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ADVANCED THERMAL ENERGY STORAGE USING LATENT HEAT OF FREEZING FOR SUSTAINABLE ENERGY APPLICATIONS

[1]**Dr. P. Bhargavi**
Assistant Professor
Department of Mathematics
Lal Bahadur Shastri Government First Grade College
R.T. Nagar, Bengaluru, India.

Abstract: Water has high thermal conductivity and has high latent heat storage capacity. Water turns into ice under regular freezing conditions and the heat released during the freezing/ solidification of water is stored in the form of energy as latent heat of freezing. Energy storage units uses this form of energy to balance the supply- demand cycle. The research in this field is gaining importance because of the requirement of energy shortage, Freezing/solidification problems fall under the category of Phase change problems or moving boundary problems, which determine the moving boundary position and the rate of the solidification. Rate of solidification determines the amount of heat stored and time taken to reach the stage, which depends highly on the thermal conductivities of the material medium and the initial and boundary conditions that are imposed to solve these problems. Forward Finite difference technique is used to solve the partial differential equations and solved the governing equations using the Scilab software. Result conclude that there is a significant effect on the evolution of freezing and dehydrated regions and on the rate of mass transfer.

Index Terms- **Freezing, Energy Storage Units, Phase change Problems, Latent Heat, Sustainable energy.**

I. INTRODUCTION

The latent heat of freezing, also known as the heat of fusion, is the amount of heat energy required to change a substance from its liquid state to its solid state at a constant temperature and pressure. Thermal energy storage (TES) systems are crucial for balancing the intermittent nature of renewable energy sources and improving the overall energy efficiency of various applications. Among the various TES methods, latent heat of freezing has gained significant attention due to its high-energy storage density and long-term storage capability. This research paper presents an advanced-level study on thermal energy storage using the latent heat of freezing, exploring its principles, materials, applications, and potential advancements. The paper reviews current research, identifies challenges, and proposes innovative solutions to optimize the performance and expand the utility of latent heat TES for a sustainable energy future. Creating a highly accurate mathematical model for latent heat storage during freezing requires a detailed understanding of the physical processes involved. Such models typically involve partial differential equations and may be quite complex.

Transient heat transfer problems described by non-linear partial differential equations along with the moving interface conditions are special type of boundary value problems known as moving boundary problems or Stefan Problems. Freezing/melting problems are referred as Stefan problems, as Physician Joseph Stefan first encounters these problems and proposed a model for the polar ice-melting problem. The essential and common feature of a system undergoing phase change is that a moving interface exists separating two regions of different thermo-physical properties at which energy is absorbed or released, separating the two phases. The objective of the paper is to get mathematical understanding of the latent heat released or absorbed during the freezing process to develop energy storage units as an alternative for the green energy. It includes development of mathematical model to quantify the process in order to predict the amount of heat released or stored in the process. This involves various process parameters that describe the dynamical mechanism of heat transfer process.

In the context of thermal energy storage systems, this property plays a crucial role in determining the efficiency and performance of the storage medium during the freezing and thawing processes. Several factors can affect the latent heat of freezing in thermal energy storages:

Material Properties: The latent heat of freezing is primarily determined by the material that is used as the storage medium. Different materials have different molecular structures and bonding energies, which directly influence the amount of energy required to change their state from liquid to solid. Common materials used in thermal energy storage include water, phase change materials (PCMs) like paraffins or salts, and other specialty substances.

Temperature: The latent heat of freezing is generally specified at a specific temperature. As the temperature varies, the amount of energy required for freezing can also change. It is important to consider the operating temperature range of the thermal energy storage system and how it affects the latent heat of freezing.

Pressure: In most cases, the latent heat of freezing is relatively independent of pressure for solid-liquid phase transitions. However, for certain materials or at extreme pressures, there might be slight variations in the latent heat value.

Purity of the Material: Impurities in the storage material can affect the phase change behavior and alter the latent heat of freezing. Higher purity levels generally result in more predictable and consistent phase change characteristics.

Heat Transfer Rate: The rate at which heat is supplied or extracted from the storage medium during freezing impact the efficiency of the process. If the heat transfer rate is too slow, the freezing process might be sluggish, and if it is too fast, it could lead to inefficiencies or uneven phase change.

Thermal Conductivity: The thermal conductivity of the storage material influences how effectively heat is distributed within the material during the phase change. Higher thermal conductivity can facilitate uniform freezing.

Confinement: The confinement or container used to hold the storage material can affect the freezing process. It may influence heat transfer, pressure, and expansion during freezing, which, in turn, can influence the latent heat of freezing.

Super cooling: Super cooling is the phenomenon where a liquid remains in a metastable state below its freezing point before it eventually solidifies. Super cooling can affect the actual freezing point and the amount of energy required to initiate freezing.

Crystal Structure: The crystal structure of the solid phase formed during freezing can impact the latent heat of freezing. Different crystal structures have different energy requirements for formation.

Previous Cycling: Some thermal energy storage systems undergo multiple freezing and thawing cycles. The latent heat of freezing might vary with each cycle due to changes in the material's properties over time.

Understanding these factors is crucial for designing efficient thermal energy storage systems that utilize the latent heat of freezing to store and release thermal energy effectively. The appropriate choice of storage material and the consideration of these factors can lead to improved energy storage performance and overall system efficiency

1.1 STAGES DURING THE FREEZING

A survey conducted on stages during freezing explained the process of freezing as summarized by Figure 1. Freezing of pure water follows the curve "ABCDEF" showing relationship between time and temperature starting from a temperature at A above freezing. The first thermal change that can be observed from the figure1 is undercooling/super cooling, below the freezing point of 0^oC, from B to C, before the inception of crystallization. This is non-equilibrium, metastable state which is analogous to activation energy necessary for the nucleation process. Before the nucleation phenomenon begins, water can be super cooled by several degrees. The system nucleates at point C in the figure1 and releases its latent heat faster than the heat that is being removed from the system. The temperature increases instantly to the initial freezing temperature at point D. The brief period from C to D is frequently called the stage of nucleation and dendritic ice formation. The time during which the crystal formation is happening is shown in the figure as the time line DE. Freezing rates promote the formation of many small ice crystals during this period. The partially frozen mixture will not cool until all of the "freezable" water has crystallized; hence, the line DE occurs at nearly constant temperature. The freezing time is defined as the time from the onset of nucleation at C to the complete removal of latent heat at E. After crystallization is completed, the temperature drops from E to F as sensible heat is released. For water freezing inside a pipe, line DE would be one of annular ice formation, and the line EF would be that of final cooling of the solid plug of ice to surrounding temperature.

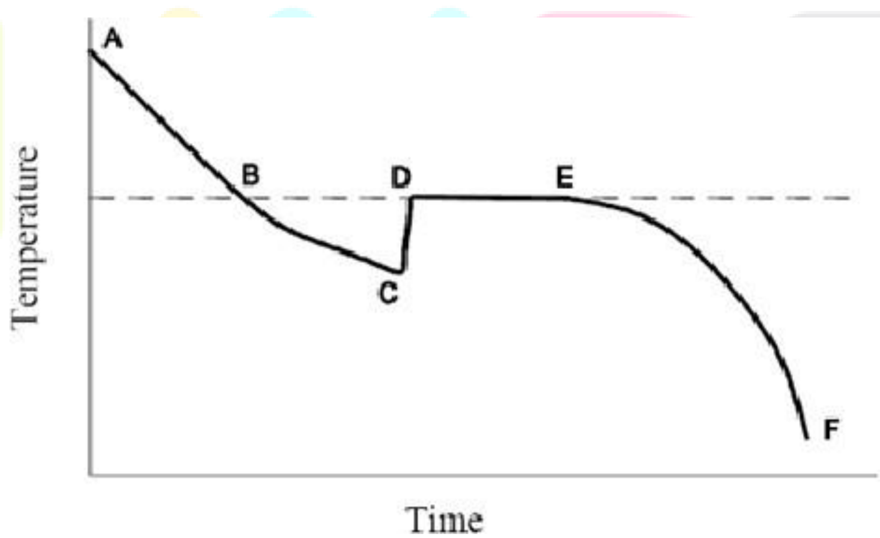

figure 1: stages during freezing of water

II. NEED OF THE STUDY

One of the key features of the Phase Change Materials (PCM) and the phase change processes is the application of this phenomenon in the energy conservation units. Removal of latent heat in the process of solidification is stored as the internal thermal energy and is reused when there is a peak demand for it. Ice storage tanks are serving as a better option in the ever-growing demand for the conservation of energy. There are three types of thermal storage sensible heat storage, latent heat storage, and hybrid storage involving latent and sensible heats. Latent heat storage systems are most preferred storage systems because of its high-energy storage capacity and its constant temperature during the charging and discharging processes. In addition, these are cost effective compared with the other storage systems. Thus, water is converted into ice when the demand for electricity is low, and ice is melted during periods of peak demand to help with cooling and air conditioning loads. This helps to reduce the cost in energy conservation mechanisms as latent heat energy storage systems are an important mode of energy conservation techniques.

III. LITERATURE REVIEW:

Latent energy storage systems (LHESS) are important thermal energy storage systems, which uses this energy whenever the crisis arises. This method of storing energy in the form of latent heat is gaining importance and it is the most convenient way compared to other energy storages. The paper by Wilson Ogoh et al. [1], studies the numerical investigation of the Stefan problem and validation with the analytical solution is done. A finite element analysis for the one-dimensional problem of melting using COMSOL Multi-physics is developed. The study focuses on the solid-liquid phase change heat transfer process-taking place inside a simple rectangular enclosure heating from one side. Temperature pro le in the PCM and the e etc. of melting temperature on the phase change behavior are studied. To in- crease the latent heat, specific heat is modified and modified specific heat approach is used for the study. Conduction mode of heat transfer was adopted for the numerical simulations. Incorporating a mushy region in the physical modeling of the PCM, through the modified specific heat, has an effect on the temperature pro le in the liquid PCM and the melting front behavior. Lamberg et al. [2] has conducted Numerical and experimental investigation for two different kind of PCM storage in melting and freezing processes. Numerical results validation with experimental results was the main objective of the paper. Two experimental PCM storages, with and without heat transfer enhancement structures, were designed and constructed. Numerical methods adopted used Enthalpy method and an effective heat capacity method and are solved using FEMLAB simulation software. Numerical results are compared with the experimental results and have shown good approximations for the temperature distribution of the storages in both melting and freezing processes. Whereas the effective heat capacity method, compared to Enthalpy method has shown good agreement, because of the chosen temperature range. Rotchana Prapainop et al. [3] solved solidi cation of ice formation numerically using finite volume method. The model is developed with the fixed grid and, latent heat source approach and piecewise-linear pro le of variables in space were considered. Second-order accurate piecewise-linear temperature pro le is assumed for temperature. Detailed investigations is carried out on the effects of different types of interface conductivity approximation and the explicit, Crank-Nicolson, and the fully implicit schemes on the accuracy and efficiency of finite volume modelling. The approximation of interface conductivity strongly influences numerical results. It is found that the use of harmonic mean produces unsatisfactory results as the freezing front advances through the control volume and the discontinuity does not remain at the cell faces as in composite interfaces. The explicit scheme has shown excellent time efficiency for the convergence.

Voller [4] develops a model for the moving boundary problem of solidi cation for tracking the solidification front in the presence of an under-cooled liquid. The model is solved numerically using fixed grid formation for the enthalpy based binary alloy coupled heat and mass transport problem. New solution using Enthalpy method is validated with known closed form similarity solution for the solidi cation of a binary alloy in a one-dimensional domain. The advantage of this method over the previously available methods is that this method addresses to deal with a jump in the specific heat and the liquid under cooling aspects. In addition, this model uses the liquid fractions in a particular range to identify the phase change nodes. The proposed numerical model evaluates the location of the interface, temperature, concentration pro les at different time. Comparison of the numerical results with the analytical solution shows an agreement to the desired extent. Solidification problem of pure water in circular enclosures is studied in the paper by Esam M. Alawadhi [5]. The enclosure is subjected to constant boundary conditions and thermo-physical properties and the study of circular enclosures has many practical applications such as cooling of water in circular tubes and thermal storage systems. In this problem, effect of natural convection of liquid water on the solidification rate is taken into account, which is neglected, and conduction mode of heat transfer is considered in many problems. The important dimensional less parameter is the Rayleigh number (Ra), which is defined as $Ra = \frac{g\beta\Delta T R^3}{\nu\alpha}$. ANSYS software is used to solve the governing equations and linear quadrilaterals are used to discretize the domain. Obtained results are compared with the experimental results and a good accuracy has been established.

A challenging model for the simulation of production of ice in turbulent seawater is described by Vanessa Covello et al. [6]. This is multiphase modelling describing all the stages of ice production based on Boussinesq approximation, modelling the behavior of seawater using the equation of state considering the mixture ice seawater as a dense compressible fluid. This equation links the seawater density to temperature, salinity and pressure. The time discretized model equations by projection method are solved using finite volume solver. Low Mach number asymptotic analysis is performed to investigate the behavior of multiphase equations in the incompressible limits. The density of the ice-seawater is given by $\rho = \varphi_1\rho_I + (1-\varphi_1)\rho_w$, where φ_1 stands as ice volume fraction and ρ_I, ρ_W are ice and water densities. The model is able to explain the interaction phenomenon occurring between phases when ice volume fraction is large. The drag force between liquid, the particles, and the particle-particle interaction force terms are included in the modelling in the momentum equations. The model adopted a special modelling approach for the numerical simulation of multiphase owes of the industrial interest.

In recent times, a phase change problem in cylindrical geometry for the solidi cation of pure water is discussed in the paper by Adil et al. [7]. Heat equation in polar form for a 3-dimensional cylindrical region is taken into consideration.

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial Z^2} \ldots\ldots\ldots\ldots\ldots (3.1)$$

Where $\alpha = \frac{k}{\rho C}$

This equation is reduced to a two-dimensional geometry considering that heat transits along the radial and axial directions through conduction. Freezing of pure water in a cylindrical domain are very important in both for theoretical purpose and for industrial applications, for the development of heat storage systems based on the latent heat and very less papers in the literature discussed about these types of problems. In the first approach the heat flux was fixed from the down of cylindrical domain and the position of interface line was at 18cm and $T_0 = 24^oC$ at time, $t = 0$. The chosen dimensions of cylindrical domain were 48 cm of diameter and of the length 90 cm. The r-axis and the Z-axis were insulated and proper bound- ary conditions according to the geometry were chosen. Numerical investigation was carried out using ADI (Alternating Direction Implicit). It has been proved that the Ice growth is fastest in the bottom part, than the other parts of enclosure, as this region is close to the heat ux. Temporal distribution of temperature in different regions of the cylindrical domain was obtained and the results I

IV. MATHEMATICAL MODELLING

A simple rectangular one-dimensional region is considered for the model with water as the material medium. Because water has high latent heat storage capacity and the model is described by governing model equations which is one dimensional heat conduction equation with a source term of latent heat. Initial and boundary conditions along with energy balance equation at the interface or convective boundary condition. Energy balances at the interface and heat transfer takes place. The mechanism involved in heat transfer problems is complex phenomenon and there exits many process parameters that contribute or affect this process. Frozen region is considered as the active region for the discussion.

To create a mathematical model for latent heat energy storage during freezing, we can consider the following assumptions and equations:

Assumptions:

- The system consists of a material with a specific heat capacity, density, and latent heat of fusion.
- The material undergoes a phase change from liquid to solid during freezing.
- The heat transfer occurs only in one dimension (along the thickness of the material).

The mathematical model is formulated using the heat conduction equation, incorporating the latent heat released during freezing. The process of latent heat storage during freezing involves both heat conduction and phase change. The general heat transfer equation for a one-dimensional system is

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + L\,\frac{\partial \varphi(x,t)}{\partial t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.1)$$

$T(x,t)$: Temperature of the material at a given position x and time t

L: Latent heat of fusion of the material.

x: Spatial coordinate

c: Specific heat capacity of the material.

ρ: Density of the material.

k: Thermal conductivity of the material.

α: Thermal diffusivity of the material, calculated as α = k / (ρ * c).

$\frac{\partial T}{\partial t}$: Partial derivative of temperature with respect to time.

$\frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right)$: Heat conduction term representing heat transfer along the thickness

$\frac{\partial \varphi}{\partial t}$: the rate of change of source / sink term pertaining to the latent heat L

The phase change fraction φ is defined as:

$\varphi = 0$, for $T \leq T_f$ (temperature at or below the freezing point)

$\varphi = {(T - T_f)}/{\Delta T}$, for $T > T_f$ (temperature at above the freezing point)

T_f: freezing point temperature and ΔT is a small temperature range around T_f.

To solve this mathematical model, we need to apply appropriate initial and boundary conditions. An initial condition is the initial temperature distribution in the material and the initial position of the moving boundary, and boundary conditions could include fixing the temperature at certain boundaries or specifying heat fluxes.

Initial conditions at time $t = 0$ are

$$s\,(0) = 0 \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots \;(4.2)$$

$$T = T_0 \;\; for\; x \geq 0 \quad \ldots\ldots\ldots\ldots\ldots \;(4.3)$$

T_0 is the initial freezing temperature.

The free boundary condition at $x = s(t)$ is

$$T(s(t), t) = T_0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots \;(4.4)$$

$$k\,\frac{\partial T(s(t))}{\partial t} = L\,\frac{ds}{dt} \qquad \ldots\ldots\ldots\ldots\ldots \quad (4.5)$$

Convective boundary condition at the fixed interface is

$$k\,\frac{\partial T(0,t)}{\partial x} = h(T(0.t) - T_s) \;\ldots\ldots\ldots \;(4.6)$$

where h is the heat transfer coefficient and T_s is the surrounding temperature.

This mathematical model is solved using finite difference method to simulate the freezing process and calculate the temperature distribution within the material over time. Approximate the spatial derivative using the central difference scheme, and the temporal derivative using the forward difference scheme taking the grid points ($i = 0,1,2, \ldots . N$) in the x direction and ($j = 0,1,2, \ldots . . M$)

in t direction. By analyzing the results, we can study the heat transfer, energy storage, and other relevant characteristics during the freezing process and optimize the design of latent heat energy storage systems.

RESULTS AND DISCUSSIONS

Figure2 shows that semi-analytical solution obtained is validated against the Neumann analytical solution for the given heat transfer coefficient h = 75 and $ste = 0.1$. We can observe the agreement of the results between the semi-analytic and the original solution.

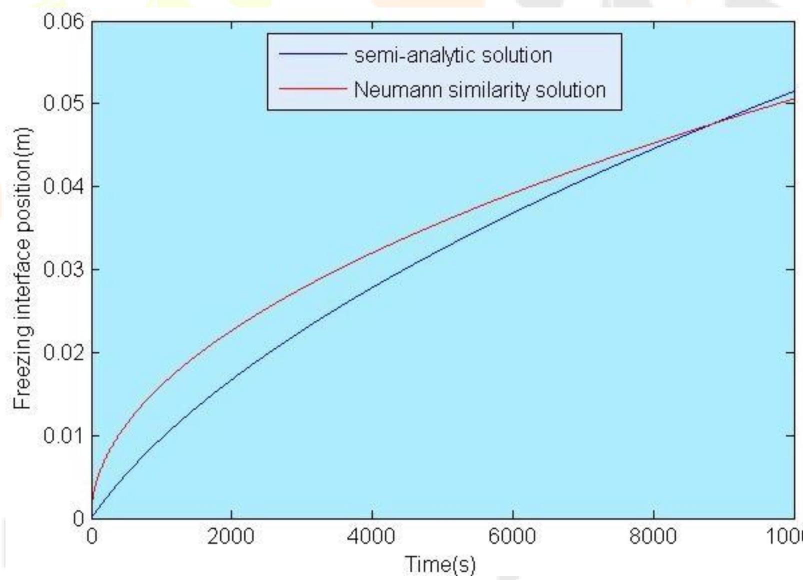

figure2: freezing interface position at different time interval

From figure 3 we can observe, the growth rate of interface position $s(t)$ for the time period of 10000s, for different heat transfer coefficients h. In the initial period growth is sharp and increases and increasing with increasing h .

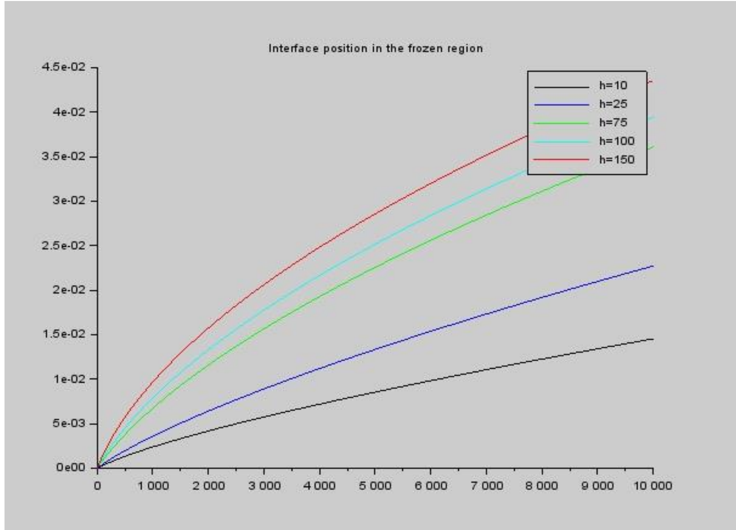

figure3: Moving interface position at different time intervals

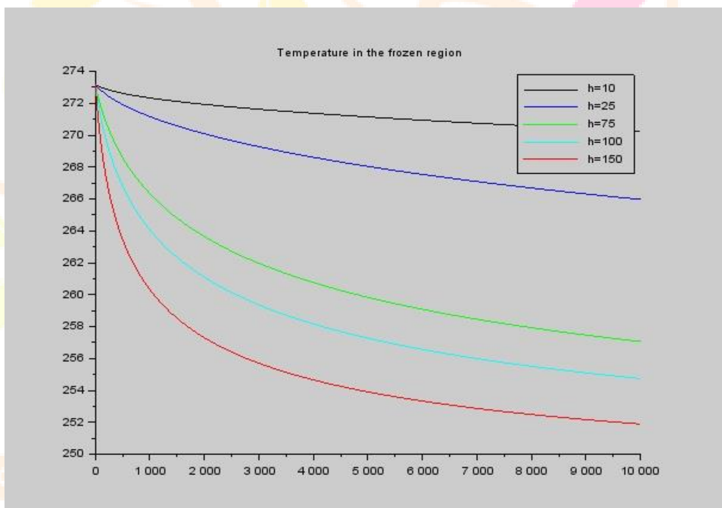

Figure 4: Temperature distribution at different time intervals

The sharp decrease in temperature in the frozen zone is studied for different heat transfer coefficient. From figure 4 we observe that higher the value of h, the temperature in the frozen zone falls sharply. We can conclude that there is a significant effect of heat transfer coefficient on both growth rate of moving front and on the temperature field. These results will help next to relate the latent heat function with the heat transfer coefficient to study the thermal storage systems.

CONCLUSION

Modelling of time dependent moving boundary problems is a complex phenomenon, which requires different parameters to describe. In this study for ice storage systems, a simple heat diffusion equation is solved for interface position and temperature distribution. To analyze the effect of latent heat further analysis is needed to develop thermal storage systems for energy conservation.

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