

# Unsteady thermal performance analysis of a room with serial and parallel duct radiant floor heating system using hot airflow

Oğuz Bozkır<sup>a</sup>, Suat Canbazoğlu<sup>b,\*</sup>

<sup>a</sup> Department of Technical Programs, Malatya Vocational School, İnönü University, 44080 Malatya, Turkey

<sup>b</sup> Department of Mechanical Engineering, Faculty of Engineering, İnönü University, 44280 Malatya, Turkey

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## Abstract

In this study, the unsteady thermal performance of a test room heated by circulating hot airflow under the floor was analyzed with a developed mathematical model based on heat transfer equilibrium among the air flow, the floor and the indoor air. The time variations in the indoor air temperature for the serial duct floor heating system were investigated theoretically and experimentally. The time variations in the floor surface and the indoor air temperatures were predicted theoretically for the parallel duct floor heating system. Experiments on the time variations of the dimensionless numbers such as  $Nu$  for the airflow in duct and the indoor air,  $Gr$  for the indoor air and the heat ratios of convection and radiation to total heat for the serial duct floor heating system were performed. The theoretical and experimental results showed a good agreement.

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## 1. Introduction

Floor heating systems have been used since ancient times due to their advantages compared to other heating systems. However, the higher temperature of the floor surface may not be pleasant for everybody. The floor heating system for large volumes and high spaces such as hangars, gymnasiums, churches, mosques, etc. seems a preferable alternative for human physiology as the temperature gradient on vertical direction in a room heated from floor is negative. The cost of this heating system is also very reasonable for large volumes and high spaces. In floor heating, a more comfortable room can be obtained due to the fact that the velocities of air flow resulted from heat transfer with natural convection are smaller than 0.1 m/s as the temperature distribution in indoor air is more homogenous than other heating systems. Floor heating systems are affected less in cold days when sudden temperature drops occurred because heat is accumulated in the floor.

On-off valve control and control with two parameters for radiant floor heating systems with hot water experimentally investigated [1]. The temperatures of floor and indoor air selected as two parameters and controlled by a valve. They

concluded that the control system with two parameters provided a better temperature control for indoor air. The study on the optimal control of a floor heating with hot water [2] showed that the room temperature during a day can approximately be kept constant by controlling inlet energy to boiler and mass flow rate of hot water. In another study, a building heated by using a simulator program the permanent heating was more stable and efficient than temporary heating [3].

The floor heating of a classroom by hot water obtained with a solar energy system [4] and the floor heating of a room, whose floor consists of electrically heated panels and whose window is integrated with a passive solar energy system were reported [5]. The floor heating of a room, which has a rock bed under its floor to accumulate the heat of circulating air heated with solar energy was also investigated [6].

In the literature, studies are mainly on the radiant floor heating systems using hot water but to the authors' knowledge there is not enough study about radiant serial and parallel duct floor heating by circulating the hot airflow. The primary objective of this study is to obtain unsteady thermal performance of rooms having serial and parallel duct floor heating systems by applying a mathematical heat equilibrium model for unsteady heat transfer among the hot air flow, floor material and indoor air. The second objective is to define the availability of these heat sources in radiant

\* Corresponding author.

E-mail address: [scanbazoglu@inonu.edu.tr](mailto:scanbazoglu@inonu.edu.tr) (S. Canbazoğlu).

### Nomenclature

$A_c$	the surface area of room ceiling
$A_k$	the ceiling area of air duct
$A_0$	the upper surface area of floor
$A_w$	the surface area of room walls
$c_0$	specific heat of the indoor air
$c_m$	specific heat of the floor (mosaic)
$c_p$	specific heat at constant pressure of the air
$D_h$	hydraulic diameter of the rectangular air duct
$Gr$	Grashof number
$h_k$	convective heat transfer coefficient between the hot air flow in duct and the floor
$h_0$	convective heat transfer coefficient between the floor surface and the indoor air
$k$	conductive heat transfer coefficient of the air
$K_c$	total heat transfer coefficient of room ceiling
$K_w$	total heat transfer coefficient of the room walls
$L$	characteristic length of the floor ( $=A_0/P$ )
$m_0$	mass of the indoor air
$Nu_L$	Nusselt number for heat transfer between the indoor air and the floor surface
$Nu_{D_h}$	Nusselt number for heat transfer between airflow in serial duct and the floor
$P$	perimeter of upper surface of the floor
$q$	convective or radiation heat transfer per unit area
$q_T$	total heat transfer per unit area
$Q_L$	heat loss in the walls and ceiling of the room
$Ra_L$	Rayleigh number for heat transfer between the indoor air and the floor surface
$Re_{D_h}$	Reynolds number for the air flow through serial duct under the floor
$t$	time
$T_a$	the temperature of airflow in the duct
$T_{ac}$	calculated actual indoor air temperature
$T_e$	the atmospheric air temperature
$T_i$	initial indoor air temperature
$T_0$	indoor air temperature
$T_1$	inlet temperature of airflow into the duct
$T_2$	exit temperature of airflow into the duct
$T_f$	film temperature of airflow in the duct ( $=(T_1 + T_2)/2$ )
$T_m$	floor surface temperature
$V_m$	volume of floor material
$V_0$	volume of the indoor air
$\alpha$	thermal diffusion coefficient ( $=k/\rho c_p$ )
$\beta$	thermal expansion coefficient ( $=1/T_f$ )
$\rho$	air density
$\rho_m$	floor density
$\rho_0$	density of the indoor air
$\nu$	kinematic viscosity of the air

serial and parallel duct floor heating systems if there are waste heat sources such as available hot airflow, hot exhaust or chimney gases.

## 2. Mathematical model

The detailed vertical and horizontal views of the test cell of a single room and the floor of serial duct used in the mathematical model and experimental study are shown in Fig. 1a and b [7].

Heat equilibrium of the floor can be written as,

$$h_k A_k (T_a - T_m) - h_0 A_0 (T_m - T_0) = \rho_m c_m V_m \frac{dT_m}{dt} \quad (1)$$

where  $T_a$ ,  $T_m$ ,  $T_0$ ,  $h_k$ ,  $A_k$ ,  $h_0$ ,  $A_0$ ,  $\rho_m$ ,  $V_m$ ,  $c_m$  and  $t$  are the airflow temperature in duct, the floor surface temperature, the indoor air temperature, convective heat transfer coefficient between hot air flow in duct and the floor, the ceiling area of air duct, convective heat transfer coefficient between the floor surface and the indoor air, the upper surface area of floor, the mass of floor, specific heat of the floor and time, respectively. The density and specific heat of floor material are equal to the constant values such as  $\rho_m = 2200 \text{ kg/m}^3$  and  $c_m = 879 \text{ kJ/kgK}$ .

The heat transfer to the room can be defined as,

$$h_0 A_0 (T_m - T_0) = \rho_0 c_0 V_0 \frac{dT_0}{dt} \quad (2)$$

Rearranging the Eqs. (1) and (2), the Eqs. (3) and (4) gives the following forms,

$$\frac{h_k A_k}{\rho_m c_m V_m} (T_a - T_m) - \frac{h_0 A_0}{\rho_m c_m V_m} (T_m - T_0) - \frac{dT_m}{dt} = 0 \quad (3)$$

and

$$\frac{dT_0}{dt} - \frac{h_0 A_0}{\rho_0 c_0 V_0} T_m + \frac{h_0 A_0}{\rho_0 c_0 V_0} T_0 = 0 \quad (4)$$

Arranging the Eqs. (3) and (4) with the assumptions such as  $M = (h_k A_k)/(\rho_m c_m V_m)$ ,  $N = (h_0 A_0)/(\rho_m c_m V_m)$  and  $K = (h_0 A_0)/(\rho_0 c_0 V_0)$ , the Eqs. (3) and (4) can be written in a more simple form as,

$$\frac{dT_m}{dt} + MT_m - MT_0 - NT_a + NT_m = 0 \quad (5)$$

and

$$\frac{dT_0}{dt} - KT_m + KT_0 = 0 \quad (6)$$

The Eqs. (5) and (6) are the first order differential equations with constant coefficient and they must be solved simultaneously. Rearranging the Eqs. (5) and (6) by eliminating  $T_m$ , a second order differential equation with constant coefficient can be defined as,

$$\frac{d^2 T_0}{dt^2} + (K + M + N) \frac{dT_0}{dt} + NKT_0 = KNT_a \quad (7)$$

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