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Dynamic Solar Energy Transmittance for Water Flow Glazing in Residential Buildings

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Abstract

The U-factor, the solar energy transmittance (g value) and Visible Transmittance (VT) are window properties required to calculate the energy performance of a building. But the relative importance of these properties depends on site and building specific conditions. The ratio between visible transmittance and g value is a fixed value in traditional double glass panes. In cold climates the designer should select the highest g value to reduce heating so that winter solar gains can offset a portion of the heating energy need. A low g value is the most important window property in warm climates. In moderate climates, with significant air conditioning costs or summer overheating problems, windows with lower g values reduce summer cooling and overheating, but they also reduce free winter solar heat gain. Coatings provide double glass panes with static values so that building designers can use available design guidelines and simplified methods to choose the most appropriate type of glass according to the climate zone, the use and occupancy of the building. The aim of this paper is to study the behavior of water flow glazing (WFG) in regards to the g value and the visible transmittance. Circulating water through the chamber absorbs infrared radiation, reduces the temperature of the interior glass pane and provides control over the thermal load striking the surface. Dynamic g values and VT coefficients can be achieved in WFG by means of changing the flow of water and fluid dyes. This paper includes a new methodology to choose the most appropriate water flow glass depending on its range of g value and VT in residential buildings. This methodology will end up in a simplified method to select thermal and optical features of water flow glazing before running a simulation.

Keywords: Dynamic windows, solar energy transmittance, water flow glazing, energy savings.

Nomenclature

c	Mean specific heat capacity of the building, J/kg K.
g	g value of the glass.
gON	g value for water flow glazing at maximum flow rate.
gOFF	g value for water flow glazing without water circulation.
hi	Interior heat transfer coefficient, W/m2K.
I(t)	Impinging radiation on the glazing, W/m2.
$\bar{I}$	Mean impinging radiation on the glazing, W/m2.
m	Mean thermal mass of the building, kg.
q(t)	Internal heat loads, W/m2.
q	Mean internal heat loads, W/m2.
S_G	Total building glazing surface area, m2.
S_B	Total building opaque envelope surface area, m2.
S_F	Total building floor surface area, m2.
U_B	Opaque envelope thermal transmittance, W/m2K.
U_G	Glazing thermal transmittance, W/m2K.
U_W	Water thermal transmittance, W/m2K.
θi(t)	Indoor temperature, K.
θi	Mean indoor temperature, K.
θe(t)	Outdoor temperature, K.
θe	Mean outdoor temperature, K.
θw(t)	Water temperature inside water flow glazings and cooling ceiling, K.
θw	Mean water temperature inside water flow glazings and cooling ceiling, K.
τ	Building characteristic time, h.

INTRODUCTION

The analysis of the thermal behavior of buildings is indeed complex [1], [2]. Building energy demand represents about 41 % of all energy consumed in the European Union [3]. Glazed surfaces play an important role in the energy performance of a building and, therefore, should be chosen carefully. Several types of advanced windows exist in the market nowadays. New technological advances like active glazing have been being developed recently to achieve near zero energy buildings. The glazed area in the facade, the orientation and location of the building and the thermal insulation of the opaque envelope are relevant factors when it comes to optimizing the energy performance of a building.

In order to assess the energy performance and energy efficiency of glazing surfaces, it is necessary to have reliable and handy models. Various computer simulation programs are available [5], where the energy balance of a building is calculated. Despite the accuracy of these programs, they are complex and impractical for the purposes of estimating the optimum properties of a window for a certain building and location during the predesign phase of a building.

Mathematical simple models which provide accurate results by working with few parameters regarding the properties of the windows can be found in specialized literature [6]. One of the most recognized models is the one developed by Karlsson and Roos [7]. In the aforementioned paper energy performance is compared among different windows by calculating a single parameter: the balance temperature.

Most of the scientific articles in this regard are focused in developing models which are then used to compare energy performance of different glazing [8], [9]. The main goal of this paper is to develop a new method in order to understand the relations among the different parameters and variables that influence the problem. The properties a window should have in order to maximize energy savings can be calculated with this model. After obtaining these values, a glazing that matches the optimum properties can be found in the market.

Sun irradiation represents a major concern when it is present [10]. Evaluating how it affects the different regions inside a building is not simple, as many factors have to be taken into account: visual properties of the glazing, internal reflections and different types of radiation [11]. Thermal loads are generated inside the building due to occupancy, equipment and lightning among other factors. Energy gains or losses due to thermal transmittance through the walls and glazing are key in thermal performance of buildings, as well. Finally, thermal inertia of the building envelope is another factor that plays an important role in regards to thermal behavior. Depending on the mass and mean specific heat it will be feasible to maintain the interior air temperature within a comfort range [12]. Advanced glazing materials offer many opportunities for enhancing the optical and thermal performance of windows and the building envelope [13], [14].

Water-Flow Glazing (WFG) combines the transparency and lightness of the glass with the thermal inertia of heavy and opaque solutions. A WFG consists of two glass panes making up a chamber in which a water layer flows in a controlled way. Such windows may be considered as Building-Integrated Solar Thermal (BIST) collectors [15].

Due to its spectral properties, the water captures most of the solar infrared radiation, letting the visible component enter the building. This makes the glazing as luminous as a conventional one, though at the same time reduces the heat flow towards the inside of the building. Moreover, the circulation of the water allows buildings that are equipped with active glazing to apply energy saving strategies which would not be possible with conventional glazing [16]. Sun energy can be harvested with this mechanism as water absorbs most of the Near Infrared Radiation (NIR). The coefficient used to measure the solar energy transmittance of glass is known as the g value. It represents the amount of solar energy passing through the glass. By changing the flow rate of the WFG, the g value also changes. When the flow of water is maximum, g value is the minimum gON. On the other hand, when water is stagnated g value is the maximum gOFF. This new ability to change the g value of glazing is an advance that can help optimize the thermal behavior of buildings both over winter and summer [17].

In winter time it is usually necessary to absorb the highest quantity possible of radiation to heat up the building. Lowering the g value is the optimum solution. Nevertheless having a lot of glazing area can increase the energy losses through the glazing. On the other hand, over summer season the g value should be reduced as much as possible as radiation is important and temperatures are usually higher. The optimum solution in summer is to block radiation. Due to these two opposed situations it is difficult to select a glazing with optimum properties for both seasons. Water flow glazing is a feasible solution to avoid this problem because the g value can be controlled by changing the flow of water.

Radiant cooling systems offer lower energy consumption than conventional cooling systems. Cooling ceilings are composed of panels suspended from the ceiling, but can also be directly integrated with continuous dropped ceilings. Water flow glazing panels are also better suited to ceilings in buildings with high internal cooling loads.

The aim of this paper is to present a practical method for assessing the thermal performance and behavior of a building and understand the relation among the different parameters and variables that influence the problem. This method will allow the architect to determine the design parameters which optimize the energy efficiency of the whole building over the design period.

On section 2, the assumptions made to state the building thermal model are explained and a general equation is presented. On section 3, the general equation is applied to residential buildings by stating further assumptions. The same study but for summer and winter season is presented on section 4. On section 5 the results of the simplified method are discussed.

SOLAR HEAT GAINS IN SCIENTIFIC PAPERS.

The solar gain also known as solar heat gain or passive solar gain refers to the increase in temperature in a building as a result of solar radiation. The solar gain depends on the angle of incidence in a certain moment as well as on the ability of the glazing to transmit or shield radiation.

Objects struck by sunlight absorb the short-wave length radiation from the light and reradiate the heat in form of long-wave radiation. Some materials like usual glazing have the ability to let short-wave radiation pass through themselves. This radiation is absorbed by the floor and walls that become warmer and re-emit the energy as longer- wave radiation.

To measure the ability of a glazing or shading surface to let short-wave radiation pass, several coefficients are used. In Europe the most common one is the g-value. It goes from 0 to 1: 0 indicates 0% of radiation passing through the glazing and 1 indicates 100% of radiation passing through a glazing. It is important to bear in mind that some authors do include, as stated in several papers, the angle of incidence of the radiation while some others do not, considering that the g-value is a property of the glazing. In our models we are not taking into account the angle of incidence in the g-value because we have already included this effect in the radiation empirical data.

In the United States the most common coefficient to measure the solar energy transmittance of glass panes is the Solar Heat Gain Coefficient (SHGC). The difference between both is that, apparently, the g-value usually refers to a glass pane and the SHGC refers to a whole window including frame material and screens.

Many programs available today for assessing the energy performance of windows are complicated and require a lot of configuration parameters that are not useful during the pre-design phase of a building. On the other hand, there are authors that present a simple model to assess the energy performance and cost efficiency of windows [7]. This model works with a single parameter, the balance temperature. This parameter shows whether the solar radiation and the heat losses are useful or not for maintaining the inside temperature within a comfort temperature range. This model allows designers to decide the glazing parameters in order to reduce the power consumption and the dependency on HVACs. The model also considers the solar radiation, orientation of the windows, thermal leakage and thermal mass of the building.

ASSUMPTIONS TO STATE THE BUILDING THERMAL BEHAVIOR MODEL

Several assumptions are made in order to obtain a thermal behavior equation for a general building even with water flow glazing in façades and cooling ceilings.

For instance, the interior air temperature inside the building is considered uniform, al- though time dependent. This assumption is made in order to present a zero dimensional model. The goal is to understand the thermal behavior of the building and not to obtain the accurate temperature field of certain room. It is reliable to find a uniform interior temperature if the air inside is circulating. This usually happens when people is working or moving inside a building or ventilation systems are installed.

The temperature inside the water flow glazing and the cooling ceiling is considered uniform once again. If the flow rate is high enough, the temperature increase of water in its course through the glazing is not significant. In case there is no flow rate, water is expected to match the exterior temperature and thus, be uniform as well. Nevertheless the water is provided by the system at a certain temperature which can vary with time.

Regarding the impinging radiation in the glazing surfaces, many authors consider several kinds (direct, diffuse, ground-reflected, etc.) which present different properties [18]. In this model an overall impinging radiation *I(t)* is considered for each of the oriented glazed surfaces comprising the effects of all forms of radiations. A percentage of this radiation is transmitted which is deter- mined by the g value of the glazing. All the radiation entering the building is considered absorbed and the amount of it escaping is neglected.

The opaque envelope blocks all incoming radiation. The heat generated due to solar energy absorptance in the walls is not considered, as most of it will be transferred to the exterior environment. The effects on the interior are considered negligible. Due to air circulation, this phenomena is not supposed to affect the uniform exterior temperature.

The thermal heat flux through the building envelope is estimated following the Newton's rule, proportional to the differences in temperature times the thermal transmittance of the envelope and the exposed surface area.

All the building thermal mass is represented by a single parameter, m, to preserve the zero dimensional nature of the model. In the same way the mean specific capacity of the building is represented by c. The product of these two values determines the thermal inertia of the building. The bigger the values, the slower the change rate will be.

At last, the heat generated inside the building due to people, machinery, lighting, equipment and every other kind of thermal power generator is represented by the variable *q(t)*. This variable is related to the building floor surface area as it represents the quantity of power generated per square meter of building floor.

In conclusion this model comprises weather conditions, opaque walls, regular glazing, water flow glazing, cooling ceilings and internal loads which are the main elements influencing the thermal behavior of the building. Taking into account all the aforementioned assumptions is possible to state the dependency of the different design parameters and variables with the following differential equation:

$$mc\frac{d\theta i}{dt} = SBUB(\theta e - \theta i) + SF[q + hi(\theta w - \theta i)] + SG[UG(\theta e - \theta i) + Uw(\theta w - \theta i) + gI] \quad (1)$$

Four different terms (Internal Energy, Opaque Envelope, Cooling Ceiling + Internal heat gains and Water flow glazing) are present in the equation regarding all the aforementioned effects which play an important role on the thermal behavior of the building.

Reorganizing the equation is possible to express the inside temperature and its derivative as a function of the independent variables, multiplied by certain non-time-dependent coefficients. Finally, it is convenient to turn this ordinary differential equation into an algebraic equation to simplify the expression and understand better the relations between the different parameters and variables. This can be done by integrating each one of the terms in the equation for a given period of time, τ , the characteristic time. The design parameters are constant in time and the variables are turned into mean values when the integration is performed. The integral of $d\theta i$ is the only term that is canceled under the assumption that the variations of θi with time is periodical. The following expression for the equation is obtained:

$$\theta i = \frac{SBUB+SGUG}{SU}\ \theta e + \frac{gSG}{SU} I + \frac{SFhi+SGUW}{SU} \theta w + \frac{SF}{SU} q \qquad (2)$$

where $SU = S_B U_B + S_G U_G + S_F h_i + S_G U_W$

In the following sections, equation (2) is simplified to take into account different scenarios of residential buildings and seasons.

CASE STUDIES.

Residential buildings in winter season.

Residential buildings have the particularity that internal loads are negligible as they represent a very low power input to the system ($q = 0$). In consequence, cooling ceilings are not a necessary nor convenient solution for these type of buildings ($S_F h_i = 0$). The terms related to internal heat loads and cooling ceiling presented in equation (2), are not taken into account this time.

Considering that during winter is recommended to maximize the value of g in order to increase the solar heat gains, the water flow system is turned off and thus g achieves its maximum possible value, *gOFF*.

Taking into account that water temperature is expected to match the exterior temperature because it is not flowing ($\theta e = \theta_W$), the last term in equation (2) can be ignored as well as the thermal transmittance through water ($U_W = 0$). These assumptions lead to the following equation:

$$\theta i = \theta e + \left[\frac{SG}{SBUB+SGUG}\right] I\, gOFF \quad (3)$$

Essentially, the interior temperature will tend to match the exterior temperature or be higher depending on the radiation term. By increasing the g value to its maximum *gOFF* a raise in temperature is fostered. This is useful in winter season. A factor comprising the surface areas of glazing and opaque envelope as well as the thermal transmittance values affect the interior temperature. Choosing wisely these design parameters will make it easier to maintain the interior temperature within a comfort range without the use of HVAC systems. Reorganizing equation (3) and defining the parameter α as $UG(\theta i - \theta e)/I$ expression (4) is obtained.

$$\frac{\alpha}{gOFF-\alpha} = \frac{SGUG}{SBUB} \quad (4)$$

The parameter α is determined when the interior temperature is set with a value corresponding to a desired comfort temperature, weather conditions (exterior temperature and radiation) are known for a certain building and a value for the thermal transmittance of the glazing has been chosen. Given also a value for *gOFF* and the thermal transmittance of the opaque envelope, a relationship between the glazing surface area and the opaque envelope surface area is determined.

Equation (4) can help architects decide how much glazing area a building should have to optimize its thermal behavior in winter season.

When $\alpha > gOFF$ ($\theta i > \theta e$) or $\alpha < 0$ ($\theta i < \theta e$) there is not possible configuration to maintain the desired interior temperature in the building, as S_G/S_B should be negative. The first situation happens usually in winter season when the impinging radiation is very low or there is not sun at all, the differences in temperature are high and the thermal transmittance of the glazing is also high.

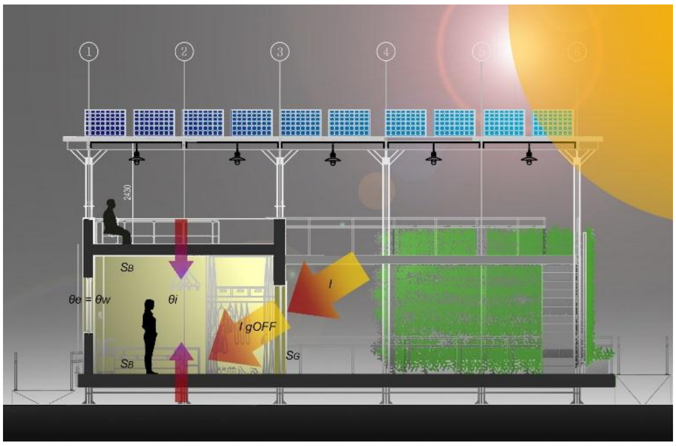

Figure 1. Residential building in winter session.

When α = 0, no glazing surface is convenient at all, more heat is going to be lost through the window than gained from radiation. As the value of α increase from zero towards the value of *gOFF* , the more glazing area the building should have. When the value of α is near to *gOFF* no opaque envelope surface area is convenient at all. In conclusion, for values of α close to zero, most of the envelope should be wall. On the other hand, for values of alpha close to *gOFF* most of the envelope should be glazing.

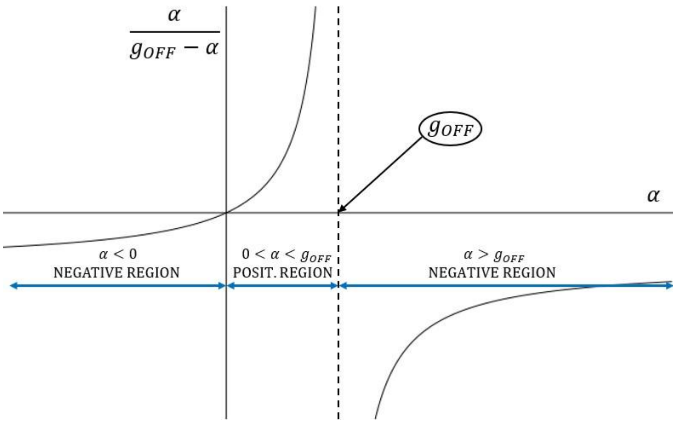

Figure 2. Relation between $gOFF$ and α.

Residential buildings in summer season.

Making the same assumptions used for residential buildings in winter ($q = 0$, $S_F = 0$) the terms related to internal heat loads and cooling ceiling presented in equation (2), are also dismissed.

Considering that during summer it is recommended to minimize the value of g in order to restrict the solar heat gains, the water flow system is turned on to the maximum flow rate and thus the g value achieves its maximum possible value, *gON* . If the flow rate is high enough, it is possible to consider that all the heat transferred from the interior of the building floor to the exterior is captured by the water flow. In the equation this is considered by neglecting the heat transferred through the glass ($U_G = 0$) and considering ($U_W = Ui = hi$).

The outside temperature is close to the interior comfort temperature over the summer time so the heat loss through the walls is negligible ($U_B = 0$). Equation (2) turns into equation (5).

$$\theta i = \theta e + \frac{1}{hi}\,[I\ gON] \qquad (5)$$

The capability of the system to maintain a comfort temperature can be assessed with this simple expression.

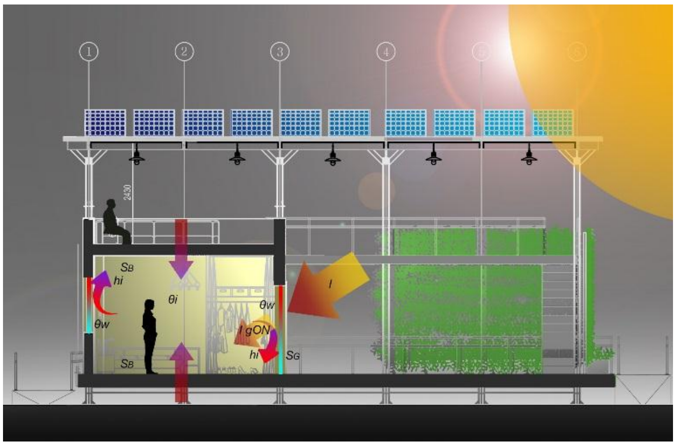

Figure 3. Residential building in summer session.

When the exterior radiation is very high, the transmittance coefficient hi is low or the differences in temperature between the interior and the water are low it is not possible to maintain the comfort temperature inside the building. To solve this situation cooler water can be provided to the system in order to approach the value of the right-hand side of equation to *gON*. Another possibility is to diminish the value of *gON* by adding dyes to the water or layers to the glazing.

DISCUSSION OF RESULTS.

In order to understand the influence of the parameters some test cases are run. Firstly, equation (3) is used in table 1. The following values are fixed in winter conditions: mean outdoor temperature θe = 0C; mean impinging radiation on the glazing in winter, I = 400W/m2; thermal transmittance of opaque envelope, U_B = 0.5W/m2; thermal transmittance of glazing, U_G = 2W/m^2; area of opaque envelope S_B = 600m^2; area of glazing S_G = 25m^2.

Table 1. Indoor temperature in residential buildings in winter conditions.

Residential building in winter							
θe (C)	U_B(W/m^{2}K)	U_G(W/m^{2}K)	S_B (m^2)	S_G (m^2)	g	I (W/m^2)	θi (C)
0	0.5	2	600	25	0.2	400	5.71
0	0.5	2	600	25	0.8	400	22.86

The results in table 1 show that indoor comfort conditions are possible by setting the g value at 0.8, due to the solar radiation.

The equation (5) is used in tables 2 and 3. The following values are fixed in summer conditions in table 2: mean water temperature θw = 19C; mean impinging radiation on the glazing in summer, I = 800W/m2; convection-radiation coefficient, hi = 8 W/m^2 K; area of floor and roof S_F = 150m^2; area of glazing S_G = 25m^2.

Table 2. Indoor temperature in residential buildings in summer conditions.

θw (C)	h_i(W/m^{2}K)	S_F (m^2)	S_G (m^2)	g	I (W/m^2)	θi (C)
19	8	150	25	0.2	800	21.86
19	8	150	25	0.8	800	30.43

The results in table 2 show that indoor comfort conditions are possible by setting the g value at 0.2 if the impinging solar radiation is I = 800W/m2.

Table 3 shows the results of adapting the g value as the solar radiation is changing. The same values are used for all the parameters except for the mean impinging solar radiation.

Table 3. Indoor temperature in residential buildings with variable solar radiation.

θw (C)	h_i(W/m^{2}K)	S_F (m^2)	S_G (m^2)	g	I (W/m^2)	θi (C)
19	8	150	25	0.2	800	21.86
19	8	150	25	0.3	700	22.75
19	8	150	25	0.4	600	23.29
19	8	150	25	0.5	500	23.46

By changing the flow of water through the WFG the g value varies from 0.2 to 0.5 and the Indoor temperature is kept within a comfort range

CONCLUSIONS

Buildings are amongst the major energy consumers in the modern world. In the European Union, buildings consume as high as 40%. Glazed surfaces play an important role in the energy performance. The innovative design of water-flow glazed window can help utilize a large amount of solar energy without affecting the aesthetic outlook of the building. The solar energy can be stored in the form of hot water and serves the building occupants. On the other hand, the space cooling load and AC system energy consumption can be effectively reduced.

A simple model for choosing the right g value of the optimal glass has been developed and analyzed. The model takes into account the solar radiation, thermal properties of opaque envelop, thermal and optical properties of the glazing, internal loads and thermal mass.

For residential buildings there are different strategies in summer and winter. Variable g value gives a building its dynamic properties making it possible to keep comfort conditions and store or reject solar energy.

The thermal comfort is improved and it may also lead to lower power needs and thus simplify heating and cooling systems.

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