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Building-façade integrated solar thermal collectors: Energy-economic performance and indoor comfort simulation model of a water based prototype for heating, cooling, and DHW production

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ABSTRACT

This paper presents the design and the thermodynamic analysis of a new prototype of flat-plate solar thermal collector, suitable for building integration, using water as working fluid. The main novelty of the proposed solar thermal collector is the use of cheap materials and simple design solutions, taken into account with the aim to reduce the manufacturing and installation costs towards the improvement of the market penetration of this technology in the near-term future. The collector is suitable for domestic hot water production and for space heating and cooling, achieved through the use of adsorption chillers. A suitable dynamic simulation model for the system energy, comfort, economic, and environmental performance assessment is developed by taking into account both active and passive effects related to the building integration of the solar collector.

The developed simulation model, implemented in a suitable MatLab computer tool, is experimentally validated; the main results of the validation process are discussed in this paper. Moreover, in order to show the potential of the presented building integrated collector prototype and of the related simulation tool, a suitable case study is developed. It refers to a residential unit of a multi-floor building where the prototype collectors are integrated on the South façade. Simulations are carried out for 2 building envelope weights and 9 different weather zones. Interesting outcomes from the energy, economic, environmental, and comfort point of views are obtained.

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1. Introduction

Nowadays the building sector is responsible for 40% of the total primary energy consumption and for 30% of greenhouse gas emissions in OECD Countries [1]. Buildings final energy consumptions are mainly due to Heating, Ventilating and Air Conditioning (HVAC) systems and to Domestic Hot Water (DHW) demand. Therefore, to increase the efficiency of the building sector, several saving strategies must be taken into account. In this framework, the European Directive 2010/31/EU for building energy efficiency encouraged the adoption of Renewable Energy Sources (RES) and the development of the related technologies [2].

Due to the high availability of solar radiation, the solar based renewable technologies are the most promising, among the other typologies, in terms of energy saving and carbon emission reduction. Photovoltaic (PV) panels, Solar Thermal Collector (STC), and hybrid systems are currently the most applied technologies for building applications [3,4]. The adoption of these systems as Building Added (BA) (e.g. applied to the building envelope by means of suitable supports) is worldwide very common, especially in European Countries. Their utilization into buildings will be mandatory in new constructions as well as in refurbished ones in order to reach the minimum renewable energy ratio required by the current normative [5]. However, the new trend is to overcame the BA configuration in order to obtain Building Integrated Solar (BIS) systems [3], mainly due to their better functional and aesthetic impact, higher possibility to exploit solar energy in building and capital cost reductions [6]. In addition, the switch to the building integrated configuration is suitable in case of high-rise buildings or urban areas with limited outdoor space. In typical

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European buildings (medium and high rise dwelling/office ones in the urban context), the implementation of solar systems into the building façades represents one of the few possible ways to exploit solar energy [6]. Therefore, with the aim to increase the RES utilization in buildings, BIS systems (e.g. Building Integrated Photovoltaic (BIPV) panels, Building Integrated Photovoltaic/Thermal (BIPV/T) panels, Building Integrated Solar Thermal System (BISTS), etc.) are considered as very promising technologies, boosting the shift of the building envelope from a passive to an active system component [7].

A number of technological, aesthetical and economic issues [8] are obstacles to the BIS use. Technological aspects are still the main problem of BIPV/T systems, as discussed in Ref. [9]. Moreover, in case of BISTS systems, the economic issue is probably the most limiting one. Indeed, existing STS available on the market are usually too expensive to have an appealing return of the investment, especially if compared to PV systems. To make BISTS more competitive and to avoid the double conversion (from electricity to thermal energy by means of PV panels), it is advisable to develop cost effective STS with the aim to boost their building integration [3].

The building integration of solar systems may influence the building energy demand for space heating and cooling and the indoor comfort conditions. This result, known as passive effect, is due to the variation of the amount of incident solar radiation absorbed by the building envelope, whose thermophysical properties are also modified. Therefore, the integration of BIS systems into the building envelope causes a free heating gain effect during winter and a superheating effect during summer.

Many studies about BIS systems are available in literature. The majority of them refer to numerical analyses focused on BIPV collectors, whilst fewer investigations about BIPV/T or BISTS exist [10,11]. Novel system configurations are proposed in several papers, focused on BIPV/T systems [12,13], standard STC [14,15], and façade integrated transparent STC [16,17]. Moreover, few studies are available in literature on the analysis of the whole building/system interaction. Fewer papers focused on the passive effects of the BIS systems on the building thermal behaviour are available, e.g. Refs. [13,18]. Therefore, BIS systems passive effects analysis still represents a lack of knowledge in BIS research area. The few numerical and experimental analyses assessing the BIS systems passive effects [19,20] refer to the very specific case studies or climate zones [21], with no data about the annual performance of the system. In this regard, it is worth noting that the yearly analysis is crucial in order to understand the convenience of a specific device over the year from both energy and comfort point of views [34]. Moreover, different weather conditions should be taken into account to verify their influence on the BIS effects and to provide useful design criteria for the BIS spread.

The available literature also shows a lack of investigations on the interaction between the BIS system and the coupled HVAC system, as discussed in Refs. [10,11]. In addition, few papers available in literature, especially in case of water solar thermal collectors, analyses the variation of the hygrothermal comfort due to the BIS adoption.

In this framework, one of the goals of this paper is to analyse the energy performance of a low-cost water solar collector prototype, designed for the integration into building façades. With the aim of trying to overcome the above mentioned economic issues, the presented innovative solar thermal collector prototype is made of very simple and cost-effective materials, which could boost the BISTS adoption due to the more profitable initial cost.

In order to study the energy performance of the proposed water STS prototype, a suitable simulation model is developed and validated by means of experimental data, collected at Limassol (Cyprus). In addition, to assess the mutual interaction between the STS and the building, a holistic approach is taken into account. This represents one of the most remarkable novelty of the presented dynamic simulation tool. As mentioned above, it should be considered that very few studies considering the BIS effect in terms of thermal behaviour can be found in literature. Therefore, in this paper such lack of knowledge is completed from different points of view. In particular, the developed simulation tool is capable to assess the whole building-system energy, economic, environmental and comfort performance, with a specific focus on the passive effects analysis in term of heating/cooling demand and indoor comfort. To this aim, the building model, based on the simple hourly method which is based the EN ISO 13790 Standard [22] has been suitably modified. The presented simulation model allows one to easily investigate several building-plant systems by varying both constructive and operating parameters, while taking into account different weather conditions. In order to exploit all over the year the thermal energy produced by the water prototypes, the simulated HVAC system consists of a solar heating and cooling (SHC) plant. The new simulation model presented here developed on purpose for analysing the building integration of the solar thermal collector prototype presented and the related energy and comfort performance on a dynamic and annual basis. Such aspects are novel in the available literature concerning BISTS [13]. In particular, the developed simulation model is able to compute all the corresponding passive thermal effects (due to the building integration) by calculating the additional heat gains obtained. Reduced heating loads/demands and additional cooling ones can be dynamically assessed. By taking into account passive effects, the thermal comfort analysis of indoor spaces is carried out by means of a specific tool included in the code. Growth and decline of the occupants' comfort, occurring during winter and summer, respectively, can be also analysed when the HVAC system is switched off (free floating of the indoor air temperature). By all such innovative features of the simulation tool developed the design and operating details concerning the BIS applications can be obtained. Note that, such new investigation approach will be very useful to solar collectors manufacturers and building designers as soon as the solar devices will be commercialised as elements to be directly integrated in the building envelope.

2. Prototype design features

The water solar thermal collector prototype consists of: i) a single layer low iron glass cover; ii) a header and risers copper pipe line; iii) a selective surface (TiNox) absorber plate; iv) an insulation layer (glass wool); v) a galvanised metal sheet case. Table 1 includes the main geometrical features of the prototype, whose main novelty is the manufacturing cost, which is remarkably lower than the ones of commercial solar collectors. In fact, thanks to the selected materials, the total cost of the device is estimated to be equal to 95 €/m^2, being substantially lower than the cost of a typical commercial solar thermal collector (usually higher than 300 €/m^2). Note that the considered cost is assessed by taking into account the detailed retail prices of all the collector elements, whilst a cost reduction is expected by applying economy of scale. The collector operates thermosiphonically, increasing the cost effectiveness of the system. This solution causes a decrease of the auxiliary energy consumption, lower charges for maintenance and a better result in term of lifecycle analysis.

Note that as the prototype was conceived to be implemented into building façades by suitable hangs, it was tested by applying it to a brick made, as shown in Fig. 1. Here, the experimental set up used for testing the prototype is shown.

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