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Theoretical analysis of the performance of different cooling strategies with the concept of cool exergy

Ongun B. Kazanci [a, *], Masanori Shukuya [b], Bjarne W. Olesen [a]

[a] International Centre for Indoor Environment and Energy – ICIEE, Department of Civil Engineering, Technical University of Denmark, Nils Koppels Allé, Building 402, 2800 Kgs. Lyngby, Denmark

[b] Department of Restoration Ecology and Built Environment, Tokyo City University, 3-3-1 Ushikubo-nishi, Tsuzuki-ku, Yokohama 224-8551, Japan

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A B S T R A C T

The whole chains of exergy flows for different cooling systems were compared. The effects of cooling demand (internal vs. external solar shading), space cooling method (floor cooling vs. air cooling with ventilation system), and the availability of a nearby natural heat sink (intake air for the ventilation system being outdoor air vs. air from the crawl-space, and air-to-water heat pump vs. ground heat exchanger as cooling source) on system exergy performance were investigated.

It is crucial to minimize the cooling demand because it is possible to use a wide range of heat sinks (ground, lake, sea-water, etc.) and indoor terminal units, only with a minimized demand. The water-based floor cooling system performed better than the air-based cooling system; when an air-to-water heat pump was used as the cooling source, the required exergy input was 28% smaller for the floor cooling system. The auxiliary exergy input of air-based systems was significantly larger than the water-based systems.

The use of available cool exergy in the crawl-space resulted in 54% and 29% smaller exergy input to the power plant for the air-based and water-based cooling systems, respectively. For floor cooling, the exergy input to the power plant can be reduced by 90% and 93%, with the use of ground, and use of the ground and the air in the crawl-space, respectively. A new approach to exergy efficiency was introduced and used to prove that the exergy supply from the ground matches well with the low exergy demand of the floor cooling system.

1. Introduction

Tightening targets for energy efficiency and energy use reduction in buildings have had significant effects both on residential and non-residential buildings in Europe [1]. The development of passive, low-energy, near zero-energy, and zero-energy buildings has been stimulated by these regulations and environmental concerns, and nearly zero-energy building (nZEB) levels are dictated for new buildings by 2020 in the European Union [1].

The international focus on the residential sector is increasing, and although the energy performance of buildings has increased, issues with the thermal indoor environment and air quality have been reported in low-energy and passive houses [2–4]. One prominent problem is overheating and it has been reported from Denmark [5], Sweden [3,6], Finland [4], and Estonia [7]. These findings indicate that cooling in residential buildings is becoming more important and almost a necessity.

Air-based or water-based systems can be used to heat or cool buildings. Although different studies have evaluated the performance of air-based and water-based heating and cooling systems for office buildings [8–10], and benefits of radiant panel heating and cooling in net zero-energy buildings [11], so far there has only been little focus on residential buildings and dwellings regarding cooling systems and their exergy performance.

In addition to the insights to different systems by energy analyses, exergy analyses articulate more precisely and accurately the different quality of energy sources and flows. "Cool" and "warm" exergy concepts enable us to quantify and to properly account for the "warmth" and "coolness" of a heat source or sink, and exergy flows from these sources and sinks [12–14].

In this study, the exergy performance of different space cooling systems was compared using a single-family house as a case study.

* Corresponding author.
E-mail address: onka@byg.dtu.dk (O.B. Kazanci).

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The whole chain of exergy flows were considered from the source until the environment. The effects of cooling demand (studied by means of installing internal vs. external solar shading), space cooling method (floor cooling vs. air cooling with ventilation system) including auxiliary exergy use for pumps and fans, and the availability of a nearby cool exergy source (intake air for the ventilation system being outdoor air vs. air from the crawl-space, and air-to-water heat pump vs. ground heat exchanger as cooling source) on the system performance regarding energy, exergy demand and exergy consumption were studied. The cool exergy concept was used to analyze the crawl-space and the ground.

2. Analyzed space cooling systems

The eight different cooling systems that were studied in this paper are described here, before explaining the exergy calculation method that was used to perform the case studies.

2.1. Determination of the design cooling load

The studied house was assumed to be located in Copenhagen, Denmark. Construction details, description and details of the heating, cooling and ventilation systems of the actual house are given in Refs. [15] and [16].

The space cooling load was determined with the assumption of steady-state conditions. The outdoor air temperature was assumed to be 30 °C, which is also the environmental (reference) temperature for exergy calculations. For all cases, the indoor temperature was 26 °C (air temperature and mean radiant temperature). The relative humidity indoors was assumed to be 55%, resulting in a dew point temperature of 16.3 °C.

The house was supported on 30 cm high concrete blocks and this created a crawl-space between the ground and the house's floor structure. When the intake air was taken from the crawl-space, the fresh air temperature coming into the air handling unit (AHU) or to the indoor space was 21.3 °C, due to the pre-cooling of the outdoor air by the ground surface under the crawl-space.

The internal heat gain was assumed to be 4.5 W/m^2 which represents two persons at 1.2 met and other household equipment. For the floor cooling cases, a ventilation rate of 0.5 air change per hour (ach) was used to provide fresh air to the indoors [17]. For the air cooling cases, the supply air flow rate was calculated based on the cooling load. For all cases, an infiltration rate of 0.2 ach was assumed.

For Copenhagen, Denmark (56° Northern Latitude), in July at noon, assumed direct solar radiation on the South and West directions were 390 and 149 W/m^2, respectively, and the diffuse solar radiation was 32 W/m^2 [18]. The shading coefficients for internal and external solar shading were assumed to be 0.6 and 0.1, respectively (blinds, 45° inclination, light colored) [18]. The resulting space cooling loads for different cases are given in Table 2 and Table 3.

Table 1
Summary of the case studies.

Case	Shading	Cooling	Source	Intake air
1	Internal	AC	AWHP	OA
2[a]	External	AC	AWHP	OA
3[a]	External	AC	AWHP	OA
4[a]	External	AC	AWHP	OA
5	External	AC	AWHP	CS
6	External	FC	AWHP	OA
7	External	FC	AWHP	CS
8	External	FC	GHEX	CS

[a] Supply air temperatures and air flow rates are different for Cases 2–4. Further details are given in Table 3. AC: air cooling, FC: floor cooling, AWHP: air-to-water heat pump, GHEX: ground heat exchanger, OA: outdoor air, CS: crawl-space.

2.2. Details of eight cases studied

In order to compare the exergy performance of different cooling systems, the house was assumed to be cooled with a water-based radiant floor cooling system or an air cooling system with the supply of cold air from the air handling unit. The following assumptions were made during the calculation procedure:

- In the actual house, there was a heat exchanger between the radiant system and the heat pump, but for the calculations this heat exchanger was neglected and it was assumed that the water in the floor loops circulated directly through the evaporator of the heat pump. The same was assumed for the air-cooling coil in the AHU.
- The supply air was 100% outdoor air (no recirculation), and the indoor air was assumed to be fully mixed (mixing ventilation).
- It was assumed that there was no heat gain to the floor cooling system, pipes and ducts from the outdoors.

A summary of the investigated cases is given in Table 1, and schematic drawings of the eight cases are given in Fig. 1.

2.2.1. Floor cooling cases

For Case 7 and Case 8, the heat to be removed by the floor was 876 W, and for Case 6 it was 1183 W. This corresponds to a cooling load of 19.5 and 26.3 W/m^2-cooled floor area, respectively, and a corresponding average floor surface temperature of 23.2 and 22.2 °C. In order to achieve these surface temperatures, the required supply and return water temperatures were 18.6 and 21.6 °C for Case 7 and Case 8, and 16.5 and 19.5 °C for Case 6. For all cases, the temperature difference between supply and return water flows was assumed to be 3 °C. For Case 7 and Case 8, this resulted in a mass flow rate of 250 kg/h, and for Case 6 it was 338 kg/h. A floor covering resistance of 0.05 m^2 K/W was assumed for all cases to keep the effects of floor covering resistance on the system performance to a minimum [15].

The cooling output, floor surface temperatures and the mass flow rates were calculated according to [19–22]. The summary of floor cooling cases is given in Table 2.

Table 2
Summary of the floor cooling cases.

Case	Space cooling load [W]	Supply and return water temperature [°C]	Cooled floor surface temperature [°C]	Water flow rate [kg/h]
6	1183	16.5/19.5	22.2	338
7 & 8	876	18.6/21.6	23.2	250

2.2.2. Air cooling cases

The required ventilation rates were calculated based on the space cooling loads and the temperature difference between the supply air and room air temperatures. The water flow rate in the air-cooling coil was calculated based on the heat to be removed from the intake air and the temperature difference in the supply and return water flows to and from the air-cooling coil. The heat to be removed from the intake air corresponds to the required amount of heat to lower the temperature of the intake air to the required