A Solar Wall Simulation Module

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A solar wall is a complex part of the building envelope, as it acts as an energy collector, passing solar energy from the exterior surface into the building with a time delay and in the same time reducing thermal losses during periods with no sunshine. A module for simulating solar walls in a Danish building simulation program (tsbi3) has been developed to analyze the interaction between a solar wall and the building behind. Among the more solar wall specific features, the module includes equations for calculation of solar transmittance through systems of multiple transparent insulation materials and for air-flows driven by the stack effect.

Introduction

In Denmark the most commonly used building energy simulation program is *tsbi3* (Thermal Simulations of Buildings and Installations) developed by the Danish Building Research Institute (Johnsen et al. 1993). *tsbi3* is a PC program for analysis of energy consumption and indoor climate in a building divided into multiple thermal zones, under real climatic conditions. The present version of the program was not capable of simulating solar walls on the building, without tricking. This has been a desire from the projecting and consulting engineers who are using the program.

The Danish ministry of energy funded the development of a module for simulating solar walls in *tsbi3*. This work has been undertaken by a study of the special processes in a solar wall compared to normal building constructions and the development of a new version of *tsbi3*.

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Processes in a solar wall

Fundamentally a solar wall is a part of the thermal envelope designed to absorb solar energy on the exterior surface and transport it into the room behind, and in this way reducing the energy requirements of the room. Because of this special function some of the thermal processes in a solar wall are different from those in a normal wall.

A solar wall is, in its simplest form, a normal construction with a system of transparent insulation materials placed on the outside surface (figure 1). Solar energy is transmitted through the transparent cover system and absorbed by the first opaque layer (the absorber) of the wall. Energy absorbed on the absorber is transported to the room behind either by conduction in a solid wall or/and by air flow either internally in the solar wall or from the solar wall into the room behind. These two processes make the solar wall differ the most from a normal wall.

Beside of these special processes a solar wall is subject to very high temperatures, especially at the absorber and just behind it (typically 70-80°C). This high temperature level means that the transmission coefficients of the materials are higher than the normally used transmission coefficients determined at 10°C (with a temperature difference of 2°C). A temperature dependent transmission coefficient for some of the materials in a solar wall will be implemented in a second version of the module.

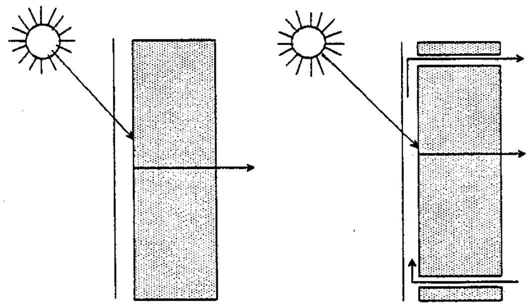

Figure 1 Two types of solar walls, the mass wall (left) and the ventilated solar wall eg Trombé wall.

value ≤ 1 W/m²). At the side of the solar wall the surface resistance may have to be changed, dependent on what kind of analysis one is going to perform. To analyze the overheating problem in the summer, the surface resistance have to be decreased to take into account the high temperature at the back of the solar wall. This considerations are valid in modrate to cold climates, in warmer climates the overheating problem may arise the whole year, and the surface resistance may be changed according to this.

The program checks the thermal resistance of the constructions and compares it with the surface resistance. If the surface resistance is outside some defined limits, a warning is given indicating that certain analysis can't be performed without large uncertainties including a suggestion for a change, to perform the alanysis warned about.

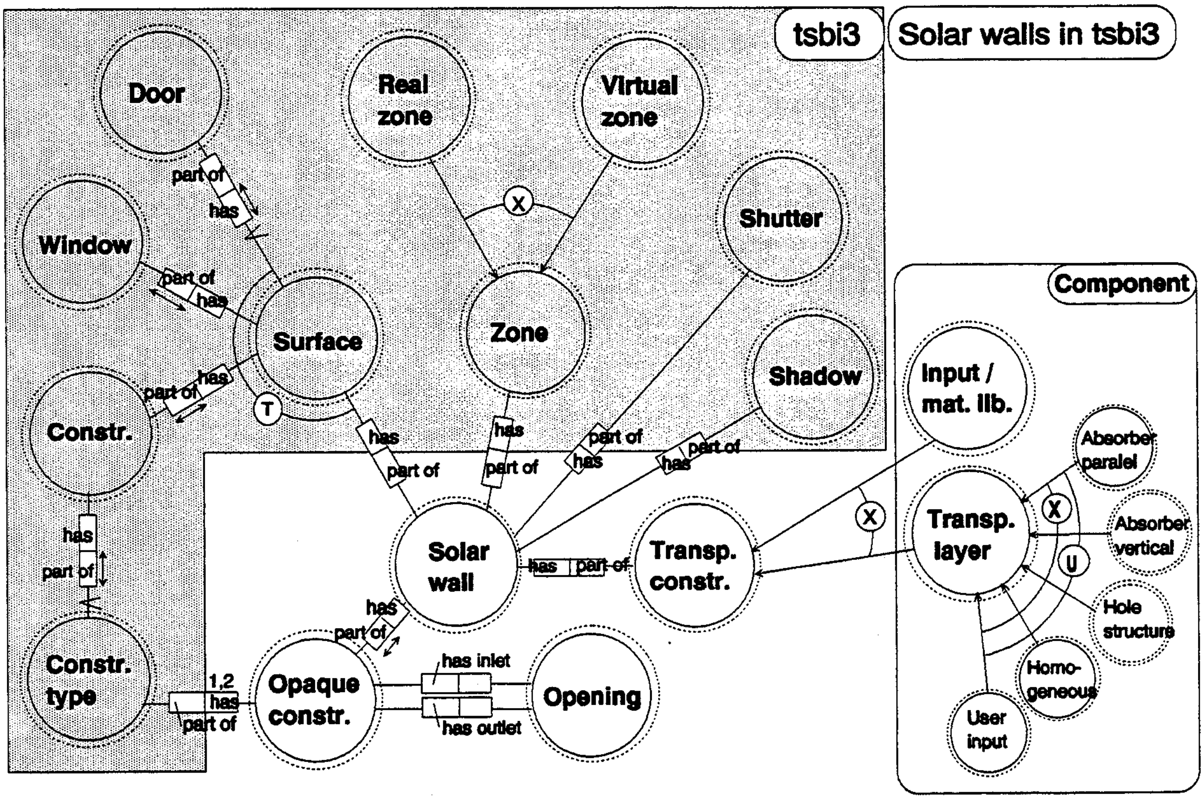

Figure 2 NIAM diagram of Solar Wall extension to *tsbi3*

Routines for prediction of varying surface resistance coefficients have been considered, but found too expensive (simulation time) to introduce. Investigations (Jørgensen 1992) supports this attitude, as the temperature at the front of the cover is of the same magnitude as the rest of the thermal envelope, if the cover is well insulated (U-

Interaction with tsbi3

The solar wall module is, like *tsbi3*, written in ANSI C. In this way it is easy to reuse code and modules from the original program. The interface to the solar wall module is an extension to the *tsbi3* menu system where the solar wall is defined as a subsurface of a surface, in line with windows, doors and constructions. The connection between the solar wall module and *tsbi3* can be illustrated as shown in the NIAM diagram (Turner 1990) in figure 2.

In the first version of the solar wall module the construction model is the same as the one found in *tsbi3*, but in a second version, a special construction model using temperature dependent transmission coefficients for the materials in the construction just behind the absorber, will be investigated. Routines for solar wall specific processes are included, ie the handling of transparent insulation materials and natural convection in enclosures. Some of the routines developed specially for the solar wall module, ie the module for handling transparent insulation materials, will be reused in a planned integrated program package for building design tools.

Transparent insulation materials

The transmission of solar energy through the transparent cover is treated in three separate ways.

- The user can give the transmission coefficient for the whole cover system as discrete pairs of angle of incidence and transmission coefficient as input. From the group of pairs the program makes a 3rd order polynomial curve fitting to determine the transmission coefficient for the actual angle of incidence.
- Transmission coefficients can be obtained form a standard library, holding measured values for a variety of cover systems measured at **one** laboratory site.
- The user can give the transmission characteristics for the individual transparent layers as input. The program calculates the overall transmission coefficient from these inputs.

Calculation of the transmission coefficients for the transparent cover system is performed in an integrated preprocessor before the simulation is started. The preprocessor is only, for the time being, capable of calculating transparent materials of the absorber parallel and the homogenous types (figure 3).

Calculation of the transmission coefficients for transparent insulation materials of the absorber vertical and the hole structure are strongly dependent on the quality of the product and the accuracy of the geometric description of the material. Equations for transparent insulation materials of rectangular Honeycomb (absorber vertical) and in some cases circular Honeycomb, are found in the literature, but differ much from manufacturer to manufacturer.

In cases with cover systems which include transparent insulation materials of the hole structure or the absorber vertical types, it is necessary to give the transmission coefficients for the transparent layer in question as user input at a minimum of four different angles of incidence.

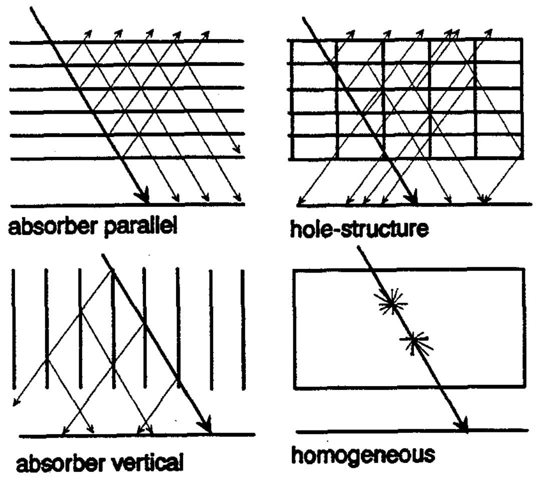

Figure 3 Four categories of transparent insulation materials.

The preprocessor

The calculation of a precise transmission coefficient for a system of transparent insulation materials is essential for a correct calculation of the amount of solar energy transported through a solar wall. In conjunction with the solar wall module, an integrated preprocessor for calculation of transmission coefficients for the total system of transparent insulation materials, has been developed. The transmission coefficients for 7 discrete angles of incidence for the total system of transparent insulation materials are calculated and stored before the simulation begins. The same polynomial curve fitting, as used for the calculation of the user given transmission coefficients for whole cover systems or the individual transparent layers, is used for the calculation of the transmission coefficient at the actual angle of incidence during simulation.

In a transparent cover system with two or more transparent materials of the absorber parallel or the homogenous type, the transmission coefficients are calculated (Duffie & Beckman 1991) from the knowledge about the reflection coefficient (r) and the transmission coefficient (τ_a). The transmission coefficients for each transparent layer are calculated in the two main polarization directions ($\parallel/\perp$), based on the absorption coefficient in the transparent layers alone (index a).

$$\tau_{(\parallel,\perp)} = \frac{\tau_a(1-r)^2}{1-(r\,\tau_a)^2} = \tau_a\frac{1-r}{1+r}\left(\frac{1-r^2}{1-(r\,\tau_a)^2}\right) \qquad 1$$

$$\rho_{(\parallel,\perp)} = r + \frac{(1-r)^2\,\tau_a^2\,r}{1-(r\,\tau_a)^2} = r\,(1+\tau_a\tau) \qquad 2$$

The resulting transmission (τ) and reflection (ρ) coefficients of two transparent layers (index *1* and *2*) are calculated as the average of the coefficients found (by equations 1-2) in the two main directions of polarization:

$$\tau = \frac{1}{2}\left[\left(\frac{\tau_1\tau_2}{1-\rho_1\rho_2}\right)_{\perp} + \left(\frac{\tau_1\tau_2}{1-\rho_1\rho_2}\right)_{\parallel}\right] \qquad 3$$

$$\rho = \frac{1}{2}\left[\left(\rho_1 + \frac{\tau\rho_2\tau_1}{\tau_2}\right)_{\perp} + \left(\rho_1 + \frac{\tau\rho_2\tau_1}{\tau_2}\right)_{\parallel}\right] \qquad 4$$

Calculation of cover systems with more than 2 transparent layers are performed by assuming the coefficients of the material with index *1*, in equation 3-4, to be the previously calculated coefficients and the coefficients with index *2* to be the coefficients of the next transparent layer and so on for the following layers until the whole transparent system has been calculated.

If one or more layers in the transparent system are of the hole structure type or the absorber vertical type, the user have to give the transmission coefficient for these layers as input for at least 4 angles of incidence (different from 90°, measured from the normal vector of the surface). Internally the program assumes the transmission coefficient to be zero at 90° angle of incidence. Calculation of the transmission coefficient for the total system of transparent insulation materials is then processed as described above, assuming the transmission coefficients for the two main directions of polarization to be uniform.

Natural convection within a solar wall

Solar walls often contain vertical enclosures either for transport of air (energy) or for protecting the innermost transparent cover material from the hot absorber.

In the definition of a solar wall, *tsbi3* offers the possibility of defining none to two vertical enclosures. An enclosure is defined to be at the side of an opaque construction, facing the ambient (direct or indirect). A connection from one enclosure to another or to a zone is done by a definition of openings. Openings are defined by the height, the with and the number of uniform openings connecting two enclosures or an enclosure and a zone. Information about the difference in height between the two set of openings leading air to and from an enclosure is also required.

The air flow to and from the enclosures is driven by the stack effect. The static pressure of an enclosure is predicted from the knowledge of the temperature in the enclosure.

In most solar walls there is some distance between the absorber and the back side of the innermost transparent layer (to prevent damage of the transparent cover) in which air can circulate. An other enclosure may be situated behind the absorber, divided from the room by a wall and finally the room itself can receive air from the solar wall (figure 4).

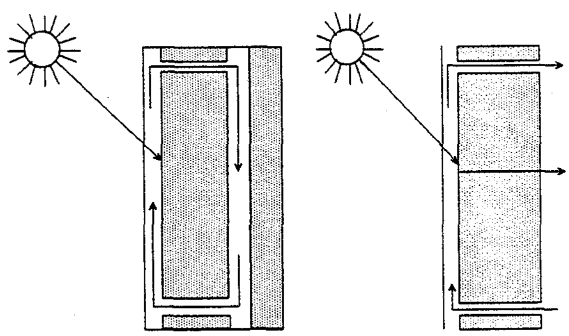

Figure 4 Principal diagram of two solar walls with internal enclosures for air flow.

Air flow through any defined opening is calculated knowing the pressure difference (ΔP) between the two enclosures / zones, the density (d) of the air on each side of the opening and some geometric characteristics of the openings.

Two types of openings in the separation walls of a solar wall are assumed to be found. These types are described as a crack and a hole (Hensen 1991). A crack is defined by the height being much smaller than the width of the crack. The air flow through a crack is calculated from:

$$\dot{m} = dk\Delta P^{x} \quad 5$$

where $x = 0.5 + 0.5\, e^{(-500\, h)}$

$k = l\, 9.7\, (0.0092)^{x} / 1000$

d is the density of the air in the enclosure / zone the air is coming from

h is the height of the crack and

l is the length of the crack

The second type of opening between two enclosures is a hole, defined by the height of the hole being of the same magnitude as the width. Air flow through a hole is calculated by:

$$\dot{m} = 0.65 l h \sqrt{2 d \Delta P} \quad 6$$

Definition of how the enclosures are connected are given in the *"openings"* sub-menu of the *"solar wall"* menu (figure 5) as an identification of in which construction(s) the openings are located and what construction(s) are on both sides of the actual construction.

A *Solar wall* is treated as a zone internally in the simulations, but not defined as a separate zone. Whenever an enclosure is defined in a solar wall the width of the enclosure is required for the calculation of the convective heat transfer.

Menu structure

As the solar wall module is an extension of *tsbi3* the input structure and the user interface are the same as found in the *tsbi3* program.

The input phase of the simulation is based on menu-choices on the screen. The easiest way to navigate through the menu structure is by pointing with a mouse. However the program will run without a pointing device.

The menus are pop-up menus guiding the user - in a logical way - through the input phase of the definition of the building model. The simulation as well as the results analysis are integrated parts of the menu structure. In the main menu (top left on the screen) the simulation and the results analysis are invoked by clicking the *simulation* or the *results* menu.

In the input menus (the *edit model* choice of the main menu) the level of detail raises when moving from left to right on the screen. A sample (screen dump) of the menu structure in *tsbi3* is shown in figure 5. The user is guided through the description of the building model and the solar wall by menu choices. The definition of the solar wall is done in the same menu as the items: windows, doors and constructions ie as a subsurface to a surface. The constructions in the solar wall are defined in a menu similar to the menu the for definition of all other building constructions in the model.

In the *simulation* menu of the main menu the user can, among other things, specify the number of iterations used in each time-step, the solar model to use (three different), the parameters to be shown on the screen during simulation and the parameters to be stored in a binary results file for later hourly analysis in the *results* section of the program. The definition of which periods of the year to simulate is done in this menu too. The simulations can run interactively or references to building models can be stored in a file for batch simulations when the computer is not used for other purposes.

Selecting the *results* menu in the main menu the user gets access to analyzing the results of previously performed simulations. Results from different building model simulations can be analyzed in the same graphic or tabular outputs. All parameters chosen in the *hour-values* menu in the *simulation* menu can be analyzed on an hourly basis. Even if some parameters for determining the energy balance are not chosen in the *hour values* menu, the program saves the variables for the energy balances on a weekly, monthly or whole simulation period basis.

All on-screen results analysis can be printed directly or saved in external files, named after the building model plus an extension indicating the type of file.

Tabular output is being saved as ASCII-formatted files. Graphic outputs are saved in HPGL files for use in word-processors or graphic programs.

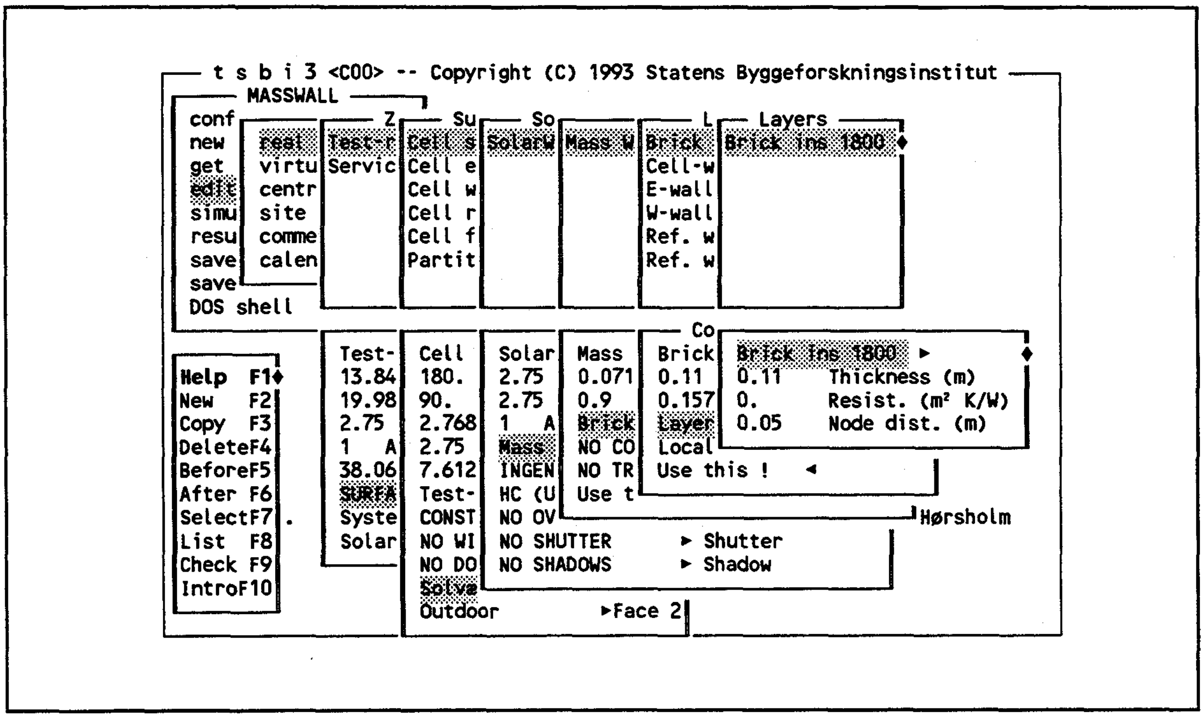

Figure 5 Screen dump of menu structure in *tsbi3 C*

Input requirements

The minimum input requirements for modelling a solar wall in the *tsbi3* model are, in addition to the input requirements for the description of the building model; information about the geometry of the solar wall and its eventual openings for air movements. Optical properties and R-value of the transparent cover system as well as material properties of the wall behind the absorber have to be defined.

In standard libraries properties for some materials are found. Standard libraries exists for complete constructions with cross-reference to a library for opaque materials, containing λ-values, density and specific heat capacity for the materials. Values for R-value and transmission coefficients for some transparent cover systems are found in a database, holding measured values for the transparent cover system, measured at one laboratory.

The R-value and transmission coefficient of the transparent cover system can be defined (similar to the definition of an opaque construction from entries the materials database) by picking transparent layers from a database.

Accuracy

The accuracy of the total performance of solar wall module is dependent on the accuracy of the building simulation program laying behind it. In those cases where *tsbi3* was known fail, because of estimates are valid for "normal" temperature levels only or where *tsbi3* is known to have weak points (ie transparent insulation), special equations were introduced. The accuracy of these new equations are chosen with consideration of the speed of the simulations.

The new handler, in the solar wall module, of transparent insulation is an improvement compared to the old version in which transmission through windows are calculated from knowledge of the transmission coefficient for normal incidence only. In *tsbi3* the transmission for all angles of incidence were calculated from the shape of the transmission curve for normal building glazing. This assumption is incorrect when introducing coated glass panes, materials different from glass and even worse for transparent insulation materials of absorber vertical or hole structure types.

The improvements in the solar wall version of *tsbi3* compared to the original one, are only introduced for the solar wall part of the building model. However the above mentioned improvements will be adopted in the integrated building design tool, which is being developed in Denmark as a national implementation of the CEC project COMBINE (CEC 1992).

Preliminary validation

The building simulation program *tsbi3* (original version) has been validated in many ways. *tsbi3* has been part of an comprehensive blind validation exercise undertaken by IEA (International Energy Agency) task 12. In this exercise simulations have been performed, on a well described building, by people who did not know the measured results (Lomas et al 1993) to compare with. Results from *tsbi3* showed to be in line with both the measured results and with most of the results calculated by other programs in the exercise.

The solar wall module has been used for simulation of solar walls installed in two test buildings at the Thermal Insulation Laboratory at the Technical University of Denmark. The two buildings are not representative for normal residential buildings as they consists of one room equipped for test purposes only. Results from these validation exercise were not ready when writing this paper, but will, hopfully, be presented at the conference.

One of the buildings (a test cell) has been used for validation experiments for the ESP-r program in the CEC project PASSYS (CEC 1993). Datasets from this validation exercise have been used in the validation of the solar wall module. The model of the test cell without a solar wall has been used for a national validation project of the *tsbi3* and showed good agreement between measured and predicted values of the test room temperature.

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