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DETAILED MODELING OF SOLAR FLAT-PLATE COLLECTORS WITH DESIGN TOOL KOLEKTOR 2.2

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ABSTRACT

The mathematical model and design software tool KOLEKTOR 2.2 with user-friendly interface for detailed modeling of solar thermal flat-plate collectors has been built and experimentally validated for different solar thermal flat-plate collector concepts. The design tool is applicable especially for design and virtual prototyping of new solar flat-plate collectors resulting in efficiency curve determination, for parametric analyses to obtain information on different parameters influencing the collector performance and especially for investigation of thermal performance of advanced solar collectors (building integrated, evacuated collectors, etc.). Examples of parametric analyses made for selected construction elements together with modeling possibilities of the design tool KOLEKTOR 2.2 are presented in this paper.

INTRODUCTION

Computer modeling of solar thermal collectors is a principle approach for testing of new construction concepts and improvements in the development and design stage for developers and manufacturers. Virtual prototyping of solar collectors can save the investments into number of prototypes and foresee the collector performance in advance. Analyses of individual construction parts and detail parameters impact on the collector performance are needed to make the decisions on efficient solar collector concepts for given application, operation and climatic conditions with respect to economic parameters of the construction.

A mathematical model is always a simplification of reality to a certain extent. Too complex mathematical models and numerical programs require a huge amount of computer time for calculations; too simplified models do not take important influences of detail collector parameters into account and result in considerable uncertainty in calculation. To find a good compromise between simplicity of the model and its accuracy is crucial for development of any design and simulation tool.

Although the theory of flat-plate solar collectors is well established and can be found in basic literature (Goswami et al., 1999; ISES, 2001; Duffie, Beckman, 2006), there is a lack of user-friendly design programs for solar collector performance modeling considering the detailed geometrical and physical parameters of collector. Several authors evolved simplified analytical models considering the temperature independent solar collector overall heat loss coefficient (linear dependence of efficiency), neglecting the absorber temperature distribution or temperature difference between absorber surface and heat transfer fluid. Such models are not comparable with physical experiments and cannot predict the real performance behaviour and evaluate efficiency characteristics of solar collectors.

A theoretical model of solar collector has been introduced in TRNSYS Type 73 (TRNSYS, 2004) but with simplified calculation of collector heat loss coefficient U insufficient to cover wide range of parameters affecting the collector heat loss. A more theoretical model with several detailed input parameters and calculation of heat transfer coefficients in the individual parts of the collector (in air gaps, inside pipes, at outer surfaces) has been evolved as Type 103 (Fraisse, 2003).

The design program CoDePro (Koo, 1999) for energy performance calculation of solar flat-plate collectors has been developed with use of the Energy Equation Solver. It allows a very detailed specification of collector geometrical and material parameters. It covers a large segment of solar collectors (unglazed, single and double glazed) and evaluates also optical properties of the collector, e.g. incident angle modifier. On the other hand, the features of CoDePro analogous to TRNSYS Type 103 do not allow energy performance modeling of advanced solar collectors, e.g. collectors integrated into building envelope, evacuated flat-plate collectors or solar collector with glazing made of transparent insulation structures.

The presented model and design tool KOLEKTOR 2.2 has been developed to overcome the drawbacks of previous models. KOLEKTOR 2.2 is based on detailed calculation of heat transfer from the collector absorber to ambient and from the collector absorber to heat transfer fluid. The advantage of the design tool is its universality for wide solar flat-plate collectors stock from evacuated to atmospheric, separately installed or building integrated, covered with different types of glazing (single glazing or transparent insulation structures), operated with different heat transfer fluids, etc.

MATHEMATICAL MODEL

The core of the design tool KOLEKTOR 2.2 is a mathematical model of solar flat-plate liquid collector solving one-dimensional heat transfer balances. The solar collector is defined by means of main levels: glazing exterior surface (p1), glazing interior surface (p2), absorber (abs), frame interior surface (z2) and frame exterior surface (z1). These levels are schematically outlined in Fig. 1. Detailed geometrical and physical properties of individual parts of the solar collector, climatic and operation parameters are the input parameters of the model. Basic outputs of the model are usable heat gain Q_u [W], efficiency η with respect to the reference collector area (gross area A_G, aperture area A_a) and output heat transfer fluid temperature t_{out}.

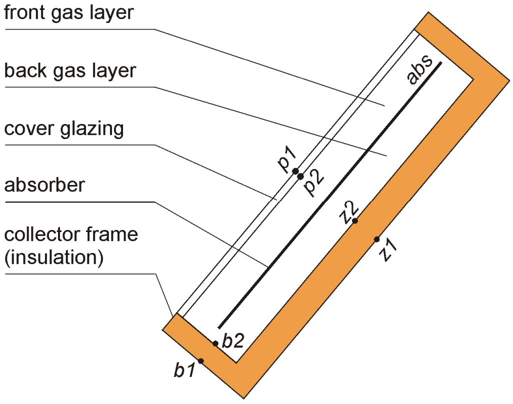

Figure 1 Main temperature levels in solar collector model

The mathematical model of solar collector consists of external energy balance of absorber (heat transfer from absorber surface to ambient environment) and internal energy balance of absorber (heat transfer from absorber surface into heat transfer fluid). The model solves the energy balance of the solar collector under steady-state conditions according to principle Hottel-Whillier equation for usable heat power

$$\dot{Q}_u = A_a F_R \left[\tau\alpha G - U\left(t_{in} - t_a\right)\right] \qquad (1)$$

where A_a [m^2] is aperture area, F_R is collector heat removal factor, τ is cover glazing transmittance, α is absorber absorptance and U is overall heat loss coefficient of solar collector. Operation conditions area solar irradiation G, heat transfer fluid input temperature t_{in} and ambient temperature t_a.

Through the external energy balance of absorber (see Fig. 2) the heat transfer by radiation and by natural convection in the air gap between absorber surface and glazing (event. frame), heat conduction through glazing (event. frame) and heat transfer by convection and radiation from external glazing (event. frame) surface to ambient is solved. To calculate the heat transfer coefficients properly, temperatures of main collector levels should be known, but on the other side the temperature distribution in the collector is dependent on the heat transfer coefficients. Therefore, the external energy balance of absorber is solved in an iteration loop starting from a first temperature estimate for each main level based on given input temperature t_{in} and ambient temperature t_a. The external balance iteration loop yields in overall collector heat loss coefficient U [W/m^2.K].

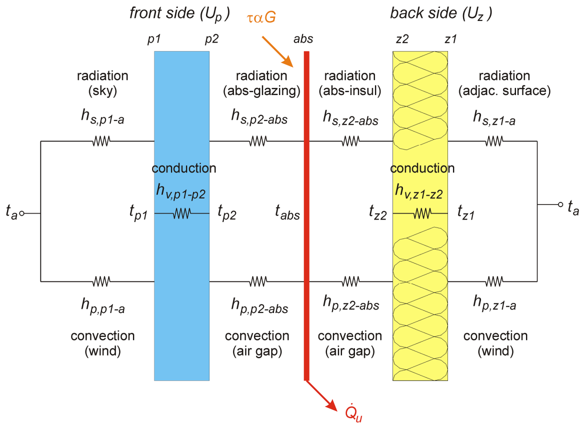

Figure 2 Schematic layout of external energy balance of absorber

The internal energy balance of the absorber assesses the heat transfer from the absorber surface into heat transfer fluid provided by fin heat conduction, by heat conduction through the bond between absorber and pipes and by forced convection from pipe internal surface to fluid. Internal balance results in determination of collector efficiency factor F' [-] and collector heat removal factor F_R on the basis of input parameters, operational and climatic conditions and results from external balance. Main outputs from internal balance are output fluid temperature t_{out}, mean heat transfer fluid temperature t_m and particularly absorber temperature t_{abs}, which governs the calculations in the external balance. The internal balance proceeds in its own iteration loop with respect to relative dependence between mean fluid temperature t_m and forced convection heat transfer coefficients in absorber pipe register.

As both external and internal balances are interdependent, a superior iteration loop has been introduced to transfer the results from external balance to internal (overall collector heat loss coefficient U) and from internal balance results to external balance (absorber temperature t_{abs}).

DESIGN TOOL KOLEKTOR

The mathematical model of solar flat-plate liquid collector has been transformed into the design tool KOLEKTOR 2.2. The design tool is a computer program with user-friendly interface created in Visual Basic Studio environment. Detailed geometrical and physical parameters of individual solar collector parts are entered through appropriate tool cards (general design parameters, absorber, glazing / insulation, calculation, see Fig. 13 in appendix). Besides the basic collector parameters and characteristics the tool allows to enter also internal air pressure in the collector (for modeling both flat-plate atmospheric and evacuated collectors), slope of collector, type of heat transfer fluid (water, water-ethyleneglycol solution, water-propyleneglycol solution with defined mixing ratio) and to choose the separate free-standing installation or building envelope integration of collector (with given thermal resistance of envelope). The design tool allows to choose from various empirical models to calculate the heat transfer coefficients (e.g. forced convection in pipes, natural convection in air gap, sky radiation, wind convection) collected from different authors and thus to trace the influence of heat transfer coefficient model selection on the calculated performance of solar collector. There is often a number of possible models for calculation of heat transfer coefficients available but with rather different resulting values, e.g. wind convection models and their influence on calculated collector performance should be verified (sensitivity analysis). Data entered into tool cards and choices made can be saved into text file (*.kol) for later use.

Output results of the design tool are the solar collector performance for given boundary conditions or efficiency curve of solar collector at standard boundary conditions (t_a = 20 °C, G = 800 W/m^2, w = 3 m/s) related to mean fluid temperature. Heat transfer coefficients in the individual parts of solar collector and nominal stagnation temperature t_{stg} are displayed for detailed analysis. Results of calculation (collector efficiency curve) can be saved into spreadsheet file (*.res). The software tool is freely available from website of authors (Matuska, 2008).

EXPERIMENTAL VALIDATION OF MODEL

The mathematical model has been experimentally validated in the frame of solar collectors testing according to the European standard (CEN, 2005) in the Solar Laboratory operated under the Department of Environmental Engineering at the Faculty of Mechanical Engineering, Czech Technical University in Prague. Different construction designs of tested solar collectors (here called K1, K2, K3) have been chosen to validate the results of the mathematical model with instantaneous efficiency data obtained experimentally under steady-state conditions. Experimental data and efficiency curves calculated from the model are graphically compared.

Experimental data points of the solar collector efficiency are coupled with uncertainty bars in the graphs. Expanded efficiency uncertainty has been assessed for experimental data from both type A (statistical) and type B (instrumental). Uncertainties considering the coverage factor 2 with 95% level of confidence (Mathioulakis, 1999, Müller-Schöll, 2000) and for usual steady state conditions of measurements is between 3 and 4 %.

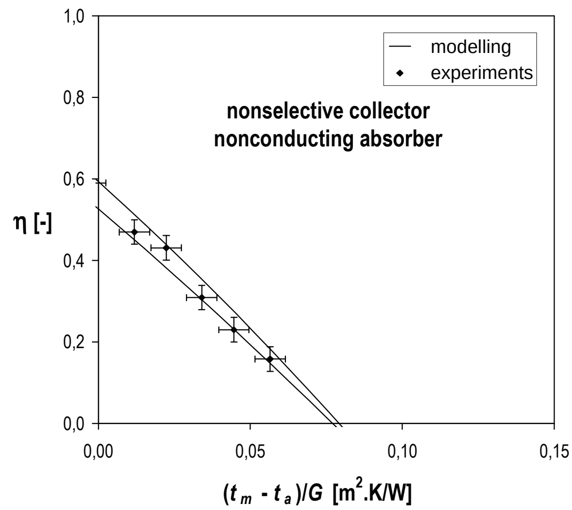

Figure 3 Experimental validation of the mathematical model (collector K1)

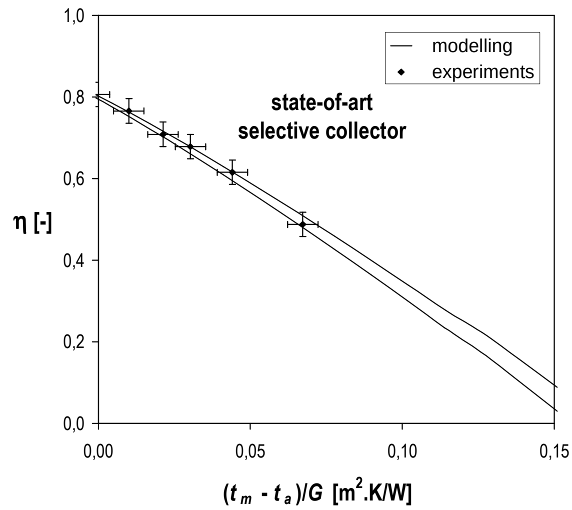

Figure 4 Experimental validation of the mathematical model (collector K2)

The theoretical calculation of the efficiency curve by the model is also subjected to uncertainty of input parameters. While geometrical parameters are easily available with a high degree of confidence, several parameters defining the properties of collector elements are found uncertain within a narrow range (e.g. absorber and glazing properties parameters, mostly ± 1 %), middle range (e.g. conductivity of insulation layer dependent on its temperature and density, ± 10 %) and a broad range (e.g. emittance of absorber back side, insulation or collector frame, > 30 %). Each of these variable collector parameters has a different impact (sensitivity) on the resulting efficiency value; from high effect of absorber and glazing optical properties to negligible effect of frame external surface emittance. Uncertainty of input parameters and its influence to calculated efficiency has been expressed by two borderlines where the collector efficiency values can be found in reality.

Fig. 3 shows an experimental validation of the model for an atmospheric solar flat-plate collector K1 consisting of a nonselective absorber without conductive bond to register pipes (steel absorber is bond to copper pipe only by spot grip-contact). Standard safety glazing and mineral wool insulation are used in its construction. The determination of absorber-pipes bond conductance is a main source of uncertainty in the calculation.

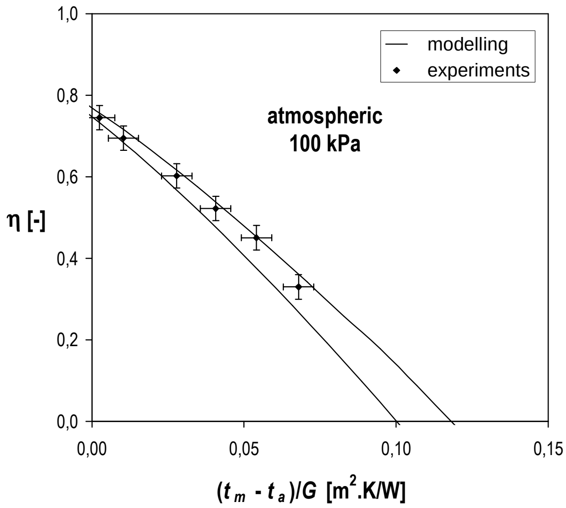

Figure 5 Experimental validation of the mathematical model (collector K3, atmospheric interior pressure, 100 kPa)

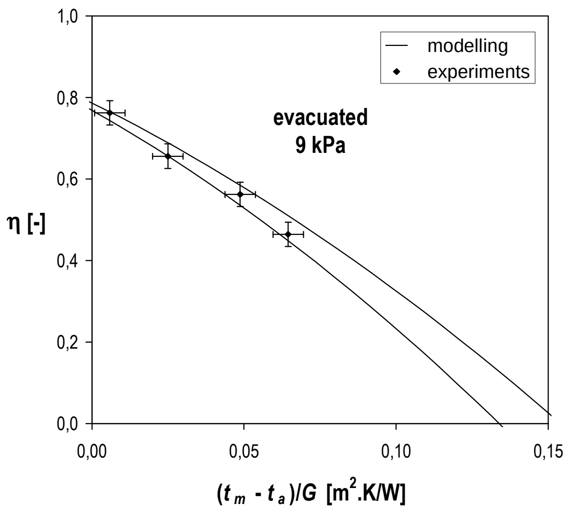

Figure 6 Experimental validation of the mathematical model (collector K3, low interior pressure, 9 kPa)

Collector K2 is a representative of high-quality solar collectors with state-of-the-art copper laser welded absorber. High performance selective coating and solar antireflective glazing properties from optical testing reports were provided thus reducing the uncertainty of calculation to very low values (see Fig. 4). Due to sufficient back side insulation the influence of uncertain internal and external surface emittances has decreased to a minimum.

The mathematical model has also been tested in the field of solar flat-plate evacuated collectors. Validation has been performed for the evacuated collector K3 with selective absorber and no insulation applied at the back of absorber (only air layers at given pressure). The collector envelope consists of moulded metal frame and low iron glazing. Support pillars to bear the underpressure stress are placed between glazing and back side of the collector and penetrating the absorber through holes (elimination of thermal bridges). The atmospheric variant of the collector K3 (interior pressure 100 kPa) has been evaluated as a base case (see Fig. 5). Then, the evacuated variant has been tested with interior pressure reduced to 9 kPa (see Fig. 6).

Experimental validation of the solar flat-plate collector model has allowed the use of the universal design tool KOLEKTOR 2.2 for virtual prototyping of efficient solar collector constructions, including evacuated collectors for building integration applicable to advanced solar systems (solar heating and cooling systems). Results from validated model can be widely applied in parametric analysis of solar thermal systems with solar collectors in numerous building simulation tools to investigate the system thermal performance and solar collector behavior.

ANALYSES

The design tool is applicable especially for design and virtual prototyping of new solar flat-plate collectors resulting in efficiency curve determination, for parametric analyses to obtain information on different parameters influencing the collector performance and especially for investigation of thermal performance of advanced solar collectors (building integrated, evacuated collectors, etc.). To show the features and modeling possibilities of the tool, several examples of parametric analyses made for selected construction elements of solar collector are presented.

Solar collector with geometrical and physical properties shown in Table 1 has been used as a reference case for analyses.

Example 1 – Absorber coating

This principal educational example considers reference solar collector with two variants of absorber coatings. While absorber of nonselective collector has IR emittance 0.90 (black paint) absorber of selective collector is equipped by high-quality selective coating with low emittance 0.05. It is obvious that the collector with low-emissive absorber coating will achieve lower heat loss and first derivation (slope) of efficiency curve will show lower values compared to the nonselective alternative. Efficiency curves for solar collectors shown in Fig. 7 are appended with stagnation temperatures. Stagnation temperatures are the absorber temperatures achieved in the state of no heat removal from collector given for reference extreme climatic conditions (irradiation 1000 W/m^2, ambient temperature 30 °C) and represent the requirements for temperature resistance of materials used in solar collectors.

Table 1 Main design parameters for reference solar flat-plate collector used in analyses

PROPERTY	VALUE
Width x length	1 x 2 m
Glazing transmittance	0.91
Absorber absorptance	0.95
Absorber material	copper
Absorber thickness	0.2 mm
Width of absorber fin	125 mm
Riser pipes diameter (outer/inner)	10/8 mm
Bond conductance	67 W/mK
Back and edge frame insulation	30 mm
Heat transfer fluid	water
Specific mass flow rate	0.015 kg/s.m^2
Slope	45°
Separate installation, atmospheric	

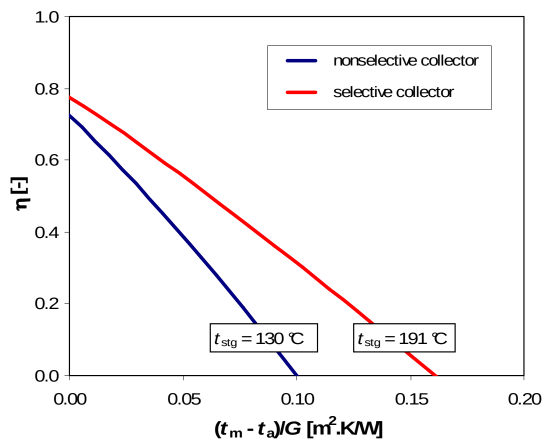

Figure 7 Efficiency curves for solar collectors with different absorber coatings

Example 2 – Absorber fin width

Width of absorber fin given by distance between riser pipes of absorber determines the number of risers per collector width and also material content (mostly expensive copper) in solar collector. On the other side the absorber fin width influences efficiency of solar collector as shown in Fig. 8. Geometrical and physical properties of solar collector elements are taken identical with reference collector except the variable fin width.

Collector performance with three values of fin width (50, 125, 200 mm) has been compared. The solar collector with narrow fins has a better heat removal from absorber surface as generally known from heat exchangers basics and therefore it has higher efficiency, especially for the low temperature range. However, higher material content due to smaller distance between riser pipes can provide an economical drawback of such construction. The use of the design tool for parametric analysis coupled with economical calculations can provide an optimisation of the solar collector construction.

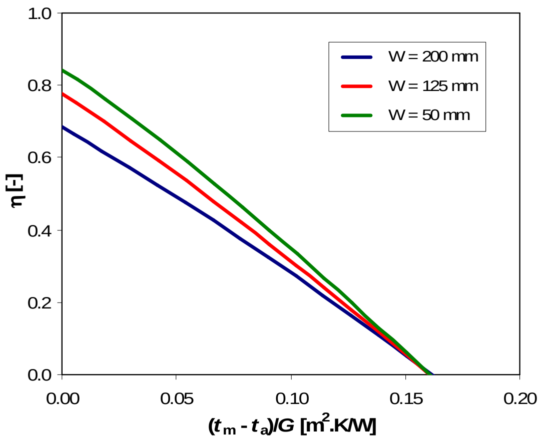

Figure 8 Efficiency curves for solar collectors with different distance between riser pipes (fin width)

Example 3 – Thermal insulation of collector frame

Heat loss from absorber through glazing to ambient environment for solar collectors with low-emissive absorber (emittance 0.05) is around 75 % of overall collector heat loss. A question focusing on the impact of frame insulation level on the collector efficiency and its performance in solar heating system arises. Optimization of reasonable thermal insulation thickness for usual applications can be easily performed using the design tool. Outputs from the design tool in form of efficiency curves as shown in Fig. 9 can be entered as inputs into any solar heating system simulation software.

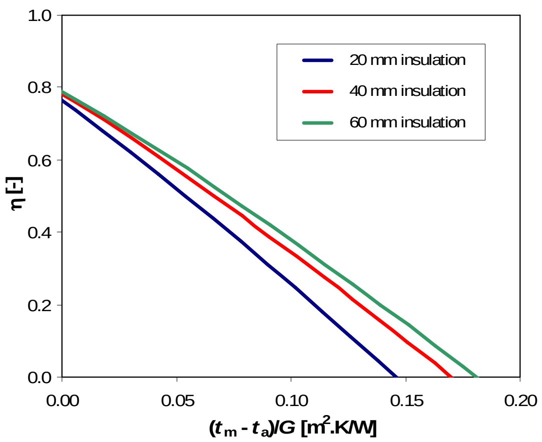

Figure 9 Efficiency curves for solar collectors with different level of frame insulation

Between the collector with 40 and 60 mm of frame insulation is no considerable difference. Especially if the supposed average operation range lies around the reduced temperature difference of 0.05 m^2K/W (solar domestic hot water system). Although the efficiency curve seems to be considerably worse for 20 mm than for higher insulation levels, coupled simulation in TRNSYS software has shown that only few percents difference in solar fraction is monitored between such collectors used in solar heating systems with standard design parameters (solar fraction 60 %, excess heat gains in summer without utilization).

Example 4 – Slope of solar collector

The slope of solar collector determines not only incident solar irradiation on the aperture area but determines also heat loss through the front air layer between absorber and cover glazing. Horizontal air layer with absorber at the bottom will show considerably higher Nusselt numbers (higher natural convection heat transfer coefficients) than air layer of vertical position. A comparison of slope impact on efficiency of solar collector is shown in Fig. 10.

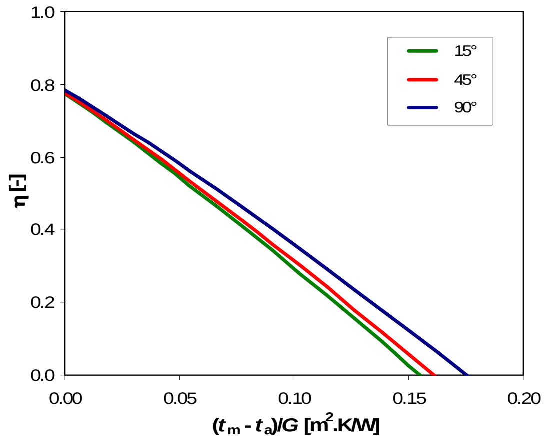

Figure 10 Efficiency curves for solar collector inclined with different slope angle

Example 5 – Heat transfer fluid

Solar collectors are experimentally tested with water as heat transfer fluid to assure uniform internal heat transfer conditions in collector and associated clear reproducibility of results between two testing institutes. How will the collector efficiency decrease when considerably more viscous antifreeze aqueous mixture of propyleneglycol (50/50) is used in a real solar thermal system is a rightful question of user. Fig. 11 shows almost no effects of used heat transfer fluids on efficiency of solar collector (in order of 1 %).

A detailed analysis of heat transfer coefficients available in the design tool can show that the internal heat transfer coefficient for water is about one third higher than for the mixture (both in laminar convection regime) but only with small impact on total heat transfer from absorber surface to heat transfer fluid as described by efficiency factor *F*'.

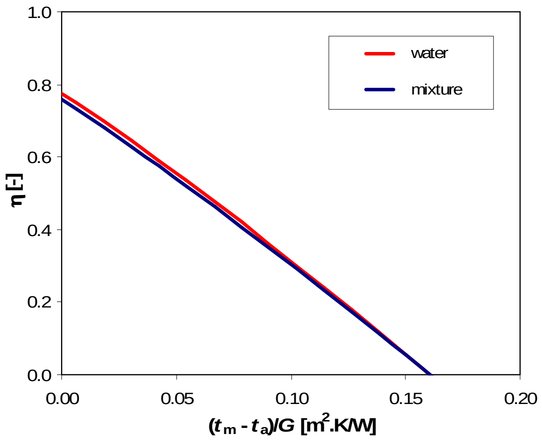

Figure 11 Efficiency curves for solar collector with different heat transfer fluids

Example 6 – Evacuation and building integration

The efficiency of a solar flat-plate collector can be considerably improved if the front air layer is maintained at lower pressure than atmospheric. Fig. 12 shows a comparison of reference solar collector (case ATM, see Tab. 1) with the identical solar collector but with evacuated air gap to reasonable 10 kPa (case EVA). Third collector with identical construction of flat-plate evacuated collector is considered as building envelope integrated (case EVA_INT). This collector is directly integrated into roof with insulation layer (R6, 240 mm of thermal insulation). Such construction offers a radical improvement in efficiency and performance of solar evacuated collector at high temperatures needed e.g. for solar cooling or industrial processes.

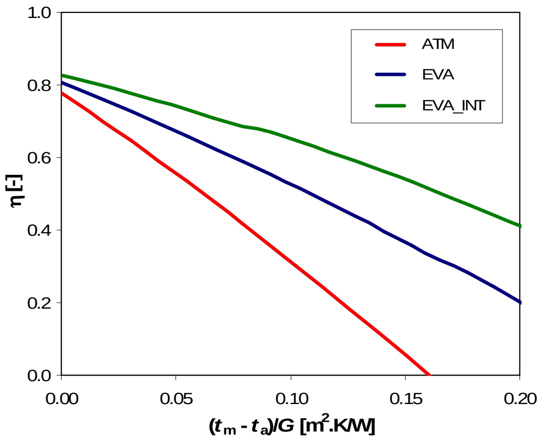

Figure 12 Efficiency curves for advanced solar collectors (atmospheric, evacuated, envelope integrated evacuated collector)

CONCLUSION

The principles of the mathematical model and design tool KOLEKTOR 2.2 for design and virtual prototyping of solar flat-plate collectors has been described. The design tool allows the determination of solar collector efficiency curve, parametric analysis to obtain information on different parameters influence on collector performance and especially for investigation of thermal performance of advanced solar collectors (building integrated, evacuated collectors, etc.). The model has been validated by experimental data from testing of solar collectors with different construction concepts (atmospheric collector with spectrally non-selective and selective absorber; evacuated collector with selective absorber under different interior pressures). Analyses presented in examples have shown some of possibilities and features of the design tool.

ACKNOWLEDGEMENT

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APPENDIX

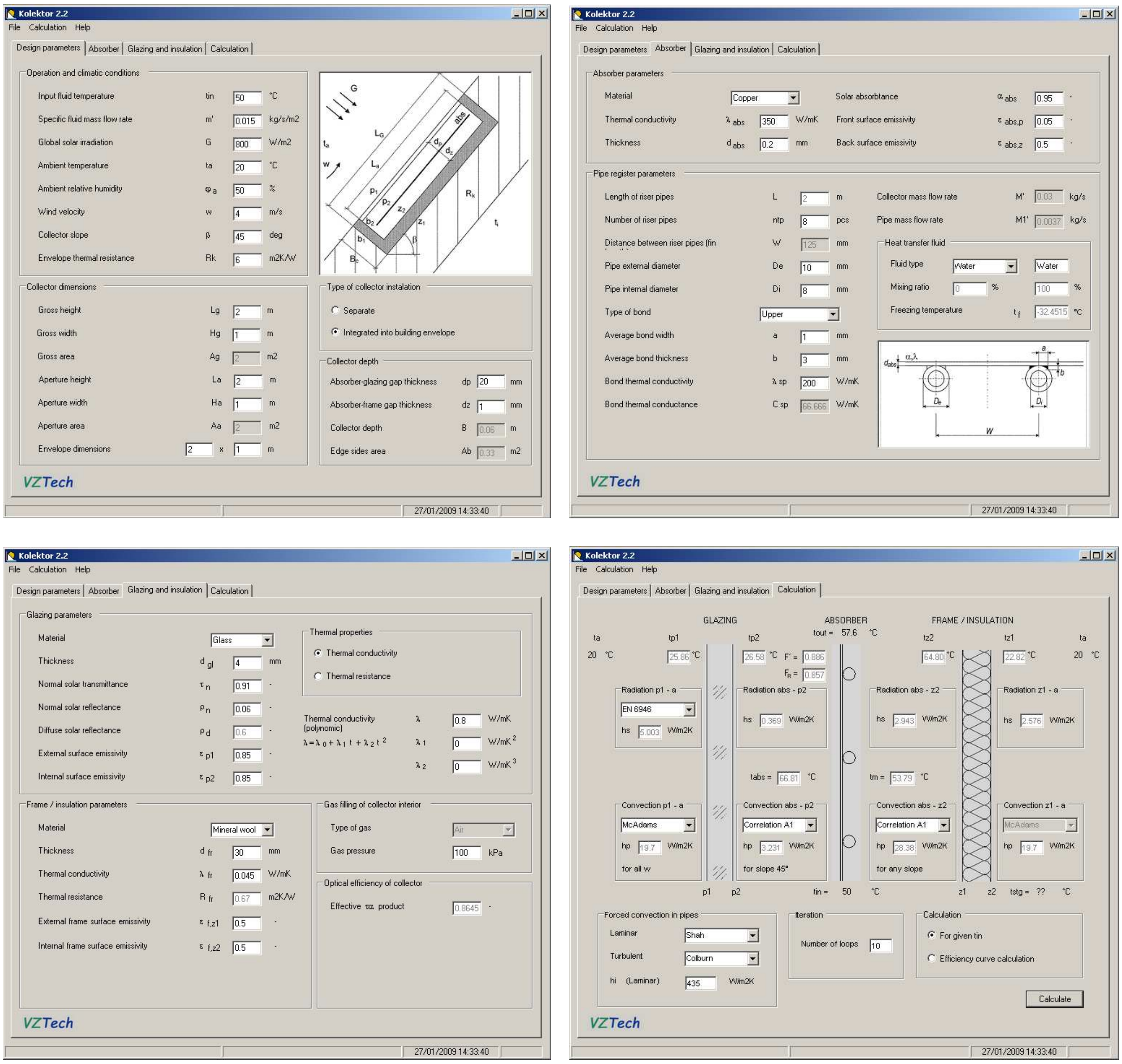

Figure 13 Tool cards of KOLEKTOR 2.2.