Models of Sub-Components and Validation for the IEA SHC Task 44 / HPP Annex 38

Part B: Collector Models

A technical report of subtask C

Report C2 Part B – Final Draft

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IEA Solar Heating and Cooling Programme

The *International Energy Agency* (IEA) is an autonomous body within the framework of the Organization for Economic Co-operation and Development (OECD) based in Paris. Established in 1974 after the first "oil shock," the IEA is committed to carrying out a comprehensive program of energy cooperation among its members and the Commission of the European Communities.

The IEA provides a legal framework, through IEA Implementing Agreements such as the *Solar Heating and Cooling Agreement*, for international collaboration in energy technology research and development (R&D) and deployment. This IEA experience has proved that such collaboration contributes significantly to faster technological progress, while reducing costs; to eliminating technological risks and duplication of efforts; and to creating numerous other benefits, such as swifter expansion of the knowledge base and easier harmonization of standards.

The *Solar Heating and Cooling Programme* was one of the first IEA Implementing Agreements to be established. Since 1977, its members have been collaborating to advance active solar and passive solar and their application in buildings and other areas, such as agriculture and industry. Current members are:

Australia	Finland	Singapore
Austria	France	South Africa
Belgium	Italy	Spain
Canada	Mexico	Sweden
Denmark	Netherlands	Switzerland
European Commission	Norway	United States
Germany	Portugal	

A total of 49 Tasks have been initiated, 35 of which have been completed. Each Task is managed by an Operating Agent from one of the participating countries. Overall control of the program rests with an Executive Committee comprised of one representative from each contracting party to the Implementing Agreement. In addition to the Task work, a number of special activities—Memorandum of Understanding with solar thermal trade organizations, statistics collection and analysis, conferences and workshops—have been undertaken.

Visit the Solar Heating and Cooling Programme website - **www.iea-shc.org** - to find more publications and to learn about the SHC Programme.

Current Tasks & Working Group:

Task 36	*Solar Resource Knowledge Management*
Task 39	*Polymeric Materials for Solar Thermal Applications*
Task 40	*Towards Net Zero Energy Solar Buildings*
Task 41	*Solar Energy and Architecture*
Task 42	*Compact Thermal Energy Storage*
Task 43	*Solar Rating and Certification Procedures*
Task 44	*Solar and Heat Pump Systems*
Task 45	*Large Systems: Solar Heating/Cooling Systems, Seasonal Storages, Heat Pumps*
Task 46	*Solar Resource Assessment and Forecasting*
Task 47	*Renovation of Non-Residential Buildings Towards Sustainable Standards*
Task 48	*Quality Assurance and Support Measures for Solar Cooling*
Task 49	*Solar Process Heat for Production and Advanced Applications*

Completed Tasks:

Task 1	*Investigation of the Performance of Solar Heating and Cooling Systems*
Task 2	*Coordination of Solar Heating and Cooling R&D*
Task 3	*Performance Testing of Solar Collectors*
Task 4	*Development of an Insolation Handbook and Instrument Package*
Task 5	*Use of Existing Meteorological Information for Solar Energy Application*
Task 6	*Performance of Solar Systems Using Evacuated Collectors*
Task 7	*Central Solar Heating Plants with Seasonal Storage*
Task 8	*Passive and Hybrid Solar Low Energy Buildings*
Task 9	*Solar Radiation and Pyranometry Studies*
Task 10	*Solar Materials R&D*
Task 11	*Passive and Hybrid Solar Commercial Buildings*
Task 12	*Building Energy Analysis and Design Tools for Solar Applications*
Task 13	*Advanced Solar Low Energy Buildings*
Task 14	*Advanced Active Solar Energy Systems*
Task 16	*Photovoltaics in Buildings*
Task 17	*Measuring and Modeling Spectral Radiation*
Task 18	*Advanced Glazing and Associated Materials for Solar and Building Applications*
Task 19	*Solar Air Systems*
Task 20	*Solar Energy in Building Renovation*
Task 21	*Daylight in Buildings*
Task 22	*Building Energy Analysis Tools*
Task 23	*Optimization of Solar Energy Use in Large Buildings*
Task 24	*Solar Procurement*
Task 25	*Solar Assisted Air Conditioning of Buildings*
Task 26	*Solar Combisystems*
Task 27	*Performance of Solar Facade Components*
Task 28	*Solar Sustainable Housing*
Task 29	*Solar Crop Drying*
Task 31	*Daylighting Buildings in the 21st Century*
Task 32	*Advanced Storage Concepts for Solar and Low Energy Buildings*
Task 33	*Solar Heat for Industrial Processes*
Task 34	*Testing and Validation of Building Energy Simulation Tools*
Task 35	*PV/Thermal Solar Systems*
Task 37	*Advanced Housing Renovation with Solar & Conservation*
Task 38	*Solar Thermal Cooling and Air Conditioning*

Completed Working Groups:

CSHPSS; ISOLDE; Materials in Solar Thermal Collectors; Evaluation of Task 13 Houses; Daylight Research

IEA Heat Pump Programme

This project was carried out within the Solar Heating and Cooling Programme and also within the *Heat Pump Programme*, HPP which is an Implementing agreement within the International Energy Agency, IEA. This project is called Task 44 in the *Solar Heating and Cooling Programme* and Annex 38 in the *Heat pump Programme*.

The Implementing Agreement for a Programme of Research, Development, Demonstration and Promotion of Heat Pumping Technologies (IA) forms the legal basis for the IEA Heat Pump Programme. Signatories of the IA are either governments or organizations designated by their respective governments to conduct programmes in the field of energy conservation.

Under the IA collaborative tasks or "Annexes" in the field of heat pumps are undertaken. These tasks are conducted on a cost-sharing and/or task-sharing basis by the participating countries. An Annex is in general coordinated by one country which acts as the Operating Agent (manager). Annexes have specific topics and work plans and operate for a specified period, usually several years. The objectives vary from information exchange to the development and implementation of technology. This report presents the results of one Annex. The Programme is governed by an Executive Committee, which monitors existing projects and identifies new areas where collaborative effort may be beneficial.

The IEA Heat Pump Centre

A central role within the IEA Heat Pump Programme is played by the IEA Heat Pump Centre (HPC). Consistent with the overall objective of the IA the HPC seeks to advance and disseminate knowledge about heat pumps, and promote their use wherever appropriate. Activities of the HPC include the production of a quarterly newsletter and the webpage, the organization of workshops, an inquiry service and a promotion programme. The HPC also publishes selected results from other Annexes, and this publication is one result of this activity.

For further information about the IEA Heat Pump Programme and for inquiries on heat pump issues in general contact the IEA Heat Pump Centre at the following address:

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Visit the Heat Pump Programme website - http://www.heatpumpcentre.org/ - to find more publications and to learn about the HPP Programme.

Contents

1 Executive Summary

Solar thermal and heat pump systems are one of the key elements for our future high efficient energy supply. In this context, realistic and reliable description of solar thermal collectors in solar heat pump systems is of great importance. This report gives an overview of solar thermal collector models.

For system simulations most of the existing numerical models for glazed solar collectors are applicable. However, for unglazed collectors the typical operating range is extended to low temperatures. As a result, little experience exists under these operating conditions where significant changes of the collector performance may be expected for instance due to condensation of water vapour on the collector surface. In recent works in and outside T44/A38, the effect of condensation has been included to establish collector models for unglazed collectors.

Validation and application of unglazed collector models has been conducted and is described. The investigated models show good agreement with measurements. In addition, work on condensation, in particular, real applications and the transfer of the results to systems simulations along with validation is still needed.

Additional collector models have to be applied for the simulation of photovoltaic thermal (PVT-) collectors. The vast majority of commercially available PVT collectors in combination with a heat pump are modified PV modules and therefore unglazed. Although more experience is needed in this area, first validation measurements reveal, that a simple extension of thermal models by an electrical model suffices for good accuracy in thermal and electrical modelling. To conclude, no principal difficulties are to be expected and a first model with some validation data is already presented.

Overall, adequate models are available allowing the description of liquid cooled glazed and unglazed collectors. Nevertheless, further validation work should be conducted to confirm the reliability of the models in the extended low temperature applications. This should not be restricted to condensation but also to night-time operation without solar radiation or any other effect in the low temperature operating range. Both, collector model validation from experiments and system model validation and long-term experience from field measurements should be included.

2 Introduction

Solar heat pump systems offer a promising alternative for a high efficiency heat supply of buildings. In addition to the use of solar thermal heat at the temperature levels required by the demand, in these systems solar collectors may also be used as a heat source for the heat pump. The aim of the T44/A38 is the evaluation of solar and heat pump systems and therefore the modelling of solar thermal collectors as part of the system. Commonly performance models are applied for this purpose in system simulation environments as TRNSYS, Matlab or IDA-ICE. They allow the assessment of different systems and configurations.

As a result of the collector application as a heat source of the heat pump its operation range and therefore the validity of the collector models is extended. However, this gave rise to completely new and so far neglected collector operation conditions. There are four effects that have an impact on the performance of solar thermal collectors in an application as a heat source for heat pumps:

- Condensation of water vapour on the absorber surface that is colder than the dew point
- Operation without solar irradiance, i.e. operation as an ambient heat exchanger
- Rain on the absorber surface of the unglazed collector
- Frost accumulation on the absorber surface that is colder than the freezing point

This report presents a general energy balance for the collector (Chapter 3), gives an overview on existing solar collector models (Chapter 4), methods of system evaluation (Chapter 5), model validation against measured data from literature and recent task measurements (Chapter 6) and a comprehensive compilation based on the model properties (Appendix B). It summarizes the current state of the art of collector modelling for the simulation of solar heat pump systems, based on work performed both inside and outside T44/A38.

3 General energy balance for a solar thermal collector

The energy balance shown in Eq. 1 is valid for glazed and unglazed collectors although discussed for an example of an unglazed collector. The energy balance for glazed collectors can be seen as a simplification of the unglazed energy balance that usually disregards wind dependencies and does not account separately for long wave radiation exchange, condensation, icing and rain as these influences are not significant for glazed collectors.

Uncovered collectors on the other hand can gain heat by the convective and long-wave radiation heat exchange with the ambient as well as by condensation (if operated below the dew point of air) and possibly by freezing of water vapour on the collector surface. The overall collector heat gain $\dot{q}_{gain}$ can be seen as the sum of different heat gains (see Eq. 1). The possible heat gains consist of the absorbed shortwave radiation $\dot{q}_{rad,S}$, long-wave radiation exchange $\dot{q}_{rad,L}$, convective heat exchange that is split into sensible heat exchange $\dot{q}_{air,sens}$ and latent heat exchange $\dot{q}_{air,lat}$ with the air, by heat conduction $\dot{q}_{k}$ usually at the rear side, and energy gains from the rain $\dot{q}_{rain}$. The latent heat exchange may be further split into the condensation $\dot{q}_{air,cond} > 0$, evaporation $\dot{q}_{air,cond} < 0$, frost formation $\dot{q}_{air,frost} < 0$ and frost melting $\dot{q}_{air,frost} > 0$. To be precise, all these terms may appear not only on the front but also on the rear side of the absorber.

Eq. 1 $$\frac{\dot{Q}_{gain}}{A_{coll}} = \dot{q}_{gain} = \dot{q}_{rad,S} + \dot{q}_{rad,L} + \dot{q}_{air,sens} + \dot{q}_{air,lat} + \dot{q}_{k} + \dot{q}_{rain}$$

with $$\dot{q}_{air,lat} = \dot{q}_{air,cond} + \dot{q}_{air,frost}$$

The useful heat output of the collector $\dot{q}_{use}$ has to account additionally for the energy balance of the effective thermal capacitance c_{eff} of the collector (see Eq. 2):

Eq. 2 $$\frac{\delta T_{coll}}{\delta t} c_{eff} = \dot{q}_{gain} - \dot{q}_{use}$$

Where $\delta T_{coll}/\delta t$ is the time-derivative of the average temperature of the thermal mass of the collector. Incoming heat flows are counted positive and outgoing flows are counted negative.

All collector models attempt to provide a solution for the energy balance presented in Eq. 1 and Eq. 2, most of them neglecting or simplifying one or more of the heat transfer mechanisms. Depending on the model used, these influences are treated differently or even neglected completely. Appendix B gives an overview of models known to the authors of this report. Every model neglects some of the influences presented and therefore has to be checked in detail depending on the application and purpose of the simulation. Some common simplifications are:

- In contrast to the assumptions made in most models, the heat transport effects in and around the collector are nonlinear. For instance the quasi-dynamic collector model of EN 12975-2 and the TRNSYS model type 832 respects the different influences in terms of a straightforward linearization approach.
- Most conventional covered flat plate collector models do not explicitly distinguish between short wave and long-wave radiation exchange.
- Most models for glazed collectors do not account for latent heat gains and usually neglect the relationship between the collector sensible heat exchange with air and the velocity of the air (wind) above the collector plane.

4 Solar thermal collector models

4.1 Overview and delimitation

Solar thermal collectors convert solar radiation to heat. Additionally, heat pump systems allow their operation as an air heat exchanger in absence of solar radiation. Strictly speaking all solar thermal collectors can be combined with heat pumps, and consequently any solar thermal collector with a combination of the following collector attributes can be applied:

- Glazed (covered) or unglazed (uncovered) collectors
- Thermal or photovoltaic thermal (PVT-) collectors
- Concentrating or non- concentrating collectors
- Liquid-cooled or air-cooled collectors

At the current status the vast majority of the solar collectors in combination with heat pumps and accordingly this report are non-concentrating, liquid- cooled, thermal collectors. Thus, the most distinguishing attribute of the collectors is currently glazed or unglazed.

A glazed collector absorbs solar radiation behind a transparent cover inside the collector. At the same time, the transparent cover/ glass pane hinders the convectional heat transport to the ambient. Unglazed collectors do not have a cover above the absorbing surface. Consequently, unglazed collectors have a direct contact to the ambient air and higher convectional losses.

The collector models are discussed in terms of performance and design models. The **performance models** (see section 4.2) are the most commonly used for thermal collector modelling and system assessment. Together with measured performance data, these models are the basis for most dynamic simulations. In contrast, the physical or **design models** of collectors (discussed in section 4.3) are generally used for design and detailed collector investigations only.

The most significant performance changes and uncertainties in combination with heat pump systems are expected for **unglazed collectors**, for which models are presented in section 4.4. Nevertheless, certain heat pump systems on the market are combined with collectors that are designed and have to be modelled differently. Aspects of these **special collector designs** and their modelling are discussed in section 4.5.

4.2 Performance models

In most simulations solar thermal collectors are described by a performance model. The required performance parameters are generally obtained by steady state or quasi-dynamic performance measurements according to EN 12975 (2006) or ISO-9806 (2007). Independently of the applied measurement method of test centers (stationary or quasi-dynamic method), the collector performance is commonly published by steady state performance equations for example given in (Eq. 4) and (Eq. 5). A vast number of data for different collectors can be obtained by manufacturers or from collections of performance data sets (Appendix C).

The complete quasi-dynamic collector efficiency equation according to EN 12975 (2006) ISO-9806 (2007, p.98) is valid for glazed and unglazed collectors and given in (Eq. 3).

Eq. 3 $\eta = \eta_{o,b} \cdot (k_{\Theta b}(\Theta_b) \cdot G_b + k_{\Theta d} \cdot G_d) - c_1 \cdot \Delta T - c_2 \Delta T^2 - c_3 \cdot u \cdot \Delta T + c_4 (G_L - \sigma T_a^4) + c_5 \cdot \frac{\delta t_m}{\delta t} - c_6 \cdot u \cdot G^*$

The equation is derived from an extension of the stationary model (Perers 1993). Within the equation the following influences are respected:

- Angle dependency of the incident beam and diffuse radiation
- Temperature dependant heat losses
- Wind dependency of heat losses
- Heat capacity of the collector
- Long-wave radiation losses

For steady state conditions and assuming 100% perpendicular incidence of solar radiation simpler models are used and presented for glazed collectors in (Eq. 4) and for unglazed collectors in (Eq. 5).

Eq. 4 $\dot{Q}_{glazed} = A \cdot G \cdot \eta_{glazed} = A \cdot G \cdot \left(\eta_{0,b,glazed} - a_1 \frac{\Delta T}{G} - a_2 G \left(\frac{\Delta T}{G}\right)^2\right)$

Eq. 5 $\dot{Q}_{unglazed} = A \cdot G'' \cdot \eta_{unglazed} = A \cdot G'' \cdot \left(\eta_{0,b,unglazed} \cdot (1 - b_u u) - (b_1 + b_2 u) \cdot \frac{\Delta T}{G''}\right)$

The net irradiance G´´ is defined as: $G'' = G + \left(\frac{\epsilon}{\alpha}\right) \cdot (G_L - \sigma T_a^4)$

The presented performance models have a physical background (Hottel & Woertz 1942; Duffie & Beckman 2006, p.296). This means they are derived from an energy balance of the collector applying linearization and simplification of the different terms.

According to standard measurement procedure the provided data is derived from measurements at constant nominal mass flow rates. The models respect flow rate variations by the change of the arithmetic average fluid temperature. For high flow rates this seems an acceptable simplification as the arithmetic fluid temperature is close to the real average fluid temperature. For lower flow rates however this effect can be considered either by a multi-node approach of the model or a flow-rate correction term according to Duffie & Beckman (2006).

The thermal collector capacity effects are usually respected in terms of one effective capacity. Depending on the applied model this effective capacity is then either distributed within the model along the fluid path or respected as one lumped capacity.

Condensation in flat plate collectors could lead to reliability problems and therefore should be of interest. A significant heat gain by condensation in flat plate collectors or even in vacuum tube collectors is not expected and will therefore be neglected. Tests show very low heat gains by condensation for conventional flat plate collectors and vacuum tube collector (Citherlet et al. 2011). In collector experiments at low temperature operation the condensation effect should still be considered to avoid humidity on the absorber that totally changes the emissivity but also the absorptance from normal “dry” conditions. Nevertheless, as long as condensation is regarded only in terms of reliability and not for quantifying reasons a simple calculation with a Mollier diagram outside the actual collector model seems sufficient.

Naturally, the right model choice strongly depends on the purpose of the simulation, the collector design (glazed, unglazed, air cooled, liquid cooled), and practical considerations as the availability for a certain the simulation platform.

For typical solar thermal applications the existing collector models allow exact investigations in dynamic simulations. Nevertheless, combined with a heat pump the application range might include operation at low temperatures. Therefore, the following discussion will focus on unglazed collector models, because here the most significant changes are to be expected.

4.3 Design models

For design purposes, more detailed physical collector models are employed. Design models are able to predict the physical behaviour of the collector in order to find optimized solutions with no need to construct expensive prototypes. Moreover, since these models use physical data as inputs, they do not need experiments and are able to analyze aspects that parametric performance models obtained under specific conditions cannot.

In general, design models often end up in generating collector performance data, which allows easy calculation of the annual solar yield within dynamic simulations or are directly integrated to dynamic simulation programs (Koo 1999; Matuska et al. 2008; Cadafalch 2009; Carbonell & Cadafalch 2012).

The mathematical description of the physical processes that are relevant for design models of collectors can be found in Duffie & Beckman (2006). However, gains from water vapour condensation for operating conditions below the dew point or the use of the collector as an ambient air heat exchanger are not included in these descriptions and are not included in most of the known design models.

4.4 Unglazed collectors

Despite its restricted temperature range the obvious advantages of unglazed collectors are their low price and low complexity. For this reason they have been considered as heat source of heat pumps since the first heat pump boom in the 1980´s (Soltau 1989) and are of special interest for metal roof manufacturers.

In the last years, simulation models for unglazed collectors for different applications have been developed and new models are still under development. Three recent unglazed collector models include condensation and are integrated to the TRNSYS environment and in one case to IDA-ICE. All of these respect the influences mentioned above (Capacity, IAM, wind, long-wave radiation). Furthermore, all of them integrate the condensation model of Pitz-Paal (1988) whereas the collector model is of complete different origin:

1. Iterative, non-linearized physical model of Frank (2007), Type 222
2. Quasi-dynamic model of Perers (2010, p.200) Type 136 (132 in TRNSYS 15)
3. Steady state performance model Bertram et. al. (2010), Stegmann et. al. (2011), type 202+203.

All of the three models are applied within scientific context.

In addition to the heat gains from solar radiation and convection unglazed collectors benefit from heat gains due to condensation. These condensation gains are temperature and humidity dependent and occur only for operation below the dew point temperature on the surface of the collector. The possible significance of condensation is stressed by measurements of Pitz-Paal (1988) and Eisenmann (2006) that revealed condensation heat gains up to 40% of the collector performance for particular operating conditions.

Other mathematical models for these effects have been presented since the 1980's by several authors Massmeyer und Posorski (1982), Pitz-Paal (1988); Eisenmann (2006). Keller

(1985, pp.397–400) also describes how latent heat gains can be modelled in unglazed solar collectors in combination with heat pumps.

4.5 Special collector designs

In this section differently designed collectors and their models are briefly described in the following:

Photovoltaic- thermal (PVT) collectors combine solar thermal with photovoltaic electricity production.
Most investigations were conducted with glazed PVT collectors. Identical to the glazed thermal collectors no significant additional yield due to the extended operation range is to expect. Glazed PVT collectors can therefore be modelled with state of the art PVT models as given in (Mattei et al. 1998; Rockendorf et al. 1999; Ji et al. 2008). Special attention should be paid to condensation and therefore water within the PVT- collector as an electric device.

In many cases of commercially available PVT collectors in a heat pump system the PVT collector is a modified PV module and therefore unglazed. Further, unglazed PVT- collectors are one interesting option for heat pump systems as they can generate additional electrical yields by lowering the temperature of the PV. The TRNSYS Type 203 (Stegmann et al. 2011) offers the opportunity to model unglazed PVT collectors with a combination of an electrical and thermal performance model. Experiments and long-term measurements in the field revealed that the developed thermal steady-state PVT- model could be applied to PVT-collectors with the same accuracy as for thermal collectors.

The **glazed collector with forced convection** is a new collector development in combination with a heat pump system. The collector is an extended glazed collector with an integrated electrical fan that can boost ambient air through the rear side of the collector absorber. Depending on the modus of the fan the collector can switch between high and low convective heat transfer rates to the ambient. So far, no experience in modelling this type of collectors has been published. The particular collector (Solaera) is offered by the company Consolar only.

Air collectors can be described by physical models or performance models similar to liquid cooled collectors. It is assumed that the necessary model extensions and experience especially from condensation modelling of unglazed collectors could be transferred to unglazed and glazed air collector models. (Besides, for practical reasons condensation on the absorber or inside the air channels of collectors might cause serious problems in the air channel system and is presumably avoided anyway.)

Massive solar-thermal collectors adopt a massive material (typically concrete) with high thermal capacity as absorber instead of metal. These can be fully or partially integrated in the building envelope and therefore offer an interesting option for low cost absorbers in combination with heat pump systems and plenty of heat pump concepts with these absorbers have been investigated in the 80ties and 90ties. However, the potential of low- costs gave again rise to a lot of recent research activity and collector modelling specially dedicated to massive solar- thermal absorbers (D'Antoni & Saro 2012). Nevertheless, in the current status the modelling of massive solar- thermal absorbers focusses on design models and on models for system simulations.

Direct expansion solar-thermal collectors are connected to the cold side of the heat pump fluid cycle. Correspondingly, the collector evaporates the refrigerant and is operated with liquid fluid and gas. This minimizes the temperature difference between collector and heat pump and allows collector operation without a hydraulic pump. Typically, unglazed collectors are applied. Several works have been published related to model the system and collector (Morrison 1994) and to measure direct expansion solar assisted heat pump systems (Anderson & Morrison 2007), (Anderson et al. 2002). The model according to (Morrison 1994) describes the thermal performance for the unglazed collector according to a steady state performance model (see Eq. 5). The collector performance parameters are derived by measurements with forced flow according to 12975-2 and assume the internal collector heat transfer comparable to those with the internal evaporation process. The collector heat gain to the evaporator is determined assuming that the collector fluid temperature and the evaporator temperature of the heat pump are identical.

5 System evaluation with collector models

5.1 Dynamic system simulation

Dynamic simulations enable the detailed evaluation of a wide variety of influences that are neglected in rough calculation methods. Typical simulation platforms for dynamic simulations are Matlab/Carnot, TRNSYS, Polysun, T-sol, or IDA-ICE. These platforms allow the simple combination of in- and outputs of different models and likewise the simulation of a complete system. In other words, this allows the comparison of different boundary conditions, hydraulic system configurations, component sizes or control strategies over any user defined period. At this point, the exact modelling of the interaction between heat sources, sinks and their relation with the solar thermal collector plays a key role.

Numerous solar thermal collector models exist and are well validated for conventional applications where the collector heat gains arise from solar irradiation and the operation temperature is higher than the ambient air temperature. Although the existing collector models are extended to fit the requirements of the new operation range the models should applied cautiously. For instance a new model including condensation won´t be suited to simulate an application where it is mostly operated below freezing point. Accordingly, the validity of the models and their application should be checked in new applications.

5.2 Calculation methods

Calculation methods are a simple and fast method to estimate the yield of a solar thermal collector of a given system. In most cases the solar fraction f_{sav} (dimensionless) and the specific collector yield $\dot{q}_{coll}$ (kWh/m²a) are used for system or collector comparison and dimensioning. All known methods are based on performance models of solar thermal collectors.

In general there are three basic calculating methods to assess solar thermal collectors and their energy performance:

1. Constant operating temperature

   A constant operating temperature of the collector is assumed and the solar yield is calculated for a known orientation under representative weather conditions. This method completely neglects the complexity of the solar thermal system as well as the interaction between solar thermal yield and operating temperature. Examples are (Perers et al. 2011; Duffie & Beckman 2006, p.672; Rockendorf et al. 2001). Although the results are not applicable to real systems, they allow a good first assessment of solar collectors under certain applications and a comprehensive comparison of different collectors for a given temperature application range.

2. Derived correlations (f-chart)

   Correlations from complex system simulations and/or measurements are derived that allow the prediction of the solar yield or solar fraction under variable conditions. Examples are the f-chart method (Duffie & Beckman 2006), (Letz et al. 2002), (Letz et al. 2009) or recent extensions of the f-chart method (Carrera et al. 2011). Duffie & Beckmann (2006, p.691) even give an example of combining the f- chart method for a solar thermal system with the heat pump orientated bin method.

   The weakness of these methods is their particular restriction to the investigated system configurations and dependencies as collector or storage size. Nevertheless, the principle has its charm. It offers a straightway method for dimensioning, a reliable prediction of solar thermal system performances and yields and respects changed climate conditions for the system under investigation.

3. Rules of Thumb

   The roughest, least scientific but nevertheless often used method is to use empirical rules of thumb for a certain application and climate. Rule of thumb values may be derived from simulations, field measurements and last but not least experiments. Typical result of any dynamic simulation is the specific collector yields and solar fractions for a typical system.

The presented calculation methods are easy to use, well known and often applied by experienced designers having dimensioned solar collector fields for similar applications in the past, e.g. domestic hot water systems for single family houses. However for cases such as: complex systems, unusual heat loads, unusual applications or other influencing factors that make rough estimations unreliable (e.g. an obstructed horizon), dimensioning, optimization and performance evaluations of solar thermal systems (and their components), dynamic system simulations and/or measurements are used.

6 Model validation

6.1 Glazed and unglazed collectors

The accuracy of solar thermal collector characterization has been intensely investigated since the 1970´s. A good example for the coordinated work on collector modelling and testing is IEA Task 3 “Performance Testing of Solar Collectors” in the 1990´s. The latest effort to harmonize measurements and model quality of solar thermal collectors in Europe is done within the currently running Quaist project (http://www.qaist.org/). Nevertheless, continuous efforts are made to simplify the testing and modelling procedure.

A comprehensive validation of steady state and dynamic models for unglazed collectors is presented by Hilmer (1999). As a result commonly used models with one capacity show good agreement to measured data of 10 minute time steps for constant mass flow rates. For varying mass flow rates in the measurement hourly averaged data in the simulation is well applicable under the condition of identical average mass flow rates.

The correlation model based on efficiency curve has been analyzed and validated (see for example Perers (1993)). Recently, Carbonell & Cadafalch (2012) compared the correlation model with a physical model based on an extension of the work described in (Duffie & Beckman (2006). The models were applied for flat plate solar collectors and compared against each other under dynamic conditions. The physical model showed a good behaviour while the correlation model performed very well except for time steps lower than collector residence time and for strong variations of fluid inlet temperature.

Validation of the steady state model (Bertram/ Stegmann) was undertaken and for the three measured systems (Bertram et al. 2008; Stegmann et al. 2011), the result is identical. The annual yield is calculated with high accuracy less than 2%. In contrast, the standard deviation between the measured and calculated values of the daily yield is significantly higher (within 6%). Figure 1 displays the simulation and measurement results of the daily collector yields for an one year system measurement (Stegmann et al. 2011) as an example. The simulation is conducted with collector performance parameters from EN-12975 measurements, the measured meteorological data and the measured inlet temperature in the system. The same method is applied for Figure 2, which displays the measured and simulated performance in the course of the day for an unglazed collector mounted on a test rig.

Perers (2011) validated a quasi-dynamic model in a TRNSYS simulation against a spread sheet calculation method with constant inlet temperature including and found good agreement between the two.

Philippen (2011) studied the effect of inclination on the convective heat transfer coefficient of uncovered collectors at low wind speeds and with operation below the dew point at night. From empirical Nusselt relationships for natural convection heat transfer it can be concluded that the inclination influences the convective heat transfer. However, the analysis of measured data showed that increased heat gains for larger slopes of collector inclination can be explained by the increased long-wave radiation that was measured with a pyrgeometer. After taking into account the influence of long-wave radiation exchange on the energy balance of the absorber, no significant influence of the inclination on the convective heat transfer was detectable. At the same time, measurements on uncovered absorbers with selective coating showed that due to the optical propertiesof water, the surface temporarily loses its selectivity as soon as dew forms on the surface.

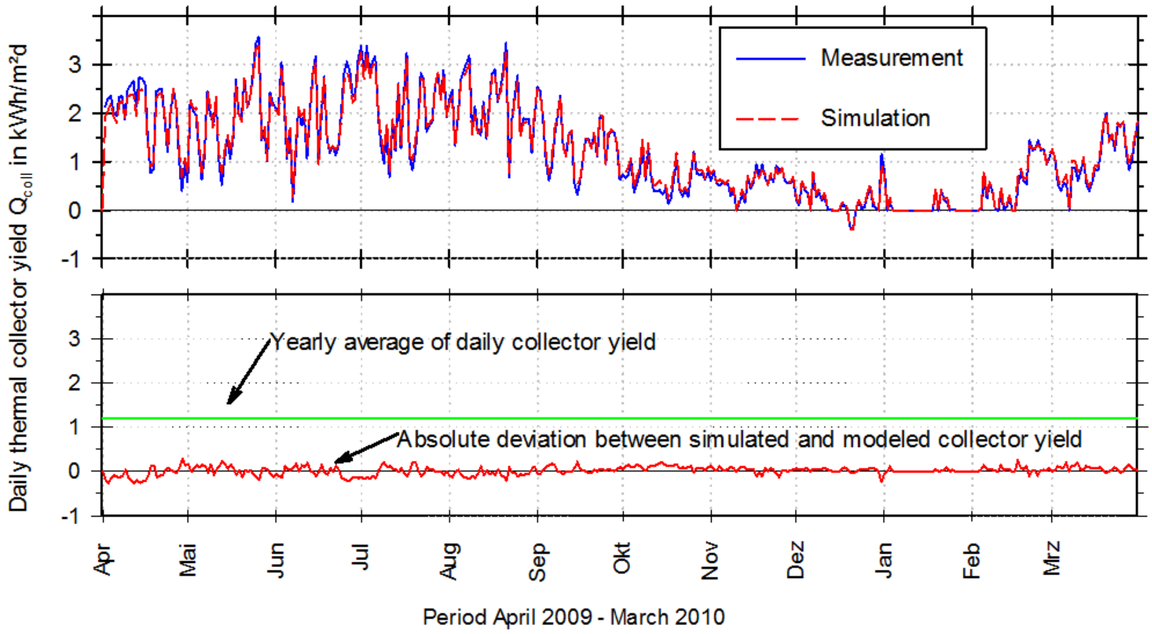

Figure 1: Daily measured and simulated collector yields for a measured solar heat pump system "Dreieich" in the course of one year. The unglazed PVT- collector supports a borehole heat exchanger. Electric yields are respected but not displayed. Measurement and simulation are conducted in 1 min time step resolution.

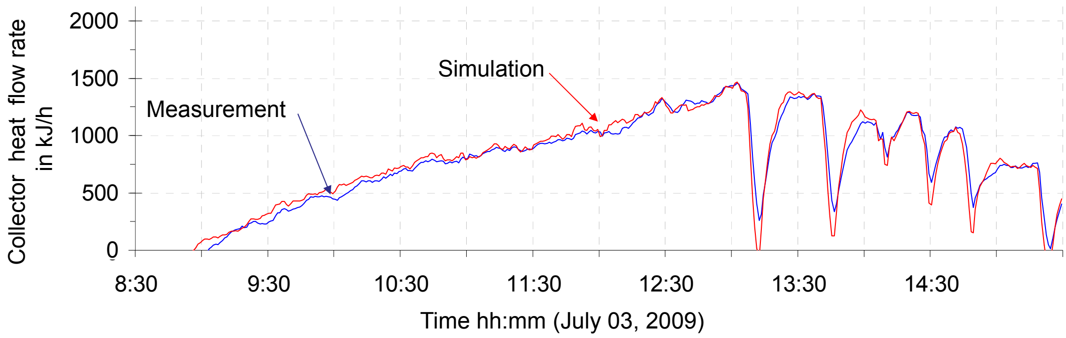

Figure 2: Measurement and simulation of the collector heat flow rate in the course of one day. The mass flow rate and the inlet temperature of the collector are held constant at 62 kg/m²h and 44°C. The solar radiation is unsteady after 13:00 due to clouds. Measurement and simulation resolution are 1 min time steps.

6.2 Condensation

6.2.1 Experiments

Several measurements with different validation methods have been conducted on condensation effects of unglazed collectors. However, the measurement of condensation heat gains on unglazed collectors is extremely difficult. The condensation heat flow rate cannot be measured directly but only as part of the total collector heat gain mixed with heat gains from radiation and convective. Besides, condensation may occur only partly on the surface or the condensed water might even just evaporate after the absorber reaches higher temperatures.

First outdoor measurements of this condensation effect within the context of thermal performances of unglazed collectors have been made by Pitz-Paal (1988) and Soltau (1989). Depending on the operation point, values from 0 to 15 W/m² have been calculated for the condensation effect. The measurement uncertainty is significant. The total average quadratic measurement deviation lies between 4.5 and 8.5 W/m².

Related works validating the developed model have been conducted in (Eisenmann et al. 2006; Bertram et al. 2008) with metal roof collectors. Here indoor measurements in a small wind tunnel without solar radiation confirmed the model of Pitz-Paal. The calculated deviations between model and measurement are less than 20%. However higher deviations (up to 100%) are measured for very small temperature differences between absorber and ambient air temperature.

Perers (2011) validated the model with outdoor measurement for the quasi-dynamic collector model. An unglazed collector is measured under dynamic conditions over several days with constant inlet temperatures. The applied collector performance parameters have been derived from accompanying measurement from the identical test rig. The model reproduces with excellent accuracy the collector heat gains against with and without condensation and was integrated to TRNSYS type 136 (132 in TRNSYS 15) and an IDA ICE model which showed almost identical results for the collector performance and the condensation effect. The given statistical data shows excellent model accuracy for the collector parameters. The comparison between measurements and simulation revealed R = 0.99.

6.2.2 Condensation impact on systems

Accompanying to the model validation some studies and estimations were made to evaluate the significance of condensation in the course of a year or under the aspect of its influence on the system performance.

In Germany, estimated annual condensation heat gains are less than 10% (Pitz-Paal 1988, p.62) whereas first measurements revealed a much smaller fraction of condensation. Measurements on a single family dwelling in Limburg (DE), the condensation yield was determined to be 3.7% of the annual collector yield which corresponds to 19 kWh/(a m²) (Bertram et al. 2010). Thereby, condensation shows a significant dependency on the season. During the summer months, only 0.8% of the total collector yield is induced by condensation, while in winter this value is increased to 13%. The applied method for the determination of condensation under real operation conditions is to validate a model including condensation against the collector in the system. With this validated model and the measured data (long-wave radiation, humidity, ambient air temperature and collector inlet temperature etc.) the fraction of the condensation yield can be determined for real operating conditions.

In connection with the work of the collector modelling Perers investigates the influence on systems by the described method of constant inlet temperature. For Swedish climate, a fraction of 10 to 25% of the collector heat gains have been stated depending on the operating temperature, with a tendency to a higher yield increase in humid climates (Perers 2006).

A TRNSYS simulation study (Bertram et al. 2010) revealed a negligible influence on the seasonal performance factor. Here, the maximum calculated difference in the SPF is calculated to be 0.015 or correspondingly about 0.35% of the electricity consumption. But, in the investigated case the unglazed collector is an additional heat source to a ground heat exchanger. Higher influence can be expected for systems having unglazed collectors as heat source only and for other climates.

Further results on condensation and night-time operation are expected from measurements of a 50 m² unglazed collector field in Bishkek (Kyrgyzstan). The collector supports a combined heat and power plant with a so-called open district heating net. The refilled water of the open district heating net is heated to the supply temperatures using fossil fuels. This refill water has a constant temperature of approx. 12°C and is preheated by unglazed collectors. In this application the unglazed collectors is often operated below the ambient temperature and at night without any solar radiation. The collector performance and all relevant meteorological data were measured that allows the detailed investigation on condensation.

6.3 Experimental validation in IEA SHC Task 44 / HPP Annex 38

Two TRNSYS simulation models Type 136 (Perers 2010) and Type 202 (Bertram et al. 2010) have been tested by Citherlet (2012) for different real weather conditions in Yverdon-les-Bains (CH). The results were then compared to the field measurements of unglazed collectors. For daytime tests, both models show good agreement with measurements (within 5%), see Figure 3. Time resolution of the measurements is 10 seconds and for simulations a time step of 30 seconds was chosen.

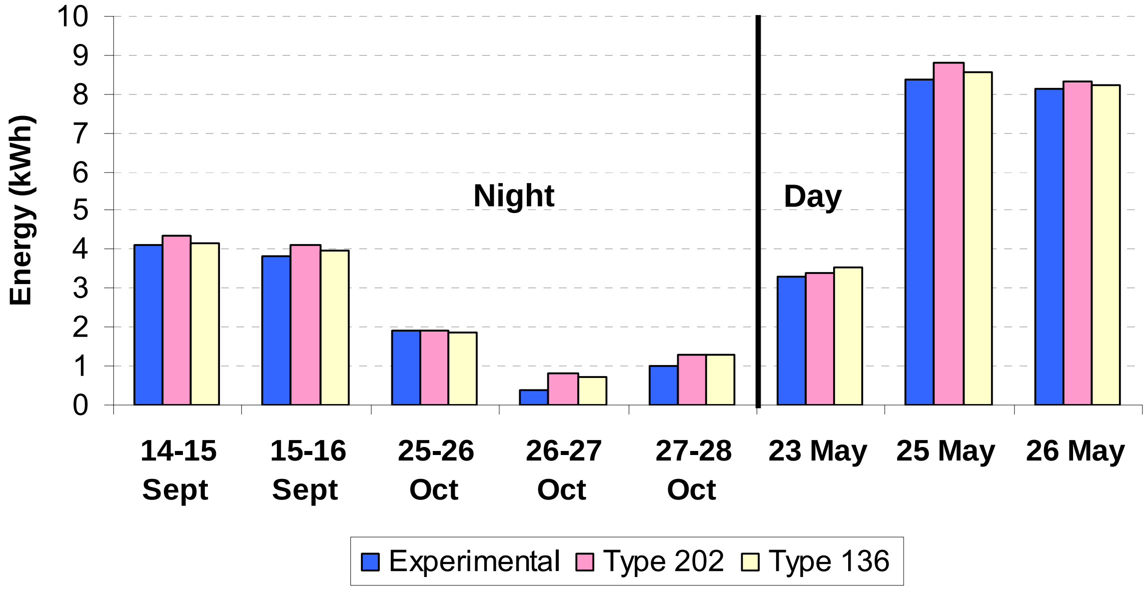

Figure 3: Energy obtained with the standard unglazed collector for different days or nights

Field measurements show that important heat gains are also obtained with no solar irradiation, see Figure 4. Even for these particular conditions, the models are quite close to the measurements; see for example the first three nights on Figure 3. Discrepancies arise for nights where the ambient temperature was close to the collector's temperature and important relative differences (up to 100%) were detected; see last couple of nights on Figure 3. These discrepancies happen mostly because of changes of emissivity when condensation occurs, as in this case the main energy transfer mechanism is long-wave radiation. Nevertheless, this corresponds to low absolute energy differences.

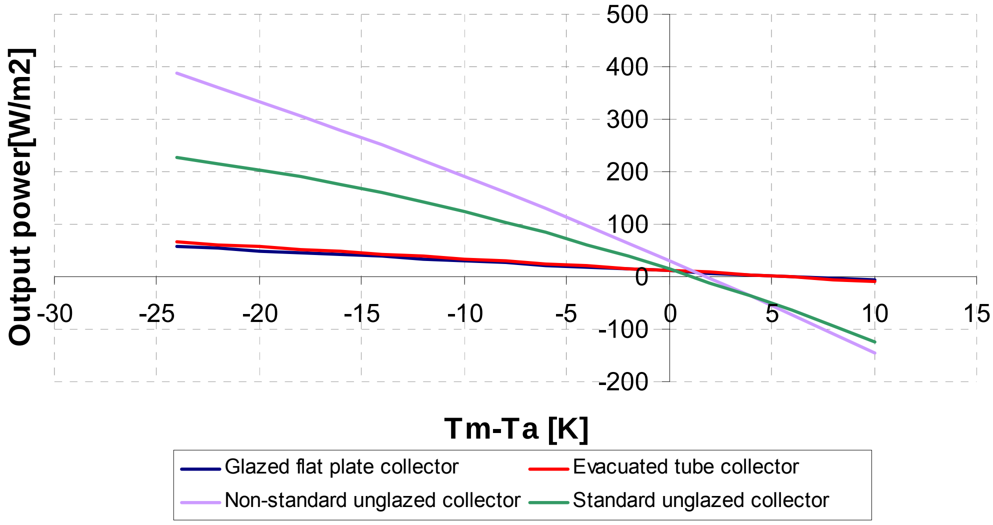

Figure 4: Measurement of the collectors' power for zero solar irradiation

Table 1: Performance characteristics of solar thermal collectors tested in Yverdon-les-Bains

Collector design		**Flat plate**	**Evacuated tube**	**Unglazed standard**	**Unglazed non-standard***
η_0	-	0.791	0.821	0.959	0.959
a_1	W/m^2K	3.104	2.824	8.91	12**
a_2	W/m^2K^2	0.022	0.0047	0.047	-
Gross area	m^2	2.53	3.51	1.87	1.87
Absorber area	m^2	2.23	2.0	1.85	1.85

* *Solar unglazed collector with no rear insulation*
** *Estimated value*

Because of the good agreement obtained for the whole test by the two simulation models under any conditions, the precision of the output power of each model was further investigated by integrating the absolute value of the power difference of collector's output between the models and the measurements. Results shown in Figure 5 provide a measure of the accuracy of the models' behaviour.

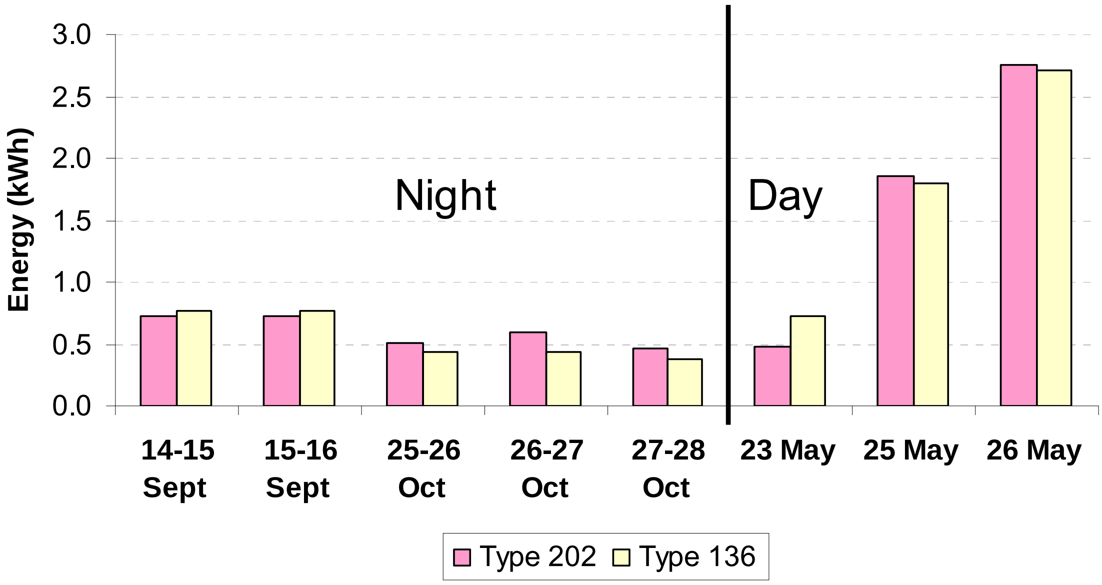

Figure 5: Comparison of the integrated difference between the output power of the TRNSYS models and the measurements

The differences are less important in Figure 3 because they only show the difference at the end of the test as the values in Figure 5 take into account all differences during the test whether they are positive or negative using their absolute values.

The two simulation models provide relatively good daily results when compared to the measurements. However, more simulations should been done for longer periods to be able to estimate the annual incertitude of these models. They also do not take into account frost or rain heat gains.

Citherlet et al.(2012) have also conducted some preliminary tests with frosting occurring at the surface of the absorber. First results over a 24 hours test in December showed that heat gains of 6.3 kWh/m^2 can be achieved (cloudy conditions). As collectors models do not take into account frost (or condensation under these conditions), results obtained are 40% lower than measured values.

The effect of rain is also being investigated. The annual potential rain yield near Yverdon-les-Bains was estimated at around 2% or about 10 kWh/m^2. However, for an accurate representation of the thermal behaviour of the collector, the effect of the rain must also be considered. Further testing is underway to confirm and extend the validity of the first findings for both frosting and rain case studies.

In order to provide an estimation of the condensation energy flow, buckets were placed under the solar collectors in order to recover the water condensing on the surface of the absorber (Citherlet et al. 2011). The measurements were then compared with the condensation energy given by the two TRNSYS models, see Figure 4.

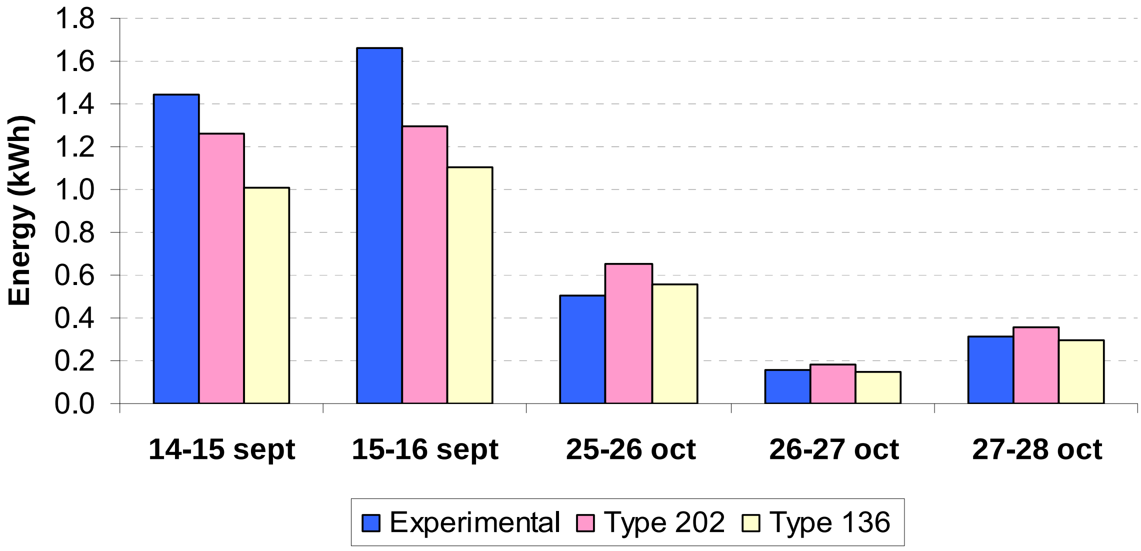

Figure 6: Condensation energy flow for different nights

For differences between the collector and the ambient temperature (first two nights in Figure 4) simulation provides less condensation energy than measured. However when the collector's temperature is close to the ambient temperature, both models agree well with the measurements.

Due to the selective change during condensation phase, tuning of the parameters related to condensation (e.g. emissivity, internal thermal heat conductivity or convective heat loss coefficient of absorber) would be of interest. Thus simulations on the condensation energy can be closer to measurements for one given condition. However, results revealed that condensation parameters are very much dependent on the operating conditions so that no general parameters could be found leading to acceptable simulation results under all investigated conditions. For this study, given the impossibility to measure condensation parameters, theoretical values from the literature were taken into account to model all weather conditions.

6.4 Hints for model application in system simulations

Unexpected difficulties arose within the IEA SHC Task 44 / HPP Annex 38 work from the implemented computer code of approved models. In the extended operation range otherwise well approved and field-tested collector models for glazed and unglazed collectors proofed to calculate obviously wrong thermal collector behavior. Up to now, all errors could be tracked down to program simplifications that are relevant only outside conventional operation and because the programming was not intended to be combined with heat pumps. In one case the program code switched the collector calculation off during night time (no radiation) to save computing time. In another case the collector without mass flow rate, no solar radiation and below ambient air temperature lead to extremely low absorber temperatures, extremely far below the ambient air temperature. Errors occurred under the following conditions or combination of those:

- No solar radiation

- Operation below ambient temperature
- Very low mass flow rates
- Long-term simulation of multiple years
- Simultaneous simulation of multiple collectors at different temperature levels

The mentioned difficulties are programming code and not model difficulties and have been fixed in most cases. Still, blind model use must be avoided and the proper functionality of the models has to be checked before the background of the particular application.

6.5 Validation summary

The starting point for the recent validations are the existing collector models, which are well validated for glazed and unglazed collectors in domestic hot water and space heating applications. The highest impact on the energy yield is expected for unglazed collectors due to condensation yields. As a matter of fact, condensation is implemented and validated with good accordance to short and long-term measurements in the last years. This includes unglazed PVT, too.

Nevertheless, there is no documented experience on icing and no model that respects changing emissivity during condensation. Due to these effects, the collector modeling especially close or below operation temperatures of 0°C includes always additional uncertainty, although the absolute impact to the collector yield is expected small.

7 Conclusion

A comprehensive collection of glazed and unglazed solar thermal collector models exists for conventional applications. These models are implemented to most of the common simulation platforms and are well applicable for simulation of solar and heat pump systems and a broad set of performance data is provided by test centres and manufacturers. However, heat pump applications can shift the operating range of collectors to lower temperatures. There is quite less experience with collectors operating under these conditions and apparently extensions or model improvements have been made and may still have to be made to include condensation effects. Therefore, in this report a special focus is laid on effects that are particular to the combination of solar collectors with heat pumps, such as condensation effects.

Three recently developed unglazed collector models are presented that include condensation effects. All three models are implemented in the system simulation environment TRNSYS and extend established collector models by including an additional condensation model. Measurements and modelling results confirm the relevance of condensation which can reach 40% of the heat flow rate of the collector under specific operating conditions.

Some first work on validation of these models was conducted that shows good accuracy for the condensation model and its implementation to the unglazed collector model. However, as part of the task work the developed models investigated are compared. Further work should include the transfer of the validation results and field experience into market near simulation environments and dimensioning tools. In other words, the models, mainly applied in scientific context, should be transferred, where necessary, to commonly used simulation tools and dimensioning methods. Consequently, further work should be done on the question for which climate and system solution condensation is to be considered.

Overall, condensation on unglazed collectors in heat pump systems is expected to add a significant part of the collector yield and should therefore be considered. Nonetheless, it has not been shown for any case that condensation necessarily lead to a significantly changed thermal behaviour of the system. In this context more general information about the impact of condensation and convective operation (without radiation) is required. This is most relevant for heat pump systems having unglazed collector as heat source only and in warmer and/or wet climates.

However for covered collectors, special attention has to be made to condensation since most collectors are not constructed to cope with condensing effects and may face deterioration of the selective surface, soaking of the insulation or other damages. If a covered collector is used for operating conditions below the dew point, then it has to be constructed hermetically tight or special attention has to be paid when selecting the absorber coating, insulation, other materials and the construction itself in order to obtain a product that can deal with condensation without being deteriorated.

8 Symbols

A	Area in m²
a_1,a_2	Loss coefficients for stationary glazed collector model, $Wm^{-2}K^{-1}$, $Wm^{-2}K^{-2}$
b_1,b_2,b_u	Loss coefficients for stationary unglazed collector model, $Wm^{-2}K^{-1}$,$Jm^{-3}K^{-1}$,sm^{-1}
c_{1-6}	Parameter coefficients for quasi-dynamic collector model
c_{eff}	Area specific effective heat capacity of the collector in $J\ m^{-2}\ K^{-1}$
G_b	Solar beam irradiance in collector plane in $W\ m^{-2}$
G_d	Solar diffuse irradiance in collector plane in $W\ m^{-2}$
G,G^*	Global or total irradiance in horizontal plane in $W\ m^{-2}$
G''	Net irradiance in collector plane in in $W\ m^{-2}$
G_L	Long wave radiation (incident from sky + ambient) in the collector plane in $W\ m^{-2}$ with wavelength > 3µm
$k_{\theta,b}$ (Θ)	Incidence angle modifier for solar beam radiation
$k_{\theta,d}$	Incidence angle modifier for solar diffuse radiation
$\dot{Q}$	Heat flow rate in W
$\dot{q}$	Specific heat flow rate in $W\ m^{-2}$
T	Absolute temperature in K
ΔT	Temperature difference between average fluid and ambient temperature in K
T_a	Ambient air temperature in K
u	Wind speed above the collector in $m\ s^{-1}$
η	Collector efficiency in –
$\eta_{o,b}$	Zero-loss collector efficiency for beam irradiance at normal incidence
σ	Stefan-Boltzmann constant ($5.67 * 10^{-8}\ W\ m^{-2}\ K^{-4}$)
Θ	Incident angle of beam radiation to the collector
$\frac{dt_m}{dt}$	Time-derivative of the average fluid temperature of the collector in K/s
τ	time in s

Subscripts

gain	Heat gain of the collector
coll	Collector
rad,S	Absorbed short wave radiation with wavelengths < 3µm
rad,L	Long wave radiation exchange with wavelengths > 3µm
air,cond	Heat exchange from condensation or evaporation of water vapour
air,lat	Latent heat exchange
air,sens	Sensible heat exchange with the ambient air

air,frost	Heat exchange from frost formation or melting on the absorber
k	Conductive heat exchange
rain	Heat exchange from rain
use	Usable heat output (of the collector)
m	Average
a	Ambient

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Appendix A – Working group collector modelling

Working group members collector modelling of the IEA SHC Task 44 / HPP Annex 38:

Table 1 – Working group members of collector model group in Task 44.

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* Working group leader

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to Matteo D’Antoni D'Antoni Matteo (matteo.dantoni@eurac.edu) from EURAC research center (Italy) for providing information on massive absorbers

to Jorge Facão Jorge Facao (jorge.facao@lneg.pt) and Maria João Carvalho from LNEG (Portugal) for providing information on collector models used for direct evaporation.

Appendix B – Collection of collector models for dynamic system simulation

Collector models table

Name/ID	Platform(s)	Type of collector				Type of model	IAM				heat exchange			capacities	comments	documentation / validation reference
		ETC	FPC	UC	AIR		b0/b1	R	biax	table	wind	cond	IR			
TRN Type 1	TRNSYS	-	√	-	-	g	√	-	√	√	-	-	-		tau-alpha also physically	D: SEL 2006
TRN Type 71	TRNSYS	√	-	-	-	g	-	-	√	√	-	-	-	-		D: SEL 2006
TRN Type 72	TRNSYS	√	√	-	-	b	√	-	√	√	√	-	-	-	tau-alpha also physically	D: SEL 2006
TRN Type 73	TRNSYS	-	√	-	-	w	-	-	-	-	√	-	-	-		D: SEL 2006
TRN Type 132	TRNSYS 15	√	√	√	-	g	√	-	√	√	√	-	√	1 x 2		D: Perers & Bales 2002
TRN Type 136	TRNSYS	√	√	√	-	g	√		√	√	√	√	√	1 x 1	based on Type 132	D/V: Perers 2010, Perers & Bales 2002
TRN Type 202/203	TRNSYS	-	-	√	-	g			√	√	√	√	√	N x 1	Unglazed coll. or PVT	D/V: Eisenmann et al. 2006; Bertram et al. 2010
TRN Type 222	TRNSYS 15	-	-	√	-	w	√	-	-	-	√	√	√	1 x 1	including rear-side losses	D: Frank & Vajen 2006; Frank 2007
TRN Type 301	TRNSYS	√	√	-	-	g	√	√	√	√	√	-	√	N x 1		D: Isakson & Erikson 1994
TRN Type 303	TRNSYS	-	-	√	-	g	√	-	-	-	√	-	√	1 x 1		D: Hornberger N/A
TRN Type 561	TRNSYS	-	-	√	√	w	√	-	-	-	√	-	√	No info.		D: TESS 2006
TRN Type 832 v5.00	TRNSYS	√	√	√	-	g	√	√	√	√	√	√	√	N x 1 N= 1-100	based on Type 132	D: Perers & Bales 2002; Haller et al. 2009
RDmes grey	RDmes	-	√	-	-	g	√				-	-	√	1 x 1		Carbonell et.al. 2012
RDmes white1	RDmes	-	√	-	-	w	√				√	-	√	N x 1	IAM from optical properties	Carbonell et.al. 2012
RDmes white2	RDmes	-	√	-	-	w	√				√	-	√	1 x N		Cadafalch 2009
Matlab_Carnot	Matlab/Carnot	-	√	-	-	w	No information available							10 x 1		D: Isakson & Erikson 1994
T-Sol	T-Sol	-	√	-	√	g	No information available									D: T Sol user manual
Polysun	Polysun	√	√	√[a)]	-	g	√	-	√	√	√	-	√	1x1	Standards: USA, EU, China	D: Polysun user manual & collector test standards

[a)] *Collector performance coefficients can be changed for absorber temperatures below the air temperature.*

Explanations

Name/ID	*distinguishes the model from others. Not a platform name, but platform may be part of the name such as is the case for the TRNSYS model names starting with "TRN" or the models of "RDmes".*
Platforms	*Simulation platforms the model is available for. The same mathematical model may be implemented for different platforms*
Type of collector	*ETC = evacuated tube collector; FPC = flat plate collector; UC = uncovered collector; AIR = air collector.*
Type of model	*w = white box (physical); g = grey box (semi-empirical, empirical correlations with physical background); b = black box, e.g. efficiency map read from a table*
IAM	*Incident Angle Modifier approaches: b0/b1 = first or second-order IAM ASHRAE / (Duffie & Beckman 2006, p. 298);; r = Ambrosetti-r (Ambrosetti & Keller 1985); biax = also biaxial IAM calculation possible; table: IAM can be read in from a performance map table / data file.*
heat exchange	*effects on the heat exchange considered: wind = effect of wind speed; cond = condensation when operated below dew point; IR = infrared radiation balance Beam and diffuse radiation is considered for all models.*
capacities	*number of heat capacity nodes along the fluid path times number of heat capacities from fluid to ambient temperature. E.g., 10 x 2 means that 10 nodes along the fluid path are considered and two nodes (e.g. fluid and absorber capacity and temperature) from fluid to ambient temperature. N = variable number of nodes.*

documentation/validation reference: D = documentation only; V = validation. For validation results, original literature that is cited should be consulted.

Abbrevations

ASHRAE	*- American Society of Heating, Refrigerating and Air-Conditioning Engineers*
RDmes	*- RDmes Technology S.L. Online Software engineering*
SERC	*- Solar Energy Research Center, Sweden*
SP	*- Swedish National Testing and Research Institute*

Literature related to the collector model collection

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Appendix C – Collector performance data

Collections of collector performance data could be found in addition to data provided by manufacturers under the following addresses:

Glazed Collectors

- ITW Institut für Thermodynamik und Wärmetechnik (Germany)
  http://www.itw.uni-stuttgart.de/abteilungen/tzs/PDF-Pruefberichte/
- SPF Institut für Solartechnik (Switzerland)
  http://www.solarenergy.ch/Kollektoren.111.0.html
- Solar keymark database (Europe)
  http://www.estif.org/solarkeymark/regcol.php

Unglazed Collectors

- ist- Energieplan and ISFH - Instiut für Solarenergieforschung Hameln (Germany)
  http://www.ist-energieplan.de/3_Aktuelles/buchbestellung.php