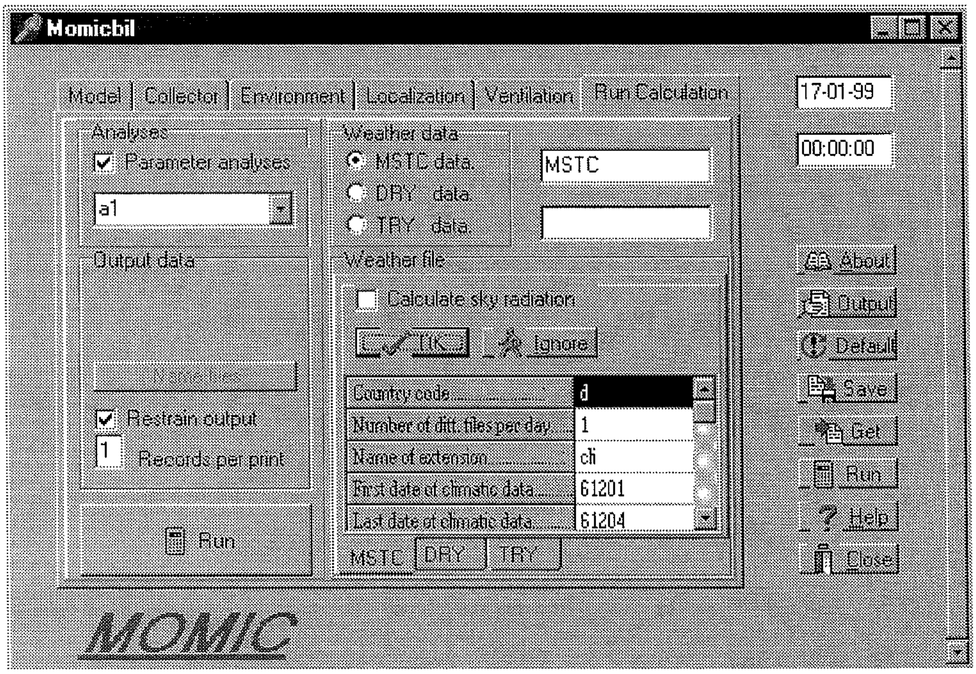
Compilation of publication and results from project C2: Modelling of microclimate in collectors.

Working Group on Materials in Solar Thermal Collectors.

IEA Solar Heating and Cooling Programme.

Working Document of Working Group.

Ole Holck



REPORT

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DEPARTMENT OF BUILDINGS AND ENERGY

TECHNICAL UNIVERSITY OF DENMARK

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Preface

This document describes investigations of ventilation and condensation of solar collectors in anticipation of being able to improve the long-term durability of solar collectors.

The intent of the present work is improvement of the existing computer model for calculation of microclimate data in collectors. Improvement of the existing computer model is a part of the work within the working group "Materials in Solar Thermal Collectors" of the IEA Solar Heating and Cooling Programme.

The project has been carried through under the subsidy for sustainable energy of the Danish Energy Agency.

Some of the results were presented in the form of papers at Congresses:

EuroSun 1998 International Conference in Portoroz, Slovenia.
NorthSun 1997 International Conference in Espoo-Otaniemi, Finland.
EuroSun 1996 International Conference in Freiburg, Germany.

The project has been carried out at the Department of Buildings and Energy, Technical University of Denmark.

Abstract

It is important to avoid condensation in solar collectors, most of all because wetness of the absorber can damage the selective surface and cause corrosion on the absorber plate.

During night time the cover of collectors will cool below ambient temperature due to thermal radiation to the cold sky. In climates where the air during night time becomes saturated with humidity (the relative humidity is 100%), condensation will form on the outside and inside of the collector glazing. If too much condensation takes place on the inside of the glazing, it will start to fall off on to the absorber surface.

The intent of the present work is improvement of a existing computer model for calculation of microclimate data in collectors.

Calculations with the model give insight in the humidity and temperature for artificial or realistic climatic data. This design tool makes it possible to calculate the effect of ventilation and insulation materials.

Results from investigation of ventilation rates together with a model of the moisture inside the collector are built into the computer program.

It has been found that modelling of the moisture transfer in backside insulation is essential to determine the humidity in the air gap of the collector.

The objective is to develop guidelines for solar collector design to achieve the most favourable microclimate condition for materials. As a tool the computer model will be useful to fulfil this. Guidelines for collectors will be essential for manufactures to improve the long-term durability of solar collectors.

Contents

Foreword

In the former task X "Solar Materials Research and Development" of the IEA Solar Heating and Cooling Programme a case study was conducted aimed at establishing a computer model for calculation of microclimate conditions in collectors. In Denmark as well as in the Netherlands computer models were developed for simulations of the microclimate [4], [5]. The intent of the present work is improvement of the existing computer model for calculation of microclimate data in collectors. Improvement of the existing computer model is a part of the work within the working group "Materials in Solar Thermal Collectors" of the IEA Solar Heating and Cooling Programme.

Other related activities within the working group is a parallel measurement of microclimatic parameters for collectors placed in the different climates of the participating laboratories and is done on the same kind of reference collector.

Collector test methods of relevance for micro-climate in collectors have been studied as a part of the work together with individual studies of the influence of wind, fluid dynamics, influence of insulation materials, air ventilation rates and time of wetness. Work is carried out within these issues, at the following institutes:

Swedish National Testing and Research Institute, SP. (Sweden)
Solar Energy Testing and Research Group, ITR. (Switzerland)
Fraunhofer Institute for Solar Energy Systems, ISE. (Germany)
Building and Construction Research, TNO. (the Netherlands)
Department of Buildings and Energy, IBE.(Denmark)

Input facility in the computer program has been established to receive weather data from the measurements on the reference collector. In order to verify the model, the computer program is provided with characteristic data for the reference collector.

It has been found that the characterization of the collector due to ventilation rate is somehow not so easy, not even for the ventilation due to chimney effects which have well known theory. Including effects from wind makes it extremely difficult.

The use of simulation with computational Fluid Dynamics (CFD), has been necessary for the assessment of the behaviour of air flow through the ventilation holes. The disadvantage of CFD simulations is the computer time needed. Therefor only a 2d stationary simulation of the collector is accomplished. Results from CFD simulations verified by measurements of air velocities in the openings are incorporated in the computer program as a characteristic for the collector.

Time periods from the years 1996 and 1997 have been chosen to examine some parameters of influence and to validate the use of the computer program. We are looking at the importance of taking the influence of wind into account, and we are looking at the rear-insulation thickness and what influence the insulation has on the humidity in the solar collector gap.

Humidity inside the collectors is one factor that can be optimised to keep the most favourable microclimate condition for the inside component of the collector.

During the design of the collector placement and size of ventilation holes, properties of the insulation materials, thickness of backside insulation and dimension of the solar collector box are properties that can be used for this optimizing. The humidity in the air gap is balanced by the ambient air humidity and by the humidity in the insulation. The former balance is conducted by the air exchange and depends on the tightness of the collector box including the ventilation holes, the latter balance is conducted by desorption and adsorption of moisture in the insulation.

International Energy Agency and Solar Heating and Cooling Programme.

International Energy Agency, headquartered in Paris, was founded in November 1974 as an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD) to coordinate the energy policies of its members. The twenty-three member countries seek to create the conditions in which the energy sectors of their economies can make the fullest possible contribution to sustainable economic development and the wellbeing of their people and the environment.

The policy goals of the IEA include diversity, efficiency and flexibility within the energy sector, the ability to respond promptly and flexibly to energy emergencies, the environmentally sustainable provision and use of energy, more environmentally-acceptable energy sources improved energy efficiency, research, development and market deployment of new and improved energy technologies, and cooperation among all energy market participants.

These goals are addressed in part through a program of collaboration in the research, development and demonstration of new energy technologies consisting of about 40 Implementing Agreements. The IEA's R&D activities are headed by a small Secretariat staff in Paris. In addition, four Working Parties (in Conservation, Fossil Fuels, Renewable Energy and Fusion) are charged with monitoring the various collaborative agreements, identifying new areas for cooperation and advising the CERT on policy matters.

The Solar Heating and Cooling Program was one of the first collaborative R&D agreements to be established within the IEA, and, since 1977, its Participants have been conducting a variety of joint projects in active solar, passive solar and photovoltaic technologies, primarily for building applications. The twenty members are:

Australia	France	Spain
Austria	Germany	Sweden
Belgium	Italy	Switzerland
Canada	Japan	Turkey
Denmark	The Netherlands	United Kingdom
European Commission	New Zealand	United States
Finland	Norway	

Description of the Working Group.

The Working Group was established in the autumn of 1994 as an extension of work which had been conducted on solar collector absorbers in Subtask B of Task 10 (Solar Materials R&D). Sweden assumed the leadership of the group in the initial phase of work.

The objectives of the Working Group are:

- To develop or validate durability test procedures for solar collector materials.
- To generalise test procedures for standardisation.
- To develop guidelines for solar collector design to achieve the most favourable microclimate conditions for materials.

The following areas have been identified for joint research work:

- Durability and Life-time Assessment of Solar Absorber Coatings

- Antireflecting Devices for Solar Thermal Applications
- Methods for Characterisation of Microclimate for Materials in Collectors
- Durability Aspects on the Use of Polymeric Materials in Solar Collecting Devices

In each of these areas a number of well-defined projects will be conducted, see **Table 1**. It is the responsibility of the appointed Project Leaders to take the necessary actions needed to initiate, conduct and report the work in the form of internal working documents, or most preferably through conference papers. A summary report on the results of the entire working group will be documented in the form of an IEA Technical report. The main responsibility for managing the joint research work will be placed on the Project Leaders. The part played by the Working Group Leader will be that of a co-ordinator. The activities of Working Group have been scheduled for a time period from October 1994 until a follow-up task will be started.

Table 1 Projects defined for the Working Group MSTC and project leaders

A	**Durability and Life-time Assessment of Solar Absorber Coatings**
A1	Experience of absorber durability from solar installations in use *(Project Leader Bo Carlsson, Sweden)*
A2	Application of IEA method for durability assessment of absorber coatings *(Project Leader Ueli Frei, Switzerland)*
A3	Generalisation of recommended test procedures in form of an International standard proposal *(Project Leader Bo Carlsson, Sweden)*
A4	Cyclic condensation tests for durability assessment *(Project Leader Michael Köhl, Germany)*
A5	Durability of absorber coatings used in evacuated collectors *(Project Leader Ueli Frei, Switzerland)*
B	**Antireflecting Devices and Transparent Polymeric Materials for Solar Thermal Applications**
B1	State-of-the-art review, cost benefit analysis and selection of candidate materials for further studies *(Project Leader Arne Roos, Sweden)*
B2	Characterisation of materials with respect to optical, mechanical and durability properties *(Project Leader Arne Roos, Kenneth Möller, Sweden)*
C	**Methods for Characterisation of Microclimate for Materials in Collectors**
C1	Collector test methods of relevance for microclimate in collectors (rain and air tightness) *(Project Leader Svend Svendsen, Denmark)*
C2	Modelling of microclimate in collectors *(Project Leader Ole Holck, Denmark)*
C3	Test procedures for measurement of microclimatic parameters *(Project Leader Ueli Frei, Switzerland)*
C4	Measurement of microclimatic parameters in collectors *(Project Leader Michael Köhl, Germany)*

D **Transparent polymeric materials for solar collectors**
D1 Identification of new types of transparent polymeric materials
(Project Leader, Sweden)

3. Work plan Project C2.

3.1. Objective of project.

The intent of the present project is improvement of the existing computer model for calculation of microclimate data in collectors.

- o The air flow due to temperature differences.
- o The pumping due to gust effects.
- o The moisture transfer in backside insulation.
- o The hygroscopic properties of the materials.
- o The variations of the operating condition.
- o Include empirical model of air pollution.

1) DK will develop the computer model, the remaining participants will, if needed, test the model and give input for improvement and algorithms.

    1.1) Provide test result for checking the suitability of the data format.
    1.2) Clear interface between ventilation and wind.
    1.3) Implement moisture transfer in insulation.
    1.4) Include model of pollutants provided by SP into the computer model.

2) The computer model will be validated by measured data for selected periods from project C4. Air exchange rate measurements in the form of tightness test are carried out by NL and DK for realistic input in the model. DK measures upper and lower part of the collector separately.

    2.1) Monthly reporting of data (investigate the possibilities offered by Internet).

    2.2) CFD as a tool for analyses of sensitivity and the need of stratification model. (The CFD model should include air flows between the absorber-strips, and air-exchange with the insulation and moisture phases).

3) Sensitivity of the output from the computer program for variations of relevant input parameters will be examined. The sensitivity analysis with the model will be defined by the participants, based on practical input. The calculations will be done by DK.

    3.1) Investigations with multivariate regression to clarify relevant input data to sensitivity analysis.
    3.2) Define relevant input parameters for the sensitivity analysis with the model.

4) Based on the practical experience, the outcome of the calculations and the measurements in C4, guidelines are developed and agreed upon.

Finally the computer model will describe the combined heat and moisture transport in the collector. Calculations with the model give insight in the humidity and temperature for artificial or realistic climatic data. (For instance the humidity distribution during the year). This design tool makes it possible to calculate the effect of ventilation.

The goal will be the creation of parameter sensitivity studies for accelerated testing and simple models for estimation of the micro-climate in collectors as a part of guidelines for collector design.

The objective of the working group is to develop guidelines for solar collector design to achieve the most favourable microclimate condition for materials. As a tool the computer model will be useful to fulfil this. Guidelines for collectors will be essential for manufacturers to improve the long-term durability of solar collectors.

These guidelines will be used by developers and manufacturers. As spin-off of the project the computer code will be available for designers, manufacturers, engineers, and researchers.

3.2. Activity plan of project

The activity plan of project is given in the table below

	Activity Plan	Target date	Action by	Milestone
1)	Extended computer model.	01-09-97	DK	01-09-97
1.1)	Checking suitability of data format.	01-02-97	ALL	
1.2)	Ventilation and wind interface.	01-04-97	NL, D, DK	
1.3)	Moisture transfer in insulation.	01-09-97	DK	
1.4)	Influence of pollutants.	01-04-97	S	
1.5)	Status report.	11-04-97	DK	11-04-97
2)	Validation of model.			
2.1)	Monthly reporting of data.	01-01-97	ALL	
2.2)	CFD as a tool.	01-09-97	NL, D,	
3)	Sensitivity test of the computer program.			
3.1)	Multivariate regression.	01-04-97	D	
3.2)	Define sensitivity analysis.			
4)	Guidelines, developed and agreed upon.			

Remark:

- Assistance in the model development.
- Assistance in analysing the influence of wind.
- Assistance in sensitivity analysis.
- Assistance in the guidelines and calculations.
- Practical input from industry.

3.3. Participation plan of project.

The participation plan of project is given below.

Participation Plan		Manpower in months
TNO Building and Construction Research	the Netherlands	2?
Solar Energy Testing and Research Group ITR	Switzerland	0.5?
Fraunhofer Institute for Solar Energy Systems	Germany	2?
Swedish National Testing and Research Institute	Sweden	0.5?
Technical University of Denmark (Project leader, Ole Holck)	Denmark	6
	Total	**11**

4. Extended computer model

4.1. Line of actions in the model.

In order to model the microclimate in the collector a model is set up based on the

heat balance,

ventilation rate,

and

moisture balance.

4.2. Heat balance.

The heat balance is set up for one square metre cut of a solar collector. So there are supposed to be no differences between the middle and the corners of the collector. The thermal capacity of the collector is assumed to be located in the cover and in the absorber including fluid and half of the back insulation. The cross section of the collector is shown in figure 1.

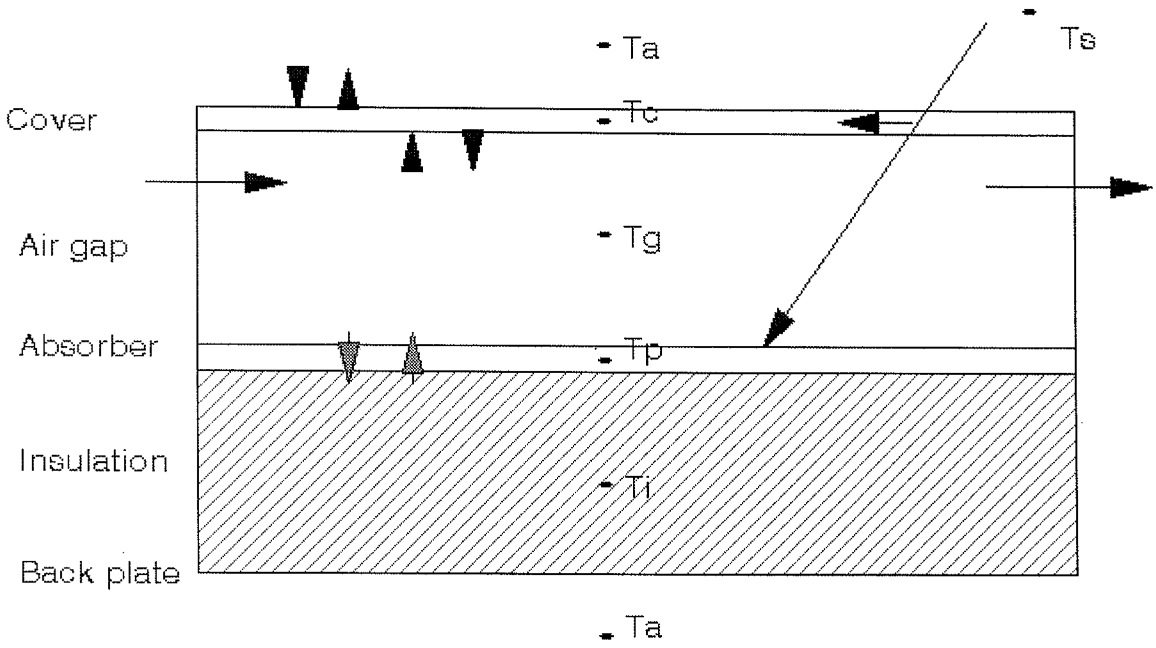

Figure 1. Cross section of the solar collector.

To determine the temperature some differential equations can be set up and solved.

$$C_p \frac{dT_p}{dt} = G(\tau\alpha) - h_{cb}(T_p - T_a) - h_{cg}(T_p - T_c) - h_{rg}(T_p - T_c)$$

$$\begin{aligned} C_c \frac{dT_c}{dt} &= G\,a_c + h_{cg}(T_p - T_c) + h_{rg}(T_p - T_c) \\ &- h_{vg}((T_p + T_c)/2 - T_a) - h_{co}(T_c - T_a) - h_{ro}(T_c - T_s) \\ &- q_{ei} - q_{eo} \end{aligned}$$

The heat transfer by convection and thermal radiation is in the differential equations given as the product of heat transfer coefficient and the temperature difference to get a linearized form. The error due to the linearization is small because the heat transfer coefficient is calculated for each time step, and the time steps are so short that the temperature changes are quite small. For the collector in operation, the boundary conditions for Tp are set to the measured value for Tp. In this case there is only one differential equation to solve.

The solar transmittance-absorption product is given for a normal incidence and corrected for the incidence angle using the incidence angle modifier coefficients.

The heat loss due to conduction in the back insulation is calculated from the following equation.

$$h_{cb} = k_i / e_i$$

The heat transfer coefficient for natural convection in the air gap is calculated from the following expressions given by [1]:

$$h_{cg} = Nu_g \ k_g / e_g$$

where
$$Nu_g = 1 + 1.44\left[1 - \frac{1708}{Ra_g \cos s}\right]^{+}\left(1 - \frac{(\sin 1.8 \cdot s)^{1.6} \cdot 1708}{Ra_g \cos s}\right)$$
$$+ \left[\left(\frac{Ra_g \cos s}{5830}\right)^{0,33} - 1\right]^{+}$$

where the meaning of the positive exponent is that only positive values of the terms in the square brackets are to be used. If it is negative a zero is used.

$$Gr_g = \frac{g \, \beta \left(T_p - T_c\right) e_g^{\ 3}}{\nu^2}$$

$$\beta = 2/\left(T_p + T_c\right)$$

$$Ra_g = Gr_g \ Pr$$

The heat transfer coefficient for thermal radiation in the air gap is calculated from the following expression:

$$h_{rg} = \frac{c_s\left(T_p^{\ 4} - T_c^{\ 4}\right)}{\left(1/\varepsilon_p + 1/\varepsilon_c - 1\right)\left(T_p - T_c\right)}$$

The heat transfer coefficient for thermal radiation from the cover to the sky and the ground is calculated from the following expressions.

$$h_{ro} = 0.5\left(1 + \cos s\right)\varepsilon_c \ c_s\left(T_c^{\ 4} - T_s^{\ 4}\right)/\left(T_c - T_s\right)$$
$$+ 0.5\left(1 - \cos s\right)\varepsilon_c \ C_s\left(T_c^{\ 4} - T_a^{\ 4}\right)/\left(T_c - T_s\right)$$

$$T_s = 0.0552 \cdot T_a^{\ 1.5}$$

The relation between the temperature of the air and the sky is from [1] and both temperatures are Kelvin. If measured data for the sky temperature are available, they should be used.

The heat transfer by convection from the cover to the ambient air is calculated according to [2] from the following expressions:

$$h_{co} = Nu_o \, k_o / L$$

$$Nu_o = \sqrt{Nu^2{}_{lam} + Nu^2{}_{turb}}$$

$$Nu_{lam} = 0.664 \, Re_+^{0.5} \, Pr^{0.33}$$

$$Nu_{turb} = \frac{0.037 \, Re_+^{0.81} \, Pr}{1 + 2.443 \, Re_+^{-0.1} (Pr^{0.67} - 1)}$$

$$Re_+ = \sqrt{(Re)^2 + (Re')^2}$$

$$Re = V_w L / \nu$$

$$Re' = 0.64 \, Gr^{0.5}$$

$$Gr = Gr(L') = \frac{(L')^3 g \, (T_c - T_a)}{\nu^2 (T_a + T_c)/2}$$

$$L' = L$$

The heat transfer by evaporation/condensation at the cover outside is calculated according to [2] from the following equations.

In [2] the expression is only used for condensation. It is assumed to be valid also for evaporation. Of course evaporation can only take place if the cover is wet.

$$q_{eo} = h_{co} \frac{M_D \, r_c}{0.9 \, M_L \, C_{pa} \, p} (p_{ws}(T_c) - p_{ws}(T_{dewa}))$$

As the heat of varporization and the specific heat of air do not vary much with temperature, typical values are inserted in the equation.

$$T_c \geq 0 : q_{eo} = 1.7 \cdot 10^{-2} \, h_{co} \, (p_{ws}(T_c) - p_{ws}(T_{dewa}))$$

Below the freezing point the heat of vaporisation is somewhat higher.

$$T_c \leq 0 : q_{eo} = 1.9 \, 10^{-2} \quad h_{co} (p_{ws}(T_c) - p_{ws}(T_{dewa}))$$

The water vapour saturation pressure is calculated according to [3].

The heat transfer by evaporation/condensation at the cover inside is calculated from the amount of transferred water that comes out of the moisture balance.

The heat transfer coefficient due to ventilation is calculated from the expression.

$$h_{vg} = m_{vg}\ C_{pa}$$

where m_{vg} is the mass flow rate of air through the air gap in kg/s m^2.

4.3 Ventilation rate.

Ventilation contribution

The solar collector is ventilated by wind and thermal driven pressure. The influence of wind can be divided into the influence of the mean wind speed and the influence of the fluctuating wind (gusts). The mean wind speed causes pressure around the solar collector that will ventilate the solar collector through its cracks and apertures. A gust of wind will move the cover and thus create a change of pressure inside the solar collector which is neutralized through cracks and apertures. The thermal driven pressure is due to the lifting power that the warm air will have compared with the open air, thus taking in air below at the temperature of the surroundings and emitting heated air at the top. Furthermore the actual heating and cooling of the solar collector (thermal expansion) will cause ventilation.

The ventilation can be split up, according to which driving force creates the ventilation, as follows:

1) ventilation due to thermal expansion of the air in the collector (breathing),
2) ventilation due to the stack effect (thermal buoyancy),
3) ventilation due to constant wind,
4) ventilation due to pumping effects of the wind gusts on the glazing.

The ventilation of the air gap depends on the tightness of the collector casing. To characterize each solar collector, they are going through a tightness test where the pressure difference between inside and outside are measured for different value of air flow.

We consider the steady and the fluctuating parts of the wind separately. By the steady component (constant wind) we mean a temporal average over a period of one hour. From meteorologic data we have the one hour mean wind speed at 10 meters height, and by using a logarithmic wind profile we can predict the constant wind speed that interferes with our collector.

It is necessary for us to get information of the fluctuating part of the wind only with the knowledge of the 10 meter mean wind speed. For that we use an energy spectrum for the country part in question, from which we have the total kinetic energy contained between to frequencies. In order to have a simplified model we use the kinetic energy for the whole spectrum and the frequency f from which the spectrum has max density and then model the fluctuating part of the wind with a harmonic oscillation at frequency f and the amplitude corresponding to the kinetic energy.

Thermal Driving Pressure

To start an air current over a given distance, in this case the height of the solar collector, there must be a driving pressure which is just as large as the pressure loss of the distance. The driving pressure is the pressure difference, equivalent to the gravitation powers, which is due to difference in density (natural driving pressure). The neutral level is where the inside pressure and the outside pressure are equal. At other levels there is a pressure difference, ΔP.

$$\Delta P = \Delta\rho g z = \rho_0 \left(\frac{273}{T_a} - \frac{273}{T_i} \right) g z$$

Where z is vertical co-ordinate measured from the neutral plane, g is the acceleration due to gravity and ρ_0 the density of the air at 0°C, Ta the ambient temperature and Ti the temperature in the solar collector.

The placing of the neutral plane depends on the placing of the leakages as well as the difference of resistance for draw and pressure. The volume flow rate is measured at variable pressure differences for the respective solar collectors.

If at first there is assumed a linear variation of pressure up through the solar collector and an even distribution of leakages, the neutral plane and the volume flow rate can be found for given static driving pressure. The admissing volume must be equal to the volume leaking out. Then the integral of the volume flow rate from neutral plane to the top of the solar collector is equal to the integral of the volume flow rate from neutral plane to the bottom of the solar collector.

$$\int_0^x V(\Delta P)_{\text{vacuum}}\, dx = \int_0^{1-x} V(\Delta P)_{\text{overpressure}}\, dx$$

The power functions found at the pressure tests are designated V(ΔP),

$$V(\Delta P) = B(\Delta P)^M$$

and the driving pressure is

$$\Delta P = \rho_0 \left(\frac{273}{T_a} - \frac{273}{T_i} \right) g z$$

where Z is the vertical projection of the height of the solar collector. The pressure variation expressed by the integration variable is thus:

$$\Delta P(X) = \Delta P \cdot x$$

where x is between 0 and 1.

The integral becomes:

$$\int V(\Delta P) dx = \left(\frac{\Delta P}{B} \right)^{\frac{1}{M}} \frac{M}{1+M} \left[x^{\frac{M+1}{M}} \right] = a\left[x^b\right]$$

X is hereafter found by the term:

$$a_{vacuum} x^{b_{vacuum}} = a_{overpressure} (1-x)^{b_{overpressure}}$$

and the flowing volume is:

$$V = a_{overpressure} (1-x)^{b_{overpressure}}$$

If the leakages are divided equally around the top and the bottom of the solar collector the pressure difference for entering the gap is equal to the pressure difference for the aperture, therefore:

$$V = V(P/2)_{overpressure}$$

It turns out, however, that it is difficult to make theories about the division of leakages in the solar collectors.

At the tightness tests the volume flow rate through the solar collector is measured at various pressure differences and at regression expressed in terms of approximate functions.

Assuming that the exponent b is approximately 1/2, the pressure difference needed is only an 1/4 · 1/2 of the reality if the test is performed with a collector whit aperture all over the surface.

The volume flow rate is hereafter found for a given pressure difference ΔP, as the pressures from the functions by inserting the pressure divided by 8.

On these grounds we will be able to express the volume flow rate as a function of the pressure difference for each leakage-tested solar collector.

$$V = V(\Delta P/8)$$

In that allowance is made for the humidity of air the differential pressure (the driving pressure) is determined from:

$$\Delta P = \left(\rho(T_{a}, P_{wa}) - \rho((T_p + T_c)/2, P_{wg})\right) h \cdot g$$

Where h is the vertical projection of the solar collector and g is the acceleration due to gravity

The density of the air is found according to [3]:

$$\rho_a \, (1/V) \, (1+W)$$

Where:

P_w is the partial pressure of the aqueous vapour.

$$V = \frac{R_a T}{p}(1 + 1.6078\,W)$$

$$W = 0.62198\,p_w/(p + p_w)$$

With data for T and P_w for the open air and the air in the solar collector we have hereby defined the driving pressure and the volume flow rate.

The mass flow of damp air is now found from:

$$m_{vg} = 0.5\left(\rho(T_a, P_{wa}) + \rho\left((T_a + T_c)/2, p_{wg}\right)\right)V(\Delta P)$$

where a mean value is used for the density of the air.

These terms form the mathematical model for thermal driving pressure.

Wind

One of the things that contribute to ventilation of solar collectors is the wind. Below we will therefore investigate the behaviour of the wind in the border layer closest to the surface of the ground.

In the investigation we will not deal with disturbance of the wind owing to buildings and roof surfaces, but only look at the undisturbed wind profile caused by roughness at the surface of the ground and the wind speed in the higher layers.

The model for the wind that we want to explain shall be a simple conversion of the meteorological mean wind speed into a constant wind speed - and determined gusts on the solar collector. Therefore considerations on wind types are also omitted (inversion, convection), but a neutral state where the air is in balance is assumed.

A further simplification is in that we only look at the component in the direction of the wind, instead of a three-dimensional vectorial field.

At the closer inspections of the wind we look at the constant wind and the fluctuating wind separately. By the constant wind is meant a middling of the wind over a period of one hour. The mean wind speed rises along with the height above the surface of the ground which is described by a wind profile.

The fluctuating part or turbulence has not been fully theoretically described, we therefore look at the problem statistically and make use of empirical expressions depending on tests.

The lowest 1-2 km of the atmosphere are normally turbulent in the daytime. In this layer there are radical changes of movement, heat and moisture. This layer is called the planetary border layer (PBL) or the friction layer, ref. [10].

At night, with a light breeze, the layer is thinner, often smaller than 100 m.

On days and nights with a wind, especially with a thick cloud cover, PBL is quite turbulent, and the depth is determined by the wind speed and the roughness of the surface. We can define the depth of the PBL-layer by h, which is the thickness of the turbulent part above the surface of the ground, called the depth of the mixed layers. Areas where the temperature rises upwards are called inversion, areas of inversion suppress the turbulence.

Neutral states (the temperature rises isotropically upwards) appear when there is a strong wind on cloudy days and nights.

The friction speed in the neutral state is given by:

$$U_* = \frac{K_a V_z}{\ln z / z_0}$$

Where V_z is the wind speed in level z, z_0 is the length of roughness and K_a von Karman's constant. Under unstable conditions, sunny days with some wind, we have both mechanical turbulence and heat convection.

Under stable conditions on clear nights with light breeze only the lowest layer with inversion is still turbulent.

The lowest part of PBL is called the surface layer.

There is no precise definition of the surface layer, which is the designation for the part of PBL immediately over the surface of the ground where vertical variations can be ignored.

As thickness of the surface layer normally the lowest 10% of the PBL-layer are used. In the daytime with strong wind the layer may have a thickness of 100 m, and on a clear night with little wind under 10 m.

The simplification applied in the surface layer is that the direction of the wind is not changed with the height. Therefore the mean wind speed can be described as $\bar{U}$ alone and is only a function of the height z.

The variation with the height is primarily controlled by three parameters: surface tension, vertical heat flux from the surface and roughness of the ground.

The classical logarithmic wind profile is:

$$V = \frac{U_*}{K_a} \ln\left(\frac{z}{z_0}\right) \quad z \geq z_0$$

At mechanical turbulence the logarithmic wind profile is started above the roughness elements, below this height the velocity falls slower. We extrapolate the logarithmic part down to a height where V is 0, and define this height as a new surface which is z = d + z0 above the visual ground surface. d is typically 80% of the height for the greatest roughness element as e.g. houses, [10]. d is called the shear length. Hereby the wind profile is given by:

$$V = \frac{U_*}{K_a} \ln \frac{z - d}{z_0}$$

U_* is determined from the meteorological wind speed (10 m height) to be:

$$U_* = \frac{K_a}{\ln\left(\frac{10 - d}{z_0}\right)} V(10)$$

Ventilation model due to wind

In the ventilation model due to wind we define two numbers to characterize each collector. One for the stiffness of the collector cover and one for the tightness of the collector box. The stiffness number depends on the cover. The stiffness number is one for cover made of glass and 0.15 for cover made of plastic. For the stiffness number we apply stiff. The tightness number is determined from the tightness test.

The tightness number is defined as the driving pressure in dPa which gives an air-exchange of the collector of one time an hour. For the tightness number we apply Tight.

The model consists of the following empirical expression made by results from indoor experiments.

For the gusts we have a contribution to ventilation expressed as:

$$N_g = \frac{2.48 \cdot A - 1}{\text{stiff} \cdot \text{tight}}$$

For the local constant wind we have a contribution to ventilation expressed as:

$$N_c = \frac{0.33\ V_{lok} + 0.18}{\text{stiff} \cdot \text{tight}}$$

The numbers N_g and N_c give the air exchange in times per hour per square metre. Those numbers can be scaled in the computer program to increase or decrease the influence of wind.

4.4 Moisture balance.

From the heat balance we know the temperatures before and after the time step. Based on the mean values of the temperatures a moisture balance is set up.

	The mass of the water vapour in the air in the gap after the time step
=	the mass of the water vapour in the air in the gap before the time step
-	the mass of the water vapour removed by ventilation of the gap due to the stack effect
-	the mass of the water vapour removed by ventilation of the gap due to influence from wind.
-	the mass of the water vapour removed by expansion of the air in the gap due to increase of the temperature
-	the mass of the water vapour removed into the insulation materials
-/+	the mass of the water condensed/evaporated from the inside of the cover.

<u>The mass of the water vapour removed by ventilation of the gap due to the stack effect</u> is calculated on the basis that the mass flow of dry air in and out of the collector must be identical.

$$M_{ai} + M_{wi} = m_{vg}\ \Delta t$$

where

M_{ai} mass of dry air coming into the collector, kg/m^2

M_{wi} mass of water vapour coming into the collector, kg/m^2

t time step, s.

$$W_i = M_{wi} / M_{ai} = 0.62198 \frac{p_{wi}}{p - p_{wi}}$$

$$p_{wi} = p_{ws}(t_d)$$

where

W_i humidity ratio of the air going into the collector

p_{wi} partial pressure of water vapour in the air going into the collector, Pa

$p_{ws}(t_d)$ pressure of saturated water at the dew point temperature of the air entering the collector, Pa

t_d dew point temperature of the air entering the collector, °C

We have:

$$M_{ai} = \frac{m_{vg} \Delta t}{1 + 0.62198 \frac{p_{wi}}{p - p_{wi}}}$$

$$M_{wi} = M_{ai} W_i$$

$$M_{wo} = M_{ai} Wg$$

$$\Delta M_{wV} = -M_{wi} + M_{wo}$$

where

W_g humidity of air in the collector

M_{wo} mass of water vapour coming out of the collector by ventilation due to the stack effect, kg/m^2

ΔM_{WV} mass of water vapour removed by ventilation, kg/m^2

The humidity ratios are assumed to be constant during the time step. Their mean values are used.

The mass of water vapour removed by expansion of the air in the collector due to increase of temperature is calculated from

$$\Delta M_{we} = \Delta M_{ae} \; W_g$$

$$\Delta M_{ae} = V_g \left(\rho_a (T_{ge}) - \rho_a (Tgs)\right)$$

$$Tg = (T_p + T_c)/2$$

where

ΔM_{we} mass of water vapour removed by expansion of the air in the collector due to increase of temperature, kg/m^2

ΔM_{ae} mass of dry air removed by expansion of the air in the collector due to increase of temperature, kg/m^2

V_g volume of the gap, m^3/m^2

ρ_a density of dry air, kg/m^3

T_{ge} temperature of the air in the gap at the end of the time step, °C

Tgs temperature of the air in the gap at the start of the time step, °C

$$\rho_a = \frac{p}{R_a T}$$

The mass of water condensed on or evaporated from the inside of the cover is calculated as follows.

If the partial pressure of water vapour in the air in the collector is higher than the pressure of saturated water at the temperature of the cover, condensation will take place and vice versa. The following relation from [3] between the humidity ratio and the partial pressure of water vapour is used.

$$p_{wg} = p \frac{W_g}{W_g + 0.62198}$$

Where

p_{wg} partial pressure of water vapour in the air in the gap, Pa

If p_{wg} is higher than p_{wsc} at the cover temperature, condensation will take place until Wg has dropped to

$$W_{sg} = 0.62198 \frac{p_{wsc}}{p - p_{wsc}}$$

The increase of condensate is then calculated from

$$\Delta M_{wc} = \left(W_g - W_{sg}\right) M_{ag}$$

where

W_{sg} humidity ratio of the air in the gap at saturation

P_{wsc} pressure of saturated water at the temperature of the cover, Pa.

M_{ag} mass of dry air in the gap, kg/m^2

ΔM_{wc} increase of condensate in the inside of the cover, kg/m^2

The above expression is also giving the amount of water evaporated from the inside of the cover.

Moisture and ice at the cover.

The temperature at the cover is adjusted due to the heat of fusion when the temperature passes the freezing point.

The largest amount of condensation that is capable of staying on the surface is depending on the slope of the collector.

At the outside this amount of condensation is:

$m = 261{,}109 \cdot s^{-0.407}$

and at the inside the amount of condensation is:

$$m = 225{,}828 - 34{,}247 \cdot \ln (s)$$

4.5 Moisture in insulation.

A transient model for calculation of combined heat and moisture transfer in the insulation is adopted. The only thermal effect on the moisture flow is through the influence on vapour pressures. The construction is divided into three finite control volumes in layer with the same materials. The layers are indexed from the surface facing the outdoor climate i= 1 at the back plate to the surface at the absorber plate i = 3. A vapour (Z[Pa m^2s/kg]) resistance is inserted at the absorber plate and at the back plate. See figure 2. The time steps follow the main programme.

Transfer functions to be used by the numerical model are designated by H, while HO designates the capacity terms. Indices q and v are used for reference for heat conduction and vapour diffusion.

The relation between vapour pressure and moisture content is given by the sorption curve. Therefore it is requested that the temperature is known so that the vapour pressure can be calculated.

The temperature profile is calculated implicitly and the moisture content is calculated explicitly.

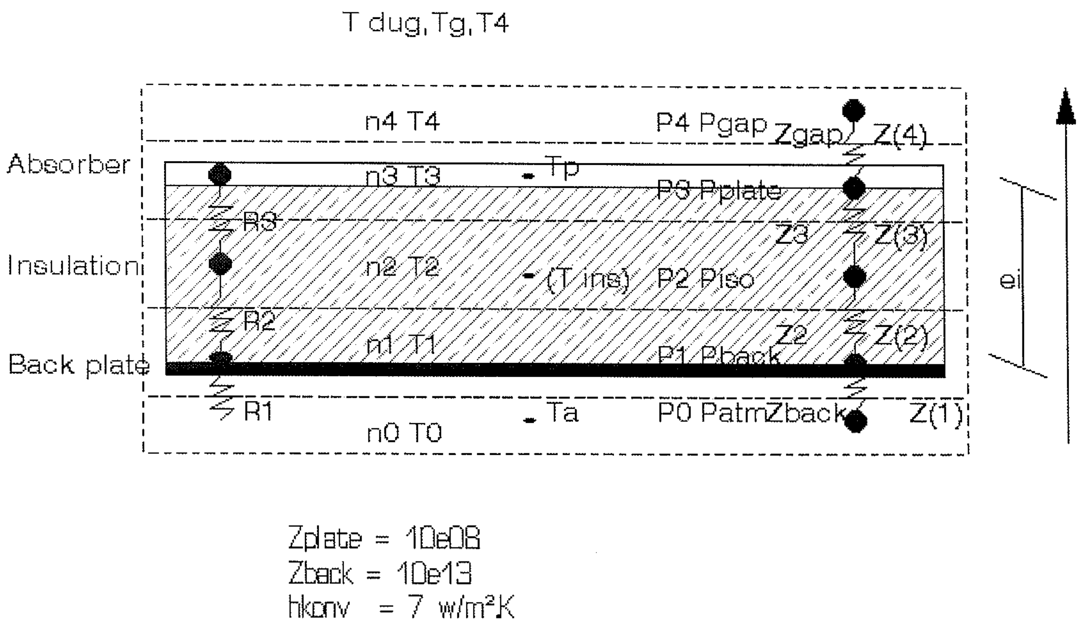

Figure 2.

5. Users manual.

The computer model describes the combined heat and moisture transport in the collector. Calculations with the model give insight in the humidity and temperature for artificial or realistic climatic data. (For instance the humidity distribution during the year.) This design tool makes it possible to calculate the effect of ventilation.

Input facility in the computer program named "MOMIC", an abbreviation of Modelling Of Microclimate In Collectors, has been established to receive weather data from data files. Three possibilities of data files are implemented. Two for artificial climatic data in a form used by the Danish Test Reference Year, TRY, and the Design Reference Year, DRY, and one for realistic climatic data, designed to receive weather data from the measurements on the reference collector, IEA MSTC.

Properties not influenced by time can be entered by using different tab-sheets in the program. They are stored on files with the extension ".dat". Old versions can be stored and retrieved by the Button command "Save" and "Get".

The format of the file for artificial climate data refers to DRY and TRY's users manual. The file name is with no restrictions. The format of the file name for realistic climate data is with restrictions and is expected to follow the format proposed by the Working Group.

Example G60611t1.dat (thermal data June 11th, 1996 from Germany)

1	Code for the country.		
	C	Switzerland.	
	D	Denmark.	
	G	Germany.	
	N	Netherland.	
	S	Sweden.	
2	Year	(6 for 1996)	
3,4	Month	(01...12)	
5,6	Day	(01...31)	
7	Data Code		t = thermal w = Wind (if different samples are used)
8	Number to distinguish different files per day, if they occur.		
ext	Arbitrary, No restrictions.		

The parameter needed for the calculations shall occur in correct order. More parameters tailed behind these will not disturb the program.

The data shall be separated by "," or " ".

The program expects the order in which the data occur to be as follows.

```
ntime    := round(tal[1]) ;
T        := tal[2] ;
rh       := tal[3] ;
Pamb     := tal[4] ;
p        := pamb*100;
Gsol     := tal[5] ;
vw       := tal[6] ;
vsd      := tal[7] ;
vd       := tal[8] ;
ir       := tal[9] ;
T_abs    := tal[10] ;
T_abs    := tal[11] ;
T_abs    := tal[12] ;
T_agt    := tal[13] ;
T_agm    := tal[14] ;
T_agb    := tal[15] ;
T_cov    := tal[16] ;
T_cov    := tal[17] ;
T_covb   := tal[18] ;
T_insu   := tal[19] ;
rh_insu  := tal[20] ;
CD_abs   := tal[21] ;
CD_cov   := tal[22] ;
rh_agt   := tal[23] ;
rh_agm   := tal[24] ;
rh_agb   := tal[25] ;
```

The first parameter "ntime" is hours and minutes represented by one figure. (Example 110 is one hour and 10 minutes.) The pressure "Pamb" is expected to be in mbar.

Not all parameters are used in the calculations, but they are used for output.

Two output files are generated by the computer program, one with the input data including a heading to specify the columns and one with the result of the calculations for each data-line in the input file.

For artificial climatic data, the variation of the operating condition is limited to a max. value of the absorber plate temperature. When using realistic data the measured absorber temperature is used as a fixed data value and will substitute variation in the operating conditions.

If needed, for instance if the collector is built for integration, the back plate temperature can be set as a fixed value.

The computer model will take into account the following objects:

- o The air flow due to temperature differences.
- o The pumping due to gust effects.
- o The moisture transfer in backside insulation.
- o The hygroscopic properties of the insulation.
- o The variations of the operating conditions.

"MOMIC" menu consists of 6 tab-sheets and controls the input to the program.

The tab-sheets are activated by moving the cursor to the selected field and then click.

The tab-sheet "Model" includes the time step for the calculations. Using an IEA MSTC data file with a time resolution for the properties of 5 minutes, the time step multiplied by the number of steps for each data line should be 300 sec.

Using a TRY or DRY data file the time step multiplied by the number of steps for each data line should be 3600 sec.

Insulation material properties can be chosen from table, but still the thermal conduction and insulation thickness have to be specified in the tab-sheet "Collector".

The tab-sheet "Collector" includes collector properties.

The parameter "pr" is used for set temperature for the absorber (max. value).

The tab-sheet "Environment" includes properties concerning the environmental conditions.

The pressure of the ambient air will be written over by the input from data file in the case IEA MSTC file.

The tab-sheet "Localization" includes properties for orientation and localization.

The tab-sheet "Ventilation" includes properties concerning ventilation rate. Results from a tightness test are represented by the factor a1 and the exponent b1.

Setting the next two factors fwg and fwd to zero, the effect of gust and direct wind is not taken into account and the following parameters will not influence the calculations.

The tab-sheet "Run Calculation" starts the calculation part of the program. The user will be asked for information about the weather data file.

Before running the calculations specify output data file or except the default

RES1.OUT, RES2.OUT.

Choose type of weather data file MSTC, TRY or DRY. For MSTC input files the sky radiation can be calculated or the input value from the data file can be used.

Press OK button after specifying the name of the data files.

To make sensitivity studies of parameters, a parameter can be chosen from a table.

This will course several calculations with this parameter varied in a suitable range.

The relative humidity is visible on the screen as soon as the calculations are started.

The computer program will generate two output files. The first is with few exceptions parameters calculated in the computer model. The second output file is with few exceptions measured data from the input file including headlines to specify the columns.

6. Validation of model

6.1 Data acquisition system

In general the change in relative humidity is small in the winter time. Probably in the range of 85% to 95%. In the summer it would vary between 60% and 95%. The absolute humidity ambient is in the range from 2 g/kg to 14 g/kg.

At the test facilities for measurements of microclimate in Denmark the extreme value for each day is stored.

From those data we have the range of 75% to 100% for the relative humidity in the winter time. The humidity ratio is between 3 g/kg and 16 g/kg. In the summer we have the range of 71% to 100% for the relative humidity. The humidity ratio is between 5 g/kg and 36 g/kg.

The extreme wind velocity over the year varies between 0 and 10 m/sec. with no special relation to the seasons.

The temperature varies between 4°C and 35°C in the summer time and between-3°C and 20°C in the winter time.

There is not used an event-driven data logging except for the gust. The standard deviation of the wind for a period of 5 minutes controls the storing interval to be 5 sec. for the gust if the standard deviation exceeds a limit.

The test facility measurement procedure is described in the report "Test procedure for measurements of microclimatic parameters."

In the autumn of 1997 the test facility is used for measurements of various working conditions.

The used data-logger is from Campbell Scientific (CR10). The CR10 is programmed with a pre-written program down-loaded from PC. CR10 stores 30,000 data points in internal memory. At midnight each day the data is transmitted to a file on the computer. The data-logger is expanded with an AM416 multiplexer. The connection is made so that the AM416 adds 32 differential inputs to the CR10.

6.2 Results from dry-out test

Introduction and objective of test.

With high relative humidity at night the inside of the cover may be sufficiently below the dew point so that condensation occurs on the surface. If the condensation is not re-evaporated by ventilation or solar heat gain, droplets of water can fall down and cause corrosion on the absorber plate.

In the winter time the change in relative humidity is small, in the range of 85% to 95%. In the summertime it varies between 60% to 95%. The absolute humidity ambient is in the range from 2 g/kg to 14 g/kg.

This test is intended to assess the occurrence of condensation at the inside of the collector cover and the behaviour of the microclimate at high ventilation rates. The test is an alternative to a dry-out test where water is injected into the collector gap.

The advantage compared to the dry-out test is that the water comes into the collector forced by a realistic method, this gives better opportunity to simulate the situation by use of the computer program and a more realistic distribution of the moisture in the collector box.

The disadvantage is that wetness of the collector might not occur. That happens if the condition for accumulation of water in the collector is not present. Under such condition high ventilation rate or ventilation for some time will bring the absolute humidity in the air gap to the same level as the ambient absolute humidity and nothing happens further. Increase of the ventilation rate will only give a quicker change in air and a negligible influence on the temperature, but no influence on the humidity.

The influence is, when condition for accumulation is present, that the amount of condensation will increase and make the accumulation of condensation more visible.

The condition where the accumulation of water into the collector takes place is when the temperature at the cover at night is frequently lower than the ambient dew point temperature. Depending on the moisture content balance with the surrounding air. Hygroscopic materials can be seasonal moisture sources or leeks. Therefor the insulation can course an accumulation of moisture at daytime when the insulation after a sunny period is dry and the ventilated air is dried out by diffusion to the insulation.

Preparation of the collector.

Connect a plastic hose to the collector with connection to the air gap by drilling a hole in the collector box. The hose is sealed around the hole by silicone. If the thermal ventilation exceeds the forced ventilation, the rules for thermal ventilation are present and the connection of the plastic hose will not disturb the ventilation through the back-side holes in other way than changing the pressure condition inside the air gap.

The inner diameter of the hose is approximately 6 mm. If the hose is transparent, it is possible to observe the condensation in the air leaving the collector.

Test procedure and instrumentation.

The apparatus consists of a controllable air source (could be a vacuum cleaner and a vario transformer), capable of sucking air out from the collector at different flow rates. An air flow meter with an accuracy of 10 l/h is installed to measure the rate of air flow.

The air source and air flow meter are connected to the collector. (The used one is a gas meter, type positive displacement dry gas meter, in connection with a clock measuring the time during the test. The range is between 25 l/h and 5000 l/h with an accuracy of 1%.

During the test the collector is in operating condition at 60°C, through the night the collector will cool down to ambient temperature, and at daytime on sunny days the collector will dry out to ambient humidity. The time for forced ventilation is noted and the test should go on for at least one week to be sure that condition appears for accumulating moisture. After stopping the forced ventilation the operating condition should be unchanged for another two days to see the dry-out effect of the accumulated moisture. If it is inconvenient another set temperature than 60°C can be used.

As a ventilation rate I suggest a flow of 700 l/h corresponding to an air exchange at 20 times an hour. It is important to observe the collector for condensation on the cover in the morning at eight o'clock and in the afternoon at four o'clock wintertime. This is of course not necessary if the measuring of time of wetness works well.

Computer simulation of the condition under dry-out test.

For the constant ventilation test the computer program is manipulated by setting a ventilation rate at the specified time.

Simulating the dry-out test is more complicated because it is necessary to specify the amount of moisture in the collector at the specified time, and in what form the moisture consists in the collector. The amount of moisture in the air is limited to the saturation condition and the water in the insulation is limited by a high relative humidity if we are not considering the wetness of the insulation to be in the over-hygroscopic region. The rest of the moisture is considered to be bound as condensation on the inner side of the cover.

The simulation needs one day of measured data for stabilising the condition in the collector.

Result from test.

Results from a dry-out test from Switzerland is analysed by comparing with the computer program.

The collector was injected by water at 9 a.m. The amount of water injected is about 40 g corresponding to 0.25 g water per litre collector volume and a whole collector volume of 160 l.

Before injection there is some water in the collector. The temperature in the gap is 50 C and the ambient humidity is 7.5 g/kg. The moisture content in the insulation is supposed to be 0.4% weight per cent, the density of the dry insulation is 100 kg/m^3:

In the air	-	7.5 g/kg 1.1 x 0.035 x 7.5	=	0.3 g
Insulation	-	0.4 x 0.01 x 100 x 0.05 x 1.48	=	30 g
Condensation	-		=	0 g
Moisture at the beginning			=	30.3 g
Injection			=	40 g
Content after injection			=	70.3 g

In the air	-	69g x 0.035m^3 x 1.1kg/m^3	=	2.7 g
Insulation	-	0.913% x 100kg/m3 x 0.05m x 1.48m^2	=	67.6 g
with the relative humidity at 88%				
Condensation	-		=	0 g

Moisture condition in the air gap after injection.

Temperature 46 C, moisture content 70.3 g

rH	w_gap	Moisture In the air	Moisture in insulation	Moisture content of dry insulation	rH_insu	Moisture as condensation on the cover
%	Kg/kg	g	g	%	%	g
100	0.069	2.7	67.6	0.913	88	0
95	0.065	2.5	67.8	0.916	88.1	0
76	0.051	2	68.3	0.923	88.4	0
52	0.034	1.3	69	0.932	88.8	0

From the measurements it seems that there is some stratification of the humidity in the collector gap. Therefore 3 computer runs have been made with the initialisation condition taken from the measurements. The next three figures compare computations with measurements of the relative humidity.

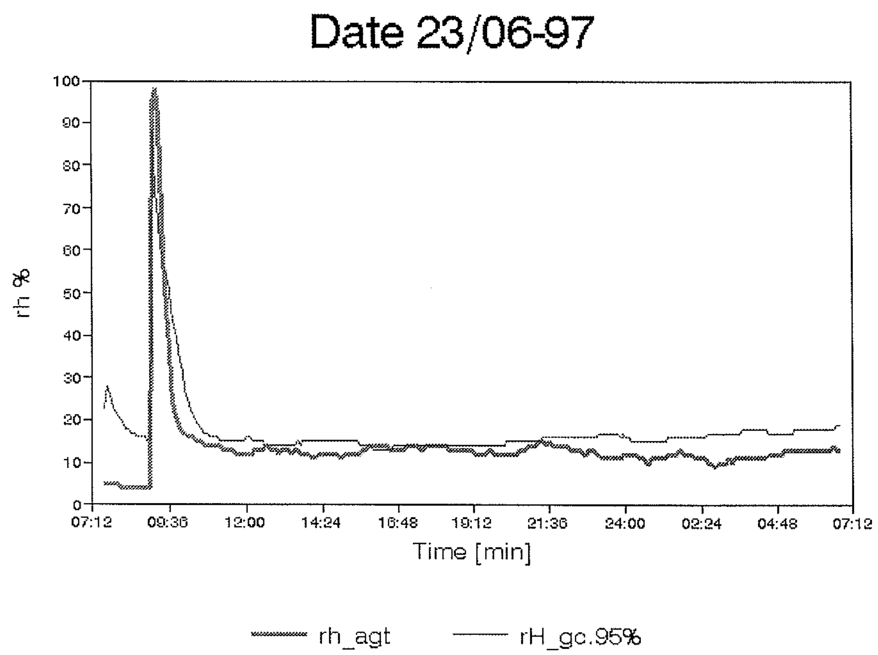

Figure 3. The condition in the top of the collector. It seems that the computations fit after the first air exchange have eliminated the high humidity and the condition in the air gap is similar to the ambient condition.

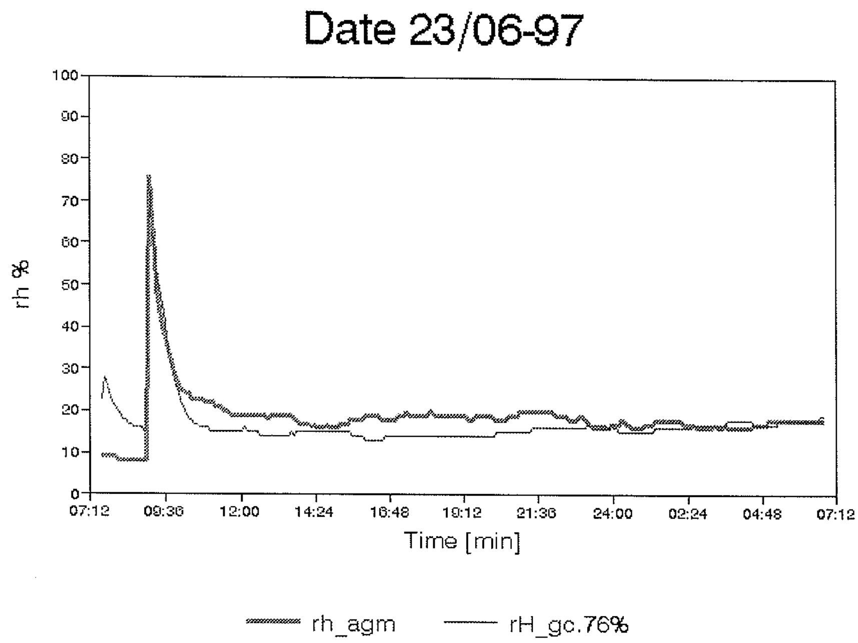

Figure 4. The condition in the middle of the collector. It seems that the right slope of the dry-out is present, caused by the air exchange. At the end of the period the humidity fits whit the condition calculated.

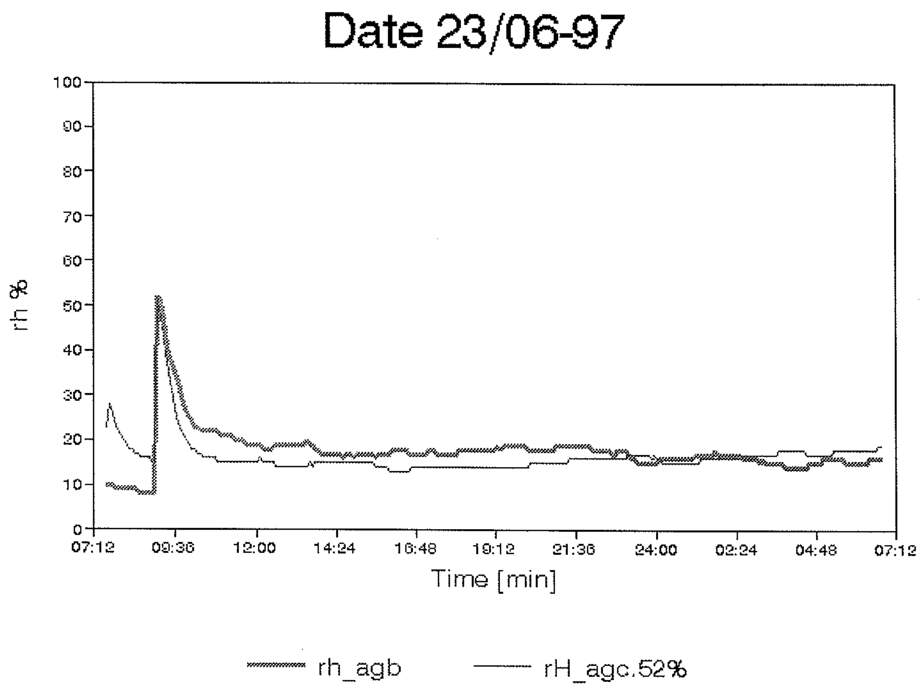

Figure 5. The condition in the bottom of the collector. It seems that the humidity fits whit the condition calculated at the end of the period and the condition is similar to the ambient condition.

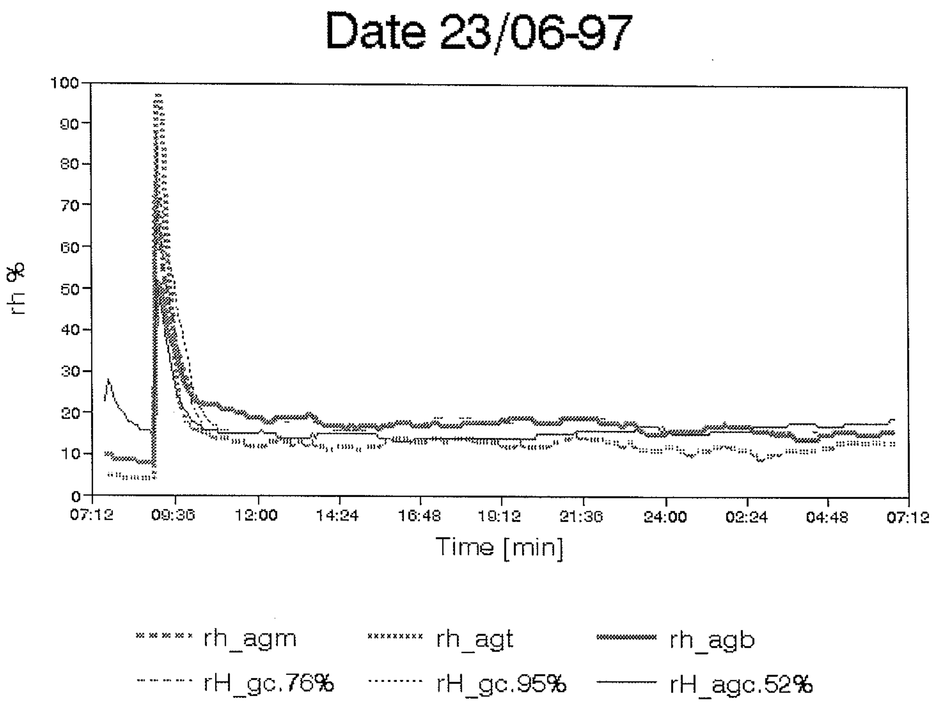

Figure 6. The computed humidity fits in somewhere between the top condition and the bottom condi-tion in the collector.

The initialization of the computer program will then be a starting situation with a high relative humidity of 100 % and a moisture content in the insulation at 0.9 % weight per cent. No condensation occurs at the cover inner side and at the measured values of relative humidity there seems to be no constant period, which would have been expected if condensation takes place. The computed curve seems to drop down faster than the measured one and this could be caused by local water droplets that are not ventilated out by the air exchange.

For a new dry-out test it could be valuable whit a two-step injection procedure first to fill up the insulation and next fill up the condensation on the cover inner side.

Result from the test with constant ventilation from Denmark is analyzed by comparing with the computer program.

Several tests had been performed with constant ventilation with different levels of ventilation rate.

At the beginning of August there was a very hot season in Denmark and we had a high humidity at night. At 15th August a test was run with constant ventilation at 700 l/h. Comparing the measured values of the relative humidity inside the collector with calculations from the computer program, we have a good agreement.

In the morning at 8.15 a.m. we observe some condensation at the inlet part of the cover and some condensation at the inner side of the hose sucking air out from the collector. At 8.45 a.m. all condensation has disappeared, but then the air gap is still supplied by moisture from the insulation. At 2.24 p.m. the insulation is dry and will now obtain moisture from the ventilation air and this goes on until 9.30 p.m. shortly after the condensation takes place at the cover at 9.00 p.m.

Usually the condensation shows up at the inlet section of the surface.

In the daytime the temperature in the gap is very high and the measured relative humidity is not reliable because we are out of the range of the instruments. It will not effect the curves of relative humidity, but conversion to absolute humidity is not possible. At night there is a very high relative humidity outside.

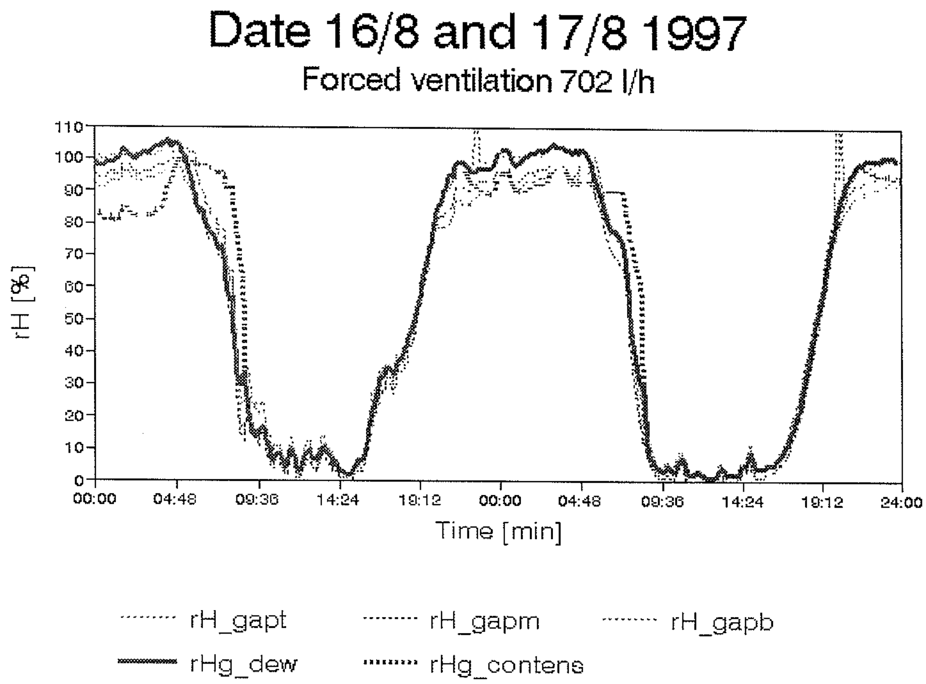

Figure 7.

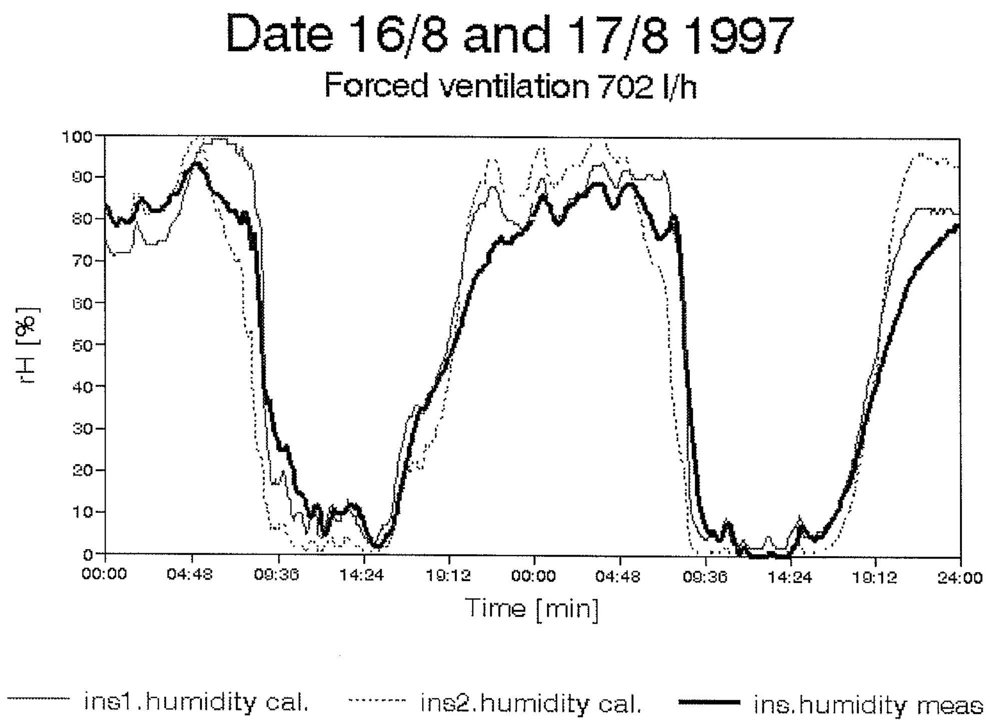

Figure 8.

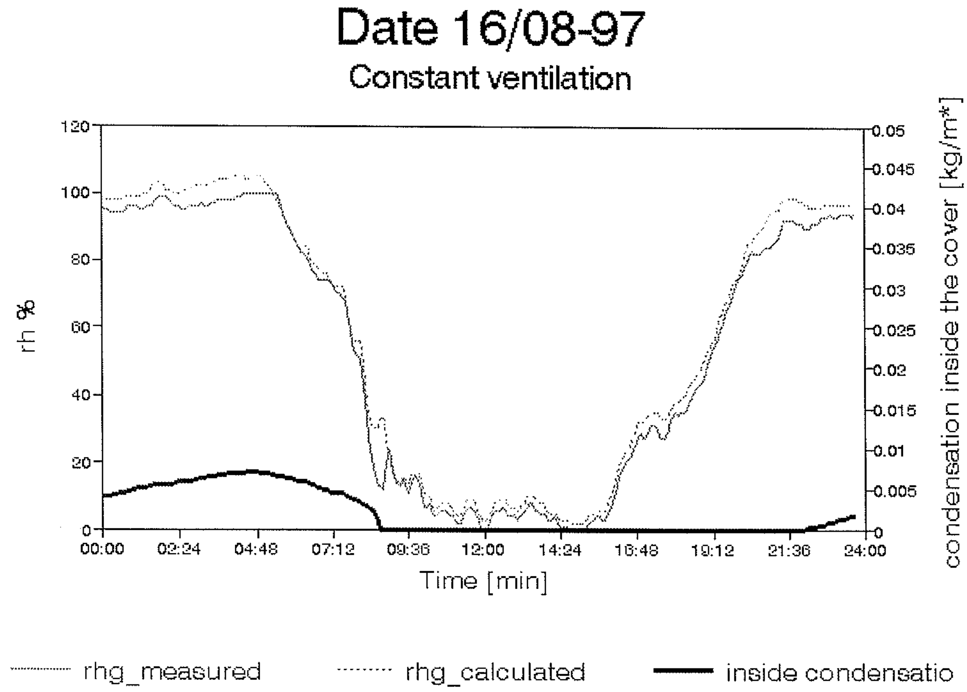

Figure 9.

6.3 Comparing model with measurements.

The correlation between micro-climate and ambient climate is described by the ventilation rate which means the air flow rate into the collector. The driven forces for ventilation of the collector is primarily an air pressure difference between the surroundings and the air gap. The pressure difference might be caused by thermal buoyancy, wind or gusts.

In the participating laboratories the air tightness of identical reference collectors was determined by applying a defined pressure difference. The tightness test gives the air flow through the collector box for different pressure differences between the inside of the collector and the ambient.

The result from the tightness tests have good agreement between the tests of the collectors. The use of these test for the assessment of the ventilation rate has been found problematic because the pressure range of interest for this air flow is zero to only a few Pa.

CFD calculations are made to see in detail the behaviour of the fluid dynamics in the collector.

The ventilation rate is determined by steady state simulations for two given boundary conditions, the former corresponding to a normal operating condition and the latter corresponding to a stagnation condition. From the theory of chimney effects we can relate a pressure difference to the temperature condition of the collector.

The CFD simulations give us the impression of a linear behaviour and by incorporating this in the computer program we get a better agreement with the measured microclimate data.

The collector cover temperature and gap temperature calculated are in the range between the measured temperature at the bottom and the top of the collector. The relative humidity calculated corresponds closely to the measured relative humidity. Figure 10 shows the computed humidity in the gap, the measured humidity in the gap, the ambient humidity and in the bottom of the graph the wind velocity. The graph is visual aids for the days between 9th April and 15th April 1997.

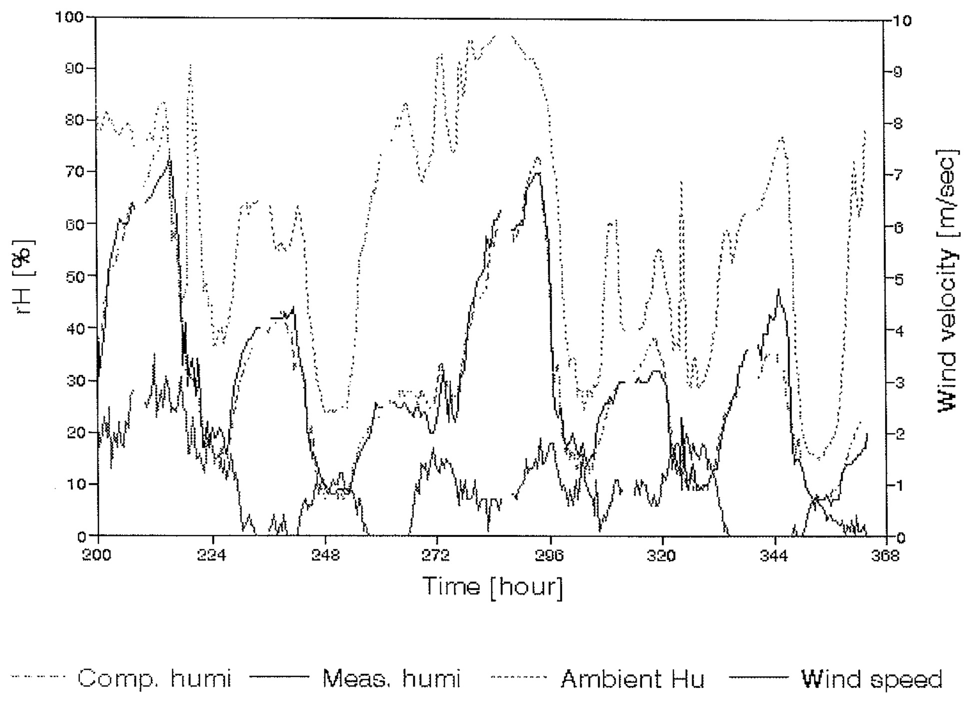

Figure 10. The lines representing the computed humidity and measured humidity in the gap match each other.

The figures inthe next following paragraphs are identical except for the lines corresponding to the computed humidity.

7. Sensitivity test of the computer program.

7.1 Influence of wind.

The influence of wind on the microclimate inside the collector has been investigated for time periods with very high wind speed. This has been done by analyzing the measured data statistically to see if there was a correlation to be found between wind velocity and the humidity i the air gap.

The conclusion of this analysis is that no correlation is found for wind components and the humidity inside the collector.

For modelling purpose, however, it is important to see more in detail on the influence of wind. Conclusion is difficult to draw from a statistically analysis, therefor the model is provided with an empirical dependence between wind velocity and ventilation rate.

By looking at simulated and measured data and by scaling up the influence of wind dependence in the model, we see how the agreement of the curves is improved. This is done for December in Denmark, the same period as analyzed statistically. The result of this investigation is remarkably good and encourages us to conclude the opposite than the statistical analyses have done.

To verify the conclusion several other periods of time were investigated.

The final solution is that there exists a dependence of wind velocity on the ventilation rate for the reference collector and certainly also a dependence of the humidity inside the collector.

On figure 11 the influence of taking wind into account in the model is shown by ignoring the influence and comparing with figure 10 in paragraph 6.3.

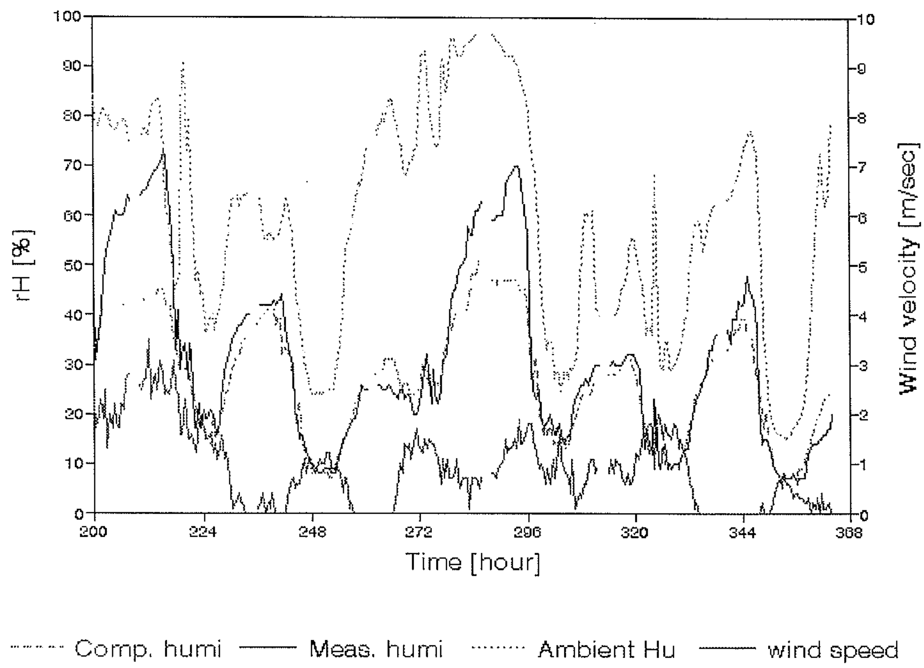

Figure 11. Ignoring the influence of wind leads to disparity between the lines representing the measured and computed humidity.

7.2 Influence of insulation materials.

The insulation materials lower the humidity during cold periods but can cause fog on the cover during the dry-out period with a warm collector. This can damage the collector and give a bad visual aid impression of the collector. On figure 12 the calculated higher humidity is attributed to the back-side insulation that has a thickness of half of the original thickness.

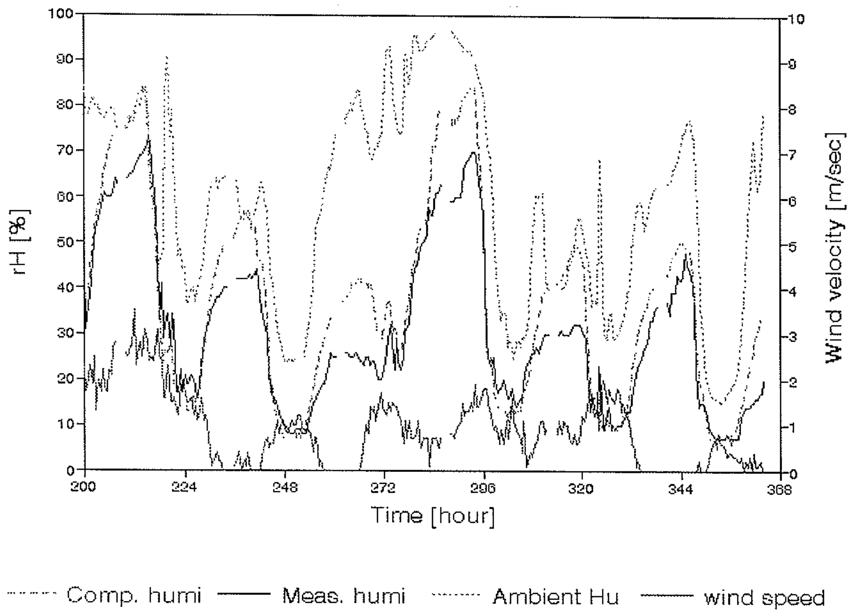

Figure 12. Incorporation of the reverse insulation thickness of half of the original thickness indicates a higher level of humidity.

To analyze the effect of relevant parameters on the humidity in the air gap and the occurrence of condensation on the inside of the cover the computer program offers a feasibility to make a parameter analysis. The result of such an analysis concerning the thickness of the rear insulation is presented in figure 13. The number of readings with humidity higher than a given rate and condensation more than the amount 0.01 g/m^2 is shown. The humidity in the air gap gets lower with increased rear insulation thickness, but the occurrence of condensation has an optimum for a thickness around 20 mm.

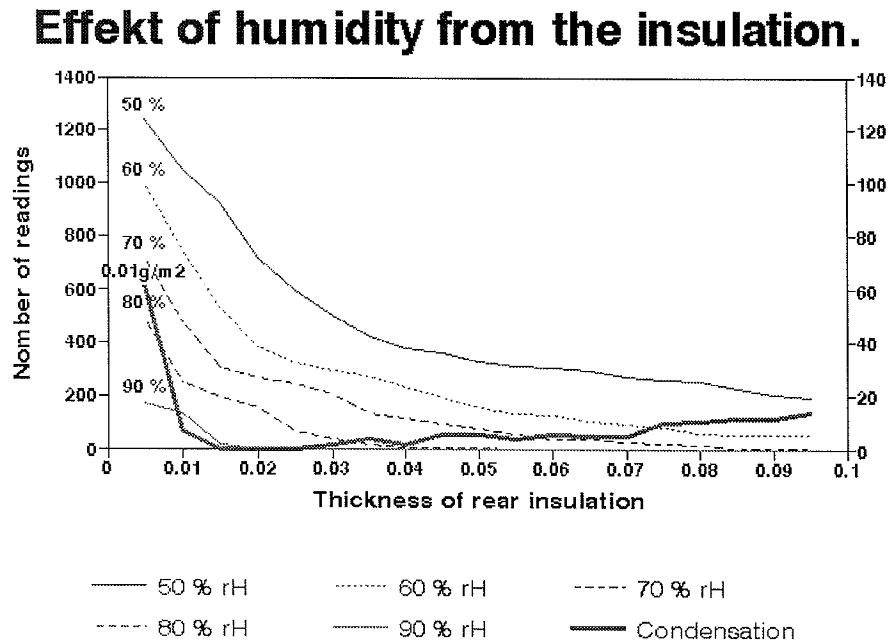

Figure 13. Parameter analyses of rear insulation thickness.

7.3 Influence of changing the ventilation holes size.

Calculations are made to investigate the influence of changing the ventilation holes size. This is done for a hole size double the original hole size and a hole size half the original size.

The effect of making the ventilation holes double size is similar to the effect shown in figure 3 for backside insulation with a thickness of half of the original. With ventilation holes with a size half the original size, a dryer situation appears.

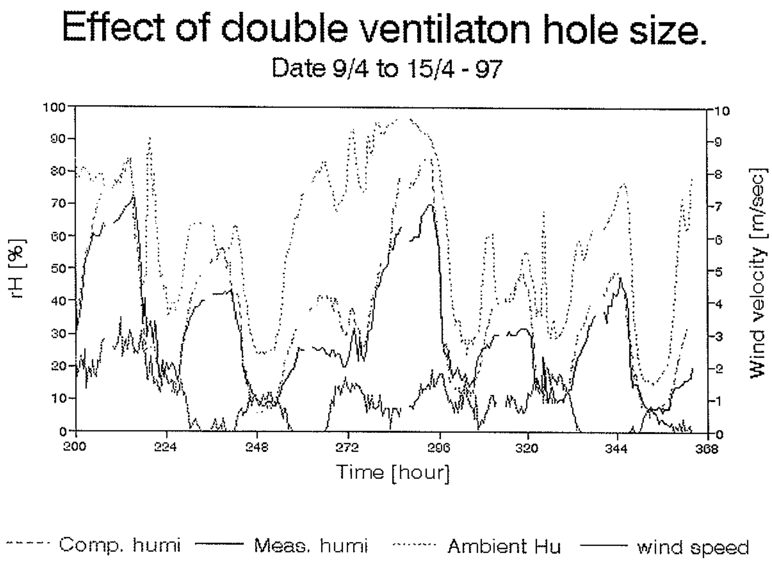

Figure 14. Incorporation of a hole size double the original hole size indicates a higher level of humidity.

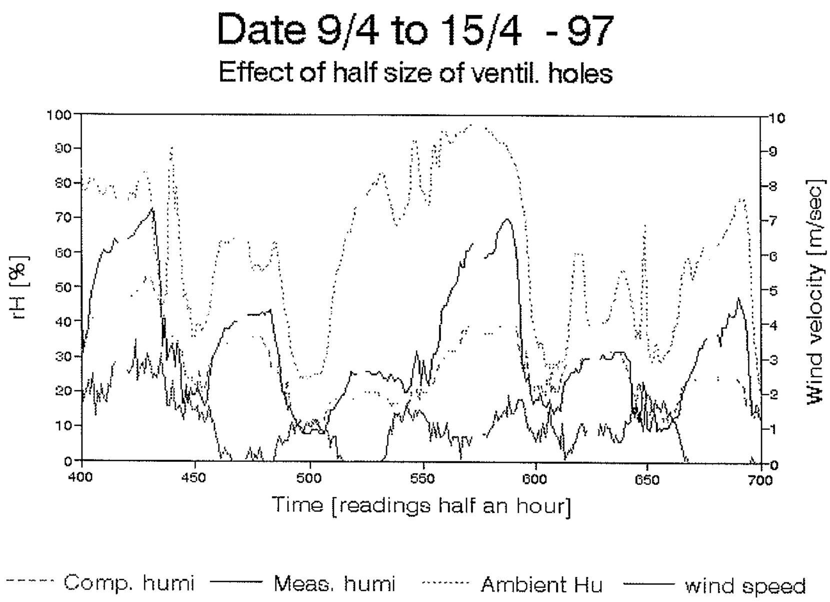

Figure 15. Incorporation of a hole size half the original hole size indicates a lower level of humidity.

To analyze the effect of ventilation a parameter analysis on a1 (a1 is a characterization factor for the tightness of the collector) is shown in figure 15. Increase of ventilation will increase the frequency of condensation except for a very tight collector.

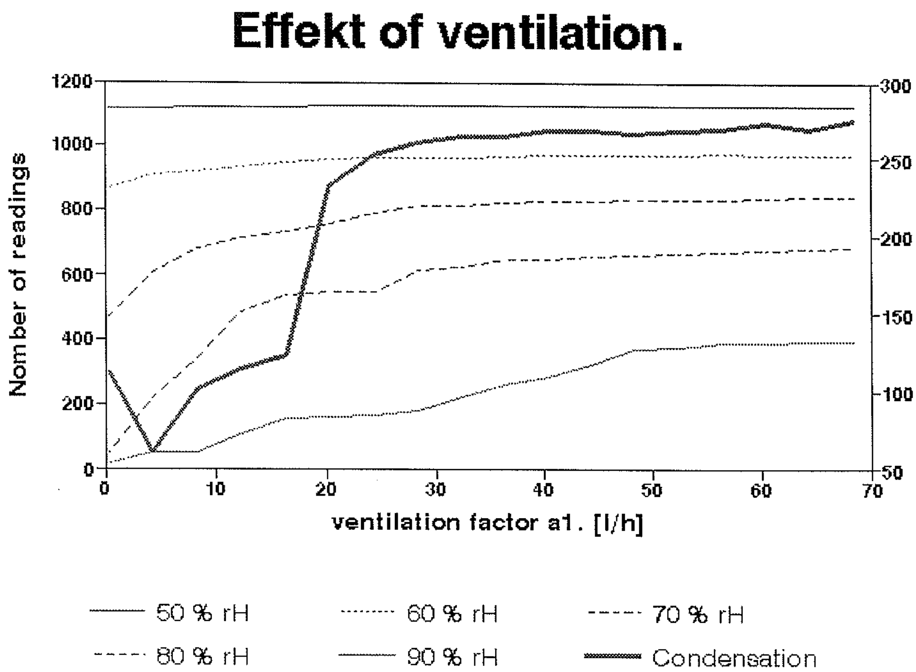

Figure 16. Parameter analyses on a characterization factor for the tightness of the collector.

8. Conclusions

Results from investigation of ventilation rates together with a model of the moisture inside the collector are built into a computer program. The computer program is used in connection with measurements of the microclimate in a reference collector.

The relative humidity and the formation of condensation inside the collector can be influenced by optimizing the ventilation rate and the insulation materials of solar collectors.

Calculations with the computer program show that there exists a dependence of wind velocity on the humidity inside the collector and that the insulation materials can lower the relative humidity in cold periods and later raise the level at the dry out period with a warm collector. A final judgement will need a calculation for a whole year and the computer program will then give the result as the time and amount of the formation of condensation inside the collector and time with height level of humidity in the collector gap.

This is important and can be used for creation of parameter sensitivity studies for accelerated testing and guidelines for solar collector design.

In this way the producers can be advised whether their solar collectors ought to be additionally tightened, or whether more ventilation openings should be made.

Acknowledgement

This project has been funded by the Danish Energy Agency and is a part of the work within the working group "Materials in Solar Thermal Collectors" of the IEA Solar Heating and Cooling Programme.

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Symbol	**Designation**
A	amplitude
a_c,alfac	the solar absorptance of the cover
C_c	the thermal capacity of the cover
C_p	the thermal capacity of the absorber, the fluid and half of the rear insulation
C_{pa}	specific heat of air, j/kg °C
C_s	Stefan-Boltzman constant, W/m^2 K^4
CD_abs	(time of) wetness, cover
CD_cov	(time of) wetness, absorber
d	displacement length

e_g	thichness of the air gab, m
ei	the thickness of the insulation
ε_p	emittance of the absorber plate
ε_c	emittance of the cover
ftaualfa	transmittance-absorptance product
fvvgt	ventilation due to stack effect
fmwg	mass of water vapour in the gap
fdmwv	mass of water vapour removed by ventilation
fdmwe	mass of water vapour removed by expansion of the air
fdmwci	mass of water vapour removed by condensation on the inside of the cover
g	gravitational constant, m/s^2
G,Gsol,E	the solar irradiation on the solar collector
Gr	Grashof number
h	the height of the air gap
h_{cb}	conduction through the rear insulation
h_{cg},fhcg	natural convection in the air gap
h_{rg}	thermal radiation in the air gap
h_{co}	convection from the outside of the cover
h_{ro}	thermal radiation from the outside of the cover
h_{vg}	ventilation of the air gap
ir	infrared radiation
k_g	thermal conductivitey of air, W/m °C
k_i	the coefficient of thermal conduction of the rear insulation
K_a	von Karman's constant
K_o	thermal conductivity of the ambient air, W/m °C
K_p	correction factor for the period
L	characteristic lenght, m
M_{ag}	the mass of dry air in the air gap
M_D	molecular weight of water
M_L	molecular weight of air
M_{wo}	the mass of aqueous vapour getting out of the solar collector
M_{wi}	the mass of aqueous vapour getting into the solar collector
m_{vg}	total mass flow of aqueous vapour and dry air
ntime	hours and minutes
N	air-exchange

N_c	air-exchange at a constant wind
N_g	air-exchange at gusts
Nu_g	Nusselt number for the gab
Nu_o	Nusselt number for the convection
Nu_{lam}	Nusselt number for laminar flow
Nu_{turb}	Nusselt number for turbulent flow
p	total baromatric pressure, Pa
Pamb	total barometric pressure
p_w	partial pressure of aqueous vapour
p_{wa}	partial pressure of water in the open air
p_{wg}	partial pressure of water in the air of the air gap
$p_{ws}(T_c)$	water vapor saturation pressure of the cover temperature, Pa
$p_{ws}(T_{dewa})$	water vapor saturation pressure of the dew point temperature of the ambient air, Pa
P	period
Pr	Prandtl number for the air
qEp	solar radiation absorbed by the absorber
qEc	solar radiation absorbed in the cover
qcb	heat loss by conduction through the back
qcg	heat loss by convection in the gap
qrg	heat loss by radiation in the gap
qco	heat loss by convection from the outside of the cover
qro	heat loss by radiation from the outside of the cover
qvg	heat loss by ventilation of the gap
q_{ei}	evaporation heat loss from the inside of the cover
q_{eo}	evaporation heat loss from the outside of the cover
r_c	heat of vaporization of water, J/kg
rh	relative humidity ambient
rh_gc,rh_agc	relative humidity air gap computed
rh_insu	relative humidity insulation
rh_ag	relative humidity air gap
Ra_g	Raleigh number for the gab
R_a	the gas constant for air
Re	Reynolds number for forced convection
Re′	Reynolds number for natural convection

Re_+	Reynolds number for forced and natural convection
s	slope of the collector, deg.
stiff	coefficient of rigidity
t	time
T	the temperature of the air
tight	fraction of tightness
T_a,ta	the ambient temperature
T_s	the temperature of the "black body" of the sky
T_c,tc	the temperature of the cover
T_p,tp	the temperature of the absorber
T_g	the temperature of the earth
T_abst	absorber temperature (top)
T_absm	absorber temperature (middle)
T_absb	absorber temperature (bottom)
T_agt	air gap temperature (top)
T_agm	air gap temperature (middle)
T_agb	air gap temperature (bottom)
T_covt	cover temperature (top)
T_covm	cover temperature (middle)
T_covb	cover temperature (bottom)
T_insu	insulation temperature
T_{gs}	the temperature in the air gap at the beginning of the time step
T_{ge}	the temperature in the air gap at the end of the time step
U_*	friction velocity
vvgg	ventilation due to gust
vvgv	ventilation due to direct wind
V_g	the mass of the air gap
V_w	wind velocity at the collector cover, m/s
V_z	wind velocity in level z
V(10)	meteorological wind at an altitude of 10 metres
$V(\Delta p)$	power function found at pressure tests
V_{lok},vw,v	local wind velocity
vsd	standard deviation of wind velocity
vd	wind direction
W	absolute humidity

wa	absolute humidity ambient
wgin	absolute humidity insulation
W_i	absolute humidity of incoming air
W_g,wg,wgm	absolute humidity of air in the air gap
W_{sg}	absolute humidity in the air gap at the state of saturation of the air
Z	vertical co-ordinate
z_o	the length of roughness
$(\tau\alpha)$	the transmission absorption product of the solar collector
ΔP	the difference pressure
ρ_a	the density of dry air
$\rho(T_a, p_{wa})$	the density of the open air
$\rho_a((T_p+T_c)/2, p_{wg})$	the density of the air in the air gap
ΔM_{wv}	the mass of aqueous vapour removed by ventilation
Δt	time step
ΔM_{we}	the mass of aqueous vapour removed by expansion of the air in the solar collector
ΔM_{ae}	the mass of dry air removed by expansion of the air in the solar collector
ΔM_{wc}	the increase of condensate on the inside of the cover
ν	kinematic viscosity of ambient air
ν	kinematic viscosity, m^2/s^2

Annex A: Collector test of relevance for microclimate in collectors.

1. Procedure of air tightness test of a solar collector box.

Procedure for a tightness test:

Introduction/Objective

The collector box is tightness tested to assess the ventilation of the collector. The tightness test gives the pressure differences between the inside of the collector and the ambient for different airflow through the collector box.

The result from the tightness test is needed for calculation of ventilation rate.

Scope.

The collector is tested in the laboratory for not more than one week before sending it to the next participant.

Normative references.

Definitions.

Requirements and classification.

Preparation of the collector.

Connect a plastic hose to the collector with connection to the air gap at the hole in the collector box clearly marked "Airflow connection" by the Fraunhofer Institute. The hose is sealed around the hole by silicone.

The inner diameter of the hose is approximately 6 mm.

The pressure sensor is mounted in a similar way at the hole in the collector box clearly marked "Pressure sensor".

Principle.

Apparatus.

The apparatus consists of a controllable air source, capable of supplying a value of positive or negative pressure at the collector for different collector leakage flow rate. An airflow meter with an accuracy of 10 l/h is installed to measure the rate of leakage and a micro-manometer with an accuracy of 2%, capable of measuring a gas pressure down to 1 Pa, is installed to measure the difference in pressure inside and outside the collector.

The air source, airflow meter and micro-manometer are connected to the collector.

The tightness test is made in two steps. One with air sucked in (under pressure), and one with air blown out from the collector (over pressure).

The used Instrument in Denmark is a gas meter, type positive displacement dry gas meter, in connection with a clock measuring the time during the test. The range is between 25 l/h and 5000 l/h with an accuracy of 1%. The pressure is measured with an FC0510 Micromanometer from Furness Controls Limited with an accuracy of 0.02 Pa, overruled by the changing of the pressure over time.

Test procedure.

Test procedure and instrumentation.

A controllable air source (could be a vacuum cleaner and a vario transformer), capable of sucking air out from the collector at different flowrates. An airflow meter with an accuracy of 10 l/h is installed to measure the rate of airflow.

The air source and airflow meter are connected to the collector.

No leaks between flow meter and collector.

First the collector is tested with overpressure in the collector box at 6 levels of air rate. The two lowest levels are optional if the range is out of practicability of the apparatus. Four readings of the pressure should be taken at each level. Next the collector is tested in the same way, but with an under pressure in the collector box instead of overpressure.

The levels needed for airflow range are 200, 400, 600, 1000 and 1500 l/h.

The same procedure is repeated with the ventilation holes closed at airflow ranges 100, 150 and 200 l/h.

Test conditions

Temperature and wind

The collectors are tightness tested at ambient temperature with no wind.

Pressure and flow-rate range

The pressure range is +/- 1 Pa to +/-200 Pa

The flow rate range is from 2 l/min to 200 l/min

Report.

The results are given by four tables clearly marked with ventilation holes open and overpressure or underpressure and ventilation holes closed and overpressure or underpressure. The total pressure p is given in [Pa] and the flow rate V(p) is given in [l/h].

Holes open Overpressure		200 l/h	400 l/h	600l/h	1000 l/h	1500 l/h
Pressure-readings	1 2 3 4					
Holes open Underpressure		200 l/h	400 l/h	600 l/h	1000 l/h	1500 l/h
Pressure-readings	1 2 3 4					
Holes closed Overpressure		100 l/h	150 l/h	200 l/h		
Pressure-readings	1 2 3 4					
Holes closed Underpressure		100 l/h	150 l/h	200 l/h		
Pressure-readings	1 2 3 4					

Outline the used instrument for measuring airflow and pressure.

Air flow:

Pressure:

2 Rain tightness.

The rain tightness of the solar collector box is very important in order to avoid severe problems with a very humid microclimate that will have a strong negative effect on the durability of the collector. The risk of water penetration is increased when the collector is exposed to both rain and gusts. The gusts will deflect the cover and create movements of air into or out of the collector box.

Rain penetration test.

A rain penetration test is included in the project, as lack of rain tightness of the collector box leading to ingress of water has to be avoided in order to obtain an acceptable microclimate.

The collector shall not permit the entry of either free falling rain or driving rain. The water is not allowed to come into contact with parts that should be dry under all circumstances. Penetration of water is only to be found in parts of the collector designed to drain off water. Water can penetrate through leaks in the collector box when water runs off the surface or the water could be sucked in through cracks and apparatuses.

Special circumstances may be present, and not in all cases the test method will fit in. Consideration must be made in cases where the construction differs from normal practice, special mounting construction, collector design with curved glazing or unglazed could be present or the back could be very open.

Besides the reporting of the amount of water penetration and the places where the water penetrated, it is important to give information of the deflection of the cover and the back of the collector. This information is useful for characterization of the collector for ventilation due to gusts.

The rain penetration test is included in the CEN-standard draft. The equipment for the performing of rain penetration tests is available in many testing and research institutes. Documentation of the possibility of making rain penetration tests is:

Sweden, SP

Mechanical deflections of the cover take place in a cyclic way with a positive or negative load of 500 Pa. This can be done in connection with the collector exposed to rain in the form of a spraying system with nozzles.

Maximum tested object width: 3.6 m

Maximum tested object height: 2.8 m

No tilt of the collector is possible.

The collector is not sprayed from the back.

Switzerland, SPF

Mechanical deflections of the cover take place in a cyclic way with a positive or negative load of 600 Pa. This can be done in connection with the collector exposed to rain in the form of a spraying system with nozzles.

Denmark, DTU

Mechanical deflections of the cover take place in a cyclic way with a positive or negative load of 600 Pa. This can be done in connection with the collector exposed to rain in the form of a spraying system with nozzles.

Maximum tested object width: 2.0 m

Maximum tested object height: 3.0 m

An inquiry shows us that testing equipment is available at the following institutes:

Swedish National Testing and Research Institute, SP, Sweden.

Solar Energy Testing and Research Group, ITR, Switzerland.

Danish Technological Institute, DTI, Denmark.

Technical University of Denmark, DTU, Denmark.

and that the facility is planned for the next mentioned institutes:

Fraunhofer Institute for Solar Energy Systems, ISE, Germany. (Planned)

Building and Construction Research, TNO, the Netherlands. (Planned)

Department of Renewable Energies, INETI, Portugal. (Planned)

Deflecting the cover.

Due to gusts the cover may deflect and cause a positive or negative pressure in the collector box. This again will lead to a flow of air out of or into the collector box. If a flow of air into the collector box takes place the risk of having rainwater penetrating the collector box is increased. Besides that the movements of the cover due to wind gusts may in some constructions have a negative influence on the water tightness of the sealing systems.

Three ways of creating negative pressure in the collector box and deflecting the cover are possible.

Firstly by connecting a vacuum pump to the collector box, secondly by mounting the collector in the opening of a box in which the pressure can be varied and thirdly by applying a mechanical load to the cover.

The first method, using a vacuum pump, is not recommended because the test is not realistic as neither the pressure nor the air flow into the collector box is a result of the deflection of the cover. A realistic pressure difference as driving force for air ventilation between outside and inside of the collector box is approximately 15 Pa and the pressure causing the deflection of the cover is 600 Pa. The test is only suitable for detecting where leakages may take place.

The advantages of this method are low costs for equipment as only a vacuum pump is needed.

The second method is "The pressure box method". In this method a certain differential pressure between the cover and the back of the collector is established. The collector is mounted in the opening of a box. If the pressure in front of the collector only influences the glass and the pressurized side is in front at the glazing the driving forces are due to the deflection of the glass and the method is realistic for collectors built into the roof.

The advantage of this method is a more realistic system for collectors built into the roof and a uniform distribution of the pressure over the area.

Disadvantages are that apparatus are room consuming as the spraying system should be inside the pressure box. The method is not suitable for collectors mounted with no integration in the roof or collectors mounted on a rack. This is because the pressure on the top of the collector will be the same as the pressure beneath the collector, the collector is inside the pressured box and the system will be similar to the first method. The method differs from reality by the missing air flow passing the collector.

The third method is based on an apparatus where a number of suction cups can be placed on the cover of the collector. The cover is deflected inward or outward corresponding to the test pressure that is applied and maintained for a short time. Depending on the deflection of the cover and the air tightness of the collector box a differential pressure between the inside and the outside of the collector box will be created and an air flow into or out of the box will take place.

The advantage of this method is that it is a realistic method of simulating gusts both for collectors built into the roof and for collectors mounted on top of the roof or at an open frame. The apparatus is easy to build together with spraying systems and can easily be mounted on outdoor test facilities.

Disadvantages are the costs of the apparatus. For collectors built into the roof water must not enter the collector from behind, therefor a simulated roof had to be made for the collector. The test method is not appropriate to unglazed solar collectors or collectors with curved glazing, this is due to the adhesion of the suction cups.

One more method is to be mentioned. That is the use of a wind tunnel, where the collector is mounted inside, and the air flow is pulsating. If no such tunnel is available this method will be too expensive.

Differences in collector types and the way of mounting the collector.

Tiles are the dominant type of roof cladding in Holland and the bulk of the collectors is mounted directly on the timbers and has a gutter system to carry off water. The back of the collector is not prepared to withstand a large amount of water as this will never be a normal circumstance during the lifetime.

Without exception the collectors are of a very open type with regard to the ventilation. Care should be taken not to make a direct ventilation connection through the roof construction. This is to prevent that exfiltrated air with high humidity condenses inside the collector.

In the rest of Europe the collectors are often mounted on top of the roof or at an open frame.

Test results from the rain tightness test.

The rain penetration test has been performed with the reference collector in Switzerland and in Denmark, and in both countries no sign of penetration shows up. The test condition is according to the actual version of the CEN WG1 draft standard.

Results from rain tightness test made in Switzerland:

Switzerland measured humidity during and after testing.

Collector name	-	Schweizer
Inspection	-	No serious increase in absolute humidity in collector during test where the collector is exposed to both rain and mechanical deflections of the cover.
		No sign of water penetration during the rain tightness test.

Results from rain tightness test made in Denmark:

Collector name	-	Schweizer
Inspection	-	No sign of water penetration during a 4-hour test without deflection of the cover.

A slight amount of moisture shows up at the inlet corner of the cover during a test where the collector is exposed to both rain and mechanical deflections of the cover.

No serious sign of water penetration during the rain tightness test.

Procedure for rain penetration test

Objective

This test is intended to assess the extent to which collectors are substantially resistant to rain penetration under conditions without wind and with gusts. They shall normally not permit the entry of either free falling rain or driving rain. Collectors may have ventilation holes and drain holes, but these shall not permit the entry of drifting rain.

Apparatus and procedure

The collector shall have its fluid inlet and outlet sealed, and be placed in a test rig at the shallowest angle to the horizontal recommended by the manufacturer. If this angle is not specified the collector shall be placed at a tilt of 30 degrees to the horizontal or less. Collectors designed to be integrated into a roof structure shall be mounted in a simulated roof and have their underside protected. Other collectors shall be mounted in a conventional manner on an open frame or a simulated roof.

In order to simulate the effect of gusts the cover of the collector should be deflected mechanically i.e. by use of suction cups and pneumatic cylinders. The load can be applied in different ways but the equipment should be able to apply both negative and positive loads on the cover in a way that allows the cover to move in a flexible way.

The collector shall subsequently be sprayed on all sides using nozzles or showers for a test period of four hours without deflection of the cover.

The collector shall be sprayed with water while exposed to a cyclic deflection of the cover.

Detection of ingress of water

The collector shall be mounted and sprayed as explained above while the absorber in the collector is kept warm. This can be done either by circulating hot water at about 50 C through the absorber or by exposing the collector to solar radiation. The penetration of water into the collector shall be determined by inspection, looking for water droplets or condensation on the cover glass.

The heating up of the collector should be started before the spraying of the water in order to secure that the collector box is dry before testing.

Test conditions

The collector shall be sprayed with water at a temperature lower than 30 C with a flow rate of more than 0.05 l/s per square metre of collector aperture. The duration of the test without deflection of the cover shall be 4 hours. The mechanical deflections of the cover shall take place in a cyclic way with a positive or negative load of more than 600 Pa. The maximum load shall be kept for about 3 seconds and the total of one cycle should not be more than 20 seconds.

Requirements of water tightness

The definition of water tightness is that penetrating water is not allowed to come into contact with parts that should be dry under all circumstances, glass panes and interior parts should not become wetted and in the case when water penetrates, this may only be found in the parts designed to carry off water.

The pass/fail-criteria for the part of the collector test without deflection of the cover:

Area with visible sign of rain penetration, must not exceed one per thousand of the aperture area. And in addition the sign of rain penetration shall vanish after end of exposure to rain in a time not exceeding one hour.

The pass/fail-criteria for the part of the test with the collector exposed to a cyclic deflection of the cover:

Area with visible sign of rain penetration, must not exceed one percent of the aperture area. And in addition the sign of rain penetration shall vanish after end of exposure to rain in a time not exceeding one hour.

Results

The collector shall be inspected for water penetration after each part of the test. The results of the inspection i.e. the amount of water penetration and the places where the water penetrated shall be reported.

In connection with the mechanical deflection of the cover it is important to report the movements of the cover and the movement of the back of the collector.

The amount of water penetrated is reported as percentage of the aperture area with sign of water penetration.

Conclusion

Under no circumstances the collector may permit the entry of either free falling rain or driving rain. The pulsating air pressure applied to the cover of the collector is therefore chosen as an extreme value. The maximum load of 600 Pa corresponds to a velocity of the wind at 30 m/s and corresponds to used practice for windows and building components. The pass/fail-criteria for the part of the collector test with deflection of the cover are more gently due to the extreme condition.

Standards of other building components according to rain-tightness.

European standard

DIN-EN86, Jan. 1981.

Prüfverfaren für Fenster, Prüfung der Schlagregendichtheit unter statischem Druck

CEN/AC 89 N 438 E, Mar. 1995.

Building components - Determination of resistance of external wall systems to driving rain under pulsating air pressure.

Dutch standard

NEN 3661 2nd print, July 1988.

Requirements on air permeability, water tightness, rigidity and strength.