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Assessing the thermal performance of three cold energy storage materials with low eutectic temperature for food cold chain

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ABSTRACT

Development a novel inorganic salt eutectic solution for cold energy storage material (ESM) have succeeded conducted in this study. The eutectic solutions shows a low melting temperature and high latent heat of fusion value as effect of addition nano copper powder into the eutectic solution. We report a new simulation technique of thermal property as well as test results of three inorganic salts. The thermal property of three inorganic salts were simulated using the differential scanning calorimetry (DSC) method with the help of three binary phase diagrams. The simulation shows the liquidus temperature of each binary phase diagram conforming nicely to the theoretical prediction of the Gibbs-Duhem equation. In order to predict cold storage keeping time, we derived a heat transfer model based on energy conservation law. Three ESMs were tested for their cold energy storage performance and thermal properties aging for durability. The empirical results indicate that, for food cold chain, the melting point rule is superior with less deviation. With this information, one can pre-estimate the basic design parameters with great accuracy; the cost of design and development for a new cold storage logistics system can be dramatically reduced.

1. Introduction

With increasing demand from human quality of life, there is a booming need for sustaining freshness of agricultural, animal, and fishery products as well as processed food. The manufacturing, storage, transportation, distribution and consumption of their raw materials and finished products must be carried out under stable low temperatures to maintain their freshness. This whole process chain can consume lots of energy to keep stable low temperatures. Thus, the research on energy-saving resources and technologies may give energy-related industries competitive edge. Potential is expectant for development of advanced multi-temperature logistic systems for food cold chain [1–4] featuring high efficiency, high quality, low pollution, low cost, multiple functions and related applications. However, before deployment of such advanced multi-temperature logistic systems, it will take plenty of time to determine the proper combination of charging amount of chosen ESM for different ambient temperatures and required cold storage keeping times. The purpose of this research is to present enhancement of cold energy storage performance by using eutectic mixtures of different PCM salts and water. We obtained experimental data using a cold energy storage system complimented by calculations of eutectic temperature and latent heat.

Five types of refrigeration systems are commonly used by the food cold chain industry: i.e., air-conditioning, ice thermal storage, refrigerating brine, ice crystal, and eutectic solution type [1–4]. In this study, we focus on refrigeration systems using the eutectic solution(s) as phase change materials (PCM) for energy storage. The main advantage of this solution is that cold energy is stored via energy conversion during the off-peak idle period of electric distribution system and later utilized at a suitable time, such as at peak period of electric distribution system. This technique maximizes recycle and reuse of energy. The common cold-energy-storage-agents include inorganic salts, organic salts, organic compounds, some hydrocarbon oxides, polyalcohols and fluorides [1–9]. Among common cold-energy-storage-agents, there is an interesting phenomenon of continuous phase transitions that was first reported by Singh et al. [8] for polyalcohols (solid state phase transitions) and these materials, which may see use in applications such as concentrated solar energies as a secondary storage system, also follow the same trend. In some cases the energy absorbed in the continuous phases is more than of the main first order transition

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Nomenclature

A_o outer surface area of the cold storage insulated cabinet, m^2
A_i inner surface area of the cold storage insulated cabinet, m^2
$\overline{T}_m$ uniform melting temperature of ESM, $^\circ C$
$\overline{T}_{Wall}$ uniform wall temperature as a lumped system, $^\circ C$
$\overline{T}_{Am}$ uniform ambient temperature surrounding the cold storage insulated cabinet, $^\circ C$
τ time, s
$\tau_{keeping}$ cold storage keeping time, Hr
Q_j thermal energy flux across a wall of the cold storage insulated cabinet along j direction, W
T_C central temperature of the cold storage insulated cabinet, $^\circ C$
T_{Wall} wall temperature of the cold storage insulated cabinet, $^\circ C$
$U_{Wall\text{-}c}$ overall heat transfer coefficient between the central position of the cold storage insulated cabinet and the inner wall surface of the cold storage insulated cabinet, $W/m^2\text{-}^\circ C$
$U_{Am\text{-}Wall}$ overall heat transfer coefficient between the ambient surrounding the cold storage insulated cabinet and the outer wall surface of the cold storage insulated cabinet, $W/m^2\text{-}^\circ C$
k_{Wall} thermal conductivity of the wall, $W/m\text{-}^\circ C$
L_{Wall} wall thickness of the cold storage insulated cabinet, m
$A_{effective}$ effective wall area, m^2
Q total thermal energy flux across the wall, W
H specific enthalpy or latent heat, J/g
V material volume, m^3
dv differential volume, m^3
da differential surface, m^2
ρ density, g/m^3
U overall heat transfer coefficient, $W/m^2\text{-}^\circ C$
ΔT temperature difference, $^\circ C$
$\overline{T}_{Ice\ bank}$ uniform ice bank temperature, $^\circ C$
R thermal resistance, $^\circ C/W$
R_{Total} overall thermal resistance, $^\circ C/W$
h_i convective heat transfer coefficient of the inner wall surface of the cold storage insulated cabinet via natural convection, $W/m^2\text{-}^\circ C$
h_0 convective heat transfer coefficient () of the outer wall surface of the cold storage insulated cabinet wall via natural convection, $W/m^2\text{-}^\circ C$
$q_{j,outer}$ heat transfer rate from the ambient to the outer wall surface, W
$q_{j,wall}$ heat transfer rate from the outer wall surface to the inner wall surface, W
$q_{j,inner}$ heat transfer rate from the inner wall surface to the cold storage insulated cabinet center, W
$T_{wo,j}$ outer jth wall surface temperature, $^\circ C$
$T_{wi,j}$ inner jth wall surface temperature, $^\circ C$
$T_{Am,j}$ ambient temperature outside of the jth wall surface, $^\circ C$
$A_{j,effective}$ effective jth wall area, m^2
$L_{Ice\ bank}$ thickness of ice bank, m
q_j heat transfer rate through the jth wall of the cold storage insulated cabinet from the ambient, W
$h_{i\rightarrow Center,j}$ convective heat transfer coefficient of the inner jth wall surface to the center of the cold storage insulated cabinet via natural convection, $W/m^2\text{-}^\circ C$
$A_{i\rightarrow Center,j}$ inner jth wall surface facing the center of the cold storage insulated cabinet, m^2
$T_{Ice\ bank}$ ice bank temperature, $^\circ C$
T_E eutectic temperature, $^\circ C$
T_L liquidus temperature, $^\circ C$
${}_C C_{Thumb\ rule}$ first thumb rule for the cold storage keeping time
${}_E C_{Thumb\ rule}$ second thumb rule for the cold storage keeping time
T_{Ci} central temperature inside the cold storage insulated cabinet equipped with the ith ESM, $^\circ C$
T_{Ei} eutectic temperature of the ith ESM, $^\circ C$
T_{Am} ambient temperature, $^\circ C$
ΔH_i specific enthalpy change of the ith ESM, J/g
M_i weight of the ith ESM sealed inside each ice bank, g
C_p sensible heat or specific heat, $J/g\text{-}^\circ C$
$A_{o,j}$ outer surface area of the jth wall in the cold storage insulated cabinet, m^2
$A_{i,j}$ inner surface area of the jth wall in the cold storage insulated cabinet, m^2
CL length of the cold storage insulated cabinet
CH height of the cold storage insulated cabinet
CW width of the cold storage insulated cabinet
L_{CS} wall thickness of the cold storage insulated cabinet
$R_{Wall,i}$ thermal resistance of the $i\text{-}th$ wall, $^\circ C/W$

peak. This needs very careful evaluation of the peaks and the continuous phases from the DSC [8]. What's more, UV light and oxygen in the air may deteriorate organic salts, organic compounds, some hydrocarbon oxides, polyalcohols and fluorides. Inorganic salts not only have no such a problem, but also usually possess stable thermal properties in solution form, that is to say, low eutectic point and large latent heat. Moreover, they do not decompose to release harmful gases into air. Inorganic salts are friendly to the ozone layer. We select three inorganic salts, i.e., ammonium chloride (NH_4Cl), strontium chloride ($SrCl_2$), and magnesium nitrate ($Mg(NO_3)_2$), for this study. By mixing nano copper powders into ESMs, we were able to observe heat transfer enhancement to ammonium chloride solution.

2. Principle of cold energy storage

ESM concerned in this study is a matter with large latent heat during phase change or phase transition, such as inorganic salts, organic salts, organic compounds, some hydrocarbon oxides and fluorides, especially inorganic salt hydrates [1–9]. Phase transition, at which the two phases of a substance, such as liquid and vapor, have identical free energies and therefore are equally likely to exist, takes place when the thermodynamic free energy of a system is non-analytic or discontinuous in the first derivative or the second derivative of the free energy with respect to some thermodynamic variables [10]. Below the boiling point, the liquid is the more stable state of the two, whereas above the gaseous form is preferred. Phase transitions can be divided into two largely categories: the first-order and the second-order phase transitions. During any first-order phase transition which shows evidence of a discontinuity in the first derivative of the free energy with respect to some thermodynamic variable, a system whose temperature will stay constant as heat is added, either absorbs or releases a fixed (and typically very large) amount of energy per volume. Second-order phase transitions, also named as continuous phase transitions, are continuous in the first derivative of the free energy with respect to