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Radiant floor cooling coupled with dehumidification systems in residential buildings: A simulation-based analysis

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ABSTRACT

The development of radiant cooling has stimulated an interest in new systems based on coupling ventilation with radiant cooling. However, radiant cooling systems may cause condensation to form on an active surface under warm and humid conditions during the cooling season. This phenomenon occurs when surface temperature falls below dew point. To prevent condensation, air humidity needs to be reduced with a dehumidification device or a mechanical ventilation system. There are two main options to achieve this. The first is to use dehumidification devices that reduce humidity, but are not coupled with ventilation, i.e. devices that handle room air and leave air change to infiltrations. The second is to combine a mechanical ventilation system with dehumidifying finned coils.

This study analyzes the floor radiant cooling of a typical residential apartment within a multi-storey building in three Italian climate zones by means of a detailed simulation tool. Five systems were compared in terms of both indoor thermal comfort and energy consumption: radiant cooling without dehumidification; radiant cooling with a soft dehumidification device; radiant cooling with a dehumidification device which also supplies sensible cooling; radiant cooling coupled with fan coils; and radiant cooling with a mechanical ventilation system which dehumidifies and cools.

1. Introduction

Radiant systems are a successful and interesting solution when high comfort levels and low energy-consumption are required. In recent years, applications with embedded radiant surfaces (e.g. floor, ceiling, wall) have become increasingly popular; they were first used for heating purposes, but are nowadays used for cooling purposes, as well.

The main advantage of radiant systems is the low and high temperature of their heat-carrier fluid in heating and cooling mode respectively, which means they can be coupled with renewable or waste energy resources, e.g. heat pumps driven by renewable energy [1]. In these cases, an optimally designed system will be more energy efficient than a traditional system and, as a consequence, CO_2 emissions can be decreased. The use of radiant systems in heating mode has been investigated by several authors [2]. More critical, however, is the use of radiant systems for cooling, especially in warm and humid climates. In these cases, the inlet temperature of the heat-carrier fluid in the radiant systems has to be controlled in order to prevent condensation forming on the radiant surface.

Latent load is a combination of external air moisture and water vapor gain. Several air dehumidification techniques are available, and an independent humidity control system is generally adopted [3]. Radiant systems need to be coupled with an additional system that addresses latent load, balances sensible load, if any exists, and controls the humidity level within the air system [4]. Radiant systems are also typically coupled with a dedicated outdoor air system [5,6] in order to ensure better indoor air quality. Below are some studies on the matter.

Vangtook and Chirarattananon [7] analyzed ceiling radiant cooling under a range of weather conditions in Thailand by means of an experimental and simulation study. They limited the temperature of the fluid supplied to the radiant system to 24 °C in order to prevent condensation forming on the cooling surface; due to this need, the capacity of the radiant ceiling was not sufficient to meet the load during the hot period of the year. However, in that condition the radiant cooling helped to reduce the mean radiant temperature that affects the thermal comfort.

Song et al. [8] investigated a radiant floor cooling system coupled with a dehumidification system which cooled and dehumidified outdoor air before it flowed into an apartment in Korea. They studied the system via both experimentation and computer simulations, finding a suitable control strategy that solved the problem of floor surface condensation.

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Nomenclature

COP	coefficient of performance (W/W)
DC	dehu-conditioner
FC	fan-coil
ID	isothermal dehumidifier
MV	mechanical ventilation
P	thermal power (W)
$P_{Sensible}$	sensible thermal power (W)
P_{Tot}	total thermal power (W)
PMV	predicted mean vote (–)
RF	radiant floor
RH	relative humidity (%)
T	temperature (°C)
U	thermal transmittance (W/(m^2 K))
Super-Subscripts	
cond	condenser
da	dry air
evap	evaporator
in	inlet
out	outlet
v	water vapor
Greek symbols	
τ	time (s)

Salvalai et al. [9] analyzed the energy consumption and thermal comfort performances of an office building by conducting computer simulations for several climate zones in Northern, Central and Southern Europe. They investigated a number of cooling technologies and found that radiant cooling reduced energy consumption and improved thermal comfort. However, a suitable ventilation control strategy was fundamental.

Oxizidis and Papadopoulos [10] compared radiant and convective systems in terms of energy consumption and thermal comfort by carrying out computer simulations of a single office in Thessalonica, Greece. They considered the floor, ceiling and wall radiant surfaces, concluding that hybrid solutions (e.g. a radiant system and an air system) in warm and humid climates ensure low energy consumption and good thermal comfort.

In Italy, the humidity level is much higher than in Northern Europe, and a device to control indoor humidity is therefore essential, as a radiant cooling system must prevent condensation forming on the radiant surface. Current dehumidification systems can be divided into two categories: portable dehumidifiers and dehumidifiers designed specifically to be used with radiant systems. The following systems are purpose-designed for combination with low-temperature radiant systems: isothermal dehumidifiers and dehu-conditioners. In these devices, the thermodynamic cycle is combined with water, which ensures radiant systems perform more effectively than traditional dehumidifiers and employ less power. Traditional dehumidifiers are very common, especially in residential buildings. Other HVAC systems that can be coupled with radiant systems include mechanical ventilation devices with supplemental dehumidification, and fan coils. This paper analyzes radiant floor cooling integrated with dehumidification devices for an apartment in three Italian climates, in terms of thermal comfort and energy performance.

2. The numerical model

Hourly computer simulations based on the test reference years were carried out to evaluate the performance of cooling and dehumidification systems in apartments, in terms of both thermal comfort and energy consumption. To achieve this, the DigiThon multi-room model [11] was used. This model is based on the transfer function method [12] and it simulates all types of radiant system, since respective transfer functions can be pre-calculated via a detailed two-dimensional model based on the finite-difference or finite-element methods. It also considers the full thermal balance [13] for each room, taking into account internal loads, solar radiation, ventilation and infiltration. Below is a brief description of the model's approach; the interested reader can find further details on the DigiThon model in Ref. [11], where a validation of the model with test measurements is also reported.

In the DigiThon model, each room surface can contain sub-surfaces (named *regions*), e.g. a window or a part of the wall made of different materials. Each sub-surface is discretized by means of elements, named *tiles*, corresponding to inner and external surface thermal nodes. When a radiant system has been installed, fluid thermal nodes are added to account for the heat-carrier fluid within the pipe. Finally, the air thermal node is considered for the room's entire air volume, which is assumed to be completely mixed. Thermal balance is noted for each of the room's thermal nodes; this leads to the formulation of a linear system of equations, which can be easily solved step-by-step. The temperature of each thermal node is calculated, after which the heat flow is also calculated.

The DigiThon model also simulates adjacent rooms. In this case, each room is solved one-by-one via a calculation of the internal surface temperature of the corresponding tile for the adjacent room (when clearly established), which is used as a boundary condition on the external surface. In order to ensure that results do not depend on the order in which the rooms are calculated, the boundary condition is evaluated at the previous time step. At time step τ, at the external thermal node of tile *N* in *Room* 1, the internal surface temperature of the adjacent tile (i.e. tile *M* in *Room* 2) is applied in accordance with Eq. (1) (see Fig. 1). This approach allows us to reduce the computational time of the simulation since the

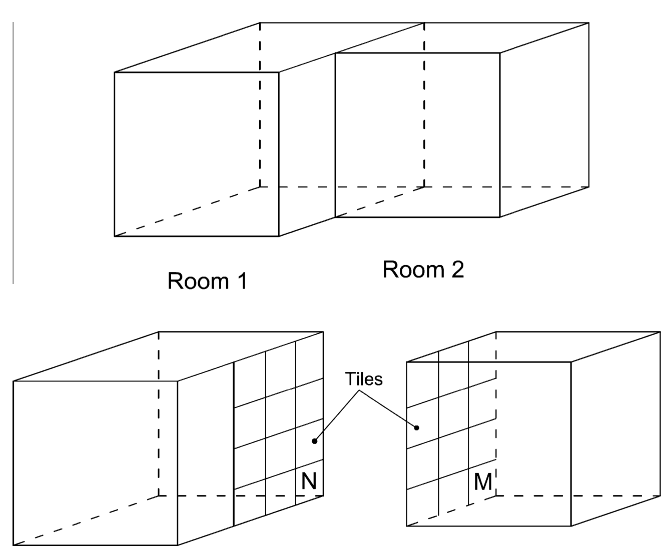

Fig. 1. The multi-room model approach.