EXPERIENCES AND LESSONS LEARNED FROM 30 YEARS OF DYNAMIC COLLECTOR TESTING, MODELLING AND SIMULATION

Bengt Perers[1], Peter Kovacs[2], Ulrik Pettersson[2]

[1]SERC Dalarna University Borlänge Sweden and Department of Civil Engineering, Technical University of Denmark.

[2]SP Technical Research Institute of Sweden, Borås Sweden.

Abstract

Dynamic testing and modeling (in contrast to Steady State line of action) of solar collectors is to prefer in most climates, except for the most extreme locations with clear skies every day. A very important part of dynamic testing and modeling is not only the thermal capacitance correction, but also the split of the solar radiation absorption modeling, into beam and diffuse and the modeling of the collectors' incidence angle dependency for both beam and diffuse radiation. These optical features are in most situations more important than the accuracy of the dynamic and thermal loss part of the model. This can be seen from the statistical analyze when evaluating test data. The t-ratios i.e. the parameter values divided by their standard deviations, are generally much higher (often 10 times higher) for the optical parameters than for the thermal loss ones. There are also important details concerning solar radiation measurements for beam and diffuse including alignment of sensors and test object, that are often not considered, which will be discussed and lessons learned will be given. A misalignment of just a few degrees of the collector test stand or the solar sensors will immediately show up in a dynamic test evaluation, especially when analyzing the incidence angle modifier behavior and thermal capacitance of a collector.

To achieve good results in dynamic testing it is essential to understand the basic concepts of the method and to use this understanding when designing a test rig and collecting data during a test for later analyze. It is very desirable to use a continuous parameter feedback during the test, so that the test conditions can be changed hour by hour to derive more accurate results and shorten the testing time. Such advice will be discussed in the paper. Some of these findings has not yet reached the EN12975 standard level, and suggestions for revisions and improvements will be presented that have general application also for non standardized testing, for example research and development testing.

1. Introduction

This work presented here with dynamic testing, modeling and evaluation was started at Studsvik in Sweden in a pilot plant project for solar seasonal storage systems in 1979 (Rosén and Perers, 1980 and 1983). There was a need to accurately test and model the components and system to be able to further develop the concept into full scale. One of the tools was online simulation of all major components including the office building and comparison to measured results. In this attempt it was found that quite simple first or second order models could be applied with reasonable accuracy for this purpose. Especially the collector model was developed quite far already at this time as the plant was heated with medium concentrating CPC collectors that required that the optical modeling was up to date even of today's requirements. Also a one node capacitance correction term was applied and it was found that this could improve the model quite satisfactory for all day evaluation of the performance. An annual performance calculation software was also programmed based on this collector model to evaluate new CPC (Compound Parabolic Collector) collector designs in comparison to other collectors. (Perers, 1980). This collector model was later used and further developed in the Minsun software for optimization of seasonal storage systems within IEA SH&C Task VII (Chant and Håkansson, 1985). The construction, first year monitoring and evaluation experiences for the project was also presented at ISES in Perth 1983. (Perers 1983).

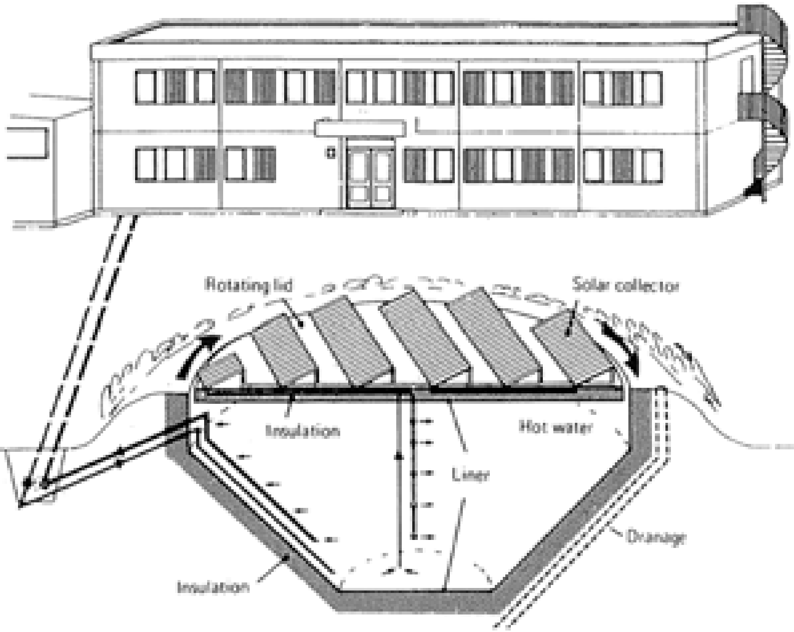

Fig. 1: The solar seasonal storage system at Studsvik Sweden built in 1979 that was heating the low energy office building behind. On line dynamic modeling and evaluation was tested here to understand the components and system better.

At the ISES 2009 conference there were several papers showing that the concept of dynamic testing in the EN 12975 standard in the form of the QDT method was failing or not giving satisfactory results. This was partly due to that the method was not correctly applied or fully understood. One example is the very important control of the test conditions so that the optical and thermal loss parts of the collector equation can be separated accurately in the evaluation step. If the inlet temperature is not varied enough and uncorrelated to the solar radiation, no method can accurately distinguish optical, from thermal loss parameters. This is the general reason why field test data often give unsure or even wrong parameter results as the inlet temperature variations are very much limited by the system and often also correlated to the solar radiation. There are charts proposed in the standard that should be used to verify that there is enough and independent variation in different input variables. Especially important is as mentioned above that the collector inlet temperature is varied enough and in an uncorrelated way against the solar radiation in the collector plane.

Figure 2 is an attempt to illustrate this. The performance of a collector is in the first order characterized by a plane in the figure. A stationary test just works in a small part of the plane at high irradiation conditions except for the incidence angle test. A dynamic test can use points all over the plane and the coefficient can be very well determined if the spread of points is out to all the corners. Perhaps one even can recommend to prioritize test points close to the corners. The stationary test just spans a small part of the surface. The there are second order model terms that also need variation in the test conditions that are important achieve too.

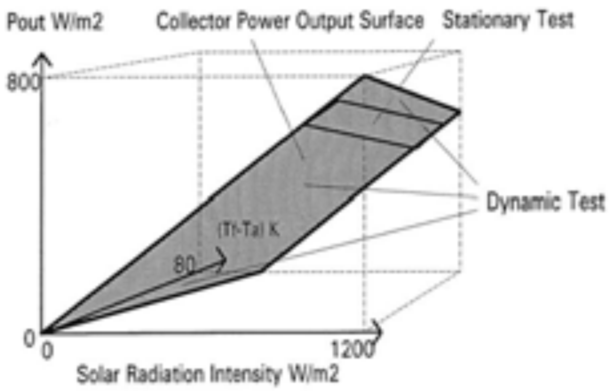

Fig. 2: The power output plane for a solar collector illustrating the importance of having systematic variation in both solar radiation and inlet temperature (Tf-Tamb) to determine the "power" plane.

The QDT method is a compromise between complexity, accuracy and cost of a test, so of course there can be better solutions if time and money is available for test and evaluation. The QDT method as described in the standard is also very much limited by the old requirement to derive also stationary (SS) test data during the same test sequence, for backwards compatibility. If leaving this requirement for backwards compatibility the QDT method can be further improved and more accurate parameter values can be derived.

It is also important to understand that the concept of dynamic testing in the QDT method is directly connected to simulation, if the same model and parameters are used in the simulation tool. The evaluation of a test performed with the QDT method can be seen as the opposite of simulation. The parameters derived from a QDT test give practically zero error for the total energy output of the collector during the test period. The collector parameters are determined for minimum error in *power output* and not in efficiency as in the SS method. If the test conditions are variable and representative enough, the simulation model is then validated at the same time in every collector test, for the specific collector type. This is not generally understood but a basic principle of the QDT method (Perers, 1995). This principle is now implemented in the new calculation tool developed in the QAIST project that will be presented separately at this conference (Perers et. al, 2011). Figure 2 illustrates this chain of methods and tools where the testing is one important part.

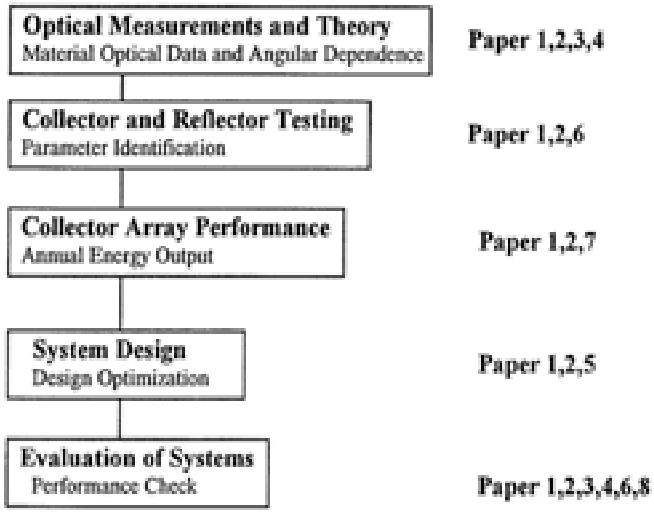

Fig. 3: The chain of tools where collector testing and the model an parameters are very well integrated in the chain if a dynamic test is applied. The paper numbers are from The Phd (Perers, 1995)

In connection to the development of this annual calculation tool it was also identified the need to correct stationary (SS) test data concerning zero loss efficiency, as this parameter in an (SS) test evaluation will be dependent on the diffuse fraction during the stationary test points. This correction is avoided in a dynamic test. This error has until now been neglected and not even understood. In a separate paper (Kovacs, 2011) this is described and quantified and a correction method is shown. This correction method is now part of the standardized annual calculation tool in Excel.

The application of night time data for determination of heat loss parameters will also be discussed. This may shorten the testing time dramatically if the collector model and method is designed for this. In a separate paper at this conference it is described how testing and modeling of an unglazed collector operating below the dew point, can give accurate results using such a test procedure.

This paper will explain the essentials of QDT testing and present experiences gained during the last decades of research and international cooperation in this field. From this platform dynamic testing and simulation can be further developed in the application for standardized testing but also as a powerful tool in research and product development. Also stationary collector testing may gain from some of these experiences.

This paper is focusing on liquid heating collectors and outdoor testing, but some parts are also applicable to air collectors and solar simulator testing.

2. Checklist for improved dynamic collector testing

Careful design of the test rig:
-Stable pressurization of the loop to avoid under-pressure anywhere in the loop and suck air into the fluid.
-Durable and rigid piping materials and components that will not leak or cause sudden flow restrictions.
-No air in the test loop. This can be avoided by deaeration devices in the loop and proper mounting and maintenance of the expansion vessel. A sight glass close to the inlet to the collector is a good tool to detect air and also particles and fluid deterioration in the test loop. Note that cold water contains a significant amount of air that will be released when the fluid is heated the first hours. This air has to be removed too.
-Flow and temperature sensors should be located in rising flow to avoid air at these points.
- There should be a filter in the loop and regular checks should be done so that the fluid is clean and not degraded or mixed with residues of other fluids. Some flow meters are affected by degraded fluids.
-Water is the best fluid for accuracy as the thermal properties are very well known. But the influence of changes of the fluid properties on the collector performance can't be completely neglected. The performance is often slightly lower for glycol/water than pure water. But it also depends on the flow rate and absorber design.
-Enough straight pipe length should be present before and after the flow meter.
-Fluid temperature sensors in mixing flow after a bend or a special mixing insert.
-Good thermal insulation between collector and temperature sensors in and out of the collector and around the sensor location.
-Temperature sensors well inserted into and directed against the flow and same arrangement for in an outlet temperature.
-The ambient temperature sensor radiation shielding and location is more important than generally thought. A location in the shade behind the collector can be quite a good compromise as a first order arrangement. A forced ventilated and shaded ambient sensor is the best option but needs attention too, as small animals like spiders may clog the inlet of air after some time.
-The diffuse radiation measurements with normal shading ring needs attention too, even if it looks like a simple device. During dynamic testing the shading ring has to be perfectly "in operation" all day and shading the whole glass dome and not only the detector surface. Even a small misalignment of the diffuse sensor in tilt or azimuth or misalignment of the two rods holding the shading ring may give shading only a part of the day and then strange intermediate diffuse values the rest of the day. This destroys the accuracy of the evaluation. It has also happened that the diffuse sensor is wrongly assembled and gives strange errors due to wrong geometry.
-Possibilities to check and calibrate sensors during measurements by double mounting arrangements is very efficient to allow more testing time.
-Rigid fixtures in metal for solar sensors, carefully aligned parallel to the collector. Never use wood here, that easily bend, when the moisture content changes after some time! Even small misalignments hardly seen can cause large errors at higher incidence angles se fig. 4.

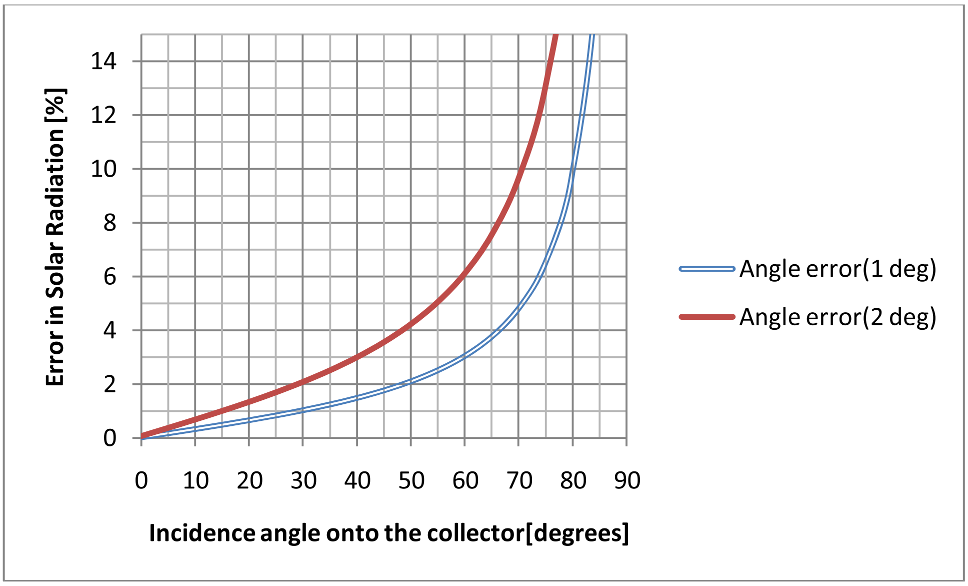

Fig. 4. Error due to a small misalignment of a solar sensor away from the collector plane (Perers 1993)

-Check that the test stand is due south. Also tracker azimuth calibration. The polar star is very close to north as a double check.

-No shading of collector or solar sensors during a testing day. Even thin shadows from a flag pole, Street lamp or wind mast will cause strange and wrong results.
-A parallel test rig design with two or more similar collectors in operation is very powerful when looking for small improvements on a collector. One collector can be kept unchanged as a reference all the time.

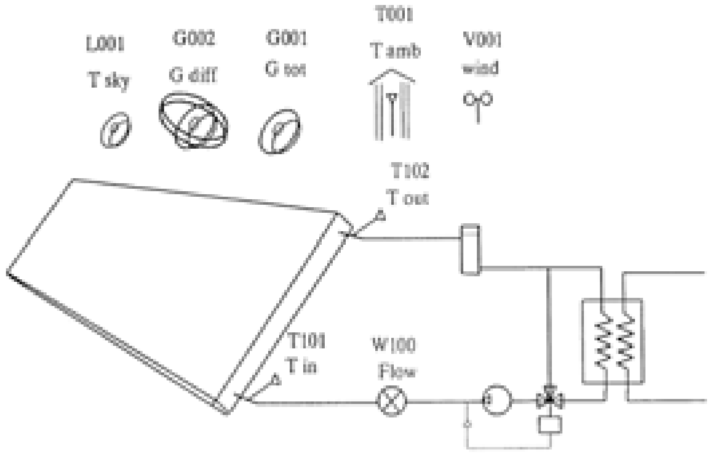

Fig. 4: A simplified sketch of a test rig layout with sensors and temperature control. Note also the deairation device after the collector that is also working as an expansion vessel. Many variants are possible.

Measurement equipment:
-Dataloggers have to be of high class as both thermocouples and the most accurate thermopile solar sensors have very low output signals in the mV or even uV range. The common mode rating is very important too. Double ended inputs are recommended. Avoid loggers with common grounding of minus.
-Mechanical multiplexers should be avoided. After some years the contacts can cause irregular measurement errors.
-Shielding of cables and grounding of the shield only in one end is very important. A cable shield should be grounded preferably at the data logger. Measurement cables and AC cables should be separated.
-Cable connections should be protected from water and made of corrosion resistant materials.
-If PT100 sensors are used for temperature measurements, four wire connections/cabling should be used so that the cable length will not influence the accuracy.

Check during testing:
-Check and clean the glass domes of the solar sensors preferably each day. Sometimes birds can find it pleasant to sit on or close to these sensors and shade and may give bird droppings that of course is destroying the measurements accuracy totally.
-Check that there is no condensation inside the solar sensor glass domes. Dry the glass surfaces and change or dry the desiccant if condensation will occur.
-Check and clean also the collector glazing at start of the test and when necessary.
-Check for fluid leaks (pressure meter readings and visual inspection of condense in the collector. Condensation can be caused by micro absorber leaks.)
-Check for small rain leaks in the collector glazing frame and edges (It is not meaningful to test and evaluate a collector accurately with condensation inside.)
-Check incoming data every working day.
-Check of time in the data file/logger especially if several loggers are used. Use wintertime.
-A preliminary collector model calculation of expected collector output (online simulation) is a very powerful tool to find problems with measurements, test rig and test object during testing.
-Perhaps the most important “on line” check is that the inlet temperature has been varied enough and independently in relation to the solar radiation. A plot of (Tf -Ta) versus Gtot is very useful to see if this requirement is fulfilled. There should be points all over this diagram and especially in the “corners” if the test has enough data.
- Online simulation is very effective to find out problems early in new collector designs that otherwise will lead to a lot of unnecessary testing time. This can be heat pipes with wrong pressure or too little fluid, or micro leaks in the absorber or rain leaks into the collector as a few examples.

Check between tests
-Calibration of all sensors at regular intervals as recommended by the manufacturer or according to the standard.

-Check that Tin- Tout shows close to zero and save the residual value for later correction, when short circuiting the collector connections with flow in the test loop. Preferably run at elevated temperatures too.
-Check for condensation in solar sensors and change the desiccant inside at regular intervals or if needed.
-Check the gas pre-pressure in expansion vessels of closed loop type and assure that they are mounted with the fluid connection upwards to avoid air being trapped on the fluid side of the membrane.

Test sequence design:
This is perhaps one of the most important possibilities to improve accuracy and at the same time shorten a standard collector test. By varying the inlet temperature in a systematic way during the day, much more information can be gained from the test data and collector, than keeping the temperature constant all day.

There is also a potential for use of night time measurements, of the heat losses but there are theoretical problems due to the reversed heat flow direction in the absorber that need to be solved to achieve the best accuracy. Some collectors like heat pipe designs can't use this possibility. For many collector designs the inaccuracy is limited and night measurements can be very helpful to assure the accuracy of the parameters when unexpected daytime results occur.

Tools for data evaluation and calculation of annual collector performance:
When enough test data have been collected, a lot of small steps remain before it is possible to identifying the collector parameters in an accurate way. Incidence angles onto the collector have to be calculated accurately. Up to date asymmetrical biaxial incidence angle formulas are given in (Perers 2011). Data has to be scaled to standard units and pre-calculated according to the collector model. The collector aperture area has to be measured accurately according to the standard and used in the evaluation, as it affects all parameter values. Data has to be checked and strange data has to be deselected. Averages of 5 to 10 minutes have to be created. After that comes the parameter identification that can be done with MLR (Multiple Linear Regression) but also other tools. Here is though important the statistical method will minimize the error in ***collector output power*** and not outlet temperature or efficiency that is common alternatives. Then the parameters will be optimized for the wrong output quantity for the later use in simulation and annual performance calculation. The difference may seem academic but it introduces and unnecessary uncertainty in the parameter values. The model that is validated is also rewritten in another form than later used in simulation and annual performance calculations, so the direct model plus parameter validation step and connection is lost.

These evaluation steps can preferably be done in Excel. But other tools can also be used. In a separate paper a first version of a tool developed in the open source statistical software R is described (Bacher and Perers 2011). The goal of this tool is to cover the whole evaluation chain and derive the results starting from raw data in one single run, but of course with intermediate user checks on the way. *This R tool also gives good documentation of all the steps taken in a "run" - text file*

After the parameters have been determined it is very desirable to also be able to give a standardized annual energy output for the collector. A new Excel tool is now available for this purpose (Perers 2011) that has been developed within a European cooperation project QAIST, in a work package lead by SP in Sweden. A detailed description of this tool is given in the paper mentioned.

System simulation:
The parameters and model from the EN12975 - QDT method can now also be accurately used in system simulation with for example TRNSYS.

A TRNSYS Type 832 is available from the IEA SH&C Task 26 and 32 work, that can take the parameters directly from a test and with exactly the same model as during the evaluation of the test to simulate the collector performance very accurately in a system.

The collector array part UMSORT of the Minsun software (Chant and Håkansson 1985) has also been kept alive and updated for this purpose for accurate research and development calculations.

A TRNSYS Type 136 very close to Type 832 but including also condensation effects for extreme low temperature operation together with heat pumps, is available for research use. This model was recently validated directly against test data using test parameters for a longer period (Perers et. al. 2011. This kind of validation is a further step to assure am accurate connection between testing and system simulation.

3. Discussion and Conclusions

When applying dynamic testing, it is very important to have all links in shape: Test rig, test rig control, measurement equipment, test object not to forget and finally the analysis tool. After these steps a standardized calculation of collector annual performance can be done with a new Excel tool (Perers, 2011) using exactly the same model and parameters but standardized climate data for the location choosen.

The perhaps most forgotten part of dynamic testing is the strategy for test rig control of the inlet temperature. The inlet temperature has to be varied a lot and uncorrelated to the solar radiation in opposite to stationary testing, where a stable inlet temperature is very important for accurate results. Here the EN 12975 standard can be improved for the QDT testing by easing the requirement for backwards compatibility.

The most forgotten sensors are often the solar ones. They are extremely important for the accuracy of the test results, not only concerning calibration, but also mounting, alignment and maintenance like cleaning and check of condensation inside.

No test is fully automatic. A good test requires experienced persons that check the test and data regularly and take action immediately when something is wrong, preferably every working day. Efficient display of the ongoing measurements is very helpful here. Also remote connection should be available from the office.

On line simulation in the measurement system of the expected collector output and comparison to the measured, continuously during test, can help a lot to give early warnings if something is wrong with sensors, wires, test rig or test object.

In the future more advanced statistical model and parameter analysis tools may be applied (Bacher et. al, 2011). Then it may be possible to use almost instantaneous measurements like 2 second data to use the full dynamic information of a solar collector test and gain very much information every testing hour. This may shorten the testing time dramatically and also give a deeper understanding of the performance of different collector designs.

4. Acknowledgements

This paper is based on a very long experience from national and international cooperation in this field. The IEA participation within IEA SH&C tast III, VI, 14 and 26 has been very important to continously add to this knowledge and get more reliable collector tests. The implementation into the EN 12975 standard as the QDT method has been done very much by SP in Sweden and ITW in Stuttgart during a long period.

5. References

Bacher, P. and Perers, B. (2011). Open source software for MLR modeling of solar collectors. ISES, Kassel. (this conference)

Bacher, P, Madsen, H, Perers, B. (2011) Models for the heat dynamics of solar collectors for performance testing. ISES Kassel (this conference)

CEN, European committee for standardization. (2006) *"EN 12975-2:2006, Thermal solar systems and components - Collectors - Part 2: Test methods"*

Chant, V.G., Håkansson, R. (1985). The Minsun optimisation program. Application and users guide. IEA SH&C Task VII, Ottawa September 1985.

Duffie,J.A. and Beckman W.A. (2006) Solar Engineering of Thermal Processes.

Fischer S., Heidemann W., Müller-Steinhagen H., Perers B., Bergquist P., Hellström B. (2004). Collector test method under quasi dynamic conditions according to the European Standard EN 12975-2. Solar Energy. Vol 76 pp 117-123

McIntire, W.R. and K.A. Reed, (1983) Orientational relationships for optically non-symmetric solar collectors. Solar Energy, 1983. **31**(4): p. 405-410.

P. Kovacs, B. Perers, U. Pettersson, (2011). Improving the compatibility of collector parameters between Steady state and Quasi dynamic testing for new collector designs. ISES Kassel (this conference)

Perers, B., Kovacs, P., Olsson, M., Persson M., Pettersson, U. (2011). A new tool for standardized collector performance calculations. ISES Solar World Congress, Kassel 2011.

Perers, B. (1993) "Dynamic Method for Solar Collector Array Testing and Evaluation with standard Database and Simulation Programs." Solar Energy Vol 50. No 6. pp 517-526

Perers, B. (1995) "Optical modeling of Solar Collectors and Booster Reflectors under Non Stationary Conditions." PhD Thesis. Uppsala University. ISBN 91-554-3496-7.

Perers, B. (1997) "An Improved Dynamic Solar Collector Test Method for determination of Nonlinear Optical and Thermal Characteristics with Multiple Regression." Solar Energy 59 163-178.

Perers B. (2006) "A Dynamic Collector Model for Simulation of the operation below the dew point in Heat Pump Systems." Eurosun Conference Glasgow

Perers, B. Roseen, R. (1983). The Experiences from the Central Solar Heating Demonstration Plant at Studsvik. ISES conference, Perth, ISBN 0-08-029947-4. Pp 426-432

Perers, B. Roseen, R. (1980). Solvärmecentralen i Studsvik Resultat 1980. (Solar Heating Central Results 1980) Studsvik AB, Sweden, (Studsvik/E1-80/141).

Theunissen P.H., Beckman W.A. . (1985)Solar transmittance characteristics of evacuated tubular collectors with diffuse back reflectors. Solar Energy, Vol 35, No. 4, pp. 311-320.