Cooling Energy Needs in Non-Residential Buildings Located in Mediterranean Area: A Revision of the Quasi-Steady Procedure

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Abstract

With the Italian Interministerial Decree of 25 June 2015, the evaluation of the cooling energy requirements for residential and non-residential buildings has become mandatory. In Italy the UNI TS 11300-1 is the reference standard for the calculation of cooling energy requirements, by integrating the quasi-steady models of the international standard EN ISO 13790. The Italian standard takes into account some corrections in order to obtain even more precise results, but the deviances are still evident for non-residential buildings equipped with large glazed surfaces. Therefore, these models have to be calibrated further for Mediterranean climatic characteristics because the results are still discordant with those obtained by dynamic simulation codes. With reference to Mediterranean climatic conditions, a new correlation to use in the quasi-steady calculation procedure, derived from summer gain utilization factors, is proposed. The latter were calculated by means of TRNSYS simulations, varying the percentages and the typologies of the windowed surface and the time constant class of a reference non-residential building. The main factors causing the divergences in the results were identified and a proper calibration of the quasi-steady procedure contextualized to the summer Italian climatic conditions is proposed, in order to obtain cooling requirements closer to those provided by TRNSYS.

1. Introduction

For many years, designers have been looking for simplified procedures for the calculation of energy demands in buildings, to use as alternative to complex dynamic simulation codes. This need is still more evident in summer, where the variability of the external forcing on the building envelope makes the calculation of the cooling energy requirements difficult. In this field, the literature provides different simplified procedures that can be derived by direct and indirect methods (ASHRAE, 2005). Quasi-steady procedures employed at monthly level were proposed (Bauer and Scartezzini, 1999) by introducing the concept of the gain utilization factor (in winter) and the loss utilization factor (in summer) in order to take into account the dynamic effects on the thermal energy demands. Moreover, the summer procedure is similar to those employed in winter by inverting the role of thermal losses and energy gains. Other simplified methods for the cooling energy demand calculation are the Dutch model (NEN 2916, 1994; Van Dijk and Spiekman, 2003; Van Dijk et al., 2005) and the so-called Schibuola model (Schibuola, 1999). The first uses a loss utilization factor, while the second a gain utilization factor. Beccali et al. (2001) carried out a comparison between the two models, highlighting how difficult it is to assess a cooling energy model similar to those already employed for the calculation of heating energy requirements. Other analyses concerning the quasi-steady procedures to use in the cooling period can be found in Mazzarella (2000) and in Prada et al. (2011) to investigate the role of the loss utilization factor. Finally, also international standards have adopted the quasi-steady procedure for the summer calculation such as CEN (CEN, 2005) and ISO (ISO, 2008). The latter represents the reference document for the determination of the energy required for space heating and cooling, from which the Italian regulation UNI 11300-1 was derived (UNI, 2014). However, the original procedure was developed for continental climates where the differences between summer energy gains and thermal losses are limited. Instead, in the Mediterranean climatic context the opposite occurs, especially in well-

Part of
Pernigotto, G., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). 2018. Building simulation applications BSA 2017. bu,press.
https://doi.org/10.13124/9788860461360

insulated building envelopes equipped with large glazed surfaces, typical of the non-residential sector. Despite the fact that an appropriate procedure to correct the loss utilization factor contextualized to the Mediterranean climate was proposed by Corrado et al. (2007), the deviations of the cooling energy requirements determined by dynamic codes remain large for the mentioned building typology.

2. The Quasi-Steady Approach

The calculation method described in the ISO 13790 standard is based on a monthly energy balance between thermal losses and heat gains in steady-state conditions. Successively, the dynamic effects on the cooling energy needs are taken into account by the loss utilization factor, which considers the mismatching between thermal losses and energy gains, and an adjustment of the setpoint temperature for intermittent cooling or set-back. Both depend on the time constant of the building and on the monthly heat balance ratio (defined in ISO 13790 as the ratio between the monthly energy gains and the monthly thermal losses). So, the cooling energy demand can be determined in function of the loss utilization factor as:

$$Q_{C,nd} = Q_{C,gn} - \eta_{C,ls} \cdot Q_{C,ht} \tag{1}$$

where the latter is calculated by the relation (if the heat balance ratio is higher than zero):

$$\eta_{C,ls} = \frac{1-\gamma_C^{-a_C}}{1-\gamma_C^{-(a_C+1)}} \tag{2}$$

According to the Italian UNI 11300-1 standard, the superscript a_C depends not only on the building time constant, but also on the ratio between glazed and floor surfaces. This coefficient was calibrated by means of different cases study developed for Mediterranean climates and can be determined by the following correlation (Corrado et al., 2007):

$$a_C = 8.1 - 13 \cdot \xi + \frac{\tau}{17} \tag{3}$$

strongly different from the correlation suggested by ISO 13790 for continental climates:

$$a_C = 1 + \frac{\tau}{15} \tag{4}$$

The coefficients that appear in Equations (3) and (4) were evaluated by multiple regression of different values of the loss utilization factor calculated by the inverse solution of Equation (1). The actual cooling energy needs, and the equivalent values to the steady-state thermal losses and energy gains, can be provided by dynamic codes, by applying procedures as the "Black Box" method (ISO, 2008). The ISO 13790 standard provides also another method to calculate the cooling energy demands, which employs a gain utilization factor:

$$Q_{C,nd} = (1-\eta_{C,gn}) \cdot Q_{C,gn} \tag{5}$$

where the thermal losses appear indirectly because involved in the calculation of the same factors. It is easy to demonstrate that:

$$\eta_{C,gn} = \frac{\eta_{C,ls}}{\gamma_C} \tag{6}$$

In this paper, regarding a reference non-residential building located in two different places of the Italia peninsula, a new correlation for the "a_C" parameter derived from the summer gain utilization factors, is proposed. The latter were calculated by the inverse solution of Equation (5) employing results provided by TRNSYS v.17 code (Klein at al., 2012). Successively, the cooling energy requirements obtained with the proposed procedure were compared with the TRNSYS results, in order to quantify the result deviances.

3. The Reference Building

The energy evaluations were carried out with reference to an office building (Fig. 1) varying the glazed surface, the glazed system, the building time constant, and climatic data. In the latter case, the same building was located in Rome (Lat. 41.9°N) and Cosenza (Lat. 39.3°N) by employing monthly average daily climatic data listed in the Italian UNI 10349-1 standard (UNI, 2016). It consists of ten storeys with a conditioned volume lower than 10,000 m³. The ground floor is equipped with "pilotis" to avoid heat transfer towards the soil. The remaining nine floors have the same size with a rectangular form (10×30 m) and a longitudinal development in the east-west direction. The overall height is 33 m and the stairway is externally located in the north façade to avoid the presence of non-air-conditioned spaces. The reference building was considered as a single thermal zone conditioned by a centralized plant with the same indoor air temperature regulation. Table 1 shows the cases studied and indicates the percentage of the windowed surface (WWR, in function of the vertical opaque walls), the windowed system, the ratio of the glazed area to floor area, and the building time constant. The case studies were conducted for both localities. Time constant values variation was obtained by modifying the glazed surface area, the windowed system and the surface of internal walls. Their calculation was carried out by considering a mono-capacitive model of the building fabric.

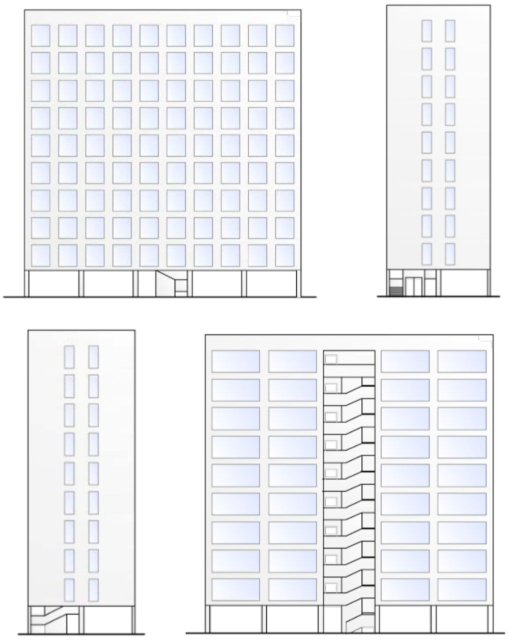

Fig.1 – Non-residential reference building with WWR of 50 %

Table 1 – Cases study conducted on the reference building located in Rome and Cosenza

Case	WWR	Windowed System	ξ	τ [h]
1	50 %	Double	0.37	47.9
2	25%	Double	0.19	64.5
3	50%	Double	0.37	87.0
4	10%	Double	0.07	79.7
5	75%	Double	0.52	39.0
6	50%	Single	0.37	29.6
7	50%	Triple	0.37	53.4

4. Simulation Results

By applying the "Corrado" method in alternative to the Black Box approach (Corrado et al., 2007), the TRNSYS simulations allowed us to determine the gain utilization factors from Equation (5), for every case in the considered locations. The mentioned method allowed us to calculate energy gains and energy losses "equivalent" to the steady-state conditions. These values, together with the actual cooling demands, are requested for the inverse solution of Equation (5). The indoor set-point temperature was set to 26 °C supposing a continuous operation regime of the cooling plant. The calculation of the gain utilization factors was preferred to the calculation of the loss utilization factors because the latter, derived from Equation (1), could tend to infinity in presence of reduced thermal losses. Moreover, the procedure has highlighted two critical aspects:

- the utilization factors are calculated by considering the involved energies in the whole months, while the UNI TS 11300-1 considers the fraction of month included in the cooling period. Consequently a mismatch between the equivalent and the steady-state values of the heat balance ratios was detected;
- the "ac" correlations were formulated considering equivalent heat balance ratios, but the latter could be strongly different from those determined in steady-state conditions, which will be used in Equation (2), providing different values of the utilization factors.

Regarding the locality of Rome, in Fig. 2 the cooling energy requirements (in kWh) determined by TRNSYS and by the ordinary UNI TS 11300-1 steady-state procedure, are presented for the seven considered cases. The results concern the seasonal cooling requirements determined as the sum of the monthly needs. The deviations among the obtained results (TRNSYS results as reference) range between 4.9 % (Case 4) and 21.2 % (Case 5). Similar values were determined for the other locality.

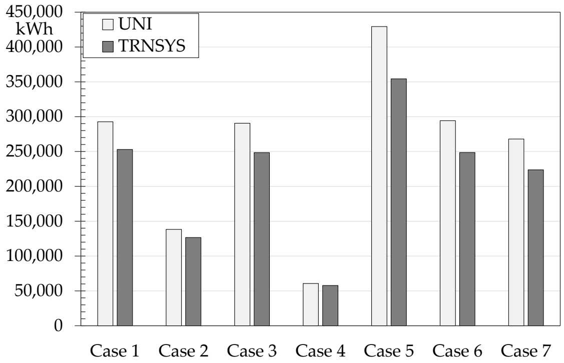

Fig. 2 – Rome: cooling energy requirements for the reference building in the considered cases (in kWh per year)

The deviations are limited for envelopes equipped with limited windowed surfaces, contrarily the differences are more marked with the glass surface growth. Except for Case 4, percentage differences always greater than 10 % were detected. If we suppose that the reference building is conditioned by electric heat pumps with seasonal EER of 2.5, in Case 5 the deviation between the UNI procedure and TRNSYS produces an electric energy overestimation greater than 75000 kWh at seasonal level, corresponding to 18750 € in expenses for electricity (in continuous regime operation). Therefore, these percentages cannot be neglected and they produce an evident mistake in the summer energy performances reported in the building energy certificate. Regarding the comparison between equivalent and steady-state monthly energies, the observed deviances can be summarized as follows:

- noticeable errors are detected for the thermal losses when the monthly average daily temperature value of external air is next to the internal setpoint;
- solar gains determined with the UNI procedure are always overestimated compared to TRNSYS results, but the deviances among the monthly energy remain almost constant.

5. Discussion

The evaluations of the monthly energy gains and monthly thermal losses in steady-state conditions are "adjusted" by the application of the utilization factors. However, in the UNI 11300-1 the latter are calculated by Equation (2) using heat balance ratios different from those employed for the identification of the parameter aC. Therefore, a more precise evaluation of the steady-state heat balance ratio is recommended in order to calculate utilization factors more similar to those derived from the "Corrado" method. Thus, a better quantification of the summer thermal losses and summer energy gains is required. However, it is very difficult to assess the envelope thermal losses in steady-state conditions, because the external air temperature can rise or drop below the internal setpoint. In the Mediterranean climatic context, the thermal losses can be very limited during the cooling period, therefore elevated heat balance ratios could be achieved. In order to avoid this condition, the use of the reciprocal value of the heat balance ratio seems to be more appropriate. From the energy gains point of view, instead, the constant monthly difference between the steady-state and the equivalent solar gains suggests that other geometrical and optical aspects concerning the building have to be analysed in detail. Fig. 3 presents the trend of the gain utilization factors determined through the 14 examined cases, in function of the reciprocal value of the heat balance ratio. The dependence of the dynamic coefficient on the time constant is less pronounced when compared with the loss utilization factor. If we suppose to use Equation (7) for the interpolation of the gain utilization factors derived from TRNSYS, a multiple regression allowed us to identify the superscript "aC" values that better fit the equivalent heat balance ratios.

$$\eta_{C,gn} = \frac{\gamma_C^{-1} - \gamma_C^{-(a_C+1)}}{1 - \gamma_C^{-(a_C+1)}} \tag{7}$$

Successively, by setting the dependence of the coefficient aC from the time constant and the ratio between windowed and floor surfaces, the following correlation was determined:

$$a_C = 7.25 \cdot \xi + \frac{\tau}{10} \tag{8}$$

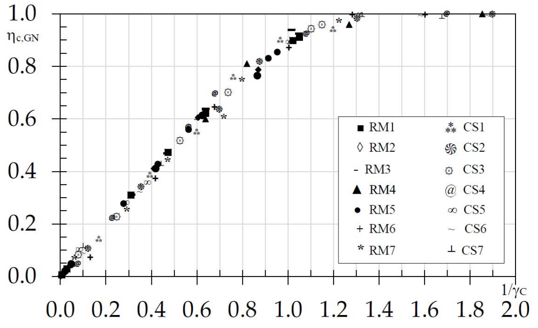

Fig. 3 – Trend of the gain utilization factor vs. reciprocal of the heat balance ratio for Rome (RM) and Cosenza (CS)

Negative values of the gain utilization factor can be obtained when also the heat balance ratios assume negative values (thermal losses are an additional load). This condition happens when the monthly average daily temperature value of external air is higher than the internal setpoint. In this case, the gain utilization factor can be set equal to the heat balance ratio. In Fig. 4 the energy requirements determined by utilization factors evaluated with the ordinary procedure exploiting the Equation (3) (UNI_1) and determined with the new proposed correlation (UNI_mod), are shown. In the same figure, the actual cooling needs determined by TRNSYS are also reported. In every case, the second correlation allows for better results when compared with those provided by TRNSYS. The deviations are more limited, in particular for the examined cases the percentage errors detected are reduced respectively:

- from 15.7 % to 11.5 % for Case 1;
- from 10.3 % to 4.5 % for Case 2;
- from 16.9 % to 12.7 % for Case 3;
- from 4.9 % to -3 % for Case 4;
- from 21.2 % to 15.1 % for Case 5;
- from 18.4 % to 13.2 % for Case 6;
- from 19.8 % to 15.5 % for Case 7.

Similar results were achieved for the second city, therefore they are not reported. If in Equation (7) heat balance ratios closer to the equivalent ones are employed, better results can be achieved. A noticeable improvement can be obtained with a more precise determination of solar gains in steady-state conditions and by using the reciprocal of the heat balance ratio. By setting:

$$\gamma_{C,gn} = \frac{1}{\gamma_C} \tag{9}$$

Equation (7) can be rewritten as:

$$\eta_{C,gn} = \frac{\gamma_{C,gn} - \gamma_{C,gn}^{(a_C+1)}}{1 - \gamma_{C,gn}^{(a_C+1)}} \tag{10}$$

with $\gamma_{C,gn}$ that assumes compact values.

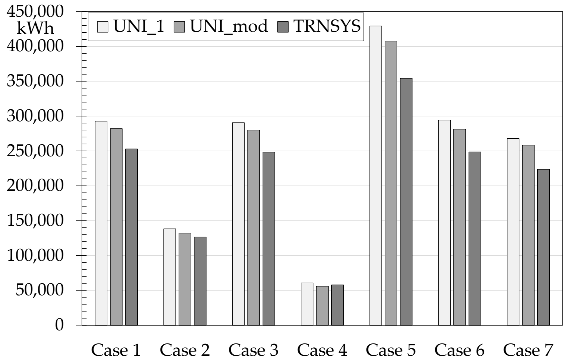

Fig. 4 – Rome: comparison among the cooling energy requirements (in kWh per year) for the reference building determined with ordinary a_C values (UNI_1), the proposed a_C values (UNI_mod) and with TRNSYS

5.1 Improvement in Steady-State Solar Gains Evaluation

The difference determined at a monthly level between steady-state energy gains and equivalent energy gains is almost constant; a comparison is shown in Fig. 5 for Rome for Cases 4 and 5. Therefore, a common aspect concerning solar gains calculation in steady-state conditions has not been adequately considered. Regarding building envelopes equipped by large glazed surface, in fact, the part of solar radiation reflected by the inner surface in the air-conditioned volume, escaping newly through the same glazed surface, is not quantified. This fraction of solar radiation does not become a cooling load for the internal environment, and it cannot be neglected. Moreover, this aspect is cited by ISO 13790 as a "noise" source for the evaluation of the utilization factors, and in the calculation of the equivalent energy gains, TRNSYS considers this solar gain rate adequately. In order to evaluate the missed contribution related to the escaping solar irradiation, an absorption coefficient of the indoor environment (or cavity absorption coefficient) can be introduced.

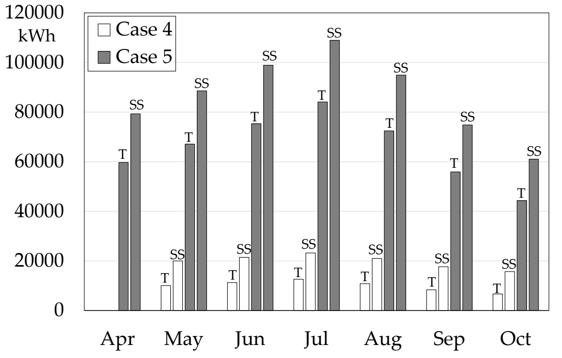

Fig. 5 – Rome: comparison between solar gains obtained with steady-state model (SS) and TRNSYS (T) for Cases 4 and 5

Fig. 6 shows the trend of this coefficient, in function of the ratio between glazed surface and global opaque surface Ψ (including floor, ceiling, and inner surface areas) and for three types of the usual clear glass by assuming a mean solar absorption coefficient of internal walls equal to 0.35 (Oliveti et al., 2011). The difference among the three considered windowed surfaces is related to the different optical properties of the glasses that determine a different amount of entering and escaping solar radiation. For a Ψ factor of 0.1, corresponding usually with a whole glazed wall, the cavity absorption coefficient is about 0.7, therefore 30 % of the incoming solar radiation does not become a cooling load for the indoor environment. Contrarily, for Ψ ratios lower than 0.05 (typical in residential buildings), the role of α_{cav} can be neglected. The relations to use for α_{cav} calculation for clear single, double, and triple pane are respectively:

$$
\begin{aligned}
\alpha_{cav} &= 1 - 2.00 \cdot \exp[-1.60 \cdot (\frac{0.35}{\Psi})^{0.33}] \\
\alpha_{cav} &= 1 - 1.87 \cdot \exp[-1.64 \cdot (\frac{0.35}{\Psi})^{0.33}] \qquad (11) \\
\alpha_{cav} &= 1 - 1.86 \cdot \exp[-1.78 \cdot (\frac{0.35}{\Psi})^{0.31}]
\end{aligned}
$$

By modifying the steady-state solar radiation transmitted through windowed surfaces by the cavity absorption coefficient, the new comparison with solar gains determined by TRNSYS at seasonal level, is shown in Fig. 7.

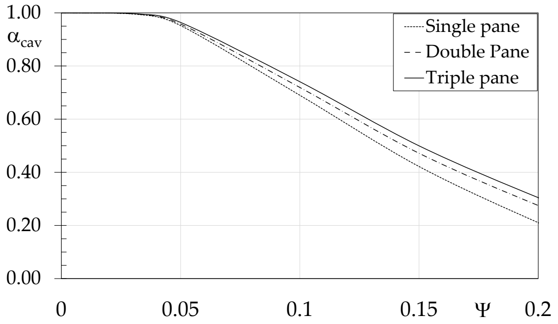

Fig. 6 – Cavity absorption coefficient of the solar radiation in function of the ratio Ψ and for three types of clear glass

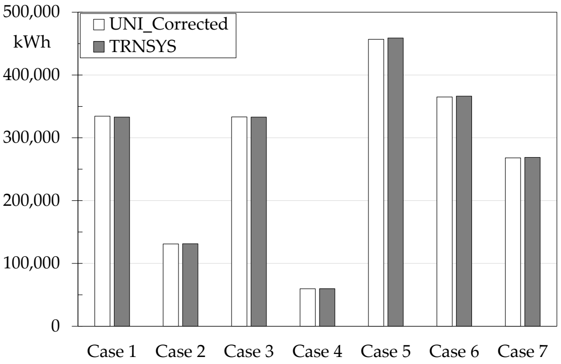

Fig. 7 – Rome: seasonal solar gains obtained by considering the cavity absorption coefficient in the steady-state procedure and comparison with TRNSYS

The values concerning the equivalent heat balance ratio provided by TRNSYS, those determined by the ordinary steady-state model, and those calculated by the corrected solar gains, are listed for Rome in Table 2. Despite the errors concerning the thermal loss evaluations, the correction of the solar gains allows for a calculation of the heat balance ratios close to the equivalent ones, and the deviances are reduced when the lower is given by the outside air temperature. Similar deviations were obtained for the second locality. Finally, the cooling energy requirements was calculated in function of the gain utilization factor determined by Equation (10) by employing the coefficient a_C determined by Equaiton (8) and the heat balance ratios calculated with corrected solar gains. Considering that Equation (8) was derived by TRNSYS results, where the aspects concerning the "escaping" solar radiation were already taken into account, the monthly energy gains that appear in Equation (5) have to be calculated without solar gains correction. The latter aspect, in fact, is successively adjusted by the application of the gain utilization factor. Fig. 8 shows the results for Rome for the 7 analysed cases by observing a reduction of the deviances in the cooling energy requirements. The proposed quasi-steady approach provides a slight overestimation, but the detected percentage errors now are always lower than 5 %. In particular, these errors are equal respectively to 4 % for Case 1, -0.9 % for Case 2, 4.6 % for Case 3, 4 % for Case 4, 4.5 % for Case 5, 1.8 % for Case 6, and 2.8 % for Case 7. Similar results were obtained for Cosenza. The detected errors are mainly linked to the employment of the correlations appearing in Equation (8) and Equation (11).

	Case 1			Case 2			Case 3			Case 4			Case 5			Case 6			Case 7		
	$\gamma_{C,gn1}$	$\gamma_{C,gn2}$	$\gamma_{C,gn3}$	$\gamma_{C,gn1}$	$\gamma_{C,gn2}$	$\gamma_{C,gn3}$	$\gamma_{C,gn1}$	$\gamma_{C,gn2}$	$\gamma_{C,gn3}$	$\gamma_{C,gn1}$	$\gamma_{C,gn2}$	$\gamma_{C,gn3}$	$\gamma_{C,gn1}$	$\gamma_{C,gn2}$	$\gamma_{C,gn3}$	$\gamma_{C,gn1}$	$\gamma_{C,gn2}$	$\gamma_{C,gn3}$	$\gamma_{C,gn1}$	$\gamma_{C,gn2}$	$\gamma_{C,gn3}$
Apr	1.02	0.88	1.01	-	-	-	1.05	0.87	1.00	-	-	-	0.91	0.75	0.89	-	-	-	1.03	0.86	1.09
May	0.64	0.55	0.64	0.87	0.76	0.85	0.64	0.54	0.63	1.27	1.18	1.28	0.56	0.47	0.56	0.87	0.68	0.72	0.64	0.54	0.69
Jun	0.31	0.24	0.28	0.41	0.34	0.38	0.31	0.24	0.28	0.64	0.54	0.59	0.28	0.21	0.25	0.42	0.30	0.32	0.31	0.24	0.30
Lul	0.03	0.02	0.02	0.03	0.03	0.03	0.04	0.02	0.02	0.05	0.04	0.05	0.03	0.02	0.02	0.05	0.02	0.03	0.03	0.02	0.02
Aug	0.01	0.04	0.04	0.00	0.05	0.06	0.01	0.04	0.04	-0.01	0.08	0.09	0.01	0.03	0.04	0.02	0.05	0.05	0.00	0.04	0.05
Sep	0.47	0.40	0.46	0.61	0.54	0.61	0.47	0.40	0.46	0.82	0.83	0.89	0.43	0.35	0.41	0.62	0.50	0.53	0.47	0.39	0.50
Oct	1.05	0.95	1.09	1.34	1.26	1.39	1.02	0.94	1.08	1.85	1.81	1.94	0.95	0.83	0.97	1.49	1.18	1.24	1.04	0.93	1.16

Table 2 – Rome: heat balance ratios determined by TRNSYS ($\gamma_{C,gn1}$), by ordinary steady-state procedure ($\gamma_{C,gn2}$) and by correcting solar gains with the cavity absorption coefficient α_{cav} ($\gamma_{C,gn3}$)

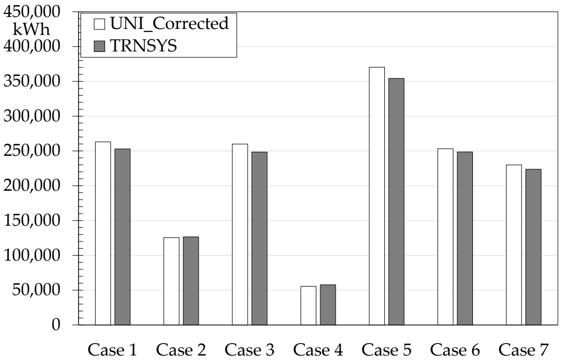

Fig. 8 – Rome: comparison of the cooling energy requirements determined with the proposed procedure and evaluated by TRNSYS for the reference building and for the 7 examined cases

6. Conclusion

An alternative correlation to determine the utilization factors required for the calculation of cooling energy requirements with the quasi-steady approach, is proposed. The correlation was derived by interpolating the values of the summer gain utilization factors, because in the Mediterranean climatic context the calculation of the loss utilization factor could be affected by reduced thermal losses. The equivalent monthly energy values, concerning energy gains and energy losses and the actual cooling needs, required for the evaluation of the gain utilization factor, were determined by the TRNSYS code. Successively, the results provided by the proposed procedure were compared with the TRNSYS cooling demands in order to quantify the deviances. A noticeable improvement in the results has been achieved by introducing a correction factor for the solar gains through glazed surfaces. For a building equipped with large glazed surface, the steady-state procedure does not consider the fraction of solar radiation “escaping” from the air-conditioned space due to the inner surface reflection. By correcting the steady-state solar gains by an appropriate cavity absorption coefficient, heat balance ratios close to the equivalent ones determined by TRNSYS, were achieved. This aspect allowed a more precise calculation of the utilization factors, as well as the evaluation of cooling energy demands similar to those provided by TRNSYS for a reference non-residential building. Regarding the 14 examined cases, the percentage errors on the cooling requirements, calculated by using the TRNSYS results as reference values, are always lower than 5 % considering different building configuration and two different localities.

Nomenclature

Symbols

a	Utilization factor parameter [-]
α	Absorption coefficient [-]
γ	Heat balance ratio [-]
η	Utilization factor [-]
Q	Monthly energy [kWh]
τ	Time constant [-]
ξ	Glazed/floor area ratio [-]
Ψ	Glazed/opaque area ratio [-]

Superscripts/Subscripts

C	Cooling
cav	Cavity
gn	Gain
ht	Thermal loss
ls	Loss
nd	Energy requirement

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