European Cooperation in the field of Scientific and Technical Research

COST Action TU1205 (BISTS)

Building Integration of Solar Thermal Systems

Title: Report on the validation of developed codes, both thermal and optical

Date: July, 2015

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Contents:

Abstract

The present study has been conducted in the frame of the COST Action TU1205 and presents an overview on the validation of developed codes, thermal and optical, within the field of Building-Integrated Solar Thermal (BIST) systems. The results reveal that there are specific requirements for BIST modelling. Regarding validation methodologies, on-site validation has been conducted for several types of systems (active façades, etc). On the other hand, indoor solar simulators facilitate solar research in cold climates while test cells offer an intermediate between a real building and an experiment in the laboratory.

1. Introduction

Architectural integration is an important issue in the spreading of solar thermal technologies (Munari Probst and Roecker, 2007). Even if some types of architecturally-integrated solar thermal systems for example Trombe wall (Steemers and den Ouden, 1984) exist several years ago, over the last years there is an increasing interest for this specific type of systems, known as Building-Integrated Solar Thermal (BIST). BIST, and in general BI solar systems, provide multiple advantages (higher aesthetic value, etc) in comparison with the configurations which are added (and not integrated) on the building (Kalogirou, 2013) known as Building-Added (BA) systems. For BI solar applications, factors such as the balance between aesthetics and performance (Zomer et al., 2014) play an important role.

In the literature, there are some studies about BI solar systems; nevertheless, most of these investigations are about BI Photovoltaic (BIPV) configurations (Lee et al., 2014; D´Orazio et al., 2014). There are only few studies about BIST systems regarding for example façade-integration (Maurer and Kuhn, 2012; Maurer et al., 2013) and gutter-integration (Motte et al., 2013a, 2013b; Notton et al, 2014).

Since building integration is a crucial factor in the spreading of solar thermal systems (Munari Probst and Roecker, 2007), further investigation in the field of BIST is needed. Certainly, the experimental works are important for testing a system behaviour; however, modelling can be utilized to predict a system performance, saving time and cost. Thus, further modelling investigations along with experimental testing for BIST systems are necessary. There are also innovative components for BIST systems (Source: http://solarintegrationsolutions.org/) which need new models to demonstrate their benefits.

The present study aims to fill the gaps which exist in the literature in the field of BIST modelling by providing useful information about the developed codes, both thermal and optical. Emphasis is given on the codes which have been built and validated, identifying critical aspects such as the requirements of BIST simulation and validation methodologies.

2. Specific requirements of BIST modelling and simulation

Certainly, BIST modelling could provide useful information. Nevertheless, there are some specific requirements related with BIST simulation which should be taken into account. In the following paragraphs some studies which highlight methods of modelling of BIST, and in general of BI solar systems, are presented.

In the study of Chen et al. (2012), methods and algorithms of modelling passive solar potential and innovative façade-integrated solar systems for high-latitude applications were presented. Custom thermal network models for different collectors were developed by means of MATLAB for steady state and transient analyses. The simulation results were validated with experimental data under a solar simulator with a prototype combining components such as Unglazed Transpired Collector (UTC), transpired glazing and Photovoltaic/Thermal (PVT) collectors on structural insulated panel wall. The goal of that study was the evaluation of the potential of energy conservation and renewable generation by the proposed solar façades designed for Northern locations.

Athienitis and O'Brien studied issues related with modelling and design of net-zero energy solar buildings and integration of dynamic building envelope systems. Aspects such as modelling of complex perimeter zones with advanced envelopes and daylighting, integration of active and passive systems and comfort were presented. The challenge in fenestration design is related with solar gain control vs. daylight utilisation. The solar gains should be taken into account in the design and control of high performance buildings in an integrated manner. A key challenge is balancing the need for daylight throughout the year, passive solar gains in the heating season and need to limit excessive solar gains during cooling season. Moreover, there is a need for prediction of weather and building model for model predictive control. The impact of motorized blinds and light dimming should also be taken into account. Another issue is related with indoor environmental quality and it includes parameters such as thermal comfort, air quality, acoustic and visual comfort.

In general, BIST elements have a variable *g* value or solar heat gain coefficient (Maurer and Kuhn, 2013). This means that heating and cooling demand depends on irradiance and operation of the collector. Standard collector models consider only the ambient temperature. For BIST elements, the temperature of the interior should be also considered. The performance of a BIST collector can be higher than in BA systems due to the decreased back losses. Models which include the energetic coupling between absorber and building interior can provide accurate predictions.

3. Validation methodologies

3.1. On-site validation

Ji et al. (2011a; 2011b) studied a dual-function solar collector. The developed numerical model was validated based on experimental data. Other examples of studies which include model validation by means of experimental data are those of: Diarce et al. (2014) regarding a Computational Fluid Dynamics (CFD) model for an active façade; Chan and Tzempelikos (2012) concerning a method for assessing the integrated energy performance of passive and active multi-section façade systems; Pappas and Zhai (2008) about an integrated and iterative modelling process for analysing the thermal performance of Double-Skin Façade (DSF) cavities; Rundle et al. (2011) about validation of CFD simulations for atria geometries; Li et al. (2014) concerning an investigation of BIPVT configurations with UTCs by using CFD; Sohel et al. (2014) regarding a dynamic model (for air-based BIPVT systems), validated by operational data collected from BIPVT systems installed in two unique buildings. In addition, Chemisana et al. (2011) presented a study about a BICPVT (concentrating PVT) with Fresnel lenses: models for the electrical/thermal behavior of the module were developed and experimentally validated.

3.2. Test cells

Test cells represent an intermediate between a real building and an experiment conducted in the laboratory. Test cells also have an important advantage: the initial and particularly important boundary conditions can be controlled to a much higher degree than in real buildings while still maintaining dimensions and thermophysical properties very close to those found in rooms of real buildings (Loutzenhiser et al., 2006).

An empirical validation of modelling solar gains through a glazing unit by using building energy simulation programs was presented by Loutzenhiser et al. (2006). An experiment performed in conjunction with the International Energy Agency Task 34/Annex 43 was utilised to assess the performance of four building energy simulation codes used to model an outdoor test cell with a glazing unit (Loutzenhiser et al., 2006).

Strachan (1993) presented a work about model validation by using the PASSYS test cells. PASSYS project was a European action by ten countries in the field of passive solar architecture. The focus for all the activities was a network of test cells throughout the member countries of PASSYS. Within PASSYS, laboratory measurements were used in conjunction with the test cells to provide thermophysical properties for input to model simulations. The cells were room-sized (Strachan, 1993).

Marques da Silva et al. (2015) conducted a study about measuring and estimating airflow in naturally ventilated DSFs. A test cell was assembled at the National Laboratory of Civil Engineering of Lisbon, in Portugal. The main scope was to assess the thermal behaviour of a DSF operating under Mediterranean climate, by adopting several ventilation modes (air supply, air exhaust, inside air curtain, outside air curtain and buffer) and different shading devices (roller blind and venetian blinds) in different positions and with different slat angles.

Moreover, Jiru and Haghighat (2008) modelled ventilated DSFs by means of a zonal approach. The case adopted for the development and verification of the DSF models was an experimental test cell at the department of energy, Polytechnic University of Turin, Italy. The test cell was of 2.5 m height, 1.6 m width and 3.6 m length. The south facing side of the cell (1.6 m width, 2.5 m height) had a mechanically ventilated DSF with an outer double-pane façade and an inner façade.

3.3. Laboratory

In the field of laboratory testing are included tests by means of indoor solar simulators, facilitating solar research in cold climates. A solar simulator can be used in a variety of experiments. An indoor lab can provide consistent experimental conditions independent of weather and time of day (Source: University of Minnesota). In the following paragraph, some studies (regarding several types of solar systems) with solar simulators are presented.

Chen et al. (2012) conducted a study about modelling of passive solar potential and innovative façade-integrated solar systems. The simulation results were validated with experimental data under a solar simulator with a prototype.

At this point it should be noted that it is important to have well-defined heat-transfer coefficients and temperatures at the front and back of the BIST component during laboratory measurements. For instance, Maurer (2012) measured a BIST collector in a solar-simulator test facility with adjustable temperatures of the interior and exterior and standard heat transfer coefficients. A detailed physical BIST model was built based on optical measurements and CFD simulations (Maurer et al., 2012). Finally, the detailed model was calibrated to the results of the laboratory measurements.

Regarding BI concentrating PV, Baig et al. (2015) conducted an optical, thermal and electrical analysis of a dielectric-based BI concentrating PV. The solar spectrum of a Class AAA solar simulator was utilized.

Furthermore, a novel PV module with isolated cells was designed, fabricated and experimentally characterised with and without Compound Parabolic Concentrator (CPC) by utilising a multi-purpose mobile solar simulator by Paul et al. (2013). A theoretical and experimental energy flux profile of cells within the CPC was undertaken for normal incidence angle (Paul et al., 2013).

4. Validated models for different integrated solar thermal collectors

4.1. Building-added systems: modelling/simulation and validation

In this section, studies from the field of BA systems are mentioned because they could be adapted for BI aplications.

The studies of Oliva et al. (1991), Plantier et al. (2003), Cadafalch (2009) and Molero Villar et al. (2009) concern detailed physical models for solar thermal collectors which in principle could be coupled to a building.

Furthermore, Luo et al. (2014) developed a model for a nanofluid solar collector based on direct-absorption-collection concepts, by solving the radiative transfer equations of particulate media and combining conduction and convection heat transfer equations. System efficiency and temperature distributions were analysed by taking into account absorption and scattering of nanoparticles and the absorption of the matrix. The simulation results were in accordance with the experimental data.

4.2. Building-integrated systems: modelling/simulation and validation

4.2.1. Opaque systems

Opaque BI systems may refer to systems integrated into the roof of the building. Assoa and Ménézo (2014) studied a roof-integrated PVT air collector. A 2D simplified dynamic mathematical model of a solar PVT air collector with a metal absorber was presented. The validation of the numerical model was conducted by means of measured data obtained by a full-scale test bench located near Lyon.

During cold sunny winter days, when the south wall is well insulated, a considerable amount of the solar energy falling on this façade is not transferred to the inside. Ibrahim et al. (2014) presented a study about a novel closed wall-loop system to capture this wasted energy available during non-cloudy winter days and transfer it to the cooler north façade by means of water pipes embedded in an exterior aerogel-based insulating coating. The system was presented with all the mathematical equations and numerical model. The model was validated against experimental data from the literature. In order to test its performance on a full-scale house, the MATLAB numerical model was coupled to the whole building energy simulation program EnergyPlus through co-simulation. The results demonstrated that the reduction in the annual heating load for the house adopting this system relative to the one without it were between 28 and 43% for new houses and 15-20% for old houses based on the Mediterranean climate. For the case of other climates, the reductions varied between 6% and 26%. The heat losses through the north façade were reduced by around 60-88% for the Mediterranean climate and approximately 20-50% for the other climates. Fig. 1 illustrates the active embedded pipe wall loop system. The exterior walls of the configuration are composed of concrete or brick layer with an outside insulating coating based on the (super)-insulating materials silica aerogels (Ibrahim et al., 2014).

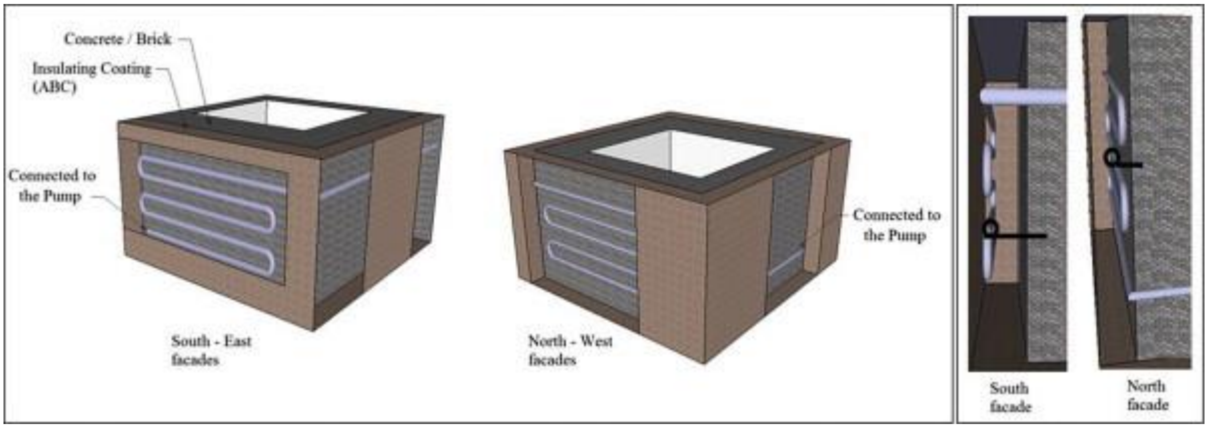


Figure 1. The active embedded water pipe wall loop system investigated by Ibrahim et al. (2014). Source: Ibrahim et al. (2014).

A dual-function solar collector system can provide passive space heating in cold winter and water heating in warm seasons. This type of system has higher annual utilization ratio than a conventional system designed for passive space heating. A coupled numerical model was developed by Ji et al. (2011a) for such a configuration (Hefei, China). By means of experimental validation, the numerical model was proved to be able to give accurate predictions. The model was a dynamic numerical model and it was developed to estimate water heating performance and solar transmission though building façade. Finite difference method was used for the model while the heat flow through the front glazing was considered as one-dimensional. Ji et al. (2011b) also conducted another study related with the above mentioned system. Two dynamic numerical models based on the finite-difference method for two different operating modes of the testing system were developed. Experimental data were used to validate the two models.

Li et al. (2014) developed and validated energy models for the simulation of BIPVT systems with UTCs. The aim of the models was to predict the cavity exit air temperature and plate surface temperature with weather and design parameters as inputs. The energy models were validated with measurements (outdoor test-facility). A good agreement between model predictions and experimental data was observed. Moreover, the effects of significant parameters on system performance were demonstrated based on literature data and simulations, by using CFD and energy models.

Buker et al. (2014) investigated a BIPVT system in terms of its performance and techno-economic aspects. The study also included an experimental validation. The integration of a unique polyethylene heat exchanger loop underneath PV modules was examined. The system was designed to act as a roof element having a heat resource for solar assisted heating and cooling technologies. A detailed thermal model was adapted to investigate the roof-unit thermal performance. Numerical simulations were carried out by using Engineering Equation Solver (EES) for the climatic conditions of Nottingham, UK and design parameters of the BIPVT. The experimental values indicated that water temperature difference could reach up to 16^{o}C and the system could achieve up to 20.25% overall thermal efficiency.

The thermal performance of a roof-integrated solar concrete collector for reducing heat gain to a house and providing domestic hot water was studied by Sarachitti et al. (2011). The solar concrete collector consisted of PVC pipes embedded in deck slab or concrete roof. In order to compare the energy savings, two test rooms were built. In the first room, the reinforced cement concrete slab was utilized as deck slab whereas the second room was equipped with a cement concrete solar collector. The experimental findings revealed that the cement concrete solar collector is very interesting as it can produce up to 40 l of hot water per day at water temperatures ranging from 40 to 50^{o}C. A mathematical model based on the conservation equations of energy was developed in order to predict the performance of the cement concrete solar collector. A reasonable agreement between measured data and predicted results was observed.

Yang and Athienitis (2012; 2014) developed a numerical control volume method to simulate an open-loop air-based BIPVT system with a single inlet. The simulated results were validated with indoor tests data. The tests were conducted under controlled test conditions by means of a solar simulator. A set of energy balance equations was used to simulate the components in the BIPVT system.

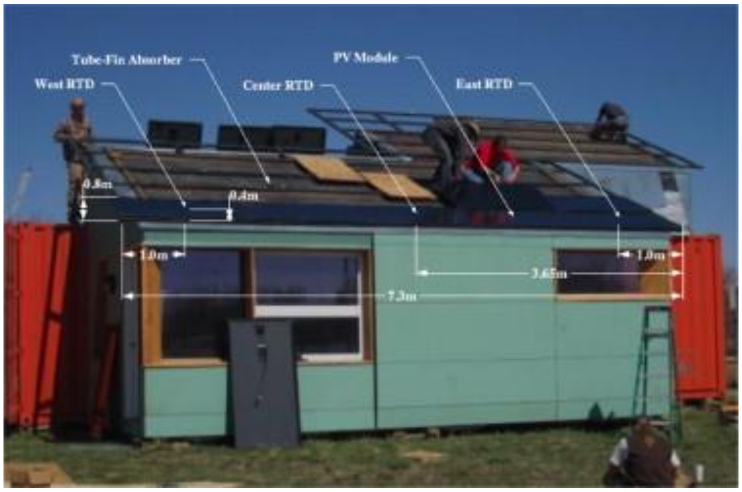
Li and Karava (2014) presented an energy modelling and performance analysis of BIPVT systems with corrugated UTCs. CFD and energy models were used for the simulation. The simulated results were validated by using measured outdoor test data. A parametric analysis was carried out to investigate the impact of the corrugation geometry and collector orientation on the thermal performance of the system.

Chen et al. (2010) investigated the thermal performance of a BIPVT system thermally coupled with a ventilated concrete slab. A simplified three-dimensional, explicit control-volume finite-difference thermal model was used for the simulation of the thermal behaviour of the system. The simulated results were validated by using measured data. The accuracy of the model was lying within the acceptable range.

A simulation model of a PVT collector with water heating in buildings was developed to analyse PV and thermal performances (Shan et al., 2013). The results revealed that the less series-connected PV modules, the lower inlet temperature of water and the higher mass flow rate of water resulted in the high PV efficiency.

Corbin and Zhai (2010) used a CFD model to simulate the effect of active heat recovery on cell efficiency and the performance of the BIPVT collector. The simulated results were verified with experimental data. A parametric analysis was conducted by using the validated model. The results showed that the heat recovery lowered both average and maximum cell temperatures compared to natural convection. In Fig. 2(a) the experimental test collector is illustrated and in Fig. 2(b) the PV temperature contours are presented (Corbin and Zhai, 2010).

a)



b)

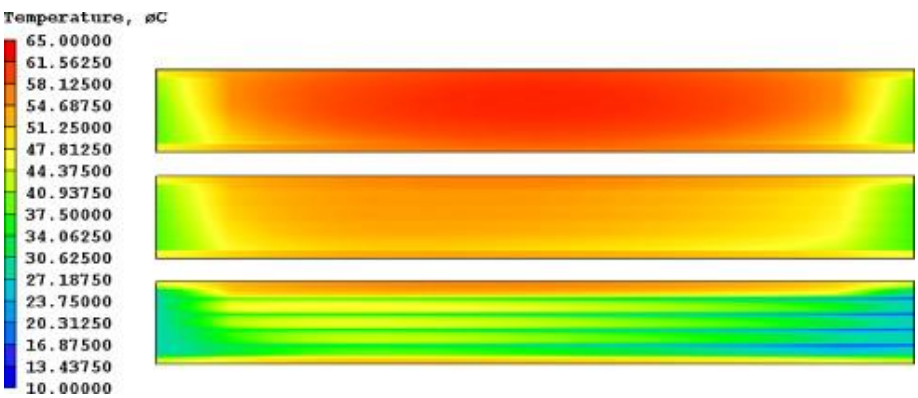


Figure 2. a) Experimental test collector and b) PV temperature contours for natural convention (top), heat recovery (middle), thermal absorber temperature contour (bottom) at 1000 W/m^2 and 10^{o}C inlet temperature. Source: Corbin and Zhai (2010).

Xiang and Gan (2015) presented a work about the optimization of a BIPVT air system combined with thermal storage. PVs combined with phase change material (PV/PCM) are hybrid solar systems which use a PCM to reduce PV temperature and to store energy for other applications. The study of Xiang and Gan (2015) included experiments on a prototype PV/PCM air system by adopting monocrystalline PV modules. Transient simulations of system performance were also conducted by using a commercial CFD package based on the finite volume method. The findings from the simulations were validated by comparing them with experimental findings. The results showed that PCM is effective in limiting temperature rise in PV device and the heat from PCM can enhance night ventilation and decrease building energy consumption to achieve indoor thermal comfort for certain periods of time.

Anderson et al. (2009) conducted a study about a BIPVT collector. The configuration was theoretically analysed through the use of a modified Hottel–Whillier model and it was validated with experimental data from testing on a prototype BIPVT collector. The results demonstrated that key design parameters such as fin efficiency, thermal conductivity between PV cells and their supporting structure and the lamination method had a significant influence on both electrical and thermal efficiency of the BIPVT.

Chow et al. (2008) presented an investigation about computer modelling and experimental validation of a BIPV and water heating system. A dynamic simulation model of the proposed system was developed. The numerical model was based on the finite-difference control-volume method. The validity of the modelling approach was verified by comparing its predicted operating temperature changes and system daily efficiencies with the measured data from an experimental rig at the City University of Hong Kong. The predictions of the model showed good compliance with the experimental findings.

Li et al. (2015a) performed TRNSYS simulation to investigate the thermal performance of a balcony wall type solar water heater system. The solar collector consisted of U-type evacuated glass tube fixed vertically on the balcony wall. The simulated collector outlet temperatures were compared with experimental data. The mean relative deviation between the two results was found to be 9.4%.

Agrawal and Tiwari (2011) developed a simulation model, by using Matlab, to investigate the electrical and thermal performance of a glazed hybrid micro-channel solar cell thermal tile. Indoor tests were performed under a solar simulator to characterise system performance and to compare the experimental data with the theoretical results. A good agreement between theoretical and experimental values was observed.

A CFD modelling of a ventilated active façade with phase change materials was conducted by Diarce et al. (2014). To validate and calibrate the developed CFD model, real-scale experimental data were used. The model was based on Fluent software. In order to model the radiation, S2S and DO sub-models were tested. RNG k–ε, standard k–ω and SST k–ω turbulence models were compared in order to simulate air flow inside the ventilated layer. The authors noted that further research is needed to improve the accuracy of the model for low-Reynolds-number turbulence conditions.

Motte et al. (2013a) investigated the performance of a novel solar collector for water heating by using numerical method. The solar collector was integrated into building gutters. MATLAB was utilised for the numerical calculations (finite difference model; electrical analogy). A good agreement between numerical and experimental results was found. The relative root mean square errors were around 5% for the water temperatures (Motte et al., 2013b).

Anderson et al. (2010) evaluated colour effect on the thermal performance of BI solar collectors. The utilized model was: 1D, steady-state, thermal model based on Hottel–Whillier–Bliss equations. The model was validated and it was adopted to calculate the fraction of a typical domestic water-heating load provided by the various theoretical coloured collectors. Moreover, an F-chart was developed for the operation of the collectors in New Zealand (Auckland).

Thermal resistance-based models were developed to simulate the performance of direct gain, indirect gain and integrated heat-pipe passive solar systems for different locations (Albuquerque, Rock Springs, Louisville, Madison) (Albanese et al., 2012). A parametric study was conducted to determine the design features that have a considerable effect on the performance. A prototype heat-pipe wall was constructed and tested for validation data. MATLAB codes were created to simulate hourly performance of the heat-pipe system, as well as direct gain and concrete and water wall indirect gain systems. A thermal network approach and an anisotropic model were used.

Regarding BICPVT configurations, Li et al. (2015b) presented a work about outdoor overall performance of a novel air-gap-lens-walled compound parabolic concentrator incorporated with PVT system. A prototype was designed and installed on a rooftop at the University of Science and Technology of China in Hefei. The optical, electrical and thermal performances of the system under outdoor conditions were analysed for BICPVT applications. Simulations and experiments were carried out to evaluate the optical characteristics of the system on two typical days. The experimental results verified the optical simulation findings.

With respect to agricultural applications, Nayak and Tiwari (2008) conducted a study about energy and exergy analysis of a PVT system integrated with a solar greenhouse. The work included validation of the thermal model with experimental data of a typical day of August (clear weather condition, New Delhi).

4.2.2. Transparent systems

4.2.2.1. Several BIST configurations

Khanal and Lei (2015) presented a work about numerical investigation of the buoyancy induced turbulent air flow in an Inclined Passive Wall Solar Chimney (IPWSC) attached to a room (ventilated space) for ventilation applications (over a range of controlling parameters). The standard k–ε turbulence model was used to model air turbulence in the solar chimney system. The numerical results revealed that the turbulent kinetic energy and turbulent intensity in the solar chimney decrease with the increase of the inclination of the passive wall. The effectiveness of IPWSC design for enhancing the thermally driven ventilation was confirmed. Additional simulations were conducted for a standalone solar chimney model. The results demonstrated that the standalone model over-predicts mass flow rate compared to that predicted by the attached model. It should be noted that the validation of the numerical model was done by comparing the numerical findings with experimental results. In Fig. 3, a schematic of the two-dimensional IPWSC studied is illustrated (Khanal and Lei, 2015).

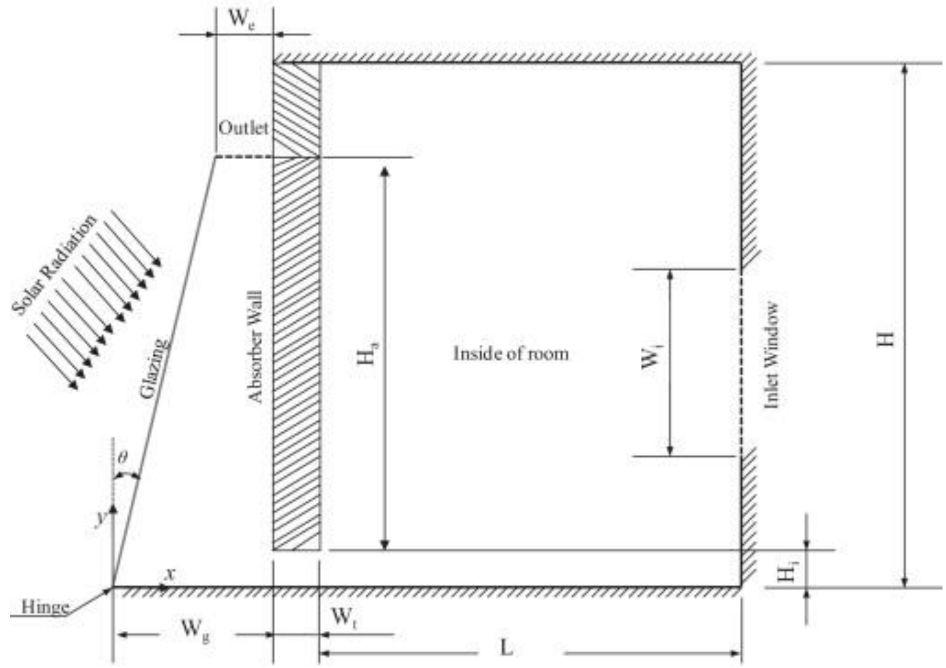


Figure 3. Schematic of the system studied by Khanal and Lei (2015): two-dimensional solar chimney (IPWSC) attached to a room. Source: Khanal and Lei (2015).

Wang et al. (2015) proposed a reasonable, simplified physical model of a built-in curtain on a glazed window. The flow/heat transfer characteristics of the simplified model were analysed. A method for the evaluation of the additional thermal resistance of the curtain was presented. The rationality of the simplified model and the accuracy of the calculations were verified by means of experiments.

Maurer et al. (2013) investigated the performance (in terms of heating and cooling) of a high-rise building incorporating façade-integrated Transparent Solar Thermal Collectors (TSTCs). It should be noted that two new TRNSYS types were developed to simulate the performance of the TSTC system as well as the passive solar gains of a glazing with venetian blinds. The simulation examined the overall performance including heating, ventilation and air conditioning of the building with façade-integrated TSTC system. Further investigation was also conducted in order to study the possibility for primary energy savings by utilizing building mass as an additional thermal storage.

A new methodology based on a ¨black box¨ model regarding building simulation programs for the modelling of solar gains through complex façades was developed by Kuhn et al. (2011). The advantage of this new methodology is that it only uses measurable quantities of the transparent or translucent part of the façade as a whole. The method was designed for complex façades such as façades with prismatic layers, light re-directing surfaces and in general, for façade properties with complex angular dependence, façades with non-airtight layers, non-flat surfaces and other complex configurations. It should be noted that the method was implemented in ESP-r and it was validated. Kuhn et al. (2011) mentioned that the method could also be implemented in other detailed simulation programs such as DOE-2, EnergyPlus or TAS thermal analysis software and it has been implemented in TRNSYS by Maurer (2012).

Maurer and Kuhn (2012) investigated the effect of variable *g* value of transparent façade collectors. A new Type 871 was developed and the model was successfully validated and used to calculate the primary energy savings. The model was built in such a way that new BIST elements can be also quickly modelled. A detailed model like Type 871 offers an accurate prediction of the collector gain, the heating and cooling load of the building and even the indoor surface temperatures to allow detailed calculations of the thermal comfort, including an optical simulation and a thermal network. Furthermore, the BlackBoxType 861 provides unprecedented accuracy in modelling glazing with blinds in TRNSYS.

Chan and Tzempelikos (2012) developed a method for assessing the integrated energy performance of passive and active multi-section façade systems combined with lighting and thermal controls of perimeter building zones by using open source language. A thermal network approach was utilized to predict indoor thermal environmental conditions and annual energy consumption of perimeter zones equipped with combinations of passive and active façade systems. The model adapted anisotropic sky models for accurate prediction of solar gains, variable angular glazing properties and non-linear interior and exterior convection and radiation heat transfer coefficients together with transient internal gains (obtained from transient lighting simulation). The baseline building (West Lafayette, Indiana) included a single room with large windows facing south. Typical Meteorological Year (TMY3) data were interpolated to represent a typical weather pattern of this city as the input value for both thermal and daylighting models. The angle-dependent glazing properties (transmittance, reflectance, absorptance) were obtained from WINDOW6 and matched with experimental data. A thermal network approach was utilized to predict indoor thermal environmental conditions and annual energy consumption on perimeter zones equipped with combinations of passive and active façade systems such as selective glazings, translucent panels, motorized shades and blinds, in conjunction with daylight-linked lighting and shading controls. Each of the components of the building system was presented as a node. In order to maintain accuracy, numerical stability and computing efficiency, a suitable time step was determined from building details, efficiency and sensitivity analysis and a modified Gauss-Siedel iteration algorithm was utilized to solve the iteration of equation sets. A previously developed daylighting model (Shen and Tzempelikos, 2012) was adopted in order to predict work plane illuminance levels and lighting demand. In terms of model validation, experimental measurements in full-scale outdoor test office spaces at Purdue University were conducted in order to compare with simulation results.

Maurer et al. (2012) conducted a study which included measurements and corresponding modelling of transparent solar thermal façades. Angle-dependent spectrally resolved optical measurements of the different collector layers were used for an optical simulation to determine the angle-dependent absorptance of each layer and the angle-dependent transmittance of the whole collector. Perez et al. (1993) sky model with Tregenza (1987) sky patches were used for accurate treatment of the diffuse radiation. The thermal network was first modelled by CFD and then it was calibrated by calorimetric measurements. The resulting detailed physical model offers multiple benefits such as predictions of the advantages, easy collector optimization and the possibility of quantifying the uncertainties of the simulation. The method to determine these uncertainties was presented.

Glória Gomes et al. (2014) conducted a numerical and experimental study of solar and visible optical properties of glazing systems with venetian blinds. Direct and diffuse fluxes of transmitted, reflected and absorbed solar and visible radiation within a multilayer glazing/shading system were taken into account. Net radiation method was adopted in order to solve the radiant energy exchange within a multilayer system. The numerical, analytical and experimental results were compared while design charts were developed to help designers and users in enhancing the thermal and daylighting indoor conditions by adjusting the slat orientation of venetian blinds.

Li et al. (2015c) investigated a novel Solar Thermal Curtain Wall (STCW) which is a solar thermal system with collectors installed as building envelope or curtain collector. The STCW combines energy production with other functional issues of architectural, structural and aesthetic. A thermal model was developed. The differential equations of the STCW were converted to numerical format through finite difference scheme and translated to TRNSYS type with FORTRAN program (which is STCW type). Except SCTW type, TRNSYS standard utility components which include type 60 detailed fluid storage tank, type 2 ON/OFF differential controller, type 3 pump and type 9 weather data reader were employed in the frame of the simulations. In order to study the thermal performance of the proposed system and validate the model, experiments were carried out on the curtain wall that was facing the south without any horizontal obstruction.

A numerical model was developed to investigate the thermal performance of a solar collector integrated into the external louvres of buildings (Palmero-Marrero and Oliveira, 2006). The model considered steady-state heat transfer and consisted of 4–6 heat balance equations, depending on the configuration. The EES software was used to model the complete water heating system, integrated-louvre collector, storage tanks and other system components. Transparent configurations were also examined.

Regarding agricultural applications of BIST, Joudi and Farhan (2014) investigated a solar air heater for heating an innovative greenhouse. The proposed greenhouse combined a traditional greenhouse with a system of solar air heaters on the roof (as one structure). It should be noted that the proposed configuration did not affect the required solar radiation inside the greenhouse for winter heating when compared with a conventional greenhouse. An energy balance method was adopted to calculate the heating load and this differs from the previous standard method which does not include soil heat storage.

With respect to BICPVT systems, Chemisana et al. (2011) designed an advanced solar unit to match the needs of building integration and CPVT generation. The proposed unit combines three elements: a domed linear Fresnel lens (as primary concentrator), a compound parabolic reflector (as secondary concentrator) and a PVT module. The PVT generator was built, analysed and characterised while models for the electrical/thermal behaviour of the module were developed and experimentally validated. The electrical performance was analysed by means of the I–V curves measured at different temperature and illumination outdoor conditions. The numerical thermal analysis was performed in detail by utilising a CFD software package. The CFD findings were well validated by using laboratory measurements.

4.2.2.2. Double-skin façades

It should be noted that in the category of transparent BIST are also included multi-skin façades, for example DSF configurations. A multi-skin façade is a type of façade which includes different layers. Between these layers air can move. The multi-skin façades can be used to provide for example heat for the building. In the following paragraphs, studies about DSF modelling are presented.

Joe et al. (2014) analyzed a multi-story DSF (Korea). Parametric and optimization studies on the DSF design were performed based on a validated model. Algorithm GenOpt was adopted for the optimization of the system. A binary version of the Particle Swarm Optimization (PSO) algorithm was utilized. It should be noted that the location of the input variable for each simulation in EnergyPlus becomes a particle and each particle includes information on a value of an objective function.

Marques da Silva et al. (2015) performed tests on an outdoor air curtain DSF test cell with a movable slat venetian blind. Measurements with no active shading as well as during night were performed. Outdoor and test cell air gap temperatures were continuously measured and wind pressure coefficients were evaluated from wind tunnel tests. The experimental findings were compared to those obtained by a simple model by taking into account both thermal and wind effects on the façade. From this comparison, discharge coefficients were evaluated (which can be utilised for characterizing the DSF behaviour).

An integrated and iterative modelling process for analyzing the thermal performance of DSF cavities with buoyancy-driven airflow by utilizing a Building Energy Simulation Program (BESP) along with a CFD package was presented (Pappas and Zhai, 2008). A typical DSF cavity model was established and simulated while the model and the modelling process were calibrated and validated against experimental data. The validated model was used to develop correlations that can be implemented in a BESP, offering the advantage of the accuracy gained from CFD simulations without the required computation time. Correlations for airflow rate through cavity, average and peak cavity air temperature, cavity air pressure and interior convection coefficient were developed. The correlations are valuable for ‘‘back of the envelope’’ calculations and for examining the accuracy of zonal-model-based energy and airflow simulation programs.

Moon et al. (2014) developed an Artificial Neural Network (ANN)-based temperature control method for energy efficient indoor thermal environment in buildings with double-skin envelope systems. A parametrical optimization process was presented. Analysis of the performance tests verified predictability and adaptability of the developed ANN model for diverse background conditions in terms of stable root mean square and mean square error values. For the validation of optimization processes set up, field measurements were performed in an actual double-skinned building (Ansan, South Korea).

Moreover, von Grabe (2002) developed a simulation method in order to investigate the temperature behaviour of double façades. The model accuracy was tested by utilizing experimental data. It should be noted that the model accuracy was improved by modifying flow resistance for multiple geometries.

Park et al. (2004) developed a lumped simulation model which was calibrated for DSF systems with controlled rotating louvers and ventilation openings. A parameter estimation technique and *in situ* monitoring of a full-scale element mounted on the south-facing façade of an existing building were utilized. The new approach was based on a postulated “minimalistic” lumped model, calibrated based on *in situ* measurements.

Balocco and Colombari (2006) conducted a non-dimensional analysis to analyse mechanically-ventilated double-glazed façade energy performance. A comparison between Nusselt number solved by means of experimental data and Nusselt number calculated by the validated multivariable correlation function was presented. Balocco and Colombari (2006) mentioned that due to its wide validity field the proposed method can be used to analyse thermodynamic performances of glass DSF with mechanical ventilation.

Jiru and Haghighat (2008) modelled a ventilated DSF system based on a zonal approach. Zonal models can offer information about airflow and temperature distribution in a ventilated space faster than CFD, but with more accuracy and details than lumped and control-volume models. In the study of Jiru and Haghighat (2008), the zonal airflow equation, power-law, was used to calculate the airflow through the shading device and cavities. The zonal energy equation was utilized to evaluate the temperature distribution in the DSF system. The predicted temperature distributions were verified by means of measured values. The case used for the development and verification of the DSF models was an experimental test cell (Torino, Italy). The results showed that the zonal models can assess the performance of the DSF system with venetian blinds while the developed DSF model can further be integrated into Building Simulation tool with HVAC (heating, ventilation and air conditioning).

Blanco et al. (2014) analysed the thermal behaviour of double-skin perforated sheet-metal façade by taking into account several parameters (perforation rates, colours, materials, wind penetration). A numerical model based on the fundamental laws of heat transfer through the shell was presented and validated by experimentation (by means of a complex data capture and storage system setup). The experimental process for the validation included monitoring metallic sheets within a range of 0–35% (perforation rates), black-white (colours) and galvanized steel-aluminium (materials) in a large-scale test campaign. Excellent agreement was observed between the outputs from the numerical model and the test campaign.

Saelens et al. (2008) compared different DSF in order to improve their energy performance. Many different zones in TRNSYS 15 were used. It was demonstrated that controlling the air flows and the heat recovery of the air between the two building skins can lead to energy savings.

4.3. Issues about the insulation of the systems

In terms of the building integration of solar collectors, it is important to ensure that the building envelope is of high insulation quality. This means that the collector must be well insulated. When a solar collector is to be mounted on an existing building, is it important the installation to be performed quickly and safely, but correctly (Gajbert, 2008). In the following paragraphs, some studies related with the role of the insulation in the field of BI solar systems are presented.

Fieber et al. (2003) developed a multi-functional wall element: a PVT on the inside of an anti-reflective insulation window with concentrating mobile reflector screens makes the system fully integrated into the building, even its interior. The proposed solar window provides electricity and warm water, passive space heating and day lighting. Moreover, the reflector screens act as sunshades and added internal insulation for the window. The reflectors have an optical concentration factor of 2.45.

There is also another study about the optimisation of reflector and module geometries for stationary, low-concentrating, façade-integrated PVs (Gajbert et al., 2007). The studied collector included a PVT absorber and the system had parabolic aluminium reflectors and PV string modules, as well as expanded polystyrene insulation. Due to the presence of the insulation material, which it is attached directly to the back of the reflector sheet metal, the façade element can serve as an integrated part of building envelope.

Matuska and Sourek (2006) studied façade-integrated solar thermal collectors for water heating in an existing building stock (Czech Republic). The thermal behaviour of the façade collectors was compared with standard roof-located collectors in solar domestic hot water systems. The application of façade solar collectors affects indoor comfort of the building (in a reasonable range). Building behaviour was not strongly affected by the façade collectors when sufficient insulation layers were used. It should be noted that the considered façade solar collector was a standard selective liquid flat-plate collector integrated into building envelope. The collector had a standard spectrally selective absorber, an air gap and single safety glazing. The building insulation layer served for the back/edge insulation of the collector. Several configurations were studied: panel or brick wall with envelope insulation with/without roof collector, etc.

Nowzari and Atikol (2009) performed TRNSYS simulation for a building integrated with a Trombe wall (Larnaca, Cyprus). A vented Trombe wall was used for the south façade of the ground floor and a direct gain window of area 6.5 m^2 was placed on the south façade of the first floor. It was verified that the presence of a 5 cm-thick extruded polystyrene thermal insulation improved building thermal comfort by about 17%.

Dowson et al. (2012) studied a polymer air collector with aerogel. Based on the measurements, the collector was modelled. A steady state model was developed to characterise the aerogel solar collector. This type of collector offers the opportunity to improve the efficiency of flat-plate solar air collectors by replacing their conventional glass covers with lightweight polycarbonate panels filled with aerogel insulation.

Hauer et al. (2012) extended an existing BA solar thermal collector model in order to couple it with a building within TRNSYS simulation environment. They used another way for this coupling than that of Maurer (2012). Hauer et al. (2013) compared the building integration with and without a gap between the collector and the building insulation. Instead of analysing air flow in the gap by CFD or measurements, they assumed very small, intermediate and very high air flows in the gap and they discussed the results.

5. Conclusions

This study presents an overview on the validation of developed codes, thermal and optical, within the field of BIST systems. Specific requirements for BIST modelling and simulation are highlighted. Representative studies from the literature are presented according to the validation methodologies: on-site validation, test cells and laboratory. In addition, literature references for validated models are cited separately into two main categories: building-added and building-integrated systems. Within the building-integrated configurations the systems are presented divided into two groups: opaque and transparent systems. Additional aspects regarding system insulation are also presented in order to provide a more complete picture of the studied issues.

The results reveal that there are some specific requirements such as solar gain control, daylight utilisation and indoor environment quality which should be taken into account in the frame of a model for a BIST system.

Regarding validation methodologies, on-site validation has been conducted for several types of systems (active façades, multi-section façades, etc). On the other hand, indoor solar simulators facilitate solar research in cold climates and in the literature there are studies about laboratory validation for multiple configurations (concentrating BIPV, façade-integrated solar systems, PV with CPC, etc). Moreover, test cells provide an intermediate solution between a real building and an experiment in the laboratory and they have been also adopted for some studies.

The literature concerning the validated models for BIST reveals that there are studies for opaque as well as for transparent systems. Within the field of transparent BIST several configurations have been modelled: façade-integrated collectors for high-rise buildings, complex façades, glazings with venetian blinds, curtain walls, double-skin façades, etc. Finally, it should be noted that there are few studies in the field of BIST in the agricultural sector and thus, it would be interesting the investigation of systems such as innovative greenhouses with BIST systems.

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