Applied Energy 160 (2015) 431–441

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

# The Solar Response Factor to calculate the cooling load induced by solar gains

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## HIGHLIGHTS

- The paper introduces a new methodology to calculate the cooling load in buildings.
- The approach is based on the calculation of the Solar Response Factor (SRF).
- The SRF measures the response to solar heat gains in terms of attenuation and delay.
- The reliability is checked against simulations on EnergyPlus with excellent results.
- Examples are provided about its usefulness and significance.

## ARTICLE INFO

*Article history:*
Received 27 February 2015
Received in revised form 3 September 2015
Accepted 20 September 2015

*Keywords:*
Cooling load
Solar gains
Glazing
Envelope
Thermal inertia

## ABSTRACT

This paper introduces an original approach for the evaluation of the cooling load due to the solar radiation incident on the glazed surface of a building. This approach is based on a newly introduced parameter called *Solar Response Factor*, defined as the overall convective heat flux released by the building envelope to the indoor space per unit radiant heat flux acting on the outer surface of the glazing.

The *Solar Response Factor* is a complex number, and can be calculated as a combination of the thermal and the optical properties of walls and glazing. In particular, the paper discusses how the *Solar Response Factor* depends on the optical properties of the envelope, on the size of the windows and on the type of walls delimiting the enclosed space.

Furthermore, under steady-periodic conditions, the use of the *Solar Response Factor* allows an easy analytical estimation of the cooling load due to solar gains. The reliability of this approach is successfully proven by comparison with a series of simulations carried out with EnergyPlus. The results provide very useful information for optimizing the thermal response of an enclosure to periodic solar heat gains.



## 1. Introduction

The accurate calculation of the cooling load in buildings is an essential step for a successful sizing of an HVAC system. In fact, errors in this step may lead to system over-sizing, which implies higher installation costs and worse performance if compared to properly sized systems.

In many buildings, the solar radiation admitted through the glazed envelope determines a major portion of the total cooling load. However, it is not easy to estimate accurately this contribution, as it is transient in nature and due to thermal storage effects induced in the building mass.

The search for methods able to describe the room response in dynamic conditions dates back to the mid 1960s, with the aim to offer a scientific basis for sizing HVAC systems [1]. At that time, the research led to the definition of rather simple methods, to be used for manual calculation of the cooling load. In particular, in 1965 the *thermal storage factors* were defined – in the context of the Carrier method – as the ratio of the rate of instantaneous cooling load to the rate of solar heat gain [2]. The thermal storage factors were determined through appropriate tables depending both on the weight per unit floor area of the opaque components and on the running time. Therefore, their use required interpolation amongst tabular data; they were also rather rough, as they did not take into account the actual sequence of the wall layers, and they lacked any sound theoretical basis, as they resulted from numerical simulations.

The *cooling load temperature difference* (CLTD)/*solar cooling load* (SCL)/*cooling load factor* (CLF) method was stated more recently [3]. Here, the space sensible cooling load due to solar heat gains transmitted through the glazing can be calculated through a series of

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http://dx.doi.org/10.1016/j.apenergy.2015.09.072

**Nomenclature**

*Variables*

| | |
|---|---|
| $A$ | surface area ($m^2$) |
| $f$ | fraction of glazed surface to the overall surface of the envelope (–) |
| $F$ | surface factor (–) |
| $g_s$ | g-value of the glazing (–) |
| $h$ | surface heat transfer coefficient ($W\,m^{-2}\,K^{-1}$) |
| $I$ | solar irradiance ($W\,m^{-2}$) |
| $n$ | order of the harmonic component (–) |
| $P$ | time period (h) |
| $q$ | heat flux released by a surface ($W\,m^{-2}$) |
| $r$ | fraction of heat flux re-emitted by the glazing (–) |
| $R$ | thermal resistance ($m^2\,K\,W^{-1}$) |
| $t$ | time (s) |
| $U$ | thermal transmittance ($W\,m^{-2}\,K^{-1}$) |
| $Y$ | thermal admittance ($W\,m^{-2}\,K^{-1}$) |

*Greek letters*

| | |
|---|---|
| $\alpha$ | absorptance (–) |
| $\varepsilon$ | long wave emissivity (–) |
| $\lambda$ | thermal conductivity ($W\,m^{-1}\,K^{-1}$) |
| $\rho$ | reflectance (–) |
| $\tau$ | transmittance (–) |
| $\varphi$ | time shift (h) |
| $\phi$ | heat flux ($W\,m^{-2}$) |
| $\chi$ | shading coefficient (–) |
| $\psi$ | thermal power (W) |
| $\Omega$ | Solar Response Factor (–) |

*Subscripts*

| | |
|---|---|
| $c$ | convective |
| $g$ | glazing |
| $lw$ | long-wave |
| $r$ | radiant |
| $si$ | inner surface |
| $sw$ | short-wave |
| $t$ | transmitted |
| $w$ | wall |

solar cooling load factors (SCL). ASHRAE has developed SCL values to be used for typical buildings in North America with the weather conditions of July 21st at a latitude of 40°N. Even though ASHRAE has suggested correction factors for climate data other than those used for standard SCL, the accuracy of this approach is questionable for locations that are not placed at 40°N. Thus, several researchers have developed their own SCL values for other specific climates, starting from the results obtained through more accurate calculation methods [4,5]. In any case, up to now this calculation method has been widely used by HVAC designers [6].

More rigorous methods have been developed in the 1980s. Most of them approach the problem by calculating a conductive, convective and radiant heat balance for each room surface (or even for each layer of each room surface), as well as a convective heat balance for the room air. The resulting set of differential equations is usually solved numerically.

This formulation is called *Heat Balance* (HB) method, and it is the basis of several energy analysis programs, such as the BLAST [7], the TARP [8] and the DOE-2 [9], implemented in a great number of commercial software tools. However, the use of these programs implies a certain computational effort, related to the need of solving, at each time step, a high number of differential equations. Furthermore, complex and very detailed input data is required, concerning the building and the local weather conditions.

The *Transfer Function Method* (TFM), also known as *weighting factor method*, is a simplification of the laborious HB method. In the TFM method, the conversion of the heat gains to cooling load is based on the use of appropriate weighting factors (transfer function coefficients). These were originally generated with reference to a typical room configuration (4.5 m × 4.5 m with a height of 3 m) [10,11]. In the late 1980s, Sowell introduced 14 influential parameters for the description of a thermal zone, enabling the transfer function coefficients to match more closely the specific room to be simulated [12]. Due to its user-friendliness, the TFM is nowadays a widely used computer-aided load calculation method in the air conditioning industry.

An approach similar to the TFM is proposed in the *Radiant Time Series* method (RTS) [13]. Here, hourly radiant heat gains are converted to hourly cooling loads using two series of twenty-four radiant time factors: a radiant time factor reflects the percentage of an earlier heat gain that becomes cooling load during the current hour. By definition, each radiant time series must total 100% [1]. Several series of radiant time factors are available in the literature, depending on the percentage of glazed surface and on the heaviness of the construction, roughly classified from light to heavy [1]. Such series were calculated by Pedersen et al. using a computer program, and obviously refer to specific rooms with peculiar features [14]. Customized RTS values can be calculated using either the HB method or experimental data, when the calculation of the cooling load refers to a zone that is not reasonably similar to the rooms considered in the literature [15]. The RTS method is rigorous and does not require iterative calculations. It is particularly suited for peak load calculation, but it should not be used for annual energy simulations. However, its main drawback is that lacking appropriate radiant time series for the specific case implies low reliability of the results. Moreover, despite its simplicity, it is not suitable for manual calculation of the cooling load.

Several peculiar approaches for the calculation of the cooling load in buildings are also available in the literature, which have been developed by researchers for specific purposes. As an example, Causone et al. [16] investigate the removal of solar heat gains by radiant cooling systems, and to this aim introduce the *Direct Solar Load* (DSL), i.e. the ratio of the solar heat gains transmitted through the glazing and directly converted to cooling load by the action of the cold surface of radiant panels. The values of the DSL are generated starting from the HB method for a significant number of case studies.

Xu and Wang [17] develop a simplified dynamic model for the calculation of the cooling load in existing buildings. Here, the effect of the internal mass (including floors, partitions, furniture, etc.) on the radiant heat gains is represented with a 2R2C model, i.e. through two resistances and two capacitances, whose values are determined by means of a genetic algorithm applied to experimental data. Similarly, Buonomano and Palombo [18] develop an in-house dynamic simulation code based on the resistance–capacitance approach (RC). The proposed code can be used for scientific research purposes, since it addresses in details all the different features of the building that must be analyzed. Another proposal in this direction is made by Ogunsola and Song [19].

Moreover, Antonopoulos et al. [20,21] use a finite-difference procedure to determine the dynamic energy response of indoor spaces under the influence of indoor energy pulses. Their method