Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

Solar Energy 80 (2006) 1443–1452

SOLAR ENERGY

www.elsevier.com/locate/solener

Façade solar collectors

Tomas Matuska *, Borivoj Sourek

Department of Environmental Engineering, Czech Technical University in Prague, Prague, Czech Republic

Received 15 November 2004; received in revised form 20 March 2006; accepted 27 April 2006
Available online 5 June 2006

Communicated by: Associate Editor Klaus Vajen

Abstract

Rational use of energy in buildings leads to a concept of active energy façades such as transparently insulated massive walls, solar thermal or PV façades, advanced glazings for daylighting purposes or double ventilated façades. The paper is concerned with the façade-integrated solar thermal collectors concept for water heating in the existing building stock in the Czech Republic (panel and brick blocks of flats), which are ready for major renovations. Thermal behavior of façade collectors compared with standard roof-located collectors in solar DHW systems was investigated. Façade solar collectors should have an area increased by approximately 30% to achieve the usual 60% solar fraction compared with conventional roof solar collectors with a 45° slope. Further increases in the solar fraction above 70% lead to a required area comparable with roof collectors but with less stagnation periods compared with roof collectors. Application of façade solar collectors affects the indoor comfort in buildings in a reasonable range. Indoor temperatures increase by no more than 1 K in all investigated configurations. Building behavior is not strongly affected by façade collectors when sufficient insulation layers are present.

Keywords: Façade solar collector; Thermal integration; Solar fraction; Building retrofit

---

1. Introduction

Many flats (apartments) in the Czech Republic (cca 2.3 million) are concentrated in housing estates (panel or brick blocks of flats). Housing estates established between the 1950s and 1970s should be subject to major renovations. Energy-conscious retrofit takes into account the reduction of building heat losses (thermal insulation, windows, mechanical ventilation with heat recovery), systems of control and measurement, devices for hot water consumption reduction or reconstruction of heating systems (distributed plants) and exploitation of renewable energy sources. Utilization of solar energy has a large potential for water heating (domestic hot water – DHW) in these buildings. However there are often problems with the location of collector fields on flat building roofs (lift housings, ventilation facilities etc.) or such a roof-located system is rejected by architects. The façade collector concept could help to overcome these technical and aesthetical barriers (Weiss and Stadler, 2001) and to

---

* Corresponding author. Tel.: +420 224 355 637; fax: +420 224 355 606.
E-mail address: tomas.matuska@fs.cvut.cz (T. Matuska).

0038-092X/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.solener.2006.04.006

Nomenclature

A_c	collector area [m^2]
A_f	facade area [m^2]
b_{nu}	unutilizability factor [–]
f	solar fraction [–]
F'	collector efficiency factor [–]
F_R	heat removal factor [–]
G	solar irradiance [W/m^2]
h	heat transfer coefficient [W/(m^2 K)]
L	hydrodynamic dimension [m]
Nu	Nusselt number [–]
PPD	predicted percentage of dissatisfied people criterion [%]
Q_s	total solar gains available from collector [kW h]
$Q_{s,u}$	useful solar gains [kW h]
$Q_{s,nu}$	unutilizable solar gains [kW h]
$q_{s,u}$	specific useful solar gains [kW h/m^2]
$q_{s,nu}$	specific unutilizable solar gains [kW h/m^2]
R	thermal resistance [(m^2 K)/W]
Ra	Rayleigh number [–]
U	heat loss coefficient [W/(m^2 K)]
V_s	hot water storage volume [m^3]
T_a	ambient temperature [°C]
T_{in}	indoor temperature [°C]
w	wind velocity [m/s]
α	absorptance [–]
ε	emittance [–]
η	solar collector or system efficiency [–]
$H_{s,d}$	daily solar radiation sum [kWh/(m^2 d)]

bring other advantages. In past, solar system performance were investigated and compared with separately installed roof collectors (Rockendorf and Janssen, 1999), but there is a lack of information on interaction between facade collector and building environment.

At present the concept is tested in first pilot installations in the Czech Republic. Technical support in the form of computer simulations is necessary to reveal potential problems and risks and to suggest efficient solutions for individual applications.

2. Façade collector design

The considered façade solar collector is a standard selective liquid flat-plate collector integrated into the building envelope. Layout of the investigated type of façade collector is shown in Fig. 1. The collector consists of a standard spectrally selective absorber ($\alpha/\varepsilon = 0.9/0.09$), an air gap and single safety glazing. The building insulation layer serves for the back and edge insulation of the collector. Façade collectors are usually available in wooden frames as large-scale installation panels. The collector panel is 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 a ventilation gap. Solar collectors are thermally coupled to the building wall. This integration brings several essential advantages in comparison with solar collectors mounted separately from the building envelope (in front of the envelope or on the flat roof). Additionally to the basic function of solar collectors, façade collectors serve also as protecting shields against atmospheric effects (weather protection) and improve thermal properties of the building with respect to passive solar gains. Furthermore, integration of collectors into building façades is an aesthetically more attractive solution compared with collector fields placed on flat roofs, which create strangely looking bodies on buildings.

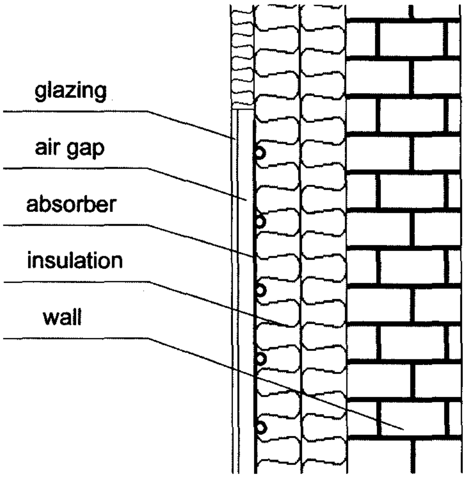

Fig. 1. Façade solar collector.

3. Collector performance

Conventional solar systems are designed to maximize annual solar gains. The basic principle how to achieve this is the proper orientation and slope of the collector field. In Central European conditions, maximum annual irradiation is received with surfaces oriented to the south and with a slope between 35° and 45°. In the case of façade collectors with a 90° slope, the reduction in the annual irradiation sum is around 30%. Fig. 2 shows the annual profile of daily solar irradiation for a roof (45°) and a façade (90°) collector based on the test reference year for Prague. The comparison shows a large difference between the summer peak and the cold season values for the roof collector and a relatively uniform profile for the façade collector which corresponds closely to the hot water demand profile (approximately constant with a decrease in the summer season). This feature allows the design of solar systems with a high solar fraction (above 50%) without extremely increased periods of collector stagnation in summer as appears in roof mounted systems with the same solar fraction.

Solar collector performance generally depends on optical and thermal losses which determine the efficiency of solar energy conversion in the collector. A detailed mathematical model KOLEKTOR was used for the investigation of solar collector thermal performance based on knowledge of thermal processes in individual parts of the collector. The model comprises absorber outer energy balance (heat transfer through glazing, air gap, and frame and absorber surface) and absorber inner energy balance (heat transfer within the absorber fins with solar radiation and piping). Absorber outer energy balance determines the temperature dependent overall *U*-value of the collector. Absorber inner energy balance obtains collector performance factors dependent on the absorber material and geometry (F', F_R). In the model, the temperature distribution in the collector is determined in an iterative loop from the input parameters. Input parameters are solar collector properties (dimensions, physical properties of individual parts), climate data and operation parameters (input temperature, mass flow). Useful heat gain, efficiency of solar energy conversion and temperature of heat transfer fluid leaving the collector are the outputs from the model. The model was created in an Excel sheet processor using Visual Basic programming.

The mathematical model was experimentally validated in the research of solar collectors with different covers (single, multiple, transparent insulations) and absorbers (non-selective, selective). For a specified set of operation conditions, a collector

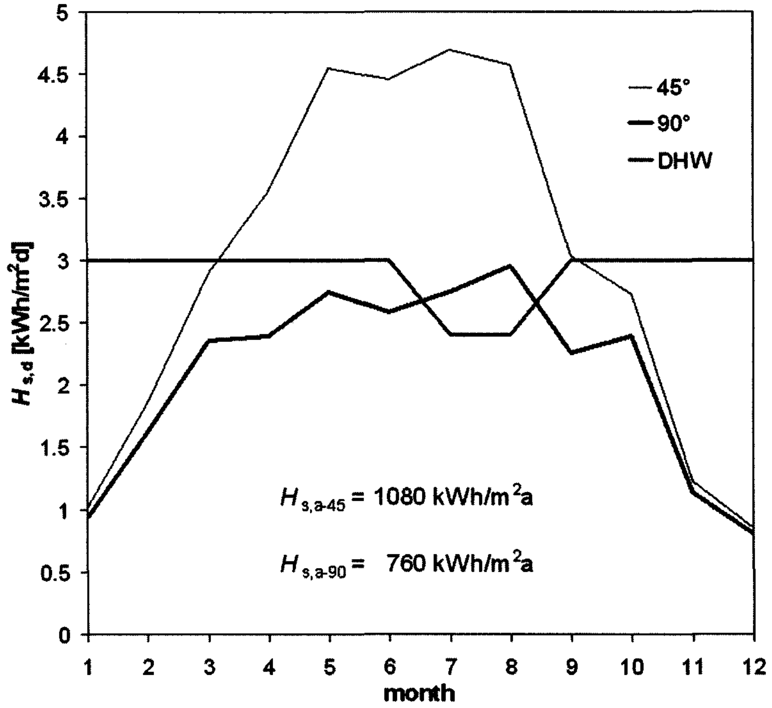

Fig. 2. Annual profile of daily solar global irradiation on sloped surfaces and DHW demand.

standard efficiency η can be determined in dependence on the reduced temperature difference $(T_m - T_a)/G$. The model is feasible for sensitivity analysis in solar collector research. It has been used for analysis of façade collector performance compared with that of a roof collector. Further description of the model can be found in (Matuska, 2003).

Façade integrated collectors compared with collectors located on flat roofs (collector slope optimum 45°) show considerably reduced heat transfer coefficients, especially for

- natural convection in the gap between the absorber and glazing,
- wind-related convection,
- back and edge frame heat loss coefficient.

Due to the vertical orientation of the air gap between the absorber and glazing, heat transfer due to natural convection is reduced in comparison with the gap with a 45° slope to approximately 80%. Fig. 3 shows the Nusselt number in dependence on the slope of the air layer according to different authors and the correlation obtained with statistical methods from the published experimental results (Matuska, 2003). The correlation was used in the solar collector model. Since the air gap is a critical part in single glazed selective collectors, this reduction is reflected in the overall collector heat loss coefficient. Standard solar collector efficiency curves determined for different slope angles (20°, 45°, 70°, 90°) are compared in Fig. 4. The curves were calculated using the mathematical model KOLEKTOR for standard weather conditions (ambient temperature $T_a = 20$ °C, incident solar radiation $G = 800$ W/m^2, wind velocity $w = 4$ m/s). From the comparison the impact of the slope on the collector performance proved to be significant namely for higher temperatures. Calculation of wind-related forced convection heat transfer coefficients for solar collectors is not a distinct problem. There is a large number of models which give completely different transfer coefficient values in dependence on the wind velocity. Some of them result from very detailed wind tunnel measurements other from measurements in real turbulent wind but only for specific conditions and collector-building configuration. In solar engineering, McAdams's (1954) simple linear model

$$h_w = 5.6 + 3.8w \tag{1}$$

is regarded as reliable for usual heat transfer coefficient calculation. Sparrow and Tien (1977) and Sparrow and Lau (1981), carried out a number of experiments to investigate local heat transfer

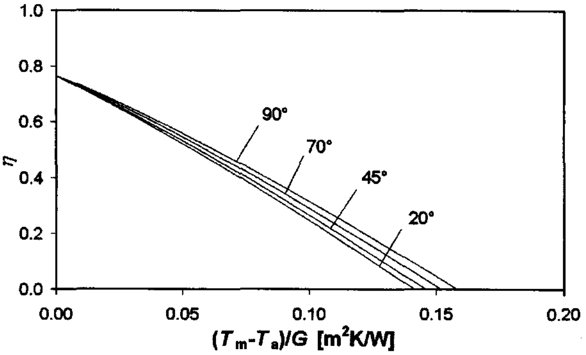

Fig. 4. Solar collector efficiency curves for different slope angles.

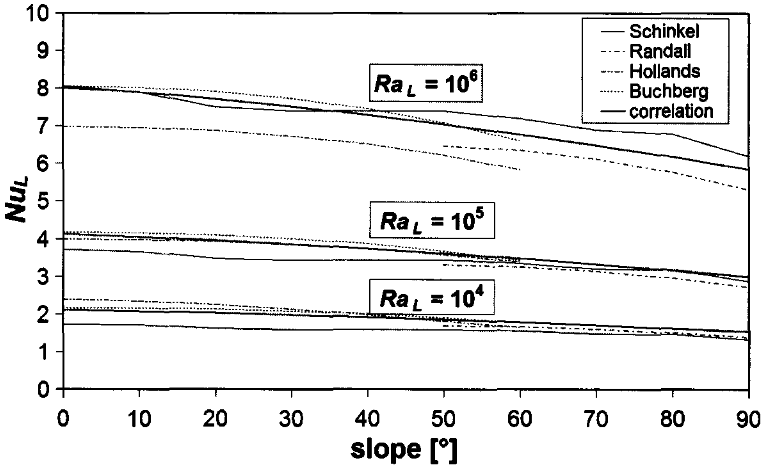

Fig. 3. Comparison of Nusselt number for inclined air layer based on experiments by different authors.

coefficients on heated plates (e.g. solar collectors) under airflow at different conditions (angles of inclination of the plate relative to oncoming airstream, different velocities, framing surfaces). It was realized that average convection heat transfer coefficients are practically independent of the incident angle of airstream. From the airflow patterns on the plate, a considerable difference was found between the local heat transfer coefficients in the center of the plate and on the edges. Higher velocity on the edges leads to higher local heat transfer coefficients, while coefficients near the center are lower due airflow stagnation. Consequently average convection heat transfer coefficients can be substantially reduced when a thermally active surface (solar collector) is framed by another thermally inactive surface (the façade surface). Sparrow and Lau (1981) gives an equation to obtain the rate of reduction of an average heat transfer coefficient

$$h/h^* = (L_c/L_f)^{1/2} \tag{2}$$

where h and h^* respectively denote the coefficients in the presence and in the absence of the frame. The hydrodynamic dimensions L_c (collector) and L_f (framing surface) are determined as characteristic lengths from

$$L = 2L_1L_2/(L_1 + L_2) \tag{3}$$

In the case of a flat roof located solar collector and a façade collector integrated in the building envelope, different values of wind-related heat transfer coefficients will be achieved. While at the glazing surface of a roof collector, the average heat transfer coefficient corresponds to wind velocity, the average heat transfer coefficient at the surface of a façade collector is lower due to the framing effect (see Fig. 5). For an investigated case of a common block of flats, the wind-related coefficient can be reduced to 60–80% of the value for a roof located collector.

Back and edge heat loss coefficients are reduced to a minimum in dependence on the thermal resistance of the adjacent façade construction and "outer" collector frame temperature at a value of 20 °C (room temperature).

The synergetic impact of these individual heat transfer reductions is shown in Fig. 6 by the comparison of the standard efficiency curves for a roof and a façade collector with adjacent construction thermal resistance $R = 1$, 3 and 6 m^2 K/W. Façade integration brings qualitative improvement in solar energy conversion efficiency and better thermal performance especially for increased collector–ambient temperature differences.

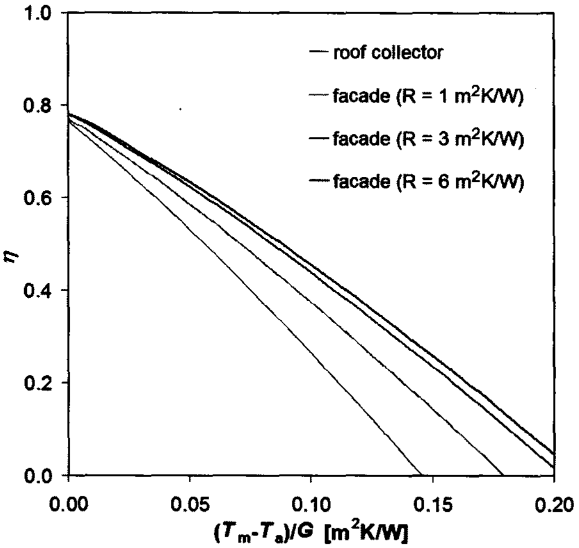

Fig. 6. Standard efficiency curves for roof and façade collectors.

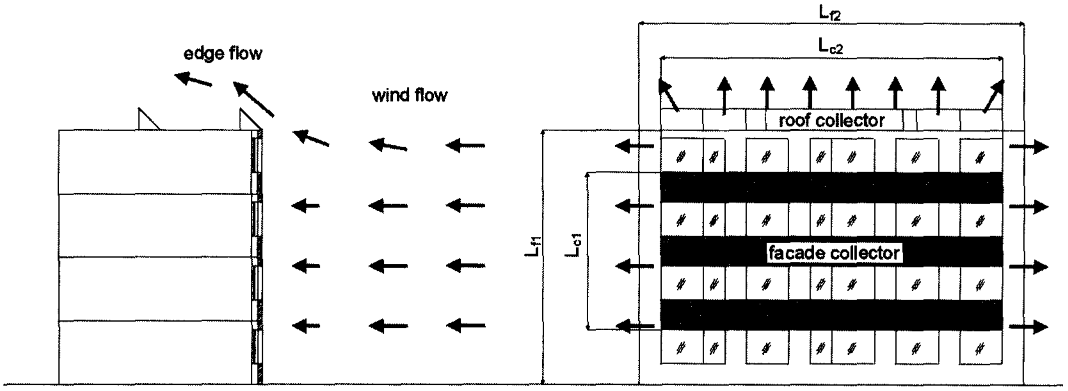

Fig. 5. Wind flow over a building with solar collectors.

4. Collector-building simulation

The energy behavior of solar systems based on façade-integrated collectors have been investigated through computer simulation. The simulation was designed to characterize the performance of a façade solar system for hot water preparation in a block of flats and to obtain information on the effect of a façade collector on the building performance. Computer simulation was performed using the Transient System Simulation Program – TRNSYS (2000). The TRNSYS model for an integrated façade collector comprised a multizone model and a solar system model both thermally interconnected. Only a single zone in the central part of the considered building façade was modeled to investigate the performance of the block of flats with a façade collector. The TRNSYS model used for simulations is shown in Fig. 7. The façade construction was divided into two surfaces, one of them was coupled to a collector absorber (absorber temperature is identical with the surface temperature of the last insulation layer). Solar systems (façade, roof) were modeled as conventional ones – collector connected to a storage tank with stratification. A façade solar collector with a 90° slope was modeled as thermally coupled to the building façade as described above. A roof solar collector with a 45° slope was modeled separately. Thermal characteristics of the collectors were obtained from detailed simulation by means of the KOLEKTOR model. Standard parameters of hot water were used (heating from 12 °C to 55 °C, max. temperature 85 °C). Solar systems were modeled with high flow forced circulation at 100 kg/(h m^2).

Two types of façades were investigated for the application of a façade collector. The first type was a middle-weight façade typical of panel blocks of flats formed by 27 cm thick ceramzit-concrete panels. This type is frequent in a wide range of buildings in large housing estates. The second type, a heavy-weight façade formed by a 45 cm thick brick wall, is typical of older buildings which preceded the panel technology. Buildings with both types of façades should be renovated taking into account construction problems, indoor comfort and energy consumption. In the model, applications with an overall thermal resistance $R = 1$, 3 and 6 m^2 K/W for the building envelope and windows with heat insulating glazing ($U = 1.7$ W/m^2 K) were considered. The total surface area of the zone façade is 9 m^2, the window area is 3 m^2 and the wall area is 6 m^2. Splitting of the wall into two surfaces allows changing the collector/façade area ratio for parametric analysis.

Simulations were performed for different cases which can be considered in decision-making for building renovation. The simulated alternatives are listed in Table 1. Parametric analysis for different façade construction resistances R, collector field surfaces A_c, required solar fractions and orientations were performed. Test reference year for Prague was used as a climate database in the system and building simulations. The principal observed parameters for the building behavior were energy consumption in the winter season, overheating characteristics (indoor temperatures, predicted

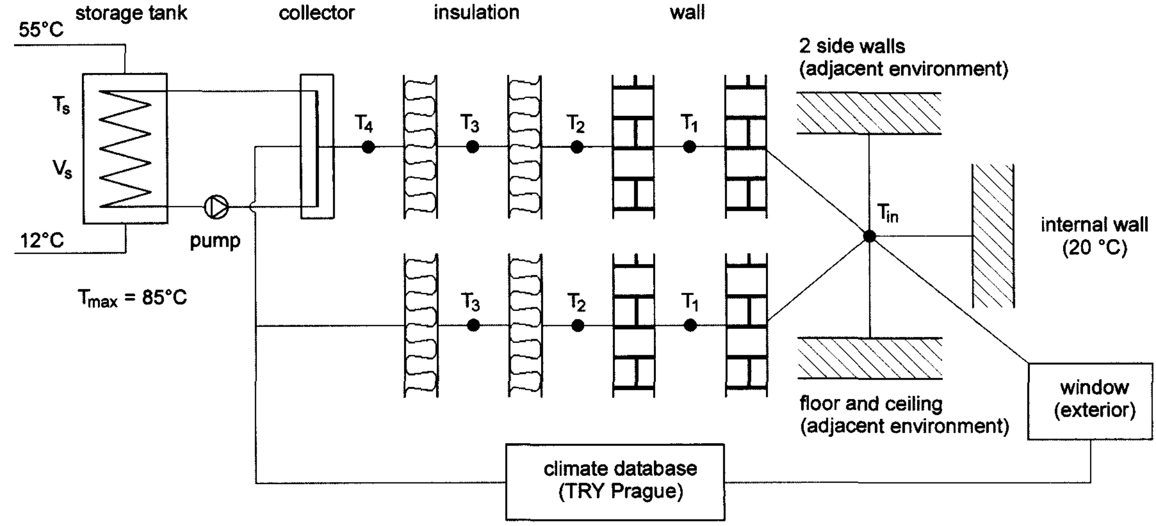

Fig. 7. Schematic TRNSYS model of solar system with a collector thermally coupled to building façade.

Table 1
Simulation Cases

Panel wall	– Basic case (envelope insulation with/without roof collector) – Integrated case (envelope insulation with façade collector)
Brick wall	– Basic case (envelope insulation with/without roof collector) – Integrated case (envelope insulation with façade collector)

percentage of dissatisfied people criterion) in the summer season and potential temperature-induced risks in the construction. Specific useful solar gains $q_{s,u}$, solar fraction f, system efficiency η and specific non-utilizable solar gains $q_{s,nu}$ due to collector stagnation were the required outputs for the solar system.

5. Results

Results of parametric simulations of the solar fraction achieved by the investigated solar systems (roof, façade) are shown in Fig. 8. The solar fraction is plotted against the specific area of the collector field A_c/V_S. Interesting solar fraction values for façade collectors result from higher insulation levels ($R = 3$, $6\ \mathrm{m^2\,K/W}$). While the façade collector area should be increased by 30% compared to a roof collector (45°) area to achieve 60% solar fraction, for a solar fraction above 70%, the required façade collector area is comparable or lower. A roof collector, however, reaches much higher levels of stagnation conditions which lead to potential operation problems and material degradation. The vertical position of the façade collector results in a well-balanced profile of useful solar gains and a very low level of non-utilizable energy gains compared with roof collectors.

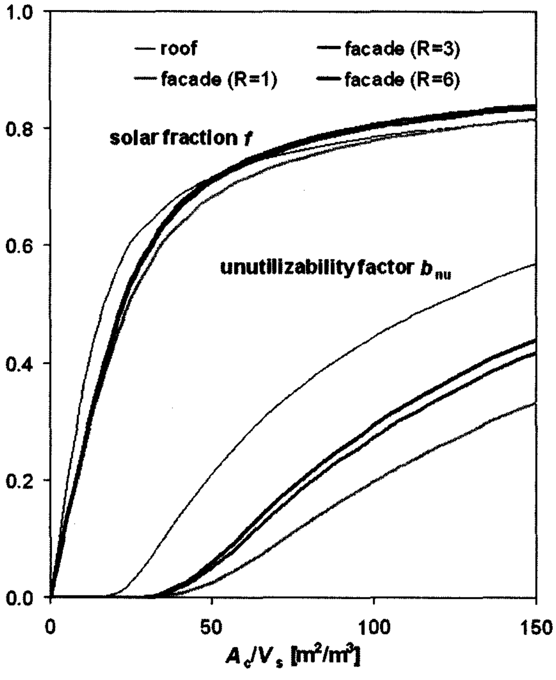

Fig. 8. Parametric analysis of roof and façade solar systems.

The non-utilizability factor b_{nu} is introduced and plotted in Fig. 8. The non-utilizability factor is defined as a ratio of solar energy gains available from the solar collector, but not used due to upper temperature limits (T_{max}) in the storage tank and the total available solar energy gains Q_s from the collector field (solar system gains $Q_{s,u}$ utilized for water heating plus unutilized $Q_{s,nu}$).

$$b_{nu} = \frac{Q_{s,nu}}{Q_s} = 1 - \frac{Q_{s,u}}{Q_s} \tag{4}$$

A comparison of solar fraction f, specific solar system gains $q_{s,u}$ and solar system efficiency η annual profiles for a roof and a façade solar system ($R = 6\ \mathrm{m^2\,K/W}$) at 60 and 70% annual solar fractions is shown in Fig. 9. The impact of the orientation of a façade solar collector on system gains and achievable solar fraction is shown in Fig. 10 (compared with a roof collector with a southward orientation).

The interaction of a façade solar system with the building has been investigated for the winter (from October to April) and the summer (from June to August) season. Performance analysis by collector-zone coupled modeling was carried out for two types of buildings: middle-weight (panel) and heavy-weight (brick). Results for the winter season are in Table 2. With an increasing heat insulation level, the heat gains caused by a façade collector tend to be negligible.

Southward-oriented buildings often suffer with overheating problems in the summer season. Temperature of the building envelope rises and considerable heat gains through the façade and windows could contribute to interior space overheating. Façade collectors, due to a good level of thermal insulation and absorber temperatures kept under 70 °C (low level of collector stagnation as resulted from system simulation), are not responsible for notable temperature increases inside the building. The average indoor temperature T_{in} and PPD value (predicted percentage of dissatisfied people criterion) inside the zone adjacent to a façade with a

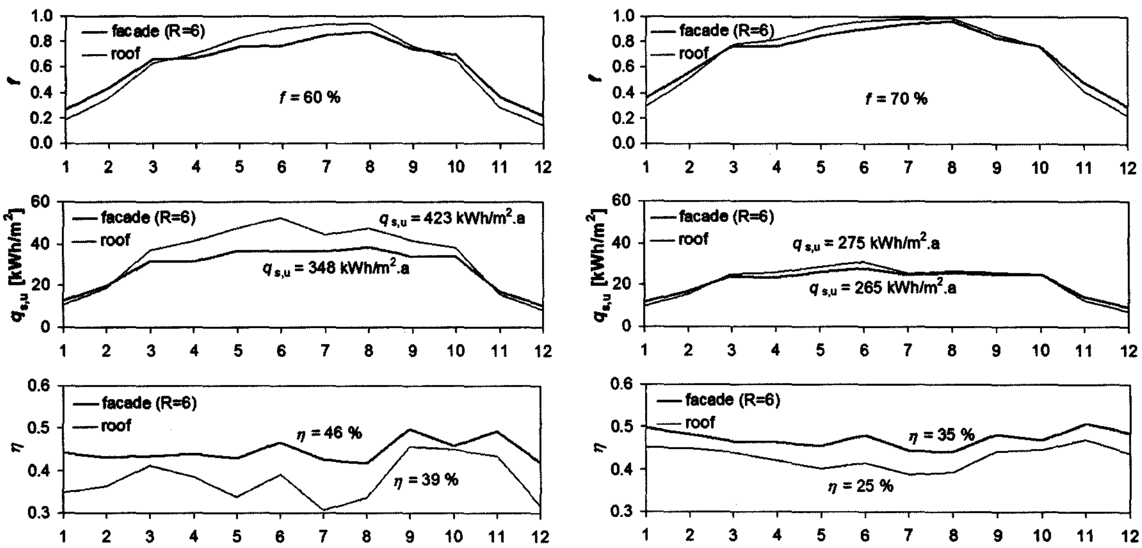

Fig. 9. Annual profiles for roof and façade ($R = 6$ m^2 K/W) system at 60 and 70% solar fraction.

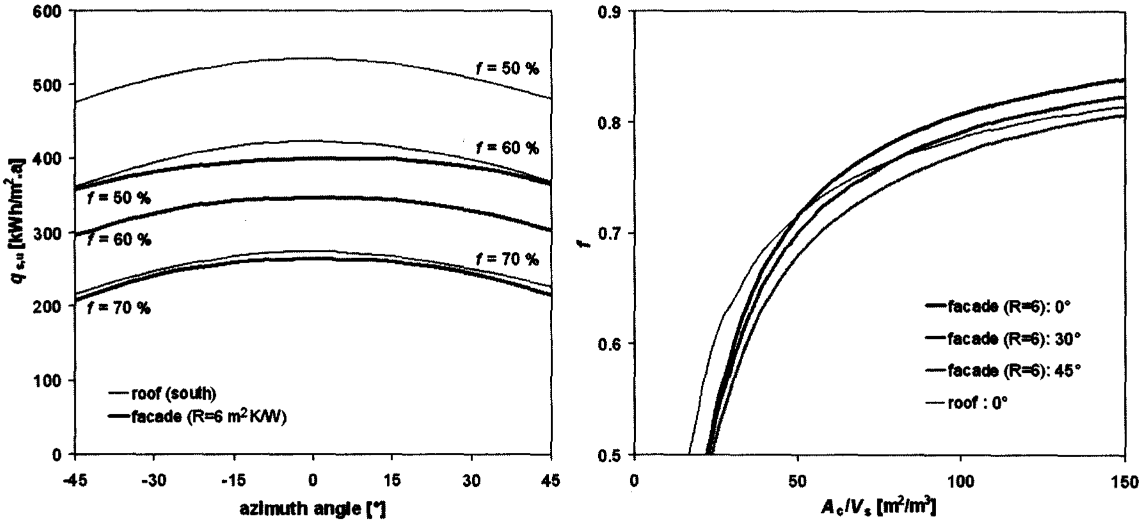

Fig. 10. Effects of façade orientation on solar gains and solar fraction.

Table 2
Façade heat gains caused by collector integration (kW h/m^2 a)

Type	$R = 1$ m^2 K/W	$R = 3$ m^2 K/W	$R = 6$ m^2 K/W
Middle-weight (panel)	9.9	4.0	2.1
Heavy (brick)	10.3	4.1	2.2

collector were derived from frequency histograms for the summer season and these are shown in Fig. 11 in dependence on the collector/façade area ratio (solar fraction 60% and 70%). In a panel wall alternative, due to a lower storage capability (middle-weight wall), higher average temperatures are observed than in the brick wall alternative (heavy-weight wall). Application of façade collectors thermally coupled to the wall raises the average temperatures by no more than 1 K.

Fig. 12 shows the temperature profiles in a façade collector-building construction (middle-weight ceramzit panel) during a typical summer day from 8 am to 8 pm. Individual modeled layers are outlined in the figure. The solar system heats the storage tank and during the day the absorber temperature rises up to 70 °C. Thermal insulation layers are affected by the absorber, the first layer extremely. It should be made of materials capable

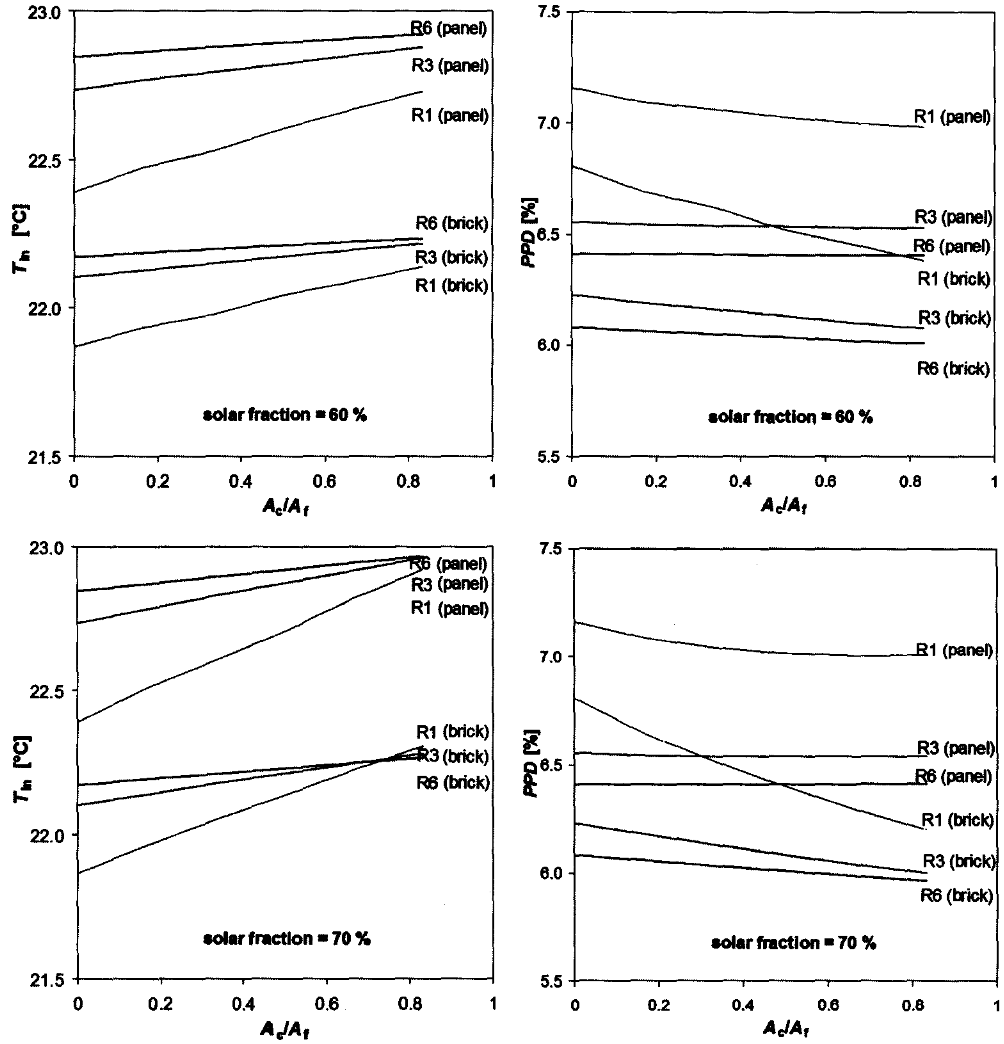

Fig. 11. Average indoor temperature T_{in} and PPD value in the zone with a façade collector in the summer season (June–August).

to withstand high temperatures (up to 150 °C), e.g. mineral wool. Further layers (ceramzit-concrete panel) are kept at moderate temperatures with minimal variations during the day. These layers are mainly affected by temperature variations inside the building. A brick wall alternative behaves in a similar way with lower variations in indoor temperatures with respect to higher inertia.

6. Conclusion and future prospects

Façade solar thermal collectors represent a new element in building design and also in old buildings retrofit. Façade solar system performance and its interaction with the building were investigated using computer simulation. The system and building were processed together; the collector absorber was thermally coupled to the building envelope.

Simulation has shown that façade solar collectors should have an area increased by approximately 30% to achieve the usual 60% solar fraction compared with conventional roof solar collectors with a 45° slope. Further increases in the solar fraction above 70% lead to a required area comparable with roof collectors but with less stagnation periods and lower amounts of energy which cannot be utilized compared with roof collectors.

Building behavior is not strongly affected by façade collectors when sufficient insulation layers are present. Façade collectors in the investigated configurations (panel, brick wall) slightly improve the thermal protection of the building in the winter

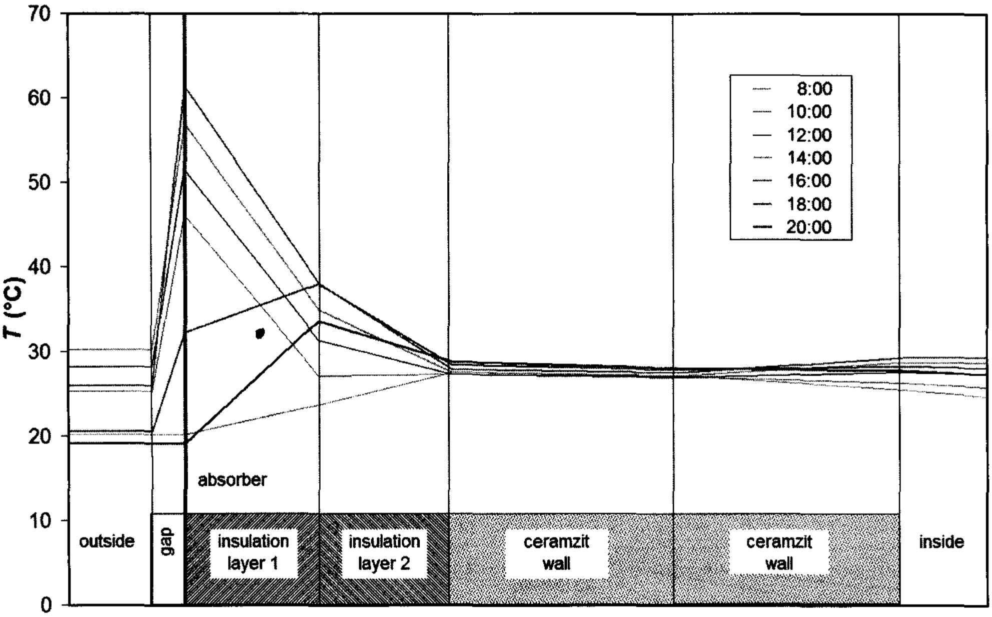

Fig. 12. Temperature profile in the façade construction (typical summer day).

season, but for higher thermal insulation levels the heat gains are negligible. Application of façade solar collectors affects the indoor comfort in buildings in a reasonable range. Indoor temperatures increase by no more than 1 K in all configurations (wall type, façade collector area), the integrated comfort parameter PPD has even better values for a higher façade collector area ratio. This results from the fact that façade collectors could partially help in cooling the façade. Heat from the absorber is efficiently removed during the daytime peaks and stagnation conditions for a façade collector are at a low level. Gains through windows affect the indoor temperature variation much more than façade collectors.

Absorber temperatures affect particularly the first layer in the envelope construction, further layers are at moderate temperatures. Temperature in the wall varies according to indoor conditions and is practically affected by the façade collector only to a minor extent. The only potential temperature hazards affecting the façade construction are concentrated in the insulation layer adjacent to the collector.

Further research in the area of solar collectors integrated directly into the façade should be oriented to building processes – topics such as water vapor transport, thermal bridges; absorber mounting etc. should be solved satisfactorily to spread the technology.

An interesting area of façade collector application is in solar systems for combined DHW and space heating (combi-systems). In these systems the area of the solar collector field is higher and summer gains may cause problem if no summer "heat consumer" is available (swimming pool, dryer, etc.). Façade integrated collectors could be a very efficient solution.

Acknowledgement

This work has been supported by research project MSM 6840770011.

References

Matuska, T., 2003. Transparent thermal insulation and their use in solar applications. PhD. thesis, Czech Technical University. Prague.

McAdams, W.H., 1954. Heat Transmission, 3rd ed. McGraw-Hill, New York, pp. 249.

Rockendorf, G., Janssen, S., 1999. Façade integrated solar collectors. In: Proceedings of Solar World Congress, Jerusalem.

Sparrow, E.M., Lau, S.C., 1981. Effect of adiabatic co-planar extension surfaces on wind-related solar collector heat transfer coefficients. ASME Journal of Heat Transfer 103, 268–271.

Sparrow, E.M., Tien, K.K., 1977. Forced convection at an inclined and yawed square plate – application to solar collectors. ASME Journal of Heat Transfer 99, 507–512.

TRNSYS v.15, 2000. Manual, Solar Energy Laboratory, University of Wisconsin.

Weiss, W., Stadler, I., 2001. Facade integration – a new and promising opportunity for thermal solar collectors. Industry Workshop, IEA-SHC Task 26, 2001.