Calculation Method For Summer Cooling With Radiant Panels

Francesco Causone[1], Stefano Paolo Corgnati[1], Marco Filippi[1]

[1]Politecnico di Torino, Torino (Italy)

Corresponding email: francesco.causone@polito.it

SUMMARY

Radiant panels achieved a growing success in the last years as a cooling system, because they guarantee improvement in comfort and energy saving.
The aim of the present work is to propose a method to evaluate the thermal behavior of radiant panels used for summer cooling. Experimental observations lead to notice that part of the radiant load hitting panels surface is directly removed by the refrigerating fluid (Direct Water Load), never becoming a room load. In order to evaluate the role of this fraction of load on thermal balance, it has been developed a specific procedure deriving from the Room transfer functions method.
Through a lighting analysis tool it has been furthermore evaluated the Direct Water Load due to solar radiation, the most important radiative load for typical office rooms, in function of geometrical configuration and surfaces reflection factors (α, ρ). The right understanding of the role played by Direct Water Load on thermal behavior of radiant panels may lead to a better design of this kind of cooling systems.

INTRODUCTION

The use of radiant panels as a cooling system is quite new in a lot of countries, but it is developing extremely fast, conquering each year relevant market slices.
The success of this kind of HVAC system is bound to design, comfort and energetic reasons. The use of radiant panels leads to have more free usable net floor space, to reduce draft risk, typical of cooling air systems, to achieve quite uniform temperatures into the rooms, to obtain significant energy saving.
For comfort reasons, anyway, the surface temperature of panels must not be lower than 19°C and in order to avoid moist condensation it must not be lower than the dew point temperature of the room. Since cooling panels can control only sensible loads and not control air humidity and quality, they are always coupled with primary air, which can provide any air control. Sometimes primary air may even help the radiative system to balance peak loads, if they grow up beyond panels thermal efficiency.
Radiative systems use wide exchange surfaces, and since human body exchanges heat through radiation approximately for the 50% of the whole balance (in cooling period), it is clear that panels temperature can be quite near to project air temperature maintaining optimal comfort condition. At the same time, since the most of heat exchanged between the body and the cooling system is through radiation, air temperature can have little higher values, without creating comfort problems, since operative temperature doesn't change so much, so the thermal sensation of people remain the same. Higher values of air temperature bring anyway to a reduction of the cooling load, for the reduction of heat dispersions through walls and air infiltration.

The most important element which can bring to significant energy saving is anyway the opportunity of using energy transfer mediums, usually water, with moderate temperature (near to 16°C) [1]. This is why these systems are often called as "low exergy", because they can work using energy which has a very limited convertibility potential, such as heat close to room air temperature and this means that radiant panels can be fed by solar collectors (solar cooling) or heat pumps [2, 3].

METHODS

Cooling Load Evaluation

In order to study a cooling system, it is essential to use a multi-step analysis which considers the effect of loads distribution during the whole day. Heat gains and cooling loads to be removed by the cooling system are not the same during different hours, because the thermal mass of the building accumulates heat (especially due to solar radiation) and after a time lag re-emits this into the room. So a specific heat gain at the time T_θ, may have its real effect on the cooling system only at the time $T_{\theta+n}$.
The most common calculation methods, as the Room transfer functions method, use therefore the concepts of Heat Gain and Cooling Load, as explain after:

- The *Heat Gain* is the amount of heat gendered or introduced into the room at a specific time T_θ
- The *Cooling Load* is the amount of heat that must be taken away from the room at the same time T_θ, in order to maintain the project conditions of temperature and humidity
- The *Heat Extraction Rate* is the real heat rate taken away from the room by the plant at the time T_θ (it is linked to the plant inertia)

The thermal inertia of the room hence correlates Heat Gains and Cooling Loads. It is possible to break Heat Gains between convective gains and radiative gains, the fist ones, working directly on air, are not involved in thermal mass absorption phenomena, the radiative gains are, on the contrary, partly absorbed by the elements of the room having relevant thermal mass. After a certain time, only a reduced part of the absorbed radiation is re-emitted into the room through infrared wave and convection. So thermal mass operates on radiative loads delaying and dimming their effect, while convective and latent loads directly become cooling loads (fig.1).
Heat Extraction Rate is mostly important for estimating energy use over time, but it is not relevant to calculate design peak cooling load, for this reason we don't consider it in our analysis.

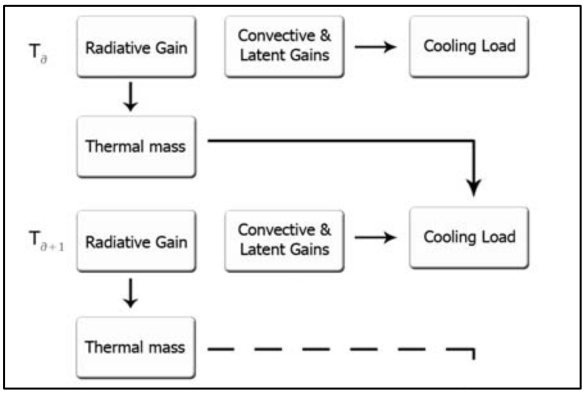

Figure 1. Heat loads scheme inside a room

Cooling Load Evaluation For Radiant Panels

Cooling load evaluation for radiant panels needs a further level of analysis, due to specific characteristics of this kind of cooling systems [4].

Radiant panels are light elements, usually in metallic alloy or plasterboard, without relevant values of thermal mass; they have on their backside a coil system for the refrigerating fluid flow (typically cold water). If a radiative flux (solar radiation, artificial light, far IR radiation…) hits the surface of the panel, the energy transfer medium directly removes it. So that radiative gain will never become a Room Load, because it will never be re-emitted through convection into the room. It is therefore possible to compare the behavior of radiant panels to the one of a well with a radiative power foisted by the temperature of the refrigerating fluid. The scheme about Heat Gain and Cooling Load previously shown (fig.1), must consequently be corrected when radiant panels are used, considering the rate of the radiative gains hitting the panels surface and directly removed by water.

Each Radiative Heat Gain at time θ must be divided in the rate F directly removed by water, called Direct Water Load (DWL) and in the remaining part (1-F) which will be influenced by the room thermal inertia (fig.2). If we consider the Room transfer functions method for predicting cooling loads, the ratio of radiative Heat Gain absorbed by thermal mass at time θ (1-F), will become a Room Load (RL) at time θ+n.

In the most general situation, in which both panels and air are used to removed sensible loads, the RL at time θ will be partly (X) contrasted by the radiative system through the Surface Load (SL), and partly (1-X) by the air, through the Cooling Load air (CLa). The sum of Surface Load at time θ, together with the Direct Water Load at time θ, represent the Cooling Load water (CLw), so the amount of heat removed from the room by the radiative system at time θ (fig.3).

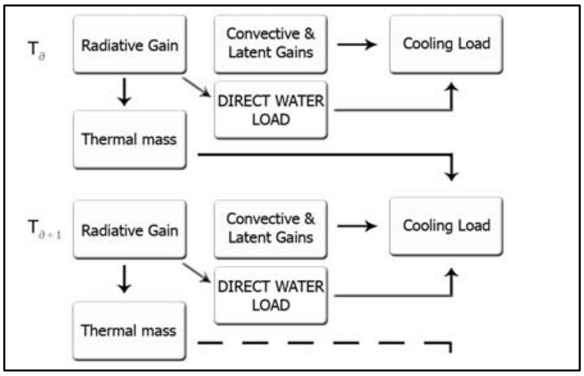

Figure 2. Heat loads scheme inside a room with radiant cooling panels

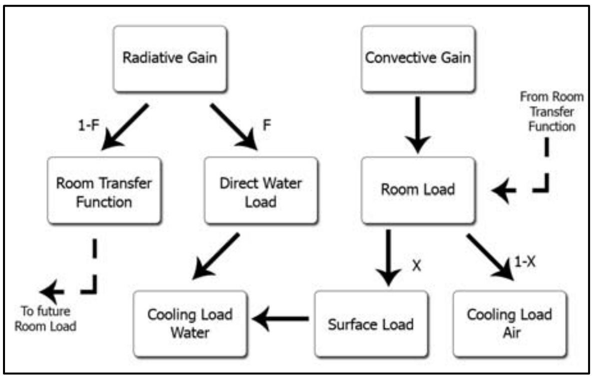

Figure 3. Cooling Load generation with radiant cooling panels

It is very important to underline the different origin of the two component of cooling load burdening at time θ on the radiative panels: the Direct Water Load directly derives from Heat Gains at time θ while the Surface Load derives from Room Loads and so its value is influenced by delay effect due to room thermal inertia and expressed by room transfer functions. This analysis is confirmed by the empirical approach adopted by some constructors, which suggest to subtract a certain ratio of the radiative gains, from the cooling load evaluated with traditional methods, before determining the efficiency of panels.

Distinguish between DWL and SL is not just a theoretical exercise, it has indeed practical design consequences [5, 6]. When it exists a high Direct Water Load, the Room Load is strongly reduced, and so the Surface Load and/or the Cooling Load Air. Since the Surface Load is limited by the panels surface temperature, when the Room Load is little, panels can anyway succeed in removing the whole sensible load or even a lower radiant surface may be

needed in order to contrast the load. It is possible otherwise to reduce the Cooling Load air, if primary air is anyway needed to control indoor climate.
It must be however underlined, that even if Surface Load or Cooling Load air are lowered by using this analytical approach, the whole load burdening on the plant is higher, because the Direct Water Load is an instantaneous load, so it is not dimmed by room thermal mass effect.
Another interesting aspect depends on the different origin of DWL and SL: if the temperature difference between air and panel surface is zero, the Surface Load is zero too, but if there is at the same time a radiative flux hitting the panel, the Cooling Load is not zero because there is a Direct Water Load. The fundamental equation for cooling load evaluation is the following:

$$\dot{Q}_{CLw} = \dot{m}_w \cdot c_p \cdot \Delta T_w, \quad (1)$$

where ΔT_w is the difference between inlet and outlet temperature of the refrigerating fluid.
So the cooling efficiency of the radiative system can be expressed as follow:

$$\dot{q}_{CLw} = \left(\dot{Q}_{CLw} / A\right) = \left(\dot{m}_w \cdot c_p \cdot \Delta T_w / A\right), \quad (2)$$

And the surface cooling efficiency:

$$\dot{q}_{SL} = \left(\dot{Q}_{SL} / A\right), \quad (3)$$

The two characteristic efficiencies are linked together through the following relation, which considers the DWL:

$$\dot{q}_{CLw} = \dot{q}_{SL} + \left(\dot{Q}_{DWL} / A\right) = \dot{q}_{SL} + \dot{q}_{DWL}, \quad (4)$$

In order to evaluate the Cooling load, DWL and SL must therefore be studied separately.

Heat Removed By Panels Surface – Surface Load
Concerning the calculation method shown before, the amount of load removed by the panels surface at each time step, depend on:

- Convective heat exchanges between room air and panels surface
- Radiative heat exchanges among panels surface and walls surfaces

The cooling power of the panels is therefore strictly bound to panels surface temperature, which is however strongly limited by moist condensation problems and comfort needs. The value of this temperature is the most critical point of the whole system thermal behavior.
The heat power removed by the panels surface can be evaluate through the follow equation:

$$\dot{Q}_{SL} = h \cdot A \cdot \left(T_{sp} - T_{op,eq}\right), \quad (5)$$

where h is the surface conductance, A is the panels surface, T_{sp} is the temperature of the panels surface, and $T_{op,eq}$ is the operative equivalent temperature of the room, expressed as follow:

$$T_{op,eq} = \frac{h_r \cdot T_{mr} + h_c \cdot T_{air}}{h_r + h_c}, \quad (6)$$

T_{mr} represents the mean radiant temperature of the room, calculated excluding the panels surface temperature. Since the most common value used in design stage is the air temperature, and since the T_{mr} is a difficult parameter to be obtained, it is commonly used a simplified equation to evaluate the heat power removed by the panels surface:

$$\dot{Q}_{SL} = h \cdot A \cdot (T_{sp} - T_{air}), \quad (7)$$

Direct Water Load Evaluation

The most difficult element to evaluate is the Direct Water Load, because its value depends not only on the characteristics of the radiative source and on the radiative properties of the surfaces of the room, but even on the geometrical shape of the room.

Generally it can be expressed as:

$$\dot{Q}_{DWL} = F \cdot \dot{Q}_{rad}, \quad (8)$$

where F represent the ratio of the radiative flux Q_{rad} which is directly removed by the heat transfer medium.

The F value has been studied with the help of two simulations tools, the first one is a simple calculation sheet, based on the Reflection method, which lets to follow the path of the radiation (solar, human body, appliances) within the room. Through the Angle Factor source-wall, the radiation is spread over the floor, the walls and the ceiling. After this, through the Shape Factor, part of the incident radiation is reflected from the walls surfaces all around again [7]. Following all the reflections it is possible to evaluate the amount of each radiative flux removed by the radiative panels.

The other one is instead a lighting analysis tool, called Lighscape and so it lets to study the F value just for solar radiation and some artificial light source, but not for fully IR radiation sources. Anyway solar radiation is the most relevant radiative flux, especially in highly glassed buildings. This second tool is able to simulate both direct and diffuse radiation, drawing maps of light distribution over the different walls, and this is extremely important to improve the accuracy of the analysis, since the first model simulates just perfectly diffusing sources and materials.

It is interesting to point out that, for solar radiation, even do not considering the UV and IR fractions, lighting tools produce just little errors, whom bring to little underestimations of the Direct Water Load. Solar spectrum is divided in four main parts, which at ground level assume the following values: ultraviolet (6%), visible (55%), near infrared (39%) and far infrared (0%) [8]. Since all kind of glass used in the construction field are opaque to far infrared radiation, it can't enter into the room, so it is not considered for cooling load evaluation. Anyway it is just a principle statement, since solar far infrared radiation at ground level is practically inexistent, because filtered by atmosphere.

To obtain the most general considerations, in the following analysis we will consider a clear glass with the common thickness of 6 mm, having the following standard characteristics:

Table 1. Solar radiation mean transmission factors, for UV, Visible and IR wavelengths

Global	UV	Visible	near IR	far IR
τ_e	τ_{UV}	τ_v	τ_{IRn}	τ_{IRf}
81%	56%	89%	74%	0%

So the solar radiation entering into the room is composed by:

2. Percentage of UV, Visible and IR entering into the room through a clear 6 mm glass

Φ_{IN}	UV	Visible	near IR	far IR
100%	4%	60%	36%	0%

The elements into the room are anyway generally considered as gray bodies, so with an emissivity and an absorption factor to infrared radiation of the 90% ($\varepsilon=\alpha=0,9$) [9]. It means that just the 10% of the IR radiation entering into the room is involved in DWL generation, the remaining 90% is absorbed by opaque elements, then re-emitted after a time lag into the room and so it is involved in SL generation. The 10% of the 36% represent just the 4% of the whole entering radiation, so using a lighting tool to evaluate the F factor, which doesn't simulate UV and IR radiation, it is committed a global error of the 8%, acceptable for engineering applications.
Furthermore, UV radiation has a little contribution to cooling load generation, its energy is principally involved in surface material aging and degradation, and just a little portion of it generates heat [10].
It is obvious that all F values obtained with the lighting tool must be multiplied for a reduction factor (0,6 for a clear glass with thickness of 6mm), in order to be referred to the global radiation, since solar loads values are expressed for the whole solar radiation.
It is interesting to notice that DWL is practically generated only by visible radiation since IR contribute just for the 4% of the entering radiation, when it is considered a clear glass with thickness of 6mm. With other kind of commercial glass this consideration is anyway correct, since the ratio τ_{IRn}/τ_v usually reduces or, at least stays the same.
Within a room with cooling radiant panels, therefore, light reflection factors of surfaces play a fundamental role in DWL, SL and CL generation. A highly reflective room, for instance, will have high Direct Water Loads, and lower Surface Loads. Furthermore peak values of Cooling Load will occur in correspondence with solar gain peak values.
For this particular condition, it is possible to state that part of the thermal inertia of a room is constantly operating with IR radiation, while another slice of it works, or not, in function of the surfaces light absorption and reflection factors. In a room with cooling radiant panels, the effective activation of the room thermal inertia depends therefore not only on the surface thermal resistance of walls, but even on surfaces light reflection factor.
On the contrary it is possible to observe that if room surfaces had lower emissivity, some more IR radiation would be involve in Direct Water Load generation and less in Surface Load generation.

RESULTS

F Value For Solar Radiation

The two analysis tools described before have been used to evaluate the F value for a radiant ceiling, as a function of different light reflection factors of the room floor, and of different room dimensions. All the other room surfaces has been considered with a constant light reflection factor of 70%, corresponding to light paint colours and a metallic ceiling.
In the following graphs, the ratio L/h is used as an adimensional indicator of the room geometry. It grows with the growing of the floor surface, in fact h is the height of the room, while L is the side of the square floor.
The following simulations consider solar radiation for a latitude of 45° North, a full glassed building, and rooms with only one surface facing outside, therefore completely glassed. This is the condition in which it is possible to reach the highest level of DWL, and furthermore it has become very common in office buildings.
The commercial lighting tool can give different F values as a function of the window orientation, because it considers both direct and diffuse radiation. It could be possible to have a F value for each orientation, each hour and day of the year, but it would require huge amounts of simulation time. The reflections method, instead, considers the window like a diffusing light source, so the relative position of the room respect to the sun is not evaluated.