ON THE INFLUENCE OF ANGULAR DEPENDENCE PROPERTIES OF ADVANCED GLAZING SYSTEMS ON THE ENERGY PERFORMANCE OF BUILDINGS

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ABSTRACT

Windows strongly influence the energy performances of buildings, especially in the new hugely glazed constructions. Many advanced glazings were produced to improve the thermal and optical properties of windows, but for these products the angular dependence of optical and solar parameters are from the traditional glass decay curves. Computer tools often do not solve the problem of the inputting of effective solar and luminous parameters of transparent surfaces, since they consider only the traditional glazings behavior. The energy loads of an office building are calculated, by means of ad-hoc models and simulations with TRNSYS, to evaluate the errors that energy building simulation programs get into, without considering the effective properties of advanced glazing systems.

INTRODUCTION

Energy performances of buildings depend on the characteristics of the building envelope, in particular transparent components and materials play a relevant role for the energy balance of constructions. As a matter of fact, during the cold season the fenestration systems of the building are the source of the larger amount of thermal losses, since the thermal resistance of glazings and frames are generally lower than the opaque components of the envelope. In summer time, on the other hand, most of the cooling loads depend on the solar gains, coming from the transparent surfaces of the building. From the previous considerations, it can be easily inferred the importance of the evaluation of windows parameters for an accurate prediction of the energy building performances.

More over, windows are fundamental for electric energy savings coming from a correct design of artificial lighting system. Transparent surfaces allow reaching such objective and, at the same time, the daylighting ensure the visual comfort for occupants.

Industries and research institutions carried on during the last decades many efforts to match the various exigencies required for fenestration: better energy performances, improved visual comfort, better mechanical properties and safety. The results of such tendencies are a wide range of new products under development or already available on the market.

Nowadays several codes and tools are used for evaluating energy performances of buildings. The optical, solar and thermal properties of transparent components and materials are essential parameters to perform accurate simulations, for this reason it is very important the way such parameters are inputted or modeled into the codes. Some of the above-cited parameters are functions of other factors, as the dependence from the angle of incidence of the solar radiation, but many tools are not complex enough to embed such functions. Few of them have such functions, but implemented for conventional glazings only. Dealing with advanced materials (TIM, diffusing glazings, laminated shading devices), it is necessary to implement ad-hoc routines, where angular dependence of solar and luminous characteristics of glazing systems are modeled. This is the only way to obtain accurate results for energy performances of buildings, equipped with innovative glazing components and materials.

EXPERIMENTAL

During the past years many new products were introduced on the market to be used as transparent components in building. It is important to evaluate their optical and thermal properties to stress the way the energy performances of buildings can be achieved.

Without going into details of the physical properties of transparent materials, it must be reminded that some parameters are not constant, but strongly depend on the angle of incidence of the solar radiation on the material surface. The luminous transmittance τ_v expresses the amount of light (solar radiation falling into the visible range) transmitted by the component respect to the incident one, and it is important to predict the luminous behavior of a built environment, equipped with the selected fenestration. The solar factor g expresses the total amount of radiation (direct component plus secondary heat transfer) transmitted by the component respect to the incident one, considered for the whole solar range.

Both parameters, as said before, are not constant but depend on the inclination of the solar radiation, as an example, the luminous transmittance curve of the traditional glass, as function of the angle of incidence. It reaches its maximum at normal incidence, keeps this value almost constant up to thirty degrees, then start decreasing and, after 60 degrees, quickly reduce its value, that becomes zero at 90 degrees. Similar behavior can be observed for the solar factor.

It is interesting to compare this behavior, typical of the conventional glass, with some advanced components. This field was investigated within the research community, because of the increasing interest such materials, to check the properties, the reliability and the performances of such components and materials. IEA (International Energy Agency) Task 18 and 27, implemented in the framework of the Solar Heating and Cooling Programme, and other Projects, financed by European Communities, were carried on during the nineties to assess measurement procedures, performances and models as well [ADOPT, 1996 and ALTSET, 1996].

The experimental works carried out during the above-cited projects outlined how, for advanced transparent components, the angular dependence of visual and solar parameters is different from the conventional glass used for windows.

To stress the difference among various components, in figure 1 and 2 are reported the plots of some transparent units, obtained as interpolation of experimental measurements, which are shortly described and numbered as follow:

S1 Conventional double glazing unit

S2 Double glazing unit, with a plastic diffusing film on the innermost surface of the inner glass. It is used for cutting the luminous radiation and maximizing solar gains.

S3 Double glazing unit, with transparent insulating material in the argon filled gap. It is used as high thermal performance components (very good in cold climate), allowing at the same time the natural light to reach the built environment.

S4 Double glazing unit, with fixed black lamellae, laminated with pvb, between two glass sheets. In this case the only wanted effect is the shading from solar radiation, without redirection of the luminous radiation.

S5 Double glazing unit, with movable high reflecting horizontal lamellae inside the air gap. It is used for shading the room from the direct radiation that is redirected by lamellae toward the ceiling and, then, diffused inside the internal space.

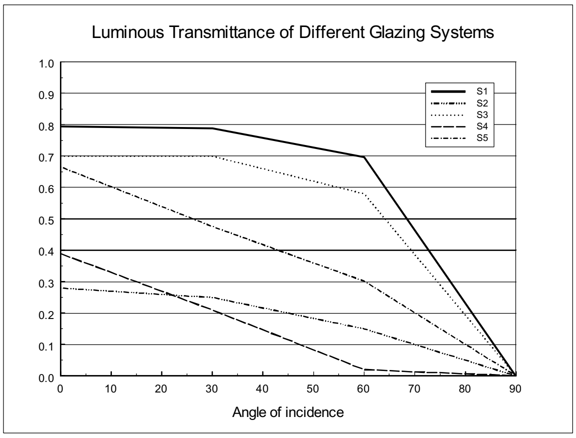

Figure 1. Angular decay of the luminous transmittance of the selected samples

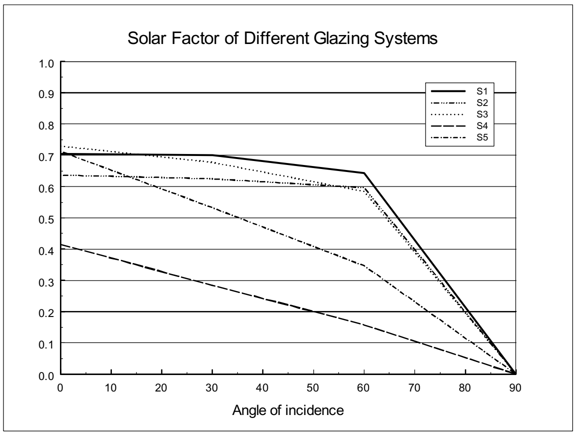

Figure 2. Angular decay of the solar factor of the selected samples

In figure 1, the luminous transmittance curves of the selected innovative samples can be compared with the plot of the conventional double glass unit. Strong differences come easily out for the two glazing systems equipped with lamellae system, where the angle of incidence dependence is strictly connected with the geometry of the system. But the other samples show different behavior as well, especially at high angles of incidence. Analogous considerations can be made for the solar factors, the curves of the selected components are reported in figure 2. Such situation can lead to consistent misevaluation of building energy requirements. As a matter of fact, the higher is the sun position, the higher will be the mistake of considering the decay curve of an advanced transparent component similar to that of a conventional one.

To highlight such behavior, in table 1 are reported the effective luminous transmittance of the samples and the relative differences between the effective luminous transmittance and the hypothetical value, they would have considering their angular decay curve like the conventional glass one. In table 2 the same data are presented for the solar factor and the same considerations apply.

Table 1. Luminous transmittance and relative differences of the selected samples

Samples		0 [°]	30 [°]	60 [°]
S2 τ_v	[-]	0.28	0.25	0.15
S2 $\Delta\tau_v$	[%]	0	9.9	44.2
S3 τ_v	[-]	0.70	0.69	0.58
S3 $\Delta\tau_v$	[%]	0	-13.8	13.7
S4 τ_v	[-]	0.39	0.21	0.02
S4 $\Delta\tau_v$	[%]	0	45.7	94.7
S5 τ_v	[-]	0.67	0.48	0.30
S5 $\Delta\tau_v$	[%]	0	27.9	52.7

Table 2. Solar factor and relative differences of the selected samples

Samples		0 [°]	30 [°]	60 [°]
S2 g	[-]	0.64	0.62	0.60
S2 Δg	[%]	0	1.20	-2.8
S3 g	[-]	0.73	0.68	0.59
S3 Δg	[%]	0	6.46	12.1
S4 g	[-]	0.42	0.28	0.16
S4 Δg	[%]	0	30.8	58.3
S5 g	[-]	0.71	0.53	0.35
S5 Δg	[%]	0	24.7	46.6

In this section some experimental results were presented, in order to outline some problems that must keep into account when developing or using models and tools for components and building simulation. Glazing requirements can be fulfilled according to the exigencies and the degree of accuracy of the implemented model; in any case the awareness of some approximations is, by this way, always kept alive.

SURVEY OF EXISTING TOOLS

Today many tools are used for modeling glazing system for building applications. Such programs evaluate:

- Daylighting, artificial lighting and visual comfort.
- Energy (cooling and/or heating) performances.
- Combined luminous and energy analyses.

In this section, it is interesting to focus the attention on the way the luminous and solar parameters are modeled or inputted into the software. Glazing products are, generally, sold on the market, supplying only normal hemispherical luminous transmittance and solar factor. No further information is supplied: angular dependence curves, diffusing or redirection properties, color performances, and so on.

There are several possibilities for inputting data in the code for simulation:

1. The software accepts only constant values of luminous transmittance and solar factor.
2. The software performs instantaneous simulations (typical of daylighting software). In this case constant values or angular parameters, if available, can be inputted. In the latter case there is a previous calculation or experimental phase performed by the user and not by the software.
3. The software accepts the normal values, then the program manages them. It can have internal routines or links with other software, able to give the effective value of such parameters, as function of the incident radiation and other geometric conditions. By this moment only parameters for conventional glasses are embedded into this software.
4. The software accepts the effective angular decay of optical and solar parameters.

In all these cases but number 4, there is no way to get accurate results from simulations, when using complex glazing system for fenestration, since it was previously outlined how different is their angular behavior, if compared to the traditional glass sheet.

Another aspect is worth to be reminded, even if not strictly concerned with this paper and regarding the visual comfort of the transmitted natural light. Daylighting codes consider the transmitted luminous

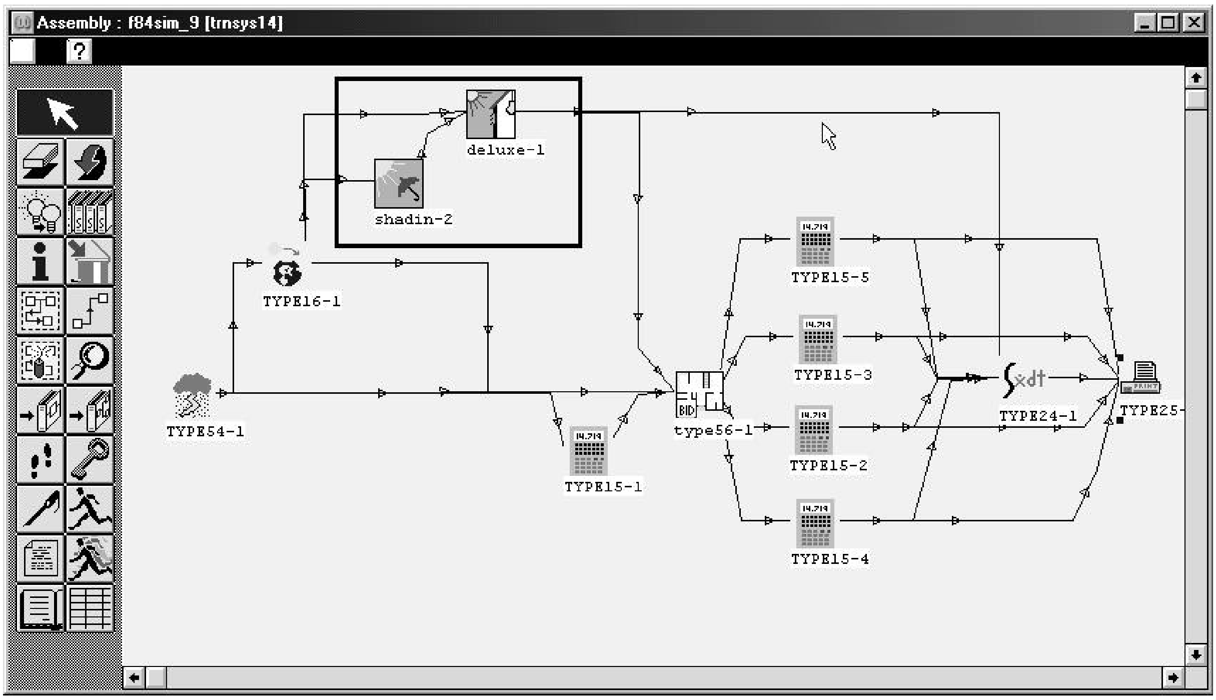

Figure 3. Scheme of TRNSYS project

radiation with two simple options only: the transparent component has a regular behavior, hence the radiation is regularly transmitted (in-going angle equal to out-going angle); the transparent component has diffusing behavior (the transmitted radiation

follows the cosine law). In this case too, there is a lack of flexibility in simulation codes. Intermediate situations, with direct and diffusing components, are not adequately treated. Inputting and/or modeling the effective diffusing behavior of the glazing is necessary to perform simulations, with a correct reproduced luminous environment.

This short survey suggests some useful considerations:

- Codes with direct input of angular parameters are suitable, if the decay curves are available by calculation or experiments. This generally happens in lighting software, where the simulation is the picture in a chosen moment.
- Codes with internal decay curves are not suitable for complex glazings, if the program is not set to accepts specific inputs for particular components (i. e. thermal and geometric definition of lamellae or transparent insulating).
- Codes with external routines or links with other program can be implemented, developing ad-hoc routines with effective angular dependant curves of luminous and solar parameter. In this case, it is also possible to implement more advance model for diffusing and redirecting properties of transparent materials.

METHODOLOGY

To quantify the influence of windows on the performance of buildings, it was decided to use TRNSYS, 1996]. It is an open code where different routines can be linked each other, in order to incorporate all those parts, supposed to be fundamental for an accurate evaluation of the energy building performances.

The aim was, in this case, to equip a reference building with different transparent systems and evaluate its energy performances. Using real (measured) angular decay curves for luminous and solar properties, it is possible to calculate the effective cooling, heating and artificial lighting loads of the building. Such results can be compared with those obtained using only normal hemispherical values of the above-cited parameters (no-angular decay curves) or obtained using the decay curves of conventional glazings.

The project implemented for these simulations, with the scheme presented in figure 3, consists of the following linked routines:

- Weather generator. It is a routine where average monthly values are inputted for the selected locality. The considered weather parameters are: air temperature, relative humidity, wind speed and direction.

- Solar generator. It is a routines implemented to calculate the solar radiation on a generic plane starting from inputted values of the solar radiation on the horizontal plane.
- Pre-Bid. It is a routine necessary to input the characteristics (geometric, thermo-physical, etc.) of the building. In this section all the components of the building must be described in detail, using the code library or creating new ones. Furthermore, the building must be zoned, grouping spaces with similar thermal conditions, orientation, working hours of occupants, etc. In this section must be specified the adopted cooling, heating and ventilation systems
- A daylighting routine, to evaluate the influence of selected glazing systems on the internal luminous environment and, as a consequence, on the artificial lighting loads [Ferro, 2000].
- A dedicated routine developed to take into account the shading effect of lamellae, present in some transparent components [Ferro, 2000].

Some of the above mentioned routines, in particular the shading device routine an the daylighting routine, were developed in ENEA and are not standard TRNSYS routines.

It is important to be aware of how TRNSYS manages windows, in order to verify eventual problems and difficulties, when using advanced, complex or innovative glazings.

The 14.2 version of TRNSYS has an embedded link to Window4 program [Window4, 1992]. Window4 is a well known computer code, developed by Berkeley laboratories, capable to compute glazing systems and windows characteristics, knowing layers materials (optical coefficients, conductivity, thickness and others), gaps (thickness, gas mixture, pressure, and others) and frame (U-value) properties. The program is quite efficient and reliable and its results can be stored as a library file readable by other programs and in particular by TRNSYS. On the other hand, the angular decay curves are fixed and, consequently, complex and innovative materials (e.g. glazing with shading devices) are not considered.

As mentioned before, the output file of Window4 is read by TRNSYS, so the only way to use experimental data is editing the file to change some of the numbers listed. The procedure is complicated by the following circumstance, concerning the thermal part of simulations: the solar factor coefficient, even if computed by Window4 and reported in the library file, is recalculated by TRNSYS, starting from the absorptances of the different layers and the heat exchange factors between the layers. This approach has some positive aspects because the g-value is not constant but changes according the boundary conditions (radiation level, wind speed, internal and external temperatures).

On the other hand, in order to use measured solar factor values, not knowing the absorptances of different layers and the inward flowing fraction for each layer, a dummy component has to be built having very unreal properties: solar transmittance equal to g-value and zero absorption in any layer.

The same problem arises with the window U-value. TRNSYS recalculates the effective U-value using the current boundary conditions and the glazing system physical description but, due to a code bug, it does not consider the conductivity of solid layer different from the glass one. Virtual components must be constructed in this case too, using fictitious gaps to achieve the effective U-value of the window.

Further complications, for both thermal and luminous parts, were found simulating samples with lamellae since the code does not accept bi-directional functions of transmission and reflection. A work around solution was found out considering those components as normal DGUs with external shading devices, having the same characteristics of the lamellae sheet.

SIMULATION

The influence of angular decay of optical and solar parameters on energy performance of buildings was tested using an office block as reference. The building is a three-level block, located in the northern outskirts of Rome; it has linear layout with the two main facades, north and south oriented, scheme in figure 4. The simulations were run for the second level only, so that no thermal fluxes exist among the different levels, but they take place through the facades only. It must be noted that the 65% of the facade is glazed, hence it is through transparent components that most of energy loads of the building arise. To evaluate the needs for artificial lighting, each room of the building was equipped with a luxmeter, whenever the illuminance level on the working plane goes under 400 lux the lighting system turns on.

The simulations were run equipping the building with innovative glazings described in the Experimental section. It was interesting to compare some particular situations, because considering all the different options would have led to too many simulations and results. Energy loads of the building were calculated the following cases:

- No angular decay curves of the selected components are inputted.
- Conventional angular decay curves for the glazing systems with lamellae are inputted.
- Effective angular decay curves of the selected components are inputted.

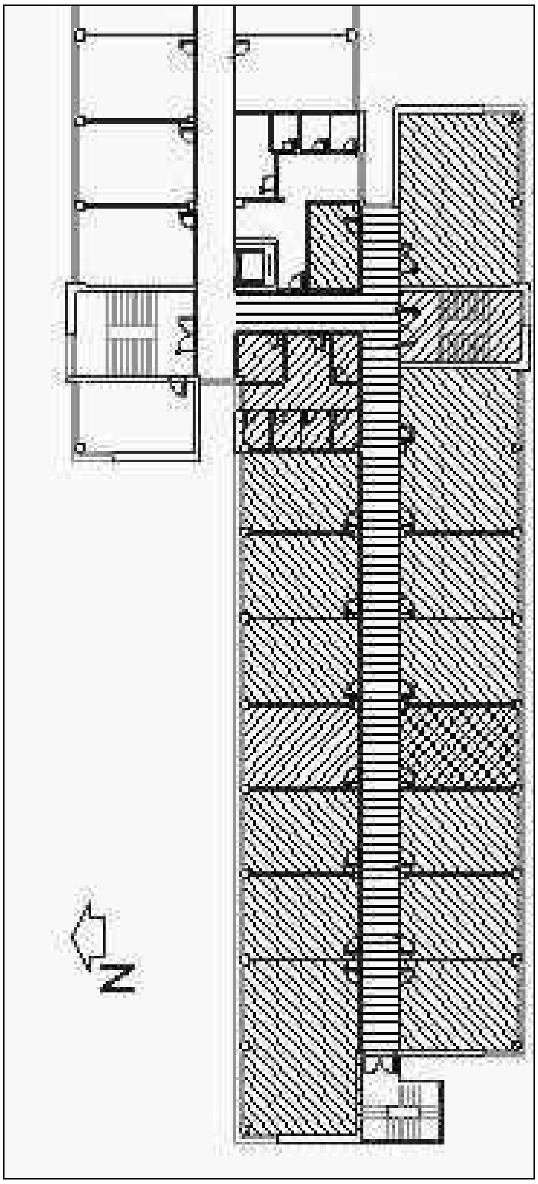

Figure 4. Layout of the building

The results of these simulations can be compared and lead to interesting details, which are summarized in next graphs and tables. In figure 5, 6 and 7 are respectively reported the heating, cooling and lighting comparisons. The loads, calculated using the fixed normal and the effective values for luminous transmittances and solar factors, are summarized in table 3. For samples S4 and S5 are also compared the loads using conventional glazing and effective decay curves (S4c and S5c in the table). The percentage differences are reported in table 4.

Table 3. Heating, cooling and lighting loads calculated with fixed normal, conventional and effective optical properties of glazings.

Samples	Heat. loads [MJ/m^2]		Cool. Loads [MJ/m^2]		Light. Loads [MJ/m^2]	
	FN	E	FN	E	FN	E
S2	83	83	168	181	74	64
S3	25	25	282	321	42	42
S4	158	131	53	79	73	61
S5	80	56	90	180	56	52
S4 c	131	131	53	78	73	64
S5c	55	56	90	165	56	55

Table 4. Relative differences of heating, cooling and lighting loads using fixed normal, conventional and effective angular decay of selected glazings.

Samples	Heating [%]	Cooling [%]	Lighting [%]
S2	0	+7	-14
S3	0	+12	-2
S4	-17	+33	-17
S5	-30	+50	-8
S4c	0	+33	-13
S5c	-1	+45	-3

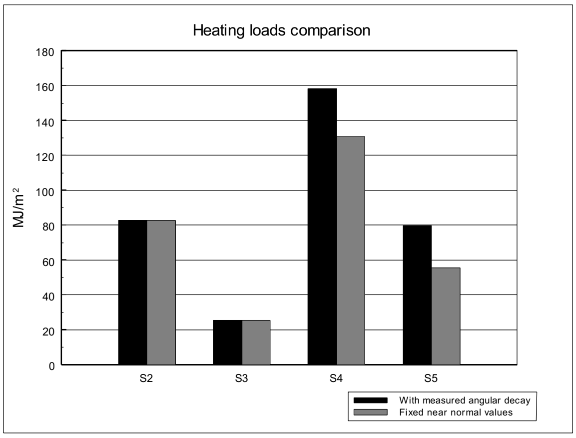

Figure 5. Heating loads comparison

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and lighting comparisons. The loads, calculated using the fixed normal and the effective values for luminous transmittances and solar factors, are summarized in table 3. For samples S4 and S5 are also compared the loads using conventional glazing and effective decay curves (S4c and S5c in the table). The percentage differences are reported in table 4.

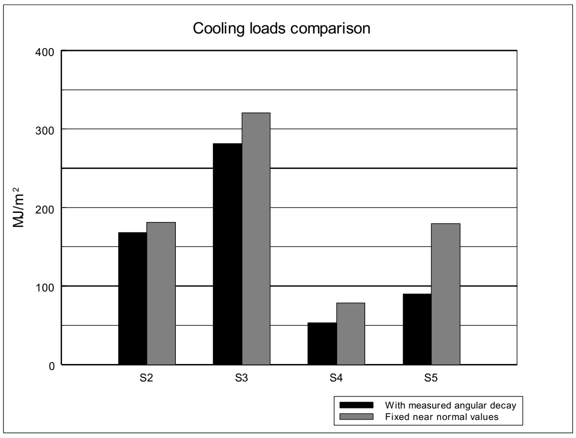

Figure 6. Cooling loads comparison

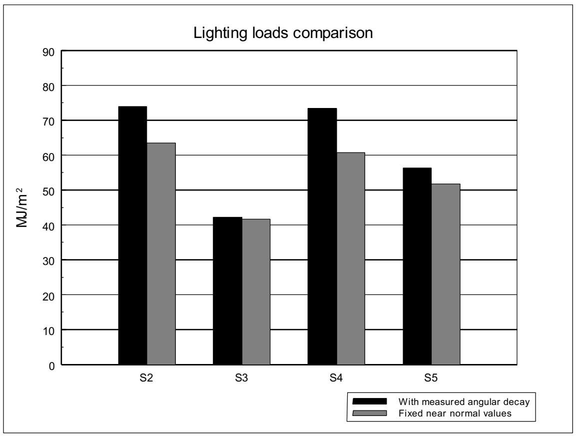

Figure 7. Lighting loads comparison

CONCLUSIONS

The analysis presented in this paper gives some useful information, concerning energy simulation of buildings. Transparent components deeply affect the energy balance of the building, especially for high transparent on opaque envelope surface ratios. If an high level of accuracy is required, and this usually happens for dynamic codes, high accuracy in inputting data is required too. This is not achievable with most of the actual codes when advanced glazing system are used. The most significant points to outline from this analysis are the following:

- The angular decay of solar and luminous parameters of advanced glazings can be very different from the conventional glasses. At high angles of incidence it can easily reach difference of about 50% or more.
- Energy performances of building can be misevaluated, if luminous and solar parameters of glazings are not inputted in a correct way. Summarizing the results reported in detail in table 3, it can be noted that for the selected building: diffusing glazings (S2) with steep decay of τ_v lead to underestimation of electric loads, and small variations of cooling and heating loads. TIM materials (S3) lead to overestimation of cooling loads, because of steep decay of g after angles of incidence higher than 60 degrees. Systems with shading devices (S4 and S5) have consistent underestimation heating and lighting loads, but heavily overestimate cooling loads, if only normal values are inputted. Inputting conventional glass decay curves instead of effective ones, there are not significantly differences for both samples in the winter season. The cooling loads are the same for S4, because of the low transmittance levels of the sample, but there is a consistent reduction for S5. In both cases the artificial lighting loads are still underestimated.
- It exists the necessity of improving codes for energy simulation of buildings, if accurate data must be collected. Adopting advanced and, as a consequence, expensive components and materials are justified only if adequate performance can obtained for the building, hence the prediction coming from such codes must be as accurate as possible.

The analysis carried out in this paper wanted to point out some trouble that simulation program run into when modeling transparent materials. Of course, not all the codes have the same aims and require the same accuracy in evaluating the energy balance of buildings: dynamic programs should use accurate data when using some components, in other cases normal values can be satisfactory for a broad analyses. In any case it is worth to outline the entity of errors and/or approximations which a not- exact inputting of solar and luminous properties of glazings lead to.

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