Design optimization of the façade-integrated solar thermal collector

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Abstrakt

This paper is concerned with the façade-integrated solar thermal solar collector. Façade-integrated solar thermal collectors outperform building-added solar thermal collectors due to smaller heat losses at the back of the collector. The paper analyzes the behavior of different facade collector designs by means of detailed mathematical model of solar thermal collector, focusing on both the performance and architectural aspects. Different configurations of the façade collectors based on single solar glazing, vacuum glazing and double glazing have been investigated. The results of simulation indicate, that in case of using vacuum glazing with special low-emissivity coating (emissivity 0.30, solar transmittance 0.85) and air gap 10 mm (FC3) is possible to achieve higher heat gains compared to standard façade collector solution (FC1). Moreover, façade collector alternative FC3 is two times thinner than FC1 alternative (16 mm against 34 mm).

Key words: facade solar thermal collector; vacuum glazing; detailed mathematical model

1. Introduction

One of the cleanest forms of renewable energy sources is solar energy, which is inexhaustible, sustainable and secure. It is becoming more attractive and can be gained without any restriction. Heat in solar energy can be collected using solar thermal collectors and used for water heating, space heating, space cooling and industrial process. Flat-plate solar collectors are simple in construction, utilize the beam as well as diffuse radiation and can be integrated into a building envelope. A wide spectrum of flat-plate collectors is available, ranging from low-cost unglazed collectors to sophisticated selective-coated single-glazed solar collectors. The typical high-quality collector on today's market is a tube-and-plate absorber with upper bond, selective coating with PVD coating and solar single glazing.

Architectural integration is a major issue in the development and spread of solar thermal technologies. Flat-plate collectors can be integrated as a construction element into the building envelope to replace the need for conventional façade materials. Currently, the architectural quality of most existing building-integrated solar thermal systems is generally quite poor, which often discourages potential new users. To master all characteristics of the system simultaneously, from the perspectives of both energy production and building design, is not an easy task, especially with the presently available solar collector systems. For new buildings, it is preferable to integrate the collector as much as possible as part of the building skin, in order to save building materials and reduce the labour costs of mounting the collectors. As attractive collector designs continue to emerge, the market for building integrated solar collectors is on the increase, mainly in countries such as Germany and Austria, where proper incentives have advanced the development of energy-generating building envelopes [1].

In this context, aim of this study is the theoretical analysis of different façade solar collector constructions.

2. Detailed solar thermal collector model

The simplest approach for performance calculation of integrated solar collectors is to neglect the building integration and to simulate the collector with an efficiency curve. This approach leads to errors in the calculation of the collectors gains. The first reason of this error is that the solar thermal collector is directly mounted on the insulation envelope of the building envelope – there is no rear ventilation, edge and back thermal losses are negligible. Fig. 1 presents a schematic drawing of a building integrated solar thermal collector.

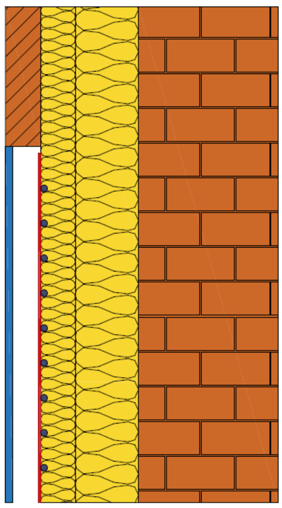

Fig. 1 – Schematic drawing of building integrated solar thermal collector.

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The second reason of the error is that the efficiency curve has been obtained under certain operation conditions (mass flowrate 0.02 kg/s.m^{-2}, slope 45°, intensity of radiation > 800 W/m^2, wind speed 3 m/s) and invalid for other operation conditions. Fig. 2 shows three solar collector efficiency curves for different slope angles obtained experimentally for the same operational conditions. The difference in performance caused by reduction of heat transfer coefficient for natural convection in the gap between absorber and glazing.

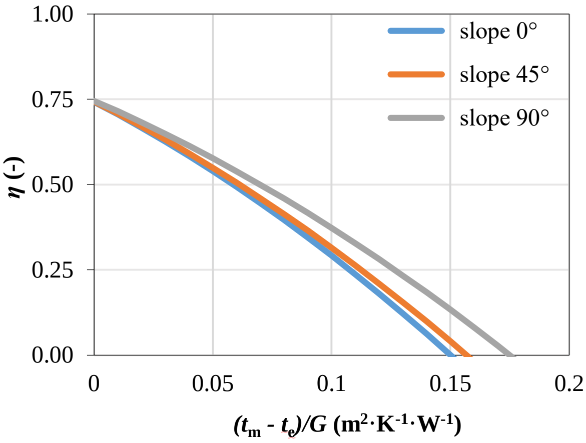

Fig. 2 – Solar collector efficiency curves for different slope angles obtained experimentally.

The optimal approach for performance calculation of integrated solar collectors is to use a detailed theoretical model of flat-plate solar thermal collector. For this reason was created a Type 205 – detailed mathematical model for flat-plate collector into TRNSYS simulation software. The mathematical model in general consists of two parts: external energy balance of absorber (heat transfer from absorber surface to ambient environment) and internal energy balance of absorber (heat transfer from absorber surface into heat transfer fluid). It allows a detailed calculation of heat transfer in the solar collector. Type 205 has been experimentally validated in the frame of solar collectors testing according to European standard [1] in the Solar Laboratory operated under University Centre for Energy Efficient Buildings, Czech Technical University in Prague accredited under Institute for Testing and Certification, Zlin. The detailed description of proposed Type 205 could be found in [2].

3. Vacuum glazing

The major effect on the performance of façade solar collector has heat loss through glazing. Heat loss reduction through glazing and consequently increasing efficiency could be achieved by using vacuum glazing. At the same time it allowed to minimize the thickness of solar collector. Flat solar collectors with low heat loss and also with a sufficiently high optical efficiency could be effectively used for integration into building envelope, which is widely available.

A standard vacuum glazing consists of two glass sheets contiguously sealed together around the periphery, the space between two glass sheets supported by a pillar array arranged on a regular square grid pattern is evacuated to a pressure of < 0.1 Pa, effectively eliminating both gaseous conduction and convection (Fig. 3) [3]. The total heat flow through vacuum glazing can be estimated by combining the heat flows due to gas conduction, radiation, and pillar conduction with the influence of external heat transfer processes, including heat flow near the edges. Low-emissivity coating is intended to reduce heat transfer by radiation in interspace. The pillars have a dimension of about 0.5 mm in diameter and behave like thermal bridges.

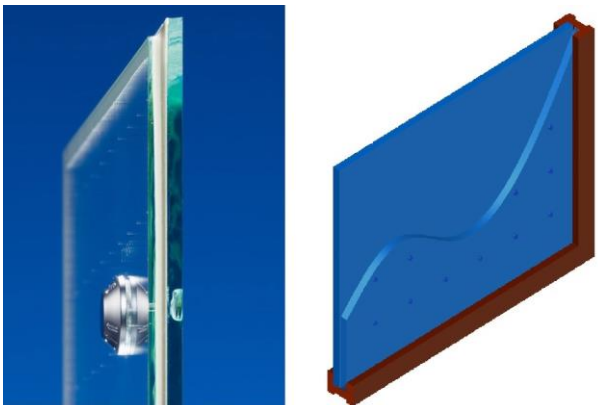

Fig. 3 – Vacuum glazing.

The total thermal conductance $h_{p1\text{-}p2}$ between the glass sheets of a vacuum glazing can be approximated by simple addition of individual thermal conductance h as [4]

$$h_{p1-p2} = h_g + h_r + h_{pil} = 0{,}8p + 4\varepsilon_{eff}\sigma T_m^3 + \frac{2\lambda a}{d^2} \qquad (1)$$

where

$$\varepsilon_{eff} = \frac{1}{\dfrac{1}{\varepsilon_1} + \dfrac{1}{\varepsilon_2} - 1} \qquad (2)$$

The relationship is valid for the interspace with pressure less than 10^{-1} Pa, ie. high vacuum.

Vacuum glazing already emerge in the portfolio of glazing supplier for use in buildings. Vacuum glazing with configuration 3-0.2-3 mm have a transmittance of solar radiation at 62-63% and heat transfer coefficient 1.4-1.5 W·m^{-2}·K^{-1} [3, 4]. Commercially available coatings have been almost exclusively developed for architecture. To ensure thermal and visual comfort in buildings, coating systems based on silver are primarily used, which can provide for extremely low emissivity (less than 0.03) and high visible transmittance (up to 0.90). Solar transmittance, however, is rarely higher than 0.60. A low solar energy transmittance, caused by reflectance of low-emissivity coating for the near infrared radiation (NIR) in the solar spectrum, is unsuitable for use in a solar collector. However values up to 0.85 and corresponding higher emissivity (between 0.20 and 0.30) can be achieved using very thin silver layers, which have been developed in the last years for triple glazing, or with metal oxides [5].

4. Façade-integrated flat plate collector

The solar thermal façade solutions available on the market still focus on the maximization of energy production. Therefore the first comparative criterion is a performance of façade solar collector. On the other hand existing façade solutions do not match the possibility of being integrated in the façade system (module size, thickness, colour and etc.). Hence the second criterion is thickness of solar collector. A maximal façade solar collector thickness was chosen 34 mm.

Different designs of façade solar collector have been theoretically investigated by using the detailed mathematical model Type 205 in TRNSYS annual simulation of solar collector heat output. The investigated alternatives are directly mounted on the insulation envelope of the building façade – there is no thermal separation between the absorber and the insulation envelope in the form of ventilation gap. Solar collectors are thermally coupled to the building wall. The building insulation layers serves for the back and edge insulation of the collector. The thickness of building insulation is 150 mm with thermal conductivity 0.04 $W \cdot m^{-1} \cdot K^{-1}$.

A first configuration of façade solar collector (FC1) is a standard selective liquid flat-plate collector integrated into the building envelope. The collector consist of a spectrally selective copper absorber (fin and tube, thickness 0.4 mm, $\alpha = 0.95$ / $\varepsilon = 0.05$), an air gap and a single solar glazing. Thickness of the air gap has been considered 10, 20 and 30 mm. Layout of the first façade solar collector design is shown in Fig. 1.

A second configuration of façade solar collector has a vacuum glazing instead of solar single glazing with different thickness of the air gap – 10 and 20 mm (FC2). Alternative (FC3) uses vacuum glazing with high transmittance low-e coating with emissivity 0.3. Different thicknesses of air gap also have also been considered – 10 and 20 mm. Alternative FC4 has no gap between the absorber and cover. Here, the absorber is bonded to the vacuum glazing by means of permanently flexible highly transparent silicone gel to reduce the size of the collector (slim collector alternative). The configurations of vacuum façade collectors FC2, FC3 and FC4 are shown in Fig. 5.

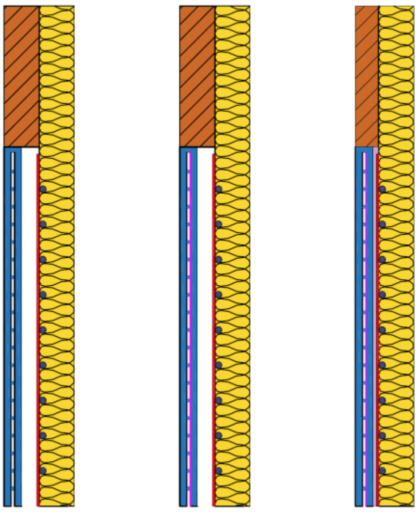

Fig. 5 – Façade collector alternatives with vacuum glazing.

The next configuration of façade collector has a double glazing (4-16-4 mm) with high transmittance low-e coating with emissivity 0.3 (FC5) and with 10 mm air gap. The last alternative FC6 has a double glazing directly bounded to the absorber as well as alternative FC4.

The configurations façade collectors with double glazing FC5 and FC6 are shown in Fig. 6.

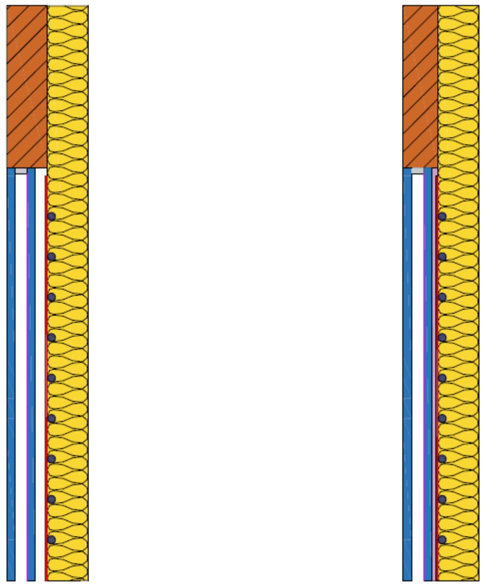

Fig. 6 – Façade collector alternatives with double glazing.

5. Results

The annual performance of the façade collector alternatives has been modelled using the detailed model for constant operating temperatures 25, 50 and 75 °C and climate conditions of Prague. Performance here is defined as specific annual heat gain of collector in $kWh \cdot m^{-2} \cdot a^{-1}$. The results are shown in Tab. 1.

Table 1. *Comparison of the specific annual energy gains for constant operating temperatures and thickness of façade collector alternatives.*

Collector design	Air gap thickness (mm)	Annual energy gain ($kWh \cdot m^{-2} \cdot a^{-1}$)			Thickness (mm)
		25 °C	50 °C	75 °C	
FC1	10	352	196	94	14
FC1	20	366	208	105	24
FC1	30	370	215	112	34
FC2	10	350	226	139	16
FC2	20	361	236	146	26
FC3	10	340	242	167	16
FC3	20	348	252	176	26
FC4	0	325	191	109	8
FC5	10	329	217	137	34
FC6	0	315	176	95	26

The results of modelling indicate, that in case of using vacuum glazing with special low-emissivity coating (emissivity 0.30, solar transmittance 0.85) and 20 mm air gap (FC3) is possible to achieve the highest solar energy gains between compared façade collector alternatives. Also it can be seen that there is a possibility of reduction of façade solar collector thickness from 34 mm to 8 mm (FC4) without a significant reduction in the energy quality of collector. The alternative FC3 with 10 mm air gap represents the optimal façade collector design with improvement in both energy and architectural quality of solar collector.
Also, in can be conducted that in the case of double glazing utilization with the air gap 10 mm (FC5) is possible to achieve higher solar gains compared to FC3, but without any improvement in architectural quality of façade collector.

6. Conclusion

Facade solar thermal collector represents a new element in a building design and also in old buildings retrofit. Different façade collector designs based on single solar glazing, vacuum glazing and double glazing were investigated using detailed mathematical model Type 205 in software TRNSYS. Compared alternatives were directly mounted on the insulation envelope of building façade. The study attest the performance of façade collectors, which can achieve and even exceed the efficiency of commercially available facade collector solutions with a very compact design. Results have shown, that there is a significant potential of using vacuum glazing in the construction of façade collectors.

Acknowledgment

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Nomenclature

a pillar radius (m)
d pillar separation (m)
p internal pressure (Pa)
T_m average temperature of glasses (K)

ε_{eff} effective emittance (-)
ε_1 emittance of the first glass (-)
ε_2 emittance of the second glass (-)
λ thermal conductivity of glass-pillars ($W \cdot m^{-1} \cdot K^{-1}$)
σ Stefan-Boltzman constant, $\sigma = 5.67 \cdot 10^{-8}\ W \cdot m^{-2} \cdot K^{-4}$

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