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Thermal optimization and performance analysis of an innovative wooden radiant heating system made for room temperature control—Laboratory and numerical investigation of prototypes

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ABSTRACT

The development of an innovative radiant heating system, made for room temperature control, requires extended laboratory and numerical analysis. The multilayered wooden structure design in particular is a challenging aspect due to thermal and hygric transport processes. This article focuses on a thermal optimization process, which aims at increasing the heating performance of first panel prototypes.

In a first step, a numerical analysis was performed evaluating design parameters, which contribute to an efficient heating curve of the system. Subsequently, prototypes were defined and produced in pilot plant scale. Comprehensive measurements, performed within a climate chamber, focused on an investigation of hygrothermal transport processes within the wooden panel. Surface temperatures were measured by means of an infrared thermographic camera and temperature sensors. Furthermore, surface heat flux was recorded and relative humidity was measured at defined positions within the panel's cross section. The obtained data sets contribute to a calibrated numerical model, which takes into account anisotropic material properties. Additionally, dimensional stability was analyzed within a double climatic chamber.

An optimized panel variant is found to have an average surface temperature 3.4 °C higher than a first prototype. Additionally, considering anisotropic material properties within a numerical model allows for the optimization of energy transport processes.

1. Introduction

Interior climatic conditions can be improved significantly by the application of radiant heating and cooling systems, which can result in significant energy savings [1]. Due to the large-area of heat distribution, considerably lower flow temperatures are required resulting in lower power consumption in comparison to conventional radiator systems [2–4]. The lower operating temperature also facilitates the use of alternative energy sources, such as solar thermal and geothermal energy. Moreover, radiant heating and cooling contribute to a pleasant and healthy room climate [5]. When compared to convection heating, radiant heating introduces less airborne particulate into a space. Due to its use of renewable resources, the newly developed wooden radiant heating system presented in this work is characterized by its ecological sustainability.

In the literature, many studies dealing with performance analysis of radiant heating and cooling systems can be found. The majority of these studies focus on radiant floor heating systems and the impact of various structural design parameters on their thermal performance. Weitzmann et al. [6] investigated the impact of floor construction and foundation on the performance of a radiant floor heating system by means of a validated numerical model. They found that the dynamic behavior as well as the structure of the foundation have main impact on the thermal losses to the ground. Zhang et al. [7] analyzed both, experimentally and numerically, the performance of a lightweight radiant floor heating system depending on certain design parameters. Their results show that surface temperatures and air temperature increase when pipe distance decreases and temperature of the water supply increases. A more comprehensive sensitivity analysis has been carried out by Sattari and Farhanieh [8], investigating radiant floor heating panels with embedded water filled pipes. By means of the Finite Element

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Method, the impact of pipe diameter, material and number of pipes, as well as cover material and cover thickness on the overall thermal performance of the heating system have been investigated. Material type and thickness of the floor cover was found to be mainly affecting thermal performance. In contrast, pipe material and diameter showed the lowest effect. A further study, carried out by Shin et al. [9], aimed at the development of design charts which can be applied in the early design process of radiant floor heating systems for a comparative analysis of different design variants with respect to thermal comfort criteria. In addition to water flow temperature and pipe spacing, three different floor-covering materials have been analyzed. However, they stated that a clear dependency between floor surface temperature distribution and thermal resistance of the floor covering material could not be found.

Further studies consider the thermal performance of heating panels dependent on their location within a room. Seyam et al. [10] analyzed the impact of a heating panel's size and position on the thermal comfort of a room by means of experiments and numerical modeling. With consideration of surface temperatures and airflow conditions, they found the heating panel location to be affecting the temperature distribution in a room. A further study, carried out by Bojic et al. [11] analyzed floor, wall and ceiling heating panels and their respective energy, environmental and economic characteristics by the use of simulation models. They showed that a floor-ceiling heating achieves best results, closely followed by a radiant wall heating system.

Moreover, some researchers analyzed the thermal performance of radiant panels by modeling the heat transfer processes within these structures. In this context, Laouadi [12] developed a numerical model which is able to exactly predict the contact temperature between tube and adjacent material. Thus, boiler or chiller (for heating or cooling respectively) can be sized efficiently and control of a panel with regard to compliance with comfort criteria is possible. Tye-Gingras and Gosselin [13] developed a modeling method for heat transfer processes in radiant panels with serpentine pipe layout. By means of this model, they analyzed the impact of tube layout on the heat transfer rate, emphasizing slightly higher heat transfer rates for a panel variant with parallel pipe layout than for a panel with serpentine pipe layout. However, the differences regarding thermal performance were marginally.

Furthermore, with regard to ceiling installation of radiant panels, researchers emphasize that it is important to insulate the panels connected to the ceiling construction in order to minimize heat losses [14,15].

Although the above mentioned studies give relevant criteria for the thermal optimization of radiant heating systems, no research work can be found that addresses the performance optimization of multilayered wooden radiant panels.

Multilayer solid wood panels have been used for several years in the construction sector, as stiffening planking in wall or floor areas, or as façade elements. The rising demand has been accompanied by an increasing functionality. As part of a research project, a heating and cooling function was integrated in the middle layer of a solid wood panel in order to create a radiant heating and cooling system for room temperature control. The system is suitable for the installation in wall, ceiling, and floor areas. A further advantage of the new solid wood panel is the high degree of prefabrication, making the system especially attractive for use in building renovations by reducing construction times and increasing construction quality.

The integration of internal temperature regulation will necessarily change the hygrothermal behavior of the panel system, which is why a detailed analysis of the hygrothermal processes during temperature conditioning is required in order to predict how the system will operate long-term and ensure its durability. This article focuses on the thermal optimization and the subsequent performance analysis of a multilayer solid wood panel with integrated functional layer during a heating process. Based on numerical analysis, prototypes are developed, which are then analyzed regarding their hygrothermal performance within a climate chamber. Findings from laboratory tests provide conclusions about the thermal and hygric material and system behavior. The influence of anisotropic material properties of wood during the heat transfer process is investigated numerically, through which informed statements about the wooden panel's performance are made.

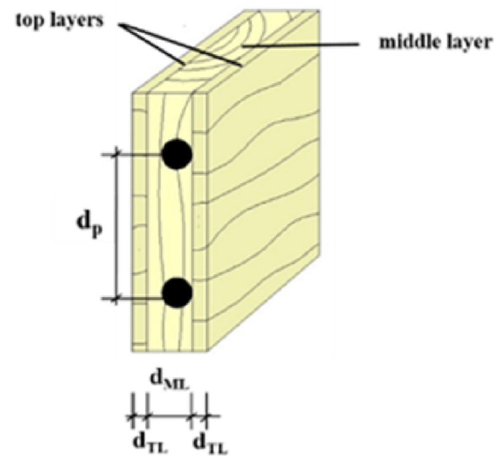

Fig. 1. Structure of a solid wood panel with functional pipe element.

2. Method

The multilayered solid wood panel to be developed consists of three layers of spruce wood offset by 90° to each other and bonded with melamine-urea-formaldehyde. A multilayer composite pipe element for liquid media is embedded eccentrically in the middle layer. During the production process, the panel is thermally pressed. Fig. 1 depicts the basic structure of a solid wood panel with integrated piping system. Based on these initial constructive conditions, a numerical simulation study with the commercial software Delphin was performed, in order to optimize heat conduction and transfer processes within the panel and in its surroundings.

2.1. Numerical simulation

In order to achieve realistic statements regarding the heating performance, a wooden panel was simulated with contact to a wall construction. This construction is depicted in Fig. 2, consisting of a brick wall with exterior and interior plaster – a common construction in Germany. This wall construction is internally insulated, having an overall thermal transmittance of 0.35 W/m^2 K. All material properties that are used as input parameters for the numerical model are given in Table 1.

The primary goal for the thermal optimization was to reach an optimal heating performance. For this reason, exterior climatic boundary conditions within the simulation model were chosen according to the German standard DIN 4108-2 [16]. The chosen exterior values were: −5 °C and 80 % relative humidity (RH). For the interior side, an unheated room was assumed, providing a climate of: 10 °C and 65 % RH. The pipe element's surface temperature was set to be constantly 35 °C. Within the simulation, several material and technological parameters were varied in order to define those variants that minimize the natural insulative effect of the wooden material.

The wooden panel basic variant consists of a 20 mm thick middle layer sandwiched between two 6.9 mm thick layers. A pipe system with a diameter of 16 mm containing the heating fluid is installed