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Characteristics of Convective and Radiative Heat Transfer in the Ceiling of TABS

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Abstract

Generally, in a room with thermally active building systems (TABS), thermal load is removed through an effective heating or cooling surface to maintain a set-point temperature of the room, and the characteristics of radiant temperature distribution of the room are thus changed according to the interior load fluctuation. Thus, because discomfort can result in cases of radiant asymmetry between surfaces, it is necessary to consider characteristics of heat transfer on the surface of the ceiling related to the operative temperature as the reference temperature during the design process. The radiant and convective heat transfer between the ceiling and the other surfaces is commonly influenced by several parameters, such as the shape of the surroundings, interior air stratification and air velocity. Because convective and radiant heat transfer coefficients between a heating/cooling surface and the room have different physical behaviors and are calculated with different reference temperatures, it is very important to determine an appropriate reference temperature when calculating the total heat transfer coefficient. Furthermore, the operative temperature can also be the reference temperature when considering the thermal comfort condition. Additionally, for the thermal output calculation of TABS during the design process, the surface heat transfer characteristics should be considered according to the room conditions. This study aims to analyze the characteristics of convective and radiative heat transfer in the ceiling of TABS, which can affect the operative temperature related to occupants' thermal comfort. For this purpose, as a ground work for calculating heat transfer between radiant surfaces and the room with TABS in the future, we have reviewed the definition, basic equations of convective and radiant heat transfer coefficients, for which the reference temperatures are the air temperature and the average unheated surface temperature (AUST), respectively and the reference temperatures. Then, we have analyzed several standards and literatures regarding the heat transfer coefficients and reference temperature. Finally, we determined key parameters that considered important in the existing standards and studies and it will be helpful to recognize and comprehend the characteristics of radiant and convective heat transfer.

Keywords – Heat Transfer Coefficient, Operative Temperature, Radiant Ceiling, TABS

1. Introduction

According to several studies concerned with heat transfer between radiant surfaces and the room, many researchers have focused on the characteristics of convective and radiant heat transfer. Because those forms of heat transfer are mainly related to their coefficients, it is very important to determine the coefficients to be chosen.

Convective and radiant heat transfer coefficients between a heating/cooling surface and the room are necessary for analyzing thermal comfort, calculating the thermal load, dimensioning the appropriate system for the space and so on. These coefficients are influenced by several parameters: shape of the surroundings, interior air fluctuation, occupancies of the space and so on. Because convective and radiant heat transfer coefficient exhibit different physical behavior as mentioned above, if there are some influences by such parameters, not only radiant asymmetry but also occupant's discomfort can occur. Therefore, consideration of the parameters is an important process for determining heat transfer coefficients.

Generally, in a room—especially with Thermally Active Building Systems (TABS)—thermal load is removed through effective heating or cooling to balance its load fluctuation, the symmetry of heat transfer and the thermal comfort of the occupants. A TABS removes heating/cooling load through the structure of the building by storing or radiating heat using pipes embedded in the concrete slab and also reduces peak load by using the time lag. Recently, this system has been widely introduced to buildings such as large-sized buildings, convention centers and so on as a technology for energy savings, although few cases have yet been implemented in Korea.

In terms of the design process, convective and radiant heat transfer coefficients are calculated with different reference temperatures when calculating the total heat transfer coefficient. Normally, the operative temperature (T_{op}) can be considered for the thermal comfort condition, and the air temperature (T_a) and average unheated surface temperature (AUST) are the reference temperatures for convective and radiant heat transfer coefficients, respectively.

As a groundwork for calculating the heat transfer between radiant surfaces and the room with TABS, this study aims at analyzing parameters in several studies and various literature that directly influence the radiant and convective coefficients. We have reviewed the meaning and the basic equations of convective and radiant heat transfer coefficients and also grasped related reference temperatures and parameters. Finally, we have analyzed the main parameters for each coefficient and determined which parameters should be mainly considered.

2. Theoretical Analysis of Related Coefficients

If there are any occupants in an interior space, the human body directly absorbs or releases radiant heat from the indoor surfaces. In this case, among the route of heat

release in the human body, heat transfer by radiation represents approximately 50%; therefore, it is very important to apply an appropriate indoor heating and cooling system. When a system is applied indoors, the predicted mean vote (PMV) that a human body can feel from radiant surfaces can be expressed by Mean Radiant Temperature (MRT), and this index can be verified according to the shape of the space such as W/D ratio, height and so on. The MRT has an influence on the operative temperature (T_{op}), which provides immediate thermal comfort to the human body. That is, a radiant heating and cooling system adjusts the operative temperature to the occupants' requirements by controlling the MRT.

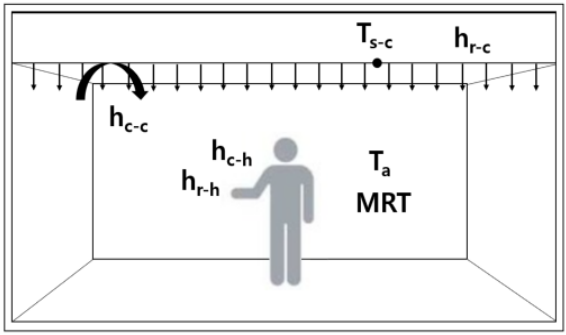

Fig. 1. Schematic design for representing physical quantity of heat transfer in a room with TABS

In this context, there is a schematic concept of several design parameters representing a room with TABS (Figure 1). In the figure, radiant and convective heat transfer coefficient of ceiling and human are expressed as h_{r-c}, h_{c-c}, h_{r-h} and h_{c-h} respectively and T_{s-c} and T_a as surface temperature of ceiling and the air temperature of the room, respectively.

2.1. Classification of heat transfer coefficients

When describing heat transfer in a room with TABS, values for radiative heat transfer coefficient, convective heat transfer coefficient and combined heat transfer coefficient are required. Firstly, the convective heat transfer coefficient (h_c) is usually related to the air movement within the space or by movement of human. There can be several equations for convective heat transfer coefficient under various conditions such as the status of human (seated/reclining/walking/active/standing) and air (moving/still). Additionally, this values are significant not only for estimating convective heat loss but for evaluating operative temperature (T_{op}).

Next, radiative heat transfer coefficient (h_r) is the value related with the status of person(sitting/standing), emissivity (ε) of the materials and especially with average unheated surface temperature (AUST).

Finally, the combined heat transfer coefficient ($h_{combined}$) is the summation of radiative and convective heat transfer coefficient. This value controls exchange by radiation and convection from surface of human body to the surroundings.

2.2. Classification of reference temperatures

The average unheated surface temperature (AUST) is a reference temperature for the calculation of the radiant heat transfer coefficient and can be calculated by considering the area of the surrounding (Equation 1).

$$h_r = \frac{\dot{Q}_r}{A(AUST - T_s)} \tag{1}$$

Q_r: radiant heat flux (W)

T_s: temperature of radiant surfaces (℃)

A: area

The air temperature (T_a) would be a reference temperature for the calculation of the convective heat transfer coefficient, which is directly influenced by relative air velocity and usually remains as a constant (Equation 2).

$$h_c = \frac{\dot{Q}_c / A}{T_a - T_s} \tag{2}$$

Q_c: convective heat flux (W)

With the mean radiant temperature (MRT), the radiant interchanges in a room is modeled by assuming that the surfaces radiate to fictitious surfaces with an area emittance and temperature that result in approximately the same heat transfer as the real multi-surface case (Equation 3).

$$MRT = \frac{A_1 T_1 + A_2 T_2 + A_3 T_3 + \cdots}{A_1 + A_2 + A_3 + \cdots} \tag{3}$$

A_n: area of surrounding surfaces (m^2)

T_n: temperature of surrounding surfaces (K)

Another methodology for calculating MRT is that the value of MRT can be determined by the shape of human body and surrounding and temperature of the surroundings surfaces (Equation 4).

$$MRT = \sqrt[4]{\sum_{i=1}^{n} \varnothing_{b,si} \cdot T_{si}^{4}} \quad (4)$$

$\Phi_{b,si}$: Shape factor between human body and surrounding surfaces
T_{si}: Temperature of surrounding surfaces (K)

The operative temperature (T_{op}) is a reference for thermal comfort analysis and therefore is related to the convective and radiant heat transfer coefficient of the human body. Because it considers both coefficients, the operative temperature is also usually involved in the calculation of the total heat transfer coefficient (Equation 5). .

$$h_{tot} = \frac{\dot{Q}_{tot}/A}{T_{op} - T_s} \quad (5)$$

3. Analysis of the Heat Transfer Coefficient

According to the ASHRAE Fundamentals [1], the radiative heat transfer coefficient is related with the human body. As the average emissivity of clothing or body surface or the ratio of effective radiation area of body (A_r) to area of Dubois (A_D) has been changed, the value of coefficient is also changed. The A_r/A_D is 0.70 for a sitting person and 0.73 for a standing person (Fanger1967), and the emissivity ε is close to unity (typically 0.95) unless special reflective materials are used or high-temperature sources are involved.

F. Causone [4] experimentally evaluated the heat transfer coefficients between radiant surfaces and the room. Causone considered the coefficients as a matter of the different reference temperatures because they may perform differently according to the system applied to the room. The radiant heat transfer coefficient is related to the average unheated surface temperature (AUST) as a reference temperature considering the view factors between surfaces. Next, the convective heat transfer coefficient is calculated with the air temperature at the edge of the thermal boundary layer. Finally, the reference temperature for the total heat transfer coefficient that considers convection and radiation simultaneously is not yet clearly defined, but the operative temperature would be appropriate.

A.J.N. Khalifa [5] investigated the natural convective heat transfer coefficient on isolated vertical and horizontal surfaces in both laminar and turbulent regimes. These correlations were mainly produced as Nusselt vs. Rayleigh correlations as a function of temperature difference for different surface orientations. With regard to the functional form of the correlations, most correlations are reported in the standard classical form $h= C(\Delta T)^n$ with the index n being 1/4 for the laminar regime and 1/3 for the turbulent

Table 1. Classification of heat transfer coefficients

	h_c		h_r		h_{total}
[1]	$14.8\,V^{0.69}(0.15 < V < 1.5)$ $4.0(0 < V < 0.15)$		$4\epsilon\sigma\frac{A_r}{A_D}(273.2+\frac{t_{cl}+\overline{t_r}}{2})$		$h_c + h_r$
[2]	Depends on the system type		Depends on the system type		$\frac{h(t_a - t_u)}{t_a - t_o}$
[3]	Air–ceiling	$\frac{h_A \text{ or } h_C}{A_F}$	Floor–ceiling	$\frac{h_F}{A_F}$	-
	Air–floor	$\frac{h_F}{A_F}$	Floor–walls	$\frac{h_F}{A_F}$	
	Air–walls	$\frac{h_{IWS} \text{ or } h_A}{A_W}$			
[4]	$\frac{\dot{Q}_c/A}{T_a - T_s}$		$\frac{\sigma\sum_{j=1}^{n} F_{\epsilon_{s-j}}(T_s^4 - T_j^4)}{AUST - T_s}$		$\frac{\dot{Q}_{tot}/A}{T_{op} - T_s}$
[5]	$C(\triangle T)^n$		-		-
[6]	$C(WLH)\triangle T N_u R_a P_r$		-		-
[7]	Wall	$\frac{1.823}{D^{0.121}}(\triangle T)^{0.293}$	-		-
	Floor	$\frac{2.175}{D^{0.076}}(\triangle T)^{0.308}$			
	Ceiling	$\frac{0.704}{D^{0.601}}(\triangle T)^{0.133}$			
[8]	$\left\{(h_{cn})^{3.2} + (h_{cf})^{3.2}\right\}^{1/3.2}$		-		-

<Nomenclature>

A: surface area (m^2)
C: constant
D: hydraulic diameter
F: interchange factor
h: heat transfer coefficient
H: height (m)
L: length (m)
Nu: nusselt number
Pr: Prandtl number
Q: heat flux(W)
Ra: Rayleigh number
t: mean temperature (K or ℃)
V: relative air velocity (W/m^2K)
W: width (m)
σ: Stefan–Boltzmann constant, 5.67×10^{-8}, $W/(m^2/K^4)$

<subscript>

A: air
c: convection
cn: natural convection
cf: forced convection
cl: clothed body
C: ceiling
D: Dubois
F: floor
IWS: internal wall surface
j: j-surface
o: outside
r: radiation
s: surface
u: inside surface of outside wall
W: wall
ε: average emissivity of clothing and body surface, dimensionless

regime. In addition, the values of discrepancies are found to be up to a factor of 2 for isolated vertical surfaces, up to a factor of 4 for isolated horizontal surfaces facing upward, and up to a factor of 4 for isolated horizontal surfaces facing downward.

A.J.N. Khalifa [6] suggested natural convective heat transfer coefficients on the surfaces in two- and three- dimensions. Khalifa revealed that available correlations are mostly affected by the size of the enclosures (width × length × height), the type of fluid used, the temperature difference, the configuration and aspect ratio, the Rayleigh number (R_a) range and the Prandtl number (P_r) range. The Rayleigh number is a dimensionless number that determines whether heat convection occurs in a layer of fluid, and the Prandtl number (P_r) is also a dimensionless number used in the calculation of heat transfer and represents the ratio of the viscosity and thermal conductivity of certain materials. If the value of Prandtl number (P_r) decreases, the occurrence of convection increases. In conclusion, a correlation for an isolated surface is unsuitable for an enclosure in a real environment and has a strong relation with the value of temperature differences.

H.B. Awbi [7] studied the surface convective heat transfer coefficients (CHTCs) for isolated surfaces. Awbi identified the possible parameters to be the shape of the enclosure; the surface temperature distribution; the presence of forced air movement caused by draughts, people, fans and other devices such as radiators; underfloor heating; solar gains and the roughness of the surfaces of real buildings in natural convection. The heat transfer coefficient can be obtained by dividing the convection heat output (W) by the product of the area of heated surfaces (m^2) and the temperature difference between the inside surface and the air. Moreover, the coefficients of each

surface are strongly related with the hydraulic diameter (m) and the surface-to-air temperature difference (K).

H.B. Awbi [8] investigated the mixed convection from heated room surfaces in a mechanically ventilated room. In a room with a mechanically ventilated system, the movement of the air is significantly greater, and great convective loss could be expected. Forced convection is especially concerned with the heat transfer between a flowing fluid and solid surfaces in which the motion of fluid is caused by external factors. Therefore, the mean heat transfer coefficient for mixed convection could be presented in terms of the limiting cases of natural and forced convections.

4. Determination of Key Parameters

As we analyze the heat transfer coefficient of convection and radiation through eight literatures above, we found out that several parameters can affect significantly the heat transfer coefficient. For the coefficient of convective heat transfer, temperature and the shape of the surface, air temperature (T_a) and the air velocity are the key parameters. And for the radiation, surface area and surface temperature, especially the averaged unheated surface temperature (AUST), are perceived as the main parameters to be focused on. And finally, for the coefficient of the total heat transfer coefficient, we can consider influential parameters both for convection and radiation.

5. Conclusions

In this study, we recognized the fundamental information of definition, reference temperature and related equation for heat transfer coefficient of convection and radiation and we finally found out key parameters which affect each coefficients. Therefore, with the conclusion through this study, we would verify how parameters differently in the future.

Acknowledgments

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