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Experimental investigation of energy-optimum radiant-convective heat transfer split for hybrid heating systems

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ABSTRACT

In this study, indoor radiant-convective heat transfer split of hybrid heating systems has been experimentally investigated in order to quantify the advantages of hybrid heating systems for thermal comfort in terms of operative temperature for thermal comfort and energy consumption. Operative temperature is a key parameter which is a function of indoor surface temperatures, clothing, air movement and dry-bulb air temperature. Controlled experiments were carried out in a special test chamber which was constructed according to ANSI/ASHRAE Standard 138. In this test chamber all interior surface temperatures and the dry-bulb air temperature were independently controlled. Two different types of electric fan heaters, with equal heating capacities but different fan powers, were hybridized with hydronic floor heating. In the series of experiments; fan heaters and the floor heating system were operated with different heating capacities simultaneously and hereby radiant-convective split was varied where the corresponding energy consumptions were recorded. During the process of obtaining the optimum radiant-convective heat transfer split; human comfort and energy consumption parameters were analyzed in terms of the operative temperature and exergy. According to the results of the experimental data and operative temperature-based optimization, optimum interval of radiant-convective split has been found to be between 0.65 and 0.75.

1. Introduction

In recent years, technology has developed rapidly and human life has complicatedly integrated with the technology in a complex form. As a result of this integration, life style has changed dramatically and humans started to spend their almost 90% of their time indoor environment. Therefore, thermal comfort becomes a real necessity rather than a luxury and HVAC systems have become significant portion of the total energy consumption of buildings. In order to increase the performance without compromise on thermal comfort, buildings need to reduce their exergy demand besides the energy demand [1,2].

One way of reducing the amount of exergy demand is to satisfy by decoupling latent and sensible loads. By decoupling these loads, each load or HVAC function can be satisfied by the most appropriate and exergy balanced source. By using hybrid (load-sharing) HVAC systems, almost all of the sensible loads can be satisfied by waste heat or other low-enthalpy energy resources, high quality energy can be required to satisfy only latent loads and/or indoor air quality needs. Thus, fan capacities and high quality energy requirement will also be largely reduced and that amount can be directly satisfied by renewable energy sources [1,3,4].

HVAC systems, generally, rely on only radiation or only convection as the dominant heat transfer mechanism. Every HVAC system and heat transfer mode has a specific range of efficient and economical operation, with its own restrictions, advantages and disadvantages. To use advantages of each system simultaneously, it may be more profitable to decouple different components of indoor conditioning and supply them by dedicated systems. A radiant panel and a forced air system may be hybridized in a practical application. A typical residential hybrid HVAC system scheme shown in Fig. 1 [4].

Panels can satisfy only sensible loads thus a stand-alone panel system generally requires separated dehumidification and ventilation systems. On the other hand, forced-air systems can satisfy both sensible and latent loads but these systems cannot control

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Nomenclature

$A_{1,2,3,4}$	Interior surface areas of the test chamber walls, m^2
A_c	Interior surface area of the test chamber ceiling, m^2
A_f	Interior surface area of the test chamber floor, m^2
A_{po}	Sum of thermally active surface areas of an ANSI/ASHRAE standard 138 test panel, m^2
AUST	Area-weighted temperature of all indoor surfaces of walls, ceiling, floor, windows, doors, etc. (excluding active panel surfaces), °C
D	Diameter of the black globe, m
DOAS	Dedicated outdoor air systems
e	Emissivity of the black globe surface, dimensionless
h_c	Convective heat transfer coefficient, W/m^2 K
h_r	Radiant heat transfer coefficient, W/m^2 K
PR	Radiant-convective heat transfer split, dimensionless
q	Total heat flux, W/m^2
q_{adj}	Adjusted (for $T_{lab\text{-}ref}$) heat loss from test chamber to the enclosing laboratory during the j^{th} test, W/m^2
q_c	Convective heat flux, W/m^2
q_j	Total heat loss from the test chamber to the laboratory during the j^{th} test, W/m^2
q_r	Radiant heat flux from effective radiant panel surface to other surfaces, W/m^2
REMM	Rational exergy management model
$T_{1,2,3,4}$	Average interior surface temperature of the test chamber walls, °C
T_a	Dry-bulb air temperature, °C (K for eq. (11))
T_{app}	Energy source temperature, K
T_c	Average interior surface temperature of the test chamber ceiling, °C
T_f	Average interior surface temperature of the test chamber floor, °C
T_g	Ground temperature, K
T_{gl}	Black globe sensor temperature, °C
T_i	Average dry-bulb air temperature of the test chamber, °C
$T_{i\text{-}j}$	Average dry-bulb air temperature of the test chamber during the j^{th} test, °C
T_{lab}	Average dry-bulb air temperature of the laboratory, °C
$T_{lab\text{-}j}$	Average dry-bulb air temperature of the laboratory during the j^{th} test, °C
$T_{lab\text{-}ref}$	Reference dry-bulb air temperature of the laboratory, °C
T_{mr}	Mean radiant temperature, °C (K for eq. (11))
T_o	Operative temperature, °C
T_p	Effective panel surface temperature, °C
T_{po}	Average temperature of the thermally effective surfaces of a ASHRAE std. 138 test panel, °C
V_a	Air velocity, m/s
ε_{act}	The actual exergy destruction, dimensionless
ε_{min}	The minimum exergy requirement, dimensionless
ψ_R	Rational Exergy Management Model (REMM) Efficiency, dimensionless

mean radiant temperature which is one of the key parameter for human thermal comfort [1,2,4].

Panel systems may be combined with a forced-air system and these combined systems are called hybrid (load-sharing) HVAC systems. Hybrid HVAC systems can control directly both air temperature and mean radiant temperature, which are the important parameters of operative temperature. Therefore hybrid systems can control operative temperature directly [1,2,4].

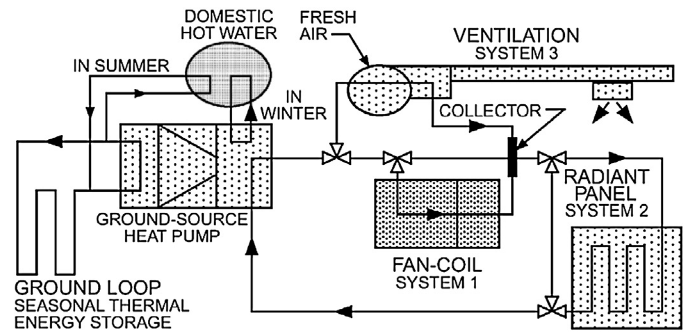

Fig. 1. Typical residential hybrid HVAC system scheme [4].

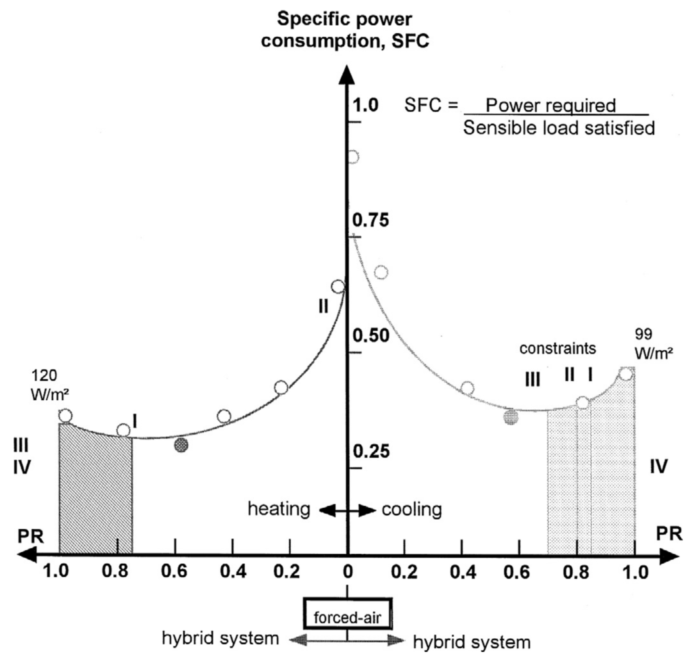

Fig. 2. Merit of hybrid system (MOH) diagram for sample design [3,5].

In hybrid HVAC systems, both radiant and convective heating/cooling sub-systems are operated simultaneously. Thus air temperature and mean radiant temperature, which are the parameters of operative temperature, can be controlled independently. Moreover, thermal comfort can be satisfied optimally according to both quantity and quality of energy.

Kilkis et al. [3,5] designed a hybrid system for The Ankara Museum of Ethnography (Turkey) [3,5]. They investigated the optimum radiant to convective heat transfer split ratio for hybrid HVAC systems analytically. According to their optimization results, the hybrid system had minimum specific power consumption when the panel ratio (radiant-convective heat transfer split), *PR*, (see Eq. (3)) is 60%. The optimization diagram is presented in Fig. 2 [3,5].

Within the scope of ASHRAE research project RP-1140, a single story adobe house, with a floor space of 232 m^2 (2500 ft^2), was built and the hybrid system was tested. The project has successfully demonstrated coupling of radiant heating/cooling panels, convective ventilation and dehumidification system, to achieve year around thermal comfort and reduce energy consumption [6].

Kilkis [2,7] has developed and investigated exergy based life cycle cost analysis of a composite (hybrid) radiant wall panel (CRWP), which collectively performs heating, ventilating and air-conditioning tasks and can also be directly supplied by low-