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Cost optimization of a hybrid HVAC system with composite radiant wall panels

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Abstract

A composite radiant wall panel was developed, which collectively performs heating, ventilating, and air-conditioning tasks at moderate temperatures such that low-enthalpy energy resources can be directly utilized. This technology eliminates the need for costly equipment over sizing and supply temperature conditioning, which are all associated with conventional heating and air-conditioning systems if low-enthalpy energy resources are to be used. An analytical life cycle cost minimization algorithm was used to optimize the new technology, which can cluster heat pipes, heat pumps, wind turbines, solar collectors, and desiccant cooling units around it using any waste or alternative energy source. Results indicate that with an optimum design, wherever low-enthalpy energy resources are readily available, this system may cost effectively reduce the fossil fuel dependency and harmful emissions of buildings.

Keywords: Hybrid HVAC system; Radiant panel; Wind energy; Green buildings; Heat pipes; Desiccant cooling; Exergy efficiency; Heat pipe; Heat pump

1. Introduction

Composite Radiant Wall Panel Technology (CRWP) optimally combines thermal radiation, natural and forced convection to establish human comfort by a single-source system. Energy saving, high exergy efficiency, more uniform indoor air distribution, and complete zoning capability are the main attributes. Preliminary results for a design case indicate that, when coupled to ground heat, this technology may reduce heating and air-conditioning loads by as much as 40%, increase overall thermal efficiency by 12 percent points, and improve exergy efficiency by more than 50 percent points in a typical house. Consequently, fossil fuel dependency may be reduced by about 90%. The capital cost of a CRWP when directly coupled to a waste energy source is equal to the capital cost of a central forced-air conditioning system. When the CRWP system is tied to alternative or waste energy sources through heat pumps and or heat pipes, the capital cost is 30% higher. However, the low operating cost, which generally is one-fifth, quickly recovers the additional capital cost. All these attributes lead to a greener and cheaper sustainable building technology and safer environment.

This technology also facilitates the direct and economical use of solar, wind, and other alternative energy resources in buildings and establishes a more suitable platform for combined heat and power (CHP) systems with higher thermal and exceptionally higher exergy efficiencies.

2. Theory

2.1. Exergy efficiency and the environment

Environmental concerns, foreign dependence and the depleting nature of fossil fuels make the exergy efficiency

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Nomenclature

AER	alternative energy ratio, dimensionless
c	thermal capacity coefficient for HVAC equipment, W/K^n
C	life cycle cost, \$/W-h
C_{hp}	life cycle cost factor for heat pipe at rated conditions, \$/W-h
C_{cw}	life cycle cost factor for composite radiant wall panel, \$/W-h
C_e	life cycle cost factor of exergy production by an HVAC system, \$/W-h
C_1	temperature coefficient ($T_{fhp} - T_a$,), K
C_2	temperature coefficient ($T_{fcw} - T_a^n$), K^n
COP	coefficient of performance, dimensionless
D_i	inside diameter of the hydronic tube or heat pipe, m
j	thermal capacity coefficient for heat pipe, W K
M	hydronic tube or heat pipe spacing on centers in the composite radiant wall panel, m
SF	size factor, dimensionless
q	total heat flux at the composite radiant wall panel surface, W/m^2
Q	thermal energy, W-h
r_p	composite wall thermal resistance, m^2 K/W
r_t	thermal resistance of hydronic tube wall per tube spacing, m K/W
T_a	dry-bulb indoor air design temperature, K
T_f	average fluid temperature, K
T_{fcw}	rated average fluid temperature of the HVAC equipment, K
T_{fhp}	rated average fluid temperature of the heat pipe, K
T_g	ground temperature, K
T_o	outdoor design air temperature, K

Subscripts

a	indoor air
A	alternative energy source
act	actual
cw	composite wall
e	exergy
D	demand
f	fluid
g	ground
hp	heat pipe or heat pump
o	outdoor
opt	optimum, optimal
t	tube
min	minimum

Superscript

n	exponent in Eq. (5)

Greek symbols

ε	exergy production, dimensionless
ψ	exergy efficiency, dimensionless

the prime engineering factor, which addresses both the rational utilization of energy resources and the protection of the environment. Buildings are responsible for about 39% of the annual US primary energy consumption and more than 70% of the total electric power consumed [1]. In addition, buildings rely primarily on high-enthalpy fossil fuels for heating, ventilating, and air-conditioning (HVAC). Therefore, their exergy efficiency is less than 10% [2,3]. This contrast shows that developing new HVAC systems with higher exergy efficiencies is a timely need. One way to address this need is to directly utilize low-enthalpy waste and alternative energy resources in new, compatible HVAC systems. Exergy (second-law) efficiency ψ of the building HVAC system is the ratio of the minimum exergy required for a given HVAC function to the actual exergy produced in satisfying that function:

$$\psi = \frac{\varepsilon_{min}}{\varepsilon_{act}} \tag{1}$$

The minimum exergy required ε_{min} is calculated from the efficiency of a Carnot cycle between the indoor space at design air temperature T_a and the temperature of the environment. For a system, which utilizes outdoor air, environment reference temperature is the air design temperature T_o. If the ground heat is utilized, then environment reference temperature is the ground temperature T_g. In the latter case, the minimum exergy required is given by Eq. (2).

$$\varepsilon_{min} = \left(1 - \frac{T_g}{T_a}\right) \tag{2}$$

For example, if the ground temperature for an HVAC system utilizing ground heat is 278 K (5 °C) in winter, and the indoor design air temperature is 291 K (18 °C), ε_{min} is:

$$\varepsilon_{min} = \left(1 - \frac{278}{291}\right) = 0.0447$$

For an HVAC system, the actual exergy produced is calculated using the energy source temperature and the environment reference temperature. For example, if a natural gas furnace at a flame temperature of 1273 K