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Research Paper

Discharging performance of a forced-circulation ice thermal storage system for a permanent refuge chamber in an underground mine

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HIGHLIGHTS

- Thermal analysis of an ice thermal storage system for a permanent refuge chamber.
- Experimental measurements used to provide and validate a correction factor.
- Correlation developed between transient discharging power and remaining ice fraction.
- Minimum cooling requirement satisfied via automatic control through correlation.
- Operational duration of system maximized via automatic control.

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ABSTRACT

This study aimed to develop a proper control strategy for a forced-circulation ice thermal storage system (ITSS) designed for a permanent refuge chamber with an accommodation capacity of 50 persons. The heat transfer characteristics of the ITSS were investigated through theoretical and experimental approaches. A quasi-steady one-dimensional mathematical model for predicting the transient discharging power was proposed. On this basis, a control strategy was proposed to fulfill the minimum cooling requirement in consideration of both effective discharging time and human comfort. The minimum required velocity of the ITSS was analyzed; from this, the effective working time of the ITSS was determined to be 64.57 h. Additionally, the heat load inside the chamber was found to be the main factor that affected the effective temperature control duration and the utilization ratio of the ice. Thus, a reserve factor, which is defined as a function of rated heat load and determined by the discharging performance model, is suggested for consideration during optimization.

1. Introduction

Refuge alternatives, which provide a well-sealed environment for isolating miners from a potentially toxic or high-temperature environment during a mine emergency, facilitate escape for miners trapped underground by fire, explosion, or rock collapse. Recently, two types of refuge alternatives, mainly classified by accommodation capacity—portable shelters/chambers and permanent chambers/stations—have been used in underground mines. A reliable environmental control and life support system (ECLSS), which contains sufficient breathable oxygen, reasonable air scrubbing, adequate food and water, and a temperature control system, is needed to sustain miners' lives while they await rescue. Considering the specifics of underground emergencies, technologies with low energy consumption are preferred [1,2].

For temperature control within the refuge space, there are generally two kinds of strategies. In one strategy, fresh air is supplied from the ground through compressed air lines or boreholes; this method can aptly control both air quality and temperature, but air lines may be destroyed in an emergency [3]. Alternatively, refrigeration equipment that uses phase-changing materials, such as the ice thermal storage system (ITSS), have widely been applied [4].

ITSSs, which utilize the latent heat of fusion of water, have been extensively researched by predecessors in the context of energy saving buildings both for charging and discharging processes, with the ultimate aim of a more efficient, stable, and economic system [5–9]. Several configurations, such as ice-on-coil or encapsulated ice, have been developed and continually optimized in recent

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Nomenclature

a	half length of side along the direction of curvature radius, m
A_c	the cross section area of duct, m^2
Cp	specific heat capacity, J/kg K
de	hydraulic diameter (inner)
De	hydraulic diameter (external)
f	reserved factor
g	gravitational acceleration, m^2/s
G	mass flux, kg/s
h	heat transfer coefficient, W/m^2 K
H	enthalpy, kJ/kg Dry air
k	thermal conductivity, W/m K
L	total length of the duct
n	rated accommodation person
Nu	Nusselt number
P	wetted perimeter of the duct
Pr	Prandtl number
Q	heat transfer; power
R	radius of curvature, m
Re	Reynolds number
RH	relative humidity, %
t	time; centigrade temperature
T	Kelvin temperature
$\triangle T_{lm}$	log–mean temperature difference (LMTD)
u	velocity, m/s
V	volume, m^3

Greek letters

α	thermal diffusivity, m^2/s
β	volumetric thermal expansion coefficient, K^{-1}
ξ	friction factor
η	residual ice ratio, %
ν	kinematic viscosity of air, m^2/s
ρ	density, kg/m^3
Δ	variation in liquid level, mm

Subscripts

act	active temperature control period
b	bulk
c	heat conduction
d	duct
dis	discharging
eff	effective
EXP	experimental
g	gas phase (air)
hl	heat load
i	number of duct segment
in	inlet position of duct
l	liquid phase (water)
lim	limited
m	melting point
n	natural convection
out	outlet position of duct
PRE	predicted
req	required
s	solid phase (ice)
st	straight tube

years. To utilize the stored energy of an ITSS, there are generally two typical methods: external melt or internal melt. Jia et al. [4] studied and developed an ice storage capsule that utilizes natural convection; it was an application of the external melt method in a refuge chamber. The experimental results demonstrated that the capsule is sufficient for eliminating the additional heat generated by four persons inside a refuge chamber.

This work focused on the discharging performance of an internal-melt-type ITSS operating under forced circulation, which is more applicable for high heat-load scenarios in permanent stations. Several studies have observed and reported that the cooling discharge rate decreases with the melting process over time [10]. Thus, it is important to determine the heat transfer characteristics of ITSSs, as they are fundamental for further optimal design. Various heat transfer models considering particular conditions have been proposed, and Oró et al. [11] summarized them well. However, these models, which are composed of basic parts that come from classical empirical formulas and correctional parts for particular configurations or application conditions, are not universal.

In this study, with the final aim of developing a proper control strategy for an ITSS for a permanent refuge station, the heat transfer characteristics of an ITSS were theoretically and experimentally studied. Then a quasi-steady one-dimensional mathematical model was developed to reveal the evolution of the instantaneous discharging performance of the system. On this basis, a control strategy for the ITSS is proposed to fulfill the minimum cooling requirement in consideration of both effective discharging time and human comfort. The method used in the study is also applicable for discharging performance determination and control strategy development for forced-circulation ITSSs with different configurations in refuge chamber applications.

2. Theoretical model for discharging performance

The ITSS targeted in this study is a stainless steel structure (shell material: SUS304; 4-mm thickness), with external dimensions of 2.5 m (Length) × 1.5 m (Width) × 2.0 m (Height), and isolated by thermal insulation with a wall thickness of 50 mm. Thus, the heat leak through the wall is neglected. The total ice storage capacity (V_s) is 5.345 m^3. An annular rectangular air duct was designed with a cross-section dimension of 300 mm (Width) × 250 mm (Height) and an approximate total length (L_d) of 7.778 m, as shown in Fig. 1. The effective heat exchange area (A_d) of the duct is 8.55 m^2. Two DC fans (24 V, 60 W), fabricated on the top at a height of 2.1 m from ground, draw sweltering air into the duct to be cooled, then blow the cooled air to the refuge space through a rectangular outlet (500 mm × 150 mm).

The following assumptions and simplifications were adopted for theoretical analysis:

- The cross section of the duct was simplified into a circle with an inner diameter ($D_{e,d}$) that is equal to the hydraulic diameter of the duct.
- The ice was transformed into a concentric annulus that covered the outside of the duct; its initial diameter (D_e) was calculated as: $D_e = \sqrt{D_{e,d}^2 + 4V_s/\pi L_d}$.
- The ice sleeve was kept homocentric with the duct during melting, as shown in Fig. 2; ice around the duct was assumed to melt uniformly, which means the ice-water interface is well defined and circular; its diameter ($D_{e,l}$) was calculated as $D_{e,l} = \sqrt{D_e^2 - 4\eta V_s/\pi L_d}$, where η is the remaining fraction of ice.