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Experimental evaluation of heat transfer coefficients between radiant ceiling and room

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ABSTRACT

The heat transfer coefficients between radiant surfaces and room are influenced by several parameters: surfaces temperature distributions, internal gains, air movements.

The aim of this paper is to evaluate the heat transfer coefficients between radiant ceiling and room in typical conditions of occupancy of an office or residential building. Internal gains were therefore simulated using heated cylinders and heat losses using cooled surfaces. Evaluations were developed by means of experimental tests in an environmental chamber.

Heat transfer coefficient may be expressed separately for radiation and convection or as one total parameter, but this choice may lead to different considerations about thermal performance of the system. In order to perform correct evaluations, it is therefore extremely important to use the proper reference temperature.

The obtained values confirm tendencies found in the literature, indicating limitations and possibilities of radiant ceiling systems improvement.

1. Introduction

The heat transfer coefficients are fundamental parameters for heating/cooling load calculations, thermal comfort analysis, dynamic thermal simulations, CFD analysis and dimensioning of radiant systems.

In a study by Loman aimed to compare thermal simulation programs [1], annual heating energy demand estimated by the software ESP and the software HTB2, varied up to 27% depending on the internal surfaces convective heat transfer algorithm used. While using the same heat transfer algorithm in both of the programs, the difference was reduced to 1%.

In the literature, several values and equations of heat transfer coefficients are given between the interior building surfaces (heated, cooled or unheated/uncooled) and the space (other surfaces and air), as resumed and by Khalifa [2–4] and by Awbi and Hatton [5,6].

Usually scientists and developers of simulation software are interested in values or equations of heat transfer coefficients estimated separately for radiation and convection, while to size HVAC systems, and especially radiant systems, a combined coefficient is needed.

These different kinds of coefficients require the use of different reference temperatures, as underlined by Olesen et al. [7], because the radiant coefficient refers to the radiant heat transfer with other surfaces, the convective coefficient to the convective heat transfer with the room air and the total heat transfer coefficient to the mix of radiant and convective heat transfer.

The radiant heat transfer coefficient expresses the radiant heat exchange between a specific surface and all the other surfaces in the room. Depending mainly on parameters that are constant (Stefan–Boltzmann constant, emissivity, view factors), it can be considered constant for any kind of low temperature radiant heating system and high temperature radiant cooling system [7].

The convective heat transfer coefficient expresses the heat exchange between a specific surface and the air boundary layer, therefore it depends on several changing parameters: air velocity, air temperature, turbulence. Several algorithms deduced from experimental tests can be used to define, from time to time, the actual value of this parameter. In the case of radiant surfaces and natural convection, high values of the convective heat transfer coefficient are possible only for: cooled ceiling, heated floor and cooled/heated walls, which are able to generate, through buoyancy forces, air movements inside the room [8]. Instead, in the case of heated ceiling and cooled floor, the convective heat transfer

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Nomenclature

A	area (m^2)
$AUST$	average unheated surface temperature (°C)
c_p	specific heat (J kg^{-1} K^{-1})
$F_{\varepsilon_{s-j}}$	radiation interchange factor [10]
F_{s-j}	view factor between radiant surface and j-surface
h_c	convective heat transfer coefficient (W m^{-2} K^{-1})
$h_{c,h}$	convective heat transfer coefficient of human body (W m^{-2} K^{-1})
h_r	radiant heat transfer coefficient (W m^{-2} K^{-1})
$h_{r,h}$	radiant heat transfer coefficient of human body (W m^{-2} K^{-1})
h_{tot}	total heat transfer coefficient (W m^{-2} K^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
Q_c	convective heat flux (W)
Q_{out}	backward heat transfer (W)
Q_r	radiant heat flux (W)
Q_{tot}	total heat flux (W)
T_a	air temperature (°C)
T_{ad}	adjusted air temperature (°C)
T_{mr}	mean radiant temperature (°C)
T_{op}	operative temperature (°C)
T_s	radiant surface temperature (°C)
T_j	j-surface temperature (°C)
T_{ref}	Reference temperature (°C)
ΔT_w	Temperature difference between water inlet and outlet (°C)
ε	Emissivity
σ	Stefan–Boltzmann constant (W m^{-2} K^{-4})

Subscript

a	air
a 0.1	air at 0.10 m
a 1.1	air at 1.10 m
a 1.7	air at 1.70 m
c	convective
h	human body
j	j-surface
r	radiant
s	radiant surface
tot	total

coefficient has low values, because few air movements are generated. Under these conditions a stable thermal stratification occurs inside the room [5].

The total heat transfer coefficient expresses the radiant and convective heat transfer between a specific surface and the room, but it cannot be calculated as the sum of the previous two coefficients because they refer to different physical phenomena, so they have different reference temperatures. While the convective heat transfer coefficient is physically defined as the surface conductance between a surface and the boundary layer, the linear radiant transfer coefficient is just a theoretic parameter, created to compare radiant heat transfer to convective heat transfer in multimode heat transfer phenomena calculations, but it has not a physical definition, since radiation does not follow a linear model [9].

In this study the heat transfer coefficients of a radiant ceiling are presented. The evaluation of the coefficients was developed using a test chamber, which simulates typical conditions of occupancy in an office or residential room. Values are compared to the ones found in the literature, underlining the importance of the choice of the reference temperature, both during tests and in the further calculations when coefficients are used.

2. Reference temperatures

The reference temperature for the calculation of the radiant heat transfer coefficient is the average unheated surface temperature (AUST) calculated taking into account the view factors between surfaces [10,11]. The AUST can be also calculated as the area-weighted average temperature [10], but the calculation with view factors is more precise.

The radiant heat transfer coefficient can be calculated from the net heat transfer among the studied surfaces and the surrounding surfaces.

$$\frac{\dot{Q}_r}{A} = \sigma \sum_{j=1}^{n} F_{\varepsilon_{s-j}} (T_s^4 - T_j^4) \tag{1}$$

$$F_{\varepsilon_{s-j}} = \frac{1}{[(1-\varepsilon_s)/\varepsilon_s] + (1/F_{s-j}) + (A_s/A_j)[(1-\varepsilon_j)/\varepsilon_j]} \tag{2}$$

$$h_r = \frac{\sigma \sum_{j=1}^{n} F_{\varepsilon_{s-j}} (T_s^4 - T_j^4)}{AUST - T_s} \tag{3}$$

$$AUST = \sqrt[4]{\sum_{j=1}^{n} (F_{s-j} T_j^4)} \tag{4}$$

The reference temperature for the calculation of the convective heat transfer coefficient, is the air temperature at the edge of the thermal boundary layer, beyond it the air temperature remains essentially constant. The coefficient can be calculated through several algorithms as resumed and by Khalifa [2–4] and by Awbi and Hatton [5,6].

The reference temperature for the calculation of the total heat transfer coefficient is not yet clearly defined. Since it expresses both the radiant and convective heat transfer between a studied surface and the room, the most appropriate reference would be the operative temperature (Table 1). It must be anyway noticed that this is just a practical solution useful to calculations, but it does not help in representing the physical phenomena occurring in the room that must be divided for radiation and convection using separate reference temperatures.

As suggested by Olesen et al. [7], the operative temperature would be a convenient solution as reference for the total heat transfer coefficient, also because it is used as reference for thermal comfort analysis. Furthermore, in EN Standard 12831 [12], the use of operative temperature is suggested also for heat load calculations.

The operative temperature, for comfort analysis, is expressed by the following equation:

$$T_{op} = \frac{(h_{c,h} T_a) + (h_{r,h} T_{mr})}{h_{c,h} + h_{r,h}} \tag{5}$$

In this equation the air temperature and the mean radiant temperature are measured or calculated in a reference point at

Table 1
Heat transfer coefficients and reference temperatures.

Heat transfer equation	Heat transfer coefficient	Reference temperature (T_{ref})
$(\dot{Q}_r/A) = h_r(T_{ref} - T_s)$	h_r	$AUST$
$(\dot{Q}_c/A) = h_c(T_{ref} - T_s)$	h_c	T_a
$(\dot{Q}_{tot}/A) = h_{tot}(T_{ref} - T_s)$	h_{tot}	T_{op}