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A COMPARATIVE SIMULATION STUDY OF SOLAR FLAT-PLATE COLLECTORS DIRECTLY AND INDIRECTLY INTEGRATED INTO THE BUILDING ENVELOPE

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ABSTRACT

Simulation analyses for solar combisystems (domestic hot water production and space heating) with different levels of collector quality (atmospheric and evacuated flat-plate collectors) and different types of façade integration (direct, indirect) have been performed. For the direct integration of solar collectors into the building facade, a simple collector-facade model has been used (TRNSYS) while indirect integration with a naturally ventilated air gap between collector and facade has been investigated with a newly developed collector-facade model representing the air flow in the gap induced by wind or buoyancy (TRNFLOW). The highest performance has been achieved by direct integration of high efficient evacuated flat-plate collectors directly integrated into the façade.

INTRODUCTION

The growing interest in solar thermal collectors for domestic hot water production and space heating increases the demand for further research and development in the building sector. To cover a high portion of energy demand, large collector areas are needed. Collector integration into the building envelope can provide the available area and offers new aesthetical and architectural possibilities. Direct integration (without air gap, thermally coupled) of solar collectors into the building envelope offers several advantages, such as lower heat loss of collectors or passive heat gains from the collector to the building in winter (Bergmann, 2002; Metzger, 2007, 2008). However, direct integration is not always desired or possible (e.g. special conditions concerning structural fire protection) and indirect collector integration (with air gap) provides another opportunity for façade-collector installations.

In previous work (Metzger, 2007, 2008), solar combisystems for domestic hot water production and space heating with different types of solar-flat plate collectors that are separately installed and directly integrated into the building envelope have been investigated through simulations with TRNSYS (transient simulation program) (TRNSYS, 2004). Based on these simulations, the building model has been extended to collect information on flat-plate collectors integrated into the building envelope with a naturally ventilated air gap between the collector and building envelope (indirectly integrated). The air flow in the gap between collector and façade has been simulated with TRNFLOW module (TRNFLOW, 2006), which is an integration of the multizone air flow model COMIS (Conjunction of Multizone Infiltration Specialists) (Feustel, 1997) into the thermal building module of TRNSYS (Type 56).

The use of solar façade collectors achieves considerable advantages especially for solar combisystems (combined domestic hot water preparation and space heating) due to natural elimination of summer extreme gains from oversized collector areas (uniform profile of irradiation). A detailed analysis has been performed to compare the solar combisystem performance characteristics (solar fraction, stagnation behaviour) and the influence on the building performance (winter heat gains, summer cooling loads) with respect to different types of integration and different levels of collector quality (heat loss – atmospheric, evacuated).

BUILDING INTEGRATION MODEL

Two principle cases of collector-building integration should be distinguished: direct (without ventilated air gap, direct contact of solar collector with thermal insulation layers of building envelope) and indirect integration (naturally ventilated gap between solar collector and building envelope). While the direct integration of a solar collector is quite easy to model by using the TRNSYS simulation tool by means of coupling the system and building elements, modelling of a collector-envelope system with a ventilated gap is not as simple regarding the calculation of the air flow and its influence on the thermal conditions in the air gap. Two distinct modelling possibilities of indirect integration have been exercised in a preliminary study to reveal the difference between the simplified and advanced approach. The simplified model considers the indirect integration with an air gap as separate installation, i.e. the air gap between the collector and building envelope has ambient environment temperature and any influence of the collector performance on the building is completely eliminated. To get closer to real behaviour of collector-envelope systems with a naturally ventilated air gap, an advanced model has been developed. In this model, the detailed air flow modelling between the solar collector and building envelope is incorporated into the collector-envelope system model. The advanced model of indirect integration of the solar collector uses the TRNFLOW multizone air flow model integrated to TRNSYS.

Direct integration model

The solar collector is directly integrated into the building envelope without air gap, i.e. the collector insulation (30 mm) is thermally coupled with the insulation of the building envelope (240 mm, R6 façade) as illustrated in Figure 1. This type of integration generally leads to a reduction of the building façade static *U*-value as well as to an overall collector heat loss reduction and thus to an improvement in the collector efficiency.

The considered model for direct integration consists of a collector model coupled to a multizone building model by means of a fictive zone (see Figure 1) with high heat transfer surface coefficients and a minimal zone volume to achieve the conditions of direct contact. All walls of the fictive zone are considered as adiabatic except the building envelope wall (240 mm of insulation) and the wall containing the collector back side insulation (30 mm). For the ficitive zone, the temperature of the exterior surface of the collector insulation layer is linked to the actual temperature of the solar collector absorber t_{abs} (surface in direct contact with absorber).

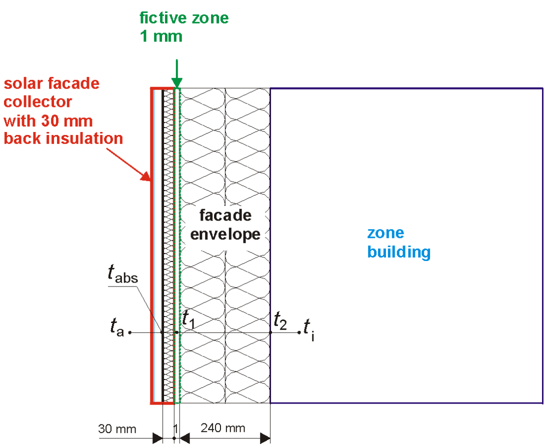

Figure 1 Direct integration of solar collector into the building envelope without air gap

Figure 2 shows the temperature profiles in the collector-façade direct integration system with an atmospheric flat-plate collector during one typical sunny summer day with all-day solar system stagnation conditions with no heat removal from solar collector. It is obvious that the direct integration model can represent the real beaviour, including e.g. thermal inertia of façade insulation layers.

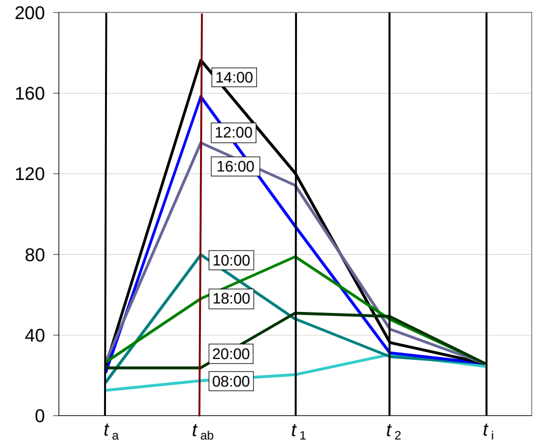

Figure 2 Temperature profiles in façade with directly integrated atmospheric flat-plate collector during summer day

Indirect integration – Separate installation

The simplified model of indirect integration considers the solar collector separately from the envelope. The air gap between the collector and building envelope is regarded as ambient environment as outlined in Figure 3. In principle, this type of model cannot sufficiently describe the indirect integration of a solar collector and its thermal influence on the building indoor environment due to elimination of any impact of the solar collector to the air gap environment. Figure 4 shows the temperature profiles for identical conditions as for Figure 2. While the temperature of the absorber results in large variation during the day the temperature in the air gap is not influenced by the solar collector and follows the same profile as the ambient temperature.

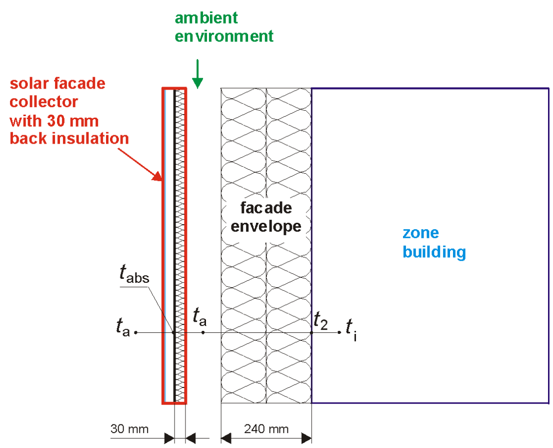

Figure 3 Indirect integration of solar collector considered as a separate installation

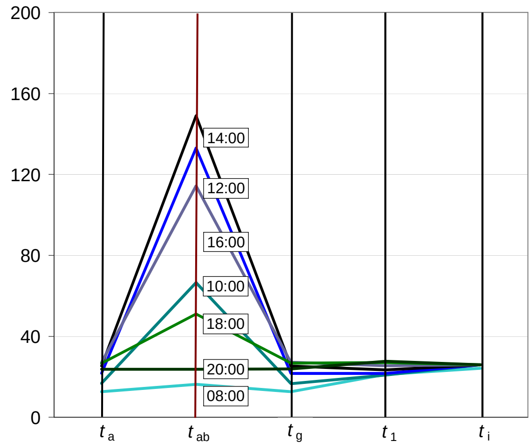

Figure 4 Temperature profiles in façade with indirectly integrated (no Trnflow) atmospheric flat-plate collector during summer day

In fact, the indirect integration creates an internal channel (air gap) with a certain ambient air flow given by boundary conditions (wind induced flow, buoyancy influence) but with temperature influenced by heat gains both from the collector (if absorber is at higher temperature than ambient) and from the building interior. On the other side, the simplicity makes this model very popular for general investigations and is easy to use without special features as air flow modeling tool or no detailed knowledge of pressure boundary conditions is needed.

The model is not further used for investigations of direct and indirect integration comparison due to unreal behaviour with no impact of the solar collector on the building envelope.

Indirect integration – TRNFLOW model

The advanced model for indirect integration uses TRNFLOW to provide complex air flow modelling in the channel located between the back side of the solar collector and the building envelope. The model developed for indirect integration considers air with external temperature entering the channel at the bottom, passing through 5 (fictive) sections and exhausting at the top of the channel (Figure 5). The quantity of 5 sections has been chosen as compromise to provide complex modelling with reasonable computation time while sufficient accuracy is maintained. A channel (air gap) thickness of 40 mm has been considered. In the TRNFLOW model the driving forces such as wind pressure, aerodynamic behaviour of input and output orifices and buoyancy are taken into account. More detailed information on boundary conditions has to be applied; geometry of the channel and orifices, wind pressure coefficients c_p, wind direction and velocity character (open terrain or city center), building altitude, etc. As the study is not focused on pressure coefficients analysis reference average c_p-values (Orme, 1998) have been used for these simulations. For a low rise building located in a semi-shielded surrounding, an averaged c_p-value of 0.4 was chosen to define the inlet of the channel and c_p = -0.6 for the outlet.

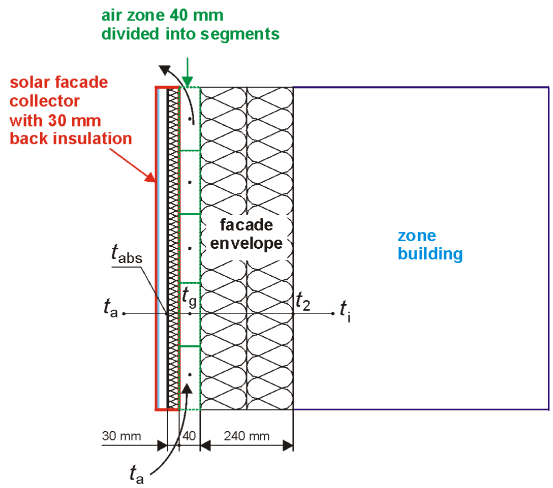

Figure 5 Indirect integration with ventilated air gap.

Figure 6 shows the temperature profiles in the collector-façade indirect integration system for identical stagnation boundary conditions as for the indirect integration without TRNFLOW (see Figure 4). The air temperatures for the lower part in section 1 (dashed line) and upper part in section 5 (solid line) of the naturally ventilated air gap are shown. At extreme conditions the simulations resulted in a temperature increase of 17 K between section 1 and section 5 of the air gap.

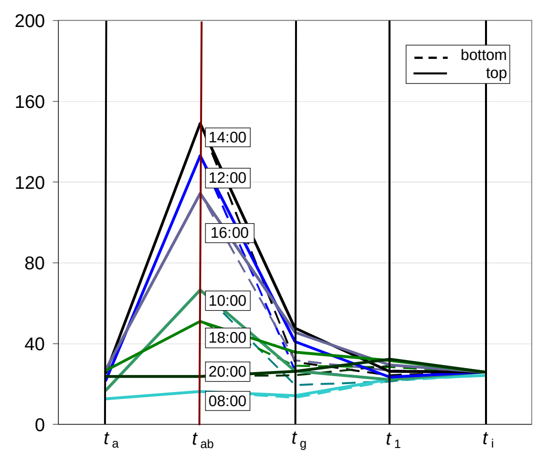

Figure 6 Temperature profiles in façade with indirectly integrated atmospheric flat-plate collector during summer day

Comparing the heat flow from the directly and indirectly integrated collector to the interior shows higher surface temperatures of the insulation in the case of direct solar collector integration. For the case of indirect integration, the heat flow to the interior is strongly reduced by the air flow; e.g. comparing the temperatures at 14:00, t_1 (between collector and building insulation, Figure2) is 120°C; whereas t_g (air gap between collector and building insulation, Figure 6) results in 31°C (section 1) and 48°C (section 5), respectively. The heat flow to the interior is further reduced for both types of integration and after 120 mm of building insulation the temperature t_2 results in 36°C (direct integration). T_2 for the case of indirect integration results in 24°C (section 1) and 26°C (section 5), respectively. Due to additional 120 mm of insulation (in total 240 mm) the heat flow from the solar collector to the building interior is further reduced.

SYSTEM-BUILDING SIMULATION

The energetic behaviour of a solar combisystem with façade integrated solar collectors has been investigated through a coupled system-building simulation in TRNSYS. Simulations have been performed to compare the solar combisystem performance characteristics (solar fraction, stagnation behaviour) and the impact on the building performance (winter heat gains, summer cooling loads) with respect to different types of integration and different levels of collector quality (atmospheric, evacuated).

The simulation model is composed of a solar combisystem model and a multizone building model with thermal interconnection between the collector and envelope as described above for different types of integration. The south façade of the building has a net area of 42 m^2 and is divided into two surfaces, one of the surfaces has been considered as facade integrated collector field and the second surface has been left as original envelope (thermally inactive). Splitting the façade into two surfaces allows varying the solar collector area A_c to the facade area A_f ratio (coverage factor) for purposes of parametric analysis.

Table 1
Major parameters of simulation model

Heated floor area / building volume	150 m^2 550 m^3
Envelope U-value	0.167 W/m²K
Ventilation with heat recovery	0,3 ACH, efficiency 75 %
Average DHW demand Q_{dhw}	200 l/day (55/12 °C) ~ 3710 kWh/y
Space heating demand Q_{sh}	4711 kWh/y
Space cooling demand Q_{sc}	867 kWh/y
Storage tank volume V_S	1200 l
Solar collector area A_c	variable 0 to 42 m²

The solar combisystem model is based on a compact integrated central heat storage tank (1200 l) with ideal stratification (variable inlets) with two heating circuits (DHW and space heating). Two auxiliary heaters were applied, first to output the DHW load ($Q_{a\text{-}dhw}$) and the second for space heating ($Q_{a\text{-}sh}$). The schematic diagram of the solar combisystem model is shown in Figure 7. The nominal heating system temperature difference was set to 55/45°C with a supply temperature control according to the ambient temperature t_a.

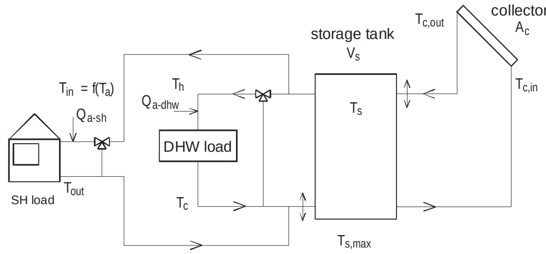

Figure 7 Solar combisystem model layout

The investigated family house has been considered in advanced low-energy standard (Q_{sh} = 31 kWh/m²y; Q_{sc} = 6 kWh/m²y) with a light-weight envelope based on mineral wool insulation with U-values typical for low-energy housing (R = 6 m^{2}K/W) and mechanical ventilation with heat recovery in the winter and no recovery in summer. The shading of south windows has been applied to exclude the excessing heat load caused by windows in summer. The major parameters of the family house are listed in Table 1. A typical meteorological year (TMY2) for Prague (Czech Republic) has been used as climate database for the simulations.

The analysis at the solar collector considers two quality levels with respect to heat loss: atmospheric (100 kPa, ATM) and evacuated (5 kPa, EVA) alternatives. The solar collector efficiency curves have been obtained from the mathematical model and design tool KOLEKTOR 2.2 (Matuska, 2008, 2009) with respect to collector integration into the building façade. Obtained parameters describing the efficiency curves have been used as collector TRNSYS model inputs for parametric studies and are listed in Table 2.

Principal observed parameters for the building performance were specific winter heat gains Δq_{SH} and specific summer cooling loads Δq_{SC} induced by collectors integrated into the façade. For the solar system performance, solar fraction f and specific stagnation time b_{st} have been evaluated.

Table 2
Efficiency curve parameters for investigated solar collectors

ALTERNATIVE	η_0 **[-]**	a_1 **[W/m^{2}K]**	a_2 **[W/m^{2}K^2]**
direct ATM	0.81	2.65	0.0054
indirect ATM	0.79	3.42	0.0057
direct EVA	0.84	1.29	0.0035
indirect EVA	0.81	2.44	0.0033

RESULTS

Solar combisystem performance

Simulation analyses for solar combisystems with solar collectors (atmospheric, evacuated) integrated into the building facade (direct, indirect integration) have been performed.

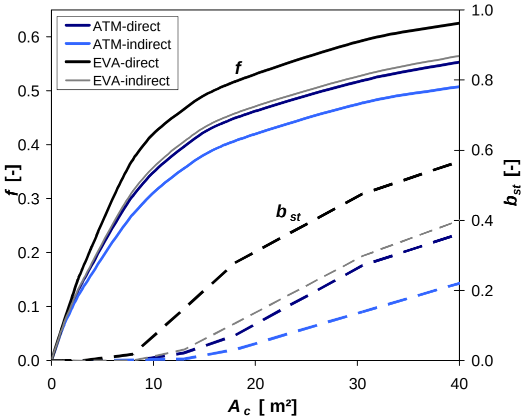

Figure 8 Solar combisystem performance characteristics for investigated variants

Figure 8 shows the thermal performance characteristics of the investigated solar combisystem expressed by means of system solar fraction f and specific stagnation time b_{st} dependent on the solar collector area A_c as variable parameter. The direct integration represents the advantage of better performance of solar collectors and higher system heat gains. The possibility to achieve up to 50 % solar fraction with facade integrated evacuated solar collectors is very promising. On the other side, a higher frequency of stagnation occurs especially for high-performance evacuated solar collectors integrated directly into the facade for usual 10 m^2 of designed collector area compared to other variants. Comparing the atmospheric collector directly integrated and the evacuated collector indirectly integrated into the facade, the performance of the solar thermal system is similar.

Impact on the building performance

The influence of facade integrated solar collectors on the indoor environment and building performance has been evaluated. Space heating and cooling demand are plotted in dependence on collector area A_c for atmospheric and evacuated solar collectors, directly and indirectly integrated into the facade (see Figure 9 and 10).

Annual specific winter heat gains and summer cooling loads have been obtained and are shown in Table 3.

Table 3
Specific heat gains and cooling loads induced by facade integrated collectors [kWh/m^{2}y]

INTEGRATION	INDIRECT		DIRECT	
COLLECTOR	**ATM**	**EVA**	**ATM**	**EVA**
Specific heat gains	3.1	3.6	9.1	13.4
Specific cooling loads	1.1	1.5	6.8	13.5

Figure 9 and 10 show that due to sufficient ventilation the impact on the building performance of both collector types (ATM, EVA) indirectly integrated into the facade is very low. However, a slight difference between the indirect integration of atmospheric and evacuated collectors can be found, i.e. the specific heat gains of the evacuated collector are 0.5 kWh/m²y higher than the specific heat gains of the atmospheric collector (0.4 kWh/m²y for specific cooling loads).

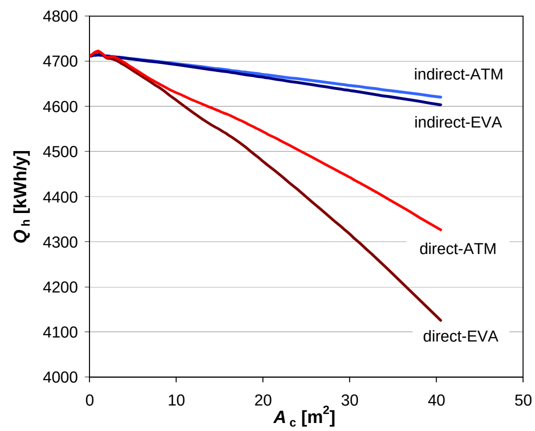

Figure 9 Space heating demand decrease induced by solar collector integration into façade

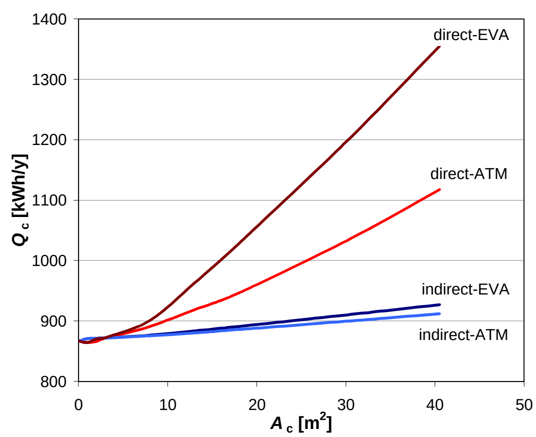

Figure 10 Space cooling demand increase induced by solar collector integration into façade

Due to the thermal coupling of the collector with the building façade the influence of the solar colector is much higher in the case of direct integration. As listed in Table 3, the specific heat gains of the directly integrated evacuated collector are almost 4 times higher (6 times higher for specific cooling loads) than in the case of ventilated air gap.

Comparing the building performance during winter and summer, the heat gains due to collector integration are higher than the cooling loads caused by collector integration. However, looking at relative numbers, in the extreme case of 40 m² collector area the cooling demand increases about 29 % (direct-ATM) and 56 % (direct-EVA) respectively, whereas the heat demand decreases only about 8 % (direct-ATM) and 12 % (direct-EVA).

CONCLUSION

The solar combisystem performance with facade integrated solar collectors (direct, indirect integration) has been investigated in a comparative simulation study for an advanced low energy house in the climate of the Czech Republic. For the direct integration of solar collectors into the building facade, a simple collector-facade model has been used while indirect integration with a naturally ventilated air gap between collector and facade has been investigated with a newly developed collector-facade model representing the air flow in the gap induced by wind or buoyancy.

Both envelope integration models have been used to determine the solar combisystem characteristics (solar fraction and specific stagnation time) and specific heat gains and cooling loads induced by different types of solar collector integration. Parametric analyses have been performed for solar flat-plate atmospheric and evacuated collectors.

Direct integration of evacuated flat-plate collectors considerably increases its efficiency and achieves the highest system performance. Nevertheless, attention should be paid in the case of solar combisystems in terms of high frequency of stagnation conditions if a large collector area is applied.

Indirect integration of evacuated flat-plate collectors brings a slightly higher solar fraction than the directly integrated atmospheric collector but the influence on the building performance is significantly lower than through direct integration.

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