Chapter

Solidification and Melting of Phase Change Material in Cold Thermal Storage Systems

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Abstract

Cold thermal storage can be used to manage peak load when the energy demand is exceeding the capacities of the electric companies. Latent heat thermal storage is more effective because it requires less spacing and has higher thermal capacity than other types. Solidification and melting are taking place in CTS and need more investigation for better performance. Phase change materials properties vary and need more investigation to select the most suitable for a certain application. The analytical equations are needed for design of CTS and get the maximum efficiency out of it. Cost effectiveness is also described.

Keywords: solidification, melting, cold thermal storage

1. Introduction

The electric energy consumption in a country like Saudi Arabia reaches its peak during summer time. Most of this consumption goes to air conditioning, i.e. 75% to 90% of total electric energy production by the Saudi Electrical Companies during summer season are consumed for cooling. This put an excessive load on the electricity suppliers during summer time, at which a peak load exists as shown in **Figure 1**. The peak load or Peak demand are terms used in energy demand management describing a period in which electrical power is expected to be provided for a sustained period at a significantly higher than average supply level.

Peak load occurs usually during the day in hot countries. Most of the energy was consumed by the air conditioning for residential and commercial buildings. Load management initiatives are usually investigated by the electric companies to smooth the system load curve (Load leveling of electricity) (**Figure 1**). Many methods are suggested to handle this problem, such as utilizing renewable energy, unfixed Tarriff, use of the electrical link, and finally utilizing of energy storage systems.

Cold thermal storages were built successfully in several projects in Saudi Arabia such as, Al Mamlaka Tower in Riyadh, King Khalid Training Center in Riyadh and King Abdulaziz University Campus in Jeddah.

1.1 Concept of thermal energy storage

Unique solution to manage the peak load, that can save energy and will not cost so much is the storing of energy. The different forms of energy that can be stored include mechanical, electrical and thermal energy. Note that the Energy storage is

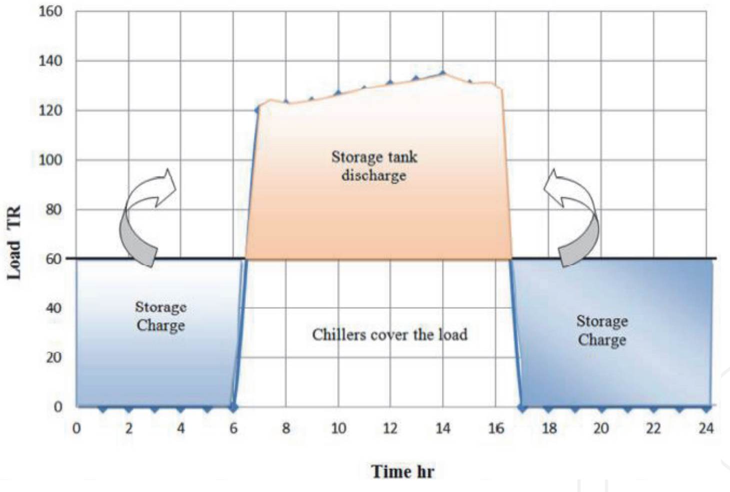

Figure 1.
Load distribution during the day (load leveling of electricity), [1].

not only reduces the mismatch between supply and demand but also improves the performance and reliability of energy systems and plays an important role in conserving the energy. Thermal energy can be stored during the un- peak period, usually at night, and re-use it during the peak load.

TES technology can reduce the generating and operating costs of cooling plant equipment. By utilizing TES, new generating plants can be eliminated. Moreover, some electric companies initiated different Tariff rate to reduce the use of electricity during the peak demands and force big consumers to store energy in the off-peak time by utilizing TES. In applications where peak loads occur only for a limited period during a year, such as worshipping places, which are used only for couple of hours during the day or the weak, TES systems can also be used, so that it can be to store the full need of cooling energy with reduced size equipment.

Thermal energy storage can be stored as a change in internal energy of a material as sensible heat, latent heat and thermochemical or combination of these. Cold storage technology has improved significantly since 1980 when electric utility companies recognized the need to reduce the peak demand on their generation and distribution systems. Chilled water, ice, or eutectic phase change materials are the cold storage media.

1.2 Classification of cold thermal storage

Cold thermal storage systems which are classified into thermal or chemical. The thermal CTS is classified into Sensible or latent heat storage system as shown in **Figure 2**.

1.2.1 Chilled water storage systems

Among all types of liquid water is selected to be the thermal storage medium, since it has the highest specific heat of all common materials (4.18 kJ/kg.°C). Chilled water with temperature 5 °C -7 °C can be generated by conventional chiller unites. The chilled water is then can be stored in an isolated concrete or stainless-steel tank for later use to meet the cooing needs, **Figure 3**. In general, in order to store 1 kWh of energy, a volume of approximately 0.1 m^3 is required. The chilled water can be pumped to the air handling unite (AHU) from the bottom of the tank and at the same time is substitute from the top by the return warm water from the AHU. Stable layers of water can be achieved due to variation of densities according on the temperature. This type of CTS is cost effective when the space is available. The chilled water tank by itself has other uses such as a back up water reservoir or for emergency fire extinguisher.

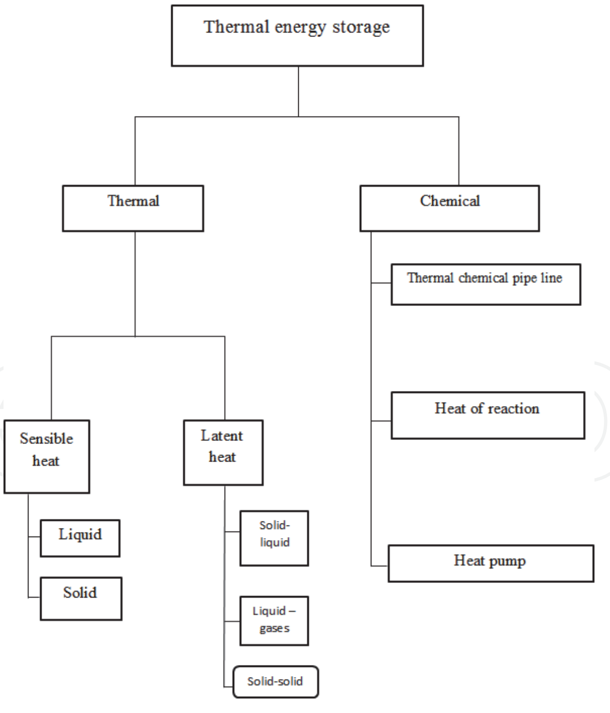

Figure 2.
Thermal energy storage types.

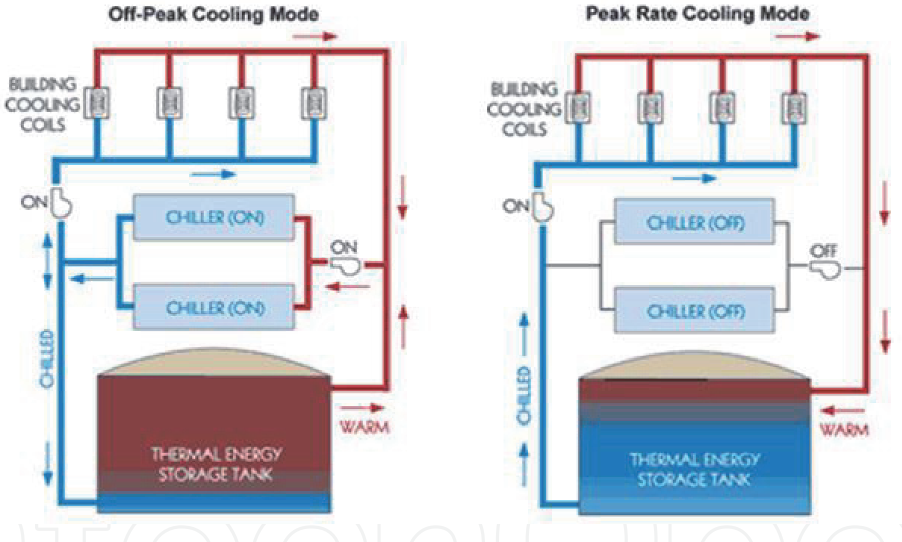

Figure 3.
Chilled water storage systems.

The quantity of stored heat in the storage tank can be calculated by

$$Q = \dot{m} C_p (T_e - T_i) \tag{1}$$

Where m is the mass of the chilled water,

1.2.2 Latent heat storage

When the materials go for a phase change from solid to liquid, liquid to gas or vice versa, it can store or release huge amount of heat which is latent heat. Latent heat storage (LHS) is getting more attractive because of the huge amount of energy that can be stored with small space which is usually one fourth less than the chilled water storage system. **Figure 4** shows the latent heat storage mechanism for solid liquid phase change.

Figure 5 shows a thermal storage system that utilizes ice. The size of the storage tank depends on the total volume of the melted liquid.

On the other hand, the ice storage system has COP of 2.5–4.1 which is less than that of chilled water storage system of 5–5.9 COP. So that the ice storage system economic benefit is beneficial for less Tarif at the off-peak time.

The storage capacity of the LHS system with a PCM medium is given by

$$Q = \int_{T_i}^{T_e} \dot{m} C_p dT + \dot{m} a_{fr} \Delta h + \int_{T_e}^{T_{fr}} \dot{m} C_p dT \qquad (2)$$

Or:

$$Q = \dot{m} \left[C_p (T_e - T_i) + a_{fr} \Delta h + C_p \left(T_{fr} - T_e \right) \right] \qquad (3)$$

The specific volumetric storage capacity of ice stores is 40–53 kWh m^3 [2].

Ice storage systems allow for innovative HVAC system design such as cold air distribution systems which have lower initial costs compared to conventional distribution systems. Ice storage systems include: Ice harvesters, Internal melt ice-on-coil storage systems, External melt ice-on-coil storage systems and Containerized ice storage systems. More details on each one of them can be found in Moncif Karaci “Energy Audit of Building System: An Engineering Approach”.

1.2.3 Thermochemical energy storage

By a reversible chemical reaction, the energy can be absorbed or released for a thermochemical system. The stored thermochemical heat relies on the amount of storage material, the endothermic heat of reaction, and the extent of conversion.

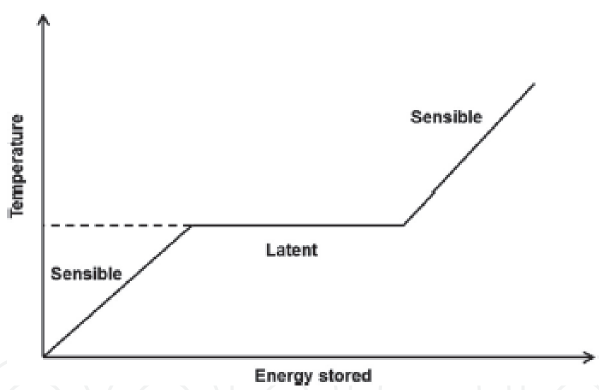

Figure 4.
Latent heat storage mechanism for solid –liquid.

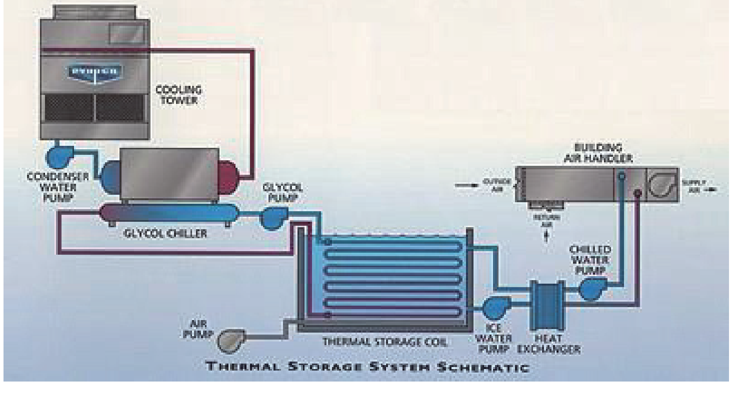

Figure 5.
Thermal storage system that utilizes ice, the size of the storage tank depends on the total volume of the melted liquid.

1.2.4 Eutectic systems

Salt and oil are two types of eutectic material. A eutectic salt can change its phase from liquid to solid at a specific temperature. These phases may have different crystal structures, or the same crystal structure with different lattice parameters. The phase change material such as Eutectic salts can have a freezing point of 8.5 °C which means less consumption of energy than ice. The PCM used in Eutectic system has less capacity than ice storage system but higher capacity than chilled water system. The eutectic system is more expensive and complex than chilled water systems and has warmest discharge temperatures (near 10 °C). More details of PCM materials can be found with [3].

1.3 Phase change materials

Phase change materials (PCM) are "Latent" heat storage materials. Unlike conventional (sensible) storage materials, PCM absorbs and release heat at a nearly constant temperature. They store 5–14 times more heat per unit volume than sensible storage materials such as water, masonry, or rock. PCM can be classified as organic, inorganic or eutectic which can be available in any required temperature range. The inorganic materials have almost double volumetric latent heat storage capacity (250–400 kg/dm3) than the organic materials (128–200 kg/dm3).

Organic materials are further described as paraffin and non-paraffins. Organic materials include congruent melting means melt and freeze repeatedly without phase segregation and consequent degradation of their latent heat of fusion, self-nucleation means they crystallize with little or no supercooling and usually non-corrosiveness. Inorganic materials are further classified as salt hydrate and metallics. These phase change materials do not supercool appreciably and their heats of fusion do not degrade with cycling.

The melting point of Paraffin varies between 5.5 °C and up to 75.9 °C, [4]. The latent heat of fusion varies from 170 kJ/kg and up to 269 kJ/kg. For the non-paraffin, the melting points also varies from 7.9 °C to 127.2 °C. They have heat of fusion ranging from 93 kJ/kg to 259 kJ/kg. The non-paraffin materials will have its own properties unlike the paraffin's, which have very similar properties. For the inorganic materials has a melting point varies from 16.7 to 102 and heat of fusion ranges from 146 to 242 kJ/kg. The high melting point allows les energy needed for those PCM to change state. The relatively high heat of fusion is another factor can affect the selection of such materials. **Table 1** shows the properties need to be considered in PCM. More details about the recommended PCM can be found in [4–6].

Properties	Features
Thermal	Melting temperature higher than or equal water freezing temperature, latent heat of fusion and heat transfer.
Physical	High density, small volume change, low vapor pressure.
Kinetic	No supercooling, adequate crystallization rate
Chemical	Stability, compatibility, toxity, non-flammable
Economics	Availability and cost effective

Table 1.
Required features for the PCM materials.

2. Charging of cold thermal storage

2.1 Fundamental studies related to cold thermal storage

Ice on tube system essentially consists of cold pipes submersed in stagnant water or cold pipes submersed in a cross flow of water. Freezing of water was studied by several researchers. **Table 2** shows a summary of the works that have been done by several researchers to study the freezing phenomena as well as melting.

Type of study	References	Finding
Freezing of water on immersed tubes bank	[7, 8]	Ice layers affect negatively heat transfer
solidification of PCM around a cylinder for ice-bank applications	[9, 10]	The inlet temperature influences the freezing process
ice formation around a horizontal long copper tube U-shap	[11]	Slope of the ice thick-ness, in which the axial distance depended on time but varied with coolant flow rate and Stanton and Biot numbers
solidification of PCM around a cylinder for an ice-bank application	[9, 10]	Lower initial temperature of the liquid phase seemed to accelerate the solidification.
Additive of stainless steel pieces, copper pieces and PCM-graphite composite material to the PCM	[12, 13]	Addition of stainless steel pieces in the PCM does not increase the heat flux significantly. However, addition of copper pieces and the use of graphite composite enhance heat transfer significantly.
Ice storage system using water–oil mixture	[14]	Slush ice is formed out of the tube surface
Analyzed ice formation around a finned-tube	[15, 16]	The finned enhanced the ice formation by 45%
Finned tubes to enhance heat transfer for forming of ice on tubes in bank geometry, **Figure 6**	[17]	Fins diameter and temperature of the coolant enhance the freezing process
Thin ring and annular fin enhancing ice formation	[18]	Thin rings have better performance in comparison to annular fins
Spray chemicals to enhance the defrosting process	[19]	Ethanol inhibits of the frost layer and on the same time provide better defrosting effect
Mathematical model for the optimization of ice making in a laminar falling film on vertical plates	[20]	The freezing time can be reduced by six times for commercial model
Studied the freezing of a falling film on horizontal tubes	[21, 22]	They showed that ice formation depends on falling film and coolant flow rates. Also, the overall heat transfer coefficients are controlled by ice thermal resistance
Investigate the impacts of shape-stabilized phase change material (SSPCM) and different control strategies on the energy consumption and peak load demand as well as electricity cost	[23]	Use of SSPCM in the building could reduce the building electricity cost significantly. However, the use of ice systems is more attractive than that of chilled water systems
Economic opportunities afforded by installing an ice storage system to existing air conditioning	[1]	Combining both the energy storage and an incentive time structured rate shows reasonable daily bill savings

Table 2.
Summary of the works that have been done by several researchers to study the freezing phenomena as well as melting.

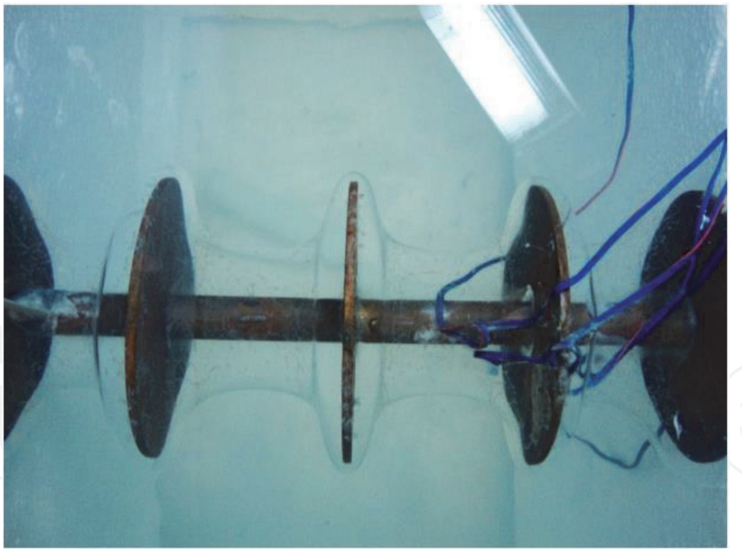

Figure 6.
Ice accumulation on finned tube, [17].

2.1.1 Falling film phenomena

Falling film can be either on vertical flat plate or horizontal tubes to maximize the heat transfer coefficient. Three main modes were shown when the liquid drop from any tube. It can take a shape of droplet, jet or sheet depending on the flow rate as shown in **Figure 7**. Combined modes usually took place. By increasing the flow rate, the mode changes to droplet-jet, jet, jet- sheet and finally sheet mode. Multi-modes can be appeared at the same time for the same flow rate, depending on the number of tubes aligned vertically. More secription of the flow pattern for the falling film can be found in [24–27]. For the purpose of freezing for the CTS, several articles talked about the possibility of utilizing the advantages of high heat transfer coefficient to be used for freezing.

For the maximum falling film flow, the sheet mode took place. This mode is shown clearly in the upper two test tubes, the rest shows sheet-jet mode. Some of the falling film splashed from the down tubes. By reducing the flow rate, jet mode is achieved and it is observed clearly on the upper tubes and the rest is a jet-droplet mode. A small amount of the falling film splashed from the down tubes. With further decrease in the flow rate, a steady droplet mode all over the test tubes was noticed with no splash from the tubes.

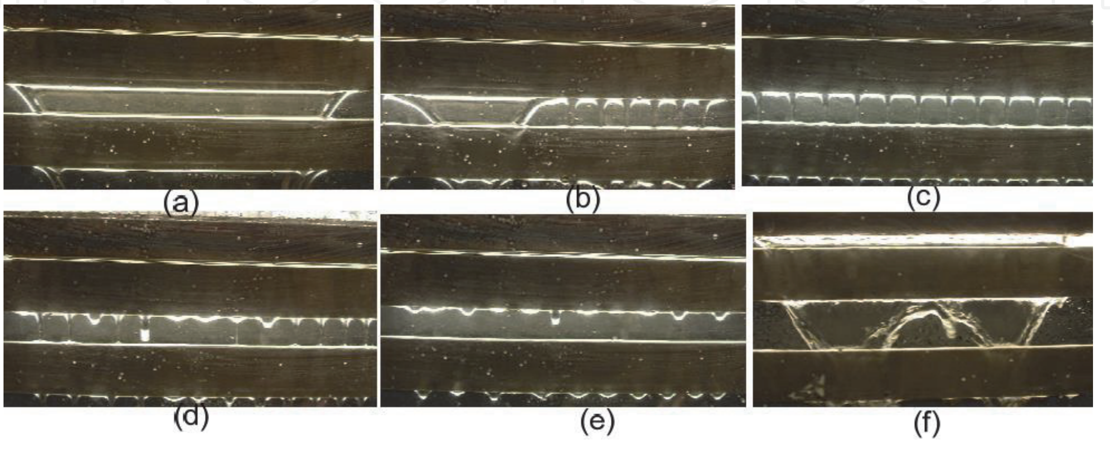

Figure 7.
Idealized innertubes falling film modes: (a) sheet mode, (b) mixed of sheet and jet, (c) jet mode, (d) droplet-jet mode, (e) droplet mode, (f) sheet mode [24].

2.2 Ice formation characteristics

The formation of ice begins usually where the inlet coolant exists due to the lowest temperature there. The regularity of ice depends on the types of stream that moves on the tubes. It is obvious that the formation of ice increases with time. However, the ice formation reduces heat transfer due to an increase in the insulation of ice (increased thickness of ice causes an increase in thermal resistance and consequently reduction of heat transfer through ice layer). It has been observed that as the ice accumulates on the test tubes, it takes longer time to remove it from the test tubes by the discharge cycle and relatively large quantity of ice is melted.

Ice accumulates circumferentially on the tube surfaces until the tube spacing is filled with ice which makes it harder in discharging process (**Figure 8**).

2.3 Heat transfer analysis for freezing

Heat transfer assessment on tubes bundle is based on detecting of temperature change, temperature of the liquid flowing through the tube bundle and temperature of outside liquid with simultaneous measuring of the current flow of liquids. This way, the real value of the heat transfer is determined at the tube bundle working under the set conditions. And subsequently, the corresponding heat transfer coefficient can be determined. Series arrangement has the advantage of high flow rate inside the tube and consequently high Reynolds number and high inside heat transfer coefficient. However, it difficult to be designed and maintain. In contrast, parallel arrangement is more convenient for industry, but reduces the inside heat transfer coefficient due to the inside flow is divided in to the all tubes and hence reducing the Reynolds number and so the inside heat transfer coefficient.

For the CTS, the heat transferred from the outside liquid to the entire coolant. The amount of heat transferred is determined from the temperature difference and the corresponding fluid flow rate. When solidification is taken place, the outside liquid loss sensible heat to reach the freezing point and then latent heat, to form ice. The rest of the outside liquid cools down while it is contacting the outside of the cold tubes.

The heat transfers from the outside liquid to the inside coolant via ice layer and the tube wall as shown in **Figure 9**. The thermal conductivity of the tube wall is usually very high comparing to the ice layer, so the tube resistance is usually ignored.

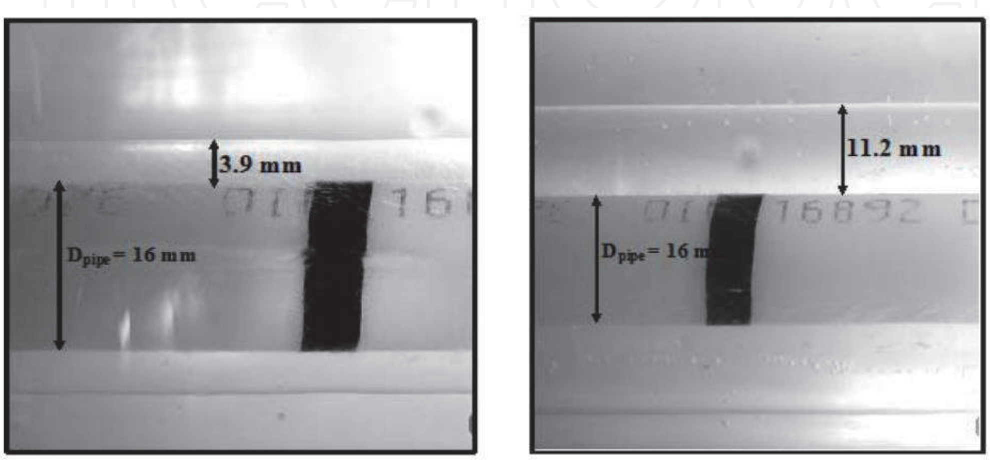

Figure 8.
Ice photo on the formed ice on the tube at time of (a) 50, (b) 198 minutes.

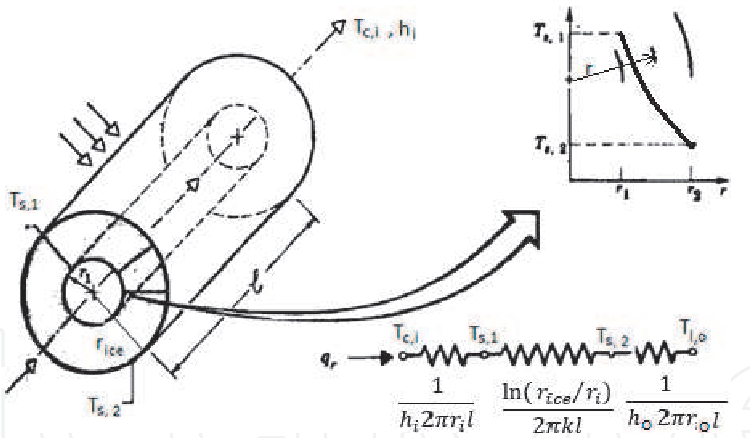

Figure 9.
Thermal resistance for ice accumulates on the tubes [28].

The rate of heat transfer from the outside fluid to the coolant inside the tube can be calculated as:

$$\acute{Q}_{ins} = \frac{(T_{\infty,o} - T_{ave,i})}{R_o + R_{ice} + R_i} \quad (4)$$

For thermal resistance shown in Fig., then

$$\acute{Q}_{o-i} = \frac{(T_{\infty,o} - T_{ave,i})}{\frac{1}{h_o 2\pi r_{ice} l} + ln} \quad (5)$$

2.3.1 Heat transfer coefficient inside the tube h_i

The inside heat transfer coefficient is given by:

$$h_i = NuK/D \quad (6)$$

Where:

In order to get *Nu, Re* must be calculated and is given by, $\Re = \rho u_m D_h/\mu$,where the velocity of the coolant at the test tube, $u_m = \acute{m}_c/\rho A_i$ and, $\acute{m}_c$ is mass flow rate of the coolant which enters to the test section.

For constant surface temperature condition, and laminar flow, Re ≤ 2300, Nusselt number is given by many researchers. One is given by Incropera, F.P. et al., as:

$$Nu = 1.86\left[\frac{RePr}{l/D}\right]^{1/3} + \left[\frac{\mu}{\mu_s}\right]^{0.14} \quad (7)$$

Where this equation can be applied for the following condition:
T_s (surface temperature) = constant.

$$0.48 < \mathrm{Pr} < 16{,}700.$$

$$0.0044 < (\mu/\mu_s) < 9.75.$$

And for turbulent flow, where Re ≥ 10,000, Nusselt number can be calculated by

$$Nu = 0.023\Re^{0.8}Pr^{0.3} \quad (8)$$

Where the ranges are.

$$0.7 \leq \Pr \leq 160.$$

$$l/D \geq 10.$$

All properties except μ_s should be evaluated at the average value of the inlet and outlet temperature, $T_{ave} = (T_i + T_o)/2$.

2.3.2 Outside heat transfer coefficient

[29, 30], developed correlations to approximate the heat transfer coefficient for the outside flow (falling film), As follows:
For high Re, (sheet mode):

$$Nu = 2.194\Re_f^{0.28} Pr^{0.14} Ar^{-0.2} \left(\frac{s}{d}\right)^{0.07} \tag{9}$$

For medium Re, (jet mode):

$$Nu = 1.378\Re_f^{0.42} Pr^{0.26} Ar^{-0.23} \left(\frac{s}{d}\right)^{0.08} \tag{10}$$

For low Re, (droplet mode):

$$Nu = 0.113\Re_f^{0.85} Pr^{0.85} Ar^{-0.27} \left(\frac{s}{d}\right)^{0.04} \tag{11}$$

The liquid properties were evaluated at film temperature T_f.
Where.

Nu is modified Nusselt number $\left(\frac{\nu^2}{g}\right)^{1/3} h/k$.
Re_f is film Reynolds number $2\Gamma/\mu$ Pr
Pr is Prandtl number $C_p\mu/k$ (1.20)
Ar Archimedes number based on tube diameter $d^3 g/\nu^2$
Eq. 4 estimate the instantaneous heat transfer ac certain time for specific ice radius. For the whole experiment run for specific time, we need to get the total heat absorbed from the outside fluid. The outside fluid is either at stationary state or moving across the tube. For the first case if the outside liquid at constant condition

$$\acute{Q}_{s,l,c} = \frac{m_l}{t} C_{p,l}\left(T_{li} - T_{lf}\right) \tag{12}$$

Where T_{li} and T_{lf} are the initial and final temperature of the outside liquid respectively.
For the second case where the outside fluid is moving across the tubes, the sensible transfer heat rate is calculated by

$$\acute{Q}_{s,l,m} = \acute{m}_l C_{p,l}(T_{li} - T_{lo}) \tag{13}$$

Where T_{li} and T_{lo} are inlet and exit temperature of the outside liquid.
Part of the outside liquid freezes on the outside tube. The freezing consumes latent heat which can be calculated as:

$$\acute{Q}_{fr} = \frac{M_{ice}L}{frozentime} \tag{14}$$

Where L is the latent heat of fusion for the PCM.

The formed ice is now cooled to a temperature below the freezing temperature which is consider as sensible heat and is given by

$$\acute{Q}_{s,s} = M_{ice}C_{p,ice}\left(T_f - T_c\right)/time \tag{15}$$

Hence the total heat transfer through the ice layer can be computed as:

$$\acute{Q}_{O-i} = \acute{Q}_{s,l} + \acute{Q}_{fr} + \acute{Q}_{s,s} \tag{16}$$

The total heat transfer absorbed by the coolant can be given by:

$$\acute{Q}_{c,act} = \acute{m}_c C_{pc}(T_{co} - T_{ci}) \tag{17}$$

where the coolant flow rate $\acute{m}_c$ (kg/s), and $T_{ci} \wedge T_{co}$ are its inlet and outlet temperature.

The average rate of heat transfer from the test tubes to the coolant at a specific time, $\acute{Q}_{c,ave}$ is calculated by the following equation:

$$\dot{Q}_{c,ave} = \left[\int_{t=0}^{t=n} \dot{Q}_c \, dt\right]/time \tag{18}$$

where:

t: is the interval time in minutes

n: is the indicated time

This integration can be obtained by the trapezoidal rule of integration:

$$\int_a^b f(x)dx = \frac{b-a}{2n}\left[f(x_0) + 2f(x_1) + 2f(x_2) + \ldots + 2f(x_{n-1}) + f(x_n)\right] \tag{19}$$

By substituting the h_i and h_o in Eq. 10 to get the overall heat transfer coefficient and then substitute in Eq. 9 to get the calculated rate of heat transfer from the test tubes to the coolant at a specific ice thickness, $\acute{Q}_{c,cal}$ which needs to be compared with the total heat transfer to the coolant $\acute{Q}_{c,act}$ which was given from Eq. 6.

The experimental overall heat transfer coefficient, h_{ov} is determined using the equation

$$h_{ov} = \frac{\acute{Q}_{,o-i}}{A_{ice}\Delta T_{lm}} \tag{20}$$

where, A_{ice} is the heat transfer area and ΔT_{lm} is the logarithmic temperature difference between the working fluid flows. The ice layer affects the heat transfer coefficient since the thermal conductivity of the ice is low and as its thickness increases the thermal resistance increases which lead to lower heat transfer coefficient.

2.4 Affecting parameters on freezing

Ice freezing quantity is affected by the outside flow rate (mode of the falling film) and its temperature, as well as by coolant flow rate and coolant temperature (**Table 3**).

2.4.1 Effects of the falling film behavior on ice accumulation

In the beginning of the freezing process high heat transfer coefficient was shown which reaches to 1000 W/m^2.K, which shows the influence of the failing film.

Parameter	Effect
Effect of time on accumulated mass of ice, **Figure 10**	Ice formation distinctly increases with time. As ice thickness increases, its thermal resistance increases and its heat transfer decreases. Because ice has a low thermal conductivity, it acts as an insulator for the heat transfer.
Effect of coolant flow rate on accumulated mass of ice, **Figure 11**	The inner heat transfer coefficient due to increase in Reynolds number and hence increases the inner heat transfer coefficient.
Effect of outer flow on accumulated mass of ice, **Figures 11** and **12** and	The outer heat transfer coefficient due to increase in Reynolds number and hence increases the outer heat transfer coefficient.
Coolant temperature, **Figure 13**	More ice accumulated on the tube
Tube diameter	Big effect, since the area is increased
Tube spacing	Low effect
Tubes arrangements Effects, **Figures 14** and **15**	Affect Ice formation. Because of flow rate and the temperature difference and the temperature variation along the tubes.
Adding Fin, **Figure 16**	Enhance the ice accumulation

Table 3.
Effects of different parameters on the performance of cold thermal storage.

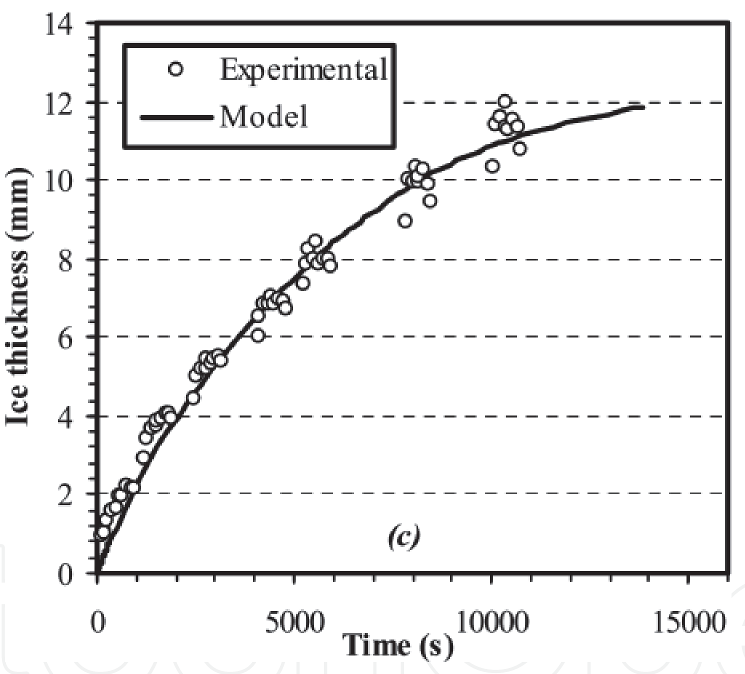

Figure 10.
The effect of ice accumulation with time on the rate of freezing.

However, by the further accumulation of ice, the heat transfer coefficient drops as of the effect of low thermal conductivity of ice. To get the best advantages of the falling film an optimum design must be applied to have quick charging and discharging operations so, more ice can be formed in short time and then collect it at the bottom of the reservoir. The falling film quantity must be adequate and the flow rate must handle the drag force of the tubes.

2.4.2 Falling film backsplash

While the falling film falls over the tubes vertically, some quantity leaves the falling film stream and falls outside the stream and drops to the bottom of the reservoir without further collision with the rest of the tubes. This phenomenon is

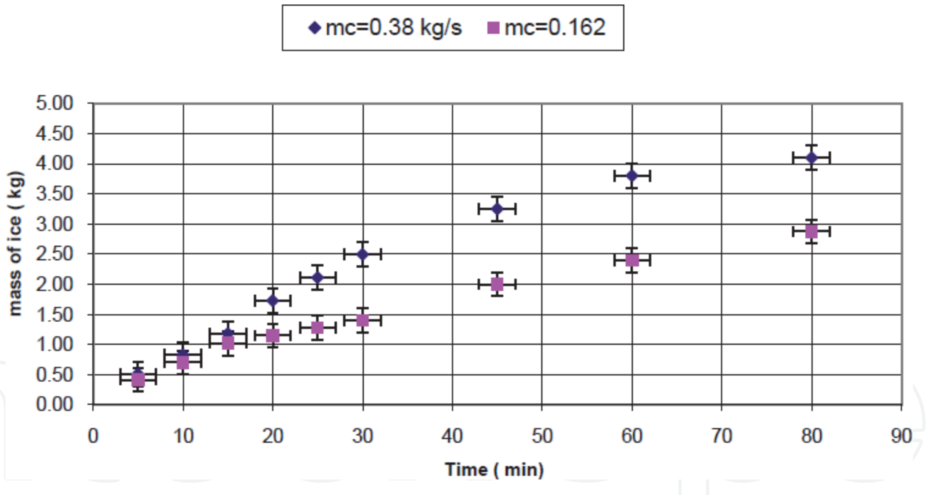

Figure 11.
Comparison of the formed ice for different coolant flow rate.

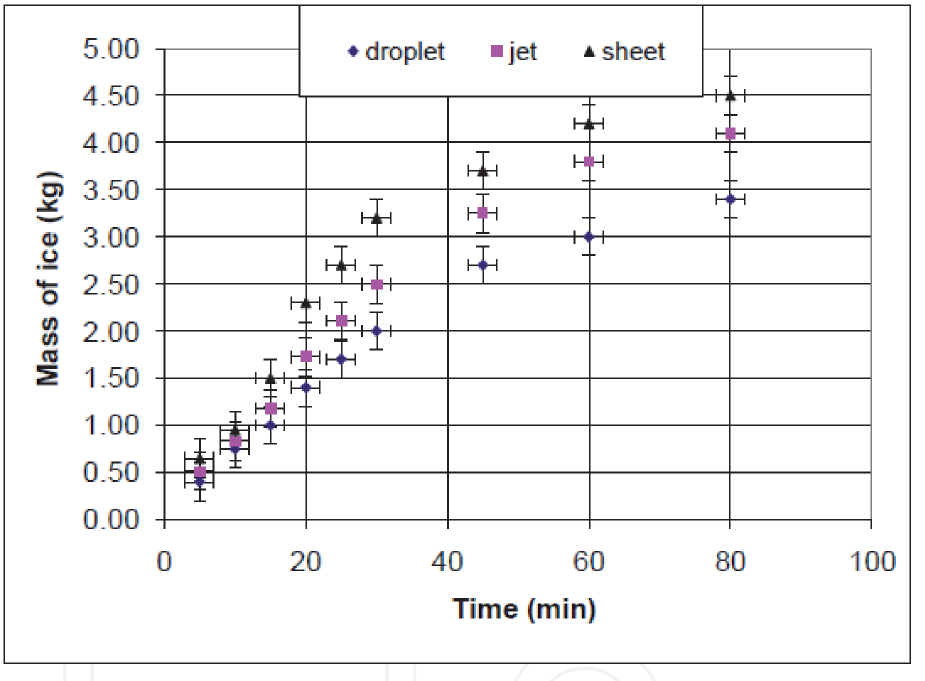

Figure 12.
Comparison of the formed for different falling film flow rate.

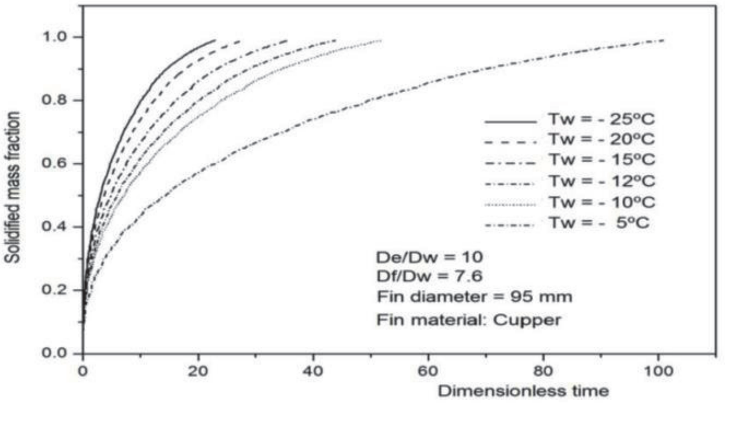

Figure 13.
Effect of variation of cooling temperature on freezing, [17].

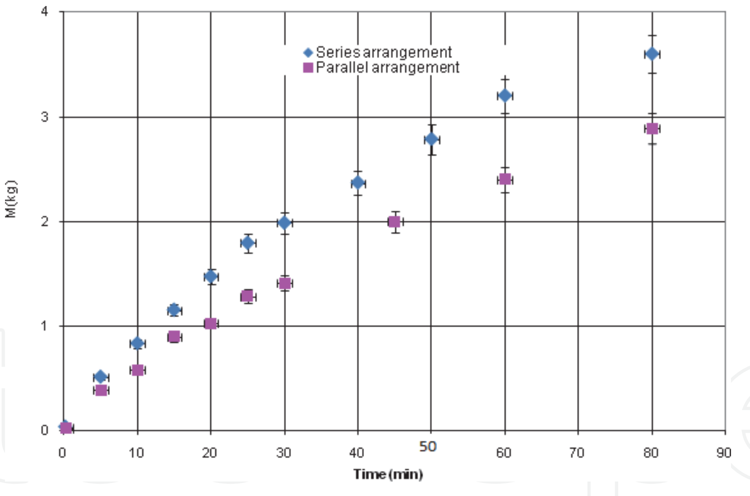

Figure 14.
Comparison of the formed ice between series and parallel arrangements for $\acute{m}_c$ *=0.162 kg/s &* $\acute{m}_l$ *=0.025 kg/s.*

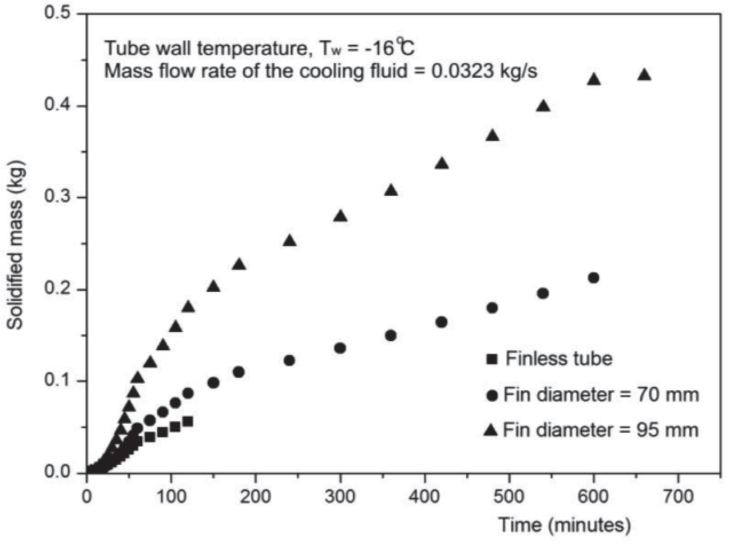

Figure 15.
Comparing of ice quantity for tube with fin and finless tube, [17].

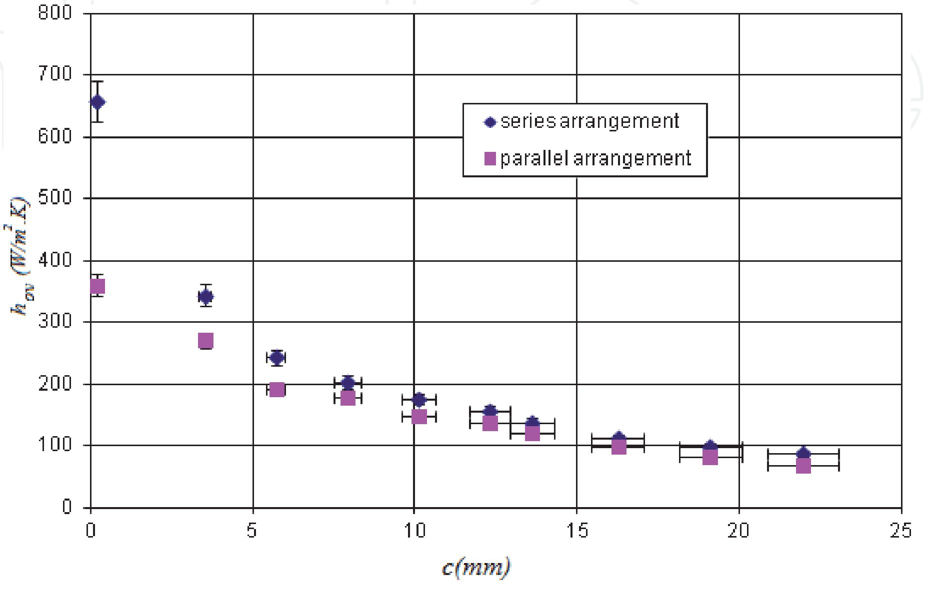

Figure 16.
Comparison of the experimental overall heat transfer coefficient between series and parallel arrangements for $\acute{m}_c$ *= 0.162 kg/s &* $\acute{m}_l$ *=0.025 kg/s.*

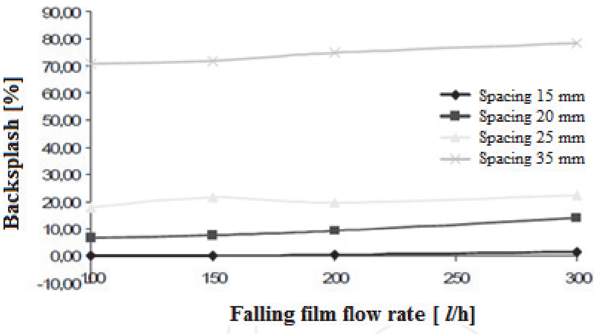

Figure 17.
Backsplash as shown in [31].

called "backsplash". The result is shown in **Figure 17** was created by Jiri Pospisil, et al. The backsplash increases with increasing of tube spacing and can reach up to 70% of the total flow falls over the test section for tube spacing of 35 mm. The backsplash also increases with increasing of the falling film flow rate but with only small percentage.

3. Discharging of ice and reusing it

In CTS systems the ice can be stored either on the tubes or in the isolated reservoir. For the ice on the tube system, the discharge system can be either inside the tube or outside the tubes. For the collected ice in an isolated reservoir, the ice must first be released from the tubes and then passing the warm water through the accumulated ice. **Table 4** provide previous effort for the discharging system to achieve the maximum capacity out of the CTS system.

Type of study	Reference	Finding
The study was on spherical enclosures	[32]	Shows an efficiency of 90% for extracting the cold out of the CTS
The study was about cooled cylinders, that are arranged in staggered and in line.	[33]	The discharge time was about half of the freezing time.
Model the internal melting for the ice on tube	[34]	The model considers the variation in temperature and discharge rate of discharge
Study the discharge on heated horizontal cylinders	[35]	Most of the melting time occurs when the tube is surrounded by ice
Modeling the discharging process for coil pipes using n-Tetradecane as a phase change material	[36]	Less time is needed for higher flow rate and inlet temperature. No big effect for the variations of the tube diameter
Study liquid–ice thermal storage system	[37]	Less time is needed for discharging, than that of charging time
Slush ice in a horizontal cylindrical capsule is studied	[38]	The melting rate increases as a function of melting time
Crystal ice formation of the solution and its removal phenomena at a cooled horizontal solid surface	[39]	Heat flux and inclination enhance the ice removal

Table 4.
Summary of the works that have been done by several researchers to study the melting phenomena.

3.1 Heat transfer analysis of discharging

The absorbed heat required to release ice consists of the following heats: sensible heat of sub-cooled ice, latent heat of melted ice and sensible heat of melted water. Thus, the experimental ice melting be expressed as

$$Qexim = Q\ smice + Q\ Lmice + Q\ sw \tag{21}$$

where

$$Qsmice = M_{mice}C_{p,mice}\ (Ts–T_0)/\tau_{mice} \tag{22}$$

and

$$QL_{mice} = M_{mice}L_{mice}/\tau_{mice} \tag{23}$$

and

$$Qsw = M_{mice}C_{p,w}(T_w–T_0\ )/\tau_{mice} \tag{24}$$

This heat is added by the heating solution Q_{hav} which is expressed as

$$Q_{hav} = \frac{\int_{t=0}^{t=n} \text{Qhdt}}{\text{time}} \tag{25}$$

where
t is the time interval, n is the indicated time, and

$$Q_h = \dot{m}_h\ C_{p,h}(T_{hi} - T_{ho}) \tag{26}$$

The overall heat transfer coefficient U_{exim} of the experimental ice releasing is expressed as follows:

$$U_{exim} = Q\ exim/[A_{ice}\ (\bar{T}_h–T_0)] \tag{27}$$

The fluid properties of water and ice are listed in **Table 5**.

3.2 Characteristics of ice releasing

The discharge cycle can melt the ice from inside to outside or from outside to inside depending on the flow of the warm brine that flow to the chiller. For the first case, the ice begins to melt from the inner surface of the formed ice toward the outer surface forming liquid between the tube surface and the ice layer. The ice layer is then decreases to the point that, it falls and collected at the bottom of the

Fluid	μ, N s m-2	ρ, kg m-3	k, W m-1 K-1	C_p, kJ kg-1 K-1
Water (0.25 °C)	1750x10–6	1000	569.6 x10–3	4.2
Ice (−5 °C)	—	920	1.88	2.040
Cold solution (−10 °C)	8 x10–3	1060	0.467	3.3488
Hot solution (25 °C)	3.37 x10–3	1050	0.43	3.30

Table 5.
Fluids properties.

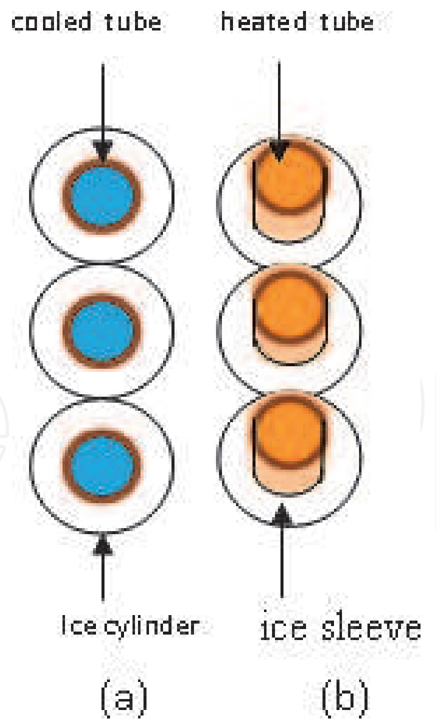

Figure 18.
Schematic for (a) ice formation and (b) ice releasing.

reservoir. **Figure 18** displays a schematic diagram for ice formation and releasing. For the second case where the warm water falls on the outside of the ice layers, the ice layer has more time to tick to the tube. In charging cycle, it is mandatory not allowing the ice layer between tubes to stick together, otherwise it will take much more time to get released.

3.2.1 Released ice percentage

During discharge process, some ice is melted and others falls to the bottom of the reservoir. **Figure 19** shows the percentage of the released solid ice for various average ice thicknesses for an experiment done by [40]. The temperature of the internal solution (the brine) is also affected the melting process as shown in the

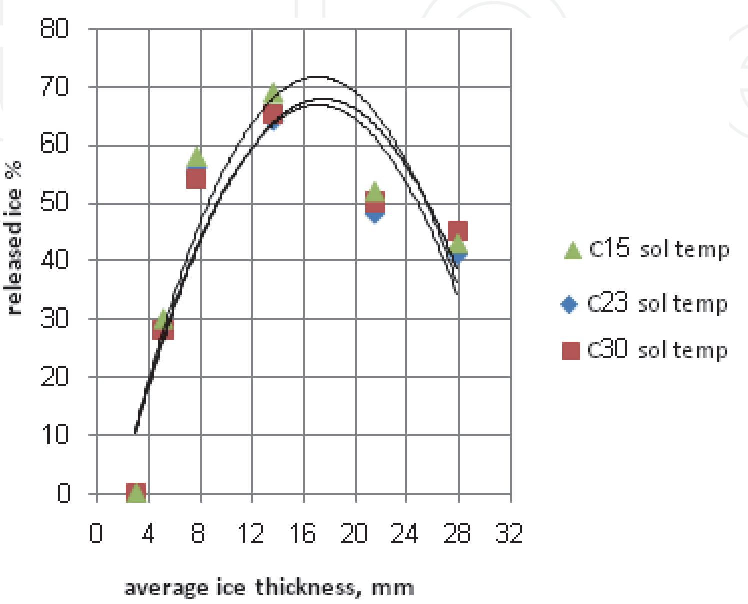

Figure 19.
Effect of heating solution temperature on released ice percentage.

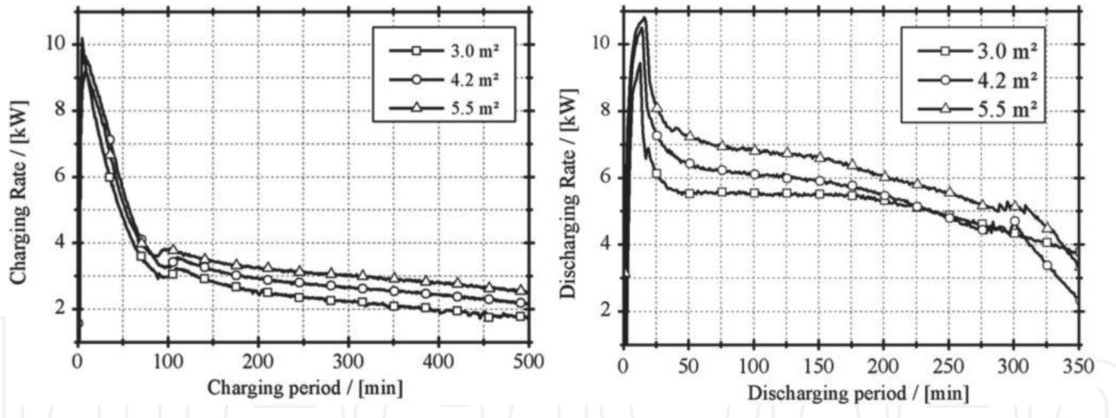

Figure 20.
Charging and the discharging rate for a 10 kW CTS system, was applied in the Institute for Thermodynamics and Thermal Engineering (ITW) of the University of Stuttgart [2].

Figure which shows a small effect on the percentage of ice releasing. Koller et al. [2] studied charging and discharging for CTS and found that the discharging is about 70% benefit of the charging system as shown in **Figure 20**.

3.3 Heat transfer coefficient for ice releasing

The experimental overall heat transfer coefficient depends on heat transfer from the heated solutions to the solid ice which consists of sensible heat for sub-cooled ice, latent heat of melted ice and sensible heat of melted water. The ice surface area and the temperature difference between the heating fluids and melting point affects the experimental overall heat transfer coefficient U_{exim}. **Figure 21** shows the variation of the experimental overall heat transfer coefficient U_{exim} for solid ice releasing

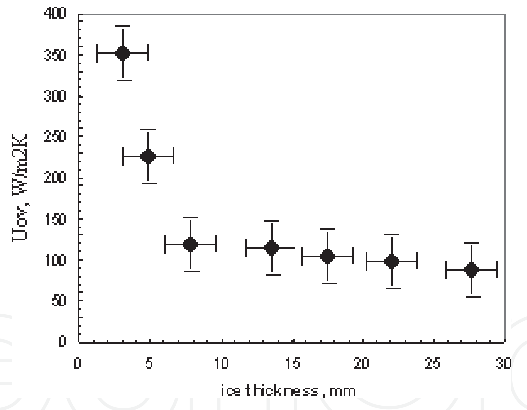

Figure 21.
Effect of ice thickness on U_{ov}.

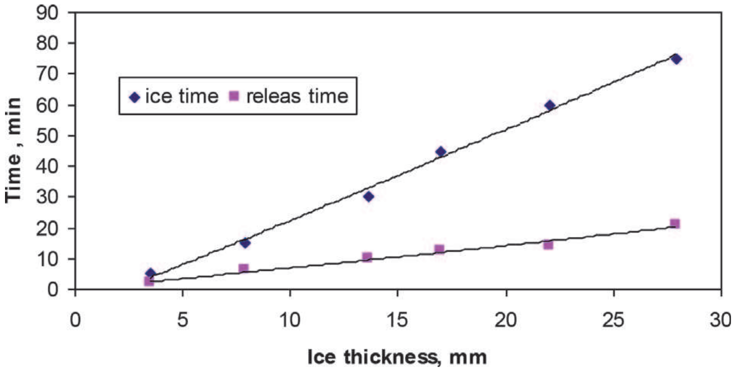

Figure 22.
Effect of ice thickness on the time of ice formation and ice releasing.

with ice thickness for the experiment done by [40]. As the ice thickness decreases as melting is taken place, U_{exim} is increasing to reach its maximum value of 350 W/m^2 K when the ice thickness decreases to 4 mm. Usually the releasing of ice time is shorter than the freezing time, which may varies from 1/2 to ¼ depending on the ice thickness and the warming solution used for discharging (**Figure 22**).

4. Enhancing both charging and discharging for cold thermal storage

4.1 Utilize thin film

Grooved tubes can be used which increases the heat transfer surface area and hence enhancing the heat transfer coefficient. The grove can also create a thin film which enhance the heat transfer as mention by [41]. Utilizing such techniques can reaches a heat flux of 1.400 MW/m^2 as shown in **Figure 23**.

4.1.1 Using extended surface on the tube

The cheat transfer can be enhanced on the cold tube by having extended surface. This will help not only in enhancing the heat transfer, but in also discharging the ice out of the tube, in cases when requires many on and off cycles to collect ice.

4.1.2 Using suitable PCMs

PCMs have features of higher melting points than ice and reasonable latent heat of fusion which allow them to require less energy during charging cycle. The economic wise play an important role in utilizing such materials in PCMs

4.1.2.1 Cost effectives of energy storage

Thermo-economic optimization of an CTS system should be carried out, which considers the environmental aspects, and cost effective. The cost includes the capital and operational costs as well as the penalty cost due to CO_2 emission. The pay back periods will be a major influence to convince investors to utilize the CTS. Electric Power Research Institute in USA have put a methodology for energy storage Valuation, shown in **Figure 24**. The methodology consists of four steps. It starts

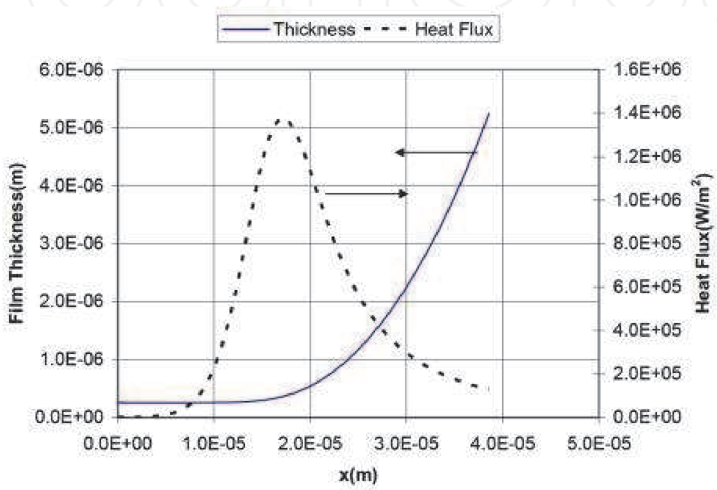

Figure 23.
Thin film evaporation scenario.

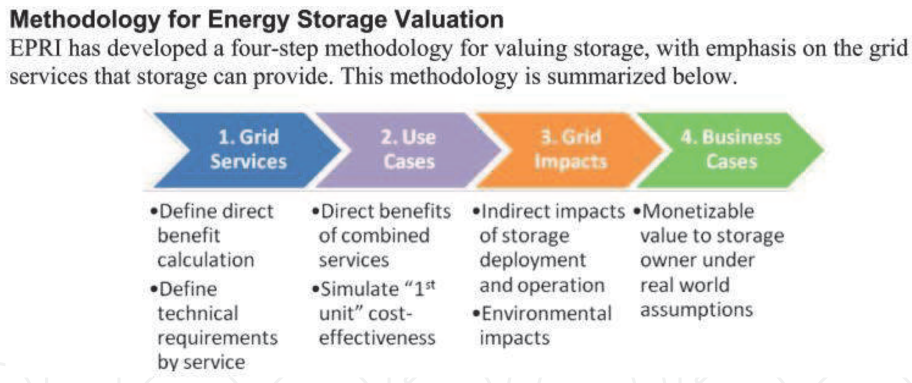

Figure 24.
Overview of electric power research institute (EPRI) energy storage valuation methodology.

by defining the expected direct benefits of the CTS and the technical requirements. It then required to simulate the unite cold effectiveness. It then need to define the indirect impact such as the environmental impact. The last step is to study the business issue, whether can this utilization of CTS convert into a cash or not. Lot of works were conducted for the feasibility study of utilizing the CTSs like [1, 42].

5. Summary

1. The rate of the ice formation depends on inlet and outlet flow rate.

2. The heat transfer coefficient is affected negatively by accumulation of ice on the tubes.

3. The tube arrangement has a large effect on ice formation and needs to be considered.

4. Falling film phenomenon can benefit the charging and discharging process and need to be optimized.

5. The heating solution temperatures have a small effect on the gained ice and releasing time.

6. The heat transfer coefficient is affected by the direct contact area between the ice sleeves and the heated tubes.

7. Cost effivenss should be conducted to study the feasibility of adopting the CTSs.

This chapter helps in the analyzing and constructing of cold thermal storage systems, which are necessary for energy saving today.

Nomenclature

a_{fr}	fraction frozen
A	area, m^2
C_p	specific heat, kJ/kg.K
D	diameter, m^2

Δh	heat of fusion J/kg
L	latent heat of fusion
ℓ	length of the test tubes, m
m	mass, kg
M	mass of ice, kg
$\dot{m}$	mass flow rate, kg/s
Q	quantity of stored heat, J
$\dot{Q}$	rate of heat transfer, W
T	temperature, °C

Greek Symbols

ν	dynamic viscosity. N.s/m2
ρ	density, kg/m3
ε	The test section heat exchanger effectiveness

Subscripts

a,f	absorbed from the falling film
ave.	average
c	coolant
e	end
f	film
fr	freezing

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