Energy performance assessment of advanced glazed façades in office buildings

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Abstract

The adoption of glazed façades in commercial building is becoming more and more widespread. The main limits of conventional transparent façades related to energy efficiency and IEQ aspects have been overcome developing a new generation of transparent building envelope components called Advanced Integrated Façades

This paper evaluates if the thermal behaviour of this kind of technologies can be correctly assessed by means of conventional performance parameters. Data from experimental campaigns on a reflective double glazed unit and on a Climate Façade under actual operating conditions have been used to estimate the correspondent equivalent U-value *and* g-value. *Subsequently, these parameters have been employed to calculate the energy balance of the same glazed façades. The validation of the parameters is then carried out through the comparison between experimental and simulated specific total hourly heat flux and specific total daily energy.*

The result shows that it is still acceptable to use conventional performance parameters for "simple" glazing technology (e.g. reflective double glazing unit). On the contrary, the adoption of such parameters in case of more advanced façade technologies leads to considerable inaccuracies and makes the predictions based on these metrics not reliable.

Keywords – advanced glazing systems; syntetyc performance parameters; experimental activity; simulation

1. Introduction and aim

Glazing façades play an important role in buildings with huge implications on the quality of the indoor environment and on architectural aspects. Highly glazed façades are widely adopted in commercial buildings, although the transparent component is often the weakest element of the building envelope, as far as energy efficiency is concerned. R&D in this field is leading to Advanced Integrated Façades (AIFs), which are technologies deeply connected to the building equipment and characterized by an active and dynamic functioning [1]. This dynamic feature is used to adapt the behaviour of the façade to different boundary conditions, and thus to achieve a better energy performance.

The development of these technologies poses the question whether their thermal properties and energy performance can or cannot be characterized by conventional parameters (i.e. *U-value* and *g-value*), and what accuracy can be achieved. The aim of the research activity is thus to assess the reliability of such parameters in the case of an AIF (i.e. a Climate Façade).

2. The glazing technologies

In order to find an answer to the research question, synthetic metrics are thus assessed for a conventional glazing technology and for an Advanced Integrated Façade, starting from two experimental data sets. Firstly the data analysis procedure was applied on a conventional technology in order to verify whether or not its energy performance could be efficiently described by the above-mentioned metrics, considering the present-day spread of this approach [2]; secondly the same procedure was performed on data monitored on a Climate Façade of an office building under actual operating conditions.

In particular, the tested conventional reference technology (REF) was a double glazed system (8/15/6 mm) made with an external reflective pane and an internal clear glass and installed and tested on an outdoor test cell facility, located in Torino, Italy (temperate sub-continental climate), and the Climate Façade (AIF) was a mechanically ventilated Double Skin Façade, located in a temperate sub-continental climate (Veneto, Italy). The façade was composed by an external extra-clear single glazing, a mechanical ventilated cavity (approx. 700 mm) with a high reflective roller screen, and a low-e internal double glazing (4/12/4 mm) [3].

3. Methods

3.1 Experimental data collection

The procedures used to collect the data during the two experimental campaigns are not here reported for the sake of brevity, but detailed information can be found in [4,5]. Surface and air temperatures were measured by means of T-type and/or J-type thermocouples (measurement accuracy ±0.3°C); heat fluxes were measured by means of heat flux meters (measurement accuracy ±5%); both thermocouples and heat flux meters were shielded with aluminum foils against the influence of the solar irradiation. Incident (on the vertical plan) and transmitted solar irradiance was measured by means of integral pyranometers (measurement accuracy ±2%).

All the physical quantities were recorded with sub-hourly rate, but energy and thermo-physical analyses were later carried out on hourly values, obtained as average of the sub-hourly readings.

3.2 Data processing and performance parameter

Two performance parameters were assessed for each technology starting from the available experimental data: the U^**-value* and the g^**-value*. The use of the superscript "*" reveals that the evaluated parameters are not, due to different reasons, equal to those that would be obtained by a calculation according to the standard ISO 10292:1994 [6] and ISO 9050:2003 [7], respectively. Both the parameters were obtained by linear regression carried out with the well-known Ordinary Least Squares method, imposing that the constant term is zero.

The experimental data available for each glazing technology (AIF and REF) were split into two different data sets, containing the same amount of days and with the same representativeness of the original data – i.e. approximately the same amount of days for each season, and days with different boundary conditions each season. One data set was used to assess the performance parameter, while the other data set was later used to estimate the ability of the U^* and g^* parameters of replicating the thermo-physical behaviour of conventional and advanced glazing technologies.

In particular, the U^**-value* [W/m^{2}K] (Eq. 1) was assessed by making use of night-time readings only, when no solar radiation acts on the glazing, according to the definition of *U-value* given by the international standard.

The g^**-value* [-] (Eq. 2) was assessed by making use of day-time readings only, when the transmitted solar irradiance I_{ind} was greater than 10 W/m^2 and dq_g , as defined in Eq. 3, was greater than 0 W/m^2. It holds:

$$U^* = \left[\sum_i^n \left(\Delta T_i \cdot dq_i \right) \right] \cdot \left[\sum_i^n \Delta T_i^2 \right]^{-1} \tag{1}$$

$$g^* = \left[\sum_i^n \left(I_{out,i} \cdot dq_{g,i} \right) \right] \cdot \left[\sum_i^n I_{out,i}{}^2 \right]^{-1} \tag{2}$$

$$dq_g = \left[\left(dq + I_{ind} \right) - \left(\Delta T \cdot U^* \right) \right] \tag{3}$$

where $\Delta T = T_{out} - T_{ind}$ [°C] is the thermal gradient between the outdoor and the indoor air, and dq [W/m^2] is the specific heat flux exchanged at the indoor surface of the glazing system (i.e. the sum of the convective and radiative heat flux in the long-wave region), I_{out} [W/m^2] is the specific solar irradiance impinging on the façade. The fit between the data set and the regression line, both in the case of U^* and of g^*, is assessed by means of the coefficient of determination R^2 [-], whose analytical formulations are not herewith given for the sake of brevity, but can be easily found in literature.

3.3 Model validation

Once the performance parameters were assessed, the capability of the two performance parameters of replicating the thermo-physical behaviour of the glazing systems was assessed by comparing the experimental data with data obtained by means of the above mentioned performance parameters.

The validation was carried out comparing the specific total hourly heat flux entering the indoor environment ($dq_{tot,sim}$, $dq_{tot,\exp}$, [W/m^2]) and the specific total daily energy entering the indoor environment ($q_{tot,sim}$, $q_{tot,\exp}$, [Wh/m^2]), which were assessed according to the following Equations 4-7:

$$dq_{tot,\exp} = I_{ind} + dq \quad (4)$$

$$dq_{tot,sim} = I_{out} \cdot g^* + \Delta T \cdot U^* \quad (5)$$

$$q_{tot,\exp} = \int_{6am}^{+1day} \left(I_{ind} + dq \right) d\tau \quad (6)$$

$$q_{tot,sim} = \left(g^* \cdot \int_{6am}^{+1day} I_{out} d\tau \right) + \left(U^* \cdot \int_{6am}^{+1day} \Delta T d\tau \right) \quad (7)$$

where the subscript $_{exp}$ is related to the experimental hourly heat flux and daily energy, and the subscript $_{sim}$ is related to the simulated physical quantities, calculated by making use of U^* and g^*.

The capability of the simulated data of replicating the experimental physical quantities, i.e. the capability of U^* and g^* of replicating the phenomena and their representativeness of the thermo-physical behaviour of glazing systems, was assessed by means of the Root Square Mean Error, *RSME* ([W/m^2] or [Wh/m^2]), and of the absolute percentage error $|\varepsilon_{\%}|$ [%], defined according to Eq. 8 and 9, respectively, where *s* refers to the simulated datum and *e* refers to the experimental datum:

$$RSME = \sigma = \sqrt{n^{-1} \cdot \sum_{i}^{n} \left(\mathrm{s}_i - \mathrm{e}_i \right)^2} \quad (8)$$

$$\left| \varepsilon_{\%} \right|_i = 100 \cdot \left| \mathrm{s}_i - \mathrm{e}_i \right| \cdot \left(\mathrm{e}_i \right)^{-1} \quad (9)$$

4. Results

4.1 Reference technology – REF: reflective double glazing unit

The U^**-value* has been assessed during the whole year considering the heat fluxes *dq* measured during the night-time (22pm – 06am), in order not to include into this value the effect of the solar irradiance. Due to the accuracy of the heat flux meter sensors and of the thermocouples, heat fluxes in the range ±5 W/m^2 have not been considered because not fully reliable, as well as thermal gradient in the range ±1 °C. The linear regression, that leads to a U^* equal to 2.12 W/m^{2}K for the (reference) reflective double glazing unit, is shown in Figure 1a, where a satisfactory coefficient of determination is reached ($R^2 > 0.9$).

Considering the meaning and the definition of the U^*, an evaluation of such a parameter in different seasons has not been performed, assuming that it does not change significantly according to different boundary conditions – i.e. the internal and external surface heat transfer coefficients are, in average, constant along the year.

On the contrary, the assessment of the g^* value has been performed for each season. This is due to the fact that the optical properties of the glazing depend, to a great extent, on the angle of incidence of the solar beam, as well as on the different thermal gradient between the glazing and the indoor, and the glazing and the outdoor environment. In Figure 1b the linear correlations between dq_g and I_{out} are shown, for the three seasons – namely: winter, mid-season and summer. The term dq_g were assessed only when $I_{ind} > 10$ W/m^2, because readings lower than this value could be inaccurate, and only $dq_g > 0$ were used in the linear regression.

The correlations led to the determination of three different g^*: 0.36, 0.32 and 0.18 for winter, mid-season and summer, respectively. For two of them, the coefficient of determination is very satisfactory, while for the summer it is slightly lower than 0.9 due to the fact that less data were available for the summer period.

Once the U^* and the g^* parameters have been assessed, the specific total hourly heat flux $dq_{tot,sim}$ has been calculated and compared against the experimental one (Figure 2a). It is possible to see that almost the totality of the data are in the range of ± 22 W/m^2 (i.e. twice the RSME), supporting the hypothesis of normal distribution of the residuals. It is worth mentioning that the dq_{tot} in the case of the reflective glazing unit spans from about -50 W/m^2 to about +300 W/m^2, and that the RSME is therefore one order of magnitude less than the physical quantities it refers to.

Similar observations can be made as far as the daily total energy q_{tot} is concerned. The capability of the U^* and g^* parameters of replicating the energy performance of the reflective glazing unit is shown in Figure 2b, where $q_{tot,sim}$ is compared with $q_{tot,\exp}$. A satisfactory agreement between simulated and experimental data can be seen, and a RSME of 101 Wh/m^2 has been found. The identified and evaluated parameters are therefore able to replicate to a great extent both the specific total heat flux dq_{tot} and the specific daily energy q_{tot}.

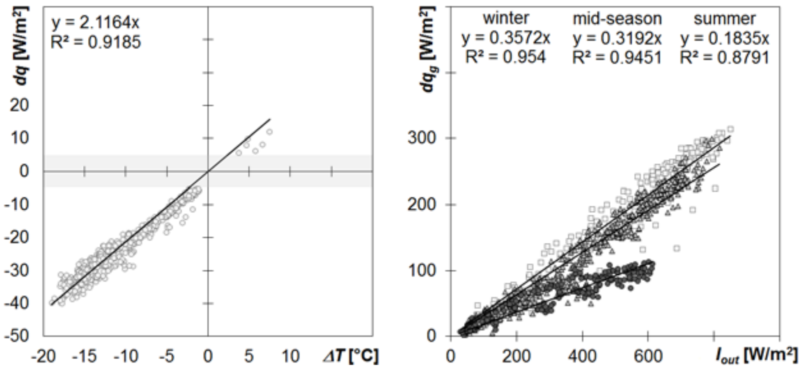

Fig. 1 REF. *a (left)*: Linear correlation and determination of the U^**-value*; *b (right)*: Linear correlations and determination of the g^**-value*.

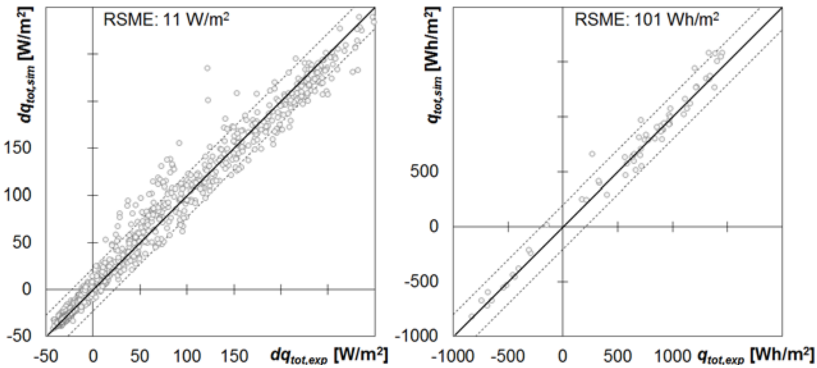

Fig. 2 REF. *a (left)*: comparison between simulated and experimental specific hourly heat flux; *b (right)*: comparison between simulated and experimental specific daily energy.

4.2 Advanced technology – AIF: Climate façade

The assessment of the U^* for the Climate Façade presents greater difficulties compared to the reference case. This is due to the fact that, during the night-time, when the U^* is evaluated, the ventilation flow in the façade's cavity is not active, since the façade works as exhaust of the ventilation system – which is not running outside working hours. Furthermore, due to the higher thermal inertia of the façade (made of several, thicker glass layers), the influence of the weather/operative conditions during the day-time on the thermo-physical behaviour in the night-time is not negligible. Therefore, the following hypotheses and limitations were adopted in order to assess the U^*: only *dq* during the late night (3am – 6am) were used; a different U^* for each season has been assessed. Furthermore, *dq* in the range ±5 W/m^2 were not considered and thermal gradient in the range ±1 °C were not considered either. This procedure leads to the assessment of U^* equal to 0.73, 0.69 and 0.61 W/m^{2}K, for winter, mid-season and summer respectively (Figure 3a). The coefficient of determination is very satisfactory for the winter and mid-season, while a worse value is found in the summer (R^2 ~ 0.84). This is probably due to the thermal inertia of the system.

Starting from the evaluated U^*, seasonal g^* are then assessed. The limitations in the selections of the dq_g were the same adopted and described in the reference case. However, it is important to highlight that, even if the linear regression leads to the identifications of three (very similar) g^*, the coefficients of determination were not satisfactory in all the cases. This fact can be explained considering that:

- the U^*-values determined during the night-time are quite different from those that occur during the day-time (but the latter cannot be evaluated due to the presence of the solar irradiance);
- the Climate Façade presents a strong dynamic behaviour, due to the ventilation air flow, that can hardly be caught by making use parameters that have been introduced considering steady state conditions.

As far as the values of g^* are concerned (0.08 for the winter and mid-season, 0.07 for the summer, Figure 3b), which are very similar in the different season, this is mostly due to the presence of the solar shading in the cavity, which greatly decreases the direct solar transmission, and reduces to a great extent the influence of the solar position and of the solar beam angle on the transmitted irradiance I_{ind}.

In Figure 4a, the comparison between simulated and experimental specific hourly heat flux is shown, for the whole year. Although the RMSE is one order of magnitude less than the physical quantities it refers to (5 W/m^2 against $-40 < dq_{tot} < 80$ W/m^2), it can be notice that a relevant number of data is outside the $\pm 2\sigma$ interval, showing a great dispersion of the residuals, and thus a great disagreement between the simulated and experimental data.

The analysis of specific daily energy q_{tot} (Figure 4b) apparently shows a better agreement between the simulated and experimental data: much less data are outside the range $\pm 2\sigma$. However, it is mandatory to state that, in this case, the RSME is almost in the same order of magnitude of q_{tot}, being RSME = 80 Wh/m^2 and the daily energy that crosses the façade in the range -300 ÷ +300 Wh/m^2. The best agreement between simulated and experimental data is achieved in the case of negative q_{tot}, i.e. when the heat loss during the day exceeds the solar gain, and thus the U^* parameter is dominant in the heat balance equation. Furthermore, it can be notice that the agreement worsens considerably when $q_{tot} >> 0$, i.e. when the solar gain becomes the dominant part of the total heat flow that crosses the façade, and the g^* plays the crucial role in the heat balance equation.

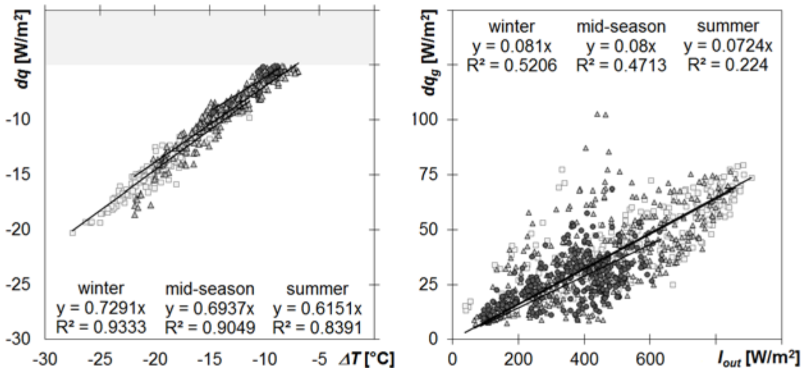

Fig. 3 AIF. *a (left)*: Linear correlation and determination of the U^**-value*; *b (right)*: Linear correlations and determination of the g^**-value*.

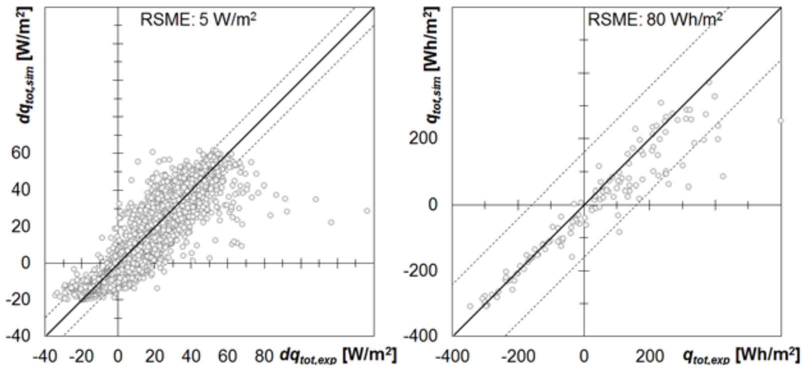

Fig. 4 AIF. *a (left)*: comparison between simulated and experimental specific hourly heat flux; *b (right)*: comparison between simulated and experimental specific daily energy.

5. Discussion

The assessment of U^* and g^* starting from experimental data is considerable easier and definitely more accurate in the case of the reference technology than in the case of an advanced dynamic façade (in this case, a Climate Façade). This fact is directly dependent on the definition of the above mentioned parameters, that are evaluated under the assumption of steady state conditions and mono-directional heat flow (for the U^*), and beam angle normal to the glazing surface combined with no thermal gradient between outdoor and indoor (for the g^*).

Nevertheless it is important to stress that, even in the case of a quite conventional glazing technology, such as the reflective glazing unit, some assumptions need to be made to obtain these parameters from experimental data. The most relevant finding, as far as the reflective glazing unit is concerned, is that the use of a unique value of g^* all along the year leads to substantial inaccuracy. A seasonal value of g^* is indeed needed in order to limit this inaccuracy and to get quite reliable results.

In Figure 5a, the relative cumulate frequency of the absolute percentage error $|\varepsilon_{\%}|$, both for dq_{tot} and q_{tot}, is plotted, for the reference technology. It gives that for about 50% of the time, the use of U* and g* leads to very accurate prediction ($|\varepsilon_{\%}| < \pm 5\%$) of the specific daily energy that crosses the façade, q_{tot}; for about 90% of the time, the absolute percentage error on q_{tot} is within the range ±25%. As far as the total specific heat flow dq_{tot} is concerned, the accuracy of the simplified model that makes use of U^* and g^* is slightly lower, but still acceptable – e.g. the absolute percentage error is within the range ±25% for almost 80% of the time.

On the contrary, the use of U^* and g^* for assessing the energy performance of the Climate Façade is far less accurate. On the first hand, the evaluation of these parameters is particularly complicated and not fully reliable. The use of these parameters in a simplified heat balance equation (such as Eq. 5) leads to quite relevant inaccuracies. For instance, the absolute percentage error (both on q_{tot} and dq_{tot}) is in the range ±5% for just about 20% of the time – mostly during the late night and early morning. Moreover, for more than half of the time, the simulated datum over-or under-estimates the experimental data by more than 25%. Finally, for more than 30% of the time the absolute percentage error, on both on q_{tot} and dq_{tot}, is higher than ±60%.

The use of these synthetic performance parameters for an advanced façade technology, such as a double glass façade, does not allow an accurate prediction to be performed and may lead substantial over/under-estimation of the energies that cross the façade on a daily basis.

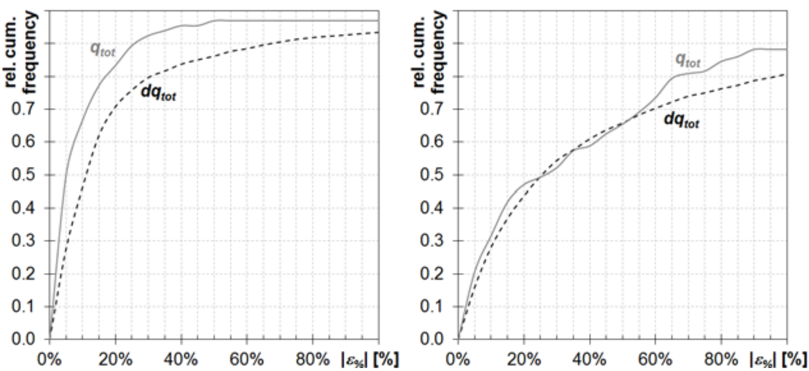

Fig. 5 Relative cumulated frequency of the percentage errore of the specific hourly total heat flux and of the specific daily total energy. *a (left)*: REF – Reflective double glazed unit ; *b (right)*: AIF – Climate Façade.

6. Conclusion

Synthetic metrics (such as *U-value* and *g-value*) are still widely adopted in present-day design of energy performance of building. Starting from data collected during two experimental campaigns on a conventional (reflective) glazing unit and on an advanced building envelope technology, i.e. a Climate Façade, synthetic metrics have been evaluated for the two technologies. Secondly, they have been used to assess the specific total hourly heat flux and the specific daily total energy by making use of the simplified heat balance equation. Finally, the simulated physical quantities have been compared with the experimental ones, and the reliability of the synthetic metrics/simplified modelling assessed.

The results show that, although the use of synthetic metrics and simplified modelling may results in some errors even in case of conventional glazing systems, it is still acceptable to use these parameters if the glazing technology is a “simple” one. On the contrary, the adoption of such parameters in case of more advanced façade technologies, coupled with a simplified heat balance equation that does not include the transient effect, leads to considerable inaccuracies in the estimation of the heat flux and energy that cross the glazing surface. Notably, simulated physical quantities under- or over-estimate experimental data by more than 25% for more than half of the time.

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References

[1] Annex 44—IEA—ECBCS Report, EXPERT GUIDE—PART 2: RBE, editors: Øyvind Aschehoug, Marco Perino, 2010, http://annex44.civil.aau.dk/.

[2] H. Manz, U.P. Menti. Energy performance of glazings in European climates. Renewable Energy, 37 (2012) 226–232.

[3] F. Zanghirella, M. Perino, V. Serra. A numerical model to evaluate the thermal behaviour of active transparent façades. Energy and Buildings 43 (2011) 1123–1138.

[4] F. Zanghirella, V. Serra, M. Perino, C. Sossai. Active transparent façade integrated with a well water cooling system: an experimental analysis. In: Proceedings of the 10th REHVA World Congress, 1–8, Antalya, Turkey, 9-12 May 2010.

[5] V. Serra, F. Zanghirella, M. Perino. Experimental evaluation of a climate façade: Energy efficiency and thermal comfort performance. Energy and Buildings 42 (2010) 50–62.

[6] ISO 10292:1994 – Glass in building – Calculation of steady-state U values (thermal transmittance) of multiple glazing.

[7] ISO 9050:2003 – Glass in building – Determination of light transmittance, solar direct transmittance, total solar energy transmittance, ultraviolet transmittance and related glazing factors.