the performance characteristics, principally power output and temperatures attained, of a commercially-available non-concentrating assembly of evacuated absorber tubes is made. The experimental results, obtained by testing under typical conditions of solar irradiation throughout the day in Bangkok, indicate that the improvement over a non-concentrating collector, suggested theoretically on the basis of ray-tracing studies, is attained in practice. The superior performance of the concentrating collector indicates its suitability both for residential and industrial applications.

1. Introduction

In a recent paper in Applied Energy [1] on "Assessment of renewables for energy security and carbon mitigation in Southeast Asia" it was concluded that " expanding the share of renewables in the energy mix can bring extensive socio-economic benefits to the Southeast Asian countries". The study concentrated mostly on power generation and hence the harnessing of solar power in the form of photovoltaics. Here we report on the alternative development of small-scale solar thermal collectors for heating and cooling. Although small-scale, since solar irradiation is considerable throughout the Southeast Asia region, were such installations widely implemented they could lead to a significant reduction in primary electricity demand. The solar collector proposed here is based on a new design of CPC trough proposed in our previous publication [2]. The collector is installed in central Bangkok and has the important characteristics of being non-tracking, therefore cheap to manufacture and maintain. Furthermore, it operates efficiently in both clear and cloudy conditions as pertain in most of Southeast Asia. The collector is completely scaleable in size and therefore suitable for a variety of residential and industrial applications.

Since the seventies of the last century there have been many suggestions for the use of compound parabolic concentrators (CPC) for concentrating solar radiation. As early as 1975, in a seminal paper, Winston and Hinterberger [3] elucidated the principles for optimisation of the concentration efficiency of such concentrating collectors for solar thermal and photovoltaic applications. Note that the designation "CPC" is often used also for collectors not always consisting of parabolas. Some earlier important examples, for both photovoltaics and for solar heating, which is the subject of this paper, we have discussed in detail in Ref. [2]. Interest in CPC continues and more recently, there have been several papers

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on design improvements [4–6]. Other papers concentrate on a wide variety of applications, indicating the versatility of CPC solar concentrators. For example, a non-tracking external CPC (XCPC) with a cylindrical absorber has been implemented [7] to drive successfully a chiller for air conditioning, which is one of the applications described in this paper. In Refs. [8–10] the straightforward heating of water is discussed whilst in Ref. [11] the collector is used to heat air. The industrial application to generate process heat up to 300° is outlined in Ref. [12] and as example, the design of a solar thermal plant for methanol reforming is given in Ref. [13]. In contrast, there are also many proposals to use the CPC solar concentrator for cooling, either refrigeration [14] or to drive a chiller for air conditioning [15] However, almost all of these proposed systems are based on the conventional CPC design with a double-minimum in cross-section or with a horizontal flat absorber at the base. In some cases only a small acceptance angle is achieved by the CPC.

The challenge for any non-tracking collector is to optimise the capture of solar energy throughout the day. This implies having a large acceptance angle but at the same time achieving an intercept factor close to 100%. This intercept factor, which we denote by $\mathcal{I}(\theta)$, where θ is the angle of incidence of radiation with respect to the vertical, is defined as that fraction of the radiation entering the aperture which is captured by the absorber plate. Our unconventional design, which we called the flat-base trough (FBT), is a significant step towards achieving this aim. It has a large acceptance angle and the desirable property that throughout the day almost 100% of solar radiation is captured by a vertically-placed flat absorber plate.

In Ref. [2] we demonstrated the superiority of the FBT with vertical absorber to the conventional CPC having a double parabola with a central peak in the cross-section and a horizontal flat-plate absorber. The main aim of this paper is to demonstrate the advantage, in terms of power harvested per tube, of embedding a flat-plate collector tube in our FBT trough rather than simply exposing the tube itself to solar radiation, as is standard in commercially-available flat-plate solar installations. Hence in an experiment we demonstrate the superior performance of a collector composed of fifteen connected FBT's to that of a commercially-available non-concentrating assembly of sixteen of the same evacuated tubes. (The slightly different number is due to the fact that our collector is composed of modules of three tubes, the commercial collector has modules of eight tubes). It is shown that the expected power concentration factor is achieved by the FBT concentrating collector so that it requires roughly only half the number of tubes as the non-concentrator to harvest the same output power.

A further novel feature of the collector design compared to commercial flat-plate collectors is the immersion of the tube header directly into the working fluid (wet connection) rather than the simple conductive dry connection usually employed. This leads to efficient direct transfer of heat to the working fluid as we demonstrate by measuring the efficiency of identical collector modules with both dry and wet connections.

As a first application of the FBT concentrator, a modular system installed on the roof of a 12-storey building at Chulalongkorn University in the centre of Bangkok, Thailand is connected to a chiller to drive an air conditioning unit, as described in detail in Section 5. In this way we show that the collector is capable of achieving output temperatures and power sufficient for residential and low-scale industrial applications.

The concentrator has been designed to operate in both direct and diffuse irradiation conditions. This is important particularly for use in tropical climates where, for example in Thailand 60% of solar irradiation is diffuse in humid and cloudy conditions. This capture of radiation from many directions is achieved without tracking by the trough shape which is designed specifically to give a large acceptance angle. A further feature of the collector contributing to wide acceptance is the arrangement of the troughs in modules of three, the two outer troughs being tilted away from the vertical. This arrangement ensures also that a smooth variation in the captured solar power throughout the daylight hours, from roughly 7 a.m. to 5 p.m., is achieved. We describe test results showing that the FBT concentrator achieves higher temperatures and increased power output compared to the non-concentrator under the typical weather conditions of, (1) bright clear skies, (2) intermittent cloud/sunshine and (3) cloudy for most of the day.

The potential for medium to high- temperature (70–150 °C) application of solar thermal collectors in industrial applications and in particular, its role in air conditioning and the consequent fuel savings, reduction in greenhouse gases, etc. is described in some detail in Refs. [16,17]. Here we demonstrate that our collector is suitable both for domestic use, where a considerable saving on the number of evacuated collector tubes necessary can be achieved, and for air conditioning of industrial buildings.

The structure of the paper is as follows. In Section 2 we describe briefly the salient features of the capture and concentration characteristics of the flat-base trough proposed in [2]. Furthermore we introduce a new dimensionless parameter, the "power concentration factor", with which to quantify the performance of a concentrating trough. Then in Section 3 we discuss the structure of the modules of three troughs. In particular we describe the comparison of the efficiencies of concentrating modules with wet and dry connection of the header pipe to the tube in which the water to be heated flows and the improvement of the transfer of heat from the absorber pipe to the working fluid, which in our case is water. The heated water is used, for example, to drive an absorption chiller for cooling purposes. The manifold header pipe from the absorber tube is now inserted directly into the flowing water. This we call a "wet" connection and is to be contrasted with the conventional "dry" design in which the header pipe is exterior to the container of the working liquid and makes a simple conductive contact with it. By arranging that the working liquid flows around the manifold header pipe the heat transfer is effected more directly.

The testing of an assembly of five connected concentrator modules (15 absorber tubes) in outside conditions is the subject of Section 4 of the paper. We compare directly with the performance of a commercially-available standard configuration of collector tubes without solar concentration and demonstrate, under the weather conditions listed above, that our design of concentrator leads to the expected increase in output power per collector tube and a significant rise in the inflow-outflow temperature difference.

In Section 5 we describe the application of the collector to air-conditioning and give data on the achievement of the power output necessary to drive the chiller. We discuss further realisable applications of the collector and then present our conclusions in Section 6. A note as to nomenclature; the assembly of three troughs into a single unit will be called "a module". The connected set of five such concentrating modules will be called the "concentrating collector". The commercially-available assembly of sixteen vacuum tubes will be called the "non-concentrating collector".

2. The concentrator trough

Here we present the pertinent capture and concentration characteristics of the flat-base trough (FBT) proposed and described in detail in [2]. This trough is composed of two overlapping parabolic segments which are truncated at their intersection and then rotated such that the gradient of the curve at the centre of the cross-section of the trough is zero, i.e. the base is flat. This is shown