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Massive Solar-Thermal Collectors: A critical literature review

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ABSTRACT

The present work reviews the literature produced so far on high-capacitance solar thermal collectors, with the aim of highlighting the wide range of possible variants and applications and sharing the information here gathered for future developments. These solar systems are here denoted with the term of Massive Solar-Thermal Collector (MSTC). The review is focused on liquid rather air technologies, because of their direct applicability to systems that supply only domestic hot water (DHW) as well as combined DHW and space heating (SH) systems. The attention on this topic is justified by the rising number of publications and energy concepts that deal with the utilization of opaque structures as low cost solar absorbers and by the similar MSTC's efficiency in low temperature range to conventional solar systems.

Contents

1. An introduction to Massive Solar-Thermal Collectors

The growth in the use of solar collectors for covering building loads (domestic hot water (DHW) preparation and space heating (SH), mainly) has shown that these systems are mature and technically reliable. Research and development of solar technologies has led to very efficient solar collectors and systems. A greater share of solar energy in residential building loads can become more significant thanks to thermally well-insulated buildings and the adoption of low temperature heat supply systems. Among technical aspects, solar technologies are also essential measures in order to comply with more and more severe building's energy requirements in terms of primary energy or CO_2 emissions reduction.

The most diffuse solar technologies are flat-plate solar collectors (FPC) and a wide range of typologies [1–5] and materials [6–8] are available on the market. From an economical point of view, traditional solar collectors are characterized by high cost of investment and this is a weighty limit in spreading further their adoption in residential applications [9,10]. Their high cost is mainly due to the use of expensive materials and to the required accurate

Abbreviations: CCC, cellular-clayey concrete; COP, coefficient of performance; DHW, domestic hot water; FDM, finite difference method; FEM, finite element method; FVM, finite volume method; FPC, flat-plate collector; GRC, glass-reinforced concrete; HWB, Hottel-Whillier-Bliss theory; IEI, initial energy investment [kWh]; LCM, lumped capacity method; MSTC, massive solar-thermal collector; RCC, reinforced cement concrete; RFM, response factor method; SAHP, solar assisted heat pump; SCOP, seasonal coefficient of performance; SF, solar fraction [%]; SFH, single family house; SH, space heating; SHDHW, space heating and domestic hot water; SPHS, swimming pool heating system; SPF, seasonal performance factor.

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Nomenclature

a	diffusivity [m^2/s]
a_0, a_1, a_2	collector efficiency coefficients [–], [W/(m^2 K)], [W/(m^2 K^2)]
A_c	collector area [m^2]
Bi	Biot Number
c_p	specific heat [kJ/(kg K)]
C	volumetric thermal capacity [kJ/(m^3 K)]
C_{eff}	effective thermal capacity [kJ/(m^3 K)]
d	thickness [m]
d_1	depth of piping grid [m]
d_g	air gap [m]
d_x	pipe spacing [m]
Fo	Fourier Number
F_R	heat removal factor
F'	collector efficiency factor
I_g	global solar radiation [W/m^2]
$\dot{m}$	mass flow rate [kg/h]
p_v	vapour pressure [Pa]
q_u	specific heat flux [W/m^2]
Q_u	heat flux [W]
s_d	equivalent layer thickness [m]
S_d	total equivalent element thickness [m]
t	time [s]
T	temperature [K]
T_S	heat removal temperature [K]
U	U-value [W/(m^2 K)]
U_0	heat transfer coefficient between fluid and ambient air [W/(m^2 K)]
U_L	thermal loss coefficient [W/(m^2 K)]
w	water uptake coefficient [kg/(m^2 $h^{0.5}$)]

Greek letters

α	absorptance
δ	pipe diameter [m]
η	energy efficiency
λ	thermal conductivity [W/mK]
μ	permeability
ρ	density [kg/m^3]

Subscripts

air	ambient temperature
av	average
conv	convective
d	daily
e	external
eff	effective
f	fluid
i	internal
sa	sol–air
sat	saturation
sp	specific
tot	total

manufacturing phases: thus, large cost reductions are needed in solar SH and DHW systems to achieve a significant penetration in the residential market.

Two general approaches can be indicated as effective strategies to reduce the economic impact of solar thermal collectors. A first trend goes in the direction of manufacturing low-cost collectors with the adoption of alternative materials (e.g. non-metallic, plastic, fibre-glass or rubber) [8,10,11], which represent valid options to traditional materials in low temperature range (delivered fluid temperature < 50 °C). A second trend goes in the direction of a better integration of solar systems in building envelope [12] and deals with a more integrated design between formal and technical aspects.

The ideal absorber material would be "inexpensive, easy to form, strong (in terms of pressure and handling), stable at temperature of 205 °C, stable under long-term exposure to ultraviolet radiation, nonporous, lightweight and completely noncorrosive" [11]. Unlikely a material cannot meet all these criteria and a compromise has to be found among all these requirements and thus additional research should be addressed in this direction.

A more effective integration of solar collection systems with the building envelope is always desirable [12–16]. Typically solar collectors are considered mere technical elements and they are installed on the roof top where the visual impact is less prominent. The integration of solar systems is affected by the "linear" design approach, in which architects deal with aesthetic and functional issues, while engineers are responsible of mere energy aspects. The consequence of this is that the degree of freedom of integrating solar thermal systems is restricted already in early design phases. A more effective collaboration between stakeholders, moving toward an integrated design approach, will improve the formal and technical quality of the building and reduce investment and maintenance costs.

In order to achieve these results from technical and aesthetic point of view, a greater design effort is necessary [12–16]. In the last decades, a technological trend has been established, which moves toward a multi-functional façade concept, in which bearing, water-proofing, sound protection, insulation and surface finishing are solved. As further improvement to this, pre-manufactured modular building elements can be also equipped by means of solar energy collection and help to fulfil DHW and heating loads. These techniques can be adopted successfully either for residential and tertiary buildings.

A significant example of possible integration of solar energy technologies in building elements, are represented by Massive Solar-Thermal Collectors (MSTCs). With this term, the authors refer to those massive structures, which are exposed outdoors and serve as active solar systems for a direct or indirect use of the collected energy in covering the building loads. MSCs have been studied since the late 70 s as reaction to the oil crisis, but no widely commercial applications have been developed so far. Evidences of their working effectiveness are limited to relative few literature references and a moderate concern has been testified through the number of patents registered. MSTCs adopt as absorber a massive material (typically concrete) instead of the metallic one and basically, they use similar techniques of floor heating systems to external vertical or horizontal structures. The working fluid is usually water or a brine–water mixture, which flows through the pipes embedded in collector's absorber. Pipe's material can be metallic (such as aluminium or copper) or plastic (PE, PE-X or HDPE). The glazing layer is adopted in order to enhance collector's efficiency by reducing the heat loss coefficient, but in some cases it is neglected because of the fragility and the high investment cost of the glass. As previously said, only few commercial systems have been developed and in order to show the whole range of possibilities, a summary of the most interesting technologies is presented in the following sections.

One of the most significant advantages of MSTCs is their thermal capacity, that induces a storage effect of solar energy and makes possible to extract heat also during periods with no availability of solar radiation. The non-negligible thermal inertia, and in some cases the lack of glass panes, changes radically the behaviour with respect to a conventional FPC. In general, the major advantages of using a MSTC can be summarized as follows: