T18/B2/WD2/96

IEA SOLAR HEATING AND COOLING PROGRAMME

TASK 18

ADVANCED GLAZING
AND
ASSOCIATED MATERIALS FOR SOLAR AND BUILDING APPLICATIONS

B2 Geometric Media

Optimization of geometric media for solar applications

W. J. Platzer[1], B. Karlsson[2], T. Ojanen[3]

[1)] Fraunhofer-ISE, Oltmannsstr. 22, D-79100 Freiburg, FRG

[2)] Vattenfall AB, Älvkarleby Laboratoriet, S-81070 Älvkarleby, SWE

[3)] VTT, Lab. Heating and Ventilation, P.O. Box 206, SF-02151 Espoo, FIN

email: platzer@ise.fhg.de

December 1996

1. Introduction

Transparent insulation materials (TIM) provide a convenient possibility to improve and to optimize many different solar systems. However, the benefit depends largely on the application investigated and on the specific transparent insulation chosen. There is an obvious need for methodologies in the field of application guidance.

Transparent insulation when compared to conventional collector covers, say for a collector with selective absorber, does improve the thermal insulation of the collector usually, but decreases the optical efficiency somewhat due to the additional optical losses in the transparent structure. Therefore quite generally collectors with transparent insulation materials are useful for

a) low ambient temperature or high operating temperatures
b) low irradiation levels and
c) large operating time. e.g. for storage collectors or passive storage walls

For these cases the improvement in insulation is more important than the reduction in optical efficiency. For flate plate collectors a parallel case is known: unglazed collectors are already sufficient for swimming-pool applications in summertime.

If one enters the realm of theoretical optimization, one discovers that many parameters may be changed and therefore enter the optimization procedure in principle. In practice, only a few parameters are assumed to be variable, and most are taken for granted. This depends largely on the viewpoint and the interest of the investigator. In this working document groups from three different countries present case studies for solar systems interesting in their country, treated with very different methodology and approach. Thus the document gives a non-exhaustive insight into the field of transparent insulation. Many other case studies can be imagined leading to positive results.

The question of optimization is only treated on the basis of energy benefits. Economical considerations are not considered in the optimization objectives. Of course, this viewpoint is very important in real life, but on a research level, the cost estimates for new systems are not stable enough to provide a sound basis for an economical judgement. On top of that the economical boundary conditions may be rather different within a relatively short period of a few years. It seems appropriate therefore to leave the economic analysis to more applied and detailed industrial oriented projects.

2. Optimisation of transparent insulation for specific applications

In the following sections different optimization case studies are presented. Some use a theoretical approach, others rely on a set of experiments. The aim is certainly very different. It reaches from the optimization of the transparent insulation material itself to the optimization of a certain design using a selected material. The first section gives a short introduction into the modelling of transparent insulation materials, as this is the basis for the material optimization. Other case studies do not need this tool but need only performance data for the investigated materials. These performance data in

collector cover, and the heat loss coefficient U describing the heat losses through the cover.

These performance data can be determined experimentally, which has been done for some of them

approximately determine these data by the computer program TSET2.0, which has been distributed by Germany to the Task 18 participants[1]. This program is based on non-spectral models of the

towards a spectral model which is not yet implemented.

2.1. ent insulation materials (FRG)

2.1.1. Optical and thermal modelling of materials

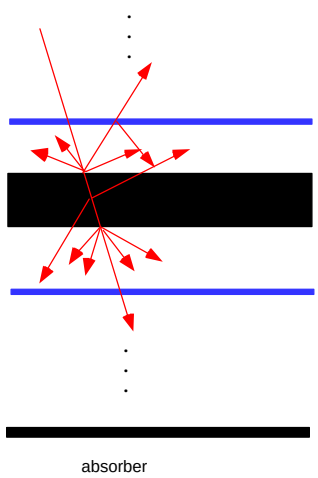


Fig.2.1: Sketch of the multilayer model

The optical transport has to deal with direct and diffuse

are dependent on wavelength. Measured data usually are

reflectance. Alternatively, the properties of individual

structures from optical data of a single plastic film. A good

data availability is the use of a spectral four flux model,

components of the radiation.

reflections) also the properties for diffuse irradiation, which

measurements.

The method combines two existing algorithms of different character, one for the multiple film

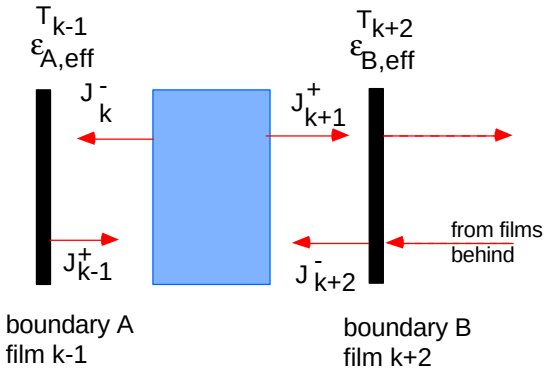
2

1

2

with Diathermanous Covers, Sol. Energy, vol. 31/3 (1983) 211-216

boundary layers (Platzer[3]). The latter algorithm was developed for and applied to a honeycomb material treated as an "effective absorbing-emitting medium".



$$e_{A,eff} = J^{+}_{k-1} / E_{b,k-1} \quad \text{with} \quad E_{b,k-1} = s \cdot T^{4}_{k-1}$$

$$e_{B,eff} = J^{-}_{k+2} / E_{b,k+2} \quad \text{with} \quad E_{b,k+2} = s \cdot T^{4}_{k+2}$$

Fig. 2.2 Pictorial and mathematical description of equivalent boundary values for combined method

The models are combined with the help of effective boundary conditions. Temperatures and surface coefficients are determined in an sequential, iterative way.

2.1.2. Results

Results e.g. for a low-e capillary glazing are presented in the following table. A comparison with the experimental data is given for two cases calculated with the model.

Table 2.1: U-value for capillary glazings (in W/m^{2}K)

gas filling	experimental	modelled
air	-	0.87
Argon	0.80 ± 0.03	0.77
Krypton	0.67 ± 0.03	0.68

Figures 2.3 and 2.4 present results for the angular dependent optical properties of these systems. In Figure 2.3 the spectral transmittance curves calculated with the multilayer model and data for the individual layers are compared with the direct measurement of the component. The difference is very small for all angles of incidence. The total solar energy transmittance g has also been calculated from these data and compared to experimental data from the calorimetric device used within the project B12. There is a systematic underestimation of the value of g for large incidence angles. It is not clear at the moment whether this is due to experimental problems for off-normal incidence or whether this is a failure of a too simple model.

[3] W.J. Platzer, Calculation procedure for collectors with a honeycomb cover of rectangular cross-section, Solar Energy, Vol. 48 No. 6, (1992) S. 381-393

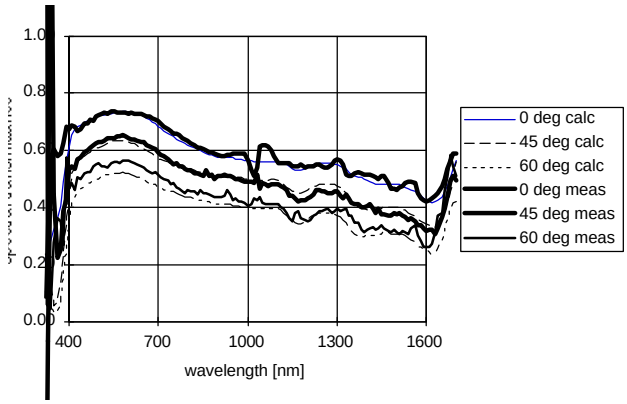


Fig. 2.3: Comparison of spectral directional-hemispherical transmittance of a capillary glazing with two sheets of glass

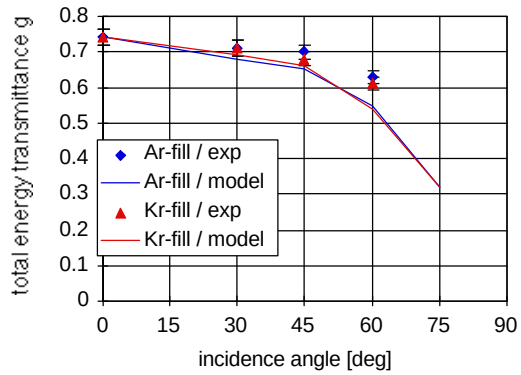


Fig. 2.4: Total energy transmittance - calorimetric measurement and model calculations from spectral data

2.2. Optimization of a honeycomb structure for a solar collector cover (FRG)

2.2.1. System

As an example an idealized integrated storage collector (ISC) with capillary TIM-structures as cover is evaluated. Optimal aspect ratios and film thicknesses are determined for selective and black absorbers in dependence on layer thickness. The effect of system operation modes on optimal parameters is shown by means of differing load flows.

2.2.2. Optimisation objective

The optimization aim is to design honeycomb covers in a way to find the optimum balance between solar gains and heat losses for TI-systems, which results in maximum solar output, e.g. the yearly output per square meter collector area. Altering certain parameters of the investigated solar system, e.g. film thickness, different materials etc., usually affects both properties. So the influence of a parameter on solar transmittance as well as on heat losses and their combined effect on the output of the solar system must be evaluated.

The optimum balance between heat losses and solar gains is also affected by weather conditions and by the analysed system itself, for instance by temperature levels, opaque insulation, air gaps and operation modes like heat loads. Therefore the system parameters and the location, for which the optimization is done, must always be specified.

For the right choice or design of honeycomb and capillary structures it is of importance to know which geometries and material densities for a given material yield best results regarding solar output. As the possible amount of different structure designs is limited the variability of solar output on deviations from optimal parameters as well as the sensitivity of optimal parameters to different applications, climates, TIM- absorber set-ups and operation modes should be known.

Previous works on TIM optimization problems did not consider the time-dependent performance of TI systems or focused on specific questions or TI-absorber set-ups (e.g.[4,5,6]). For these reasons

[4] H. Schweiger et.al., Optimization of total energy transmittance and heat transfer in a solar collector with honeycomb glazing - a numerical study, Proc. TI6, Birmingham (1993)

optimization and simulation tools have been developed, which allow variation and optimization of honeycomb and capillary TIM-structures for basically any kind of TI-application. The modular set-up allows a maximum of flexibility to study various TI-systems. Many aspects of the transparent cover, like the use of one or two glass panes, the inclination of the system, absorber emittance etc., can easily be taken into consideration. Through the link with a comprehensive solar system simulation tool external effects of climates and operation modes can be evaluated as well.

2.2.3. Method

The developed program consists essentialy of three parts (see Fig. 2.5):

- optimization and file handling procedure (OPTI)
- calculation of optical and thermal properties of TIM-covers (TSET2.0)
- system simulation (TRNSYS)

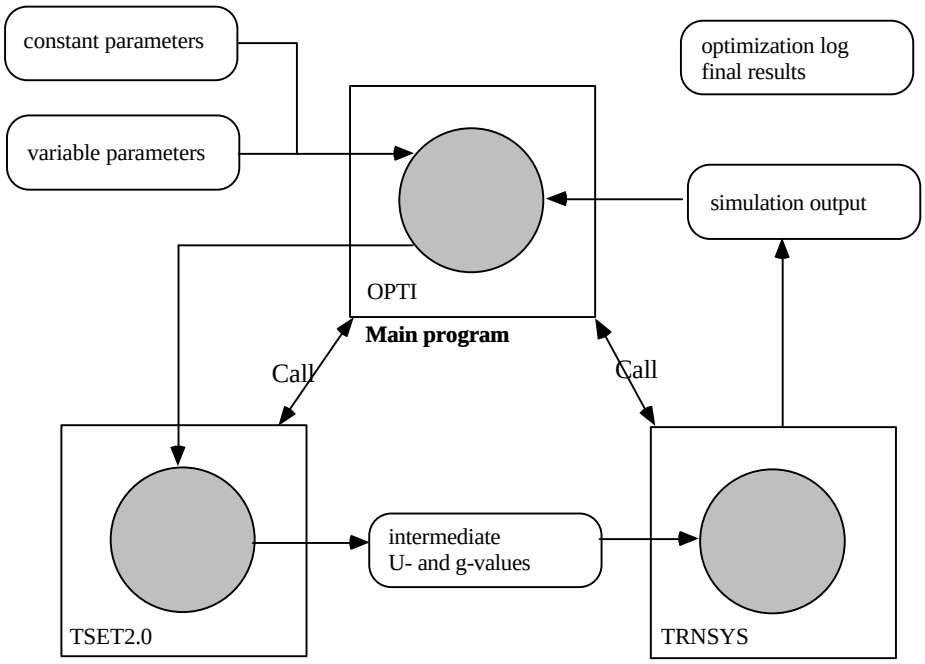


Fig. 2.5: Information and control links between the optimization programs

The data for the TIM-absorber set-up (material properties, air gaps, glass panes etc.) are provided by the user in two files; one for the parameters held fixed and one for the parameters subject to optimization. The data is passed to the program TSET2.0 by the main procedure for computing the optical and thermal properties of the transparent cover. Sufficient suppression of free convection in the cells is a precondition for the calculations. For practical cases this can be assumed - depending on temperature-levels and -differences - for aspect ratios A = D/x larger than 8 to 10 (D: TI layer thickness, x: cell diameter).

The two most important quantities characterizing the performance of a TIM containing cover are:

---

[5] L.F. Jesch et.al., Optimization of Honeycomb cell geometry for transparent insulation, Proc. TI3, Titisee/Freiburg (1989)

[6] W. J. Platzer, Optimization problems of transparently insulated systems, Proc. TI2, Freiburg (1988)

- angular dependent total energy transmittance (g-value) (or: effective transmittance-absorptance product $(\tau\alpha)_e$), which includes not only the transmitted solar radiation but also the part of solar radiation absorbed in the cover and reaching the absorber as heat;
- temperature dependent heat loss coefficient (U_f-value), which depends on the absorber temperature and the temperature difference between absorber and outer surface of the cover.

The U_f-value will vary with time as temperature levels in the system change during operation. Because the amount and direction of solar radiation is also time-dependent, dynamic simulations should be carried out to determine solar gains and heat losses in dependence of time for the net energy balance of the system considered.

Different system simulation tools - like TRNSYS, which has been chosen for our calculations - can be used. However, they must be capable to process angular dependent g-values and temperature dependent U_f-values. An adaption of these values by the main procedure is necessary to provide the values suitable for the system simulation program. Usually, for each TIM-application some programming work must be done.

The g- and U_f-values of the transparent cover, or adequate transformations, serve as inputs for the system simulation. The simulation is carried out for a whole year or for a shorter period of interest. The output of the system simulation is the quantity to be maximized or minimized (e.g. useful collector output or auxiliary energy demand).

2.2.4. Results

Only one type of transparent insulation material is considered in the following. It is made of polycarbonate (PC) with capillary structures. The TIM structure further consists of an adjacent front and back low-iron glass pane. The material properties of polycarbonate films are based on experimental data and calculated in dependence on film thickness with the support of theoretical models.

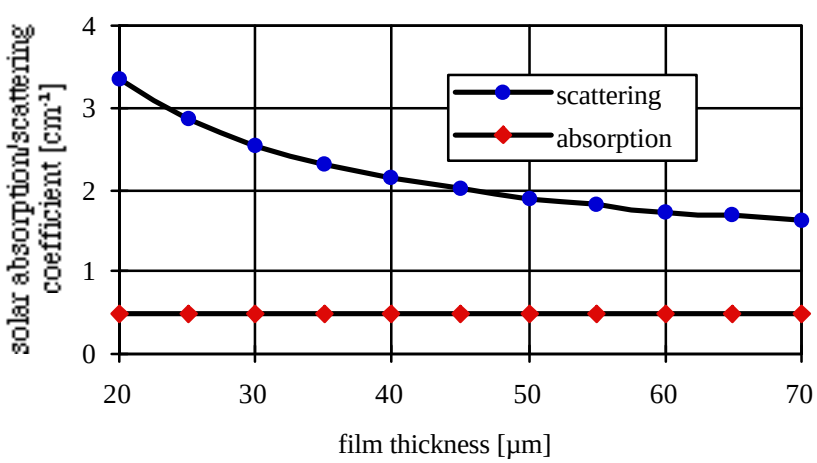


Fig.2.6: Effective scattering and absorption coefficients for polycarbonate as a function of film thickness

The ISC output increases steadily with TIM structure thickness, yet the rate of increase goes down. As the structure thickness always runs to the upper limit imposed, the optimization is carried out for different TIM structure thickness with d_F and A subject to optimization. Results for a selective (emittance $\varepsilon = 0.15$) and a non-selective ($\varepsilon = 0.90$) absorber are given in Figure 2.7 and Table 2.2.

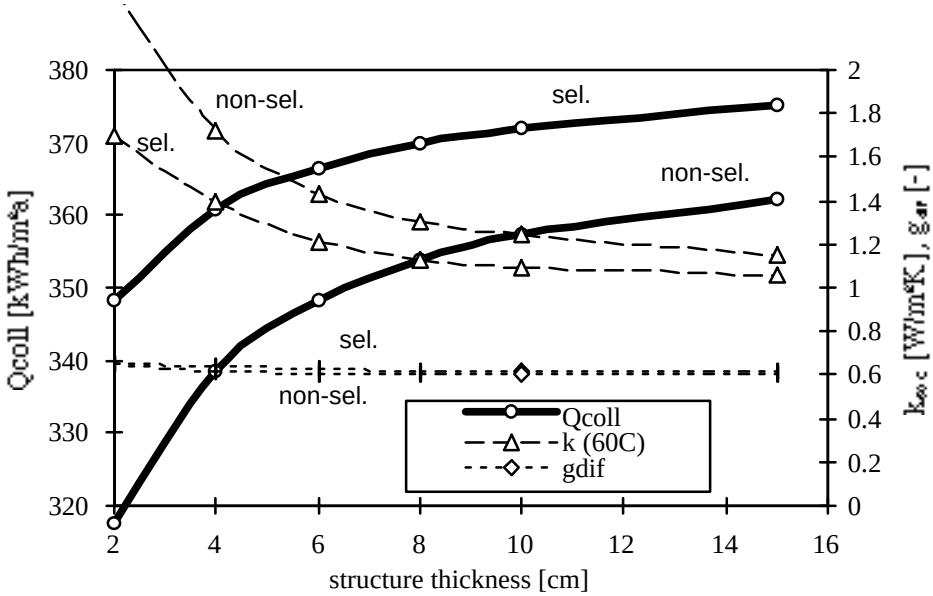


Fig.2.7: Collector output for different structure thickness with optimal parameters

It can be seen that thicker layers are more important with black absorbers. However, even very thick TIM-structures with non-selective absorbers can hardly make up for the effect of selective coatings.

Table 2.2: Optimal parameters for honeycombs of different thicknesses

	selective Absorber				black Absorber			
D [cm]	A [-]	d_F [µm]	$U_{60°C}$ [W/m²K]	g_{dif} [-]	A [-]	d_F [µm]	$U_{60°C}$ [W/m²K]	g_{dif} [-]
4	11	33	1.40	0.64	17	32	1.72	0.62
6	14	38	1.21	0.63	21	35	1.43	0.60
8	15	39	1.13	0.62	21	37	1.30	0.60
10	15	41	1.09	0.62	21	39	1.24	0.60
15	15	39	1.06	0.62	22	38	1.15	0.60

In Table 2.2 the U-values of the front cover (from absorber surface to ambient) for an absorber temperature of 60°C and the diffuse g-values are given explicitly. Due to lower radiative losses of the selective coating the U_f-value is always lower than without selective coating, even with larger cells for the selective case. At the same time more solar radiation can reach the absorber (better g-values), resulting in a better collector performance.

For the evaluated case of the integrated storage collector optimal aspect ratio as well as film thickness depend only weakly on structure thickness. Optimal cell width for thicker layers shift to larger values as aspect ratio stays approx. the same. Selective absorbers require large cells with aspect ratios around 8. For layers thinner than 60 mm optimal aspect ration would even lie below that. However, convection - its suppression is a requirement for calculation the U_f-values - is then not negligible any more. An aspect ration of 8 was therefore set as a boundary condition. With black absorbers higher aspect ratios should be used due to the improvement in U_f-value.

Optimal values for film thickness are basically the same, independent from absorber emissivity. However, there is still uncertainty, whether scattering takes place mainly in the material or at its surface. This strongly affects the calculation of the optical films parameters and in turn of optimal d_F-values. The volume fraction of scattering is expected to be about 50% at a film thickness of 50 µm, a value which was used for the present calculations. If surface scattering is more important thicker films with larger cells are the better choice. Thinner films are favorable if the volume fraction of scattering is significantly higher than currently assumed.

In addition , the precise input parameters of the model cannot be extrapolated to film thicknesses far from those of measured structures due to changing manufacturing quality (smoother surfaces can be expected with thicker films). An experimental characterization of the optical properties depending on film thickness would be necessary to clarify this problem.

2.2.5. Variability of solar output on aspect ration and film thickness

Figure 2.8 shows, how solar output of the integrated storage collector varies with deviations from optimal d_F- and A-values. Calculations were carried out for constant structure thickness of D = 100 mm, black absorber and the test reference year of Freiburg. The area of optimal values is rather flat which is important for manufacturing transparent insulation material. Small deviations from optimal values are not critical, but for d_F- and A-values far from the optimum the collector output drops considerably. Especially small cells and thick films result in a poor ISC performance.

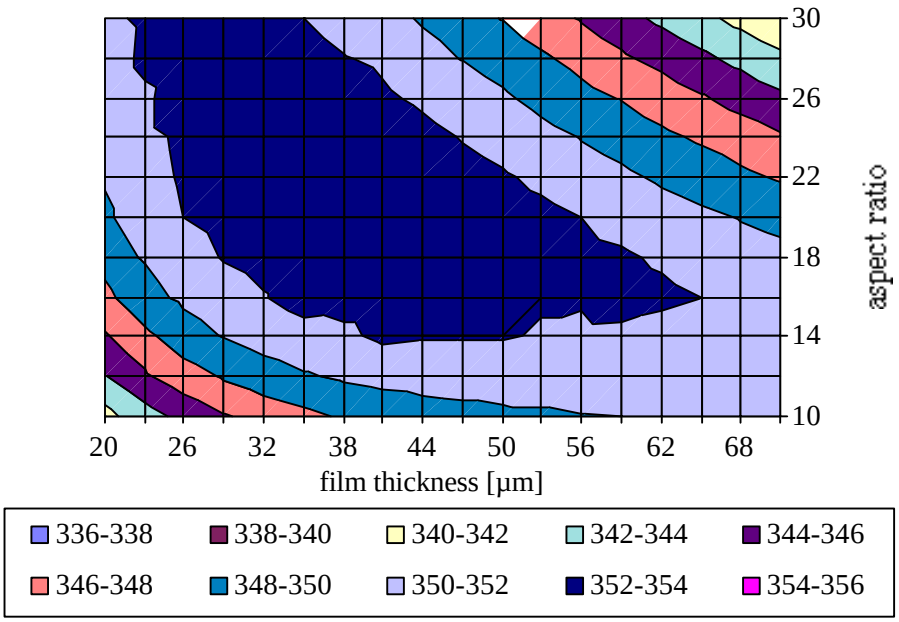


Fig. 2.8: Yearly area-specific collector output in kWh/m²a for variable film thickness and aspect ratio (Polycarbonate honeycomb, D=100mm, non-selective absorber)

2.2.6. Differing Load Flows

As an example for the influence of operation mode on optimal parameters the daily load is varied. The TIM-layer thickness is held fixed at D = 100 mm. From Table 2.3 it can be seen that optimal U_F-values and g_{dif}-values increase with higher flow rates. Optimal film thickness remains the same, but optimal cell diameter increases significantly with higher loads.

This can be explained by the different temperature levels in the collector. If more water is taken out of the storage collector, the mean temperature in the tank decreases. If temperature levels are lower, larger cells (higher g-values) lead to an optimal balance between solar gains and heat losses. With

higher temperatures (smaller loads) the importance of the U_f-value increases due to the temperature dependence of the U_f-value.

Table 2.3: Optimum TIM parameters and collector output per area for a load flow rate of 60l/day

structure thickness [mm]	aspect ratio [-]	film thickness [µm]	U_f(60°C) [W/m^{2}K]	g_{dif} [-]	Q_{coll} [kWh/m^{2}a]
selective case ε=0.15					
40	9	32	1.48	0.65	465
60	9	35	1.38	0.65	470
80	9	37	1.33	0.65	473
100	9	39	1.29	0.65	475
150	9	42	1.22	0.65	478
non-selective case ε=0.90					
40	12	33	1.87	0.64	438
60	14	35	1.61	0.63	447
80	15	34	1.48	0.63	452
100	15	39	1.43	0.63	456
150	15	38	1.36	0.63	461

2.2.7 Conclusions

A versatile method has been developed which allows to combine two existing programs with the help of a control and optimization loop. The two existing parts in our case are the dynamical simulation tool TRNSYS for hourly collector performance simulation, and TSET2.0 which is able to determine optical and thermal properties for different transparent collector covers utilizing transparent insulation materials. Other tools could be linked in a similar way. The advantages are manifold. Existing and validated tools can be linked without large effort. Intermediate results may be monitored. Updates of the simuilation tools can be provided by different parties. The calculation of the physical material properties are performed only once at the beginning of a system simulation.

In our example an integrated storage collector was optimized. Efficient systems should

- be very well insulated also on the back and on the side
- have a selective coating on the absorber
- have only one outer glass pane
- have an air gap between absorber and transparent insulation cover of at least 15mm

With respect to the honeycomb cover it can be said for collectors with selective absorbers:

- For polycarbonate honeycombs film thicknesses of about 40µm and aspect ratios of about 10 to 15 are recommended
- The material thickness should not be lower than 60mm. More than 100mm is not necessary as the improvement is minimal.

The optimum surfaces for different material parameter are usually flat. IT is not critical to deviate by some extent from the mathematical optimum. Therefore one material design is believed to be sufficient for several collector designs and in various climates.

2.3. Choice of material thickness for large-area solar collectors for district heating systems (SWE)

2.3.1. System

In Sweden, the collectors in the large solar systems used for district heating, operate at relatively high temperatures (50-90 °C). The most common TIM (Transparent Insulation Material) used in those collectors today is a flat Teflon film mounted between the cover glass and the absorber. However, because of the high temperatures, there is a need for a TIM with a lower heat loss coefficient. An interesting material, which is available on the market, is the Arel polycarbonate honeycomb, with a cell size of approximately 3.8 * 4.3 mm. This material of 10 cm thickness aimed for the operating temperature range of 90-150 °C, was previously investigated by Rommel and Wittwer[7]. Our temperature range is lower, so therefore we have also been looking at thinner honeycombs.

2.3.2. Optimisation objective

The question posed is which honeycomb thickness gives the best yearly output for solar collectors integrated into the district heating system. The material itself should be not be modified. As a reference the collector with a Teflon film as convection barrier will be taken.

2.3.3. Investigations

Laboratory measurements

The thickness dependence of the solar transmittance and the U_L-values was derived from laboratory measurements of glazings mounted with a Teflon film or with Arel honeycombs of four different thicknesses, 30-100 mm.

The solar transmittance of the TIM's were measured in a large (1 m of diameter) integrating sphere at different angles of incidence up to 60 °. Above this angle, the values were extrapolated.

The U_L-values were measured using a hot-box, which can be described as a small (0.54 m^2) collector model with an electrically heated absorber. The hot-box is unguarded, but the heat losses form the back and the edges were estimated and subtraced. Since the measurements were performed indoors, with a heat resistance between the cover and the surrounding of about 0.12 $(W/m^2K)^{-1}$, the U_L-values of the glazing had to be corrected to be valid outdoors. The values were recalculated for a heat resistance of 0.06 $(W/M^2K)^{-1}$. The resulting U_L-values at ΔT ♠ 55-60 °C were used to make a power fit. The values were then normalised to be valid in a collector, which has an over-all U_L-value of 3.5 W/m^2K when equipped with a Teflon film. This corresponds to U_L ♠ 0.8 for the back and the edges. All U_L-values are counted on the absorber area. The results are shown in Fig. 2.9.

[7]M. Rommel, V. Wittwer, Flat plate collector for process heat with honeycomb cover, Proc. Biennial Congress of ISES (1987) 641-645

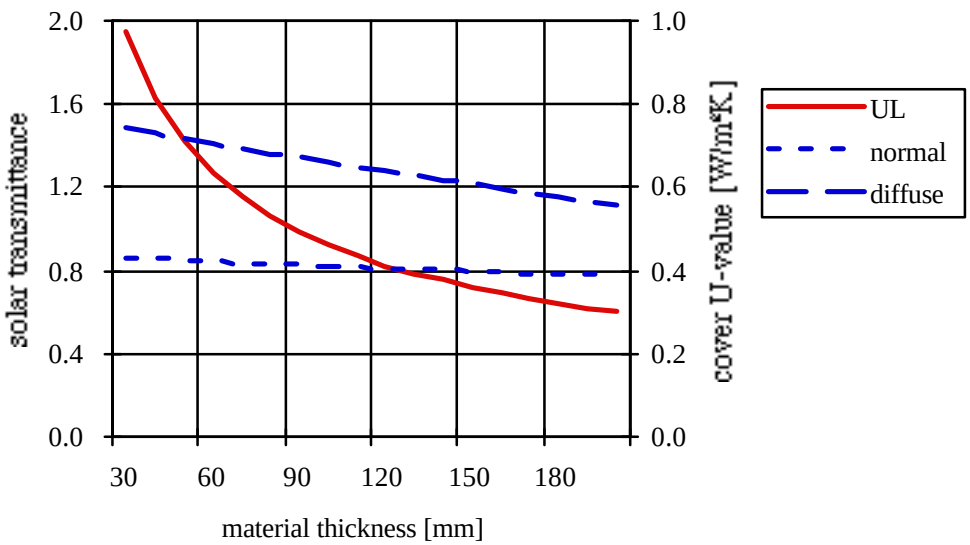


Fig. 2.9: Properties of collector cover including transparent insulation and cover glass

Simple calculations of annual performance

A model for calculation of annual performance has been derived by Karlsson[8]. The formula can be written:

$$Q = (H_{op}\ F'(\tau\alpha)_0 - F'\ U_L (T_{op} - T_{aop})\ t_{op})\ C$$

Q	=	annual energy gain (kWh/m^2)
H_{op}	=	annual incident radiation in the collector plane during operating time (kWh/m^2)
F'	=	collector efficiency factor, see Duffie and Beckman (1980)
$(\alpha\tau)_0$	=	absorptance-transmittance product at normal incidence
U_L	=	heat loss coefficient (W/m^2°C)
T_{op}	=	annual average collector operating temperature (°C)
T_{aop}	=	annual average ambient temperature during operating time (°C)
t_{op}	=	operating time (kh)
C	=	empirically based correction factor

The weaknesses of the formula are mainly:

1. The model does not take into account that collectors with low critical radiation levels (I_c) will gain additional energy at radiation levels below 300 W/m^2.

2 The angle dependence of the absorptance-transmittance product ($\alpha\tau$) is not taken into account, only the value at normal incidence $(\tau*\alpha)_0$ is used.

The model was modified by Perers and Karlsson [9]:

$$Q = H_{op}\ F'(\alpha\tau)_{eff} - F'\ U_L (T_{op} - T_{aop})\ t_{op}$$

[8] B. Karlsson, Potential Improvements of high temperature flat plate collectors, Proc. North Sun (1988) 419-455

[9] B. Perers, B. Karlsson, An annual utilizability method for solar collectors in the Swedish climate, Proc. North Sun (1990) 450-455

where $(\alpha\tau)_{eff}$ is the annually efficient, incident angle modified absorption-transmittance product. $(\alpha\tau)_{eff}$ is, however, not easily derived, so we have made some approximations in order to simplify the calculations.

Collector Measurements

Two flat plate collectors, identical except for the secondary glazing, were used for comparative performance measurements between collectors equipped with a Teflon film or with Arel honeycombs of thicknesses 30 and 50 mm. The collectors are mounted together on a stage, forming one double collector, which could be tilted and put in a tracking mode around its vertical axis. The collectors are fed with water from the same pipe, to ensure the same inlet temperature. The inlet temperature could be controlled to vary between 20 °C and 80 °C. The flow rate are also controlled to be equal for the collectors. In these measurements the collectors were tilted 45° and set in a non-tracking mode, facing south.

The Arel honeycombs were fastened to the glass with strings of silicon rubber. The depth of the collectors were about 10 cm, leaving an airgap between the absorber and the honeycombs. Each collector had a low iron glass as cover and selective absorber surfaces (Sunstrip) were used. The absorber area was about 2.5 m^2 for each collector, the glass area somewhat larger, 2.7 m^2.

The collected data from the measurements were hourly average values of inlet and outlet temperatures, air temperature, flow rates, global insolation in the collector plane, global and diffuse insolation in the horizontal plane and also the change in average collector flow temperature during the hour.

Data Evaluation

The data analysis method was to use linear multiple regression to fit data to a model of the collector performance. The method is described in detail by Perers[10].

The output parameters from the regression analysis were used as input data to MINSUN, a collector simulation programme using the same model as in the regression analysis, to estimate the annual performances. MINSUN, which is developed from TRNSYS, uses the same collector model as was used for the regression analysis. The climate data file used in the simulations were from Stockholm 1986.

The received parameters were analyzed and compared to laboratory measurements. The analysis is complicated by large shadowing effects due to a relatively small collector area. Thus the angular dependence of the thick honeycomb glazings cannot be reproduced exactly. Also the fact that the glass area is 8% larger than the absorber area makes it difficult to compare with indoor measurements. In the latter case an ideal layer structure without boundary effects is simulated. Apart from these remarks the results agree quite well.

2.3.4. Results

The results from the simulations show that with an operating temperature of 70 °C, the gain would be 70-80 kWh/m^2 or 20-25 % annually from replacing the Teflon film with a 50 mm Arel honeycomb. This is 20-30 kWh/m^2 more than for the 30 mm honeycomb. The results are close to

[10] B. Perers, Simulation and evaluation methods for solar energy systems, Swedish Council for Building Research D20:1990 (1990)

earlier predictions calculated from laboratory measurements[11]. In Figure 2.10 the annually produced energy is plotted vs operating temperature for the different collectors, the Teflon film collector having a U-value of about 3.5 W/m²K.

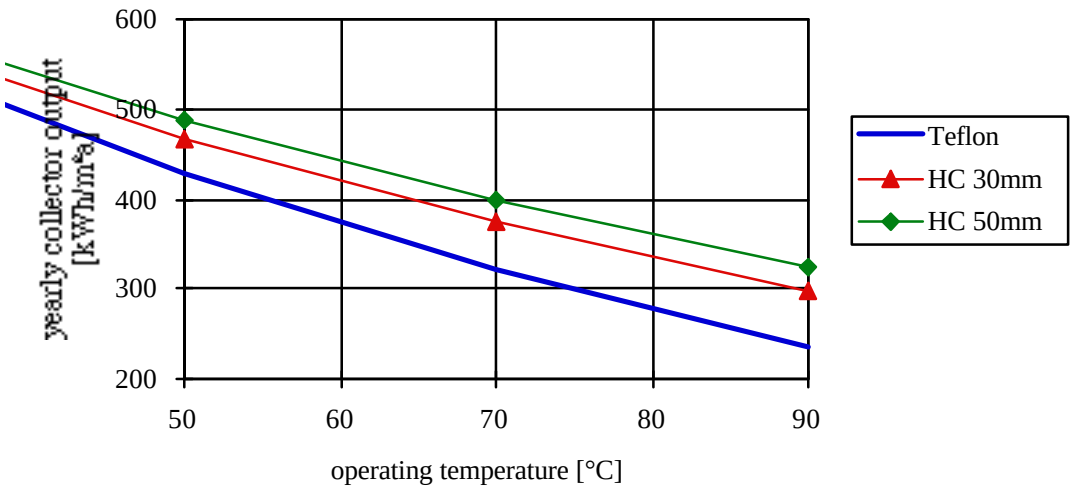


Fig. 2.10: Yearly collector output for different operating temperatures

The regression analysis indicated for the 50 mm honeycomb a decrease of the U-value of about 1.2 W/m²K compared to the collector with the Teflon film. For the 30 mm honeycomb, the reduction in U-value was about 0.8-0.9 W/m²K. This is in close agreement (within an error of 0.1 W/m²K) with the laboratory measurements of U-values. Most of the other parameters did not show any large differences between the collectors. Only the parameter including the diffuse solar transmittance, showed a clear difference. It was about 5 % higher for the Teflon film.

Further calculations with MINSUN from extrapolated parameters - using the laboratory results indicate that for operating temperature 70°C the additional gains are small: 70mm increase the output by 15 kWh/m², 100mm by about 25 kWh/m². This means that, considerung the increased efforts and costs for thicker collector covers, a 50mm honeycomb cover would be probably the best solution.

[11] B. Hellström, B. Karlsson, Evaluation of a honeycomb glazing for high temperature solar collectors, Proc. TI4, Birmingham (1991)

2.4. Selection of TIM for air-collector system (FIN)

In passive TI application the absorbing structure acts also as a thermal storage. The heat losses to the outside air and the heat flows to the adjacent room space depend on the thermal resistances of the structural layers and on the temperature levels. A significant part of the absorbed solar energy can be lost by transmission heat losses through the TI layer. In northern climate low U-values are usually required, but a TI-wall with additional thick conventional insulation at the inner side of the absorption layer has very low solar efficiency.

Figure 2.11 presents the calculated (TRNSYS) nominal heating demands of north and south facing building zones of a typical, highly insulated single family house without a TI application. Most of the windows were facing south. The nominal heating demand of the south facing building zone has usually the lowest daily level when the solar incidence is the highest. At the same time the heating demand of the northern zones of the building may be significantly higher. Typical passive application of a TI structure would decrease mainly the heating demand of the southern zone.

When using the presented TI system with convective heat distribution the utilization of solar energy can be highly improved compared with the passive case. The heat gains from TI system match better with the local heating demand of the northern zone of the building than that of the southern zone. Also the heat losses of the absorbed solar energy can be minimized when placing the thermal storage inside the building instead of having it on the building envelope.

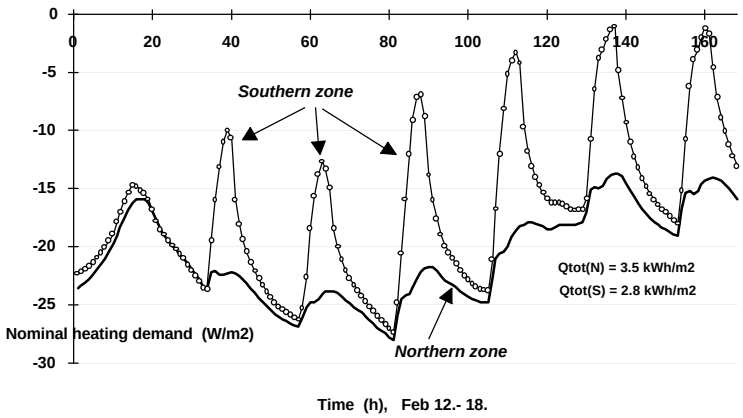


Fig. 2.11. Calculated variation of the nominal heating demand of north and south facing building zones of a single family house during one week (Feb. 12.-18. Jyväskylä, Finland).

2.4.1. System

The presented solar collector system uses natural air convection for heat distribution between separate absorbing and storage structures (Fig. 2.12). The system is integrated within the building structure and a closed air channel system connects the TI collector wall with an internal thermal storage wall. The collector wall may have low U-value, required in cold climates, and the heat losses from the internal storage wall are used to compensate the heating demand of the adjacent room spaces.

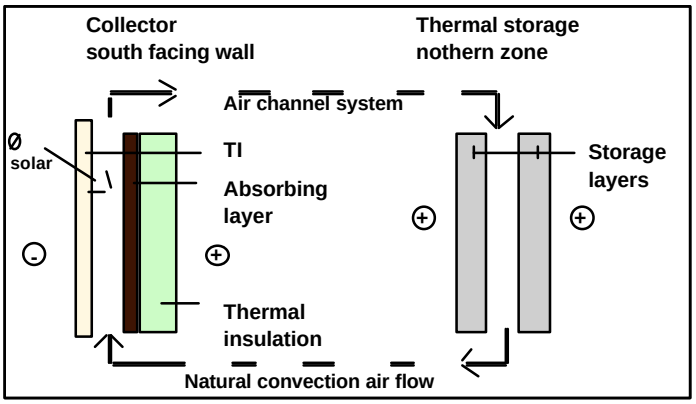


Fig. 2.12: TI solar collector wall (facing south) and the thermal storage structure inside the building are combined with a closed air channel system. Natural air convection is used for heat distribution.

2.4.2. Optimisation objective

The aim was to study the effects of the properties and dimensions of TI and absorption layers and storage structure on the thermal performance of the system.

Table 2.3. Numerically analysed cases.

Case	TIM d (mm)	Absorption layer Concrete d (mm)	Storage layer Aerated concrete d (mm)
Opaque (ref.)	_0	-	-
Passive	50	25	-
1	"	"	2 x 75
2	"	"	2 x 150
3	"	10	2 x 75
4	100	25	2 x 75

2.4.3. Method

A system consisting of 2.5 m high wall structures was studied numerically. In the 2-D analysis the air channel was assumed to be 50 mm wide. The total length of the closed air channel system was 20 m. The analysis was done for a one week period (Feb. 12.-18. 1979, Jyväskylä, Finland) having -19.9 °C mean outdoor air temperature. Six different cases were studied (Table 2.3). The U-value of the collector wall was uniform in all the other cases except in case 4.

Experimentally the objective was to analyse the thermal performance of TIM system using natural air convection for heat distribution and to confirm the numerical studies. The experiments were done using the PASSYS test cell in Espoo, Finland. The structures and dimensions of the three analysed systems were selected basing on the former numerical simulations.

Experiments were needed especially to confirm the possibilities to use natural convection in heat transport between the solar collector and storage structures, to analyse the heat flows, temperatures and the time-lags between solar radiation and heat flows into the room.

The parameters were the transparency and thermal resistance of the TI -layer and the thermal masses of the storage wall and the absorption layer in the collector structure.

2.4.4. Results

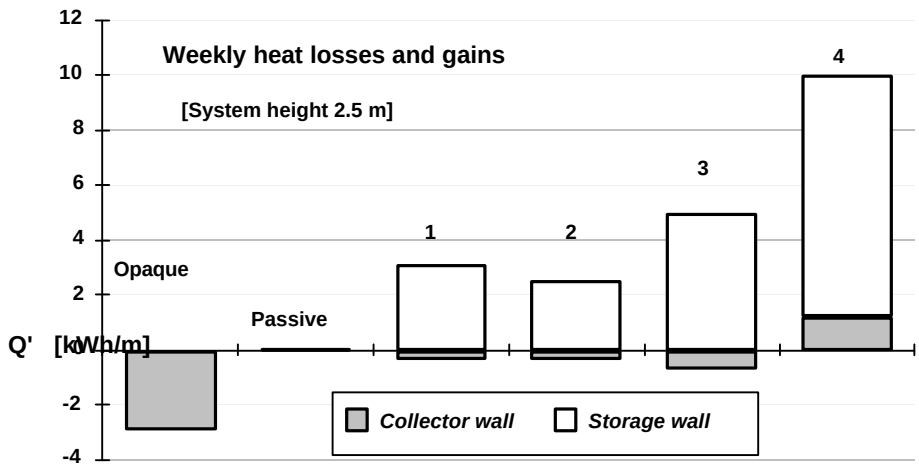


Fig. 2.13. Calculated weekly heat losses and gains through the system of collector and storage walls.

The presented system was analysed using numerical simulation and experiments done in the PASSYS test cell in Espoo, Finland. The structures and dimensions of the analysed cases were selected basing on numerical simulations. The parameters were the transparency and thermal resistance of the TI -layer and the thermal masses the absorption layer and the storage wall.

Table 2.4 presents the system configuration of one experimentally analysed case. Table 2.5 presents the average and maximum values measured during the 23 day period and Figure 2.14 the measured dynamic behaviour of the system during one selected 24 hour period starting from 6 am.

Table 2.4. One experimentally analysed systems.

Transparent layer	Absorption layer	Storage wall	Measuring period
Glass 4 mm + 100 mm TIM + glass 4 mm + 50 mm air space	50 mm concrete, black surface	150 mm aerated concrete (550 kg/m^3) on both sides of the air channel	April 3.- 25. 1995

Table 2.5. Results from PASSYS -measurements. Average and maximum values during the measuring period . The heat flows (W/m^2) are presented per transparent area. T_{abs} is the absorption surface temperature and $T_{air,c,out}$ the air temperature leaving the collector.

$\phi_{sol,out}$ av/max W/m^2	$\phi_{sol,in}$ av/max W/m^2	$\tau_{av.}$	v_{air} av/max m/s	q_{air} av/max W/m^2	T_{abs} av/max _C	$T_{air,c,out}$ av/max _C
145	69	0.48	0.10	63	40	37
831	456		0.23	305	75	71

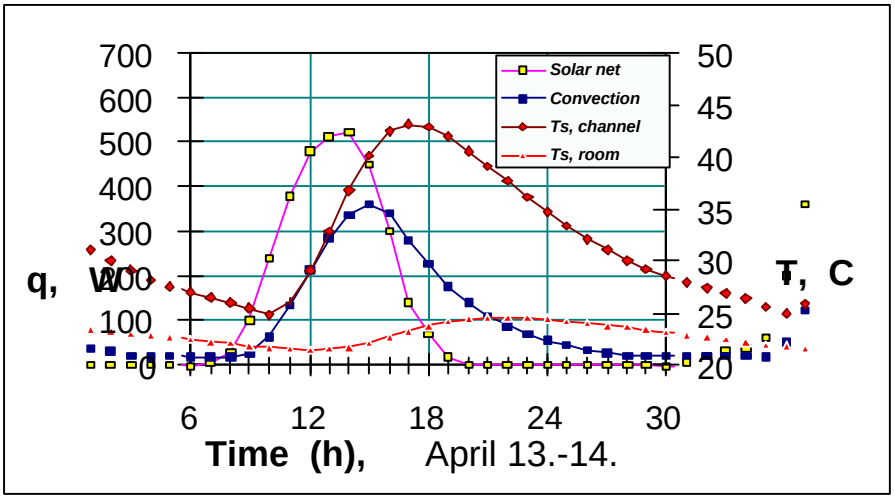


Fig.2.14: Dynamic behaviour of the system. Time-delay between net solar radiation and the convection was one hour. $T_{s,channel}$ presents the surface temperature of the storage wall by the air channel side. Total time-delay between the storage wall surface at the room side ($T_{s,room}$) and the net solar radiation was about 7 hours. Room air was maintained in constant +20 _C temperature.

The solar collector system basis on natural air convection. The air leaving the collector should be higher than that of the indoor air and the storage structure. The average air temperature in the collector was about 30_C higher than that of the outdoor air in the system with 100 mm thick transparent insulation. The corresponding temperature difference was only 16 _C in a system with two-glazed window, which means that the yearly effective operating time was significantly shorter than in the case with 100 mm TI layer.

The thermal mass of the absorption layer should be relatively high. This smooths down the temperature peaks and maintains convection flow in the channel system also after the solar radiation period. A 50 mm thick concrete was found out to be relatively suitable absorption layer. The absorption layer must have adequate thermal insulation at the room side to avoid too high heat gains to the room and to keep the U-value of the wall low enough.

The heat gains through the storage structure should meet the heating demand of the room space. The system with massive 150 mm thick aerated concrete storage wall had about 7 hours total time-delay. In many cases even higher delay would be recommended.

In the experiments only 25 - 35 % of the convection heat flow reached the actual storage wall. In further development of the system the transparent insulation could be replaced using modern glazing technology with coatings. Convective heat transfer should be improved by using light and highly insulated air channels and with possible forced convection by, for example, solar driven fans.

Conclusions

For a solar air collector system it is important to reach high air temperatures. Therefore the thermal resistance of the transparent cover should be high. Whereas with a double-glazed collector only 16 K average temperature difference to ambient could be reached, with transparent insulation of 100mm this value increased to 30K. Thus operating time could be increased.

The thermal mass of the absorption layer was investigated. It should be relatively hiugh to smoothen temperatures and allow convection heat flow even after the solar irradiation period. Also the temperature maxima can be limited inn order to avoid destruction by melting of the TI-material. 50mm concrete with adequate roomside insulation was found to be a suitable layer. However, even thicker layers up to 150mm would be optimal to match the heating demand of the room with a time delay of about 5 hours.

In the experiments only 25-30% of the convection heat flow reached the actual storage channel. Thus the air channels should be produced as light and well insulated as possible in order to improve this performance. The heat transfer between the air and the storage structure may be improved, too.

3. Conclusions

With the help of transparent insulation materials new applications seem to be possible which would not be energy efficient without the improved performance of these kind of collector covers. Theoretical models and experimental data are both useful to find optimum system designs. Theoretical models have the advantage of a fast and cheap variation of many parameters which yields insight in the local and global minima of a multi-dimensional parameter surface. Experiments on the other side have the advantage that they also show non-ideal behaviour and problems associated with building practice. They should be used especially when the degrees of freedom for the system design is already restricted by practical, economical or other considerations as a large number of experiments need a lot of time and effort.

Literature

Section 2.1

K.G.T.Hollands, J.L. Wright, Heat Loss Coefficients and Effective Tau-Alpha-Products for Flat-Plate Collectors with Diathermanous Covers, Sol. Energy 31/3, (1983) 211-216

W.J. Platzer, Solare Transmission und Wärmetransportmechanismen von transparenten Wärmedämmmaterialien, Dissertation Albert-Ludwigs-Univ. Freiburg (1988)

W.J. Platzer, S. Kühn: *Calculation of heat transport and total solar energy transmittance from spectral optical data*. Proc. of 8th Int. Meeting on Transparent Insulation Technology, Freiburg, UK (1996)

Section 2.2

H. Schweiger, A. Oliva, M. Costa, C.D.P. Segarra: *Optimization of total energy transmittance and heat transfer in a solar collector with honeycomb glazing - a numerical study*. Proc. of 6th Int. Meeting on Transparent Insulation Technology, Birmingham, UK (1993).

L.F. Jesch et al.: *Optimization of Honeycomb cell geometry for transparent insulation*. Proceedings of 3rd International Workshop on Transparent Insulation Technology, Titisee/Freiburg, Germany (1989).

W. Platzer: *Optimization problems of transparently insulated Systems*. Proceedings of 2nd International Workshop on Transparent Insulation Technology, Freiburg, Germany (1988).

W.H. Press et al.: *Numerical Recipes*. Cambridge University Press, Cambridge, 1986.

Ch. Schmidt: *Anwendung transparenter Wärmedämmung mit Wabenstruktur in integrierten Speicher-kollektoren zur Brauchwassererwärmung*. Fortschr.-Ber. VDI Reihe 19/43, Düsseldorf (1990)

W. Grieshaber: *Modellbildung integrierter Speicherkollektoren für das Simulationsprogramm TRNSYS*. Diplomarbeit, Fraunhofer-Institut für Solar Energiesysteme, Freiburg (1989).

Section 2.3

Hellström, B. and Karlsson, B. (1991) *Evaluation of a honeycomb glazing for high temperature solar collectors*. Proc. of the 4th International Workshop on TI Technology.

Hellström, B., Karlsson, B. and Svensson, L. (1990), *Performance of collectors with flat films or honeycombs*. Proc. of North Sun'90, 466-471.

Perers, B. (1990), *Simulation and evaluation methods for solar energy systems*. Swedish Council for Building Research, D20:1990.

Duffie, J.A. and Beckman, W.A. (1980), *Solar engineering of thermal processes.*

Rommel, M. and Wittwer, V. (1987), *Flat plate collector for process heat with honeycomb cover - an alternative to vacuum tube collectors.* Proc. of the Biennial Congress of ISES.

Section 2.4

Ojanen, T., *Numerically analysed applications of transparent insulations*. Proceedings of the Fourth International Workshop on Transparent Insulation Technology, Birmingham, UK, 1991.

Ojanen, T., Salonvaara, M., *Numerical simulation of structures with transparent thermal insulations and phase change materials*, ETRR-research program, Report 14. Espoo 1992. 70p.

Knudsen, J.,G., Katz, D.,L., *Fluid dynamics and heat transfer*, McGraw-Hill, 1958.

Ojanen, T., *Wall Integrated Transparently Insulated Collector System Using Natural Air Convection for Heat Distribution*, Proceedings of the Seventh International Workshop on Transparent Insulation Technology, Delft, 1994.

Ojanen, T., Xu.,M., Aho, I., *Wall Integrated TI -Collector System with Natural Air Convection Heat Distribution - Analysis and Optimization*, Proceedings of the ISES Solar Energy World Congress, Harare, Zimbabwe, 1995.