WIS{PRIVATE }

ADVANCED WINDOWS INFORMATION SYSTEM

WIS co-ordination:

H.A.L. van Dijk
TNO Building and Construction Research

Contract JOU2-CT94-0373

WIS REFERENCE MANUAL

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WIS Reference Manual

Dick van Dijk and John Goulding (editors)

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CONTRACT DETAILS

Contract number: JOU2-CT94-0373

Title: ADVANCED WINDOWS INFORMATION SYSTEM (*WIS*)

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See Preface for more details

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The software has been developed by the teams co-operating in the European research project 'Advanced Windows Information System' (the project *WIS*), under the co-ordination of TNO Building and Construction Research, with financial support from the European Commission (DG XII).

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PREFACE

Contract information:

European Commission (Joule Programme) contract number:
JOU2-CT94-0373

Title: ADVANCED WINDOWS INFORMATION SYSTEM (*WIS*)

Co-ordinator: TNO Building and Construction Research

Project leader: H.A.L. van Dijk
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Contract Duration: 1 May 1994 – 31 October 1995

'Advanced Windows Information System (the project 'WIS')'

Within the framework of the European Commission Directorate General XII Research Programme, Sub-Programme Energy Utilisation and Conservation, a project was carried out with the aim to develop a uniform European software package to assist building designers and component developers in determining the thermal and solar properties of window systems (glazing, frames, solar shading, etc.) and window components under the title: 'Advanced Windows Information System ('WIS')'.

The project started in May 1994 and the final products were completed in December 1995.

The final products are:

The WIS software package:

- a well structured, multi-purpose European information tool to determine thermal and solar characteristics of advanced windows. The tool contains appropriate databases with component properties and routines for calculation of the thermal/optical interactions of components in a window.

Documentation:

- a user guide, including a tutorial
- a detailed reference manual
- a final report on the research activities
- a plan for dissemination, technical support, maintenance and further development

The final product of the WIS project is an excellent design tool, ready to be used for a wide range of applications.

However, there is the assumption that it is the final answer to all questions and needs:

- a number of features have been developed but not yet activated, because they require a final implementation/quality testing;
- additional features have been recognised as future options which would increase the usability and/or applicability of the package; a number of these features are mentioned as 'future options' throughout this reference manual;
- new technological developments provide greater insight into the validity of the algorithms for existing products (e.g. solar shadings) and to additional algorithms for new products (e.g. evacuated glazing).
- data are being gathered to systematically fill the component data bases. This action was started only near the end of the project in order to be able to convince the manufacturers that the data we required would be compatible with the final WIS product.

  Moreover, the WIS tool is also intended to serve in disseminating the results from measurements on innovative components or measurements obtained with innovative equipment from international research projects (EU, IEA).

  Consequently, populating the databases is a process which will need to be continued;
- there is a close relationship between the development of WIS and European standardisation activities within the framework of CEN (Comité Européen de Normalisation - European Committee for Standardisation). Among the activities in CEN are the standardisation of calculation routines and/or results of calculations for the thermal and solar properties of windows. On the one hand, the CEN calculation tools are adopted (as one of the options) in the WIS software tool. On the other hand, the use of the more advanced options in WIS will help in the definition and solution of algorithms for future standardisation. This will be an important contribution during the coming years.

To accommodate such future developments, the WIS software package has been developed from the start with an 'open', object-oriented structure.

A Steering Committee has been set up to guide the further development of WIS after the completion of of the WIS research project.

WIS version 1.0

The teams co-operating in the European research project 'Advanced Windows Information System' (the project *WIS*) are pleased to present the release of WIS version 1.0.

Dick van Dijk

Co-ordinator WIS project

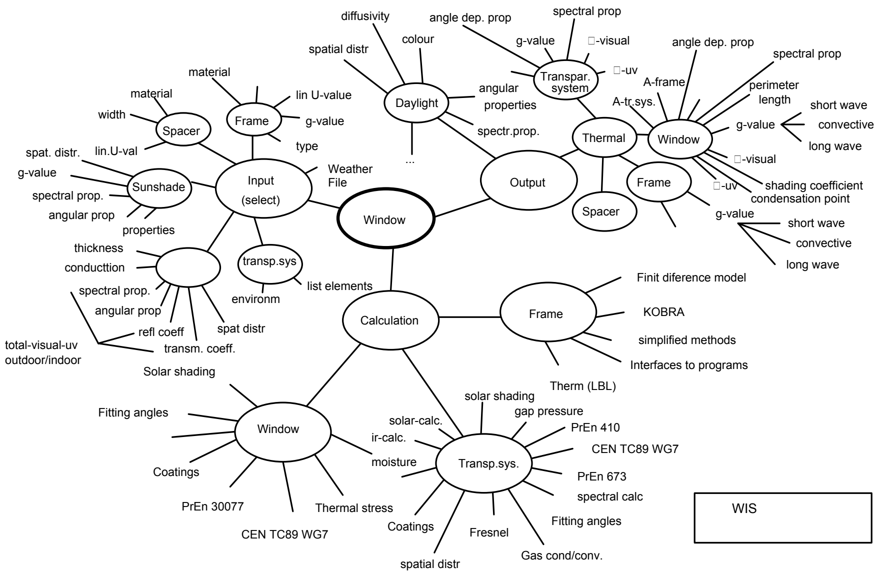

Illustration of the complex relationships which have to be prioritised and user friendly structured

DOCUMENTATION:

This Reference Manual contains the detailed description plus the necessary background information on the calculation procedures.

A **User's Guide** [1] is also available to the user.
The User's Guide includes a **Tutorial** to assist the first time user through the various screen Forms.

In order to prevent unnecessary duplication and to ensure efficiency in future updates, the Reference Manual and the User's Guide are as far as possible, complementary.

Therefore, the reader is advised to consult the User's guide for basic information concerning:

- The hardware requirements
- The set up of the software
- List of features in current version
- How to run the software

An **on line Help system**, comprising the main elements from the Tutorial, is also available to the user.

For readers who are interested in the organisation and activities of the EU research project WIS:
The final research report [2] which contains details of objectives, work method, results and conclusions on the EU JOULE project 'Advanced Windows Information System' (the project WIS), is available from The Co-ordinator, TNO .

Acknowledgements:
The co-ordinator of the WIS project acknowledges the very active and constructive contributions of all participants in the WIS projects (see on following pages), in the development of the software package and associated documentation.

Also acknowledged are all participants at the two workshops organised during the WIS project to obtain feedback from representatives from industry and building practice [3], [4].

Two workshops, organised during the WIS project and attended by invited representatives of European industry, building practice, research and public agencies, were held at TNO Building and Construction Research, Delft. Valuable feedback was received which has had a significant impact on the development of the WIS software package for use by industry, research and building designers.

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November 1995

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September 1996

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1 INTRODUCTION

1.1 General

The WIS project:
The WIS software package was developed as a cooperative activity of the participants in the European research project WIS.
The coordination of the project was in the hands of TNO Building and Construction research.
The main structure of the software tool was developed at TNO, in close consultation with the other members of the WIS team.
Because of the need to create a well-structured, easy accessible, flexible tool, the choice was made to use a strict object-oriented structure (see section 1.2).

Thermal and solar properties of windows:
The thermal and solar properties of a window system are a function of the composition of a number of components and the assumptions concerning its environment.
The main components are the transparent part and the window frame.

The transparent part consists of panes (either or not coated or structured, glass or plastic or this foil), gas or air filled gaps and shading elements parallel to the panes. The gaps may be ventilated or not.
In case of a temperature difference between inside and outside, heat will be conducted through the transparent part by conduction, convection and thermal (IR) radiation.
The panes and shading elements transmit, absorb and reflect solar radiation. Absorbed solar heat is in its turn transported to inner and outer surface of the system by conduction, convection and thermal (IR) radiation. In particular the shading elements will to some extend transmit thermal radiation and thermally driven or forced circulating air.

Major simplifying assumptions in modelling these physical processes are introduced in chapter 3.

Within the window frame the heat is also transferred by conduction, convection and thermal radiation (chapter 3).

On top of that, there is a close interaction between the edge of the transparent system and the frame. In particular in case of metal spacers in sealed double or triple glazing units, the spacer and the glass edges may act as thermal bridges for the frame, and/or vice versa.

The indoor and outdoor environments are defined by different temperatures for convection and thermal radiation heat exchange, humidity, air movement and solar radiation characteristics (see chapter 3).

Modelling window properties:
In general, the choice of calculation method may -and usually will- depend on restrictions of practical and/or legislature nature: availability of necessary input data from components, calculation rules dictated by (inter)national standards, simplifications in case of complex products, simplifications in case of complex boundary conditions.

In short: there are (too) many choices to make. The actual choice in a certain situation depends on the type of user and his/her goal.

The role of the WIS tool:
The WIS tool aims to combine the wide range of applications into one software package with different in-built choices. In this way WIS creates the uniform environment so urgently needed today.

At the start of the development of WIS individual research institutes and companies in Europe were developing their own calculation routines. National standards on the calculation of thermal and solar properties of windows and glazings used different assumptions and simplifications, leading to significant discrepancies in results. European standardizarion on these issues was leading to first draft standards, but were necessarily restricted to specific components only, in particular flat glazings.

Under those circumstances it costs a lot of effort to industry and building practice to get and provide internationally unified and accepted information. And for the research community it costs a lot of effort to be able to objectively evaluate new developments, develop design tools and provide correct input for building simulation programs.

Hence the main objectives for the development of the WIS tool were:

WIS aims to be a uniform European, user-friendly software package for widely varying applications including product development, research, and building design.

The package will allow the user to design a window composition, select specific components and avail immediately of their properties from databases, choose appropriate calculation routines, set environment conditions and format the desired output.

The tool will feature different levels of detail for different types of use, ranging from rough pre-design information to window properties based on detailed component information. The levels will be downwardly compatible, aiming at maximum support of the design process.

Various calculation and output options will allow the user to choose between output as product specifications, or as input for design tools (such as PASSPORT), for building thermal simulation software (such as ESP) or visual imaging software for buildings (such as RADIANCE).

The tool will facilitate calculations according to international standards (such as CEN) thus enabling product comparison, and will allow more advanced calculations to be performed which might be a basis for future standards.

Special attention will be paid to inclusion of advanced (e.g., highly insulating or 'smart' components and products) in the databases and routines to allow the users to select the latest techniques available or to anticipate technologies of the future.

WIS will have an 'open' structure, to accommodate future developments.

The contents of the first version of WIS reflect these objectives. It is a ready-to-use tool, suitable for a wide range of applications. On the other hand, this first version is definitely not the final answer to all questions.
The 'object oriented' structure of the WIS software package and the organisation of dissemination, support and development via a Steering Committee will accomodate future developments, such as mentioned in the Preface.

In order to offer to the different categories of users a tool which is suited to their demands, with a minimum risk of improper use, a number of measures have been built in, such as different access restrictions, component data protection and validity checks.

One of the main applications, is the use of WIS to calculate window properties according to CEN calculation rules, using CEN environemnt conditions and certified component data as input. This has been facilitated by the introduction of a special mode for 'CEN only' calculations; see section 1.4.

In WIS provisions have been made to report details on the calculations. The level of detail is user defined. This detailed report provides information on the precise context of the calculation results, see section 1.5.

A collaborative agreement has been established with the Lawrence Berkeley Laboratory (California), aiming at mutual benefit to both groups as well as to manufacturers, designers, and consumers both in the US and the EU; see section 1.6.

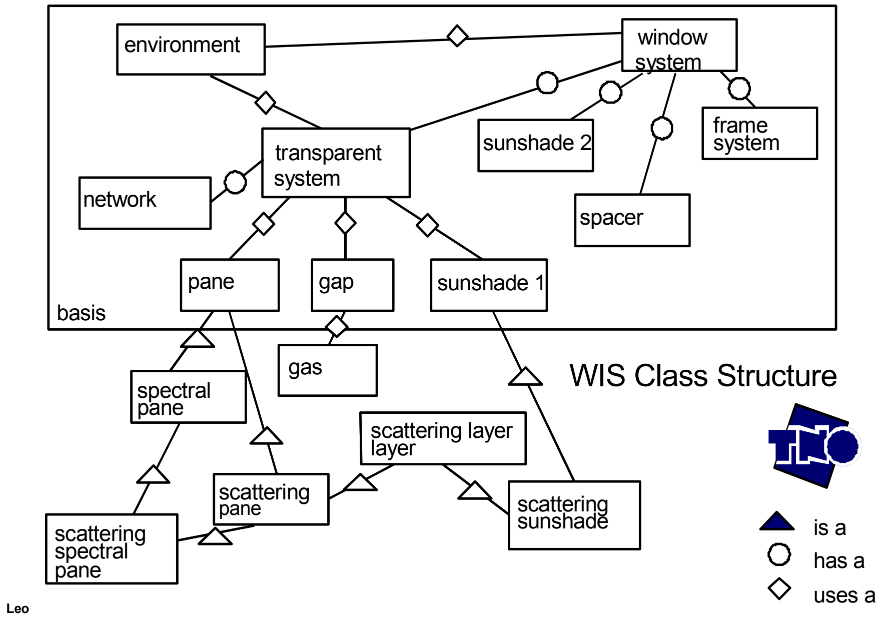


Illustration of the main classes in the WIS Object Oriented Class structure

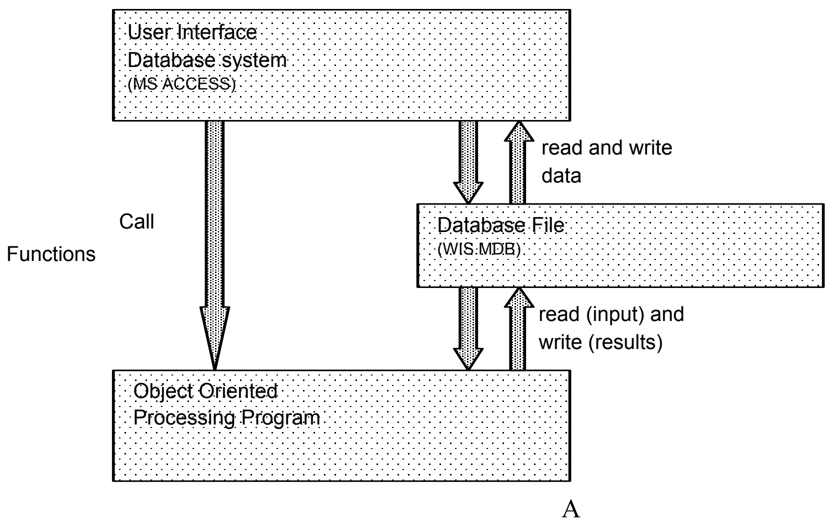
1.2 WIS SOFTWARE ENVIRONMENT AND TOOLS

During the first part of the WIS research project the main choices with regard to software environment and tools were made:

Structure: Object Oriented
Language: C^{++}
Database / user interface: Microsoft Access
Platform: Microsoft Windows

The choice of C^{++} was based on the need to create a well structured, easy accessible, flexible tool. This requires an object-oriented structure. The initial programming task and communication between the partners involved in the software development requires much greater effort compared to programming using conventional techniques and languages (such as FORTRAN). However, the greater initial effort has advantages in the long run, as the object-oriented approach makes it much easier to incorporate new modules or to revise existing ones.

The links between data bases, calculation modules and user interface are illustrated in the figure



The links between data bases, calculation modules and user interface

By the choice of an Object Oriented approach in the programming the foundation is created for efficient future developments. The makers count on the feedback from the users to determine the necessary priorities in this respect.

1.3 WIS and the link with European standardization

There is a close relationship between the development of WIS and European standardisation activities within the framework of CEN (Comité Européen de Normalisation - European Committee for Standardisation.
There is a considerable number of European standards dealing with thermal and solar properties of windows currently under development.

Chapter 3 (section 3.3) introduces specific standards and the relation with WIS more in detail.

A number of participants in WIS are actively involved in these CEN standardisation activities, thus ensuring the necessary direct links between research and standardisation.
The WIS software package will present to the European industry and building practice the latest developments in European standardisation. In addition, the more advanced and/or novel routines in WIS will serve as a basis for the development of future European standards.

'CEN only' calculation mode:
To accomodate to the demands for uniform European product information a 'switch' for 'CEN-only' calculations has been built in in WIS; See Section 3.3 and the Users Guide.

1.4 Co-operation with LBL Berkeley (USA)

The Lawrence Berkeley Laboratory (California) program WINDOW version 4 is a well-known tool for calculating the U-value and solar transmittance of glazing and combinations of glazing and frames. To some extent *WIS* and WINDOW have similar goals:

calculation of thermal and solar properties of windows
incorporation of databases with component data
continued development

There are however differences in priorities, for instance:

- WIS aims to offer a choice of different calculation methods;
- WIS concentrates on European (CEN) standards to a greater extent
- solar shading devices, ventilated windows, scattering panes are important elements in WIS
- a new WINDOW version contains a user-friendly finite-element calculation for frame heat loss including edge effect (THERM)

A collaborative agreement has been established aiming at mutual benefit to both groups as well as to manufacturers, designers, and consumers both in the US and the EU.
The objective of this collaboration is to assist each group in developing innovative and useful software, and to reduce the time and cost of software development by reducing unnecessary duplication of effort. It is the intent to harmonise calculation procedures and create compatible databases of fenestration component performance wherever this meets the needs of both groups. However, given the differing needs and schedules of each group it is not planned to develop a single software package.

First concrete results, visible in first version of WIS:
- WIS has been prepared to be linked with THERM
- compatibility of input of spectral optical data

1.5 Dissemination, technical support, maintenance and further development

A Steering Committee has been set up to guide the further development of WIS and the organisation of dissemination, support and maintenance after the ending of the WIS research project.

A working plan has been made on these topics which is based upon the following principles:

The price of the software should be as low as practicable consistent with the need to cover costs such as promotion, reproduction, delivery, technical support and maintenance; the cost of initial development will not be incorporated in the price.

Technical support will be provided for each licensed copy sold.

Documentation in the form of a user guide and reference manual will be provided.

Promotion, sales and support will be co-ordinated from a single European location, UCD in Dublin, with back-up technical support provided by TNO and the appropriate WIS participant teams.

The development of a user group will be encouraged by establishing a forum (bulletin board / conference) on the Internet World Wide Web.

Future modifications and extensions to the software, in the calculation routines and/or in the component databases, will be decided upon by the Steering Committee and kept at a single location to maintain the advantage of the Europe-wide uniformity of the package.

A number of features which are of interest only for specialists/experts will be made inaccessible (invisible) in a special version for non-expert users.

1.6 Future

The most relevant and urgent WIS *follow up activities*:

- evaluation of the organisation of dissemination, technical support and maintenance; including the systematic filling of the data bases with available commercial products (window components) and prototype products

- link with other current and future European research activities dealing with new window technologies, to ensure WIS remains: uniform European environment for product information (measured data, calculation routines) on advanced windows

- organisation of the interest and active participation of all major research teams in Europe dealing with advanced window technologies to keep WIS up to date, to incorporate new developments

- continued cooperation with LBL Berkeley

- finishing touch on the WIS software package: development and completion of specific elements which during the project were identified by representatives from the end-users as important, but could not be completed in the given short time (only 18 months)

  (see also list of features in User's Guide)

- continued link with international standardization activities (CEN TC89, TC129, ISO TC163) where window modelling is now placed high on the agenda

2 MAIN TERMS AND SYMBOLS

2.1. Introduction

This chapter contains the definition of the main terms and symbols found in the WIS user interface.

Where there are no contradictions they are in accordance with-
- ISO standard 7345/1, Thermal Insulation - Vocabulary - Part 1

and the relevant vocabulary used in:
- CEN PrEN 832, Thermal Performance of Buildings - Calculation of Energy Use for Heating - Residential Buildings (1992)

The terms and symbols used in this reference manual are defined in each individual chapter. In the current version of this reference manual no effort has been made to unify the terms and symbols.

2.2. Symbols

A	area	m^2
c	specific thermal capacity	J/(kg.K)
d	depth, thickness	m
G	incident solar radiation intensity	W/m^2
g	total solar energy transmittance	-
h	surface coefficient of heat transfer	$W/(m^2.K)$
k	extinction coefficient	-
n	refraction index	-
PSI	linear thermal transmission coefficient	W/(m.K)
Q	heat flow	W
q	heat flux density	W/m^2
R	thermal resistance	$m^2.K/W$
Ra	Colour rendering index	-
T	temperature	°C (or K)
t	time	s,h
U	heat transmission coefficient	$W/(m^2.K)$
V	volume	m^3
..	...	
β	solar incidence angle	rad, degree
Δ	difference	-
λ	thermal conductivity	W/(m.K)

ψ	see PSI	
ρ	reflectance	-
ρ	specific density	kg/m^3
Θ	temperature	^0C
ϕ	solar incident angle	rad, degree
τ	transmittance	-
..	...	

2.3. Subscripts

a	air
av	average
c	convection, conduction
calc	calculated
B	beam
D	direct
d	diffuse
e	external
h	hemispherical
meas	measured
n	at normal incidence
r	radiation
s	surface
tot	total
w	window
10	at 10 ^0C
..	...

2.4. Definitions

Definitions of the main terms:

U is the heat transmission coefficient: the density of heat flow rate in the steady state divided by the temperature difference between the surroundings on each side of the system or component, in W/(m^2.K);

τ is the solar transmittance: the density of transmitted solar radiation through a component divided by the internsity of incident solar radiation, non-dimensional;

g is the total solar energy transmittance: the density of heat flow rate leaving the component at the inside surface, under steady state conditions, caused by solar radiation at the outside surface, divided by the intensity of incident solar radiation on the component, non-dimensional.

PSI is the linear heat transmission coefficient of a linear thermal bridge: the heat flow rate in the steady state per unit length of the component, divided by the temperature difference between the surroundings on each side of the component, in W/(m.K).

2.5 Variability of properties

As explained in chapter 1 (Introduction) and more in detail in chapter 3, when it comes to the calculation of thermal and solar properties of windows, the number of possible variations in calculation procedures, assumptions, environment conditions and input data is in general very large.
This implies that the variation in output values is similarly large as well.
Therefore it is important to note that it is not sufficient to report a calculation result for a selected combination of components, but also which calculation method, environment conditions and input data were used. In section 1.4 the option of the 'CEN-only' calculation has been introduced; for those calculations a protection is built in to ensure that it is well understood how to interprete the result.

WIS provides at each level of calculation (window system, transparent system, pane, shading, frame) the option to provide a detailed report. The level of detail is user defined. This detailed report provides information on the precise context of the calculation results.

3 MAIN WIS STRUCTURE

3.1 General structure

Thermal and solar properties of windows:
The thermal and solar properties of a window system are a function of the composition of a number of components and the assumptions concerning its environment.
The main components are the transparent part and the window frame.

The transparent part consists of panes (either or not coated or structured, glass or plastic or this foil), gas or air filled gaps and shading elements parallel to the panes. The gaps may be ventilated or not.
In case of a temperature difference between inside and outside, heat will be conducted through the transparent part by conduction, convection and thermal (IR) radiation.
The panes and shading elements transmit, absorb and reflect solar radiation. Absorbed solar heat is in its turn transported to inner and outer surface of the system by conduction, convection and thermal (IR) radiation. In particular the shading elements will to some extend transmit thermal radiation and thermally driven or forced circulating air.

The typical, first simplifying assumption is that the thermal and solar properties of a transparent system may be considered as one-dimensional, perpendicular to the pane surface.
Where this is an obvious oversimplification the two-dimensional effects are taken into account in a special way. This is for instance the case for the thermally driven ventilation and the edge effect where the transparent part and the window frame meet.

Within the window frame the heat is also transferred by conduction, convection and thermal radiation. Due to the geometry of the frame the heat transfer is usually typically two (or even three-)dimensional. The challenge is to reduce the two-dimensional heat transfer characteristics into a one-dimensional property.

On top of that, there is a close interaction between the edge of the transparent system and the frame. In particular in case of metal spacers in sealed double or triple glazing units, the spacer and the glass edges may act as thermal bridges for the frame, and/or vice versa.

The indoor environment is defined by an air temperature, a mean surface temperature (for thermal radiation exchange), humidity and a certain air movement in the boundary layer of the window.
The outdoor environment is in general characterized by such variables as air temperature, temperatures of sky, surrounding buildings and ground, humidity, wind speed and direction and solar radiation. The solar radiation reaches the window as direct radiation from the sun, diffuse radiation from the (overcast) sky and ground reflected radiation.

It is arbitrary under which category the following elements should fall.

- the orientation and tilt angle of the window
- external shading devices like window rebate, awnings, etc.

We chose to place them in the category of environment, because the window responds to it similarly as it responds to a change in environment conditions.

Finally, the choice of the calculation method may -and usually will- depend on restrictions of practical and/or legislature nature: availability of necessary input data from components, calculation rules dictated by (inter)national standards, simplifications in case of complex products, simplifications in case of complex boundary conditions.

In short: there are (too) many choices to make. The actual choice in a certain situation depends on the type of user and his/her goal.

3.2 Restrictions, data protection and validation

Different levels of access:
The WIS software package has built in two different levels of access:
- a level with restricted editing and browsing possibilities for building designers
- a 'full access' level for researchers and manufacturers
  See users guide for more details

Data protection:
To prevent unwanted editing of supplied certified manufacturers data and representative sets of generic data, these input data are protected against editing or erasing.

Validity checks:
To prevent the use of physically, practically or computationally impossible data, or the creation of physically, practically or computationally impossible combinations a high number of validation checks have been built in. The user receives an on line warning at the occasion. For instance: a gap or pane width of zero mm; a gasmix not adding up to 100 percent; etcetera.
Similarly, protections are built in to check whether the available data are suited for the requested type of calculation. For instance: if the spectral data in the visible part of the spectrum are absent or insufficient, a warning will inform the user that the visual properties cannot be calculated due to incomplete data.

No guarantee:
Of course these protections are in no way a guarantee against any misuse that may be provoked by the high number of possibilities offered by WIS. They are mainly meant to protect against often made minor mistakes. For instance, it is possible to place a pane with a vulnerable softcoating at the weather exposed side of the transparent system.

On line Help System:
At all levels an on line Help system is available.
The on line Help system has been created with the use of MS Windows Help facilities. The contents of the on line Help system is based on the contents of the Users Guide. With hyperlinked keywords the user can easily and quickly browse through the different sections.

Other features to increase user-friendliness:
Other features aimed to maximize the user friendliness of the tool are described in the User's Guide.

3.3 WIS and the link with European standardization

As explained in chapter 1 (section 1.4) there is a close relationship between the development of WIS and European standardisation activities within the framework of CEN (Comité Européen de Normalisation - European Committee for Standardisation). Among the activities in CEN TC89 WG7 and WG6 are the standardisation of calculation routines and/or results of calculations for the thermal and solar properties of windows, for instance: CEN TC89 WG7, thermal and solar properties of windows (i.e., calculation models for heat loss and solar transmittance properties of window systems including solar shading and shutters); CEN TC89 WG6, indoor climate in summer (i.e., window and solar shading modelling for dynamic building models).
The most relevant standards (EN...), draft standards (prEN...) and working documents (../N...) are listed in **appendix A**.

The list shows that there is a considerable number of European standards dealing with thermal and solar properties of windows currently under development.

Concerning the method of calculating the transmission coefficient (U-value), the standards will cover any combination of glazing, edges and frames, in principle. However, the U-values for glazing can only be calculated for multiple glazing units, not for special glazing such as plastic multi-channel panels, transparent insulation, windows containing IR transparent foils, cavity venetian blinds, etc.

For calculation of the solar properties, the standards will, in principle, cover only the properties for normal incidence radiation and for standard conditions with respect to temperatures. For design purposes there is a clear need for more realistic conditions. There is also a need to develop or validate models, for instance concerning heat transfer around solar control devices such as blinds. It is expected that the development of the WIS package will stimulate future standardisation in these fields.

A number of participants in WIS are actively involved in these CEN standardisation activities, thus ensuring the necessary direct links between research and standardisation.
The WIS software package will present to the European industry and building practice the latest developments in European standardisation. In addition, the more advanced and/or novel routines in WIS will serve as a basis for the development of future European standards.

'CEN only' calculation mode:
To accomodate to the demands in this respect a 'switch' for 'CEN-only' calculations has been built in in WIS; if that switch is activated WIS only allows calculation procedures, environment conditions and component input data in the data bases which are conform the CEN rules.
On the other hand one should not forget that the whole area of standardization is a still ongoing process. As appendix A shows, most standards are still under development or their development started only recently. This implies that WIS has to be very alert to changes in the standards.

Concerning the standardization process, as stated before, WIS also wants to provide information to stimulate further standardization, by offering the possibility to compare different old and/or new options in calculation routines and component data.

3.4 Detailed reporting in WIS

WIS provides at each level of calculation (window system, transparent system, pane, shading, frame) the option to produce a detailed report. The level of detail is user defined. This detailed report offers information on the precise context of the calculation results. Moreover, it provides additional inside information on calculation details, such as node temperatures, network resistances, Nusselt numbers for free convection, transmission and reflection per wavelength and so on. This detailed information is thus available for use in other environments (building simulation, detailed studies, spreadsheet programs, etc.).
Examples are given in the WIS User's Guide.

3.5 WIS database structure

WIS contains input data for the various types of components.
Both generic and specific manufacturers data.
Generic data may be chosen in case no particular information on a certain product is available, e.g. in a pre-design stage, or for sensitivity studies.
Manufacturers data are presented as well. It is the intention to add (next version?) a clear indication on the quality of the given information.
For instance: either or not certified data, according to a certain international standard.
But also: experimental data, e.g. from a research project on an innovative product, or e.g. normally not measured detailed or special properties.

Of course, this requires a well structured system of maintenance and updating.

As mentioned before (preface, chapter 1) the structure has been created (Steering Committee) to deal with these important aspects.

4 WINDOW SYSTEM

4.1 The window system as combination of transparent system, frame and spacer

The thermal and solar properties of a window system are a function of the composition of a number of components and the assumptions concerning its environment.

The main components are the transparent part and the window frame.

The transparent part consists of panes, gas or air filled gaps and shading elements parallel to the panes.
In case of a temperature difference between inside and outside, heat will be conducted through the transparent part by conduction, convection and thermal (IR) radiation.
The panes and shading elements transmit, absorb and reflect solar radiation. Absorbed solar heat is in its turn transported to inner and outer surface of the system by conduction, convection and thermal (IR) radiation. In particular the shading elements will to some extend transmit thermal radiation and thermally driven or forced circulating air.

The typical, first simplifying assumption is that the thermal and solar properties of a transparent system may be considered as onedimensional, perpendicular to the pane surface.
Where this is an obvious oversimplification the twodimensional effects are taken into account in a special way. This is for instance the case for the thermal effects at the edge where the transparent part and the window frame meet, as explained further on.
The heat transfer in the transparent system is decribed in chapter 5.

Within the window frame the heat is also transferred by conduction, convection and thermal radiation. Due to the geometry of the frame the heat transfer is usually typically two (or even three-)dimensional. The challenge is to reduce the two-dimensional heat transfer characteristics into a one-dimensional property. This process is described in chapter 6.

There is a close interaction between the edge of the transparent system and the frame. In particular in case of metal spacers in sealed double or triple glazing units, the spacer in case of multiple glazing units and the glass edges may act as thermal bridges for the frame, and/or vice versa: the frame may act as a thermal bridge for the edge of the transparent part.

In recent international standards the interaction between frame and transparent part is represented by the one-dimensional heat loss parameter PSI. See chapter 6.

4.2 The main properties

Resultingly, as explained in full detail in chapter 6, the U-value of the window system is obtained as a combination of U-value of transparent part and U-value of frame, weighted with their respective projected areas plus the PSI-value (Ψ) of the spacer multiplied by the perimeter length of the transparent system:

transmittance of the window:

$$U_w = \frac{U_{tr} \cdot A_{tr} + U_f \cdot A_f + \Psi_g \cdot l_g}{A_{tr} + A_f} \qquad [W/m^2K]$$

where :

U_{tr} thermal transmittance of the center of the glazing (or more general: transparent system) in W/m^2K

A_{tr} visible area of the glazing or transparent system in m^2

U_f thermal transmittance of the frame with an ideal insulating filling element in W/m^2K

A_f projected area of the frame in m^2

Ψ_g linear thermal transmittance due to the combined thermal bridge effects of the spacer, glazing and frame in W/mK

l_g total visible perimeter length of the glazing in m

For the calculation of the U-value WIS needs these data. The U-values and the PSI-value are obtained as result of the calculations on transparent part and frame (chapters 5 and 6). The geometric data are obtained as:

window system area:

$A_w = h \times b$

with:
h, b is the height and width of the window system, specified as property of the Window System in the input (m).

Area of the transparent system:

$$A_{tr} = (h-2 \cdot d_f) \cdot (b-2 \cdot d_f)$$

with:
d_f is the thickness of the frame, projected in the plane of the pane(s) and specified as property of the frame (m)

The perimeter of the frame, L, is calculated as:

$$L_f = 2(h-2 \cdot d_f) + 2(b-2 \cdot d_f)$$

The property describing the condensation risk of the window system is the temperature factor (f-value).
The f-value of the window system is the minimum value of the f-value of (1) the centre part of the transparent system, (2) the frame and (3) the edge zone where frame and transparent system meet.

The g-value of the window system is a very simple conversion from the g-value calculated for the transparent part, weighted by the area of the window system compared to the area of the transparent part:

$$g_w = g_{tr} \cdot A_{tr}/A_w$$

Obviously one should be well aware whether a g-value is defined for the whole window area or only for the transparent part.
Similarly for the visual transmittance.

4.3 Orientation, tilt and external shadings

It is arbitrary under which category the following elements should fall.

- the orientation and tilt angle of the window
- external shading devices like window rebate, awnings, etc.

We did choose to place them in the category of environment, because the window responds to it similarly as it responds to a change in environment conditions.

The user of the current version of WIS will miss an input option for the orientation of the window. The orientation is needed in case the calculation has to be carried out for a given position of the sun in global coordinates. For instance in case of a calculation for a given hour from a weather sequence.

However, since the use of weather sequences is not yet activated in the current version (see chapter 7), the orientation is not yet asked for.

Similarly, the user will miss an option for the tilt angle of the window. This option is not yet offered, because of the same reason. The tilt angle has not only an effect on the angle of incident solar radiation, but also on the view factor for the thermal radiation from sky, surroundings and ground and on the convective heat exchange in gaps.

The external shading devices as window rebate, awnings, etc. are considered as elements which block part of the incident solar radiation. The modelling of these elements is described in detail in section 11.4.

4.4 Database with window systems

In the current version of WIS the number of window systems in the database is limited.
As we have seen above, the properties of the window system are constructed from the properties of the transparent system, frame and spacer. The extra input for the window system itself is very limited: only geometric data and (future) the position.
Moreover, a window system may easily be combined from various combinations of frames and transparent systems, taken the edge effect properly into account. Moreover, one particular window system may be available in a range of sizes. Storing each combination would soon lead to an inconveniently large database.
For these reasons one should be very restrictive in trying to systematically fill this database.

4.5 Future options

The following options may be considered for future updates:

Highest priority:

- Orientation and tilt angle (the latter is activated for thermal properties (convection); not yet activated for solar radiation.
- Other:
- window system consisting of different frame and/or different transparent parts in series: e.g. a large view window, combined with small top venting or daylight window

- combined window system: frame, from outside to inside consisting of separate parts

5 TRANSPARENT SYSTEM

The transparent system is composed of different panes, shading devices and gas layers.

The general approach is

1 to calculate the heat flow to each pane due to the absorption of short wave radiation due to the sun,

2 to calculate the heat transfer coefficients between all panes, shading layers and both environments,

3 to calculate the panes, shadings and gas temperatures,

4 to iterate the process from step 2 because of temperature dependent heat transfer rates

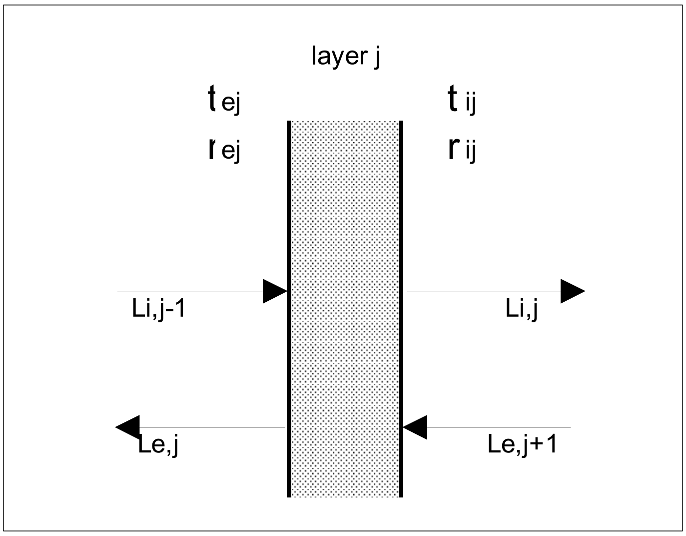
5 to calculate the aggregate properties.

5.1 Solar and light transmission

Short wave radiation calculation

Each component of the window can be described by 4 parameters :
te(j) : outside transmittance
ti(j) : inside transmittance
re (j) : outside reflectance
ri (j) : inside reflectance

The short wave radiations are represented by:
Li (j) : short wave radiation towards the room
Le (j) : short wave radiation towards the outside


layer j
t ej
r ej
t ij
r ij
Li,j-1
Li,j
Le,j
Le,j+1

The set of equations to be solved is then, for j = 1 to n (n= number of components) :

$$L_{i,j} = t_{ej} \cdot L_{i,j-1} + r_{ij} \cdot L_{e,j+1}$$

$$L_{e,j} = t_{ij} \cdot L_{e,j+1} + r_{ej} \cdot L_{i,j-1}$$

with
$L_{i,o}$ = impinging solar radiation,
$L_{e,n+1}$ = roomref . $L_{i,n}$

where roomref is the equivalent room reflectance, which can be set to 0 to compare the results on the same basis and to give standard characteristics.

The short wave heat flows absorbed by each layer Q(j) are then :
Q(j) = Li (j-1) + Le (j +1) - Li(j) - Le(j)

It is assumed that the short wave radiation is absorbed in the centre of the pane.

The short wave heat flow absorbed by the room is :
Q (n+1) = Li (n) - Le (n+1)

This calculation can be done either for solar radiation or light by taking into account the corresponding values of t and r.

If wavelength properties are known, the calculation can be done for each wavelength band by calculating Q(λ,j) and summing these values to obtain Q(j).

The calculation of reference properties is done by assuming that there is no room reflection (re(n+1)=0).

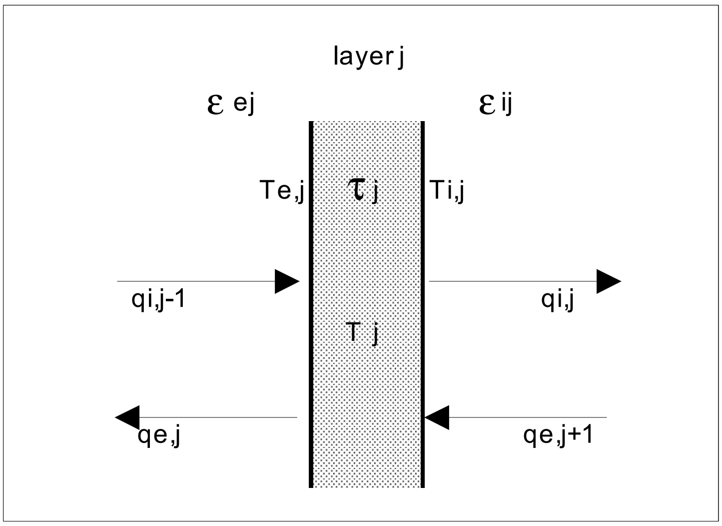
More details: see chapter 8.

5.2 Calculation of pane temperatures

It is considered that the outer and inner pane surfaces are at a uniform temperature, and that the conduction to the frame can be here neglected. The pane heat exchanges can be described as follows:

- long wave heat exchanges with the other panes and with outdoor and indoor equivalent radiant temperatures.

For a given pane, this heat flow depends on the other temperatures (outdoor, indoor and other panes) and on the emissivities and long wave transmittance at the external surfaces of the pane. If the panes can be assumed not to be transparent to long wave radiation, only the boundary temperatures are taken into account.



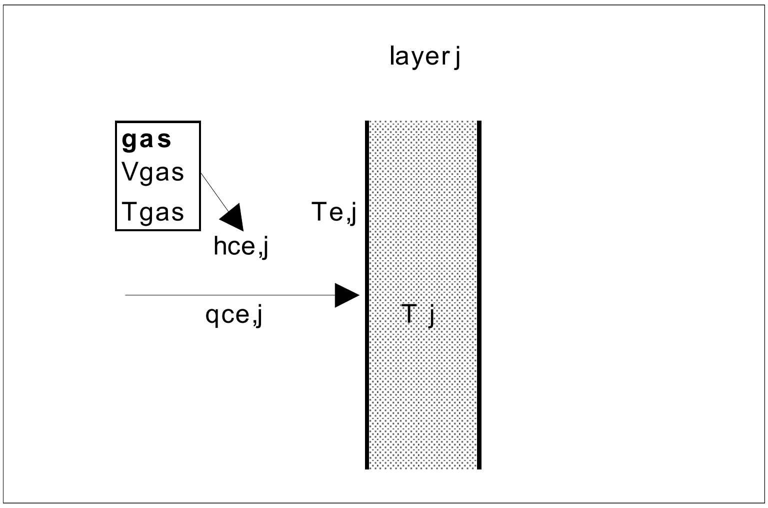
In general:

$$q_{i,j} = \tau_j \,.\, q_{i,j-1} + (\, 1 - \varepsilon_{ij} - \tau_j)\, q_{e,j+1} + \varepsilon_{ij} \,.\, \sigma \,.\, T_{i,j}^4$$

$$q_{e,j} = \tau_j \,.\, q_{e,j+1} + (\, 1 - \varepsilon_{ej} - \tau_j)\, q_{i,j-1} + \varepsilon_{ej} \,.\, \sigma \,.\, T_{e,j}^4$$

- convection

For a given side, the heat flow is related to the difference between surface and gas temperature, and to the convective heat transfer coefficient. This one depends on the gas filling the cavity; its temperature and the gas speed if the gas layer is not closed.



In general:

$qc_{e,j} = hc_{e,j} (T_{gas} - T_{e,j})$

For a closed gas layer, the equation for the gas node to be solved is

$qc_{e,j} + qci_{,j-1} = 0$

For a ventilated air layer, it becomes

$qc_{e,j} + qc_{i,j-1} + qc_{j,j-1\ add} = 0$

where $qc_{j,j-1\ add}$ is the equivalent heat exchange flow between the entering air and the average air layer temperature (see 10.2)

5.3 Calculation and use of network temperatures

The network (pane, shading and gas layer temperatures) are obtained by solving the above considered equations for given outdoor and indoor conditions.

Outdoor conditions are external temperature and solar radiation. Indoor conditions are air and mean radiant and air temperatures. Indoor humidity can be added in order to check condensation hazards regarding the temperatures of the components linked with indoor air.

points of attention: outdoor condensation hazards, long wave radiation to the sky and equivalent short wave reflectance of the room..

The heat gain HG to the room is equal to the sum of:

- the short wave radiation flow per m^2,

- the long wave heat flow per m^2 due to the inner surface temperature of the transparent system,

- the long wave heat flow per m^2 due to transmission through IR transparent layers (such as venetian blinds, foils, open weave screens, etc)

- the convective heat flow per m^2 due to the inner surface temperature of the transparent system,

- the ventilative heat flow per m^2 due to a air layer connected with the room air via a air permeable layer such as a venetian blind, screen, etc; divided by the area of the transparent system.

The standard U value is obtained by considering the following boundary conditions :

G_s (solar radiation) = 0
$T_{emr} = T_{eair} = T_e$
$T_{imr} = T_{iair} = T_i$

The U value is then equal to HG / (T_e - T_i)

The solar factor or g-value is calculated by repeating the calculation with a given G_s value and by calculating the heat flows differences between the two values and divide the result by Gs:

$$g = \frac{(HG(withseen) - HG(no\ seen))}{Gs}$$

The European draft standard prEN 673 for calculating the U-value of multiple glazings prescribes that one shall calculate the thermal resistance with fixed internal surface temperature = 17.5 C, and fixed external surface temperature = 2.5 C. The U-value is then obtained by adding the standard surface heat transfer resistances and inversion of the result.

Note that this implies that the standard environment temperatures will be quite different, depending on the thermal resistance of the glazing; although this is not realistic for practical conditions, this prEN 673 rule has been adopted in WIS in case the ‘CEN-only’ option is chosen.

NB: the fixed surface temperatures are in line with hot plate R-value measurements.

The European draft standard prEN 410 for multiple glazings prescribes that, for simplicity reasons, for the g-value calculation the same thermal resistance values are used as for the U-value calculations. It may be evident that this is a rule that becomes out of date and even complicating in case of computerised calculations such as WIS.

Nevertheless, for the time being WIS performs the calculation according to this prEN 410 prescription in case the ‘CEN-only’ option is chosen.

The solar transmittance results can be given following two ways:

1) solar factor divided in three parts : radiative short wave (solar), radiative long wave, convective

2) for some calculation methods, it is easier to split the total solar factor g as follows :

   - solar direct transmittance τ_e,
   - secondary heat transfer q_i due to the temperature difference between inner pane temperature and room temperature

   - If there is a ventilated air layer linked with the room air temperature, a tertiary heat transfer qj equal to qair has to be added.

$g = \tau_e + q_i + q_j$

Weighted environment temperatures in non-standard situation:

If the radiant and air temperatures are not equal the usual formula for the indoor (i) and outdoor (e) environment temperature is:

$$T_{env} = (h_c.T_{air} + h_r.T_{rad})/(h_c+h_r)$$

for both $T_{env,e}$ and $T_{env,i}$

This information is needed to be able to derive a non-standard U-value. The U-value is the heat flux divided by the temperature difference between indoor and outdoor environment.

In case of ventilated layers and/or layers transparent for long wave radiation, however, the shown equation for environment temperature is not complete.

Again, we look for the definition of T_{env} which produces the same result as the splitted temperatures would produce.

It can be proven that the general solution is:

$$T_{env,e} = \frac{[\Sigma (h_{jr} (T_j - T_{ref,e})] .T_{re} + [\Sigma h_{cj} (T_j - T_{ref,e})] .T_{air}}{\Sigma (h_{rj} (T_j - T_{ref,e}) + \Sigma h_{cj} (T_j - T_{ref,e})}$$

in words: the environment temperature is the weighted air and radiant temperature, weighted according to the relative contributions to the net heat flow into (from) the transparent system in the special situation that T_{rad}=T_{air}.

with j=1,...,n: each node in the system

- h_{rj} radiation link between node j and external
- h_{cj}: convective/ventilative link between node j and external
- $T_{ref,e}$: any temperature with $T_{ref,rad} = T_{ref,air} = T_{ref}$.

The equation holds for any external reference temperature. The most simple choice is to take: $T_{ref,e} = 0$

Same (mutate mutandis) for $T_{env,i}$

6 FRAMES & SPACERS

6.1 Definitions

According to the ISO DIS 10077 / prEN 30077 part 1 proposal, the thermal transmittance of the window is derived from the frame U-value, the centre of glass U-value and the thermal bridge effect between the frame, the glazing and the spacer by introducing a linear thermal transmittance Ψ_g. This procedure has the advantage, that the frame and the centre of glass U-values are independent from each other and can be determined separately by measurement or calculation. The total thermal transmittance of the window is given by the following equation:

$$U_w = \frac{U_g \cdot A_g + U_f \cdot A_f + \Psi_g \cdot l_g}{A_g + A_f} \qquad [W/m^2K]$$

where :

U_g thermal transmittance of the center of the glazing according prEN 673 in W/m^2K

A_g visible area of the glazing in m^2

U_f thermal transmittance of the frame with an ideal insulating filling element in W/m^2K

A_f projected area of the frame in m^2

Ψ_g linear thermal transmittance due to the combined thermal bridge effects of the spacer, glazing and frame in W/mK

l_g total visible perimeter length of the glazing in m

The definitions used for the frame U-value and the Ψ_g-value are illustrated in figure 6.1.

In order to determine these values by numerical 2-D calculation methods, the following two situations have to be considered:

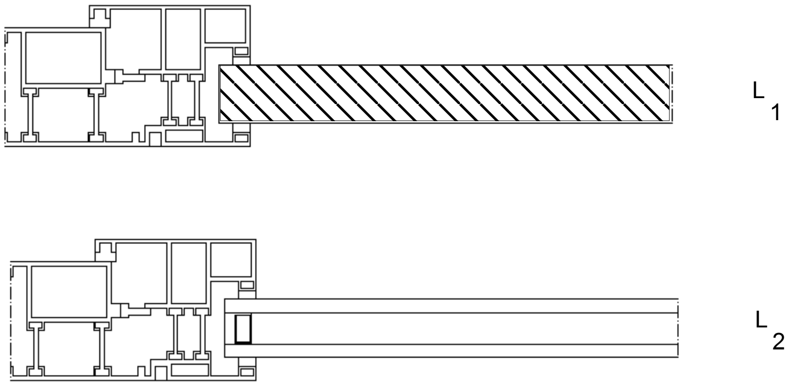


Figure 6.1 : Situation for the determination of U_f and Ψ_g

The frame U-value and the linear thermal transmittance Ψ_g are calculated from the two dimensional thermal coupling coefficients L_1 and L_2 as follows:

$$U_f = \frac{L_1 - U_p \cdot l_p}{l_f} \qquad [W/m^2K]$$

$$\psi_g = L_2 - U_f \cdot l_f - U_g \cdot l_g \qquad [W/m{\cdot}K]$$

where :

L_1, L_2 thermal coupling coefficients in W/m K , derived from the 2-D numerical calculation

U_f thermal transmittance of the frame in W/m^2K

U_p thermal transmittance of the filling element in W/m^2K

U_g thermal transmittance of the center of the glazing according prEN 673 in W/m^2K

l_p length of the filling element in m

l_f length of the frame in m

l_g total visible perimeter length of the glazing in m

6.2 Numerical calculation

WIS provides a direct link to the European thermal bridge atlas EUROKOBRA, a PC program able to make 2-dimensional numerical heat transfer calculations using a finite difference method. For WIS users a demo version of KOBRA with a limited data base of window frame profiles is available.

Layout of the KOBRA-Page for one window frame type :
Window U-value (30%frame area)

Frame U-value	3 IG normal glass	3 IG low e= 0.2	3 IG low e= 0.1

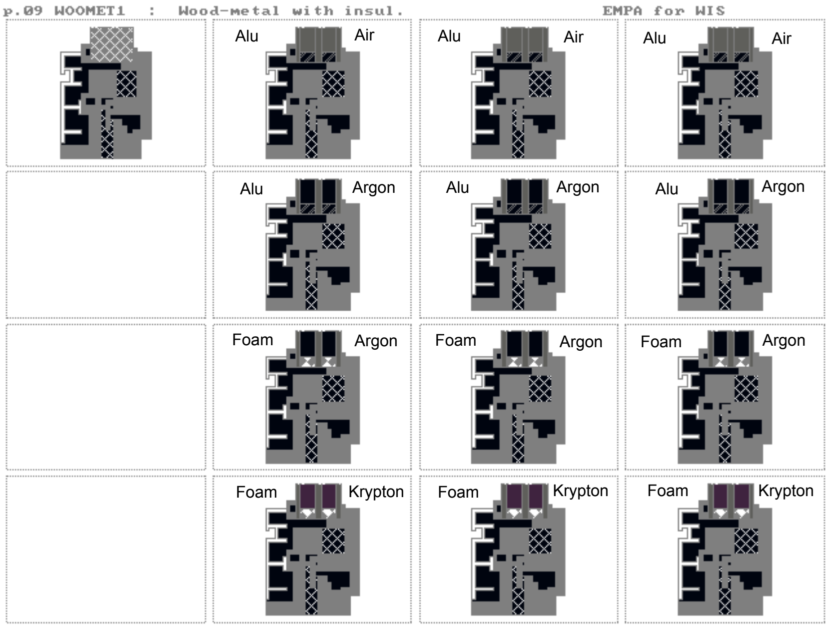


Figure 6.2 : Examples of predefined window frames in KOBRA

Isothermal lines for a metal frame with thermal break, calculated with KOBRA are shown in Figure 6.3:

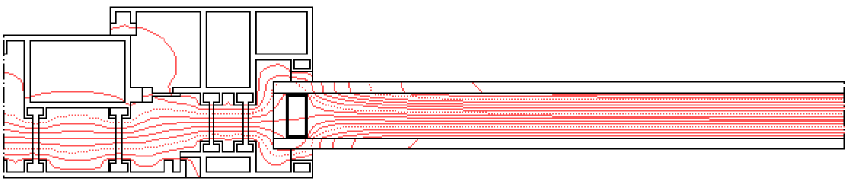


Figure 6.3 : Isothermal lines for a metal window frame with double low e glazing and Krypton gas filling.

KOBRA allows to calculate for standardised or user defined boundary conditions the following frame specifications :

- Frame U-value according to prEN ISO 10077
- Linear thermal transmittance Ψ_g of the spacer bar
- Isothermal lines of the window section
- Minimum surface temperatures

6.3 Material properties

For detailed numerical calculations the thermal properties of the materials have to be known. Table 6.1 gives the values for solid materials, table 6.2 for air cavities in frames, both laid down in the prEN ISO 10077, part 2 document. The equivalent thermal conductivity of complex shaped air cavities in window frame profiles are calculated by the following procedure (see figure 6.4).

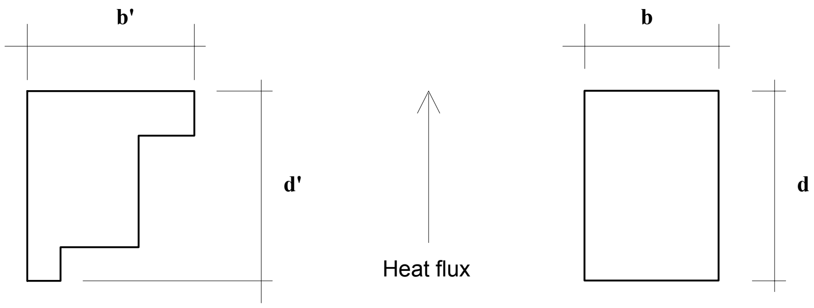


Figure 6.4 : Simplification of the geometry of the air cavities

The following rules have been applied to convert a complexed shaped air cavity into a rectangle with the same area and aspect ratio :

$$\frac{d'}{b'} = \frac{d}{b} \quad \text{and} \quad A' = A$$

The thermal resistance R of the cavity has been calculated according to prEN ISO 6946-1:

$$R = \frac{1}{h_{conv.} + h_{rad.}} \qquad [m^2K/W]$$

$$h_{conv.} = \max. \left[\begin{matrix} 0.025 / d \\ 0.73 \cdot (\Delta\vartheta)^{1/3} \end{matrix} \right] \qquad [W/m^2K]$$

$$h_{rad.} = E \cdot 4 \cdot \sigma \cdot T_m^3 \cdot \frac{1}{2} \left(1 + \sqrt{1 + \frac{d^2}{b^2}} - \frac{d}{b}\right) \qquad [W/m^2K]$$

with: $E = \frac{1}{1/\varepsilon_1 + 1/\varepsilon_2 - 1}$

T_m = 283.2 K and $\Delta\vartheta$ = 10°C:

Material	Thermal conductivity λ W/(m·K)
EPS (filling element)	0.04
Silicone foam	0.12
Desiccant (6% moisture)	0.13
Wood (soft)	0.13
Wood (hard)	0.18
PVC/Vinyl (rigid)	0.17
Polysulphide	0.19
Polyisobutylene (PIB)	0.20
Butyl (hot melt)	0.24
EPDM	0.25
Polyamide reinforced	0.30
Float glass	1.0
Stainless steel	17
Steel	50
Aluminium alloys	160

Table 6.1 : Thermal conductivity of window materials

d mm	**b** mm										
	2	**4**	**8**	**10**	**15**	**20**	**30**	**40**	**50**	**70**	**100**
2	31	32	33	33	33	33	33	33	33	33	33
4	35	37	39	39	40	40	41	41	41	41	42
6	40	41	44	45	46	47	48	49	49	49	50
8	44	46	49	50	52	53	55	56	56	57	57
10	48	50	53	55	57	59	61	63	63	64	65
15	59	61	65	66	70	72	76	79	80	82	84
20	75	78	81	83	87	91	96	99	102	105	108
30	112	114	118	120	125	129	136	142	146	152	157
40	149	151	155	157	162	167	175	182	187	196	204
50	186	188	192	194	199	204	213	220	227	238	249
70	259	261	265	267	272	277	287	296	304	318	334
100	369	371	375	377	383	388	398	407	417	433	454

Table 6.2 : Equivalent thermal conductivity in mW/(m·K) of air cavities with length d and width b (ε = 0.90 , T_m = 283 K, $\Delta\vartheta$ = 10 °C)

6.4 Spacer Ψ_g values

The Ψ_g - values of three spacer bars as shown in figures 6.5-6.7 are tabulated in the tables 6.3 to 6.5 :

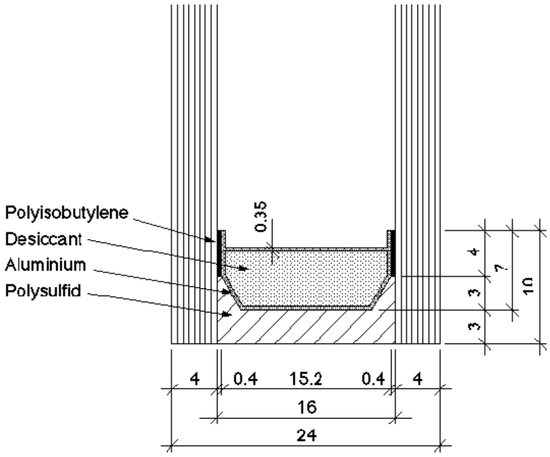


Figure 6.5 : Aluminium spacer

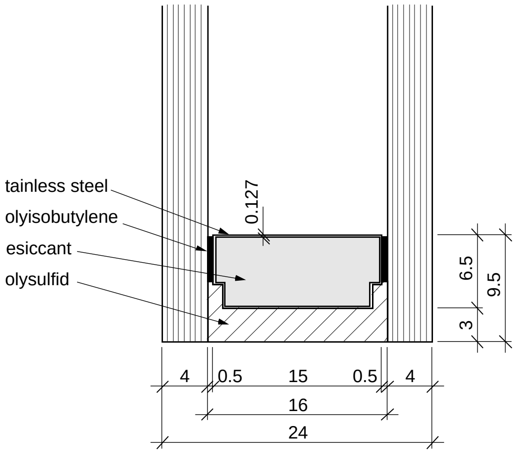


Figure 6.6 : Stainless steel spacer

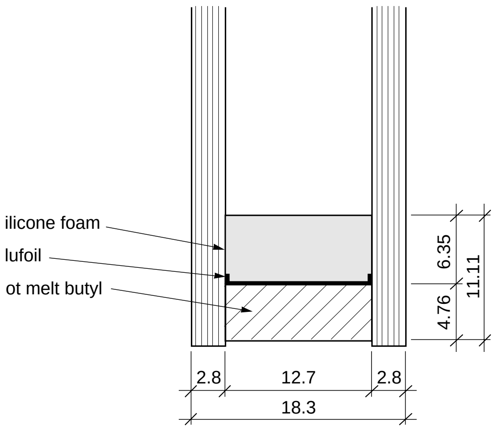


Figure 6.7 : Silicone foam spacer

Frame type	Glazing type	
	double or triple glazing uncoated glass air or gas space	double or triple glazing with low e coating air or gas space
Wood or PVC	0.04	0.06
Metal with thermal break	0.06	0.08
Metal without thermal break	0	0.02

Table 6.3 : Ψ_g - values in W/mK for aluminum spacers

Frame type	Glazing type	
	double or triple glazing uncoated glass air or gas space	double or triple glazing with low e coating air or gas space
Wood or PVC	0.03	0.05
Metal with thermal break	0.04	0.06
Metal without thermal break	0	0.02

Table 6.4 : Ψ_g - values in W/mK for stainless steel spacers

Frame type	Glazing type	
	double or triple glazing uncoated glass air or gas space	double or triple glazing with low e coating air or gas space
Wood or PVC	0.02	0.03
Metal with thermal break	0.03	0.04
Metal without thermal break	0	0.01

Table 6.5 : Ψ_g - values in W/mK for silicone foam spacers

6.5 Frame U-values

Values of U_f may be evaluated by numerical calculation methods or by direct measurements in the hot box. In table 6.6 the range and generic numbers for different frame types are given :

U_f in W/m²K				
Wood	Wood-metal	PVC	Metal with thermal break *	Metal without thermal break *
1.0 - 2.4	1.2 - 2.6	1.8 - 2.8	1.9 - 3.5	3.4 - 6.4
1.7	**1.9**	**2.3**	**2.7**	**4.9**

Table 6.6: Informative frame U-values in W/m²K
* Definition see EN ISO 10077

For metal frame the heat exchange may be strongly influenced by the geometry of the profile; the real developed area can be significantly larger than the projected area. This leads to higher frame U-values and has to be taken into consideration.

6.6 Condensation risk

The condensation risk of a window depends on the surface resistance and the thermal resistance of the window. The critical surface temperature may be defined by a dimensionless temperature factor f_{Rsi}:

$$\theta_{oi} = \theta_e + f_{Rsi} \cdot (\theta_i - \theta_e)$$

Typical surface resistance are :

R_{si} = 0.13 (m^2K/W) for normal situations
R_{si} = 0.25 (m^2K/W) for upper half of the room
R_{si} = 0.35 (m^2K/W) for lower half of the room
R_{si} = 0.50 (m^2K/W) for significant thermal shielding by objects such as furniture or curtains and blinds

6.7 Link to KOBRA and THERM

Pictures from 2-dimensional thermal calculation programs like KOBRA (realised) and THERM (under preparation) can be imported to the WIS-program by the paste function.

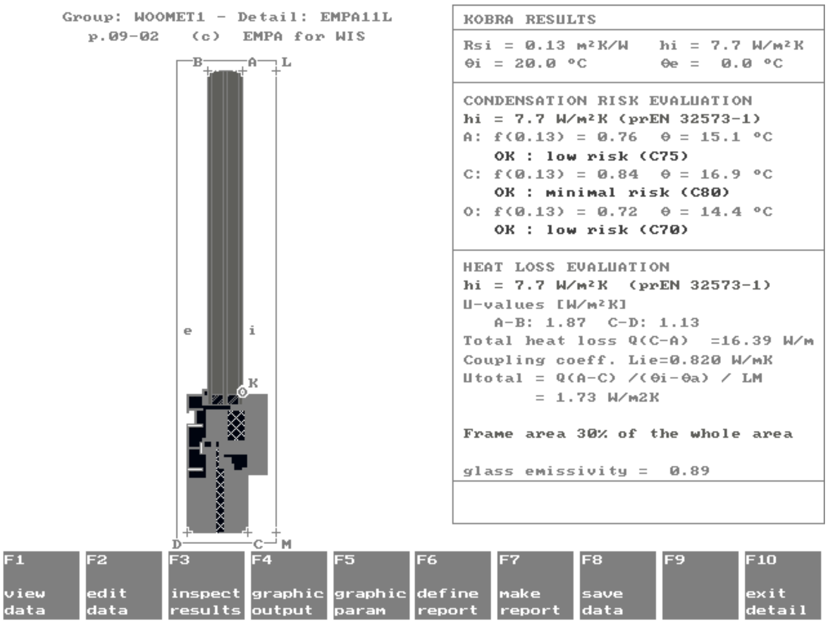


Figure 6.8 : Result screen of the KOBRA - Program

6.8 European standards

EN 673 Thermal insulation of glazing - Calculation rules for determining the steady state U value (thermal transmittance) of multiple glazing (1994)

EN ISO 6946/1 Building components and building elements- Thermal resistance and thermal transmittance - Calculation method (1995)

EN ISO 10077 Windows doors and shutters - Thermal transmittance - Part 1 : Simplified calculation method (1995)

EN ISO 10077 Windows doors and shutters - Thermal transmittance - Part 2 : Numerical calculation method
(Draft document 1995-07-01)

EN ISO 10211 Thermal bridges in building construction - Heat flows and surface temperatures - Part 1 :
General calculation methods (1995)

EN ISO 10211 Thermal bridges in building construction - Heat flows and surface temperatures - Part 2 :
Linear thermal transmittance (1995)

7 ENVIRONMENT

7.1 General

The environmental boundary conditions used for windows may be different according to the purpose of the calculation. The following situations may be considered:

- Standardised values for product declaration (e.g. CEN values).
- User defined values for design purpose (e.g. extreme winter or summer conditions for the analysis of thermal comfort criteria).
- Real weather data from measurements for a given period.

Within WIS the user can select all three options under the menu called environment. The following information has to be given :

- outdoor and indoor air temperature in °C
- outdoor and indoor radiant temperatures in °C
- direct solar radiation in W/m^2
- convective surface film coefficient outdoor in W/m^2K
- convective surface coefficient indoor in W/m^2K

For the solar factor g and the light transmittance τ_v the relative spectral power distribution has to be specified.

7.2 Standardised data

The boundary conditions for temperature and surface film coefficients in the different standards (EN/ISO or ASHRAE/ NFRC) are summarised in table 7.1. :

Standard	Boundary conditions			
	outdoor		indoor	
	θ_e [°C]	h_e [W/m²K]	θ_i [°C]	h_i [W/m²K]
EN 673	0-5	23	20-25	8
EN ISO 10077	0-5	25	20-25	7.7
EN 1098	0-5	25	20-25	7.7
EN ISO 13791	-	13.5	-	8
ASHRAE NFRC	17.8 31.7	28.6 19.8	21.1 23.9	8.3 8.3

Table 7.1 : Standardised boundary conditions

For e.g. prEN 673 actually the surface temperatures are prescribed (17.5 and 2.5 ^{0}C), not the environmental temperatures; see also section 5.3.

For the solar factor calculation the relative spectral distribution of global solar radiation has to be defined. Two sets of data are used in the international standards:

- solar spectrum for air mass = 1 (CIE No.20 and EN 410)
- solar spectrum for air mass = 2 (P.Moon; in ISO 9050)

For the calculation of the light transmittance τ_V the relative spectral power distribution of daylight (D65) multiplied by the spectral sensitivity of the human eye are given in EN 410 and ISO 9050.

For e.g. prEN 410 actually the heat transfer coefficients between the layers are to be kept the same as for the U-value calculation; see also section 5.3.

7.3 User defined data

WIS allows the user to specify detailed environmental boundary conditions. In addition to the standardised data sets the following solar radiation data may be given by the user :
(not yet activated in the β-version)

- Direct solar radiation in W/m^2
- Diffuse solar radiation in W/m^2
- Position of the sun (height and azimuth)

This information is needed when the surface temperatures of each layer of the glazing system have to be determined.

7.4 Weather data files

(not yet implemented in the β-version)
Generic hourly data can be imported from a weather data file with the standard format TRY or DRY. The environment object will calculate hourly weather data conditions acting on the window, including thermodynamic properties of the air and radiation data based on the weather data files.

Input:
Primary data is read in from Reference years such as the EC-TRY or the IEA Task 9 DRY. A custom format for WIS is also provided if none of them is available. The following primary data is needed:

A - Dry bulb temperature
B - Global horizontal irradiance
C - Relative humidity
D - Wind speed
E - Month, day and hour

No other data is required nor used. E.g. the diffuse and beam irradiation in EC-TRY or DRY are not used as they stand, they are re-computed from the primary data by the same selected procedures for all types of input files. This guarantees consistency of weather data in WIS.

Output:
The following hourly data is computed from the primary data and made available by the WIS program:

A - direct irradiance on window plane [3]
B - diffuse irradiance on window plane [1] [2]
C - cosine of angle of incident [4]
D - the sun height angle [4]
E - orientation of sun (azimuth angle, south = 0°) [4]
F - Relative air mass
G - outdoor temperature
H - sky temperature (infrared irradiance downwards from sky) [5]
I - outdoor relative air humidity
J - wind speed
K - reflected irradiance [1] [2]

7.5 External shadings not part of window

External shadings which are not close and parallel to the transparent part of the window, like overhangs, sidefins and window recess are considered as part of the external environment of the window. These elements are described in section 11.4.

7.6 References

1. "[...] irradiance components from direct and global irradiance", R. Perez, P. Ineichen,R. Seals, J. Michalsky, R. Stewart - Solar Energy Vol. 44, No. 5.

2. "[...] Perez diffuse irradiance model for tilted surfaces", R. Perez, R. Seals, P. Ineichen,R. Stewart, D. Menicucci Solar Energy Vol. 39, No 3.

3. "Dynamic models for hourly global-to-direct irradiance conversion". R. Perez, P. Ineichen, E. Maxwell, R. Seals, A. Zelenka."Solar World Congress", Vol. 1, Part II, ISES, Denver, Colorado, USA, 19 - 23.08.91.

4. "Die Berechnung von Sonneneinstrahlungsin-tensitäten für wärmetechnische Untersuchungen im Bauwesen", W. Heindl + H. Koch.
97 (1976) H. 12 Gesundheits-Ingenieur.

5. Rayonnement infrarouge du ciel".
P. Ineichen, J.-M. Gremand, O. Guisan.
Serie de publication du CUEPE No. 8.

8 PANES

8.1 General

The treatment of the solar optical properties of panes in WIS depends on the type of pane and/or the available input data.

<u>Spectral versus non-spectral</u>:

Spectral properties available:
If spectral data are available, these are read in by WIS, checked and <if accepted> used for the thermal/optical calculations of the pane and transparent system.

Spectral properties not available:
If the spectral properties are not available <or not accepted> the optical properties of the transparent system will be calculated with integral (non spectral) data only, over the full range of the solar, respectively visual spectrum.

Of course this may introduce serious errors in case successive panes and/or shading devices are used with different spectral distribution of transmittance and reflectance.

<u>Pane type:</u>

Single layer type:
a type of pane for which the fresnel laws are valid. These are used to calculate the angle dependent properties from the properties given for normal incidence. See section 8.2 part 1.

Non-single layer type:
a type of pane for which the fresnel laws are not valid, like coated or diffusing panes. Unless a special option is used for multilayered pane (see next alinea), this type of pane requires the solar optical properties for specific angles of incidence as input, in addition to the properties at normal incidence. In this case WIS will use specific interpolation rules to determine the optical properties for each angle of incidence (section 8.2 part 2).

Special option for multi layered pane:
A special option is available for a multi layered pane, in which the angle dependent solar optical properties of the pane are calculated on the basis of two sets of input of solar spectral data at normal incidence:

- the properties of the substrate;
- the properties of the substrate plus film

See section 8.3.

Scattering or diffusing pane:
So far all the panes are assumed to transmit or reflect the solar radiation specularly. A pane which redirects the transmitted and/or reflected radiation is called a scattering pane. If the scattering is homogeneously diffuse the pane is called a diffusing pane.

In the current version of WIS, it is assumed that for a scattering pane the part of the incident radiation which is redirected is homogeneously diffused (diffuse pane).

In other words, part of the radiation incident at certain angle is transmitted and reflected directly without redirection (direct-direct beam transmission and reflection), another part is assumed to be transmitted and reflected diffusely (direct-diffuse transmission and reflection). The remaining part is absorbed in the pane.

Diffuse irradiation is assumed to be transmitted and reflected as diffuse (diffuse-diffuse transmission and reflection). See also section 8.4.

At the moment WIS does not have a separate form for diffuse panes. The Tutorial advises to introduce a diffuse pane as a solar shading device. This should not be a problem, because the approximation for a diffuse pane as introduced above is exactly the same approximation as used for the solar shading devices in the current version of WIS.

In case angle dependent data cannot be calculated and no angle dependent data are available as input:

If the pane is a non fresnel type and the input of solar optical properties is restricted to the properties at normal incidence, WIS will be able to calculate the properties of the transparent system for normal incidence only.

In particular in case of a transparent system involving solar shading devices the calculation of only the properties at normal incidence would not be very satisfying, given the fact that in particular in that case the properties are strongly angle dependent.

Moreover, even if only one of the layers in the transparent system is a shading element or a diffusing pane, WIS will need the optical properties for diffuse irradiation for *each* layer. This is due to the fact that a shading element or diffusing pane introduces diffuse transmission/reflection, even in case the incident radiation consists of perpendicular radiation only. See sections 8.4.1 and 9.1 for more details on the approximation introduced to take the diffusing part into account.

Temporary rough approximation:
The availability of measured angle dependent spectral data is quite limited at the moment. In order to avoid that this implies that in many cases one will not be able to get a (rough approximating) output from WIS, a temporary solution has been built in: in those cases WIS will simply assume that the fresnel laws are valid. Because of the different properties of both sides of the non-single pane, the fresnel laws are applied to either side of the pane. Of course a warning comes along with the output, explaining that the solution is a rough approximation only.

Polarization:
The current version of WIS does not make a distinction between the two components of polarization.

In general the effect is not large, but also not negligible (e.g. few percent error at large angles). If the pane is a non fresnel type, the reflectivity has to be known for the two components of polarization. In practice this information will not be available.

Absorbed solar radiation in panes:
The solar radiation part which is absorbed in a pane or shading device is assumed to be absorbed in the middle, as already mentioned in section 5.1.

Coated side of pane:
The properties of a non-single pane type are sensitive for the position of the pane with respect to the direction of the incident radiation. Usually this type of pane is provided with a coating at one of its faces.

It is important that the coating is placed in the correct position.
A wrongly assumed position of the coating will not only lead to wrong thermal and solar properties, but may also violate the restrictions with respect to proper use of the pane. Many (e.g. 'soft') coatings are to be used only within a protected environment as in a sealed multiglazing unit.

WIS shows at which surface the coating is located and allows turning the pane if needed.

Future options:
- More realistic approximation for the extrapolation of angle dependent properties for non fresnel types of (e.g. coated) panes, as soon as validated equations are available.
- Polarization
- Retain pane properties for a pane with different thickness

8.2 Panes, single layer type

Two approaches are considered here . The first one assumes that the component follows the fresnel laws, which enable to calculate the angle dependency properties. The second ones does not need this assumption as it starts from known values at different angles by fitting the coefficient of interpolating formulas.

1 Direct application of the Fresnel laws

If Ri is the reflection coefficient at the air/glass interface, and Ti the ratio of the flow which is not absorbed we obtain:

$Ri = 0,5 [\sin^2 (i-r) / \sin^2 (i+r) + tg^2 (i-r) / tg^2 (i+r)]$

with sin i = n sin r

where n is the refraction index of the glass (can be taken equal to 1,526 for normal glass)

Ti = exp (- K *l*o / cos r)
where lo is the glass depth
K is the glass absorption fraction
lo / cos r is the distance of absorption.

For a normal incidence (i = 0), one get s in case of normal glass:

$Ro = [(n-1) / (n+1)]^2 = 0,043$
K = ln [(1 - Ro - aso Ro) / (1-Ro-aso)] / lo
ln [(0,957-0,043 aso) / (0,957-aso)] / lo
where aso is the normal incidence absorption coefficient for the glazing pane.

For any incidence angle i (angle to the normal incidence) it is then possible to calculate the absorption, transmission and reflection coefficients of the glazing pane asi, tsi, rsi by :

asi = (1-Ri) (1-Ti) / (1-RiTi)
$tsi = (1-Ri)^2 Ti / (1-Ri^2Ti^2)$
$rsi = Ri + Ri Ti^2 (1-Ri)^2 / (1-Ri^2Ti^2)$.

These values depend only upon aso as the product K.lo appears in all equations. The results do not depend on the lo value. These formulas enable the calculation of the exact values of asi, tsi and rsi as far as the Fresnel laws can be applied. The characteristics regarding diffuse radiation can be obtained by integrating the cos i . values

2 Simplified approach starting from known values at given angles

The correlation laws often used are:

$$asi = \sum_{i=i1}^{i2} ai \cos^{i}$$

$$tsi = \sum_{i=i1}^{i2} bi \cos^{i}$$

For example, the ASHRAE takes into account the values i1=0 and i2=5. This requires many measurements in order to fit the right coefficients by a mathematical procedure. A drawback of this approach is that the reference value calculated applying the equations may not equal to the measured one. Another one is that as i1=0, the values of as and ts for i=90° are not equal to 0 as they should (they are equal respectively to a0 and b0).

The choice of i1=0 and i2= 2 or 3 presents some advantages:

1) it is possible to calculate analytically the ai and bi parameters,
2) the values for 90° are always right,
3) the calculated reference values are equal to the measured ones.

Application of this approach has been made for :

- reference values at 0 (normal incidence) 30 and 60° (i2=3)
- reference values at 0 (normal incidence) and 45° (i2=2)

The second option is not yet activated in WIS, as it would require additional validation tests to check its accuracy.

If the diffuse radiation can be considered as isotropic, the absorption, transmission and reflection coefficients asd, tsd, rsd are easily calculated by :

$$asd = \sum_{1}^{i2} aj/(j+2) \qquad [1]$$

$$tsd = \sum_{1}^{i2} bj/(j+2) \qquad [1]$$

rsd =1 - asd - tsd

This formulas can be applied by bands of wavelength if the properties are known.

references

- CEN/TC129/WG9 N 193E final draft pr EN673
  Thermal insulation of glazing - Calculation rules for determining the steady state U value (thermal transmittance) of glazing.
- CEN/TC129/WG9 N.4E rev7 final draft pr EN 410

Glass in building - determination of light transmittance, solar direct transmittance, total solar energy transmittance and ultraviolet transmittance, and related glazing characteristics.

8.3 COATINGS AND FILMS

8.3.1 INTRODUCTION

This section is devoted to the description of the model used in the optical characterization and/or the calculation of the optical performance of complex glazing systems, with emphasis in those including one or more coated components.

The optical characterization consists of the calculation of the most interesting properties: transmittance and reflectance of the whole system. The main features of the model are the following:

- All calculations are done for each wave length.
- The elemental properties like interfacial reflectivity and transmissivity will be obtained from the refractive index (n) and the extinction coefficient (k), so the properties could be calculated for any incidence angle.
- It should be necessary to make a characterization process in order to obtain these properties (n, k) from experimental data obtained with non polarized radiation for a normal incidence angle.
- The calculations will be made for parallel and perpendicular polarization plane of the radiative wave, and then the properties for unpolarized radiation will be obtained averaging both components.
- If a thin film is deposited on a substrate, the interference phenomena due to the coherent waves will be taken into account into the model.

Once the optical models to obtain the reflectance and transmittance for a simple or coated pane are obtained, the global properties of the whole system will be obtained by a method based on the Net Radiation Method.

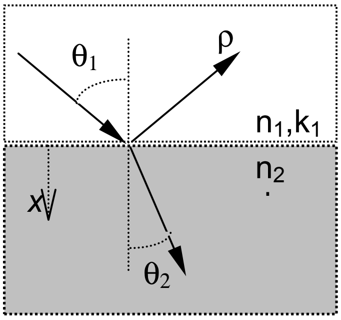
8.3.2 OPTICAL MODEL

The interference phenomena make it impossible to treat in the same way a system with or without a thin film. Next sections deal with the calculation of the properties of the elements between different media, i.e. with different refractive indexes.

8.3.2.1 Elements without thin film

All the formulation will be obtained for a general situation and then will be applied for normal incidence and unpolarized radiation.

For a single glass the extinction coefficient is very small, so the expressions for a perfect dielectric (Siegel, 1992a) can be used to obtain the interface reflectivity; a constant absorption coefficient is assumed and both polarization, parallel (*p*) and perpendicular (*s*) plane are taken into account:



$$\rho_p = \left(\frac{n_2 \cos\theta_1 - n_1 \cos\theta_2}{n_2 \cos\theta_1 + n_1 \cos\theta_2} \right)^2$$

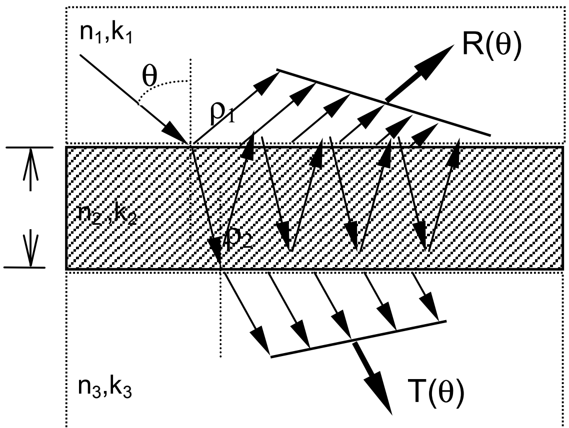
$$\rho_s = \left(\frac{n_2 \cos\theta_1 - n_1 \cos\theta_2}{n_2 \cos\theta_1 + n_1 \cos\theta_2} \right)^2$$

$$\tau = exp(-a\,x) \qquad a = \frac{4\pi k}{\lambda_0}$$

where λ_0 is the wavelength in the vacuum and θ_2 is the refracted angle calculated by the Snell's law:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

Now, by using a Ray Tracing or a Net Radiation method, to take into account the multiple reflections inside the pane of glass, the reflectance and transmittance can be obtained:



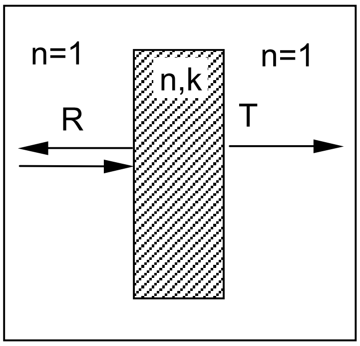
$$R(\theta) = \rho_1 + \frac{(1-\rho_1)^2 \tau^2 \rho_2}{1-\rho_1 \tau^2 \rho_2}$$

$$T(\theta) = \frac{(1-\rho_1)\tau(1-\rho_2)}{1-\rho_1 \tau^2 \rho_2}$$

These expressions are valid for both polarization planes by using the appropriate reflectivity value.

8.3.2.1.1 Characterization

Normally, the available experimental data are for normal incidence and unpolarized radiation. So, particularizing the previous expression for θ=*0* ; *n=1* and *k=0* (i.e. air) for the back and forward medium, and taking into account that the interfacial reflectivities for perpendicular and parallel polarization are the same (normal incidence), the resulting expressions are:



$$\rho = \frac{1}{2}\left(\frac{n-1}{n+1}\right)$$
$$\tau = \exp(-aL)$$
$$R(0) = \rho + \frac{(1-\rho)^2\,\tau^2\rho}{1-\rho^2\,\tau^2}$$
$$T(0) = \frac{(1-\rho)^2\,\tau}{1-\rho^2\,\tau^2}$$

From the last two equations, a expression for τ as a function of *R*(0) and *T*(0) can be obtained , and then, the ρ value by using one of the two expressions.

In a second step the *n* and *k* properties can be calculated:

$$n = \frac{1+\sqrt{\rho}}{1-\sqrt{\rho}} \quad ; \quad a = -\frac{\ln\tau}{L}$$

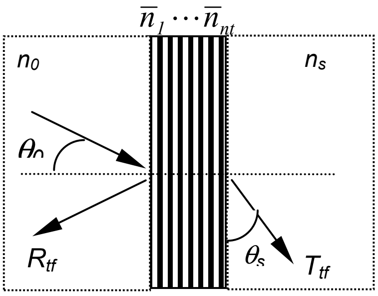
8.3.2.2 Elements with Thin Film

The model shown in this section is valid for the most common coatings deposited on the panes of glass, the absorbent thin films. As it was done in the previous section, the formulation will be made in a general case taking into account the possibility of multilayered thin films. Then, a particular, but practical, case for showing the characterization procedure will be used.

The modelization starts with the thin film alone. Then it will be considered deposited on a substrate.

Properties for the thin film assuming it is an absorbent material. In this case, it is necessary to use the complex refraction index ($\overline{n} = n - i\,k$); furthermore, due to the film thickness is lower than wavelength of the radiation, a different formulation for the interference effects between waves reflected from the first and second interfaces of the film is used.

For a multilayer thin film composed by *nt* individual films with thickness *dj*, the expressions for the reflectivity and transmisivity for both polarization components are as follow (Rubin, 1982; Siegel, 1992b):



$$R_{tf} = \left(\frac{a\,n_0' + b\,n_0' n_s' - c - d\,n_s'}{a\,n_0' + b\,n_0' n_s' + c + d\,n_s'} \right)^2$$

$$T_{tf} = \frac{n_s}{n_0} \left(\frac{2n_0'}{a\,n_0 + b\,n_0 n_s + c + d\,n_{ss}} \right)^2$$

being :

$$n_0' = \begin{cases} \dfrac{n_0}{\cos\theta_0} & \text{for parallel polarization} \\ n_0 \cos\theta_0 & \text{for perpendicular polarization} \end{cases}$$

and

$$n_s' = \begin{cases} \dfrac{n_s}{\cos\theta_s} & \text{for parallel polarization} \\ n_s \cos\theta_s & \text{for perpendicular polarization} \end{cases}$$

where the *a, b, c* and *d* coefficients are obtained from:

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} = \prod_{j=1}^{nt} \begin{bmatrix} \cos\gamma_j & \dfrac{i\sin\gamma_j}{\overline{n}'} \\ i\,\overline{n}'\sin\gamma_j & \cos\gamma_j \end{bmatrix}$$

being:

$$\overline{n}_j' = \begin{cases} \dfrac{\overline{n}_j}{\cos\theta_j} & \text{for parallel polarization} \\ \overline{n}_j \cos\theta_j & \text{for perpendicular polarization} \end{cases}$$

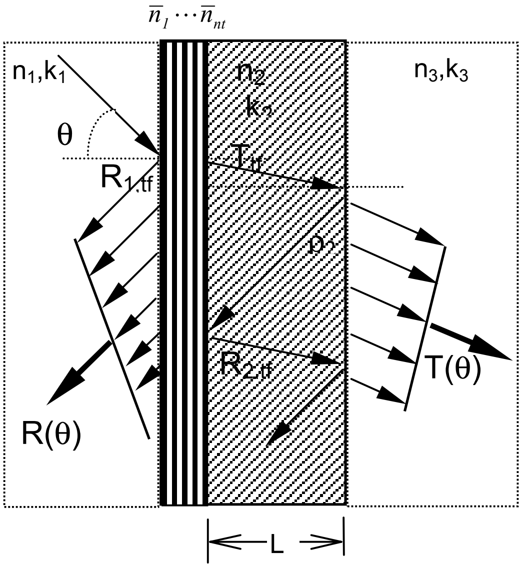
$$\gamma_{\mathrm{j}} = \frac{2\pi \overline{n}_j d_j}{\lambda}$$

$$\theta_j = \arcsin\left(\frac{\overline{n}_{j-1}\sin\theta_{j-1}}{\overline{n}_j} \right)$$

These reflectivity and transmisivity take into account all multireflected radiation inside the multilayered film.

Properties for Coated panes. Once the properties for a thin film are obtained, the properties for a combination of thin films and transparent substrates can be obtained by applying the Net Radiation method.

The expression obtained is the same as that of the simple pane, substituting ρ_1 by $R_{1,tf}$; (1-ρ_1) by T_{tf}; and the ρ_1 in the denominator by $R_{2,tf}$.



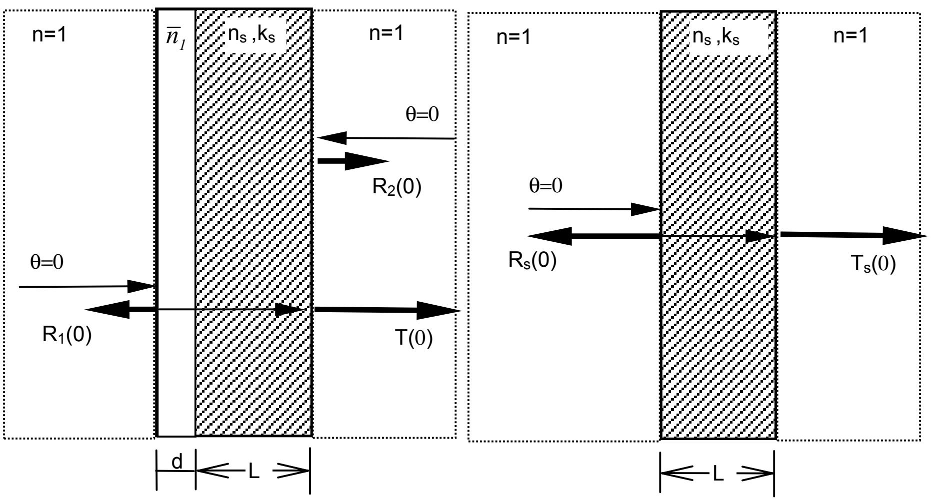
$$R(\theta) = R_{1,tf} + \frac{T_{tf}^{\,2}\,\tau^2 \rho_2}{1 - R_{2,tf}\,\tau^2 \rho_2}$$

$$T(\theta) = \frac{T_{tf}\,\tau(1-\rho_2)}{1 - R_{2,tf}\,\tau^2 \rho_2}$$

8.3.2.2.1 Characterization

The characterization process consists in obtaining the *n* and *k* coefficients for the thin film. It will be considered only one thin film.

Two different sets of experimental data are required. The first one, corresponding to the thin film plus the substrate, consists on the reflectance on both faces and the transmittance (R_1, R_2 and T). The second one, only for the substrate, consists of the reflectance and the transmittance (R_s and T_s); both of them for the normal incident, as it can be seen in next figure:



The steps to follow are:

a) To obtain n_s and k_s, from the substrate properties, $T_s(0)$ and $R_s(0)$, as it was shown in section 8.3.2.1.2..

To obtain *n, k* and *d*[1] for the thin film, solving the non-linear set of equations obtained rearranging the equations shown on section 8.3.2.2.1.:

$$R_{2,tf} = \frac{R_2(0) - \rho_s}{(1-\rho_s)\tau_s^2 - \rho_s^{\ 2}\tau_s^2 + \rho_s R_2(0)\tau_s^2}$$

$$T_{tf} = \frac{T(0) - \rho_s T(0) R_{2,tf}^* \tau_s^2}{(1-\rho_s)\tau_s}$$

$$R_{1,tf} = \frac{R_1(0) - \rho_s R_1(0) R_{2,tf}^* \tau_s^2 - \rho_s T_{tf}^* \tau_s^2}{1 - \rho_s R_{2,tf}^* \tau_s^2}$$

Starting from a initial set of values for *n, k* and *d* for the thin film, an iterative process is carried out in order to minimize the error between $R_{1,tf}$, $R_{2,tf}$ and T_{tf} (note these properties are unpolarized) calculated using the previous formulation and $R^*_{1,tf}$, $R^*_{2,tf}$ and T^*_{tf} values obtained from the experimental data.

8.3.2.3 The transparent System

Once the global properties for both types of element in a general situation have been calculated, the properties for any combination of them, can be obtained by using the matricial method shown in next section. There we will integrate the multilayer panes with the scattering or diffusing ones.

1 Notice than d is a unknown. From the point of view of the modelization it is welcome a third unknown, and it is very difficult to obtain this data from the manufacturer of the products.

8.4 TRANSPARENT SYSTEMS INCLUDING COMPLEX AND DIFFUSING PANES

The main idea of the next formulation is based on that the radiation between faces (“*RBF*”) of a transparent system can always be characterized by a matrix. In each face it is defined a “*flux vector*” ($\vec{\phi}$) which contain the next variables:

- E_j^B : Direct irradiation in face *j.*
- E_j^D : Diffuse irradiation in face *j.*
- J_j^B : Direct radiosity in face *j.*
- J_j^B : Diffuse radiosity in face *j.*

In these variables, a positive value for the received flux by the glass is assumed.

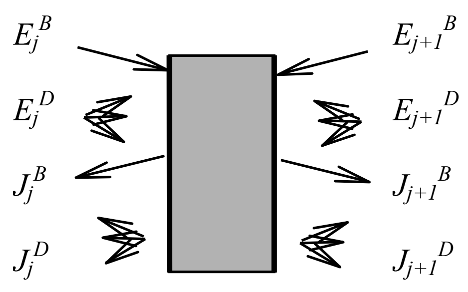
Notice than we have introduced the diffuse magnitudes, and, as it will be seen below, the diffuse properties. Doing so, any sort of diffusing or scattering material can be integrated in the same formulation, provided they can be characterized by the fractions of direct radiation which are transmitted and reflected as direct and diffuse radiation. Some indications for calculating these properties for interpane venetian blinds are given in section 9.

The RBF matrix contains the relation between the flux vectors of any two faces.

For single elements, these matrices are directly obtained from their properties (reflectivity and transmissivity for both, direct and diffuse radiation) as it will be shown in next section. For complex elements, the matrix for each component is required to obtain the matrix of the whole system.

8.4.1 RBF Matrix for a Simple Element

A simple element can be a single glass or a thin film plus a substrate as it has been shown before. Next figure shows the heat flux in a generic element, considering diffuse and direct radiation separately:



Expressing the radiosities as a function of the irradiations, the next set of equations can be written:

$$
\begin{aligned}
J_{j+1}^{B} &= E_j^B\,\tau_j^B + E_{j+1}^B\,\rho_{j+1}^B \\
J_j^B &= E_j^B\,\rho_j^B + E_{j+1}^B\,\tau_{j+1}^B \\
J_{j+1}^D &= E_j^B\,\tau_j^{BD} + E_j^D\,\tau_j^D + E_{j+1}^B\,\rho_{j+1}^{BD} + E_{j+1}^D\,\rho_{j+1}^D \\
J_j^D &= E_j^B\,\rho_j^{BD} + E_j^D\,\rho_j^D + E_{j+1}^B\,\tau_{j+1}^{BD} + E_{j+1}^D\,\tau_{j+1}^D
\end{aligned}
$$

Rearranging terms the above equations can be written as a matrix formulation as follow:

$$\{\phi\}_j = [\mathbf{LAY}]_j^{j+1}\,\{\phi\}_{j+1}$$

where:

$\{\phi\}_j$ y $\{\phi\}_{j+1}$ are the flux vector in the face j and j+1.

$[\mathbf{LAY}]_j^{j+1}$ is the RBF layer matrix.

The values of the matrix elements are:

$$
\begin{bmatrix}
-\dfrac{1}{\tau_j^B\rho_{j+1}^B} & \dfrac{1}{\tau_j^B} & 0 & 0 \\
\left[\tau_{j+1}^B - \dfrac{\rho_{j+1}^B\,\rho_j^B}{\tau_j^B}\right] & \dfrac{\rho_j^B}{\tau_j^B} & 0 & 0 \\
\left[\dfrac{\tau_j^{BD}\rho_{j+1}^B}{\tau_j^B\,\tau_j^D} - \dfrac{\rho_{j+1}^B}{\tau_j^B}\right] & -\dfrac{\tau_j^{BD}}{\tau_j^B\,\tau_j^D} & -\dfrac{\rho_{j+1}^D}{\tau_j^D} & \dfrac{1}{\tau_j^D} \\
\left[\begin{array}{l} \tau_{j+1}^B - \dfrac{\rho_j^D\,\rho_{j+1}^{BD}}{\tau_j^D} + \\ \rho_{j+1}^B\,\dfrac{\tau_j^{BD}\rho_j^B + \tau_j^D\rho_j^{BD}}{\tau_j^B\,\tau_j^D} \end{array}\right] & \dfrac{\tau_j^D\rho_j^{BD} + \tau_j^D\rho_j^{BD}}{\tau_j^B\,\tau_j^D} & \left[\tau_{j+1}^B - \dfrac{\rho_j^D\,\rho_{j+1}^{BD}}{\tau_j^D}\right] & \dfrac{\rho_j^D}{\tau_j^D}
\end{bmatrix}
$$

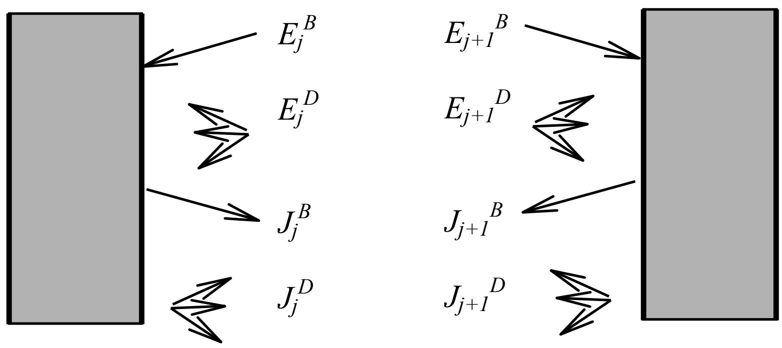
where:

- ρ_j^B : Direct reflectivity in face j.
- ρ_j^D : Diffuse reflectivity in face j.
- ρ_j^{BD}: Reflectivity of direct flux to diffuse one in face j.
- τ_j^B : Direct transmisivity from face j.
- τ_j^D : Diffuse transmisivity from face j.
- ρ_j^{BD}: Transmisivity of direct flux to diffuse one in face j.

Notice than for a transparent system, the values for diffuse have to be obtained after the direct ones corresponding to every incidence angle. So it would be required a characterization process in which the direct properties are obtained for every angle, and afterwards, the diffuse properties are calculated. For a scattering material these properties have to be obtained experimentally, or, in case a model is suitable, from modelization results.

8.4.2 RBF Matrix for a Gap or a Joint

In this case the equations presented in section 8.4.1 are not valid, and should be rewritten as follow:



$$E_j^B = J_{j+1}^B$$
$$E_j^D = J_{j+1}^D$$
$$J_j^B = E_{j+1}^B$$
$$J_j^D = E_{j+1}^D$$

or in matricial from:

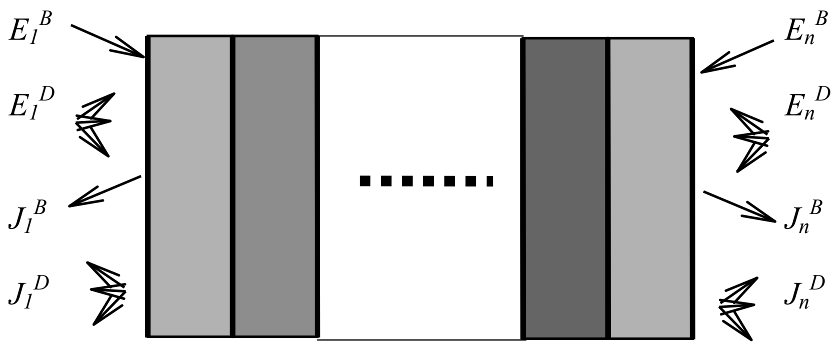
$$\{\phi\}_j = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \{\phi\}_{j+1}$$

this matrix is always the same and it is called [**INT**] matrix.

8.4.3 Calculation of the Properties for a Multilayered Pane and Multipane Windows

The technique described in this section has in particular advantages in case of complicated systems; it has not been activated in WIS yet. For information on the currently applied solar radiation balance solving technique, see chapter 5.

A multilayer pane, as it is shown in the next figure, is made by joining together some single-layer pane. If all of $[\mathbf{LAY}]$ matrix are known, the RBF multilayer pane is calculated multiplying these matrices.

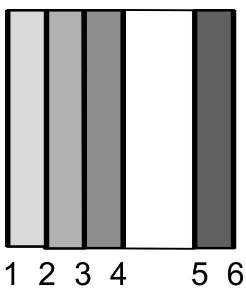


So the expression to calculate the RBF multilayer matrix is:

$$[\mathbf{MUL}]_1^n = [\mathbf{LAY}]_1^2 \, [\mathbf{INT}]_2^3 [\mathbf{LAY}]_3^4 \ldots [\mathbf{INT}]_{n-2}^{n-1} \, [\mathbf{LAY}]_{n-1}^n$$

A glazing can be made by composing single pane, multilayer pane and air or gas gaps. It matrix is obtained in a similar way, multiplying the matrices for all the elements that are between the two external faces.

Next figure shows an example of a complex glazing.



This glazing consists of one multilayer pane (including two components), a gap and a single layer pane

$$[\mathbf{GLA}]_1^6 = [\mathbf{MUL}]_1^4 [\mathbf{INT}]_4^5 [\mathbf{LAY}]_5^6$$

being

$$[\mathbf{MUL}]_1^4 = [\mathbf{LAY}]_1^2 [\mathbf{INT}]_2^3 [\mathbf{LAY}]_3^4$$

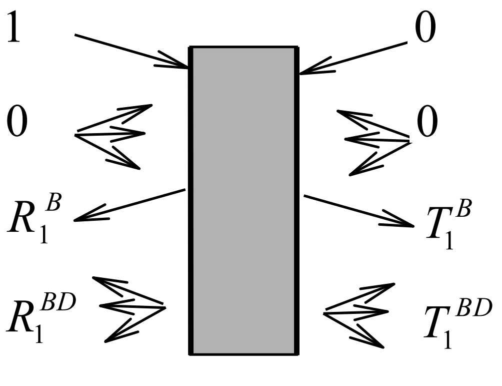
The $[\mathbf{INT}]_4^5$ matrix corresponding to a gap, is the same as $[\mathbf{INT}]_2^3$ corresponding to a join.

8.4.3.1 Calculation of Global Properties

Once have been calculated the radiative matrix for a single layer pane, multilayer pane or a multipane glazing, the global properties can be obtained using an easy identification method. all of the expression for these global properties are presented below denoting the terms of the RBF matrix as M_{ij}.

<u>Irradiation from face 1</u>

Direct radiation:



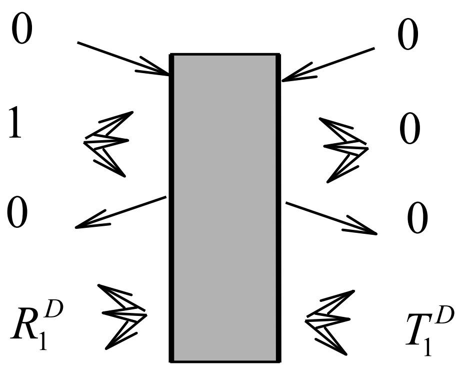
$$T_1^B = \frac{1}{M_{12}}$$

$$R_1^B = \frac{M_{22}}{M_{12}}$$

$$T_1^{BD} = -\frac{M_{32}}{M_{12} M_{34}}$$

$$R_1^{BD} = M_{42} T_1^B + M_{44} T_1^{BD}$$

Diffuse Radiation:

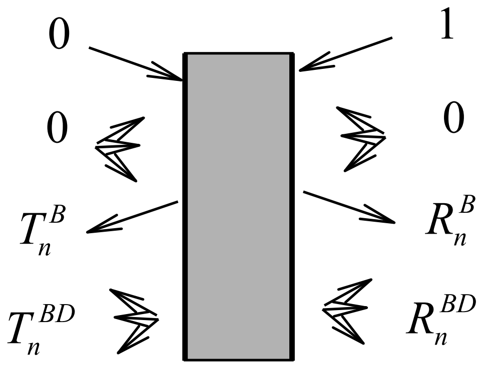


$$T_1^B = \frac{1}{M_{34}}$$

$$R_1^B = \frac{M_{44}}{M_{34}}$$

Irradiation from face n

Direct radiation:



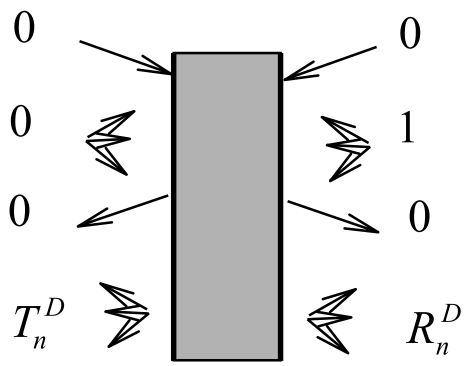
$$R_n^B = \frac{-M_{11}}{M_{12}}$$

$$R_n^{BD} = -\frac{M_{31}}{M_{34}} - \frac{M_{32}}{M_{34}} R_n^B$$

$$T_n^{BD} = M_{41} + M_{42} R_n^B + M_{44} R_n^{BD}$$

$$T_n^B = M_{21} + M_{22} R_n^B$$

Diffuse radiation:



$$T_n^D = -\frac{M_{33}}{M_{34}}$$

$$R_n^D = M_{43} + M_{44} R_n^D$$

References

Siegel R. and J.R. Howell, Prediction of radiative properties by classical electromagnetic theory, Thermal Radiation Heat Transfer, 3rd edition, Chap. 4, McGraw-Hill Book Company, 1992

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Heavens, O.S., Measurement of Optical Constants of Thin Film, Physics of Thin Films, Vol 2, 1964, Academic Press

Heavens O.S. Optical properties of thin films. Reports on Progress in Physics, XXIII, 66-69 (Cited in Rubin, 1982)

Rubin M., Solar Optical Properties of Windows, Energy Research, Vol 6, 123-133 (1982)

8.5 Transparent Insulation Materials

Introduction

Transparent insulation (TI) materials are among the most promising materials for reducing energy consumption in buildings. TI materials can be used in glazed parts of the facade or as outside insulation of opaque walls, for instance. Concerning WIS, of course, only the first usage is of interest. Examples of TI materials are

- polycarbonate (PC) honeycombs,
- capillary structures,
- polymethylmetacrylate (PMMA) foams,
- glass fiber materials
- granulated and homogeneous aerogel.

These materials are usually sandwiched within double glazings to ensure sufficient mechanical properties, weather and fire protection. See [2] for detailed information.

Treatment of TI Materials in WIS

The probably best possible approximation of TI materials in the current WIS version is to treat the transparent insulation as a collection of parallel panes (layers) with high conductance airgaps in between. This approach approximates best parallel structures like plastic foils, and is possible with some limitations for perpendicular structures such as honeycomb and capillaries or hollow core structures like foam or granulated aerogel.

The references [1] gives details on how the data that is required for each of these "panes" can be calculated.

Future Options

It is planned to build in algorithms and calculation modules for an adequate treatment of transparent insulation materials in WIS. These modules will compute thermal as well as optical properties of TI materials.

References

[1] Erhorn, H., Stricker, R.: Transparent Insulation Material Modeling, German Contribution to IEA SHC Task 12, Fraunhofer-Institut für Bauphysik, Stuttgart, 1993

[2] Platzer, W.J.: Transparent insulation materials: A review, SPIE Proc. 2255, pp. 616-627 (1994)

9 SOLAR SHADING DEVICES (LAYER TYPE)

9.1 INTRODUCTION

The solar shading devices are divided into two main classes:

- layer type, and
- external type.

The first ones are characterized by the fact they affect and their temperature are affected by the temperature of the transparent system to which they are attached to. Examples of this kind of shading are the venetian blinds (interpane, indoor or outdoor, but near from the window) and some kind of curtains.
The second one, are far enough from the transparent system to neglect the thermal coupling between the temperatures. Examples of this kind of shading are the awnings, the overhangs and some kind of external louvers.

This chapter deals with the first kind of solar shading. The second is dealt with in chapter 11, section 4.

The coupling of the shading device with the transparent system is, in addition to the effect on the temperatures above mentioned, the interaction with the radiation. Most of the layer type shading devices act as **scattering panes**, and are approximated in WIS as **diffusing panes**, in which a part of the direct radiation impinging on the layer is transmitted as diffuse radiation. Another important feature of this shading device is that they are **semitransparent** to the **infrared** radiation.

In the WIS structure, we calculate the optical properties of this kind of shading devices by means of a simplified model derived from a thermal and solar reference model, called LAMAS, developed in the frame of the JOULE II PASCOOL Project.

In this chapter we describe the basis of the reference model, because of the simplified model is the same reference model, but applied to a simpler enclosure. The last section of this part of the chapter is devoted to the WIS implementation.

For shading devices which cannot be modelled as a slat type, WIS offers the possibility to directly input the angular properties, e.g. based on measurements or other models. See section 9.6.

In WIS, the thermal properties are dealt with as part of the transparent system (see e.g. chapters 5 and 10).

9.2 THE REFERENCE MODEL

The reference model is derived for the scope of the PASCOOL Project, so it starts with a enclosure a little bit different of what can be imagined, but the objective is 'enclosure-independent' so it is perfectly valid for obtaining the simplified model.

9.2.1 DESCRIPTION OF THE ENCLOSURE

The typologies selected can be modelled as a radiant and thermal exchange in a generic enclosure conformed by the glazing surface, the opaque surface belonging to the building (set-back) and the own shading device. Figure 9.1 shows a cross section scheme with all the geometric variables defining the enclosure above cited.

The solar direction is a two-dimensional vector in the plane of the drawing, this vector depends on the solar angle at a given moment and the orientation and tilt of the external wall in which the device is located. The scheme shown in the Fig. 9.1 can be assumed as a vertical or horizontal cross section depending on the louvers position in the device (horizontal or vertical louvers). If we use θ_s , α_s for the solar azimuth and altitude and θ_w , α_w for the wall azimuth and altitude of the wall normal vector in which the device is located. For the horizontal louvers the solar angle referenced in the Fig. 9.1 can be calculated as:

$$\varphi_s = \frac{\pi}{2} - \tan^{-1}\left(\frac{\tan(\alpha_s - \alpha_w)}{\cos(\theta_s - \theta_w)} \right)$$

For the vertical louvers $\varphi_s = (\theta_s - \theta_w)$ directly.

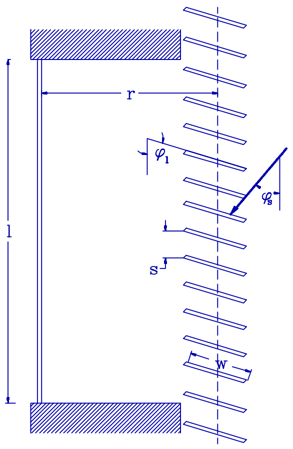

Fig. 9.1 Cross section scheme for the enclosure

9.2.2 HEAT TRANSFER EQUATIONS

9.2.2.1 Heat balance over an element

The model to simulate the thermal and radiant heat exchanges solves the surface heat balance equations (9.1) at each surface of the three-dimensional enclosure formed by the glazing, the shading device, the eventual set-back and the environment

Conduction = Convection + Short-wave radiation + Long-wave radiation

$$-k_i \left.\frac{\partial T}{\partial x}\right|_i = h_i\left(T_i - T_{air}\right) - \alpha_i E_i + \sum_{j=1}^{N_i} C^R_{i,j}\left(T_i^4 - T_j^4\right) \qquad (9.1)$$

Every part of the enclosure (glazing, louvers and set-back) is divided in different isothermal surfaces (see Fig. 9.2). So, there are as many heat balance equations as surfaces, with the temperatures of every surface as only unknowns in the equation system.

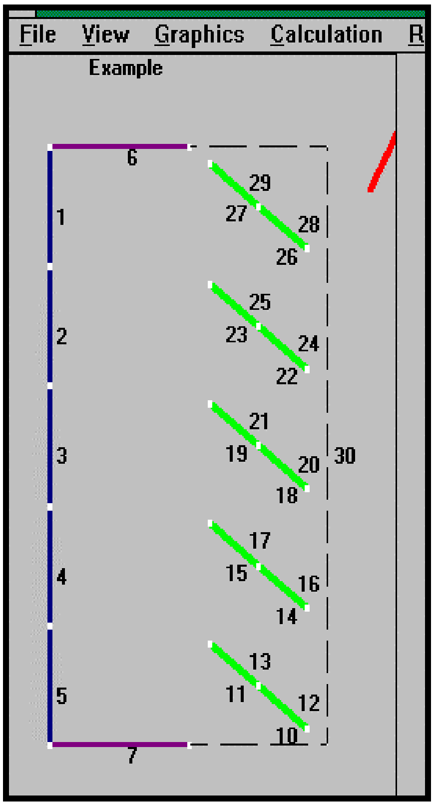

Fig. 9.2 Cross section of the device with an isothermal surface discretization
(LAMAS program).

As we are only interested in the optical characterisation of the shading, only the radiant interchange will be shown; the detailed conduction/convection heat exchange coefficients from

LAMAS are not used by WIS directly, but are available for analysis aiming to provide realistic surface average heat transfer coefficients.

9.2.2.2 Radiative exchange

GENERAL

The starting point for the development of the radiant exchange are the monochromatic equations of radiant heat flow, irradiation and radiosity in a general surface "i" of the enclosure with possible semitransparent behaviour (Rodríguez, 1990) (Fig. 9.3).

$$q_i = \alpha_i M_i^0 - \alpha_i E_i \qquad (9.2)$$

$$E_i = \phi_i + \sum_{j=1}^{n} F_{ij} J_j \qquad (9.3)$$

$$J_i = \alpha_i M_i^0 + \rho_i E_i + \tau_i E_i' \qquad (9.4)$$

Where M_i^0 is the monochromatic emittance of the surface for the considered wave length; E_i is the irradiation on the surface; ϕ_i is the primary incidence heat flux on the surface; J_i is the radiosity of the surface; and E_i' is the irradiation on the back of the surface.

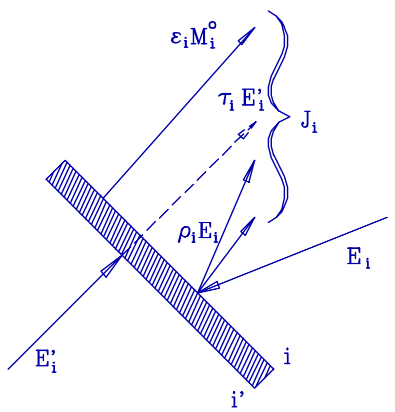

Fig. 9.3 Radiant flows over a surface with possible semitransparent behaviour

The solution of these equations is made in three steps:

1. Elimination of the radiosities between equations (9.3) and (9.4).

2. Solving the irradiations and external excitations (n equations, n unknowns) in terms of surface temperatures.

3. Evaluation of the heat flows by introducing in equations (9.2) the irradiations calculated in the previous step.

We have used a matrix notation where: [a], [r] and [t] are the diagonals matrices of radiant properties (absorptance, reflectivity and transmittance) and [F] is the matrix containing all the view factors between the surfaces in the enclosure.

The treatment of the E'_i term depends on whether the generic surface i' in figure 9.3 is included or not in the enclosure. If i' does not belong to the enclosure E'_i is a datum, if i' belongs to the enclosure then i' will be another surface j with its own heat balance equation, so that $E'_i = E_j$ or in matrix form:

$$E'_i = \vec{b}_i^T \vec{E} \qquad (9.6)$$

where:

$$\vec{b}_i^T = (00...1...00)$$

$$\vec{E} = (E_1 , ... , E_j , ... , E_n)^T$$

$\vec{b}_i$ is a vector containing n-1 zeros and a one in the row j. $\vec{E}$ is the vector with all the internal irradiations. With all the b_i vectors we can obtain the Boolean matrix B. The above considerations are formally expressed by:

$$\vec{E}' = \vec{E}_{ext} + [B]\vec{E}$$

Solving the irradiations:

$$\vec{E} = [C_E]^{-1}(\vec{\phi} + [F][\alpha]\vec{M}^o + [F][\tau]\vec{E}_{ext})$$

Where:

$$[C_E] = [I] - [F][\rho] - [F][\tau][B]$$

Using a clearer formulation:

$$\vec{E} = [E_{temp}]\vec{M}^o + [E_{coup}]\vec{E}_{e'xt} + [E_{flux}]\vec{\phi} \qquad (9.7)$$

Where:

$$[E_{temp}] = [C_E]^{-1}[F][\alpha]$$

$$[E_{coup}] = [C_E]^{-1}[F][\tau]$$

$$[E_{flux}] = [C_E]^{-1}$$

Each one of above matrices relates the irradiation impinging over every surface with the different variables that we assume known in the formulation:

- $[E_{temp}]$: Relates the irradiations with the temperature of every surface belonging to the enclosure.

- $[E_{coup}]$: Couples the irradiation values in the enclosure with the irradiation values out of the enclosure due to the openings and the surfaces with non-zero transmittance.

- $[E_{flux}]$: Becomes the primary incidence values in irradiation values on every surface, doing, like all the previous matrices. the radiant redistribution in the enclosure by inverting the $[C_E]$ matrix.

And finally the radiant heat flow results:

$$\vec{q} = [C_{temp}]\,\vec{M}^o + [C_{coup}]\,\vec{E}_{ext} + [C_{flux}]\vec{\phi} \qquad (9.8)$$

Where:

$$[C_{temp}] = [\alpha] - [\alpha][C_E]^{-1}[F][\alpha]$$
$$[C_{coup}] = -[\alpha][C_E]^{-1}[F][\tau]$$
$$[C_{flux}] = -[\alpha][C_E]^{-1}$$

This way of writing the radiant heat flow over the surfaces is analogous to the one used to write the irradiations and the physical meaning of each matrix is the same.

VIEW FACTORS

In order to cover in a general way the inherent geometric complexity of the enclosures being considered, it was required the development of a new methodology to calculate view-factors between surfaces with intermediate obstacles.

This methodology is based on Nusselt's method. The view factors are calculated for a set of points with a further Gaussian integration (Stroud, 1971). Details of the methodology can be seen in the PASCOOL Final Report.

9.3 SIMPLIFIED MODEL (OPTICAL PROPERTIES)

The simplification proposed for the solar optical domain is conceptually based on the method developed by Parmelee for direct solar radiation (Parmelee and others, 1981).The basic idea is to consider only an intermediate couple of slats to calculate the transmittances and the absorptances. The resulting problem, much simpler than the original one, is then solved by means of the reference model. To simplify the problem, we will consider flat slats and isotropic diffuse reflections.

9.3.1 ASSUMPTIONS

The two major assumptions of the Parmelee method are:

The different effect of the slats in the upper and lower parts of the shading device can be neglected.

The setback is ignored, so that all the solar radiation crossing the shading device impinges over the window.

In theory, for a shading assembly with an infinite number of slats and without setback, the method of Parmelee should give a result coincident with that of the reference model. However, the comparisons with the LAMAS software prove that this is not true. The reason for this discrepancy is that Parmelee assumes that the solar radiation (mainly the diffuse) incident over the slats is uniformly distributed in them and that the multiple reflections process in the slats can be characterized by means of only two view factors slats-glazing and slats-slats.

9.3.2 THE TWO-SLATS CASE

The improvement of the method consists in subdividing the slats in two or more segments and calculate the transmittance for an intermediate and isolated couple of slats. We changed also the Ray Tracing method used by Parmelee by the Net Radiation method applied to the little enclosure conformed by two intermediate couple of slats. The value so obtained is very close to the transmittance of the detailed model with a big number of slats and near to the glazing.

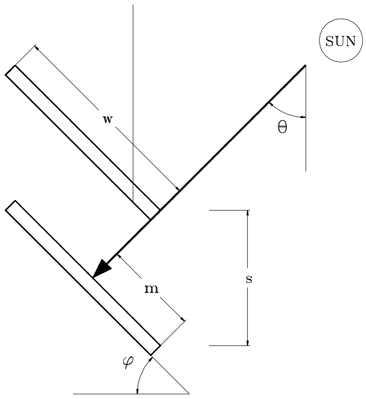

Fig. 9.5 Two intermediate slats used for the simplified model

The irradiation impinging on the glazing (E_G) is divided into three different terms:

$$E_G = E_G^P + E_G^S + E_G^D$$

E_G^P: Direct primary solar radiation passing through the slats assembly without impinging the slats as a function of the solar incident angle (we use it later to define the Primary Transmittance of the slats versus direct solar radiation, or direct to direct transmittance)

E_G^S: Direct secondary solar radiation passing through the slats assembly after reflection at the slats as a function of the solar incident angle (we use it later to define the Secondary Transmittance of the slats versus direct solar radiation, also called direct to diffuse transmittance). The direct radiation is considered diffuse after the first reflection. The specular reflection is not taken into account.

E_G^D: Diffuse radiation reflected or not from the slat assembly that impinges in the glazing (we use it later to define the Transmittance of the slats versus diffuse solar radiation).

So, if we define I_{dir} and I_{dif} as the total irradiation (W/m^2) direct and diffuse incident on a plane parallel to the glazing without any shading device, the global properties, which will be obtained with the simplified model, are defined as:

- Primary Transmittance of the slats versus direct solar radiation: $\tau_P = \frac{E_G^P}{I_{dir}}$, or direct to direct transmittance.

The calculation of primary transmittance is only a geometrical problem so:

$$\text{If } m \leq w \Rightarrow \tau_P = 0$$

$$\text{If } m \leq w \Rightarrow \tau_P = 1 - \frac{w}{m} = 1 - \frac{w}{m}\frac{\sin(\theta)}{\sin(\pi/2 - \theta + \varphi)} \qquad (9.9)$$

- Secondary Transmittance of the slats versus direct solar radiation: $\tau_s = \frac{E_G^S}{I_{dir}}$, or direct to diffuse transmittance

- Transmittance of the slats versus diffuse solar radiation: $\tau_D = \frac{E_G^D}{I_{dif}}$, or diffuse transmittance.

- Global Transmittance of the slats versus solar radiation: $\tau_G = \frac{E_G}{I_{dir} + I_{dif}}$

The reflectances and absorptances are defined in a similar way.

The definition of the equivalent absorptance of the slats (direct, diffuse and global) is done with respect to the total flux over one vertical surface parallel to the glazing, with the same area (A_G), but without shading device, so:

Direct Absorptance of the slats versus direct solar radiation:

$$\alpha_B = \frac{A_s \alpha E_s^B}{A_G I_{dir}}$$

-
Diffuse Absorptance of the slats versus direct solar radiation:

$$\alpha_D = \frac{A_s \alpha E_s^D}{A_G I_{dif}}$$

Global Absorptance of the slats versus solar radiation:

$$\alpha_G = \frac{Q_s}{A_G (I_{dir} + I_{dif})}$$

where:

$$Q_s = A_s \alpha (E_s^D + E_s^B)$$

A_s: Total area of the slats
α: Short-wave absorptance of the slat surface
E_s^D: Diffuse short-wave irradiation over the slats
E_s^B: Direct short-wave irradiation over the slats

9.4 IMPLEMENTATION IN WIS

Figure 9.6 shows the discretization made in the simplified enclosure used in the model implemented in the WIS Project. Every slat is divided into five elements (the improvement of considering more elements is negligible). The right and left virtual closing surfaces are numbered 1 and 2, and considered, as they are, perfectly transparent. Notice than different properties can be assigned to every element, in particular to every side of the slat. The process described below has to be solved for every wave length band required by the properties of the elements or by the rest of the transparent system where the shading device is installed.

Using the Boolean matrix B defined in equation (9.6) (which can be used for taking into account where is coming the radiation impinging on the back of every surface from), we can consider semitransparent elements. For instance, for the case of figure 9.6, we have only to say that radiation impinging on the back of element 8 is that of the front part of element 3, and so on.

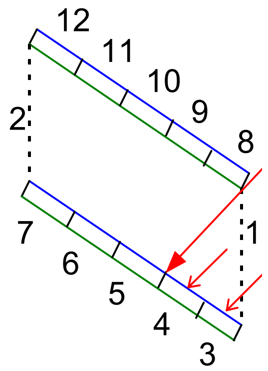

Fig 9.6: The discretization used in the simplified model

The simplified model first calculates the view factors, using the Hottel's method, assuming the shading device is bidimensional. It is an easy geometrical problem.

The second step is the calculation of the direct to direct transmittance, which is again an easy geometrical problem. (see equation (9.8))

The third easy geometrical problem is the determination of the elements in which the direct radiation is impinging (in the case of figure 9.6 elements 3 and 4); Once this is known, the equations are solved to calculate the irradiation on every surface. If the impinging direct radiation is 1 W/m^2 on a plane parallel to the shading device, the direct to diffuse transmittance is the irradiation on surface 2. The direct to diffuse reflectivity is the irradiation on surface 1.

The last step is the calculation of diffuse properties, the diffuse transmittance is the irradiation on surface 2 when it is supposed than 1 W/m^2 is impinging on the back of surface 1. The reflectivity for diffuse radiation is the irradiation on the front side of surface 1

The process is solved again for the radiation coming from the left side of the shading device.

The calculation of the angular distribution of transmission and reflection can be done spectrally and non-spectrally. If it is done spectrally, WIS requires the spectral properties of the slats for normal incidence.

The blinds are also semi-transparent for infrared (thermal) radiation. In order to obtain the IR transmissivity and reflectivity of the shading for given (IR) slat properties, the same model is used as for the calculation of transmission and reflection of solar radiation (see also section 11.3).

In the current version of WIS the threedimensional angles of incidence are not yet activated; this means that the calculations are temporarily restricted to zero azimuth angle between sun and window plane.

9.5 COMPARISON BETWEEN SIMPLIFIED AND DETAILED MODELS

The only assumption of the simplified model is the calculation of view factors in the simplified enclosure by means of the Hottel's method instead of a more detailed one including reveals etc. Taking into account that the model is going to be used either for blinds near and parallel to the glazing or interpane blinds, we don't expect big errors.

9.6 DIRECT INPUT IN WIS OF ANGULAR PROPERTIES OF LAYER TYPE OF SHADINGS

In case the type of solar shading device is not suitable for using the model described above, WIS offers the possibility to direct input the transmission and reflection for each angle of incidence. For instance with data from another model or with data from measurements in a goniophotometer. In this case the same simplification is applied: the incident solar beam is assumed to be spitted into a part which is transmitted without changing direction (direct-direct transmission), and a part which is transmitted isotropicly diffuse (direct-diffuse). Diffuse radiation is transmitted as diffuse always (diffuse-diffuse). The reflection is always considered as isotropicly diffuse.

Again, the calculation of the angular distribution of transmission and reflection can be done spectrally and non-spectrally. If it is done spectrally, WIS requires the spectral properties of the shading for normal incidence. But note that in that case there is an overlap in input: the overall angular transmissivity and reflectivity at normal incidence can be found as elements in the input matrix of angular properties, but also as the integral of the input array of spectral properties.

WIS uses the input array of spectral properties as the absolute values and treats the angular properties as relative values: the angular properties are multiplied by a correction factor in such a way that the angular transmissivity and reflectivity at normal incidence is equal to the spectral transmissivity and reflectivity integrated over the whole solar spectrum.

In this way a conflict in the input is avoided and one will still be able to see a difference in results depending on the choice of solar spectrum. It also allows the use of the same matrix with angular properties for products which are similar, but e.g. have different colours.

9.7 TRANSPARENT SYSTEM WITH LAYER TYPE OF SHADINGS AND DIFFUSE PROPERTIES OF PANES

As already explained in section 8.1: if the transparent system contains, in addition to the solar shading device or diffusing pane, a pane which is a non fresnel type and the input of solar optical properties of that pane is restricted to the properties at normal incidence, WIS will not be able to calculate the properties of the transparent system.

This is due to the fact that a shading element or diffusing pane introduces diffuse transmission/reflection, even in case the incident radiation consists of perpendicular radiation only. So WIS will need the optical properties for diffuse irradiation for *each* layer. The diffuse properties are calculated in WIS by integration of the angle dependent properties.
As service for the user, a temporary rough approximation has been made available in WIS, see section 8.1.

9.8 FUTURE OPTIONS

Future versions of WIS software may include:

- curved slats and non diffuse reflections (relevant for specularly reflecting slats)
- detailed angular transmission and reflection distribution functions (relevant for detailed daylight studies).

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10 CAVITIES

10.1 Gas and gas mixes

The thermal convective conductance of a closed cavity is calculated by

$$hg = Nu\ \lambda / s$$

where

s is the width of the space
λ is the gas thermal conductivity
Nu is the Nusselt number

$$Nu = \min (1 , A (Gr.Pr)^n)$$

where

A is a constant
Gr is the Grashof number
Pr is the Prandtl number

$$Gr= 9.81\ s^3\ dT\ \rho^2 / (Tm\ \mu^2)$$

$$Pr = \mu\ .\ c / \lambda$$

where

dT is the temperature difference between the panes bounding the cavity
ρ is the gas density
T_m is the mean gas temperature
μ is the gas dynamic viscosity
c is the gas specific heat capacity

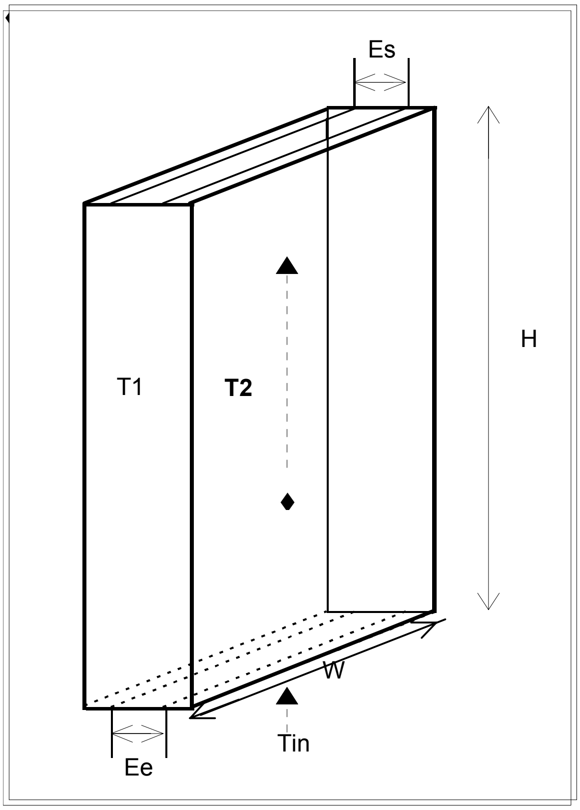
According to prEN 673, the values used for a vertical glazing are A = 0.035 and n = 0.38. The λ, ρ, μ, and c are tabulated values versus T_m given for air, argon, SF6 and krypton. Linear interpolation is used for temperature and gas mixes.

prEN contains similar equations for tilted glazing, also activated in current WIS version.

10.2 - ventilation in cavities

10.2.1 air flow and temperature calculation

Let us consider the following schedule:



with :

T_1	:	uniform temperature of pane 1
T_2	:	uniform temperature of pane 2
T_{in}	:	temperature of air entering the layer
$t_a(x)$	:	air temperature at a distance x of the air inlet
H	:	window height
W	:	window width
d	:	distance between the two panes
V	:	air speed in the air layer
Q_s	:	air flow in the air layer (m^3/s)
h_{pi}	:	convective heat coefficient between pane and air

$T_n = (T_1 + T_2)/2 - T_{in}$

ρ_{air} (kg/m^3) : volumic weight of air for standard conditions,
(i.c.: $\rho_{air} = 1.189$)
c_{air} (J/kg) : thermal capacity (i.c.: 1008)

then :
$2h_{pi}\ (t_a(x) - T_{in})\ dx\ W = -\ Q_s\ \rho_{air}\ c_{air}\ dt_a(x).$

By introducing :
$y = x / H$
$G_s = Q_s / (W.H)$

$2h_{pi}\ (t_a(y) - T_{in})\ dy = G_s\ .\ \rho_{air}\ .\ c_{air}\ dt_a(y)$

Ratio of heat transfer rate of fluid flow and fluid to pane:

with $Gr = G_s\ \rho_{air}\ C_{air} / (2\ h_{pi})$

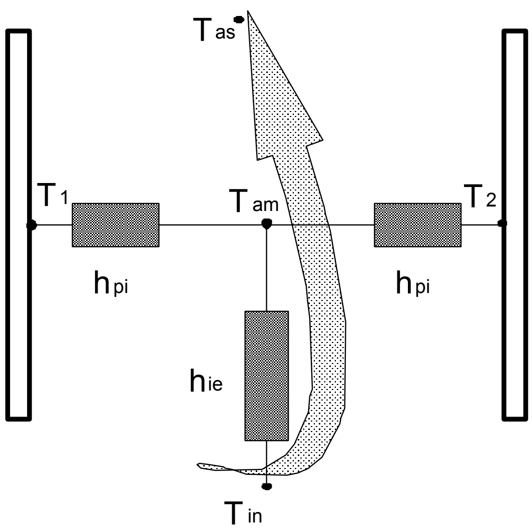
both Gr and y are nondimensional parameters

$t_a(y) = T_n\ (1 - e^{-y/Gr}) + T_{in}$ [1]

the mean value of $t_a(y)$ is :
$T_{am} = T_n\ (1 - Gr\ (1 - e^{-1/Gr})) + T_{in}$

the air temperature at the outlet is :
$T_{as} = T_n\ (1 - e^{-1/Gr}) + T_{in}$

Illustration:



10.2.2 application when air flow in the cavity is known

If the air flow within the air layer has a known value (for example due to mechanical ventilation), the above equations can be directly applied.

The heat exchanges between the pane temperatures T_1 and T_2, the mean air layer temperature T_{am} and the temperature of the entering air T_{in} are calculated by the equivalent heat exchange coefficients h_{pi} (between T_1 or T_2 and T_{am}) and h_{ie} (between T_{in} and T_{am})

$$h_{pi} = 2*g_{cond} + A_v . V$$

where g_{cond} is the thermal conductance of the closed air cavity. A_v is a coefficient which can be set to 4 W/m^{2}K per m/s. (document 033-89-Passys-MVD-FP017 p 5.4).

$$h_{ie} = 2 . h_{pi} . (abs(T_n) - dT) / dT$$

with $dT = abs(T_{am}-T_{in})$

h_{pi} and h_{ie} are in W/(m^2.K), related to the window area (i.c. H*W)

10.2.3 application when air flow in the cavity is due to the stack effect

The following equations, adopted in WIS, are subject of current standardisation activities within CEN. Where necessary the will be updated in the next version.

The air flow in the air layer due to the stack effect is:
$G_s = Cd\ Aeq\ (2\ dT\ g / (H . T_{am}))^{0,5}$

with Cd = 0,61 is the discharge coefficient
$Aeq = (1/A_e^2 + 1/A_t^2)^{-0,5}$
A_e (m^2) is the area of the air inlet section
A_t (m^2) is the area of the air outlet section
$dT = T_{am} - T_{in}$

then:
$G_s = C_2\ dT^{0,5}$ [5]
with :
$C_2 = 0,156\ Aeq\ H^{-0,5}$

An approximation for T_{am} is
$T_{am} = dT + T_{in} = T_n / (1 + 1,5\ Gr) + T_{in}$

The equations to be solved are :

$$Gr = \rho_{air} . c_{air} . G_s / (2 . h_{pi})$$

$$T_n = abs((T_1 + T_2) / 2 - T_{in})$$

$$dT = T_{in} / (1 + 1.5 . Gr)$$

$$G_s = C_2\ dT^{1/2}$$

$V = G_s . H / d$

$h_{pin} = 2 . g_{cond}$

$h_{pi} = h_{pin} + A_v . V$

The equation to be solved is then :

$G_s^3 (H . A_v / d + 0{,}75. \rho_{air}.c_{air}) + G_s^2 h_{pin} - G_s (C_2^2 T_n A_v H / d) -$

$T_n C_2^2 h_{pin} \quad = \quad 0$

Knowing G_s enables to calculate the various results as in 10.2.2

$V = G_s . H / d$

$h_{pi} = h_{pin} + A_v . V$

$Gr = \rho_{air} c_{air} G_s / (2 h_{pi})$

$dT = T_n / (1 + 1.5 Gr)$

$h_{ie} = 2 . h_{pi} . (abs(T_n) - abs(dT)) / abs(dT)$

A side aperture area can be taken into account by introducing equivalent upper and lower opening areas . If E_l is the depth (m) of the side aperture (both on right and left part of the window), and considering that the neutral plane is at middle of the height, the equivalent values of E_e and E_s to be added to the actual ones are :

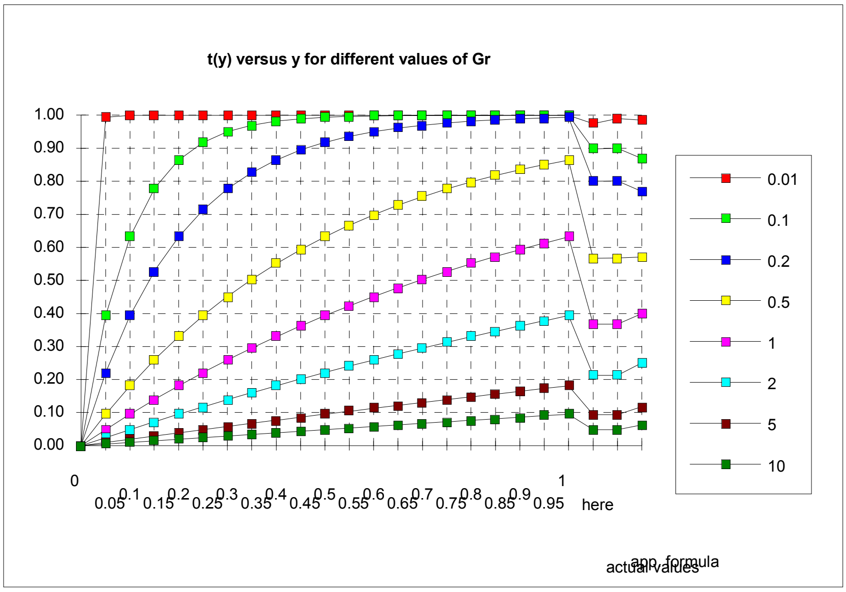
$E_{esup} = E_{ssup} = E_l. H /(2 W)$

This is a safe way to simplify the calculation. If for example the actual value of E_s is equal to 0 , It could be considered that the above formula will underestimate E_{ssup} and then decrease the air flow. Nevertheless it is not sure in this case that the higher part of the air layer will be correctly ventilated, which would reduce the efficiency of the ventilation. An accurate calculation for such a situation would require a two dimensional CFD calculation, which is far beyond the acceptable level of simplification

Of course a detailed CFD calculation or measurements may be used to obtain equivalent top and bottom aperture areas for a certain type of geometry, which can then be used as input for WIS.

NB: WIS assumes always an air flow from bottom to top or vice versa. The reported values in WIS are per unit window width.

Tn =	1	Gr							
dy	y	0.01	0.1	0.2	0.5	1	2	5	10
0.1	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.1	0.05	0.99	0.39	0.22	0.10	0.05	0.02	0.01	0.00
0.1	0.1	1.00	0.63	0.39	0.18	0.10	0.05	0.02	0.01
0.1	0.15	1.00	0.78	0.53	0.26	0.14	0.07	0.03	0.01
0.1	0.2	1.00	0.86	0.63	0.33	0.18	0.10	0.04	0.02
0.1	0.25	1.00	0.92	0.71	0.39	0.22	0.12	0.05	0.02
0.1	0.75	1.00	1.00	0.98	0.78	0.53	0.31	0.14	0.07
0.1	0.8	1.00	1.00	0.98	0.80	0.55	0.33	0.15	0.08
0.1	0.85	1.00	1.00	0.99	0.82	0.57	0.35	0.16	0.08
0.1	0.9	1.00	1.00	0.99	0.83	0.59	0.36	0.16	0.09
0.1	0.95	1.00	1.00	0.99	0.85	0.61	0.38	0.17	0.09
0	1	1.00	1.00	0.99	0.86	0.63	0.39	0.18	0.10
avg	here	0.97	0.90	0.80	0.57	0.37	0.21	0.09	0.05
avg	actual values	0.99	0.90	0.80	0.57	0.37	0.21	0.09	0.05
	app. formula	0.99	0.87	0.77	0.57	0.40	0.25	0.12	0.06



10.3 FUTURE OPTIONS

The following has been identified as priorities for future extensions:

- add wind driven ventilation

- cross validate free ventilation with LAMAS/experimental results PASCOOL

equivalent opening sizes/height for permeable shadings like blinds and air permeable screens

11 RADIATION, MORE IN DETAIL

11.1 Spectral solar properties

In chapter 7 we introduced the option to choose different solar spectra.

A calculation according to a certain international standard, e.g. prEN 410, requires properties at specific wavelength intervals.
The intervals for which the spectral properties are known from measurements are in general not equal to these required intervals.

WIS first checks the intervals as they are in the spectral input data, to see whether the information is complete. If that is not the case, WIS checks whether the information is rich enough to allow interpolation of the gaps in the data.

WIS allows up to 50% interpolation weighted by the weight factors (prEN410).

The fitting is according to a polynomial Interpolation based on 4th order Lagrange, using 5 neighbouring points.

For the checking and the interpolation WIS makes a distinction between spectral data needed to calculate solar properties, data for visual properties and values for UV properties.

11.2 Angular solar properties

The correlation laws used (as described in 8.2) are :

$$asi = \sum_{i=i1}^{i2} ai \cos^{i}$$

$$tsi = \sum_{i=i1}^{i2} i \cos^{i}$$

- reference values at 0 ° (normal incidence) 30 ° and 60°

$$asi = a1 \cos i + a2 \cos^2 i + a3 \cos^3 i$$
$$tsi = b1 \cos i + b2 \cos^2 i + b3 \cos^3 i$$
$$rsi = 1 - asi - tsi$$

$$aso = a1 + a2 + a3$$
$$as3o = a1 \cos 3o + a2 \cos^2 3o + a3 \cos^3 3o$$
$$as6o = a1 \cos 6o + a2 \cos^3 6o + a3 \cos^3 6o$$
$$bso = b1 + b2 + b3$$
$$bs3o = b1 \cos 3o + b2 \cos^2 3o + b3 \cos^3 3o$$
$$bs6o = b1 \cos 6o + b2 \cos^3 6o + b3 \cos^3 6o$$

and then :

$$a1 = 6{,}4646\ aso - 11{,}7745\ as3o + 9{,}4645\ as6o$$
$$a2 = -20{,}3940\ aso + 35{,}3234\ as3o - 20{,}3940\ as6o$$
$$a3 = 14{,}9294\ aso - 23{,}5489\ as3o + 10{,}9295\ as6o$$
$$b1 = 6{,}4646\ bso - 11{,}7745\ bs3o + 9{,}4645\ bs6o$$
$$b2 = -20{,}3940\ bso + 35{,}3234\ bs3o - 20{,}3940\ bs6o$$
$$b3 = 14{,}9294\ bso - 23{,}5489\ bs3o + 10{,}9295\ bs6o$$

11.3 Spectral properties, thermal radiation

Normal glass is opaque for thermal radiation. Most plastics too, unless in case of thin layers.

Screens may be partly transparent for thermal radiation, due to their porosity, as are solar protecting blinds. The transmittance by porosity does not change the spectral distribution (flat spectral power distribution).

Solar blinds also redirect *thermal* radiation in a way similar to the way diffuse *solar* radiation is transmitted and reflected. For the slat type of solar shading devices WIS benefits from this by using the available model to calculate the diffuse-diffuse solar transmission and reflection to calculate the thermal transmission and reflection, as already mentioned in section 9.5. At least in principle, in this case the spectral distribution of the reflection (and optionally: the transmission) of the thermal radiation at the slats is relevant.

Thin films between two air or gas layers usually have a specific spectrally distributed transmission and reflection for thermal radiation.

To summarize: in principle there may be an error introduced by the spectral distribution of the transmissivity and reflectivity for thermal radiation, e.g. in case of combinations of layers with different spectral distributions and/or in case of strongly differences between layer and environment temperatures.

In the current version of WIS the emissivity and transmissivity for thermal (infrared(IR), longwave) radiation is not considered as a function of the wavelength.

11.4 EXTERNAL SHADING, NOT PART OF WINDOW

11.4.1 INTRODUCTION. MAIN ASSUMPTIONS

As it was said in Chapter 9, the external shading devices are supposed to be not thermally coupled to the window. So, they affect only to the solar radiation, which is partially obstructed by the shading device. This is a very important assumption. Some indication of the way of taking into account the effect of the thermal coupling can be seen in the Final Report of PASCOOL Project.

For the WIS Project purposes, the problem to solve is only geometric. The basics of the procedure used can be seen in Rodríguez, 1988.

We have to calculate the fraction of the window which is sunlit. This fraction will be multiplied by the direct solar radiation to obtain the (assumed uniform) amount of direct radiation impinging the transparent system.

The diffuse solar radiation, is reduced by a fraction calculated as the view factor between the transparent system and the sky.

There is neither correction to take into account the reflection of the radiation on the shading device itself, nor splitting of diffuse radiation into the typical fractions reflected from the ground and coming from the sky. Compare prEN-ISO 13791: diffuse radiation is considered not obstructed (to accommodate for reflections not taken into account)

Tridimensional calculation not yet activated in current WIS version, only variations on altitude are considered.

11.4.2 SOLAR OPTICAL CHARACTERIZATION

The software performs the beam and diffuse shading calculations for a given window/shading device system. The shading devices included are:

- Set-backs
- Overhangs
- Awnings
- Side fins (left and right)

The input data are the 19 values describing the geometry of the shading assembly (see fig 11.1).

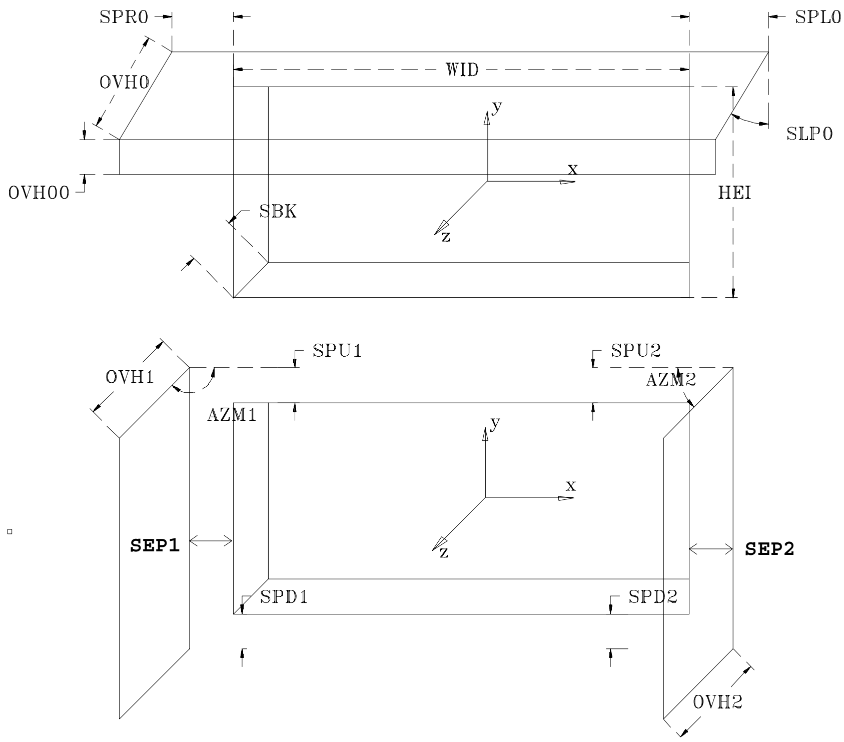


Fig. 11.1: Geometric description of a Shading Device

The output data are, on the one hand the view factors for shading of diffuse radiation (window/side fin 1, window/side fin 2, window/awning, window/set-back, window/outdoors); on the other hand the value of the sunlit fraction (direct transmissivity) of the shading device for the altitude and azimuth angles given as parameters.

The reflection of solar radiation from the shading device is not included.

The former values allow the calculation of the shading of direct radiation and the shading of diffuse radiation (Rodríguez E.A. and others, 1988). The procedure to carry out the calculation is described in next paragraphs.

Direct Radiation

The direct radiation impinging the transparent system is calculated by multiplying the original direct radiation by the sunlit fraction of the window calculated by the procedure.

Diffuse Radiation

The diffuse radiation impinging the transparent system is calculated by reduction of the original one by a fraction which is the view factor between the window and the sky.

This view factor is calculated by:

$$1 - F_{ws} - F_{wr} - F_{wo}$$

where: F_{ws} is the view factor between the window and the side fin; F_{wr} is the view factor between the window and the rebate and F_{wo} is the view factor between the window and the overhang or awning. In case any of these elements is missing the corresponding view factor is 0.

References

Rodríguez E.A., Guerra J., Álvarez S. Modelling the Effect of Remote and Façade Obstructions on the Radiation at the Outdoor Surface of Windows. Energy and Buildings for Temperate Climates. Proceedings of PLEA'88, pp. 285-290. Porto (Portugal) 1988

12 SMART WINDOWS

12.1 Introduction

Glazing system allowing the automatic and/or user-controlled modulation of solar gains and associated daylighting properties are known as so-called "smart" window systems. These systems are characterized by the variability of their physical properties. Depending on the actual state, these properties can vary significantly. Examples of smart systems are

- electrochromic glazings

The modulation of the physical properties is performed by applying electrical voltage to the system. The system for instance consists of multi-layer coatings or of a special layer consisting of tiny spheres of liquid crystals encapsulated with a flexible polymer film between two covering class panes. The system can be in one of several different states of transparency. The switching can be controlled by sensors or manually by the user.

- photochromic glazings

The system usually consists of a self-shading glass pane reacting on light. Such glazings are also used for eye glasses, for instance. Photochromic glazings are usually characterized by several different states of transparency. The switching is done automatically and cannot be overruled by the user.

- thermochromic glazings
  As the electrochromic system, a thermochromic system also consists of a special layer between two covering class panes. The modulation of the physical properties is depending on the thermal conditions in the environment. Thermochromic systems are always in one of two fundamentally different states: they can be either in transparent state (i.e. the state with highest solar/visible transmittance) or opaque/clouded state (i.e. the state with the lowest solar/visible transmittance). As for photochromic systems, the switching is done automatically and cannot be overruled by the user.

Depending on the system and the material used, the non-transparent state may be either reflective or absorbing or a combination of these.

12.2 Treatment of Smart Windows in WIS

Smart window systems are currently not built in explicitly in the WIS system, but it is possible to treat them in WIS in such a way that for each switching state, a separate system is used. This requires, of course, that the relevant properties are known (e.g. from measurements) for each state.
It is recognized that this procedure does not yet meet the minimum quality standard for user friendliness which the WIS developers tried to maintain throughout the software tool; hence: see also 12.4.

12.3 Example: thermochromic glazing

Details on examples of thermochromic materials and glazings can be found e.g. in [1,4,7]. One of the most promising approach using a gel of organic polymers allowing an adjustable switching setpoint temperature is described in [2,5].

The radiative transmission through a thermochromic switchable glazing system is similar to that of a usual double glazing system with an air gap in between. The difference is that for the reactive gel the extinction coefficient is not equal to zero and the refractive index is not equal to 1.0. Since in WIS currently a gap with a refractive index not equal to 1.0 is not possible, a pane object should be used to model the gel layer.

A detailed description of modelling of thermochromic systems can be found in [3,6].

12.4 Future Options

The thermal and optical performance of smart window systems is strongly depending on the variation of external environment conditions over time. It will therefore be necessary to simulate the systems within a certain time frame to take into account the dynamic behaviour which is characteristic for these systems.
WIS may be extended in the future with an option to introduce a cluster (array) of panes, in which each pane represents the properties for a certain state of the same smart glazing.
In that case, similarly, a clustering on the transparent system level is required. Each element in the array will represent the physical behaviour of the system for specific environmental conditions. In case WIS is also provided with an option to calculate the properties for a certain time series of environment data (se section 7.6), depending on these conditions during the

simulation, the corresponding array element will be selected automatically.
Running for instance a simulation over a typical day would give fairly good characteristic results and show the effects of the dynamic behaviour of the system.

References

[1] Boy, E., Bertsch, K., Frangoudakis, A.: Temperaturabhängige Lichtdurchlässigkeit von Baumaterialien [Temperature-dependent light transmittance of building materials], IBP Report SA 2/83, Fraunhofer-Institut für Bauphysik, Stuttgart, 1983

[2] Boy, E., Meinhardt, S.: TALD - A temperature-controlled variable transparent glass, Building Research and Practice, The Journal of CIB, no. 4, 1988

[3] Erhorn, H., Stricker, R.: Thermochromic Switchable Glazing Modeling, German Contribution to IEA SHC Task 12, Fraunhofer-Institut für Bauphysik, Stuttgart, 1993

[4] Germer, J.: Switchable Glazings, Solar Age 10 (1984), vol. 10, pp. 20-23

[5] Meinhardt, S., Möschel, J., Boy, E., Bertsch, K.: Temperaturabhängige Lichtdurchlässigkeit von Gläsern (TALD) [Temperature-dependent light transmittance of glazings], IBP Report SA 1/85, Fraunhofer-Institut für Bauphysik, Stuttgart, 1985

[6] Reilly, S., Selkowitz, S., Winkelmann, F.: Switchable Window Modeling, Contribution of USA to IEA SHC Task 12, Lawrence Berkeley Laboratory, Berkeley, 1992

[7] Reusch, G.: Selbstschattierendes Glas Thermex [Thermex, A self-shading glazing], Glaswelt 21 (1982), vol.1, pp. 16-22

13 DETAILED OUTPUT

13.1 Daylight Properties

13.1.1 Calculation of the General Colour Rendering Index

Introduction

The general colour rendering index R_a is calculated for transmitted light through the transparent system. This index is sometimes also called the CIE 1974 colour rendering index. The method used in WIS is compliant with the European standard prEN 410 (final draft) [prEN 410]. prEN 410 follows the recommendations of the CIE (International Commission on Illumination) [CIE 74]. The recommended method is called the test colour method.

The standard illuminant D_{65} is used as a reference illuminant to calculate the general colour rendering index R_a. This standard illuminant corresponds in its spectral distribution to natural daylight. For the calculation, the relative spectral power distribution of D_{65}, $D_{D65}(\lambda)$, is required. Values for this function in 5 nm steps in the visible spectral range can be found in e.g. [CIE 71] or [DIN 5033 (7)].

The maximum value of R_a is 100, which will be achieved for glazing with a spectral transmittance that is completely constant in the visible spectral range. Values of $R_a > 90$ characterize a very good, values of $R_a > 80$ a good colour rendering.

Description of Calculation Method

The only input required from the WIS main system is the wavelength dependent visual transmission $\tau(\lambda)$. It is assumed that values of this function are given in 10 nm steps in the visible spectral range (380 nm to 780 nm). The same assumption is made for the additional data input as described below. This additionally required input is taken from [CIE 71], [CIE 74], [DIN 5033 (2)] and [DIN 5033 (7)]. Although this data is available in 5 nm steps, a step size of 10 nm gives enough accuracy for the calculation.

First, the spectral power distribution of the light source to be tested, $D_t(\lambda)$, has to be calculated. For glazing in transmission, this is given by

$$D_t(\lambda) = D_{D65}(\lambda) \cdot \tau(\lambda), \qquad \lambda = 380, 390, ..., 780.$$

From this, the CIE 1931 tristimulus values X_t, Y_t, Z_t of the transmitted light are calculated using the CIE colour-matching functions $\bar{x}, \bar{y}, \bar{z}$ adopted by the CIE 1931 as

$$X_t = k \cdot \sum_\lambda \bar{x}(\lambda) \cdot D_t(\lambda)$$
$$Y_t = k \cdot \sum_\lambda \bar{y}(\lambda) \cdot D_t(\lambda)$$
$$Z_t = k \cdot \sum_\lambda \bar{z}(\lambda) \cdot D_t(\lambda)$$

Values for the colour-matching functions can be taken for instance from [CIE 71] or [DIN 5033 (2)]. The normalizing factor *k* is defined as (see [CIE 71]):

$$k = \frac{100}{\sum_\lambda \bar{y}(\lambda) \cdot D_t(\lambda)}$$

The CIE 1931 tristimulus values X_i, Y_i, Z_i for the test-colour samples i=1,...,8 illuminated by D65 through the glazing are calculated using the spectral radiance factors $\beta_i(\lambda)$ as

$$X_i = \sum_\lambda \bar{x}(\lambda) \cdot \beta_i(\lambda) \cdot D_t(\lambda)$$
$$Y_i = \sum_\lambda \bar{y}(\lambda) \cdot \beta_i(\lambda) \cdot D_t(\lambda)$$
$$Z_i = \sum_\lambda \bar{z}(\lambda) \cdot \beta_i(\lambda) \cdot D_t(\lambda)$$

The values for the spectral radiance factors $\beta_i(\lambda)$ are taken from [CIE 74], table 1. Note, that normalizing the values X_i, Y_i, Z_i is not necessary, because these values are only used in the next two formulas where normalization is not relevant.

The tristimulus values X_t, Y_t, Z_t and X_i, Y_i, Z_i are transformed to *(u,v)* coordinates u_t, v_t and u_i, v_i of the CIE 1960 Uniform Chromacity Scale diagram using the formulas

$$\mathrm{u} = 4\mathrm{X} / (\mathrm{X} + 15\mathrm{Y} + 3\mathrm{Z})$$
$$\mathrm{v} = 6\mathrm{Y} / (\mathrm{X} + 15\mathrm{Y} + 3\mathrm{Z})$$

Reference values u_r, v_r needed for D65 can be taken from table 3a in [CIE 74] as

$$\mathrm{u_r} = 0.1978$$
$$\mathrm{v_r} = 0.3122$$

The adaptive colour shift due to the different state of chromatic adaptation under the tested light source (the transmitting glazing) and under the reference light source D65 are taken into account using

$$u_i' = \frac{10.872 + 0.404\frac{c_r}{c_t}c_i - 4\frac{d_r}{d_t}d_i}{16.518 + 1.481\frac{c_r}{c_t}c_i - \frac{d_r}{d_t}d_i}$$

and

$$v_i = \frac{5.520}{16.518 + 1.481\frac{c_r}{c_t}c_i - \frac{d_r}{d_t}d_i}$$

The values c_t, d_t and c_i, d_i, i=1,...,8, are calculated as

$$c = (4 - u - 10v) / v$$
$$d = (1.708v + 0.404 - 1.481u) / v$$

The reference values c_r, d_r can be taken from table 3a in [CIE 74] as

$$c_r = 2.1787$$
$$d_r = 2.0636$$

Colorimetric values can now be transformed in the CIE 1964 Uniform Colour Space coordinates. Only one transformation is actually necessary, namely

$$W_{t,i}^{*} = 25 \cdot \sqrt[3]{Y_i} - 17$$

From $W_{t,i}^{*}$ the other two coordinates $U_{t,i}^{*}$ and $V_{t,i}^{*}$ can be determined implicitly (see below).

The difference between the perceived colour of a test colour sample i illuminated by D65 through the glazing and that of the same sample illuminated by the reference illuminant D65 is calculated using the CIE 1964 Colour-Difference Formula giving the determinant of the resultant colour shift:

$$\Delta E_i = \sqrt{(\Delta U_i^*)^2 + (\Delta V_i^*)^2 + (\Delta W_i^*)^2}$$

with

$$\Delta U_i^* = U_{r,i}^* - 13 \cdot W_{t,i}^*(u_i' - u_r)$$

$$\Delta V_i^* = V_{r,i}^* - 13 \cdot W_{t,i}^*(u_i' - u_r)$$

$$\Delta W_i^* = W_{r,i}^* - W_{t,i}^*$$

For each test colour i the special colour rendering index can be calculated:

$$R_i = 100 - 4.6 \cdot \Delta E_i$$

The general colour rendering index finally is obtained as

$$R_a = \frac{1}{8}\sum_{i=1}^{8} R_i$$

This result is rounded to the nearest integer as recommended by prEN 410.

Assumptions and Simplifications

The calculation of the general colour rendering index is done for transmitted light only. Within the calculations it is assumed that data is available for the visible spectral range in 10 nm steps.

Future Development Options

It is considered to implement the calculation of the general colour rendering index for reflected light also. The determination and graphical representation of the position of the transmitted/reflected light in the CIE colour diagram is considered.

Output Validation

Validation of the calculated colour rendering index has been performed using the examples from [prEN] and [CIE 74].

References

[1] CIE Publication No. 15 (E-1.3.1.): Colorimetry. Official Recommendations of the International Commission on Illumination (1971)

[2] CIE Publication No. 13.2 (TC-3.2): Method of measuring and specifying colour rendering properties of light sources (1974)

[3] Deutsches Institut für Normung e.V.: German Industrial Standard 5033 (part 2), Colorimetry; standard colorimetric systems, Beuth-Verlag, Berlin (1992)

[4] Deutsches Institut für Normung e.V.: German Industrial Standard 5033 (part 7), Colorimetry; measuring conditions for object colours, Beuth-Verlag, Berlin (1983)

[5] European Committee for Standardization: Final Draft prEN 410 „Glass in Building", (1992)

13.1.2 Output to Lighting Simulation Programs

Optional output to the RADIANCE lighting simulation program [1] is described in detail in section 13.2.2.

References

[1] Ward, G.: The RADIANCE 2.5 Synthetic Imaging System, Lawrence Berkeley Laboratory, Berkeley (1995)

13.2 Output as interface to simulation programs

WIS outputs can be utilised as input data for several thermal and lighting simulation tools.
Each simulation tool obviously requires different input data, more or less complex depending on its own properties and objectives.
Moreover, from inside the application it is possible to directly translate results from the calculation into formats coherent with programs like ESP and RADIANCE (see next sections).
For other lighting or thermal simulation software (e.g. PASSPORT+) the user has to take the required data from the WIS output and to convert/introduce them in the appropriate way into the simulation program.
The following sections show three examples of how the output of WIS can be utilised.

13.2.1 Output to ESP

ESP (Environmental Systems Performance) is a computer package for building and energy simulation, developed at Strathclyde University (Scotland), considered among the most accurate and detailed tools existing in the world for the simulation of thermal building performance.
It is possible to obtain directly the data for a socalled transparent multilayer construction (TMC) file.
The data required are the following:

- direct transmittance for 5 angles of incodence (0°, 40°,55°, 70°. 80°);
- absorptance of each element of the glazing cq transparent system (from inside to outside) for 5 angles of incidence (0°, 40°,55°, 70°. 80°).

13.2.2 Output to RADIANCE

RADIANCE is a lighting and daylighting simulation program that can also be used as a photorealistic renderer. This is why it is sometimes also called a synthetic imaging system [4]. RADIANCE has been developed on UNIX systems by Greg Ward at Lawrence Berkeley Laboratory since about 1985; a PC version is contained in the ADELINE (Advanced Daylighting and Electric Lighting Integrated New Environment) program package [2,3]. RADIANCE is based on a backward ray-tracing algorithm, tracing back the light distribution from the image plane to the light sources. Calculations are carried out for three different colour bands, red, green and blue.

Detailed output of WIS for the transparent system can be used as input data for RADIANCE. In RADIANCE, so-called primitive types are used to define materials and geometric entities. Several different primitive types can be used to define the material of a transparent system:

- glass

This is probably the most simple primitive type to be used for the description of a transparent system. This primitive type is optimized for thin glass surfaces, avoiding internal reflections. The input required is transmissivity at normal incidence i.e. the fraction of light that travels all the way through the material. See [4] on how to compute transmissivity from transmittance at normal incidence. If no spectral information is available from WIS, the red, green and blue entries should be set to the same transmissivity value. Optionally, a refraction index different from the default 1.52 may be given.

- dielectric

Dielectric is a generalisation of glass and gives more flexibility, taking into account, for example, the Hartmann constant. See [4] for details on how to use this primitive type.

- transdata

The material type transdata may be used to take into account arbitrary bi-directional reflection and transmittance given as interpolated data. Angular dependent data from WIS can be used for this type. See [4] for details on how to use this primitive type.

Information on how to compute the red, green and blue values from wavelength dependent output using the CIE 1931 colour-matching functions can be found in [1].

Future options

It is planned to include in WIS modules to directly output the calculated results in RADIANCE format, including material and geometric description. Calculation procedures for computing the red, green and blue values from spectral information calculated by WIS will also be included.

References

[1] Compagnon, R.: Simulations Numériques de Systèmes d'Éclairage Naturel a Pénétration latérale, PhD Thesis, École Polytechnique Fédérale, Lausanne, 1993

[2] Erhorn, H., Szerman, M.: Documentation of the Software Package ADELINE, Fraunhofer-Institut für Bauphysik, Stuttgart, 1994

[3] Erhorn, H., Stoffel, J.: Documentation of the Software Package ADELINE 2.0, Fraunhofer-Institut für Bauphysik, Stuttgart, (to be published)

[4] Ward, G.: The RADIANCE 2.5 Synthetic Imaging System, Lawrence Berkeley Laboratory, Berkeley (1995)

13.2.3 Output to PASSPORT+

PASSPORT+ is a software tool developed within the framework of the PASCOOL project. It enables to estimate the thermal performance of buildings in particular concerning the thermal behaviour during the warm season. Selected passive cooling techniques are included.
In order to exploit the WIS output for PASSPORT+ simulation the following data are needed:

In the glazing library of PASPORT+:
for each pane must be defined:
- conduction [W/m.K]
- normal absorptivity
- normal solar transmission coefficient
- IR emissivity

All these data can be easily obtained from he report on the WIS Pane level.

In the window library of PASSPORT+:
- thickness [mm] of each pane and id number
- air layer thickness [mm] between panes
- thermal resistance of the air gaps [m2K/W]

These data can be easily obtained from the report on the WIS transparent System level.

13.3 Various detailed output

As stated in section 1.5 WIS provides at each level of calculation (window system, transparent system, pane, shading, frame) the option to produce a detailed report. The level of detail is user defined. This detailed report offers information on the precise context of the calculation results. Moreover, it provides additional inside information on calculation details, such as node temperatures, network resistances, Nusselt numbers for free convection, transmission and reflection per wavelength and so on. This detailed information is thus available for use in other environments (building simulation, detailed studies, spreadsheet programs, etc.).

The contents of the detailed report are self-explaining.

Examples are given in the User's Guide (appendix of tutorial section).

Appendix A

WIS AND EUROPEAN STANDARDS

There is a close relationship between the development of WIS and European standardisation activities within the framework of CEN (Comité Européen de Normalisation - European Committee for Standardisation). Among the activities in CEN TC89 WG7 and WG6 are the standardisation of calculation routines and/or results of calculations for the thermal and solar properties of windows, for instance: CEN TC89 WG7, thermal and solar properties of windows (i.e., calculation models for heat loss and solar transmittance properties of window systems including solar shading and shutters); CEN TC89 WG6, indoor climate in summer (i.e., window and solar shading modelling for dynamic building models).
The most relevant standards (EN...), draft standards (prEN...) and working documents (../N...) are listed below. The numbers, titles and contents will be subject to future change due to the process of drafting and completing the standards.

prEN 673:1992

Title:	Thermal insulation of glazings - Calculation rules for determining the steady state "U" value (thermal transmittance) of glazing
Prepared by:	CEN/TC129
Principle:	The U-value is calculated on the basis of standard surface heat transfer coefficients, (tabulated) gas properties, gap widths and tilt angle (conduction/convection) and measured surface emissivities (thermal radiation)
Status:	Being prepared for formal vote
New title:	Glass in building - Determination of thermal transmittance (U-value) - Calculation method
ISO equivalent:	ISO 10292:1994
Application:	Central part of glazing only; for multiple glazing with N cavities; not for materials transparent for thermal radiation.

prEN 30077-1:1993

Title:	Windows, doors and shutters - Thermal transmittance - Simplified Calculation method
Prepared by:	CEN/TC89

Principle:	U-value of window calculated on the basis of the area and U-value for central part of glazing, area and U-value for frame and a linear U-value (called ψ) per unit length of perimeter for the edge of the glazing; the value for the edge correction depends on the combination of glazing and frame. Contains tabulated values for U-frame and ψ-edge
Status:	Being prepared for second inquiry within TC89
ISO equivalent:	ISO 10077
Application:	For windows including edges and frames

Draft prEN 30077-2(1995)

Title:	Window and door components - Thermal transmittance - Part 2. Numerical calculation method
Prepared by:	CEN/TC89
Principle:	Finite difference/element calculation methods for determining the thermal transmittance of frames; this standard will provide specific window frame boundary conditions and simplifications to be taken into account, in particular concerning the heat transfer in cavities (equivalent conductivity); the calculation methods have to pass the tests for thermal bridge calculation methods in EN ISO 10211/1
Status:	Working draft submitted to TC89 for comments and approval in principle
ISO equivalent:	-
Application:	Two-dimensional cross sections of window frames

CEN/TC33/WG3/N184(1994)

Title:	Blinds and shutters fitted with facade, windows and French windows - Additional thermal resistance given by blinds and shutters - Requirements - Classification - Attribution of a class to a product
Prepared by:	CEN/TC33/WG3/TG5
Principle:	Calculation of reduction in the U-value due to blind or shutter, as function of position (internal, incorporated, external), air tightness (classes) and thermal resistance of the product
Status:	Working draft under preparation by WG

ISO equivalent: -
Application: Blinds and shutters

CEN/TC89/WG7/N...
Title: ((Calculation of U-value of curtain walls))
Prepared by: CEN/TC89/WG7 + WG6
Principle:
Status: Work item, not started yet
ISO equivalent: -
Application: curtain walls

CEN/TC89/N436(1995)
Title: Windows - solar energy and light transmission of solar protection devices combined with glazing - Part 1 - simplified method
Prepared by: CEN/TC89/WG7
Principle: Simplified calculation method for the solar transmittance of combination of glazings and blinds, using glazing U-value and transmittance and reflectance of the blind material; conservative values for summer situation only (overestimates)
Status: Working draft submitted to TC89 for comments and approval in principle
ISO equivalent: -
Application: For combination of glazings and blinds; conservative values for summer situation only (overestimates)

prEN 410:1990
Title: Glass in buildings - Determination of light transmittance, solar transmittance, solar direct transmittance, total solar energy transmittance, ultraviolet transmittance and related glazing characteristics
Prepared by: CEN/TC129
Principle: Calculation based on measured optical properties per pane, plus assumed surface heat exchange coefficients and tabulated spectra.
Thermal part of calculation based on prEN 673
Status: Being prepared for formal vote
New title: Glass in building - Determination of luminous and solar characteristics of glazing

ISO equivalent:	ISO 9050
Application:	For single, double or triple glazing, near normal incidence; not for materials transparent for thermal radiation; scattering and/or non-homogeneous materials: applicable only with restrictions.

CEN/TC89/WG7/N129(1995)

Title:	Windows - solar energy and light transmission of solar protection devices combined with glazing - Part 2 - detailed method
Prepared by:	CEN/TC89/WG7
Principle:	Reference calculation method giving the equations for the solar and thermal radiation exchange and heat transfer through a window consisting of n layers like glazings, screens, blinds; the calculation requires for each layer the transmission, reflection and absorption for solar and thermal radiation, plus the air permeability; furthermore: see prEN 410. This standard will be an extension of prEN 410, allowing calculation of windows with layers which are permeable for air and/or IR radiation.
Status:	First working draft being prepared by WG
ISO equivalent:	-
Application:	Windows with venetian blinds, screens, foils, etc.

APPENDIX B

MANUFACTURERS DATA

An important feature of WIS is the possibility that the code offers to the user to perform calculations of complete window systems or of separate components, using properties of products existing in the market. The results of these calculations can be useful to the final user if:

- the calculation methodology complies with the existing normative rules (e.g. CEN rules) and
- the quality of the databases with the properties of the various products is high and regularly updated, following the progress of the techniques and the development of the materials used in the field.

From the contacts that the WIS group had during the project period with professionals active in the building area, but also with those related to glazing and other window components, it was made clear that, for the reasons mentioned above, the quality of the input data to the WIS software is of primordial importance.

The completeness however of the product data base does not depend only on the endeavour of the WIS participants, but requires also the active involvement of the manufacturers of the various products. Detailed calculations of window component or integrated systems require specific and detailed data, which, for many products, is not yet available. In order to overcome this constraint, the WIS group used generic data, but also data issued from recent research, that the participants in the group perform. This data was included and can be used for studying specific phenomena regarding the thermal and optical behaviour of window components and systems.

Proforma:
In order to facilitate the integration of the data in WIS, a proforma for input information from manufacturers was discussed during the project. This proforma should contain entries for all categories of relevant products, i.e. panes, filling gases, window frames, but also complete window systems and shading devices.

A dilemma that the WIS group did face, was that of the number of data that had to be entered in this first version of the programme. The reason was that the required data format was changing during the last one and a half year of software development of WIS. This was because of the comments and reactions received by various researchers and other building professionals that did test the test versions of the code. These remarks led to modifications and improvements of the code that resulted to changes in the structure concept, influencing also the format of the input data.

Therefore for this first version it was decided to limit the contents of the product data bases, by adding some generic data and data provided by few manufacturers.

Format of WIS spectral data:
At the end of this appendix is presented the current format for spectral data input required by WIS for panes.

Maintenance and updating:
The whole concept of the WIS project can remain a useful tool for the building professional only if these databases are going to be regularly updated. This update has not only to include new products and components but also the deletion of those that do not exist in the European Market any more. This update will be organised by the WIS Steering Committee.
As mentioned in section 3.2, it must be stressed that the product data bases are structured in a way to be protected against accidental overwriting, that could lead to wrong calculations because of the modification of product properties.

Customized WIS versions:
It is also foreseen to optionally create customised versions of WIS for specific manufacturers/clients. The basic difference between the normal and the customised version could be the presentation of specific data or other special additions to the program. Such customized version may be used by the manufacturer for demonstration purposes during his commercial campaigns, but also as design tool for further development of his products.
The Steering Committee will develop conditions for such specialised versions to ensure that it will not harm the further development and distribution of the common uniform European WIS version.

Recommended format for spectral data of panes; instructions

This format is based on the format of spectral data used for the LBL Window 4.0 program and is fully compatible with the WIS program. The requested minimum in spectrum intervals is based on the European draft standard PrEN 410.

Files: one file per glazing product

filename:	*xxxppppp*.spc	
with:	*xxx*:	(three free choice characters): acronym for manufacturer
	ppppp:	(five free choice characters): code, identifying the pane
	spc:	(fixed): identification of SPeCtral datafile

Contents per file:		**explanation:**
Units wavelength	***	fill in: SI nm or □m
Glazing thickness	***	in mm
Glazing conductivity	***	in W/(mK)
τ_{IR}	***	IR transmittance
emis=*ef eb*	***	IR emissivity front emissivity back
w1 trans Rf Rb		wavelength 1, normal transmittance, reflectivity front, back
w2 trans Rf Rb		wavelength 2, normal transmittance, reflectivity front, back
w3 trans Rf Rb		wavelength 3, normal transmittance, reflectivity front, back
etc.		etc.

The lines marked with *** are read by hand, therefore their format is not critical.
The column with R_b may be omitted in case Rb = Rf
The wavelength intervals according to PrEN 410 are (in nm):

for solar thermal properties:

from 300 until 800:	20 nm	=>	300, 320, ...
from 800 until 2100:	50 nm	=>	800, 850, ...
from 2100 until 2500:	100 nm	=>	2100, 2200, ...

for visual properties:

from 380 until 780:	10 nm	=>	380, 390, ...

for UV properties (optional):

from 282.5 until 377.5:	5 nm	=>	282.5, 287.5, ...

NB: the order of the wavelengths in the files may be random example:

Filename:

```
mnftyp01.spc
```

Contents:

```
SI  nanometers
6.0
.80
tir= 0.0
emis= 0.84 0.84
300     0.006  0.048
320     0.264  0.051
..      ..     ..
etc.
..      ..     ..
2500    0.830  0.089
```