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Article

Energy consumption reduction in a building by free cooling using phase change material (PCM)

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ABSTRACT

It is significantly important to implement energy storage systems nowadays. Latent heat thermal energy storage (LHTES) systems contain numerous advantages as a result of their small temperature variation and higher energy storage densities during storage. The present paper deals with the cooling load of a room in Zanjan, Iran using Carrier software. Then, a free cooling system using commercial paraffin RT25 was numerically analyzed as phase change material (PCM) while investigating the effects of the flow rate of the storage tank and inlet air temperature overcharging and discharging procedures. Based on cold energy storage simulation, by airflow with the temperature of 20°C at night, the paraffin is solidified in 4 h. Stored cold energy of 1.4 kW in PCM releases energy through a free cooling system within 2.1 h of July afternoon in the room.

1. Introduction

The domestic and commercial sectors consume about 40% of the world's total energy and produce a third of the greenhouse gases, a significant portion of which is spent on heating, cooling, and air conditioning. One of the effective ways to improve the use and protection of energy resources is the development of energy storage systems. Latent thermal energy storage using phase change materials has high efficiency and reliability and also, due to high energy storage capacity, has received much attention [1]. The basis for using phase change materials for free ventilation of buildings has two stages: first, at night, when the ambient temperature is lower than room temperature, the flow of cool ambient air passes through the energy storage unit, and the heat of the phase change material in the liquid state and the material begins to freeze at a constant temperature. Then, when the room temperature rises above the desired level during the day, the cool air stored in the phase change material is evacuated. As the hot air passes through the energy storage unit, the phase change material receives this heat and melts at a constant temperature, and finally, the desired cooled air enters the room. The efficiency of an open-air conditioning system largely depends on the climatic conditions of the environment. The properties of the phase change material, especially its melting temperature, are very important, and this temperature should be in the range of daily temperature changes. Airflow is very important for the successful operation of an open-air conditioning system, and if this flow is adequate, then heat transfer will be successful [2]. According to ASHRAE Standard 55, thermal comfort is a mental condition that expresses the sense of human satisfaction with environmental conditions. This standard has presented a proposed list of temperatures and airflows for different environmental conditions and buildings, which generally provides room comfort temperature in summer at 23.5°C to 25.5°C Therefore, in free ventilation applications for buildings, phase change materials are preferred with a phase change temperature of 18°C to 30°C [3]. One of the most important studies on the free ventilation system was carried out by Chinnasamy et al. [4], which aimed to reduce the air conditioning load in buildings. $Na_2SO_4.10H_2O$ hydrated salt with a melting temperature of 21°C was used as a phase changer. The prototype of this system was installed and tested in an ordinary office, so results show that 270wh of thermal energy was stored during 8 hours of office work. If the pilot system replaces conventional cooling units in the UK, CO_2 emissions will decrease by 430 tons per year. Takeda et al. [5] studied the storage system with a platform of phase change materials for air conditioning of the building in Japanese weather conditions. Room temperature for ventilation was stabilized at 26°C, and the experimental model consisted of a rectangular air conditioning duct with a granule phase change material (The phase change temperature was 22.5°C to 25°C). Using computer simulation, the potential of this system in reducing air conditioning load during summer was investigated for eight Japanese cities, and Kyoto having the highest efficiency with a reduction of the air conditioning load of about 62.8%. Yamaha and Misaki [6] considered an air distribution system with phase change materials inside the air duct, which was designed to cool the air and reduce the cost of electricity consumption in Japan. The phase change material was a combination of fatty acid and paraffin, which initially measured and recorded the properties of the compound. The charging process of the phase change material (cold storage) was done from 5 to 8 a.m., and the discharge process was from 13 to 16 pm. For a typical office building in Nagoya city, 5.4 kg/m2 of the phase change material was able to keep the room temperature constant and desirable, and the suitable melting temperature of the material for successful system performance was 20°C. Streeti and Butala [7] considered a latent heat storage unit for free ventilation, which contained 3.6 kg of commercial RT20 paraffin with a melting point of 22°C and a heat storage capacity of 172 kJ / kg. The results of numerical simulation and experimental work are very close to each other. The results showed that when the inlet air temperature is 26°C and the inlet air velocity is 1 m/s, the stored cold can keep the air below 24°C for 2.1 hours.

In the present article, first, the cooling load of one of the rooms in Zanjan, with a cold and dry climate, was calculated in the hottest month of summer (July). Then, a numerical simulation of the free ventilation system with latent heat storage using RT25 phase change material of commercial paraffin type made by the German company Robiterm, was performed to investigate the potential of free ventilation to cool the room.

2. Physical model

In this paper, a flat plate heat exchanger [8] with layers containing phase change materials is used. The reason for choosing this type of heat exchanger is flexibility in adjusting the surface area, controlling the flow rate of passing air, and easy construction. The volume of the selected control for numerical simulation is shown in Figure 1, and this geometry was created using Gambit software; the dimensions can be seen in Figure 2. Due to the temperature gradient, a smaller mesh should be used in the area adjacent to the air with the phase change material. For this research, the number of cells was calculated at 15 thousand.

3. Numerical modeling

Fluent software uses the enthalpy-Porosity method to model the melting and freezing process [9]. In this method, the location of the joint surface separating the two phases is not explicitly specified; instead, there is a value called the Liquid Fraction, which represents a fraction of the cell volume that is liquid, and this value is calculated in each repetition based on the enthalpy equilibrium [10]. The Mushy Zone is the part where the Liquid Fraction varies between zero and one, and this region is modeled like a quasi-porous medium in which the amount of porosity changes from one to zero as the material freezes. When the material inside the cell is completely frozen, the porosity is zero.

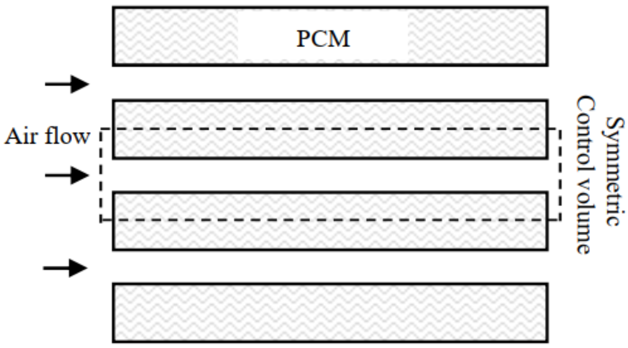

Figure 1. Selected control volume for numerical analysis

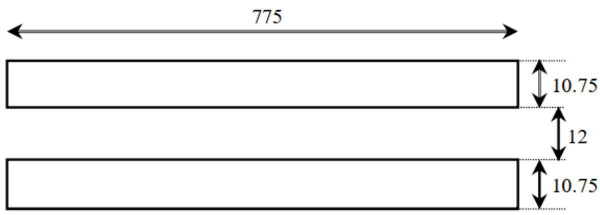

Figure 2. The geometry of problem (mm)

3.1 The governing equations

The conservation equations of mass and momentum are derived from relationships (1) and (2) [11]:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho v) = 0 \quad (1)$$

$$\frac{\partial}{\partial t}(\rho v) + \nabla.(\rho v v) = \nabla.[\mu(\nabla v + \nabla v^T)] - \nabla P + \rho g + S \quad (2)$$

S is a momentum source that contains parts of the sensitive area porosity, surface tension at the joint surface of the two phases, and other external forces entering the surface. This value is calculated using Eq (3) below [12]:

$$S = \frac{C(1-\beta)^2}{\beta^3} v \quad (3)$$

Table 1 shows the properties of RT25. According to Eq (4), the enthalpy is written as the sum of the tangible enthalpy (h) and the latent heat (h), where the tangible enthalpy (h) is obtained from Eq (5).

$$H = h + \Delta H \quad (4)$$

$$h = h_{ref} + \int_{T_{ref}}^{T} C_p . dT \quad (5)$$

Liquid fraction (β) is defined as Eq (6):

$$\beta = \begin{cases} 0 & T \le T_s \\ 1 & T \ge T_s \\ \frac{T-T_s}{T_l-T_s} & T_s \le T \le T_l \end{cases} \quad (6)$$

The amount of latent heat H can be written in Eq (7):

$$\Delta H = \beta L \quad (7)$$

Finally, the energy equation is written as an Eq (8):

$$\frac{\partial}{\partial t}(\rho H) + \nabla.(\rho v H) = \nabla.(K \nabla T) + S_n \quad (8)$$

Table 1. Properties of RT25 [13]

Property	Value
Melting and freezing temperatures	24 (C)
Latent heat	155 (kJ/kg)
Heat capacity	2000 (J/kg.K)
Density	770 (kg/m³)
Thermal conductivity	0.2 (W/m.K)

3.2 Boundary conditions

In this paper, the boundary conditions are such that the inlet air enters the system at a certain speed and temperature, so the inlet is selected as the Velocity Inlet type. In the part where the air comes out, the boundary condition of the Outflow is selected, and the boundary condition of the layers between the air and the phase change material is wall type. Due to the symmetry in the problem and according to the selected control volume, the upper and lower walls are considered symmetrical.

3.3 Initial conditions

The velocity and temperature of the air entering the tank are two important variables to evaluate the performance of the thermal energy storage system in the melting and freezing processes. To consider different states for temperature and speed, it is best to make these variables dimensionless. Reynolds number is used to de-dimensionalize the velocity, which is calculated for the flow through the channel using Eq (9). For Reynolds numbers less than 2,300, the flow is calm, and for Reynolds numbers larger than 2,300, the flow is turbulent. In order to de-dimensionalize inlet air temperature in the melting process, it is better to use the Stephen number, which is defined by Eq (10) [14].

$$Re = \frac{\rho . V . D_h}{\mu} \quad (9)$$

Where ρ is density, V is the velocity of the input air, Dh is the hydraulic diameter of the channel, and μ is the dynamic viscosity of the air.

$$Ste = \frac{C_p(T_{in} - T_m)}{L} \quad (10)$$

Where C_p is the specific heat capacity, T_{in} is the temperature of the input air, Tm is the melting temperature of matter, and L is the latent heat of matter.
The initial conditions during the melting and freezing process are briefly listed in Table 2. During the charging process, given that the rt25 phase change temperature is about 24°C, it is assumed that the initial temperature of the material in the tank is 3 degrees above the freezing temperature of 27°C.

Table 2. Initial conditions

Process	Velocity (m/s)	Reynolds number	Temperature (C)	Stephen number
Charge	7	10811	20	-
charge	9.3	14446	20	-
Discharge	3	4660	30	0.075
discharge	4	6213	31	0.088

According to Figure 3, the dry temperature of Zanjan is 20°C during the night to the morning. Also, due to low airflow, using a ventilation fan the air speed entering the tank increases. From 4 p.m. onwards, when the ambient temperature is the highest, the common ventilation of the building has been extinguished, and free ventilation is used for cooling. The air temperature entering the tank is 30°C and 31°C in the melting process with an average temperature. Also, using a ventilation fan, the air velocity entering the tank reaches 3 m/s and 4 m/s.

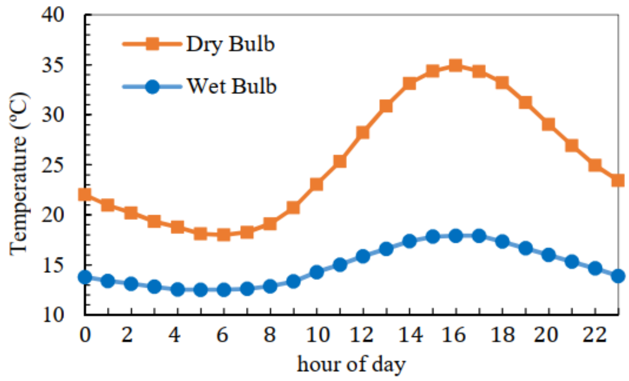

Figure 3. The temperature of Zanjan City on the hottest day of July

3.4 Solution conditions

Fluent software has two different solution methods, one based on pressure and the other one based on density in the simulation of the melting and freezing process; only a pressure-based solver can be used. The flow is transient, and the standard k-e method is used to model the turbulence. Piezo algorithm is selected for the pressure-velocity relationship, and also Presto method is selected for pressure discretization, and the second-order upstream design method is used for energy discretization. The Under-relaxation factors for pressure, density, momentum, liquid fraction, and energy are 0.7, 1, 0.3, 0.9, and 1, respectively. Convergence criteria were selected values of 10^{-4} for mass and momentum conservation and 10^{-8} for energy conservation.

4. Calculation of room cooling load

Basically, the correct estimation of the cooling load depends on the detailed examination of the load components in the ventilated environment, like complete plans of the building and the general design of the space. In this article, the building shown in Figure 4 is a residential unit with an area of 120 square meters as a south ground floor.

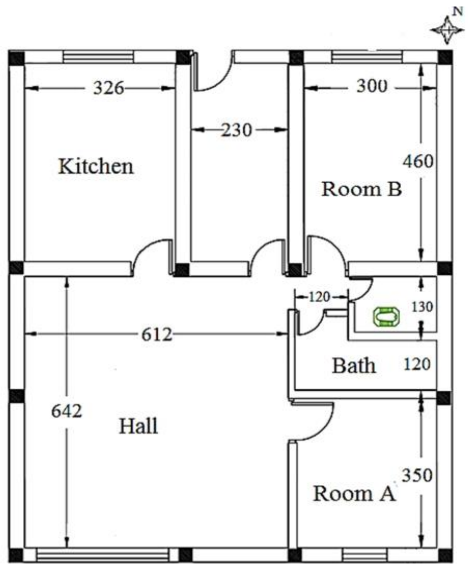

Figure 4. Plan of the building

The area of the building is asphalt, the average reflection coefficient of the ground surface is 0.2, and also the thermal conductivity of the soil in the area is 1.35 W/m.K. First, in order to check the amount of cooling load required to design the ventilation system, the cooling load of one of the rooms selected here, bedroom A, is calculated. The door of the room is made of wood with dimensions of 0.9*2.5 m^2, the window is made of aluminum with dimensions of 1.8 *1.2 m^2, and the lighting equipment consists of a fluorescent lamp and an incandescent lamp. Also, the number of people using a room is considered. By using the carrier software for July, the amount of cooling load during one day and night is calculated and shown in Figure 5. Also, the amount of aeration required for the room is about 420 m^3/h.

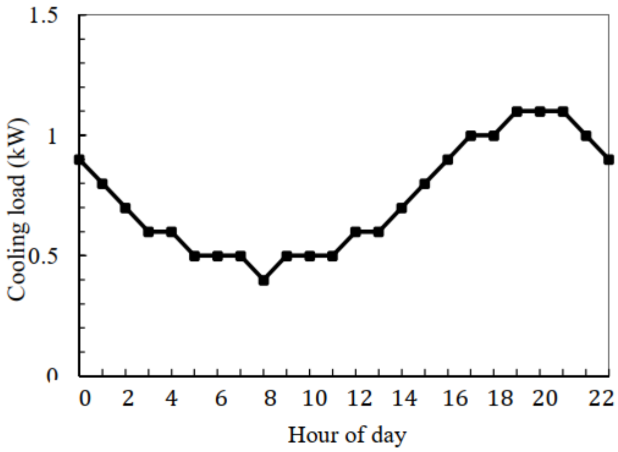

Figure 5. The cooling load of sleeping room A

5. Results and discussion

5.1 Validation of numerical simulation

To validate numerical simulation, the results are first compared with the experimental work done in reference [8] and shown in (Figure 6). The average error rate between numerical and experimental results is about 4%, which is valid numerical results.

5.2 Cooling storage process

Figure 7 shows the change in temperature of the phase change material and the output air of the system over time. With the entry of cool air into the system due to heat absorption from the material, first, the temperature of the material decreases to freezing temperature, then phase change begins, and the temperature decreases with a gentle slope. Finally, after complete freezing of the material, the temperature decreases again with a steep slope. At a constant temperature, the higher the velocity of the air entering the system, the faster the material freezes. When the air arrives at 20°C and the tank speed of 7m/s, the complete freezing of the material lasts for 4 hours. By increasing the inlet speed to 9.3m/s, the total freezing time of the material reaches 3.5 hours.

5.3 The process of discharging cooling energy

According to the profile of ambient air temperature during the day for Zanjan, the cooling energy discharge process has been studied in the following four different conditions. In the first and second cases, the Reynolds number is 6213, and the Stephen number changes from 0.075 to 0.088. In the third and fourth cases, the Reynolds number is 4660, and the Stephen number changes from 0.075 to 0.088.

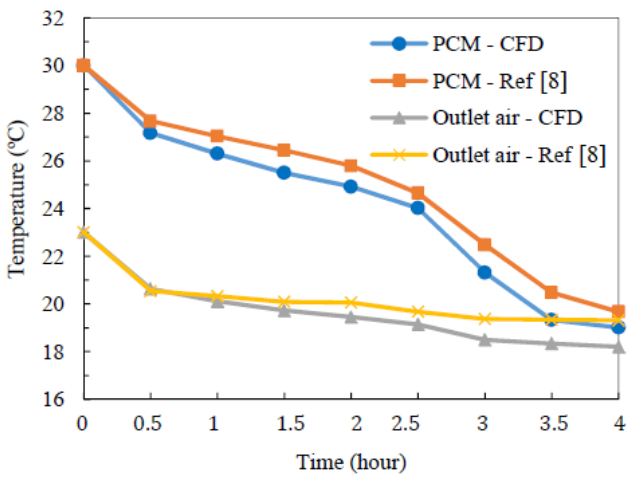

Figure 6. Validation of numerical analysis during charging process

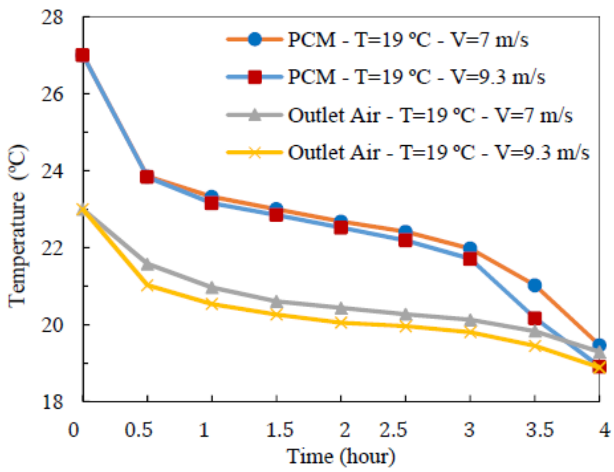

Figure 7. The temperature of the PCM and outlet air during the charging process

Figure 8 shows the temperature change of the phase change material over time. When hot air enters the tank, the frozen phase change material absorbs heat from the hot air and reaches its melting temperature after 0.5 hours. Then the phase change begins, and the temperature rises with a gentle slope, and finally, after the material has completely melted, the temperature rises again with a steep slope. The liquid fraction during the melting process is shown in Figure 9. In a constant Reynolds number with a 17% increase in Stephen's number, the melting time decreased by 0.5 hours, and in a constant Stephen number with a 25% reduction, the melting time increased by 1 hour.

One of the most important results of the paper is the temperature of the output air for ventilation of the room, which is shown in Figure 10. As time goes on and the material melts more and more, the outlet air temperature increases. Tamaskani and Esfahankalateh [15] have conducted a study with the aim of determining the range of thermal comfort for the city of Zanjan. The results show that the comfort temperature inside the room for July is about 23°C to 28.5°C. According to the calculations, the output air temperature of the storage tank for ventilation of the room up to 26.5°C is considered the permissible temperature. The results are summarized in Table 3, so in the lowest Reynolds number and the lowest Stephen number, the best situation occurs, and there is comfortable air ventilation for 2.1 hours.

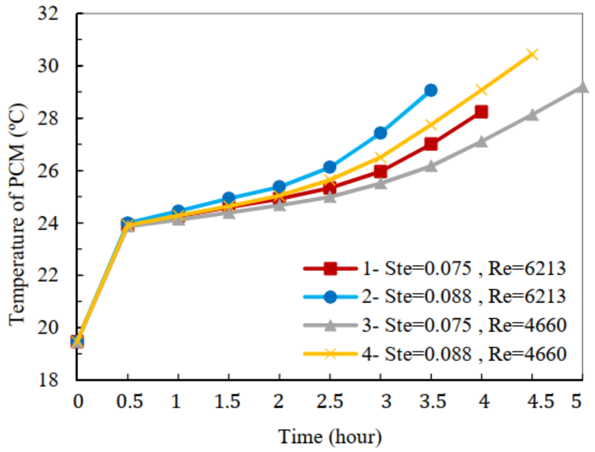

Figure 8. Temperature variation of the PCM during the discharging process

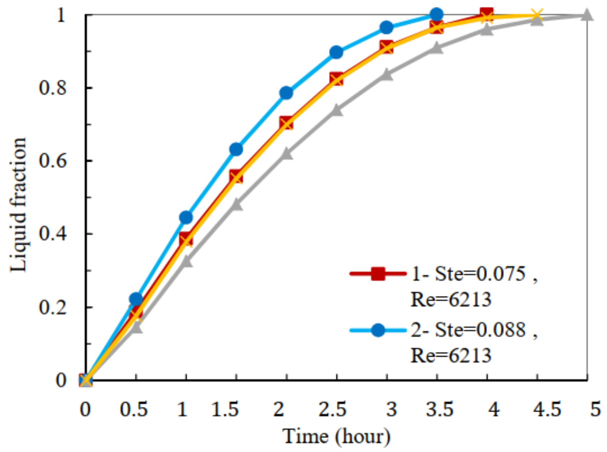

Figure 9. Variation of liquid fraction during the discharging process

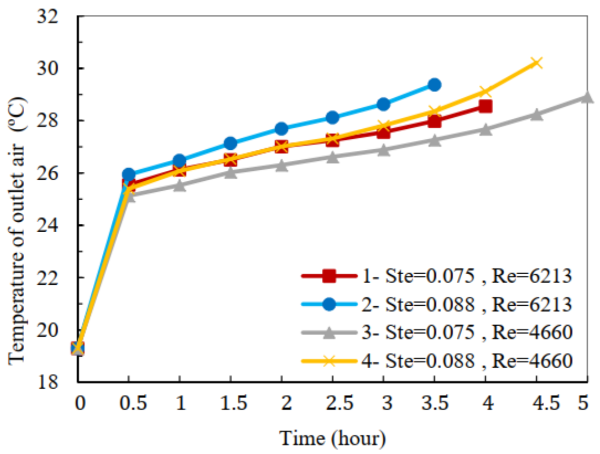

Figure 10. Temperature variation of the outlet air during the discharging process

Another important result is the amount of cooling air created by free ventilation. During the melting process, the cooling load is constantly decreasing, and the higher the Reynolds number or Stephen number, the higher the cooling load. In Figure 11, a comparison is made between the amount of cooling air required by the room and the cooling air created by the free ventilation from 16:00 onwards. According to this diagram, free ventilation has provided the required cooling air for up to 2.1 hours, an average of 1.4 kW of cooling air has been injected into the room.

Table 3. Result of discharging process

Condition	Outlet air temperature (C)	Aeration (m^3/h)	Duration of ventilation (h)	Melting rate (%)
First	25.5 – 26.5	570	1.5	56
Second	25.9 – 26.5	570	1	45
Third	25.1 – 26.5	420	2.1	74
fourth	25.4 – 26.5	420	1.5	55

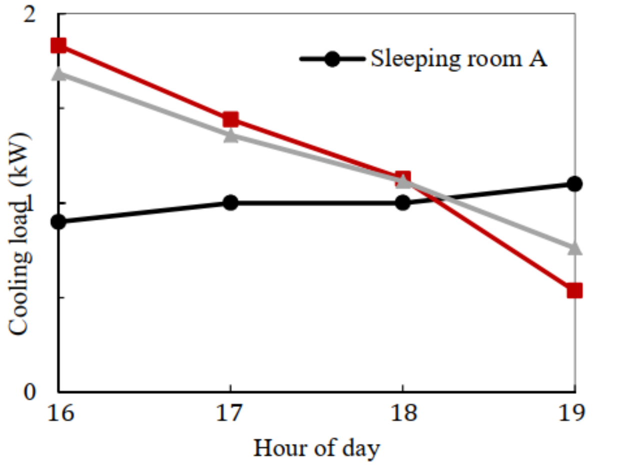

Figure 11. Comparison of cooling load during the discharging process

6. Conclusion

In this paper, the effects of temperature and velocity of the air entering the free ventilation system with cold storage were investigated by a numerical simulation, and the following results were obtained:

- In the charging process, the complete freezing of the phase change material takes 4 h to complete when the air enters the heat exchanger with a temperature of 20 ° C and a speed of 7 m/s.
- In the discharge process, in a constant Reynolds number with a 17% increase in Stephen's number, the melting time decreased by 0.5 hours, and in a constant Stephen number with a 25% reduction, the melting time increased by one hour.
- In the discharge process, in the lowest Reynolds number, which is 4660, and the lowest Stephen number, which is 0.075, the best ventilation occurs. In this case, the melting process takes 5 hours, and 2.1 hours of optimal air is available for room ventilation. The amount of aeration, in this case, is 420 m^3/h, which is sufficient. Also, during this period, an average of 1.4 kW of cooling air was injected into the room.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically concerning authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement

Datasets analyzed during the current study are available and can be given following a reasonable request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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