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Use of finite element models for estimating thermal performance of façade-integrated solar thermal collectors

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HIGHLIGHTS

- Literature review highlighted a lack in works concerning BIST models.
- A FEM based model for a coupled wall/collector system is proposed.
- The model is validated and calibrated on two real case studies.
- The model is run following standard procedure requirements for collector characterisation.
- Pro and cons of the proposed model are outlined and BIST efficiency-curve of two real systems are presented.

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ABSTRACT

Research on building-integrated solar thermal collectors is attracting increasingly more interest. Many efforts have been focused at the design level for obtaining specific building-orientated products, but there is a significant lack of standardised methods for evaluating how the efficiency of solar collectors changes when a wall is an integral part of the solar component itself. Generally speaking, experimental tests on integrated components are not easy to realise and are, in any case, expensive in terms of time and money. Physical and numerical methods can be utilised, but at the moment, there is no common approach. The present work addresses a method for the calculation of a building-integrated component performance curve by means of a finite element method model. The main idea is to exploit data measured for a simpler and non-integrated component, which are readily available, for validating and calibrating a more complex model in which the system is coupled with a building element. Simulation assumptions and outputs are designed to comply with the main standards utilised for defining solar collector performance curves. The proposed method proves that it may be a good way to assess the performance curves of building-integrated solar thermal collectors and that it is suitable for reducing test costs. The authors have also highlighted the measures that must be taken for the sample collector to better fit the BIST performance model.

1. Introduction

The proper assessment of solar energy use in building energy balance is currently a recognised challenge. In particular, the integration of a solar component into a building envelope assumes particular interest in solar thermal collector applications given that such plants benefit from being as close as possible to the area where the produced energy is used. In this regard, Building-Integrated Solar Thermal (BIST) design has been attracting increasingly more interest at every level. The scientific community recently agreed to define a BIST component as "*a plant component that, apart from its primary function as a heating/power generator, plays a specific role as a building component*" [1,2].

Thus, its nature implies that a proper assessment of its performance must be focused not only on heat production but also on the influence of heat transfer through the wall (or other building envelope element) on which it is integrated. Important studies on BIST characteristics have been conducted in the framework of International Energy Agency Task 41 research. The outcomes have noted how existing technology is generally well developed as a purely technical element whose design starts mainly from the "energy production" point of view. For this reason, the lack of "building-oriented" studies of products already available on the marketplace or still under development is remarkable and recognisable as a major barrier to the widespread use of solar thermal

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systems in building practice. International Energy Agency task researchers have proposed some guidelines for designing components that simultaneously act as building components with functional, constructive and formal/aesthetic aspects and plant components with their own technical constraints and characteristics such as *U*-value and heating power. Some research has focused on designing a solar collector with a specific in-building function, and some deliverable products are summarised at the Leso website [3]. Some of them are particularly interesting for their high level of integration—e.g., the ST roof tile and ST shade [4,5] or the rainwater gutter [6–8]. At the same time, another aspect to consider is the suitability of available solar component technologies to be adapted to building functions, making the components flexible and customisable. This implies the possibility of customisation/standardisation of size and the use of technical solutions [9] while solving technological obstacles such as watertightness or durability. Aesthetical issues are also investigated, and new shapes and colouring and finishing technical-aesthetical solutions are proposed [10].

Beyond these important building design considerations, this paper stresses the "energy integration" aspects. When a solar collector is integrated as a part of a building envelope, the thermal performance as both the collector and a building component are somehow changed. On the one hand, the building envelope influences the back heat losses of the collector and consequently alters its efficiency; on the other hand, the heat fluxes of the building envelope must be evaluated considering the solar collector as part of the envelope itself. In this regard, opaque and transparent elements must be distinguished, and an analysis of heat fluxes and temperature profiles in the integrated component is thus an important issue for better understanding the reciprocal influences in the building and the solar system.

A solar system as a thermal plant component has been studied in past decades. As merely samples, Tian and Zhao [11] and Chow [12] recently reviewed the state of the art in solar thermal collectors and photovoltaic thermal systems (PV/T) in civil applications, respectively. Tian generally focused on solar thermal collectors and related heat storage systems. Among the different technologies, he focused on the low-temperature flat plate collector, highlighting all computational and design efforts that have been undertaken on this topic and finding that mostly NIST analyses have been proposed. While reviewing PV/T systems, Chow also discussed building-integrated PV/T components (BIPV/T). It is worth noting that several results concerning temperature profiles of an integrated component come logically from the PV/T system studies. Chow et al. [13], for example, investigated the annual thermal behaviour of a BIPVT component through a finite difference distributed parameter model. In this study, the building-integrated photovoltaic/water-heating system was supposed to be integrated in the building façade, and it was demonstrated that the overall heat transmission through the wall was reduced to 38%, assuming their operation conditions, with respect to the standard building façade. Agrawal and Tiwari [14] studied a roof-integrated PV/T system by means of a one-dimensional transient model based on basic heat transfer equations. The aim was to select the appropriate PV/T system for generating higher electrical energy per unit area and the necessary heat required for space heating. Yang and Atheientis [15] studied the thermal characteristics of a two-inlet air-based open-loop building-integrated PV/T component. Data from experimental campaigns and from numerical simulations based on a thermal network model were compared in the study, and different configurations of the component were proposed. The results showed thermal efficiency increases of approximately 5% with respect to a one-inlet system and approximately 7.6% if semi-transparent PV panels are considered. Finally, Amrizal et al. [16] approached the EN 12975 standard procedure through a quasi-dynamic thermal model to determine the electrical performance of the system.

At the BIST level, Lamnatou et al. [17] provided a general overview on the state of the art of solar technologies for building integration and methods for predicting their performance. They generally reviewed the means by which solar technology has been simulated, stressing attention on the behaviour of the component and distinguishing energetic, thermal, energetic/thermal and optical simulations. Specifically, the solar thermal collector, skin façade, solar chimney, Trombe wall, PVT, and PV have been considered. The authors identified a lack in the literature of works concerning BIST models.

The same authors also proposed a review of simulation cases of coupled building/system models following the same approach and classification [18]. It is worth noting that 84 study cases belong to the first study, and 42 are from the second one. Moreover, BIST technology is specifically addressed in only 11 and 5 study cases, respectively. Most of the analysed BIST focused on transparent components and derives component performance characteristic from the results of an experimental campaign on a specific prototype. Generally, Hottel–Whillier–Bliss equations are applied and arranged for specific BIST case studies, whereas the EN 12975 approach is used as a reference for assessing efficiency curves during experimental campaigns. Giovannetti et al. [19] tested a solar thermal collector integrated into a window frame, assessing the efficiency curve in laboratory. Dowson [20] studied an aerogel solar collector by focusing on the influence of cover properties on the collector efficiency in the façade-integrated component; similarly, Anderson focused on the means by which absorber colour influences the collector performance while enhancing building integration. Both of these works are based on experimental campaigns. The authors then proposed a calculation model validated on the basis of recorded data. Wildholz et al. [21] studied a demo façade including solar thermal collectors (ST) and photovoltaic modules (PV) built up in Graz. Maurer et al. [22] and Pflug et al. [23] proposed a study on a transparent solar collector; the former focused on solar transmission through the component, collector gain and energy flux to the interior. Based on the experimental campaign data, Pflug instead focused on the necessity of determining a simplified model for façade-collector performance estimation. At a theoretical level, Maurer et al. [24] also notes the lack of a standardised method for assessing BIST performance and proposes simplified methods for adapting efficiency curves of non-integrated collectors to BIST cases. Four approaches to the problem are discussed. These models are exclusively based on simplified equations and are not compared with an experimental nor detailed simulation reference dataset. The first model, based on Whiller–Bliss equations, discharges the back losses in the case of a well-insulated building. The second model, based again on Whiller–Bliss equations, introduces some corrections to approximate the back heat flux in the case of a poorly insulated building, leading to a more reliable estimation of the efficiency curve. The third model focused on a transparent solar thermal collector to be integrated in the building façade. The former extends the efficiency curve to include the building inner surface temperature, but the authors note the need to fit the curve by monitoring the data. The last model finally introduces a parallel resistance between outdoor and indoor conditions and tested the results. Moreover, in a recent work Shen et al. [25] proposed the analysis of a building oriented solar thermal façade characterised by modular (0.48×0.35 m) simple structure. Authors proposed a stationary mathematical model of the entire wall/collector system while laboratory experimental tests were implemented for evaluating the real performances of one module of the collector.

Given this state of the art, it is clear that there is no recognised standard method available for evaluating the influence of the performance of the integrated collector, either on the plant or on the building component. Available regulation for solar collectors has