Modeling and simulation of phase change process in Ice Thermal Energy Storage

Tushar Sharma[1], Dr. Pankaj Kalita[2]
1. Centre for Energy, IIT Guwahati, Guwahati 781039, Assam, India
2. Centre for Energy, IIT Guwahati, Guwahati 781039, Assam, India

Abstract

The focus of this paper is to study the effect of phase change process of water as it undergoes heat exchange with the Refrigerant, R-22 as the heat transfer fluid. For the purpose of simulation of phase change process, COMSOL Multiphysics ® 5.3a has been used utilizing the inbuilt geometry builder. The motivation for this study comes from the experiments carried out on a lab-scale model of a small ice thermal storage for a fixed time duration. The boundary conditions used for simulation are similar to the conditions used in the actual experimental study. However, an actual comparison of both the studies is beyond the scope of the present study and needs further study and analysis. The reason for this is that the 2D model developed for the present computational study does not take into account the complexities present in the actual 3D model used for the experimental study. The present study enables us to validate the concept used in the actual experimental setup so that we can develop complex 3D user-defined functions to take into account the various complexities associated in the heat transfer process with much more accuracy.
Key words: 2D model, Phase Change, Heat Transfer, Fluid flow, Ice thermal energy storage, COMSOL Multiphysics ®

Introduction

Ice Thermal Energy Storage is a form of Latent Heat Thermal Energy Storage in which water is used as the Phase Change Material, which undergoes phase transformation during charging and discharging periods of operation.
Present study is focused on the phase change simulation using CFD analysis for the 2D model developed in the COMSOL Multiphysics ® software. Following figure illustrates the schematic of the 2D model used for modeling and simulation purpose of the fluid flow and heat transfer used in the software.

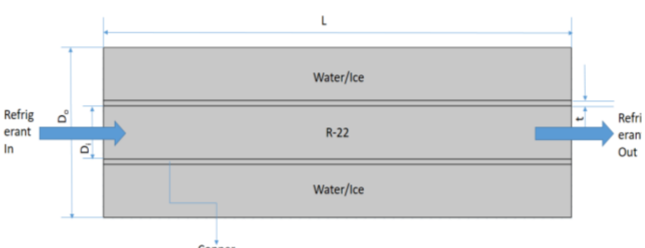


Figure 1: Schematic representation of the 2D model used for simulation

Following table shows the values of various parameters selected for dimensioning of 2D model.

Parameter	**Value (mm)**
D_i	10
D_o	32
L	100
t	1

Table 1: Parameter values for dimensioning 2D model

The geometry has been created using the inbuilt geometry builder feature and the fine mesh feature is used to generate the mesh used for the CFD simulation study. Following figure shows the Mesh generated using the mesh generate feature.

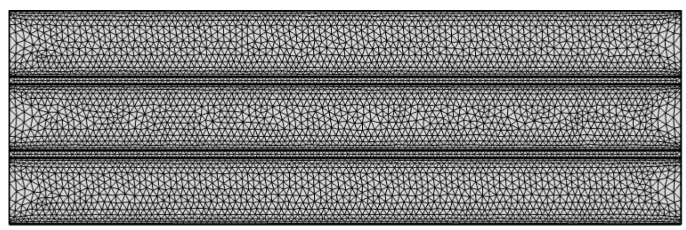


Figure 2: Fine mesh generated for the purpose of CFD simulation

Following table shows the details of the Mesh generated.

Characteristic	**Value**
Triangular elements	8272
Quadrilateral elements	1344
Edge elements	754
Vertex elements	12
Average element quality	0.827
Element area ratio	0.066
Mesh area	3200 mm^2
Average growth rate	1.379

Table 2: Mesh details for the mesh generated for CFD simulation

Theory

Latent Heat Thermal Energy storage (LHTES) forms the basic mechanism of operation of Ice Thermal Energy storage system. The way it works is illustrated in the figure 3 below.

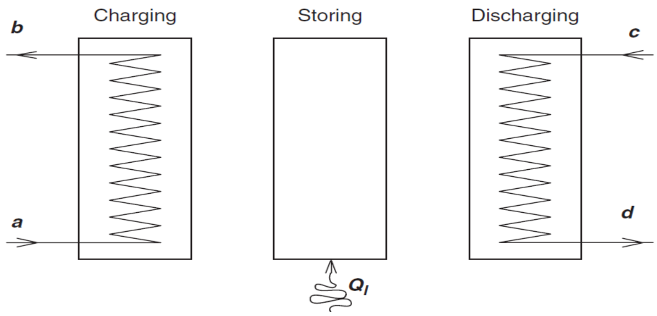


Figure 3: The three processes in a general CTES, Charging, Storing and Discharging.

Charging process

In the Charging process, the heat transfer fluid at high temperature enters the chamber where storage fluid or the Phase Change Material is stored. The melting process occurs and the temperature of the PCM starts to rise with time, till the desired temperature is achieved at the outlet of the heat transfer fluid.

Storing process

In the Storing process, Energy accumulation occurs for a very brief time in which the storage is being left idle. Ql represents the heat load infiltrating into the system from surroundings.

Discharging process

In the discharging process, the solidification/ freezing of the PCM occurs. The heat transfer fluid enters the chamber where PCM is stored at a temperature lower than what is to be maintained in the PCM and takes away the heat of fusion. Thus, making the PCM cooler in the process. Heat transfer fluid becomes relatively hotter, however the temperature at the outlet is maintained in the range, which is needed inside the Cold Storage prototype cabinet.

The boundary conditions used for simulation of heat transfer with phase change are listed in the table below.

Parameter	**Value**
Discharging T_{in}	-10 ˚C
Discharging T_{out}	-4 ˚C
Storage Fluid (Water) Temp (Discharge)	0 ˚C
Charging T_{in}	6 ˚C
Charging T_{out}	-2 ˚C
Storage Fluid (Water) Tenp (Charging)	-6 ˚C
Heat transfer fluid (R-22) mass flow rate	0.00159 kg/s

Table 3: Input parameters for discharging and charging periods of Ice Thermal Storage

Governing Equations used for Simulation of heat transfer with phase change

Conjugated heat transfer method is used as the physics that best describes our case for simulation, as the heat transfer is taking place at the interface between copper tube carrying the Refrigerant (heat transfer fluid) which is flowing and the Storage fluid (water) which is stationary and changing its phase from one phase to the other in both the processes. Following set of governing equations have been used for simulation of the heat transfer process with phase change.

$$\rho\frac{\partial u}{\partial t} - \nabla.\eta(\nabla u + (\nabla u)^T) + \rho(u.\nabla)u + \nabla p = 0 \qquad (1)$$

$$\nabla.u = 0 \qquad (2)$$

$$\rho C_p\frac{\partial T}{\partial t} + \rho C_p u.\nabla T + \nabla.T + \nabla.q = Q + q_0 + Q_P + Q_{vd} \qquad (3)$$

$$q = -k\nabla T \qquad (4)$$

$$C_p = \frac{1}{\rho}\left(\theta\rho_{phase1}C_{phase1} + (1-\theta)\rho_{phase2}C_{p,phase2}\right) + L\frac{\partial\alpha_m}{\partial T} \qquad (5)$$

$$k = \theta k_{phase1} + (1-\theta)k_{phase2} \qquad (6)$$

$$\alpha_m = \frac{1}{2}\frac{(1-\theta)\rho_{phase2} - \theta\rho_{phase1}}{\theta\rho_{phase1} + (1-\theta)\rho_{phase2}} \qquad (7)$$

In the above equations, ρ is the density of the fluid, u is the velocity of the flowing fluid, p is the pressure, Q is the heat flux, T is the temperature, C_p is the specific heat capacity, θ is the melt fraction, k is the equivalent thermal conductivity, L is the latent heat energy, α is the thermal diffusivity.
Following set of properties were used for the phase change fluid in different processes.

Mat. Properties	**Ice**	**Water**
Density (kg/m^3)	918	997
Specific Heat Capacity (J/kgK)	2052	4179
Thermal conductivity (W/mK)	2.31	0.613

Table 4: Material properties of water and ice used for simulation of phase change.

Simulation results and discussions

For the purpose of simulation, conjugated heat transfer model is used as the physics. Time dependent study is used with a total runtime of 4100 secs and a time step of 1 sec. The physics is solved for a total of 27345 degree of freedoms. The physics is solved for three variables, namely pressure (P), velocity (V) and temperature (T). Coupled direct solver PARDISO is used as the solver by COMSOL.

1. Charging Period

Following results have been observed for the Charging period. Three cut lines have been defined for the evaluation of properties along the length of the conductor. Details of the cut line are shown in the table given below:

Cut Line 1	X = -50 to X = 50	Y = 0
Cut Line 2	X = -50 to X = 50	Y = 10
Cut Line 3	X = -50 to X = 50	Y = - 10

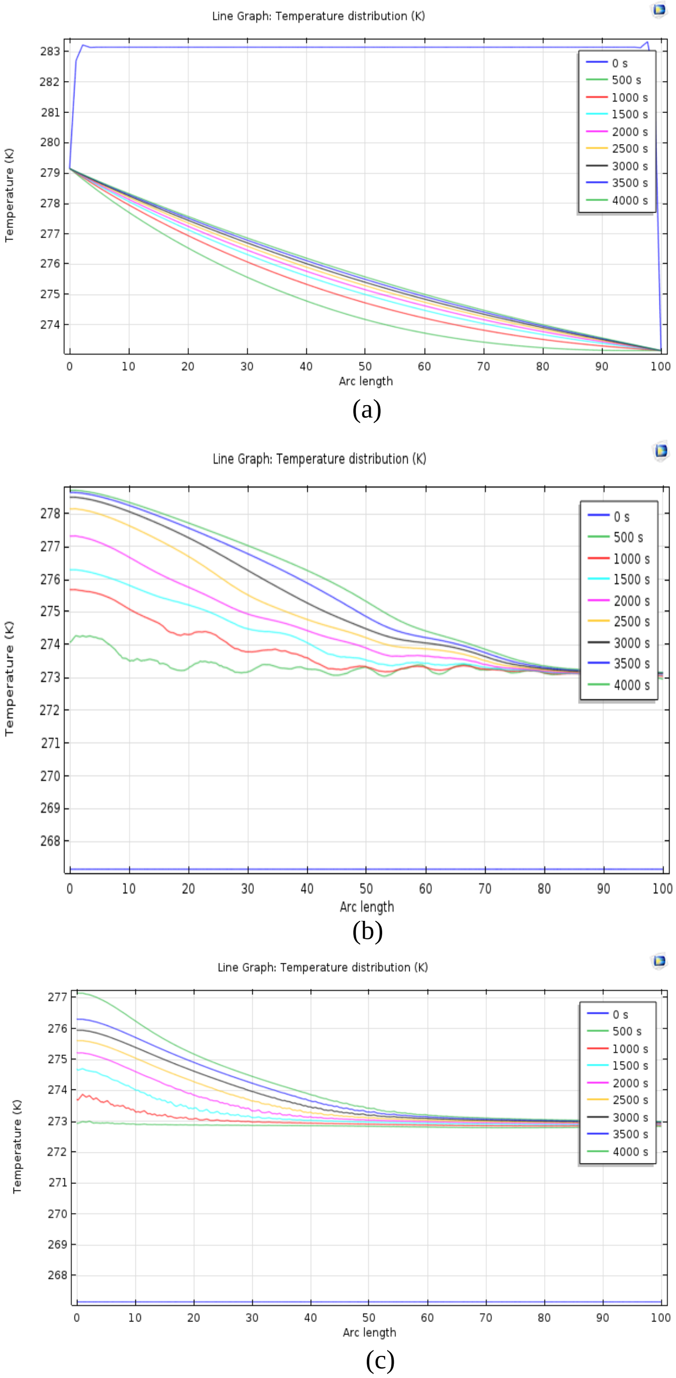


Figure 4: Variation of temperature with time across the length of the 2D model a) Mid-section b) 10 mm above the x-axis c) 10 mm below the x-axis.

Following figure shows the phase transformation during the charging period.

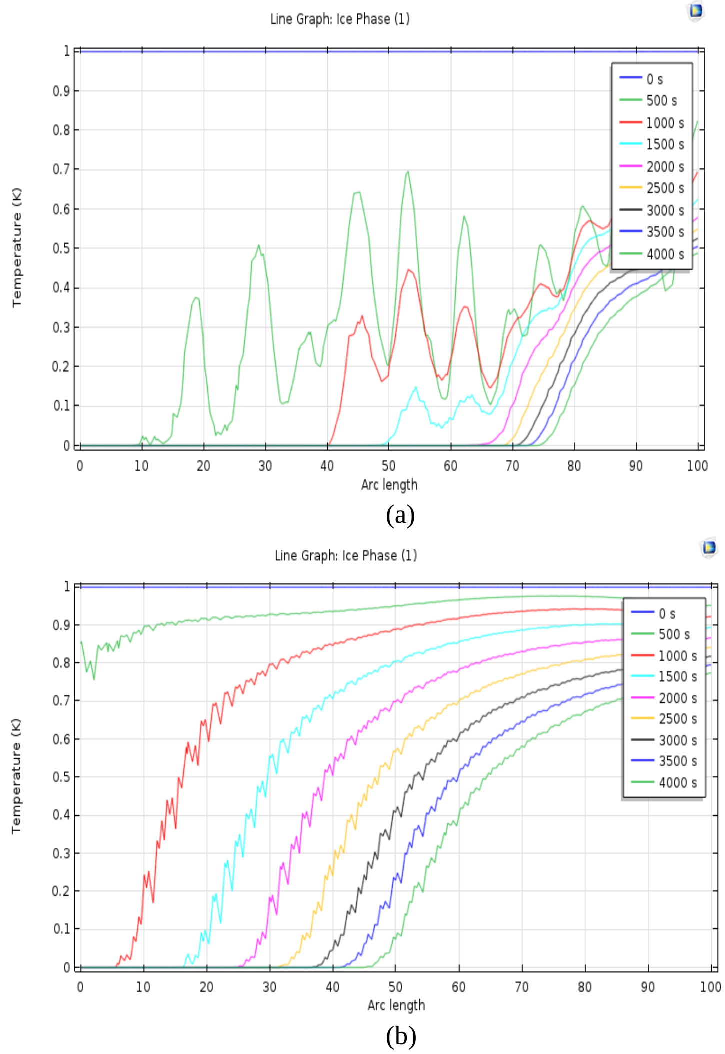


Figure 5: Phase transformation with time across the length of the 2D model a) 10 mm above the x-axis b) 10 mm below the x-axis.

It can be seen from the Figure 4 that the Temperature is increasing with time for the two cut sections inside the storage fluid zones in b) and c), while the opposite is seen in the a) inside the heat transfer fluid (R-22) as expected from the heat transfer physics. However, while moving from the left end to the right end, the temperature is reducing at any given time, which is expected, as the temperature to be maintained is lesser in right end to meet the requirements of boundary conditions.

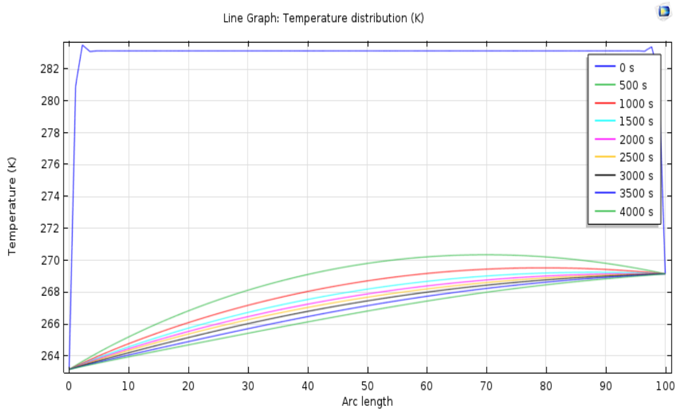
Looking for the phase transformation point of view in the Figure 5 at two cut sections a) and b), it can be said that the phase is being transformed into liquid from solid where 0 is liquid and 1 is solid. With time, transformation is taking place as expected from the heat transfer physics. However, more melting is taking place in the upper section than the lower section, which can be investigated in the future for further study.

2. Discharging period

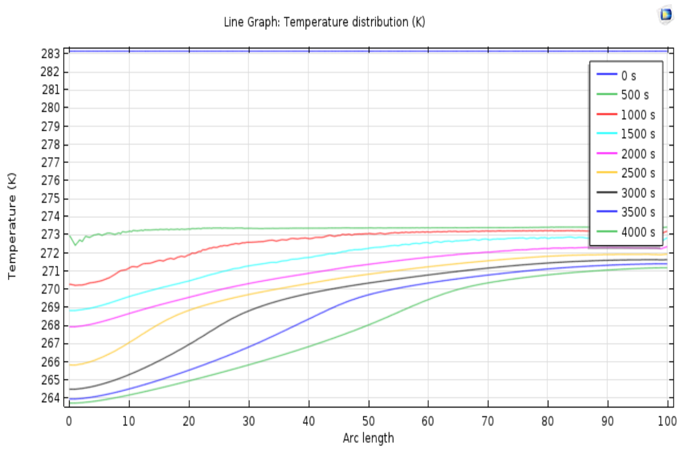
Following results have been observed for the Charging period. Three cut lines have been defined for the evaluation of properties along the length of the conductor. Details of the cut line are shown in the table given below:

Cut Line 1	X = -50 to X = 50	Y = 0
Cut Line 2	X = -50 to X = 50	Y = 10
Cut Line 3	X = -50 to X = 50	Y = - 10

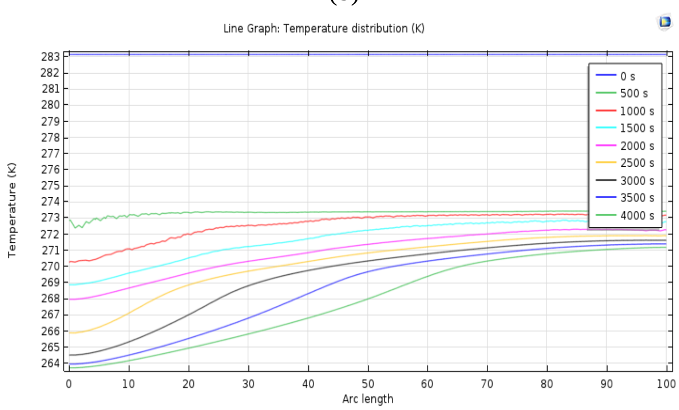
Table 6: Cut-Line for various sections in the 2D model



(a)



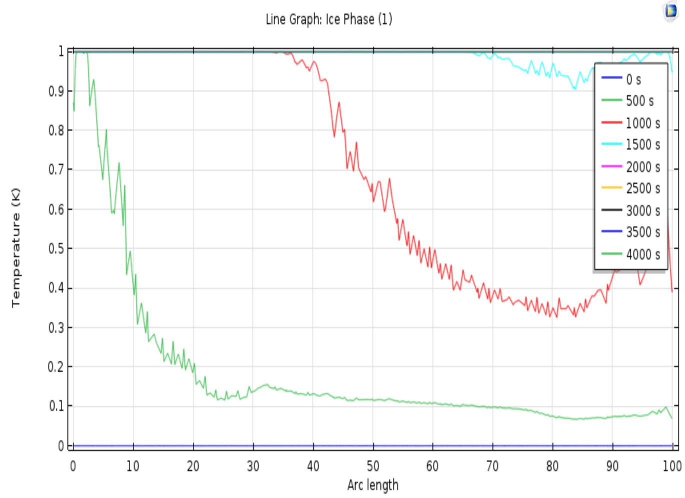
(b)



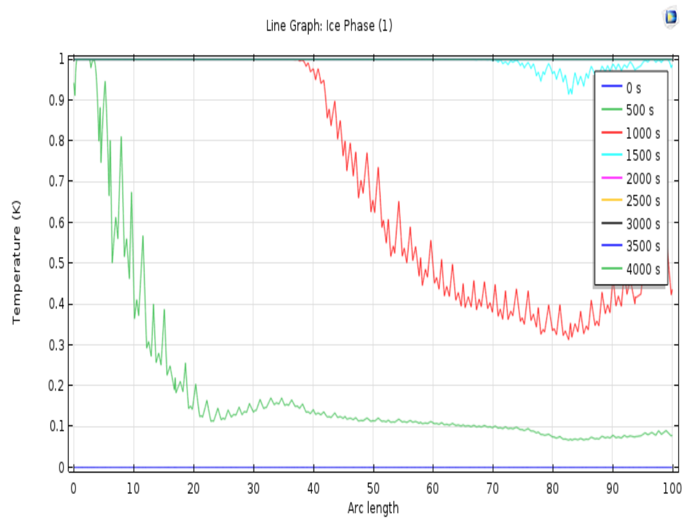
(c)

Figure 6: Variation of temperature with time across the length of the 2D model a) Mid-section b) 10 mm above the x-axis c) 10 mm below the x-axis.

Following figure shows the phase transformation during the charging period.



(a)



(b)

Figure 7: Phase transformation with time across the length of the 2D model a) 10 mm above the x-axis b) 10 mm below the x-axis.

It can be seen from the Figure 4 that the Temperature is reducing with time for the two cut sections inside the storage fluid zones in b) and c), while the opposite is seen in the a) inside the heat transfer fluid (R-22) as expected from the heat transfer physics. However, while moving from the left end to the right end, the temperature is increasing at any given time, which is expected, as the temperature to be maintained is higher in right end to meet the requirements of boundary conditions.

Looking for the phase transformation point of view in the Figure 5 at two cut sections a) and b), it can be said that the phase is being transformed into solid from liquid where 0 is liquid and 1 is solid. With time, transformation is taking place as expected from the heat transfer physics. Similar phase transformation characteristics are observed in both the halves of the 2D model.

Conclusions

From the study conducted for the phase change heat transfer, it can be concluded that the heat transfer physics have been accurately applied for both the cases viz. charging and discharging of the ice thermal energy storage. Further study can be done on more complex 3D models to accurately predict the phase transfer physics. The computational time needed for the simulation was 20 min 20 s for the charging phase and 10 min 48 s on a 4GB RAM computer. For solving more complicated problems, better computational facilities can be used to reduce the computational time and produce faster results.

References

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