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Refrigerating characteristics of ice storage capsule for temperature control of coal mine refuge chamber

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HIGHLIGHTS

- The effective refrigerating time for ice storage capsule is defined and tested.
- The mathematical relations of effective refrigerating time is derived and modified.
- The correction factor equation of ambient temperature and humidity is established.
- Three application parameters, $t_{modified}$, $N_{capsule}$, and $N_{t,capsule}$ are obtained.
- 24-h manned experiment verifies the accuracy of temperature control strategies.

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ABSTRACT

Heat transfer process and refrigerating characteristics of ice melting enclosed in a cube capsule are investigated using experiments and mathematical relations to achieve temperature control by ice storage in coal mine refuge chamber. The effective refrigerating time for ice storage capsule is defined and tested. The mathematical relations of the effective refrigerating time and refrigeration rate are derived and modified. The correction factor equation of ambient temperature and humidity is established for the revision of mathematical relations. By using the modification factor equation, the mean relative error between modified and experimental values is less than 1%. The three application parameters, namely $t_{modified}$, $N_{capsule}$, and $N_{t,capsule}$ are obtained based on the experiments and the modified relations. These parameters form the temperature control strategies in using ice storage capsule for refuge chamber. A 24-h manned experiment verifies the accuracy of the temperature control strategies.

1. Introduction

Coal mine refuge chambers provide safety shelters for miners who fail to evacuate when coal mine accidents occur. Depending on the internal and the environmental conditions however, such refuge chambers will be hot and humid [1]. Kielblock et al. [2] found that the ambient temperature inside refuge chamber rises rapidly under adiabatic conditions without air circulation, and that the temperature rise is mainly caused by human metabolism heat. Therefore, refrigeration equipment in the coal mine refuge chamber for temperature control is a fundamental requirement [1,3].

Refuge chambers require low energy consumption refrigeration equipment or technologies for temperature control through liquefied compressed gases or phase-change materials [4–6], such as the ice phase-change refrigeration. This is crucial because the minimal level of energy supply in refuge chambers during states of emergency should be addressed [7,8].

Two storing and melting techniques are available for the practical use of ice phase-change refrigeration in refuge chambers [9–11]. The first is overall ice storage through energy consumption that generates a driving force required to complete thermocycling between ice and the environment. The technique is similar to ice storage air conditioning. Trushliakov [12] and Bamsey et al. [13] systematically analysed the design requirements and application of overall ice storage as an emergency cold source in manned submersibles and spacecraft. Shen et al. [14] developed a general ice storage refrigerating system for mine rescue capsule. The manned experiment and the temperature field simulation analysis have been found to be effective for temperature control. The second technique entails enclosing ice in rectangular capsules and storing

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these in the freezer. Subsequently, the capsules can be placed in the refuge chamber based on certain replacement strategies to control internal temperature by natural convection. Despite the contributions of the second technique however, published research on the subject is quite few.

Understanding the refrigerating characteristics of ice storage capsule is useful in the design and operation of the passive ice refrigeration system. Elsayed [15] numerically simulated ice melting in a rectangular horizontal capsule with upper and lower walls exposed to forced convection heat transfer, and found that the coolant fluid temperature significantly affects the melting behaviour rather than the convection heat transfer coefficient. Hosseini [16] experimented with cylindrical and right circular truncated cones to study the ice-melting processes, including heat transfer coefficient and rate of melting. On the other hand, Chang [17] simulated transient behaviour and heat transfer for the melting of ice in porous media within a rectangular enclosure to show that heat transfer deteriorates on the hot side and improves on the cold side through time. Virag et al. [18] investigated the influence of natural convection on the melting of an ice block surrounded by water at vertical wall temperatures ranging from 2 °C to 12 °C. Huber et al. [19] developed a lattice Boltzmann method to combine thermal convection and pure-substance melting for the analysis of the transition from conduction-dominated heat transfer to fully-developed convection, as well as for the reproduction of scaling laws and previous numerical results.

The present paper aims to demonstrate the experimental investigation of effective refrigerating time of ice storage capsule and a mathematical relation that estimates the effective refrigerating time and ice storage capsule refrigeration rate. Effective refrigerating time and mathematical relation are modified based on experimental data. Secondly, this paper aims to calculate control strategies of ice storage capsule based on which, an application experiment is carried out.

2. Experimental and discussions

The time required for the ice within the storage capsule to melt the completely under different ambient conditions is the key point of refrigeration. In this paper, therefore, time is denoted as effective refrigerating time. A series of experiments was designed to measure the effective refrigerating time by simulating the daily human comfort ambient temperature and humidity in the closed environment [20–22] (Fig. 1). The ice storage capsule used was a 135 mm long cube. Seven thermocouples, each with a diameter of 0.3 mm and temperature resolution of 0.1 °C, were inserted into the top part of the said capsule. These thermocouples were numbered 1 to 7, placed at 16 mm intervals 67 mm from the surface at different directions. The first was located in the capsule centre, the first to fifth thermocouples were placed along the length configuration, and the sixth and seventh were arranged along the width. Agilent 34970A is used for temperature data acquisition, a digital thermometer determined ambient temperature, and a humidity meter measured relative humidity. All of the collected data were recorded into the computer simultaneously.

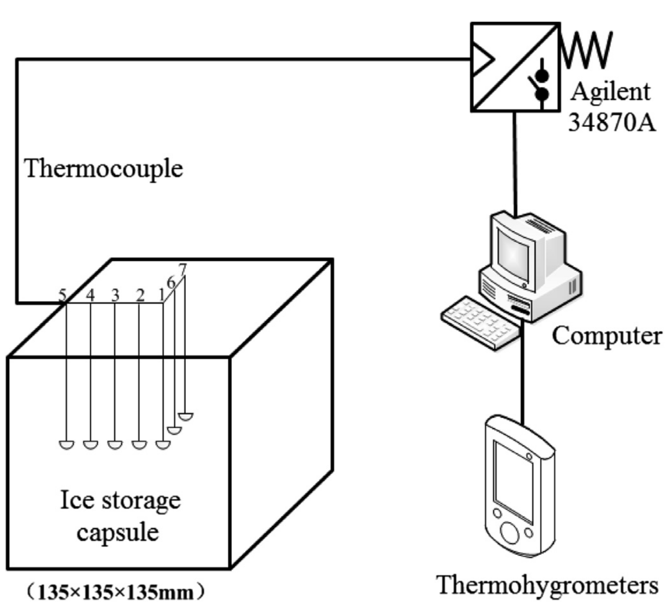

Fig. 1. Measurement device of effective refrigerating time.

At an ambient temperature within 22 °C–29 °C and relative humidity within 30%–70%, an ice storage capsule has an initial temperature ranging from −20 °C to −10 °C and a volume larger than that of a half refuge chamber (confined underground laboratory). Six experiments lasting 1400 min were carried out, in which temperature points in intervals of 30 s^{-1} were recorded. The experimental conditions and the results of effective refrigerating time are shown in Table 1.

It can be seen from Table 1 that the main influence factors of the effective refrigerating time can be obtained qualitatively through the details comparison between groups. Firstly, the effective refrigerating time of ice storage capsule is inversely proportional to the ambient temperature to the data of group 2, 3, 5, which apparently indicates that the ice melting is an endothermic process. Secondly, the effective refrigerating time also inversely proportional to relative humidity based on data comparisons between group 1 and 2 or 5 and 6. The fact that water appeared on the ice storage capsule surface during the experiment, heat exchange happened along with the wet and latent heat exchange between air and the capsule, which would accelerate the rate of heat transfer and thus reduce the ice melting time. For perceiving the experimental data and the process in a quantitative way, more detailed discussions are necessary.

2.1. Temperature variations of ice storage capsule

Considering that the variation trends of temperature measuring points are similar, the experimental curve of Group 1 was selected for detailed analysis of the ice storage capsule refrigerating process at an ambient temperature of 22 °C and relative humidity of 30% (Fig. 2).

Fig. 2 shows eight curves and the first to seventh measured points, which correspond to the temperature values of thermocouples implanted in the capsule. The ambient temperature curve is maintained at approximately 22 °C and the initial temperature of each measured point is −20 °C.

The variations of the temperature curve can be divided into three stages. Stage I covers the period from the beginning to 75 min of the experiment, during which the ice storage capsule rapidly

Table 1
The experimental conditions and results of effective refrigerating time experiments.

Group	Ambient temperature/°C	Relative humidity/%	Initial temperature of ice storage capsule/°C	Effective refrigerating time/min
1	22	30	−20	1050
2	22	50	−20	780
3	24	50	−10	640
4	24	70	−18	540
5	29	50	−20	490
6	29	70	−20	370