Design tool KOLEKTOR 2.2 for virtual prototyping of solar flat-plate collectors

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Abstract

Mathematical model and design software tool KOLEKTOR 2.2 with user-friendly interface for detailed modelling of solar thermal flat-plate collectors is presented. Mathematical model is based on internal and external energy balance of the absorber solved in iteration loops to determine the temperature distribution and heat transfer coefficients in main parts of solar collector. Mathematical model has been validated with experimentally obtained data for different solar flat-plate collector concepts (low and high performance atmospheric collectors, evacuated collector). The software tool KOLEKTOR 2.2 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 influence on collector performance and especially for investigation of thermal performance of advanced solar collectors (building integrated, evacuated collectors, etc.).

Keywords: solar collector, evacuated collector, performance modelling, experimental validation

1. Introduction

Computer modelling 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 foreseen the collector performance in advance. Analyses of individual construction parts and details parameters impact on the collector performance is needed to make decision on efficient solar collector concepts for given application, operation and climatic conditions with respect to economic parameters of construction.

A mathematical model is always a simplification of reality to certain extent. Too complex mathematical models and numerical programs require huge amount of computer time for calculations, too simplified models don't take important influences of detailed 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 [1-3], there is a lack of user-friendly design programs for solar collector performance modelling considering the detailed geometrical and physical parameters of collector. Number of authors evolved simplified analytical models considering 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.

Theoretical model of solar collector has been introduced in TRNSYS Type 73 [4] but with simplified calculation of collector heat loss coefficient U insufficient to cover wide range of parameters affecting the collector heat loss. More theoretical model with number of detailed input parameters and calculation of heat transfer coefficients in the individual parts of collector (in air gaps, inside pipes, at outer surfaces) has been evolved as a Type 103 [5].

A design program CoDePro [6] for energy performance calculation of solar flat-plate collectors has been developed with the Energy Equation Solver. It allows a very detailed specification of collector geometrical and material parameters. It covers large segment of solar collectors (unglazed, single and double glazed) and evaluates also optical properties of collector, e.g. incident angle modifier. On the other hand, the features of CoDePro program, analogous to TRNSYS Type 103, don't allow energy performance modelling of advanced solar collectors, e.g. collectors integrated into building envelope, evacuated flat-plate collectors or solar collector with glazing made of transparent 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 to wide-range of solar flat-plate collectors stock from evacuated to atmospheric, separately or building integrated, covered with different types of glazing (single glazing or transparent insulation structures), etc.

2. 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. 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 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 reference collector area (gross area A_G, aperture area A_a) and output heat transfer fluid temperature t_e.
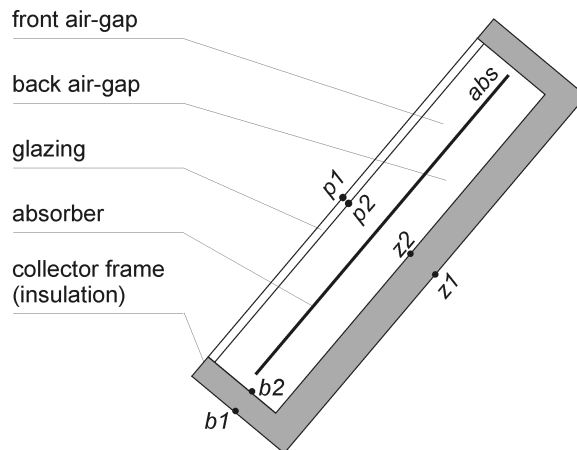

Fig. 1. Main temperature levels in solar collector model.

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). Model solves the energy balance of the solar collector under steady-state conditions according to principle Hottel-Whillier equation for usable heat gain

$$Q_u = A_a F_R \left[\tau \alpha G - U \left(t_{in} - t_a \right) \right]$$

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 for principal collector levels should be known, but on the other side the temperature distribution in the collector is dependent on the heat transfer coefficients values. Therefore, external energy balance of absorber is solved in an iteration loop starting from first temperature estimate for each main level based on given input temperature t_{in} and ambient temperature t_a. External balance loop yields in overall collector heat loss coefficient U [W/m^2.K].
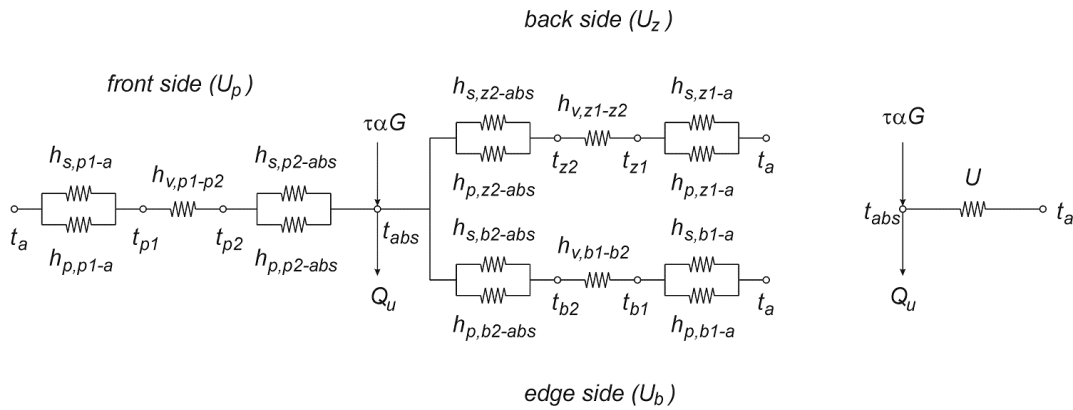

Fig. 2. Schematic layout of external energy balance of absorber.

Internal energy balance of absorber assess 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_e, mean heat transfer fluid temperature t_m and particularly absorber temperature t_{abs}, which governs the calculations in the external balance. 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, 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}).

3. Design tool KOLEKTOR

Mathematical model of solar flat-plate liquid collector has been transformed into 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. 3). Besides the principle parameters and characteristics the tool allows to enter also internal air pressure in the collector (for modelling 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). Design tool allows to choose from various empirical models for calculating 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.
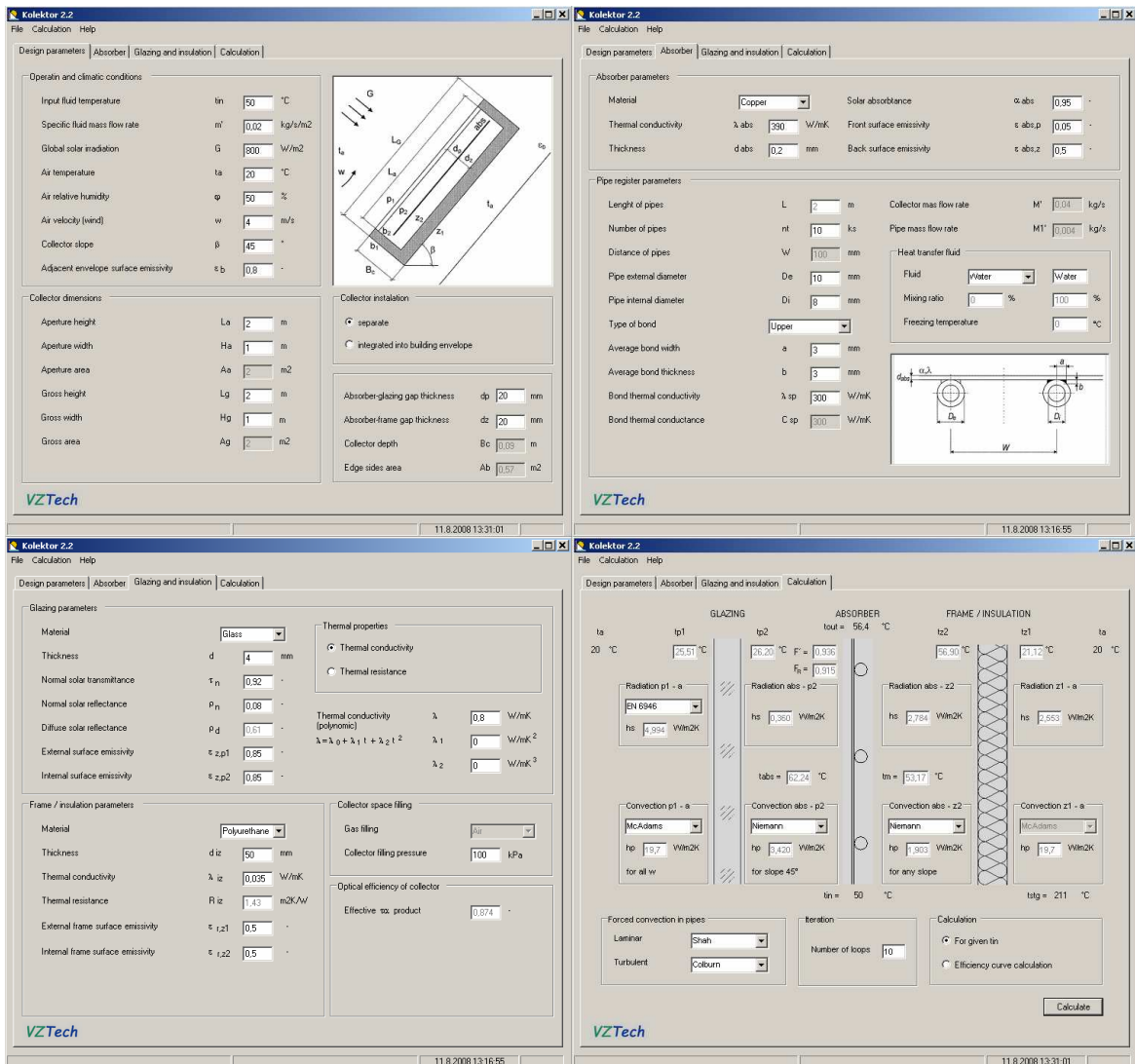

Fig. 3. Tool cards of KOLEKTOR 2.2.

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 spread-sheet file (*.res).

4. Experimental evaluation of model

Mathematical model has been experimentally validated in the frame of solar collectors testing according to European standard [5] in the Solar Laboratory operated under Department of Environmental Engineering at Faculty of Mechanical Engineering, Czech Technical University in Prague. Different construction of tested solar collectors has been chosen to validate the results from mathematical model with instantaneous efficiency data obtained experimentally under steady-state conditions. Experimental data and efficiency curves calculated from model are graphically compared.

Experimental data points of solar collector efficiency are coupled with uniform uncertainty bars in the graphs. Expanded efficiency uncertainty has been assessed for experimental data from both type A (statistical) and B (instrumental) uncertainties considering the coverage factor 2 with 95% level of confidence [5, 6] and for usual steady state conditions of measurements is between 3 and 4 %.

The theoretical calculation of efficiency curve by model is subjected to uncertainty of input parameters. While geometrical parameters are easily available with high degree of confidence, number of parameters defining the properties of collector parts is found uncertain within 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 quite broad range (e.g. emissivity of absorber back side, insulation or collector frame, > 50 %). Each of varying parameter has a different impact (sensitivity) to resulting efficiency value from high effect of absorber and glazing optical properties to negligible effect of frame external surface emissivity. 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.
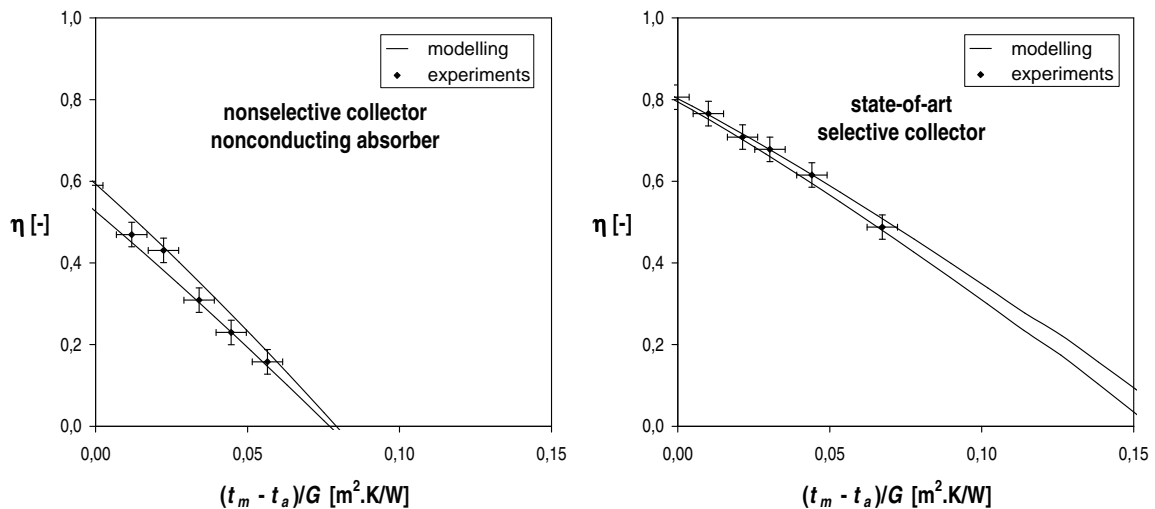

Fig. 4. Experimental evaluation of the mathematical model by collector testing (different absorber quality)

Fig. 4 shows validation of the model for two examples of different atmospheric flat-plate collectors. Collector on the left consists of 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. Determination of absorber-pipes bond conductance is a main source of uncertainty in the calculation.

Collector on the right is a representative of high-quality solar collectors with state-of-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. Due to sufficient back side insulation the influence of uncertain internal and external surfaces emissivity has decreased to minimum.

Mathematical model has been also tested in the field of solar flat-plate evacuated collectors. Validation has been performed on commercial evacuated collector 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, not considered in modelling). The atmospheric variant of the collector (interior pressure 100 kPa) has been evaluated as a reference case (see Fig. 5, graph on the left). The evacuated variant has been tested with interior pressure reduced to 9 kPa (see Fig. 5, graph on the right.
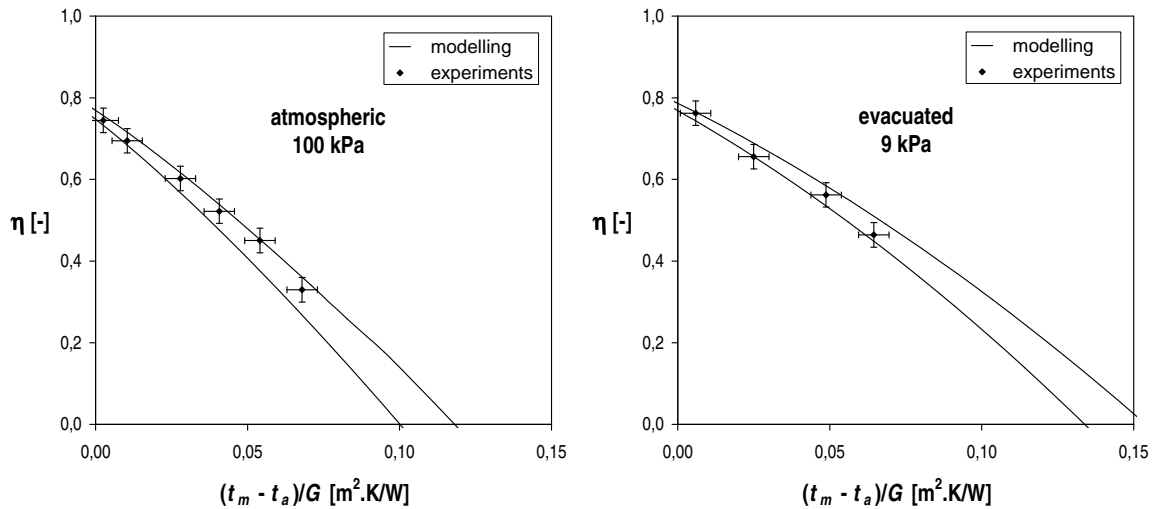

Fig. 5. Experimental evaluation of the mathematical model by collector testing (different interior pressure)

6. Conclusion and outlook

The principles of mathematical model and design tool KOLEKTOR 2.2 for design and virtual prototyping of solar flat-plate collectors have been described. 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).

The model and design tool is under continuous development. Validation of the model for unglazed solar thermal collector type is planned and huge experimental investigations are expected due to high uncertainty in modelling of wind convection heat transfer coefficients known from literature. Mathematical model of solar thermal flat-plate collector (glazed, unglazed) and design tool KOLEKTOR will stand as a basis for development of universal solar photovoltaic-thermal liquid collector model. Advanced PV/T model will allow PV collector modelling (fluid mass flow equal zero, considering influence of temperature on electric efficiency), PT collector modelling (PV reference efficiency equal zero) or PV/T collector modelling.

Acknowledgement

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