T.C.
ERCIYES UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCE
DEPARTMENT OF MECHANICAL ENGINEERING

A CFD BASED ANALYSIS OF THERMAL PERFORMANCE FOR SPHERICAL CAPSULES USED IN ICE STORAGE SYSTEMS

Prepared by
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Supervisor
Prof.Dr. Necdet ALTUNTOP

M. Sc. Thesis

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COMPLIANCE WITH SCIENTIFIC ETHICS

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COMPLIANCE WITH GUIDELINES

"A CFD Based Analysis of Thermal Performance for Spherical Capsules Used in Ice Storage Systems" named Erciyes University Graduate Thesis has been prepared accordance with Erciyes University Graduate Thesis Proposal and Thesis Writing Guidelines.

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ACCEPTANCE AND APPROVAL PAGE

The study called **"A CFD Based Analysis of Thermal Performance for Spherical Capsules Used in Ice Storage Systems"** has been prepared by **ALI JASIM MOHAMMED AL-BAYATI** supervised by **Prof. Dr. Necdet ALTUNTOP**, is accepted as a M.Sc. thesis in Erciyes University Graduate School of Natural and Applied Science Department of Mechanical Engineering by the jury.

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Director of the Institute
Prof. Dr. Mehmet AKKURT

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This thesis is dedicated to:

The sake of **ALLAH**, my only God and Creator,

My great teacher and inspiration, prophet **MOHAMMED** (Peace be upon him), who taught us the purpose of life.

I owe a debt of gratitude to **Prof. Dr. Necdet ALTUNTOP** for the vision and foresight which inspired me to conceive this thesis. Also, I would like to extend my sincere thanks to **Asst. Prof. Dr. Dogan ERDEMIR** for all contributions that he has made in implementing and completing this thesis.

My dear **wife**, who leads me through the valley of darkness with light of hope and support.

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To my **brothers and sister** and all my family who were symbols of love and giving.

All the people in my life who touch my heart,

I dedicate this research

Kayseri, August 2017

BUZ DEPOLAMA SİSTEMLERİNDE KULLANILAN KÜRESEL KAPSÜLLER İÇİN ISI PERFORMANSI BİR CFD TABANLI ANALİZİ

ALI JASIM MOHAMMED AL-BAYATI

Erciyes Üniversitesi Fen Bilimleri Enstitüsü
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KISA ÖZET

Buz enerji depolama (BED) sistemleri, birçok ticari uygulamada soğuk kapasite depolaması için yaygın olarak kullanılmaktadır. Bu termal enerji depolama sistemleri, elektrik arzı ve talebi arasındaki uyumsuzluğu çözmek için soğutma ünitelerinde bir destek sistemi olarak önemli bir rol oynamaktadır. Elektrik kullanımı aşırı ve masraflı olduğunda tepe yük değerini azaltmaktadır. Bu alandaki en umut verici kavramlardan biri kapsüllenmiş BED'dir. Suyun sınırlı olduğu kapalı kapsüllerde ve geniş bir depolama tankı yerleştirilmiş yerlerde kullanılır. Soğutma ünitesi, enerji talebinin az olduğu dönemde, depolama tankında dolaşan ısı transferi akışkanı (ITA) soğutmak için kullanılır, böylece kapsüllenmiş suyu dondurur. Kullanımın yoğun olduğu dönemde, üretilen buz, bir soğutucu olarak alan soğutma amaçlı kullanılır.

Bu çalışma sayısal olarak, kapsüllenmiş buz enerji depolamasında kullanılan bazı küresel kapsüllerin katılaşma sürecini göstermektedir. Kapsül şekli, daha iyi ısı transfer karakteristiği gösterdiğinden katılaşma sürecinde önemli bir etkiye sahiptir ve böylece şarj süresini azaltır. Hesaplamalı akışkanlar mekaniği ve ısı transferi için FLUENT 18.0 programı kullanarak altı küresel kapsül yapılandırılmış ve simüle edilmiştir. İncelenen başlıca parametreler; küresel kapsül şekli, giriş sıcaklığı ve ısı transferi akışkanı (ITA) hacim akış hızıdır. Bu parametrelerin, tam şarj süresi, ortalama toplam sıcaklık ve katılaşmış kütle parçası üzerindeki etkileri incelenmiştir. Bu çalışmada, belirli bir kapsül için daha düşük ITA sıcaklıkları ve daha yüksek ITA hacim akış hızları kullanıldığında en iyi ısı transfer karakteristiğinin bulunduğu görülmüştür. Ayrıca, giriş ITA akış oranlarındaki değişimde, kapsül şeklinin genel performans üzerindeki etkisi gözlemlendi.

Anahtar Kelimeler: Isıl enerji depolaması, BED, Küresel buz kapsülleri, Şarj işlemi.

A CFD BASED ANALYSIS OF THERMAL PERFORMANCE FOR SPHERICAL CAPSULES USED IN ICE STORAGE SYSTEMS

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Erciyes University, Graduate School of Natural and Applied Sciences
M.Sc. Thesis, August 2017
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ABSTRACT

Ice thermal energy storage (ITES) systems are widely used to store cold capacities in many commercial applications. Such thermal energy storage systems play an important role as a support system for cooling units to solve the mismatch between supply and demand of electricity, and reduce peak load when electricity use is heavy and expensive. One of the most promising concepts in this area is Encapsulated ITES. Where water is limited in closed capsules and laid in a large storage tank. During off-peak period, refrigeration unit is used to cool the heat transfer fluid (HTF), which is circulating in the storage tank, thus freezing the encapsulated water. In the peak period, the produced ice is used for space cooling purposes as a heat sink.

This study numerically demonstrates the solidification process of some spherical capsules used in the encapsulated ice thermal energy storage. Since the capsule shape has a significant impact on solidification process by showing better heat transfer characteristics, thus reducing charging time, six spherical capsules are structured and simulated by using FLUENT 18.0 software for computational fluid mechanics and heat transfer. The major studied parameters are the spherical capsule shape, the inlet temperature and volume flow rate of the heat transfer fluid (HTF). The effects of these parameters on the full charging time, average total temperature and solidified mass fraction are examined. In this study, it was found that the best heat transfer characteristics for a certain capsule were presented by using lower HTF temperatures and higher HTF volume flow rates. Also, the effect of capsules shape on the overall performance was observed, where it was changing according to the inlet HTF flow rates.

Keywords: Thermal energy storage, Ice TES, Spherical ice capsules, Charging process.

CONTENTS

A CFD BASED ANALYSIS OF THERMAL PERFORMANCE FOR SPHERICAL CAPSULES USED IN ICE STORAGE SYSTEMS

LIST OF ABBREVIATIONS

ABBREVIATIONS

CTES	: Cool Thermal Energy Storage
ES	: Energy Storage
HTF	: Heat Transfer Fluid
PCM	: Phase Change Material
TES	: Thermal Energy Storage

NOMENCLATURE

Symbol	Meaning	Unit
c_p	: Specific heat	$J/kg.K$
$Q^{\cdot}$	: Volume flow rate	m^3/s
V	: Volume	m^3
ρ	: Density	kg/m^3
m	: Mass	kg
L	: Specific latent heat	J/kg
K	: Thermal conductivity	$W/m.K$
T	: Temperature	K
V	: Velocity	m/s
h	: Sensible enthalpy	J
H_l	: Latent enthalpy	J
$D\gamma/Dt$	: Substantial derivative	
∇	: Differential operator	
ϕ	: Viscous stresses	

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The continuous raise in the level of energy consumption and depleting energy resources leads to serious energy and pollution crisis nowadays [1]. Also, total energy consumption in the world is expected to increase by 50% between 2005 and 2030 [2]. It is important to develop and expand advanced technologies to reduce energy demand and increase energy supply with the effective use of renewable energies . According to estimates, The energy consumed in buildings accounts for around 30%-40% of the world's energy consumption, making buildings the largest energy consumer [3]. This happened because of overpopulation, spend long times inside buildings, increase of indoor air quality, and global warming. The increase in the amount of energy use increases the unit price of energy. Since the significant increase in energy consumption and cost, producers and consumers have been forced to investigate methods to reduce consumption, make it more efficient to use, and less costly. If the buildings are designed, constructed and operated properly, the energy consumption costs in these buildings can be reduced considerably.

Recent technologies are already providing the world with such alternatives like photovoltaic cells, wind turbines, biomass plants and more. But these technologies have flaws. Compared to traditional power plants they produce much smaller amounts of electricity and even more problematic is the inconsistency of the production. The global demand for electricity is huge, and it's growing by approximately 3.6 percent annually, but the sun isn't always shining nor is the wind always blowing. For technical reasons, however, the amount of electricity fed into the power grid must always remain on the same level as demanded by the consumers to prevent blackouts and damage to the grid. It leads to situations where the production is higher than the consumption or vice versa. This is where storage technologies come into play, they are the key element to balance out these flaws

Energy storage (ES) is one of the fundamental technologies for energy conservation and it has a great importance in practice. Storing energy in large quantities can provide a great deal of flexibility for the operations of the utility companies, since the demanded energy does not have to be produced at the same time. Such technologies are able to provide a valuable resource to system operators by enabling energy supply and demand linkage to be resolved. Energy storage methods are divided into mechanical, thermal, biological, chemical and magnetic. Since most systems and applications deal with energy as heat, thermal energy storage could be consider one of the precious essential methods of energy storage and are seen as an important means of achieving energy conservation. If we looked at the history of thermal energy storage, we can notice that it is as old as human history. Since ancient history, people have been collecting and storing ice for later use. Nowadays, TES systems have evolved to a point where they are important in modern technologies and are still being developed.

Thermal energy storage TES is one of the most important and effective methods that can be applied to, solve the inconsistency between supply and demand of energy, and reduce peak load times when energy use is heavy and expensive. A good thermal energy storage system should allow the stored energy to be used with the least possible of reversibilities while minimizing the heat losses and maximizing the energy savings.

TES mostly used in heating and cooling applications and carried out by heating, cooling, melting, solidification and evaporation of a storage material. In other words, it is possible to restore the energy by reversing thermal processes. The choice between these storage operations depends on the period of storage to be carried out, economic conditions, operating conditions and other parameters.

Basically, there are two types of TES systems: sensible energy storage and latent energy storage. Which of these energy storage types to use, how and which material to use depends on the application and the temperature of application. latent energy storage is attracting more attention. As a latent energy storage, for example the transformation of water into ice, cold energy can be stored and used when cold conditions are needed. Cooling systems that include ice storage have a lot of advantages over water-cooled systems due to the high energy storage capacity provided by the latent energy.

Nowadays, cooling is a serious need for people. Moreover, the use of cooling systems with the effect of global warming are increasing day by day. In turn, the demand for electricity is increasing. Especially in the summer, cooling systems consume a large amount of electricity due to run at full capacity. on 10 August 2016, the highest daily electricity consumption of all time was realized with 905 million 645 thousand kWh electricity consumption in Turkey [4]. The high temperature makes people use air conditioning systems in terms of providing thermal comfort. So, it is not surprising that the highest daily electricity consumption coincides with the warmest days of summer months, in a result, it is necessary to either reduce this consumption of electricity consumed for cooling needs or shift it to a time when the consumption is low. When the distribution of electricity consumption is considered throughout the day, we can see that it doesn't show a balanced distribution [5]. With cold energy storage systems, part of the electricity consumption associated with cooling systems can be shift for times when electricity use is not heavy. In this way, electricity consumption shows more balanced distribution over the day. Thus, electricity generation facilities can be used in a more balanced and efficient manner. Because electricity generation facilities cannot accommodate consumption in the most intense periods of electricity use.

Cooling costs for closed spaces (shopping centers, airports, office buildings, etc.) are high due to the fact that cooling load is high and required to operate for long periods of time. In such areas of life, cold energy storage systems are widely used to reduce the cost of operation while meeting people's cooling needs. When the electricity unit price is low, cooling system will cool down a material by circulating a mean in the cold energy storage until the phase of the material change. After storing the cold energy for a while of time, this material is then subjected to a reverse phase change to use the stored cold energy when cooling is needed. In this case, both the cooling load and the peak load are reduced while the cooling needs are met. Ice storage is the most common type of latent and cold energy storage. In ice storage system, ice is produced and stored in a storage tank while the electricity unit price is low at night. Then the stored ice is melted, in a time when electricity load in peak levels and its unit price is high, and thus space is cooled.

Objective of the Study:

The main aim of this thesis is to analytically and numerically analyze the charging process of different spherical capsules that can be used in the ice storage system. Using the available heat transfer and fluid dynamics software, the following specific objectives are achieved:

- Effect of aspect additions of the spherical capsule on the performance of ice solidification processes
- Effect of inlet heat transfer fluid temperature and flow rate on the overall performance of capsule
- Velocity vectors analysis of heat transfer fluid around the capsule
- Temperature distribution analysis inside the capsule
- Determine the best spherical ice capsule for using it in the encapsulated ice storage system.

It is anticipated that the results put forward in this thesis will encourage designers or researchers in the field of encapsulated ice TES to dwell more on the flow characteristics, heat transfer and thermodynamic aspects of the system on a capsule level to provide better performance and efficiency of the system as a whole.

Outline:

The following research consists of several components. First, background information is provided about the energy and its ever-growing importance in today’s world. Then, the importance of energy storage is explained in detail including information about thermal energy storage. After this, the thesis Objective and Outline is laid out.

Chapter 1 addresses energy storage systems(ES) and their significant benefits, basic principles and different methods of thermal energy storage (TES), and definitions with advantages of cool TES. Chapter 2 presents an overview of previous studies. Chapter 3 shows a description of spherical capsules, Numerical Procedures that used to simulate the capsules. Chapter 4 reviews simulation results including full charging times, mass fraction, velocity and temperature analysis. Lastly, chapter 5 presents the main findings of the research

CHAPTER 1

GENERAL INFORMATION

1.1. Energy Storage (ES)

Energy storage (ES) in general term is the capture of energy produced at one time for use at a later time. ES has only recently been developed to a point where it can have a significant impact on modern technology. In particular, ES is critically important to the success of any intermittent energy source in meeting demand. For example, the need for storage for solar energy applications is severe, especially when solar energy is least available, namely, in winter.

ES systems can contribute significantly to meeting society's needs for more efficient, environmentally benign energy use in building heating and cooling, aerospace power, and utility applications. Today, ES systems are used in many areas because of its significant benefits that provide. These benefits can be listed as below[6]:

- Reduce energy consumption
- Reduce energy costs
- Shift the peak load hours by non-peak load hours
- Reduce initial and maintenance costs
- Increase indoor air quality
- Increase flexibility of operating conditions
- Minimize System Elements
- Provide efficient and effective use of system equipment
- Allows less use of fossil fuels
- Helps to reduce carbon emissions.

ES is complex and cannot be evaluated properly without a detailed understanding of energy supplies and end-use considerations. In general, a coordinated set of actions is needed in several sectors of the energy system for the maximum potential benefits of ES to be realized. ES performance criteria can help in determining whether prospective advanced systems have performance characteristics that make them useful and attractive and, therefore, worth pursuing through the advanced development and demonstration stages. The merits of potential ES systems need to be measured, however, in terms of the conditions that are expected to exist after research and development is completed. Although ES systems usually increase the initial investment cost, they repays the investment cost in a short period of time.

There are many ways to store energy as shown in Figure 1.1. These types of ES also have many different methods in themselves. Each method, with its advantages and disadvantages, requires careful design and cost calculations to select and operate.

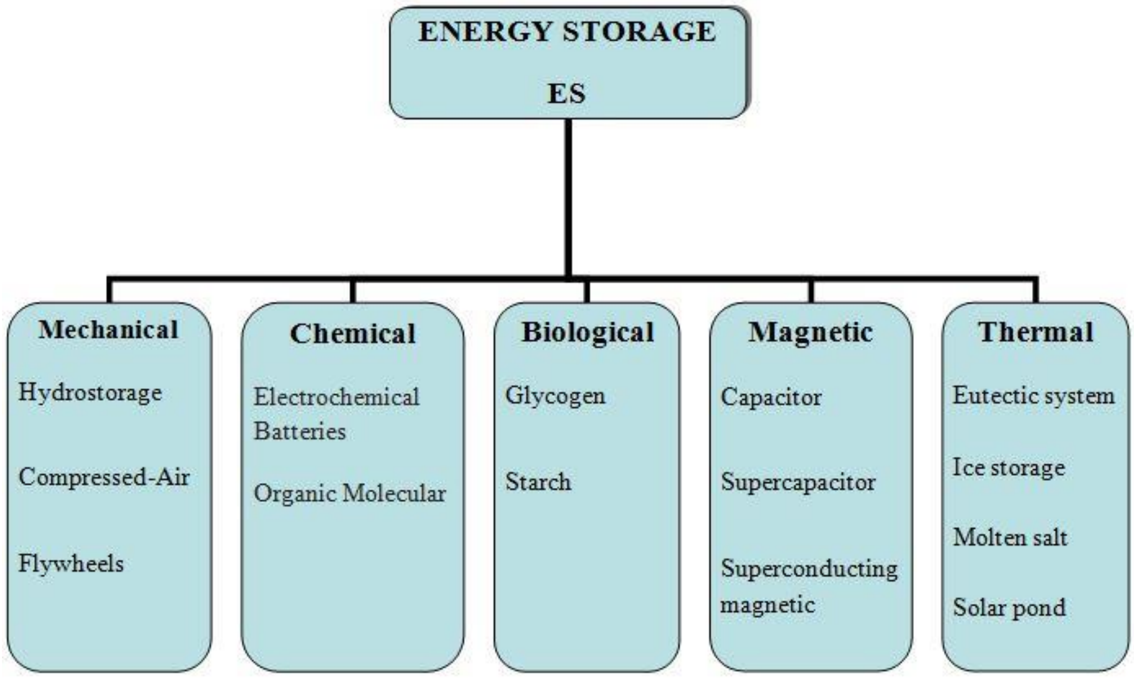


Figure 1.1. Classification of energy storage methods with some examples

Mechanical Energy is stored by applying force to a physical system. There are two basic mechanical energy storage systems that arise from that force. The first is related to the change in potential energy, while the second is related to the energy generated by mass movement, that is, kinetic energy. These two energies can be transformed into each other, as well as to heat or work. A significant energy penalty of up to 50% is usually achieved by mechanical and hydraulic systems in a complete storage cycle due to deficiencies.

Chemical energy is stored by collecting energy in the body as a result of a chemical reaction, then this energy is thrown back through a reverse chemical reaction. There is an increasing interest in storing energy as a low-temperature heat in a chemical form, but no practical systems have yet appeared. Another concept in the same procedure is storing hydrogen in metal hydrides (lanthanum, for example). The experiments of this concept are still going on. Electrochemical and molecular storage batteries are widely used as chemical energy storage types. Electrochemical ES systems have better efficiencies but their prices are very high.

Bioenergy storage can be considered as a kind of chemical energy storage created by biological processes and it is realized as an important method of storage for long periods of time. Magnetic storage is achieved by storing energy in magnetic elements as a magnetic field (e.g., in a large electromagnet). At temperatures close to absolute zero, the electrical resistance of some metals is almost zero therefore large currents can circulate in them with almost no losses. Although the electrical power can be stored in this system efficiently but its costs are high.

Thermal energy storage (TES) systems are diverse, some systems are performed by changing the temperature of a material (e.g., bricks) without changing the phase. these systems called sensible energy storage systems. Other systems are using phase changes of materials (e.g., salts, water-ice). these systems called latent energy storage systems. The latent storage can minimize the size of the storage tank by up to *100* times compared to sensible storage.

1.2. Thermal Energy Storage (TES)

Energy demands in the commercial, industrial, and utility sectors vary on daily, weekly, and seasonal bases. These demands can be matched with the help of thermal energy storage (TES) systems that operate synergistically. The use of TES for thermal applications such as space and water heating, cooling, air-conditioning, and so on has recently received much attention. Over the past half century, a large number of TES systems have developed as industrial countries have become highly electrified. Such TES systems have an enormous potential to make the use of thermal energy equipment more effective and for facilitating large-scale energy substitutions from an economic perspective. Energy may be stored in many ways, as pointed out in section 1.1, but since in much of the economy in many countries, energy is produced and transferred as heat, the potential for thermal energy storage warrants study in detail.

TES deals with the storage of energy by cooling, heating, melting, solidifying, or vaporizing a material; the thermal energy becomes available when the process is reversed. Storage by causing a material to rise or lower in temperature is called sensible TES, While the storage by phase change (the transition from solid to liquid or from liquid to vapor with no change in temperature) is a mode of TES known as latent TES. Examples of TES systems are storage of solar energy for night and weekend use, of summer heat for winter space heating, and of ice from winter for space cooling in summer. In addition, the heat or cool generated electrically during off-peak hours can be used during subsequent peak demand hours. Solar energy, unlike energy from fossil, nuclear, and some other fuels, is not available at all times. Even cooling loads, which coincide somewhat with maximum levels of solar radiation but lag by a time period, are often present after sunset. TES can provide an important mechanism to offset this mismatch between times of energy availability and demand.

Increasing societal energy demands, shortages of fossil fuels, and concerns over environmental impact are providing impetus to the development of renewable energy sources such as solar, biomass, and wind energies. Because of their intermittent nature, effective utilization of these and other energy sources is in part dependent on the availability of efficient and effective TES systems.

Moreover, TES systems can be integrated with cooling units , which operate much and consume a lot of energy, to take advantage of off-peak electricity tariffs. Cooling units can be run at night when the cost of electricity is relatively low. These units are used to cool a thermal storage, which then provides cooling for air-conditioning throughout the day. Not only are electricity costs reduced, but the efficiency of the cooling units is increased because of the lower night-time ambient temperatures, and the peak electricity demand is reduced for electrical-supply utilities.

1.3. Basic Principle of TES:

All of TES systems have the same basic principle. Energy is supplied to a storage system for removal and use at a later time. What mainly change is the storage scale and method used. A complete storage cycle involves at least three steps [6]:

a. charging,

b. storing,

c. and discharging.

During the charging period, energy is stored by changing the temperature of storage medium, then the energy kept in the storage unite until it is used. Finally, the stored energy is used by reversing the charging procedure in the discharging period. A simple storage cycle can be illustrated as in Figure 1.2. In practical systems, some of the steps may occur simultaneously (e.g., charging and storing), and each step may occur more than once in each storage cycle.

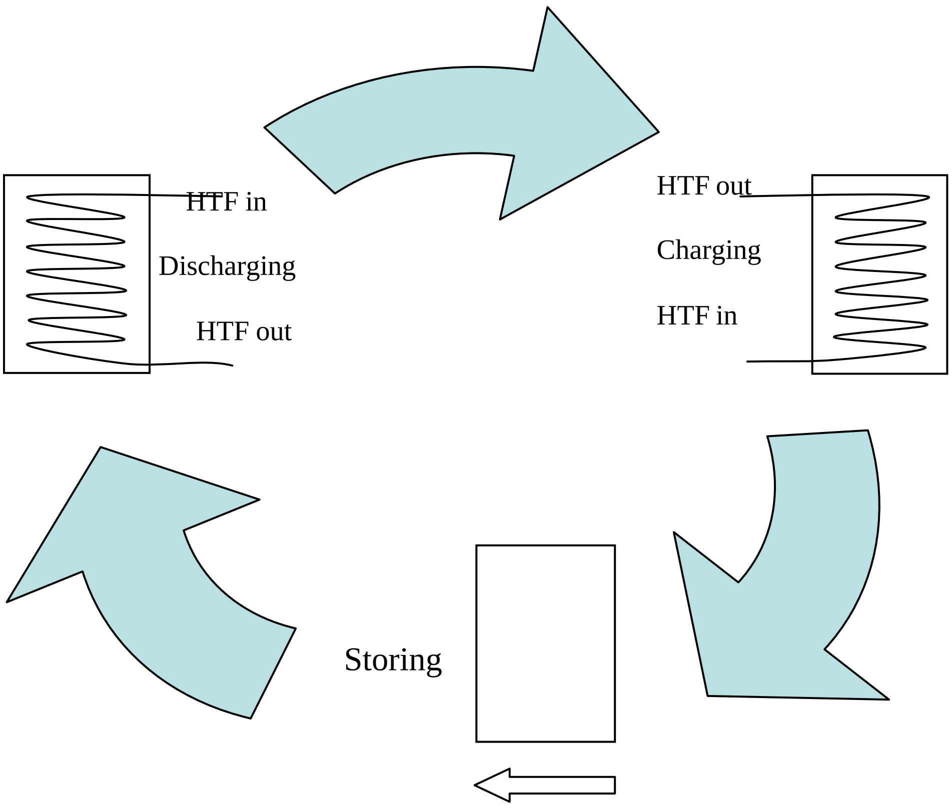


Figure 1.2. Three basic processes for TES systems

1.4. Benefits and Design Criteria of TES Systems

TES system has all advantages of energy storage systems listed in section 1.1. In addition, the following advantages can be added [6]:

- Increase generation capacity.
- Enable better operation of cogeneration plants.
- Shift energy purchases to low-cost periods.
- Increase system reliability.
- Integration with other functions.

There are numerous criteria to evaluate TES systems and applications. Some technical criteria are illustrated in Figure 1.3. Each of these criteria should be considered carefully to ensure successful TES implementation [6].

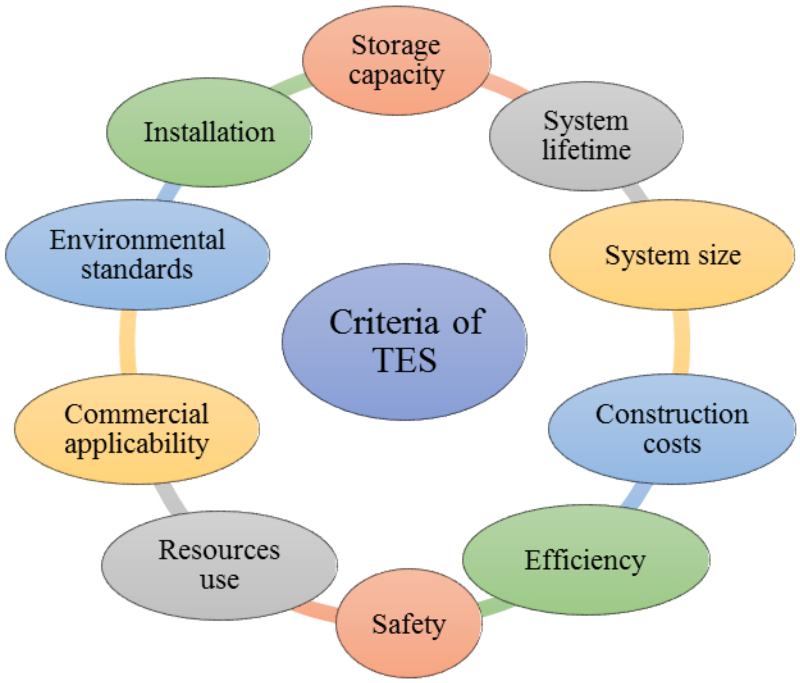


Figure 1.3. The criteria of TES system

Before proceeding with a project, a TES designer should possess or obtain technical information on TES such as the types of storage appropriate for the application, the amount of storage required, the effect of storage on system performance, reliability and cost, and the storage systemsor designs available. With all these criteria in mind, TES system can be designed seamlessly, with minimal cost and optimum efficiency.

1.5. Methods of TES:

TES can aid in the efficient use and provision of thermal energy whenever there is a mismatch between energy generation and use. Several methods of TES have been developed and investigated for building cooling, heating, industrial applications and space power systems. The most important factor for these methods is the period of storage. Long-term storage systems (annual, seasonal, etc.) require more accurate design than short-term storage systems (daily). This is because capital investment and energy losses are usually high, and units are larger and can hardly be manufactured offsite. Long-term storage, however, can be economically advantageous in multidwelling or industrial park designs, and often requires expensive energy distribution systems. As already mentioned, there are three types of TES systems as well as many applications. These methods are clearly illustrated in Figure 1.4.

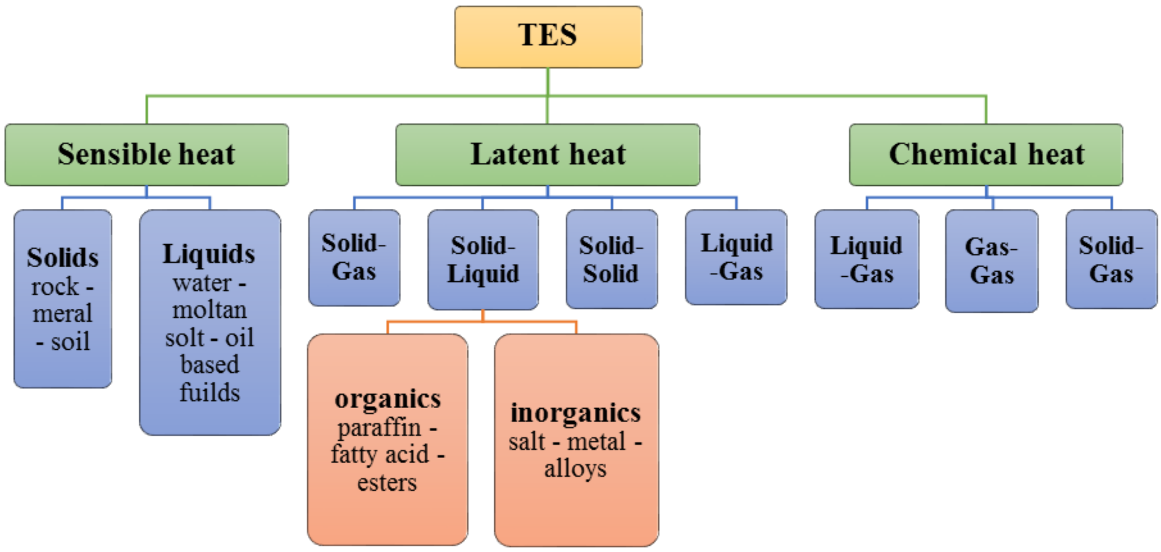


Figure 1.4. TES methods

1.5.1. Sensible TES

In sensible TES, energy is stored by changing the temperature of a storage medium such as water, air, oil, rock beds, bricks, sand, or soil.. Basically, it depends on temperature variation between the final and initial storage conditions. Sensible TES materials undergo no change in phase over the temperature range encountered in the storage process. The amount of heat stored in a mass of material can be expressed as:

$$Q = m\, c_p\, \Delta T = \rho\, c_p V\, \Delta T \qquad (1.1)$$

where c_p is the specific heat of the storage material, ΔT is the temperature change, V is the volume of storage material, and ρ is the density of the material.

As can be seen from the above expression, the most important parameters to choose suitable storage medium for sensible TES are the density and specific heat. In order to store more energy in the smallest possible volume, materials with high heat capacity and density should be preferred as a storage media. Water has a high value and is inexpensive but, being liquid, must be contained in a better quality storage than a solid. Some common TES materials and their properties are given in Table 1.2

Table 1.1. Some materials and their properties (thermal capacities at 20 ◦C) used in sensible TES [6]

Material	Density (kg/m^3)	Specific heat (J/kg K)	Volumetric thermal capacity (10^6 J/m^3 K)
Clay	1458	879	1.28
Brick	1800	837	1.51
Sandstone	2200	712	1.57
Wood	700	2390	1.67
Concrete	2000	880	1.76
Glass	2710	837	2.27
Aluminum	2710	896	2.43
Iron	7900	452	3.57
Steel	7840	465	3.68
Gravelly earth	2050	1840	3.77
Magnetite	5177	752	3.89
Water	988	4182	4.17

A typical sensible TES consists of a storage medium, a container, and input/output devices. Containers must both retain the storage material and prevent losses of thermal energy. Thermal stratification, the existence of a thermal gradient across storage, is desirable. Maintaining stratification is much simpler in solid storage media than in fluids.

Sensible TES systems are divided into high and low temperature sensible TES systems according to temperature of the storage medium. It also recognizes that it has both a long and short storage in terms of time. Working principle consists of energy charging, storing and energy discharging as mentioned earlier. The most common types of sensible TES are listed below:

1. Thermally Stratified TES Tanks
2. Concrete TES
3. Rock and Water/Rock TES
4. Aquifer Thermal Energy Storage (ATES)
5. Solar Ponds
6. Evacuated Solar Collector TES

It should also be noted that sensible TES types are preferred in terms of short periods, low capacities and operating conditions of the storage system.

1.5.2. Latent TES:

The heat transfer that occurs when a substance changes from one phase to another is called latent heat. The latent heat change is usually much higher than the sensible heat change for a given medium, which is related to its specific heat. If water is taken as an example, the difference between the amount of thermal energy required when water turns to ice and the amount of thermal energy required to change its temperature five degrees Celsius is about 16 times as shown in Figure 1.5.

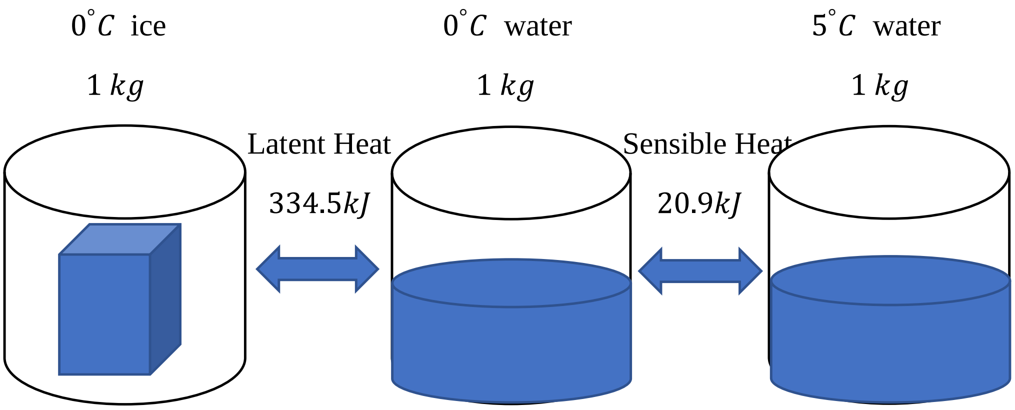


Figure 1.5. Water sensible and latent heat change quantities

Since energy densities for latent TES exceed those for sensible TES, smaller and lighter storage devices and lower storage losses normally result. Thus, latent TES system is preferred for long periods and high capacities of storage. Latent heat for a material can be calculated by the following equation:

$$Q = m\,L \tag{1.2}$$

Where m is the mass (g) of the storage material and L is specific latent heat (J/g).

The storage material used in latent TES systems is called phase change material (PCM). Some typical examples of PCMs are water / ice, aqueous salts, eutectic salts, paraffin, zeolite and some polymers. latent TES systems are divided into low and high temperature systems according to the temperature of phase change of used material.

1.5.2.1. Phase Change Material (PCM):

When a material melts or vaporizes, it absorbs heat; when it changes to a solid (crystallizes) or to a liquid (condenses), it releases this heat. This phase change is used for storing heat in PCMs. Among the thermodynamic phase changes at a constant temperature with the absorption or release of latent heat, the most suitable ones for TES are the solid–liquid and solid–solid transitions. PCMs can be used at various temperatures ranging from approximately -114°C to +885°C / 173°F to 1625°F.

Since ancient times, water-ice and eutectic salts have been used as PCMs. Perhaps the oldest application of a PCM for TES was the use of seat warmers for British railroad cars in the late 1800s. During cold winter days, a PCM, sodium thiosulfate pentahydrate, that melts and freezes at 44.4 ◦C was used. Other early applications of PCMs included “eutectic plates” used for cold storage in trucking and railroad transportation applications. Another important application of PCMs was in association with space technology, with NASA sponsoring a project on PCM applications for thermal control of electronic packages.

Basically, there are two types of PCM: organic and inorganic. Table 3.9 presents experimental data on melting temperature, heat of fusion, thermal conductivity and density data for several organic and inorganic compounds, aromatics, and fatty acids.

Table 1.2. Measured thermophysical data of some PCMs [6]

Compound	Melting temp *(◦C)*	Heat of fusion *(kJ/kg)*	Thermal conductivity *(W/mK)*	Density *(kg/m3)*
Inorganics				
$MgCl_2 \cdot 6H_2O$	117	168.6	0.570 (liquid, 120 ◦C) 0.694 (solid, 90 ◦C)	1450 (liquid, 120 ◦C) 1569 (solid, 20 ◦C)
$Mg(NO_3)_2 \cdot 6H_2O$	89	162.8	0.490 (liquid, 95 ◦C) 0.611 (solid, 37 ◦C)	1550 (liquid, 94 ◦C) 1636 (solid, 25 ◦C)
$Ba(OH)_2 \cdot 8H_2O$	78	265.7	0.653 (liquid, 85.7 ◦C) 1.255 (solid, 23 ◦C)	1937 (liquid, 84 ◦C) 2070 (solid, 24 ◦C) 1828 (liquid, 36 ◦C)
$Zn(NO_3)_2 \cdot 6H_2O$	36	146.9	0.464 (liquid, 39.9 ◦C) –	1937 (liquid, 84 ◦C) 1956 (liquid, 35 ◦C)
$CaBr_2 \cdot 6H_2O$	34	115.5	– –	2194 (solid, 24 ◦C) 1562 (liquid, 32 ◦C)
$CaCl_2 \cdot 6H_2O$	29	190.8	0.540 (liquid, 38.7 ◦C) 1.088 (solid, 23 ◦C)	1802 (solid, 24 ◦C)
Organics				
Paraffin wax	64	173.6	0.167 (liquid, 63.5 ◦C) 0.346 (solid, 33.6 ◦C)	790 (liquid, 65 ◦C) 916 (solid, 24 ◦C)
Polyglycol E400	8	99.6	0.187 (liquid, 38.6 ◦C) –	1125 (liquid, 25 ◦C) 1228 (solid, 3 ◦C)
Polyglycol E600	22	127.2	0.187 (liquid, 38.6 ◦C) –	1126 (liquid, 25 ◦C) 1232 (solid, 4 ◦C)
Polyglycol E6000	66	190.0	– –	1085 (liquid, 70 ◦C) 1212 (solid, 25 ◦C)
Fatty acids				
Stearic acid	69	202.5	–	848 (liquid, 70 ◦C) 965 (solid, 24 ◦C)
Palmitic acid	64	185.4	0.162 (liquid, 68.4 ◦C) –	850 (liquid, 65 ◦C) 989 (solid, 24 ◦C)
Capric acid	32	152.7	0.153 (liquid, 38.5 ◦C) –	878 (liquid, 45 ◦C) 1004 (solid, 24 ◦C)
Caprylic acid	16	148.5	0.149 (liquid, 38.6 ◦C) –	901 (liquid, 30 ◦C) 981 (solid, 13 ◦C)
Aromatics				
Biphenyl	71	119.2	– –	991 (liquid, 73 ◦C) 991 (liquid, 73 ◦C)
Naphthalene	80	147.7	0.132 (liquid, 83.8 ◦C) 0.341 (solid, 49.9 ◦C)	976 (liquid, 84 ◦C) 1145 (solid, 20 ◦C)

Latent TES using PCMs provides an effective way to store thermal energy from a range of sources, high storage capacity, and heat recovery at almost constant temperatures.

Requirements of PCMs: Latent TES in the temperature range 0–120 ◦C is of interest for a variety of low-temperature applications, such as space heating, domestic hot water production, heat-pump-assisted space heating, greenhouse heating, solar cooling, and so on. Otherwise, latent TES with a temperature greater than 120 ° C are widely used in nuclear installations and space crafts. So, to design a latent TES system on the most appropriate level, it is necessary to have a good knowledge of the melting and freezing characteristics of PCMs, their ability to undergo thermal cycling, and their compatibility with construction materials.

Characterization of PCMs: Many characteristics are desired of a PCM. Since no material can satisfy all of the desires, the choice of a PCM for a given application requires careful examination of the properties of the various candidates, weighing of their relative merits and shortcomings, and, in some cases, a certain degree of compromise. It should be noted, however, that properties of industrial-grade products may deviate broadly from reported values because of the presence of impurities, composition variations (mixtures, distillation cuts), and chain-length distribution (in the case of polymers). Selections should be based on assayed values of fully formulated products, whenever feasible.

1.6. Cool Thermal Energy Storage (CTES)

Cold thermal energy storage (CTES) usually implies storage of cooling capacity in an appropriate medium at temperatures below the nominal temperature of the space or processing system. The main purpose of CTES utilization is to shift electric energy used in cooling systems from expensive tariffs on-peak hours to cheap tariffs off-peak hours. Also, some system configurations can reduce initial investment costs. In the United States, "Federal Energy Management Program" announced that it saved 50 $ million a year with the help of CTES. If one or more of the cases listed below are present in place it can be considered attractive to use a cold thermal storage system for that place [6].

1. If the electricity prices are changing significantly during the day
2. A facility's maximum cooling load is much greater than the average load
3. Having incentives to install cold storage systems
4. An existing cooling system is being expanded
5. Limited on-site electric power is available.

The operating principle of CTES system is the same as energy storage systems. In other words, CTES system consists of three working periods, these are charging, stand by and discharging. The implementation of these periods varies according to type, material and amount of CTES. In CTES systems, glycol, water and eutectic salts are commonly used as storage material. Water is the storage material of choice for a variety of practical and thermodynamic reasons, including its ready availability, relative harmlessness, and its compatibility with a wide availability of equipments for its storage and handling. When cold energy is stored, the decision to make the storage process sensible or latent should be made according to the design criteria which is previously described.

1.6.1. Ice TES

Cooling capacity can be stored for later use by using ice TES systems, utilizing the latent heat of fusion of water (335 kJ/kg). Storage of energy at the temperature of ice requires refrigeration equipment that provides charging fluids at temperatures below the normal operating range of conventional air-conditioning equipment. Special ice-making equipment or standard chillers modified for low-temperature service are used. Ice CTES systems can be economically advantageous and require less space than water CTES systems. This space advantage often allows heating and cooling capacity to be enlarged within the often restricted area of existing machine rooms. An ice TES system is composed of a heat pump, an ice-making system, a storage tank, and an air-conditioning system that can be a conventional central system.

The working principle of ice TES systems; is the same as the working principles of energy storage and thermal energy storage systems. In ice TES systems, ice is obtained during charging period. Then, ice is stored in a storage tank until it is used (storage or standby period). Lastly, the stored ice is melted in order to meet cooling load of the refrigeration facility or building in the discharging period. Energy charging period is carried out at night when electricity is cheap. Conversely, the stored energy is consumed during mid-day hours when electricity is most expensive. Also, lower night-time temperatures allow refrigeration equipment to operate more efficiently than during the day, reducing energy consumption and cost.

Ice CTES systems are often classified as static or dynamic, according to the way ice is delivered to the storage tank. In the static systems, ice is formed and melted in a storage tank by means of heat transfer fluid (HTF). In other words, ice is formed, stored and used in storage tank without leaving it or mixing with the heat transfer fluid. These systems are ice-in-tube, ice-on-coil and encapsulated systems. In the dynamic type of ice CTES system, ice is produced outside the storage tank and removed from the ice-making surface continuously or intermittently by various means.

1.6.1.1. Encapsulated Ice TES Systems

Encapsulated ice TES system is kind of static systems. This system utilizes a brine solution, which is usually a glycol solution, to freeze de-ionized water which is encapsulated in plastic capsules (usually made of PVC, due to its low cost, non-volatility and high durability). The capsules are usually made in a spherical shape, but other geometries including rectangular prism, cylindrical and annular shapes are also possible. These capsules are contained in a large storage tank, and the glycol solution is cooled by refrigeration unite to lower its temperature to below the freezing point of water. During the night, the heat transfer fluid freezes the encapsulated water, and during the day, it can be used as a heat transfer medium between the load (building) and the storage tank. The heat transfer fluid receives heat from the building, and delivers it to the ice capsules. Number of capsules in the storage tank depends on the amount of energy to be stored. A view of the encapsulated ice systems is shown in Figure 1.6.

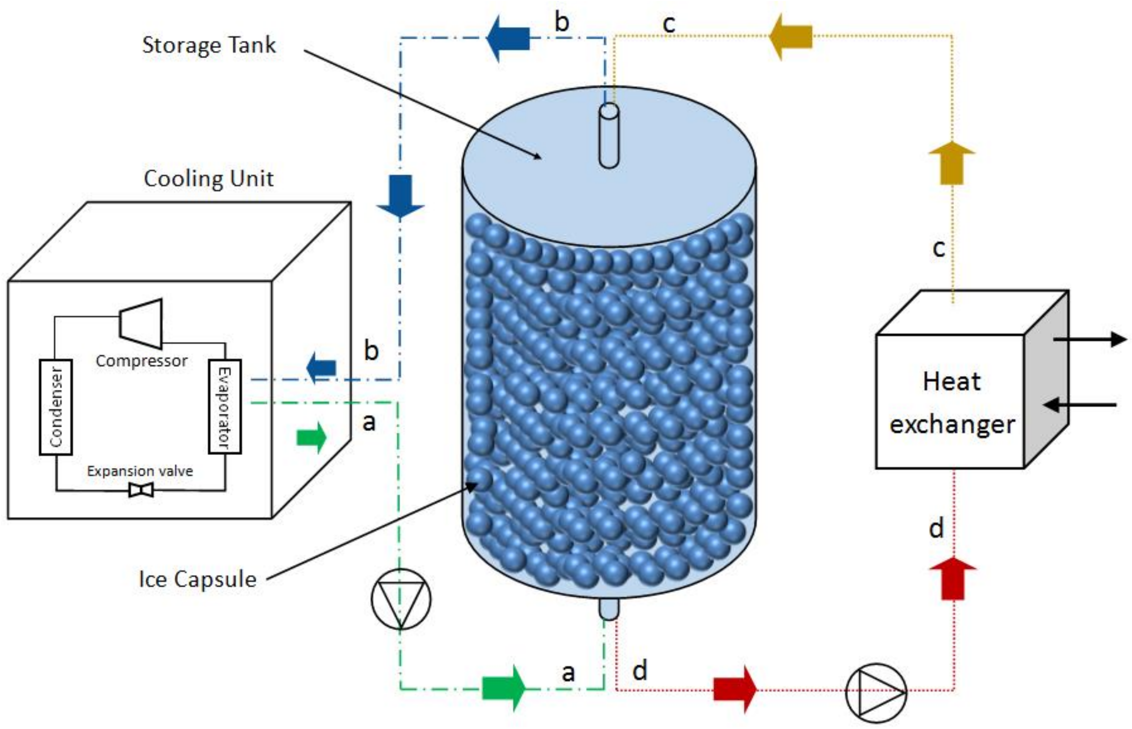


Figure 1.6. Encapsulated ice system [7]

Some commercial companies have attempted to improve the thermal performance of capsules by modifying the spherical capsule shape. Some of capsules used in commercial applications are shown in Figure 1.7. These models are self-developed capsules from companies that implement PCM systems.

Figure 1.7. Models of ice capsules [8]

Ice capsules contain, In addition to water, air (e.g., 20% air and 80% water) to avoid the thermal expansion during the solidification process. Also, small quantities of eutectic salts and gas hydrates can be added to the water to increase the temperature at which water freezes [9]. These materials have the advantage of a freezing point of 8.3 or 8.8 ◦C, which reduces energy requirements for freezing. By freezing and melting at this range, the Ice capsules can be easily used in conventional chilled-water systems.

CHAPTER 2

LITERATURE REVIEW

In this section, previous studies will be extensively reviewed. Topics, materials and methods will be determined in the light of existing works. The study will reveal the original trend according to other studies.

Ismail et al. [10] presented the results of a numerical study on the heat transfer during the process of solidification of water inside a spherical capsule under convective boundary conditions. The numerical solution was based upon the finite difference approach and the moving grid scheme. They also validated the numerical predictions by comparison with experimental results realized by the authors. The size of the spherical capsule, wall material, external bath temperature and initial temperature of water were investigated and their effects on the solidified mass fraction and the time for complete solidification were presented and discussed.

Sehar et al. [11] investigated the effect of PCM system on electricity consumption in medium- and large-scale office buildings in different climate regions. They used the "Demand Response Quick Evaluation Tool" program to analyze the system. As a result of the work done, the use of PCM system has determined energy savings. they emphasized that the climate characteristic of the location where the PCM system is located and the fact that storage is full- or partial-storage are very important.

Rismanchi et al. [12] investigated energetic, economic and environmental benefits of using PCM system for office buildings. 57% of the electricity consumption of offices in Malaysia is due to the use of air conditioners. So, the use of PCM to reduce electricity costs has been examined. In the study, the cooling load of the office was between 352 kW and 7034 kW. Calculations were made for full and partial storage using an ice-on-coil PCM system. Economically, it was emphasized that savings of between 230,000$ to 700,000$ and 65,000$ to 190,000$ could be achieved per year for full and partial storage, respectively. Regular service and maintenance procedures were also considered in these calculations.

Rismanchi et al. [13] theoretically examined the use of five different PCM systems in an office in Malaysia. They investigated systems in terms of energy and exergy. In the case of Energy yield for charging period, the system was observed with 93% for ice-harvesting PCM and 98% for capsulated PCM. On the other hand, the situation in the exergy yield was quite different where the highest rate of exergy was seen with 18% in the ice-on-coil system.

Güngör [14] evaluated PCM systems used in air-conditioning systems in terms of application potential and energy efficiency. As a result of the study, they emphasized that PCM systems are a convenient way to make the cost of electricity consumption less expensive while reducing the capacities of system equipment.

Yan et al. [2] studied long term (seasonal) cold TES with a combination of ice and cold water as a storage material. The storage tank in the system was a tank inside another where the ice was in inner tank while the cold water in the outer annular tank. Ice making was done in cold weather. In summer, ice was used to obtain cold water. In Beijing, a real building was built to study the system. An ice-on-coil PCM system was used in the study. As a result of the study, it was stated that the cost of cooling the building can be reduced to 40%.

Biyanto et al. [15] examined the application and optimization of a cooled water system for a shopping center in Indonesia. In the study, chiller capacity, cooling load and heat loss were tried to be minimized by simplex linear programming. As a result of the study, it was determined that electricity consumption could be reduced by 20%.

Rosen et al. [16] performed thermodynamic evaluation of ice storage systems. In the study, they calculated hourly cooling load over a day of an office building. As a result of this study, it was emphasized that energy analysis in determining the performance of ice storage systems would not be sufficient, and that an exergy analysis should be performed as well as energy analysis due to the energy yield is 99.7% or more at all hours while the exergy yield varies between 50.9% and 99.5%.

MacPhee and Dinçer [17] numerically assessed the thermodynamic performance of some typical ice capsules. In the study, the duration of freezing and melting were used for performance evaluation. As a result of the study, the best performance in terms of energy efficiency was shown by rectangle capsule while the best performance in terms of exergy efficiency was shown spherical capsule. Moreover, the effect of inlet HTF flow rate is more effective than the effect of inlet HTF temperature. However, it was emphasized that the effect of absence of exergy caused by viscous diffusion.

Acar and Dinçer [18] performed energy and exergy analysis for a cold TES. In their work, they made thermodynamic analyzes of ice slurry system based on the hourly cooling load. As a result of their studies, they found COP value, destroyed exergy and exergy efficiency to be 2.45, 64 kW and 47%, respectively.

MacPhee et al. [19] have numerically investigated capsulated ice storage systems. In the study, the effect of storage tank wall and heat distribution was neglected. In addition, energy and exergy efficiencies were calculated separately for different capsule shapes with different flow rates and different inlet temperatures of HTF. As a result of the study, the energy efficiency was found to be approximately 99.96% for all cases. Moreover, exergy efficiency was ranged from 72% to 92% for all cases. With these results, it was clear that energy efficiency doesn’t give very meaningful results in order to evaluate the performance of the system. So, it is more advantageous to use the efficiency of exergy. Also, it was emphasized that the spherical capsule performs better. Finally, it was stated that in order to provide solidification in a shorter time, the inlet HTF should be high in flow rate and low in temperature.

MacPhee and Dinçer [20] have analytically analyzed some encapsulated ice storage systems using the basic expressions of heat transfer and thermodynamics. They performed a one-dimensional and two-dimensional heat transfer analysis in their work. With heat transfer analysis, the temperature change from the center of the ice storage tank to the bottom was determined. Then the temperature distribution in the tank was used to evaluate the system in terms of thermodynamics aspects. As a result of the study, they emphasized that there is no serious difference between one-dimensional and two-dimensional heat transfer analysis. Also, the energy analysis, as highlighted in previous studies, was not sufficient to evaluate the system and that exergy analysis should be done also.

Amin et al. [21] numerically modeled the heat transfer flux for a single sphere. In the study, the effect of the induced density of buoyancy was discarded as the temperature changed. Water-ice in the sphere was used as PCM. As a result of the study, an empirical relation was given for the effective thermal conduction state. It was emphasized that this model can be applied to the ϵ-NTU model to analyze the melting process more easily.

Erek and Dinçer [22] investigated an ice storage system around a cylindrical tube in terms of entropy and exergy. The energy charging period was considered in the study. The study was carried out numerically and compared with experimental results. As a result of the study, it was stated that the operating conditions should be adjusted to the best values in order to reduce entropy generation.

Regin et al. [23] examined the behavior of latent PCM system using spherical capsules filled with paraffin. The system was integrated into solar water heating system. In their work, the problem was numerically solved and verified through empirical studies. Analyzes were performed for both energy charging and discharge periods. As a result of the study, it was emphasized that the operating conditions of the system should be well adjusted. In this context, it was stated that the proposed model could be used

Ryu et al. [24] examined the cold TES system used by spherical capsules with 2% sodium sulphate dehydrate. The performance of the storage tanks in horizontal and vertical positions was evaluated in terms of heat transfer rate, COP and supercooling of PCM. As a result of the study, better thermal performance was determined in the vertical position. A correlation equation involving Fourier, Stefan and Reynolds numbers was presented to calculate the amount of energy stored. They also noted the supercooling effect at the inlet and outlet of the tank.

Kousksou et al. [25] modeled a two-dimensional cylindrical tank filled with ice capsules. In their work, they have focused on supercooling effect that delays the solidification process. Also, the horizontal and vertical position of the tank were examined. At the end of their study, they stated that vertical tanks performed better.

Sakr et al. [26] conducted experimental and theoretical study on freezing and melting in capsules with different configurations. They used water as a phase change material

(PCM). The PCM was encapsulated in five different copper capsules (sphere, cylinder, pyramid, cone, and cuboids) having the same internal volume. The effect of geometrical configuration on the characterization of the freezing and melting processes was investigated. The spherical capsule showed the best thermal energy storage performance among the five test configurations.

Beghi et al. [27] have attempted to improve energy efficiency for an air-conditioning system in which the ice storage system was integrated. In the study, standard control strategies were compared to nonlinear control systems. Modeling processes were carried out through Matlab / Simulink softwares. As a result of the study, it was found that the non-linear control strategy gave better results.

Tan et al. [28] reported an experimental and computational investigation directed at understanding the role of buoyancydriven convection during constrained melting of phase change material (PCM) inside a spherical capsule. The melting phase front and melting fraction of the PCM were analyzed and compared with numerical solution obtained from the CFD code Fluent. They observed expedited phase change in the top region of the sphere and a wavy surface at the bottom of the PCM after a short period of symmetric melting due to prominence of diffusion.

ElGhnam et al. [29] experimentally examined the freezing and melting states for spherical ice capsules by using 35% glycol-ethylene as a HTF . Different spherical capsule diameters and materials were investigated. In addition, the various inlet HTF flow rates and temperatures have been performed. In the performance evaluation, freezing and melting time, freezing and melting rate, amount of stored and recovered energy and EER values were used. The study concluded that metallic capsules perform better by decreasing the diameter.

Navidbakhsh et al. [30] applied energy, exergy, economy and environment (Four E) approachs and optimizations for a partial storge of an ice storage system. Genetic algorithm was used for the optimization whereas the exergy yield and the total cost were used as an objective function. In the study, the presence and absence states of ice storage system were compared. In terms of electricity consumption, hybrid ice storage system found to be 17.1% more advantageous. Also, it was stated that the hybrid ice storage system emits 17.5% less CO2 emissions. Finally, it was estimated that the payback period of the system is 3.97 years.

Han et al. [31] analytically investigated the economic contribution of ice storage system for Jiangsu China. They used a GAMS-based named optimization program. In their work, they stated that the current electricity tariff constitutes a barrier for ice storage systems. However, they emphasized that even in such a situation, the system provides economic benefits. It was stated that the ice storage system would benefit more by regulating the electricity tariff.

Wu et al. [32] examined the usage of ice storage system in a building with 5950 m^2 of cooling area from 15,110 m^2 of total area. The building is located in Taipei City, Taiwan. As a result of the study, it was emphasized that instead of high-capacity chillers used for peak loads, lower-capacity chillers integrated with the ice storage system could be used, thus reducing the installation cost of the cooling system. In addition to this, it was stated that the building's hourly cooling load is important for the economic performance of the system. Their study has been carried out for minimum and maximum cooling loads. By avoiding the high electricity unit price in peak hours, it was estimated that savings of about $ 45,000 annually can be achieved.

Cho and Choi [33] investigated the thermal performance of freezing and melting cases for a spherical capsule filled with paraffin as a PCM. Paraffin was said to be preferred because of its low subcooling effect. It was stated that The phase change in the capsule is faster on the side of storage tank than on the center. Phase change of paraffin-filled capsules was found to be 16-72% faster than water.

Erek and Dinçer [34] investigated the heat transfer characteristics of the spherical capsule used for ice storage system of energy charging and discharging periods. Temperature and average heat transfer coefficient of HTF were taken into account. A new correlation of heat transfer coefficient was obtained from the studies. This correlation was confirmed by the experimental data. As a result of the study, it was emphasized that the heat transfer coefficient during the flow had changed seriously. Therefore, a constant and average heat transfer coefficient would not be directly evaluated during a heat transfer analysis of the system. Also, it was stated that the number of Stephan, diameter of the capsules, and order of capsules are important for solidification process.

Pu et al. [35] used a cumulative exergy analysis model for an ice storage system in which air-conditioning system was integrated. In the study, the presence and absence of ice storage system were compared. At the end of the study, it was stated that the ice storage system reduces the exergy of the system.

Lee et al. [36] used "particle swarm algorithm" to determine optimum operating conditions for an ice storage system integrated with air-conditioning system. The air conditioning system used in an office building has been taken into consideration. Also, the optimal tank volume was obtained during the optimization process. However, increasing tank volume has reduced the electricity consumption and CO2 emissions.

Chan et al. [37] assessed the performance of ice storage systems in regional cooling systems. They made their assessment for a site in Hong Kong. Parametric studies have been carried out using DOE-2 and TRNSYS programs. In the study, different storage capacities, control strategies, electricity tariffs, installation costs and electricity consumption costs were examined. In the study, it was stated that annual savings will be 1.78 million dollars when 60% of the cooling load is stored. The payback period was estimated to be around 22 years. In addition, it was emphasized that the ice-harvesting system was used and the payback period with other systems would be further reduced.

Chen and Yue [38] have tried to numerically and experimentally determine the thermal performance of a spherical capsulated ice storage system. For numerical analysis, Laplace transformation and lumped solution methods were used. The system was analyzed only for the energy charging period. It has been determined that the proposed numerical method is sufficient to determine the performance of the ice storage system. In the study, three different dimensionless parameters (Rcw, St and Ste) were used to evaluate the performance. The number of Stephan had no effect on temperature, but it had an effect on the rate of solidification.

Chen and Yue [39] theoretically and experimentally investigated the performance of an ice storage system. They have determined the thermal characteristics of the storage tank using one-dimensional model. Also, the results of this study were compared with the results of lumped solution given in the previous article [38]. As a result of the study, it was determined that one-dimensional model is effective in thermal analysis.

Calvet et al. [40] have numerically and experimentally investigated the thermal performance of encapsulated TES system. Two different graphites, GF and ENG, were added to the water in the capsule. The amount of added graphite was 13% of water volume. Adding graphite reduced the freezing and melting time by 35% and 58% in GF and ENG, respectively. In addition, this study was modeled numerically by COMSOL program. Numerical model was verified by the experimental results.

Ariffin et al. [41] studied the freezing characteristics of spherical ice capsules and examined important parameters such as temperature distribution in the capsule. In the study, increasing duration of icing by increasing spherical diameter was indicated.

Zhao et al. [42] studied two different spherical capsules. The first of them was zinc in nickel capsule and the other was eutectic salt in stainless steel capsule. *20 mm* and *50* mm capsule diameters were used. As a result, the *50 mm* capsule took longer time to solidify than the 20 mm capsule. Also, there was no significant difference in storage period between the capsules.

Carbonell et al. [43] have examined the integration of ice storage system into solar energy heating system. In experimental studies, 1 m^3 ice storage tank was used. In the study, different strategies have been tried. Similar to this study, Dott et al. [44] investigated the solar-powered ice storage heat pump systems in which the ice storage system was integrated.

Chen et al. [45] experimentally investigated the thermal performance and pressure drop of an ice storage system in energy charging period. Cylindrical capsules were used as capsules. They emphasized that the best storage performance achieves with low temperature and high flow rate of inlet HTF.

CHAPTER 3

Since in the literature review noted that ice capsules have significant effects on the system performance during energy charging period, in this study, ice capsules are modified and analysed to show better heat transfer characteristics. In this chapter, capsules designe, specification of the problem, including the assumptions used in the analysis, are clarified. The fluid flow and heat transfer equations and analysis are presented, which include the differential equations and boundary conditions needed to solve the problems. Then, an overview of the complex solution techniques that FLUENT 18.0 uses to solve this transient problem is considered. Nevertheless, before going to the simulations results, the domain specification, including mesh size, are given. Once this groundwork is laid, a thermodynamic analysis of the system will be insert.

3.1. Brief Description Of The Study

Before defining the essential aspects of the simulation it is necessary to define the scope of the present study. In most encapsulated ice storage tanks, the capsules are either of the spherical, rectangular (slab) or cylindrical geometries. The spherical capsule is far more common in industrial applications, due to its ease of manufacturing and the random assortment which can be achieved in a storage tank, eliminating the need for an internal structure to orient the capsules with the heat transfer fluid. There are many models that have been studied and used. But for the purpose of this study, only spherical capsules with various additives in form are considered. The aqueous solution of 35-wt% ethylene glycol is used as the heat transfer fluid (HTF). The main considered parameters are the volume of the spherical capsule, the inlet temperature and volume flow rate of the heat transfer fluid (HTF). The influences of these parameters on the full charging time, the average total temperature and the solidified mass fraction are examined.

3.2. Spherical Capsules Descriptions

Models are created by solidwork 2018 software. Six spherical capsules with some features in their respective form will be analyse. A standard spherical capsule (ball) is taken as a reference for new capsules in terms of volume, diameter and surface area. When the diameter of the ball is 110 *mm*, its volume and surface area are 696909.96 mm^3 and 38013 mm^2, respectively. Since the storage volume has the most importance, a constant volume will be considered for all capsules which is 696909.96 mm^3 and the diameter as well as the surface area will be change until getting the required volume. Capsules are given names according to their structures as explained below with its Figure 3.1

a. **Finned:** It has a series of semi-circular belts revolving around capsule. The diameter of each belt is 10 *mm* and the total number of belts is 7. The presence of these belts reduces the spherical diameter to 105.741677 *mm* and increases the surface area to 48459.28 mm^2 for the capsule
b. **Reversed fin:** It has the same advantages as finned capsule. But capsule belts in this model are internal and this leads to increased diameter to 113.942892 *mm* and surface area to 50006.77 mm^2 of the capsule
c. **One hole:** This capsule contains a 10-*mm* tube hole that penetrates the capsule from the center and this leads to increased diameter and surface area to 110.654068 *mm* and 41397.51 mm^2, respectively.
d. **Fin with hole:** This type combines the properties of fin and one-hole capsule with 106.394751 mm diameter and 51794.87 mm^2 surface area
e. **Two holes:** This capsule contains two holes of 10 *mm* diameter tubes that pierce the capsule from the center in a perpendicular manner. Capsule diameter and surface area are 111.276034 *mm* and 44382.47 mm^2, respectively.

f. **Fingered with hole:** It has the properties of a single hole capsule in addition to bumps or hemispherical bodies that resemble fingers and are spread on the surface of the capsule with 10 *mm* diameter of each finger. Capsule diameter and surface area are 108.427556 *mm* and 53151.69 mm^2 respectively.

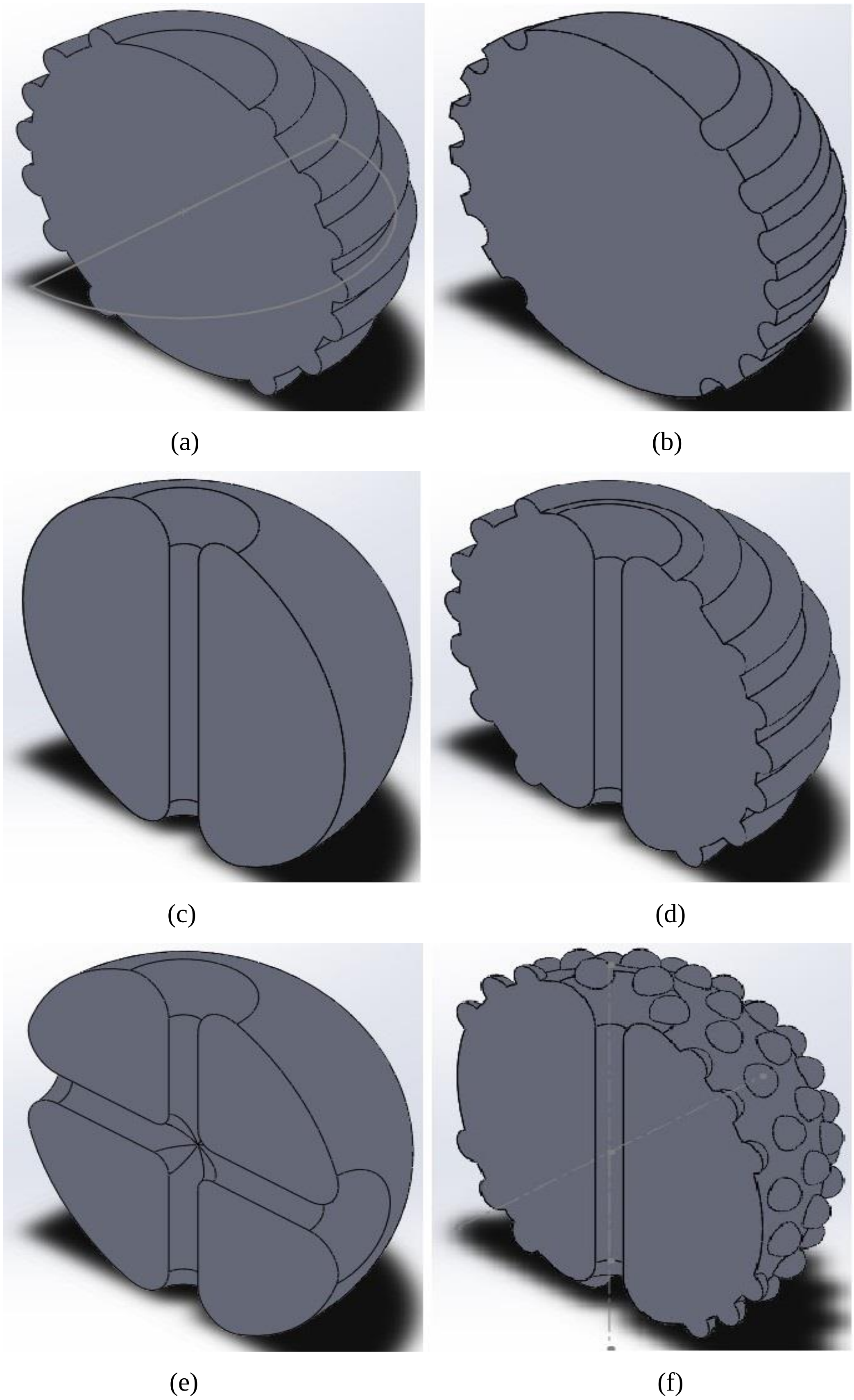


Figure 3.1. Semi-structure of (a) Finned, (b) Reversed, (c) one hole, (d)fin with hole, (e) two hole, and (f) fingered with hole capsules

3.3. Numerical Model

The present analysis will examine one capsule of each type filled with de-ionized water, and simulate its charging (solidification) process in three dimensions by using thermodynamic relations. And to facilitate that, FLUENT 18.0 software is employed to realize the required data. The spherical capsules will be compared to each other of various aspects. To achieve these comparisons, a test domain has been designed to conduct heat transfer experiments. For a better understanding of the test domain and capsule relationship, see Figure 3.2.

The below domain was constructed using Workbench 18.1 software. It has dimensions of 350 × 350 × 350 mm and filled with a 0.0428 $m^3$of the HTF. The bottom and upper sides represent the inlet and outlet of HTF, respectively. the capsule was immersed in a flowing HTF at the center of test domain. For the cases investigated here, test domain dimensions were chosen to be quite close to test domain dimensions used in experimental study of freezing of water inside spherical capsules, ElGhnam et al. [29],

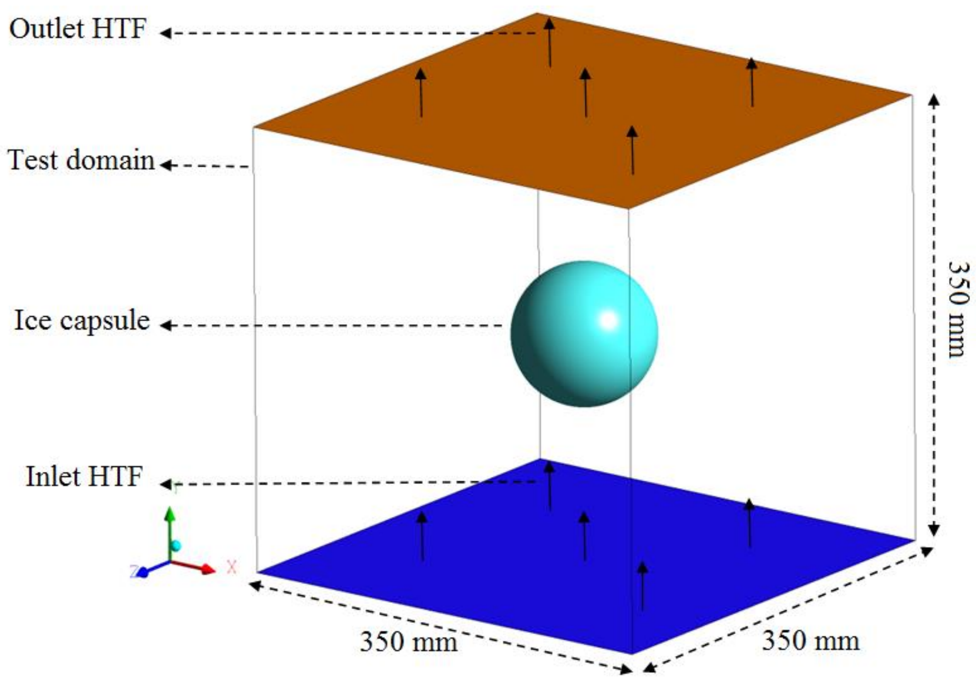
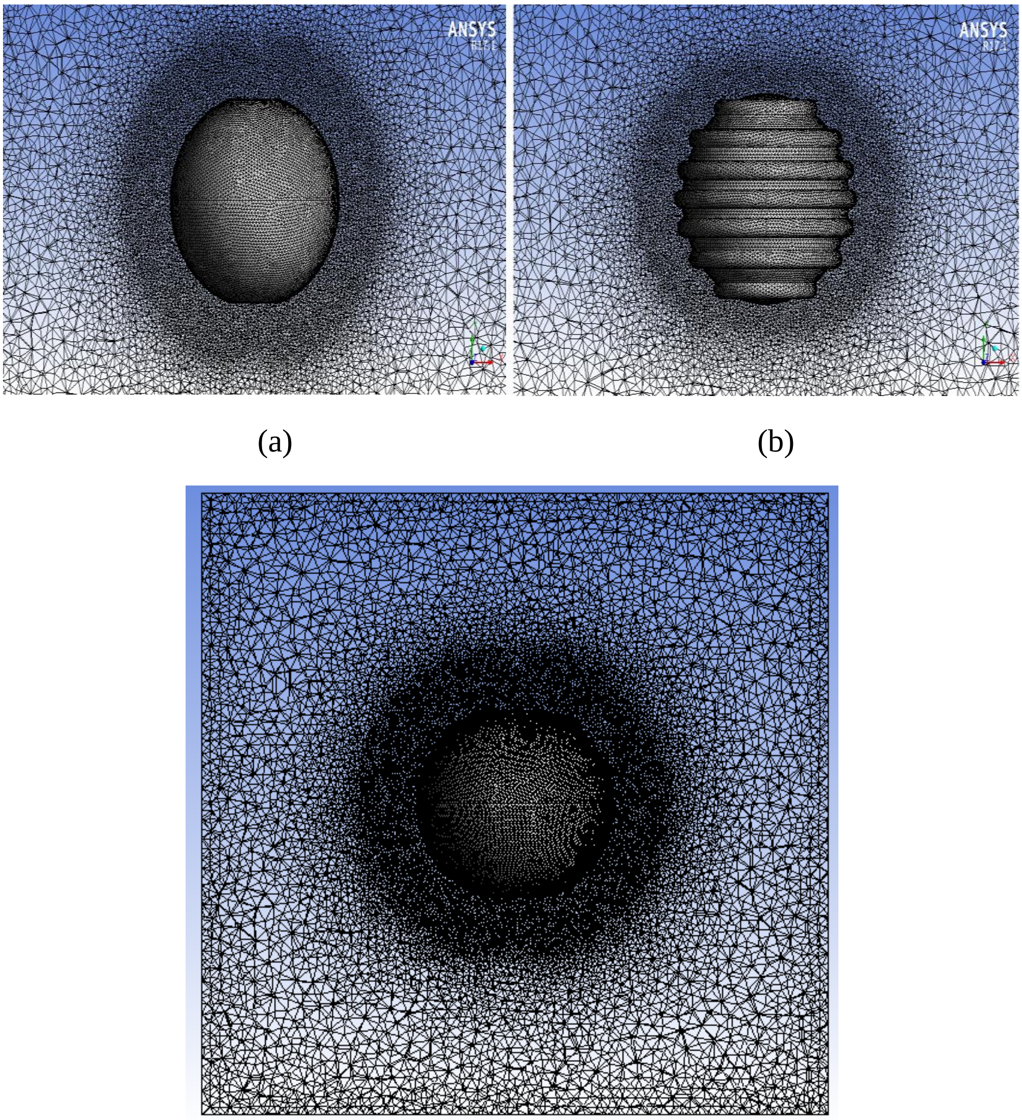


Figure 3.2. Test domain

3.3.1. Mesh Structure

When creating control volume domains for numerical procedures, one of the most important keys to the accuracy of the results is the mesh size. When splitting the computational domains into small volumes, care must be taken to ensure that sufficient volumes are available to keep the solutions accurate. From another side, if too many volumes are present, the computational times can increase significantly. Therefore, there must be a middle ground between ease of solution and computational complexity, and this is carried out by performing a sensitive mesh. For all geometries created, the mesh domains were constructed using tetrahedrons element type. The water zone was divided with a much more volumes of domain than HTF zone, where the element size was constant at 0.002 *m* for water zone. Otherwise, HTF zone did not take into account in terms of element size, but the contact region with water zone has been identified and took special cares. As illustrated in Figure 3.3.



(a) (b)

(c)

Figure 3.3. Mesh structure for (a) one hole capsule, (b) fin capsule, and (c) HTF zone

3.3.2. FLUENT Procedure

Before continuing with numerical solution, the assumptions used in this analysis are as follows:

- Negligible radiation effects,
- Capsules will have no wall thickness,
- HTF and PCM will have constant thermophysical properties,
- Materials will have no change in density during solidification,
- Negligible storage tank wall effect.

The material thermophysical properties utilized in the study are shown in Table 3.1. The properties for ice and water are considered constant at temperatures of 273K and 293K, respectively. Since this is an acceptable mean temperature at which these substances will be experiencing.

Table 3.1. Thermophysical properties of water, ice and HTF used in numerical analysis

MATERIAL	C $[J/kg.K]$	ρ $[kg/m^3]$	K $[W/m.K]$	μ $[kg/m.s]$	H J/kg	T_{PCM} K
WATER	4182	998.2	0.6	0.001003	333500	273.15
ICE	2200	915	0.0454	$1.72e^{-5}$	333500	273.15
HTF	3605	1058	0.465	0.0085		

The continuity, momentum and energy conservation equations will be solved through the Fluent program. In addition, the calculations of the turbulence effects around the sphere will be also included. Different turbulence models will be tested and a turbulence model which provides the best solution from these models will be selected. Furthermore, Solidification & Melting module will be used to model freezing process. Also, the Coupled algorithm will be used as the pressure and velocity compaction method. Moreover, in order to use the Solidification & Melting module, PRESTO! scheme should be used. Lastly, the domain used in this study must pass a number of independence tests including grid size and time step, in order to be considered a reasonable computational model.

3.3.3. Governing Equations and Boundary Conditions

The equations governing the energy and fluid flow throughout the computational mesh will be divided into two sections: PCM (water/ice medium) and HTF (glycol solution). For all geometries, FLUENT uses rectangular co-ordinates for their domains, meaning that all governing equations and boundary conditions are three-dimensional in the x, y, and z directions. Once all governing, initial and boundary conditions are known, the solver is able to begin solving the problem over time.

A. Water/ice medium: as kwown, is contained in a closed capsule with no flow conditions. Only the energy equation is considered and it is shown below:

$$\rho_{pcm} \frac{DH_{PCM}}{Dt} = k_{pcm} \nabla^2 T \qquad (3.1)$$

The substantial derivative ($D\gamma / Dt$) for any variable γ is known as:

$$\frac{D\gamma}{Dt} = \frac{d\gamma}{dt} + u\frac{d\gamma}{dx} + v\frac{d\gamma}{dy} + w\frac{d\gamma}{dz} \qquad (3.2)$$

Here, *u*, *v*, and w are the *x*, *y*, and *z* components of the velocity vector.

$$\vec{V} = u\vec{\imath} + v\vec{\jmath} + w\vec{k} \qquad (3.3)$$

The differential operator (▼), shown in the energy equation above, is a vector quantity and it is defined as:

$$\nabla = \left(\frac{\partial}{\partial x}\vec{\imath} + \frac{\partial}{\partial y}\vec{\jmath} + \frac{\partial}{\partial z}\vec{k}\right) \qquad (3.4)$$

Continuing with the energy equation, the enthalpy of water/ice medium (H_{PCM}) will be calculated as the total of the sensible enthalpy (h) and the latent enthalpy (H_l)

$$H_{pcm} = h_{pcm} + H_l \qquad (3.5)$$

Where the sensible enthalpy (h) are defined as a function of temperature:

$$h(T) = h_o + C \ (T - T_O) \tag{3.6}$$

The latent enthalpy of each cell depends on the liquid fraction (*B*) which varies between *0* for completely solid and 1 for completely liquid:

$$H_l = \beta L \tag{3.7}$$

The liquid fraction and temperature field of PCM, mentioned in the equations above, can only be solved after the initial and boundary conditions are determined. To begin with, the first condition is the temperature when the solution is initialized (i.e. at *time t = 0*), which is set to be 283*K* as room temperature. That is,

$$T_{ini} = 283K \tag{3.8}$$

Next, in order to proceed with the solution, the wall boundary condition must be introduced, which provides the temperature condition in the HTF/PCM interface. Since there should be no interruptions in temperature field, the temperatures at the outer PCM wall and the HTF must be equal. In other words, for adjacent cells on the interface,

$$T_{pcm}\left(f \in W_{pcm}\right) = T_{htf}\left(f \in W_{htf}\right) \tag{3.9}$$

Where *f* indicates the facet which is part of the wall, W, which in turn is part of the HTF/PCM interface.

B. Heat transfer fluid (HTF): The heat transfer fluid must meet a number of governing equations, because of the intricate flow conditions in the domain. First of all, as HTF is moving continuously, the energy equation becomes more complex as shown below:

$$\rho_{htf} \frac{Dh_{htf}}{Dt} = \frac{Dp}{Dt} + k_{htf} \nabla^2 T + \Phi \tag{3.10}$$

The latter term on the above equation (Φ) includes viscous stresses, and is commonly called the dissipation function.

$$\Phi = \mu\left[2\left(\frac{\partial u}{\partial x}\right)^2 + 2\left(\frac{\partial v}{\partial y}\right)^2 + 2\left(\frac{\partial w}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}\right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2\right] \quad (3.11)$$

Since the equation above needs to be solved to include velocity and pressure terms, many equations must be given before transient solutions are performed. First, the continuity equation must be met, and since HTF is assumed to be incompressible, the equation of continuity becomes:

$$\nabla.\vec{V} = 0 \quad (3.12)$$

The above equation, simply, guarantees that the mass fluxes are conserved through adjacent cells. Second, the momentum equations, recognized as the Navier-Stokes equations, must also be fulfilled:

$$\rho_{htf}\frac{D\vec{V}}{Dt} = -\nabla p + \mu\nabla^2\vec{V} \quad (3.13)$$

Thus, the momentum equations based on the velocity vectors and pressure differential within the velocity field. The change in velocity at any point in the fluid depends on the pressure gradient at that point, ▼p, as well as the viscous dampening effects.

Since there are some new equations introduced here with many variables, it will be necessary to have the initial and boundary conditions to fully solve the flow fields. Firstly, the wall boundary condition at the outer PCM wall and the HTF has already been met in the equation 3.9, so that the heat transfer fluid has a temperature equal to its inlet temperature:

$$T_{htf}(t = 0) = T_{in} \quad (3.14)$$

Since the continuity equation (3.10) must be covered, the mass inlet and outlet for HTF must be equal:

$$m_{inlet} = m_{outlet} \quad (3.15)$$

Now, after processing the governing equations and boundary conditions, the simulation can begin to solve these equations.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter deals with applications and the main numerical results. The numerical results concerning the influence of capsule shape, the inlet HTF temperature, and the inlet HTF rate on the full charging time, solidified mass fraction, and temperature average are investigated, discussed and compared.

However, before continuing on to the results of the simulations, the domain used in this study must pass a number of independence tests including mesh size and time step. Then, a model validation must be performed, in order to be considered a reasonable computational model.

4.1. Model Independence Tests

As previously mentioned, before the results of this study are charged and taken seriously, a careful investigation of the dynamics of the model must be undertaken. Sensitivity tests, including mesh sensitivity and time step independence tests must be completed and the model must perform in a satisfactory way for the results to be meaningful.

The model independence tests were performed by simulating the solidification of the water inside a normal spherical capsule with 110 *mm* diameter. The inlet and boundary conditions were set to be as follows:

- $T_{in} = 265\ K$
- $Q_{in} = 1.225\ 10^{-3}\ \ m^3/_s$
- $T_{PCM,ini} = 283\ K$

It should be noted that since the full charging time is a great indicator of the heat transfer characteristics to and from the capsules, it serves as a sufficient gauge to the overall mesh performance and time step size.

In order to make the solution's dependence on the mesh size, different element sizes are tried. A mesh independence test is implemented over meshs with different numbers of elements 1.5 million, 2.7 million, 3.5 million, 4.2 million, 5.1 million and 6.3 million. It is found that the variation in the full charging time is marginal decrease when moving from 4.2 million element to 5.1 million. Hence, there is no such advantage in increasing the number of elements beyond this value. Thus, the mesh system of 4.2 million elements is adopted for the current computation. Similarly, the full charging times are observed in time steps 2, 1, 0.1, and 0.07 *sec* to make the time step independence. Since there is no significant change in the results of full charging time after 0.1 *sec*, the time step is taken as 0.1 *sec*. The resulting independence of grid size and time step are shown in Figures 4.1 and 4.2, respectively.

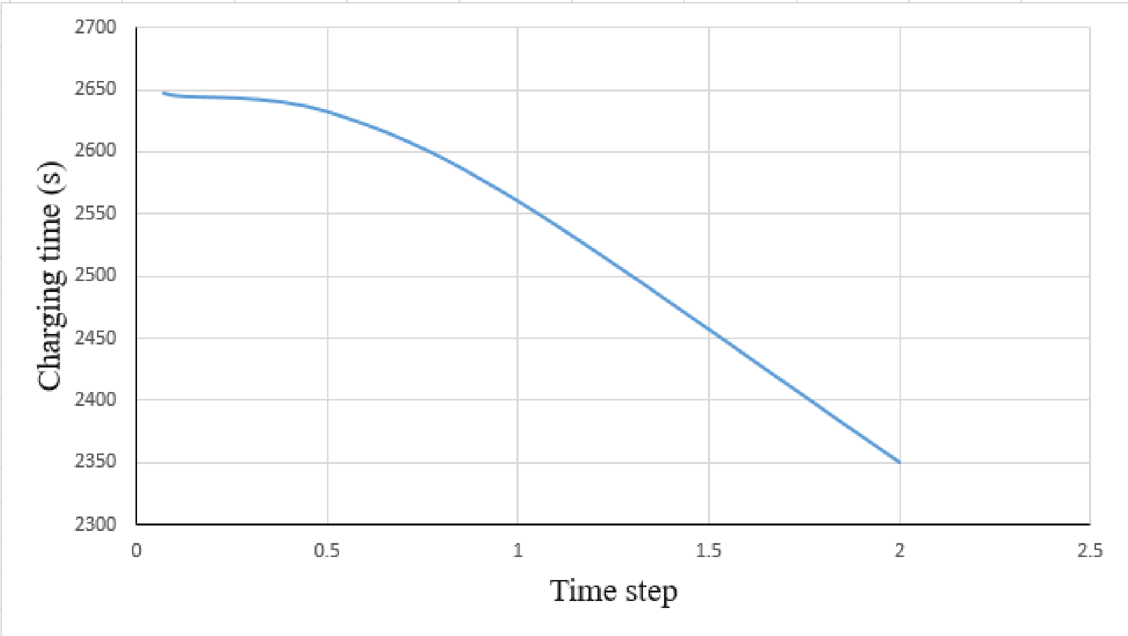


Figure 4.1. Mesh size independence

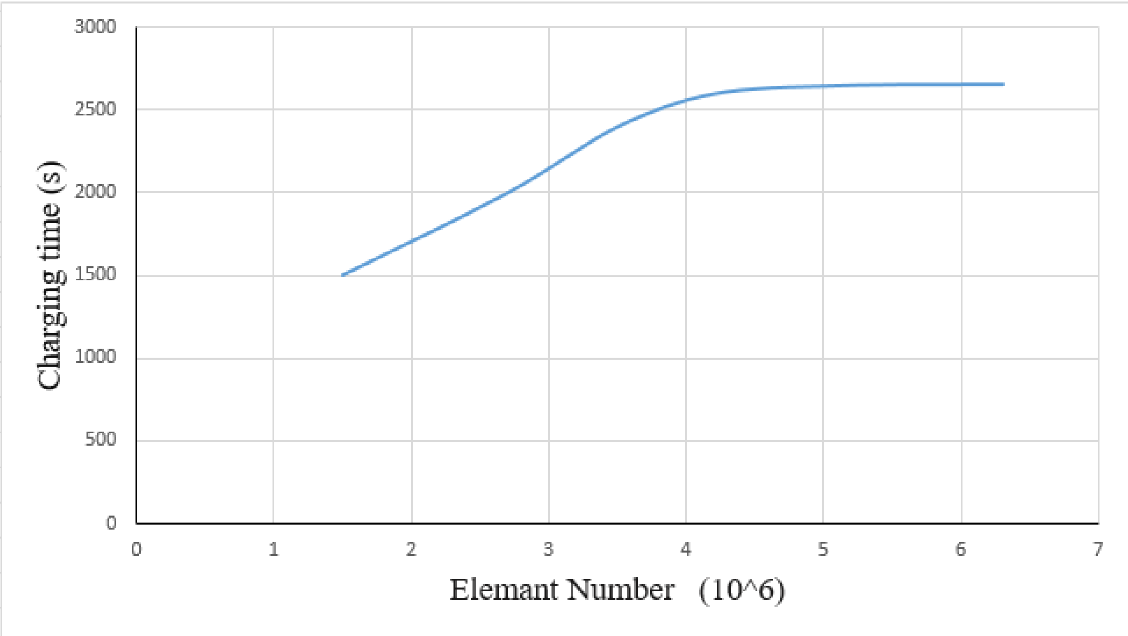


Figure 4.2. Time step independence

4.2. Model Validation

As noted earlier, the numerical results must be validated and compared with a real model to ensure the model is a viable simulation of real-world processes. A similar experiment was conducted for this one by ElGhnam et al. [29]. In this study, the process of both solidification and melting is observed in various spherical models in terms of material and diameter. The experiments were performed with ethylene glycol *35%* as a HTF and water as a PCM.

The experimental process in this study occurs as follows: ethylene glycol solution enters a steel tank with dimensions of 350 × 350 × 450 *mm*, initially at 283*K*, which contains a glass sphere with an inner diameter of 0.092 *m*. The capsule has a wall thickness of *1 mm* and contains distilled water as a PCM in 80% of its internal volume. HTF has an inlet velocity of 0.001 *m/s* and an inlet temperature of 265*K*. Fifteen thermocouples are placed on the vertical and horizontal axes of the spherical capsule to measure temperature distribution, and the transient temperature profiles are recorded. The results of both experimental and numerical solutions can be seen in Figure 4.3

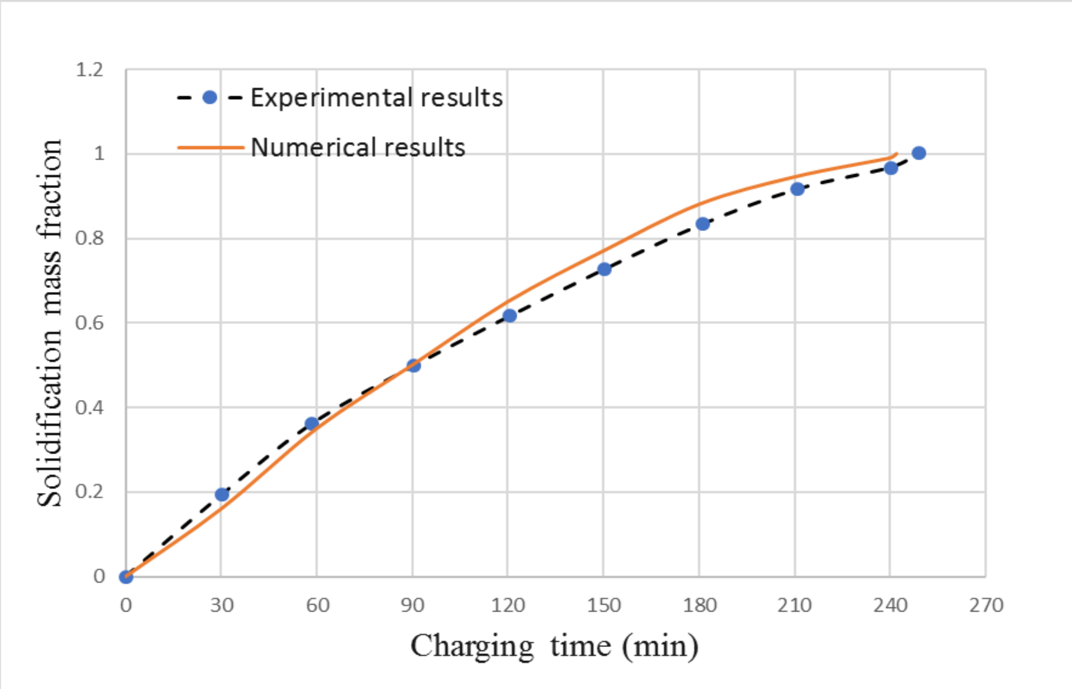


Figure 4.3. Comparison of the results obtained from the numerical study with the experimental work of ElGhnam et al. [29].

The differences between the experimental and numerical temperature profiles are most likely due to a number of factors, including contact resistance, small effects produced by the thermocouples embedded in the PCM, and possibly convection effects in the PCM. However, the overall heat transfer rates, as well as the solidification times, were of utmost importance to inspect, and the result can be summarized as follows:

- The time required for the PCM to be fully solidified was very close in both numerical and experimental cases. Fully solidification was done in 249 *min* experimentally, while in the numerical solutions full solidification took 242 *min*, which is within 97.2% of the predicted solidification time.

This similarity between the experimental and numerical results are encouraging, the purpose of this work is not only to study solidification process, but also to simulate the viscous forces and heat transfer between the flowing HTF and the PCM capsule.

Taking into account the resemblance above, now that the model has been properly validated, the charging process results of the simulation can now be considered.

4.3. Charging Process:

For all processes, the simulation was run until the liquid fraction $\beta = 0$ everywhere the PCM. Note that the initial temperature T for test region is set at 283K to simulate in a warmer region. The solidification process for all capsules was performed with three flow rates of HTF separately:

- $Q_1 = 1.225 \times 10^{-3}\ m^3/s$
- $Q_2 = 3.675 \times 10^{-3}\ m^3/s$
- $Q_3 = 6.125 \times 10^{-3}\ m^3/s$

These flow rates were chosen to be suitable enough so that they could easily be obtained in a storage tank. If the simulation's flow rates were too high, they would not be a logical estimate of the real-world storage system. It is summarized that these three flow rates, when set into rows of a hundred capsules or so, would generated a required pumping flow rate of around 8.7 to 26.1 *liters/s*, which is not unreasonable for large pump flow rates with relatively small pressure heads. In addition, Reynolds numbers around the capsules were different for a specific flow rate due to the different diameters for the capsules, as shown in Table 4.1. Since these differences are simple, they have been ignored.

Table 4.1. Reynolds numbers

Capsules	$Q_1 = 1.225 \times 10^{-3}\ m^3/s$	$Q_2 = 3.675 \times 10^{-3}\ m^3/s$	$Q_3 = 6.125 \times 10^{-3}\ m^3/s$
Finned	144	432	720
Reversed fin	141	423	706
One hole	138	413	688
Fin with hole	144	434	724
Two holes	139	415	692
Fingered with hole	145	440	729

Aside from the flow rates, the inlet HTF temperatures also varied. They were chosen to be 263K, 267K and 270K. Since heat will be transferring to the HTF during this process, there will inevitably be a large variation in the HTF temperature, and the heat transfer fluid is likely to vary within these ranges at some point in the test domain. The temperatures applied here are attempting to duplicate real scenarios, since at the test domain outlet, the HTF temperature will most likely be much warmer, due to heat transfer from the PCM.

Since the remainder of the inlet and boundary conditions has been met, the results of the charging process for all flow rates, inlet HTF temperatures and capules were simulated.

4.4. Charging Times

The easiest and most most explainable way to illustrate the differences between the capsule's processes is the charging time**.** For each simulation, the total time that taken for the liquid fraction to drop to zero was monitored, and is presented in Figures 4.4, 4.5 and 4.6 for flow rates *Q1*, *Q2* and *Q3*, respectively.

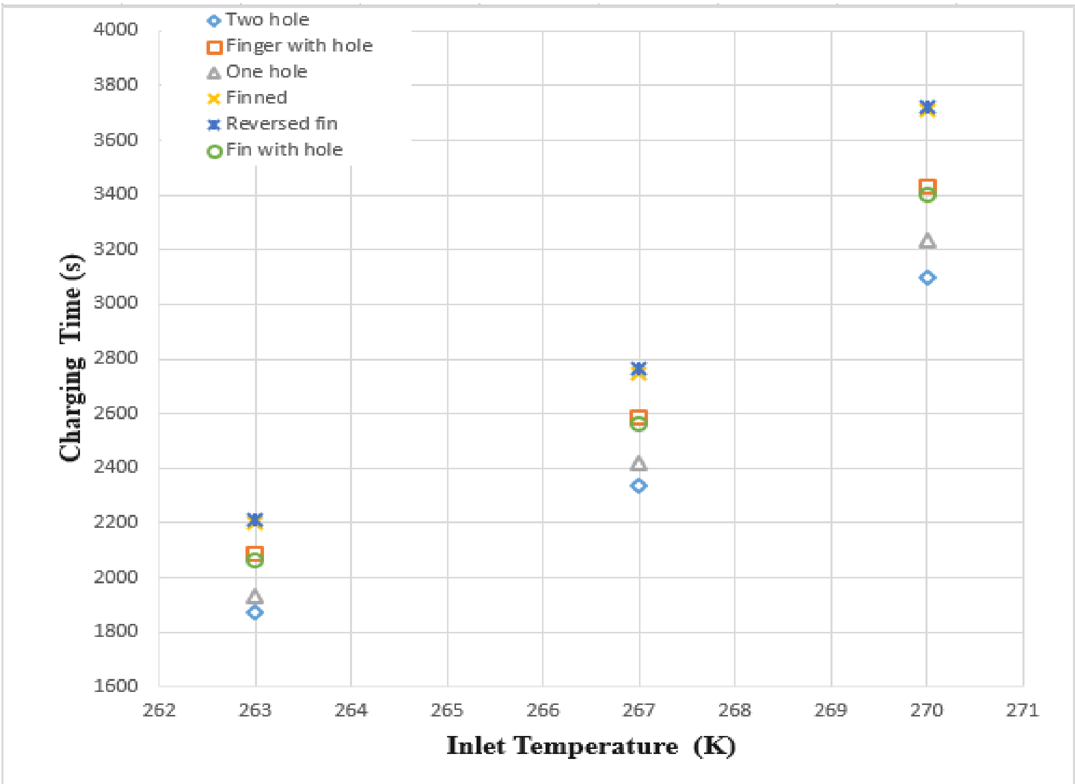


Figure 4.4. Charging times for capsules at the *Q1* = $1.225{\times}10^{-3}\ m^3/s$

After previewing these figures, three main outcomes can be met. The first is the effect of inlet HTF temperature on the full charging time. As the inlet HTF temperature increases, the full charging time also increases. This is because of the large temperature gradients that exist between the HTF and capsule when the inlet temperature is lowered. Whereas Newton's cooling law indicates that the rate of heat transfer between a convection flow and an object is proportional to the temperature's differences between them.

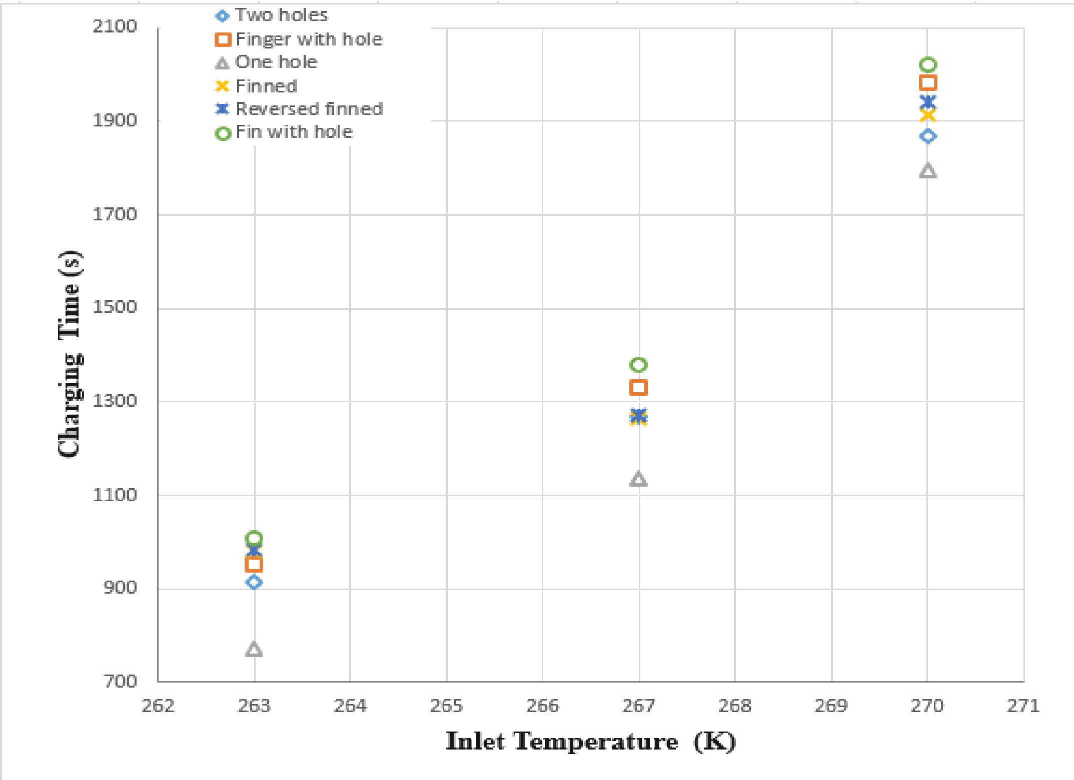


Figure 4.5. Charging times for capsules at the $Q2$ = 3.675×10^{-3} $m^3/_s$

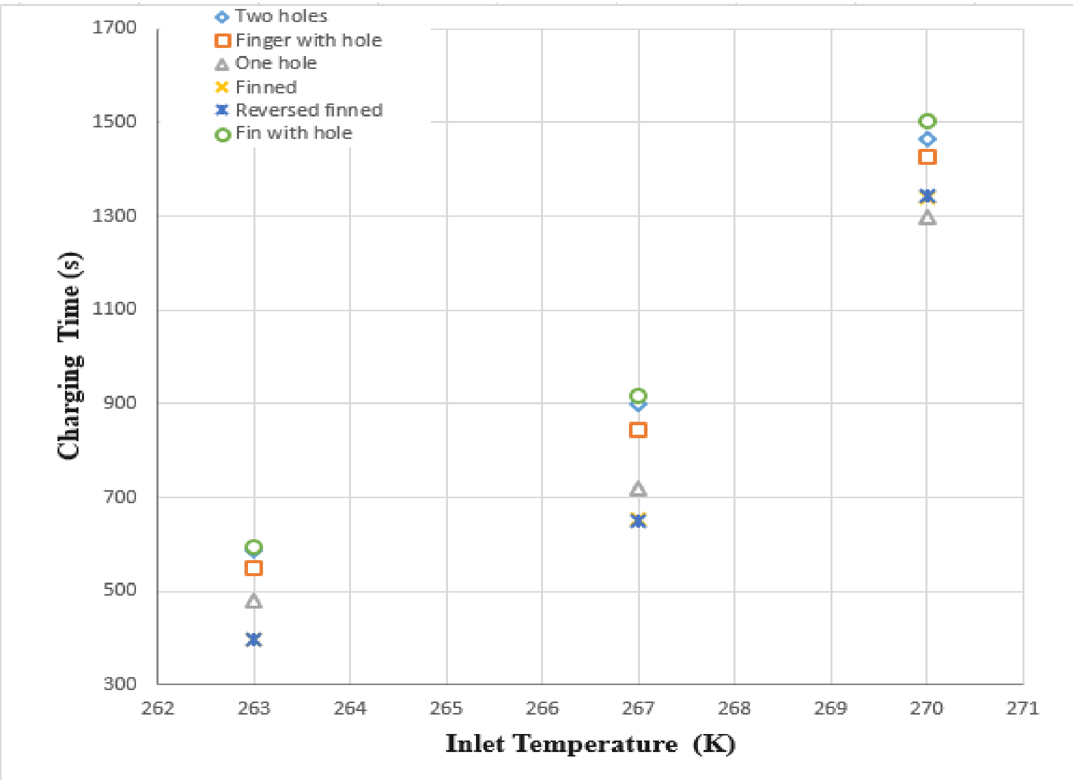


Figure 4.6. Charging times for all capsules at the $Q3$ = 6.125×10^{-3} $m^3/_s$

The second major fact that is found is the HTF flow rate, *Q*, has a great effect on the charging times. This was expected, when the HTF flow rate increased, the convection heat transfer between the ice capsule and HTF would increase significantly. Accordingly, the shorter complete charging time, the higher HTF flow rate. This is evident after tripling and quintupling the flow rate from *Q1* to *Q2* and *Q3*, the overall charging times decreased.

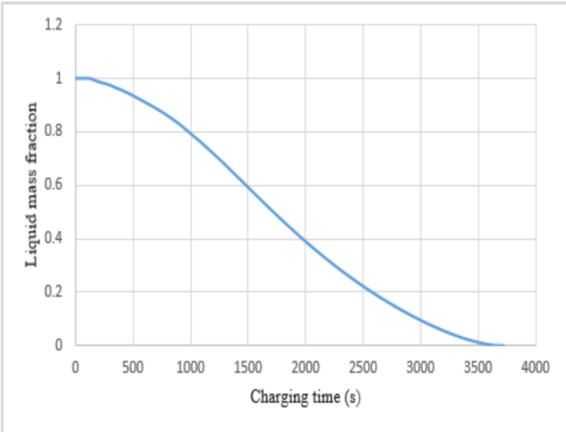
The last finding to discuss when evaluating the charging times is the impact of capsule shape. It can be seen in figures above that no capsule has achieved the fastest charging time or slowest in all cases. Where the results were different and varied according to flow rates and inlet temperatures. At the first flow rate, the fastest charging times was done by the two holes capsule followed by the one hole capsule, fingered and fined with hole, and lastly the finned and reversed fin capsules which were the slowest. Sequentially, as the HTF flow rate was increased, finned and reversed fin capsules take steps for the fastest charging times unlike the two holes capsule which was declining. This effect points to an important note about the hole when handling heat transfer at a low flow rate that the capsule which has two holes in the center has the maximum desired heat transfer characteristics. Conversely at high flow rates, the hole gives an adverse effect to the heat transfer process. Also, what draws attention in the results is that one-hole capsule remains in the first levels no matter how much the flow rate has changed.

4.5. Mass Fraction

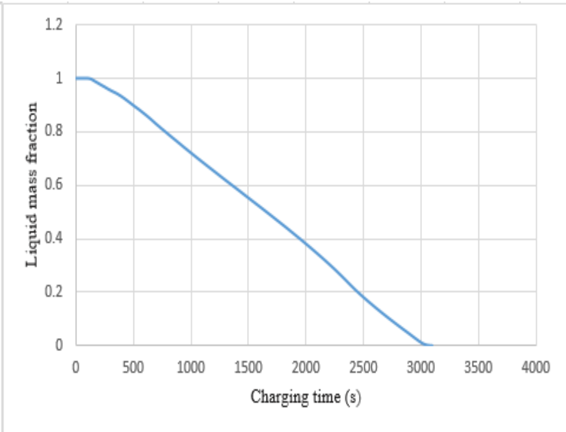
Liquid mass fraction is known as the ratio of the liquid mass to the mass of the PCM encased inside the spherical capsule. In other words, the ratio of residual liquid mass that has not been frozen to the total mass content within the capsule. Thus, the liquid mass fraction is calculated from the following formula:

$$\text{Liquid mass fraction} = \frac{m_l}{m_0} \qquad (4.1)$$

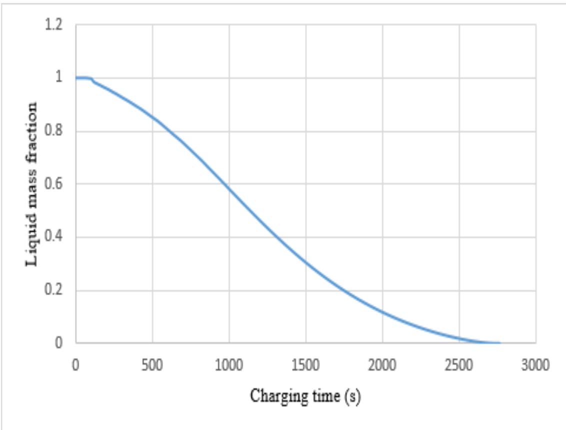
By studying the variation of liquid mass fraction with the charging time, the effect of capsule shape on the charging duration can be observed clearly. For each flow rate and inlet temperature, the fastest and the slowest charging time are compared by the liquid mass fraction as shown in Figures 4.7, 4.8 and 4.9.



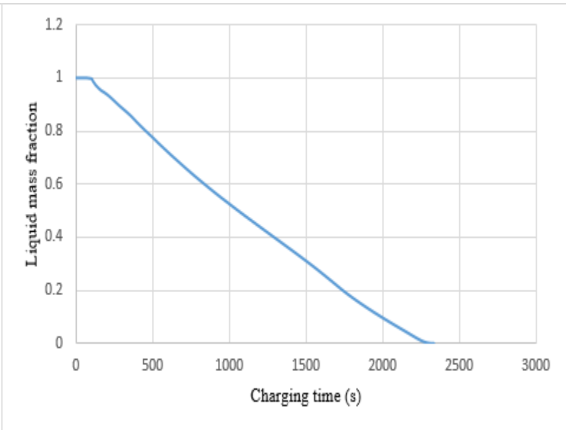
(a) Reversed fin *T=270 K*



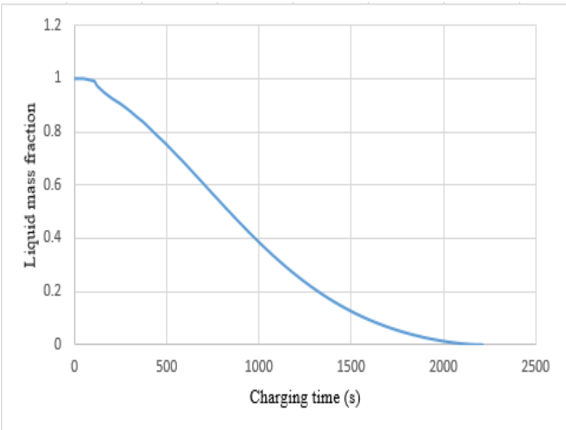
(b) Two holes *T=270 K*



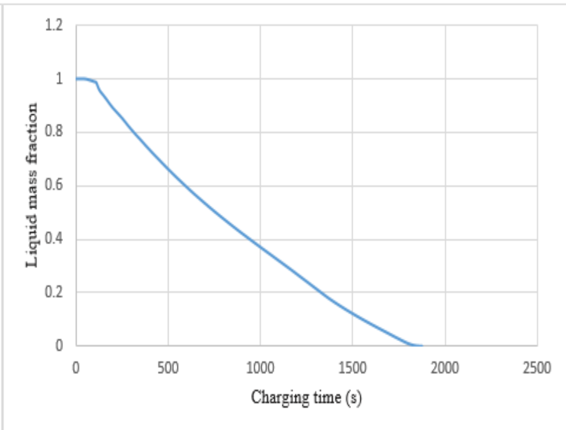
(c) Reversed fin *T=267 K*



(d) Two holes *T=267 K*

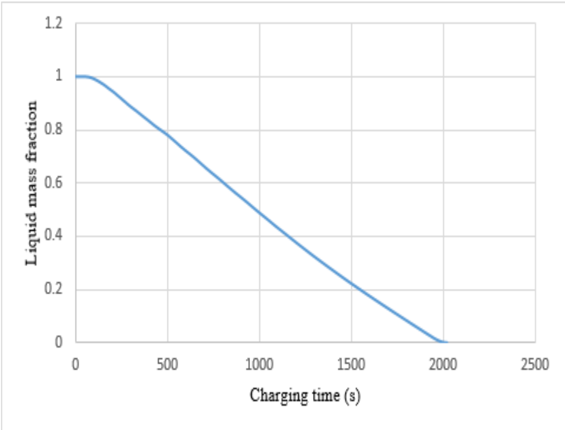


(e) Reversed fin *T=263 K*

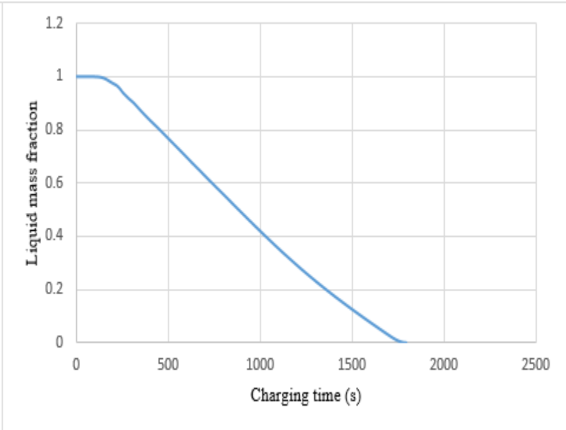


(f) Two holes *T=263 K*

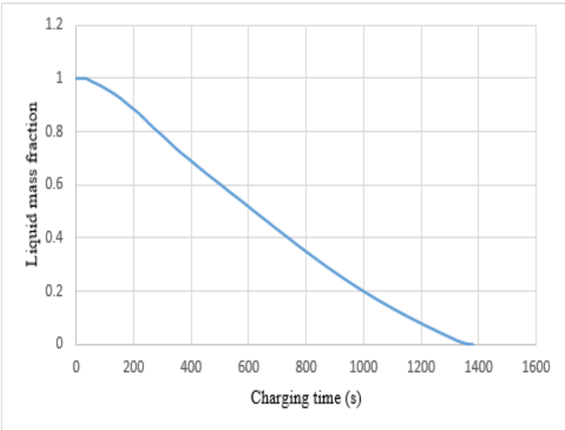
Figure 4.7. Liquid mass fraction for the fastest and the slowest charging time at $Q1 = 1.225\times10^{-3}\ m^3/s$



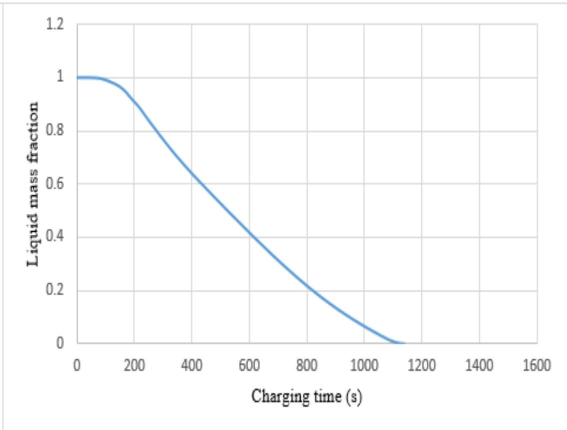
(a) Fin with hole *T=270 K*



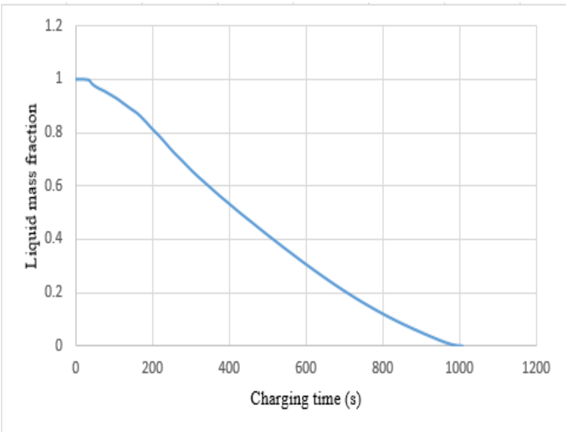
(b) One hole *T=270 K*



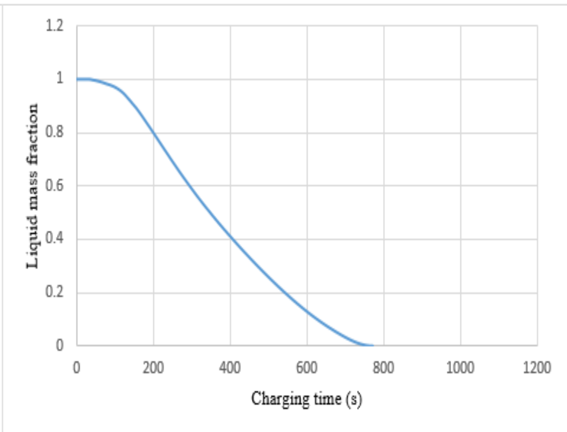
(c) Fin with hole *T=267 K*



(d) One hole *T=267 K*

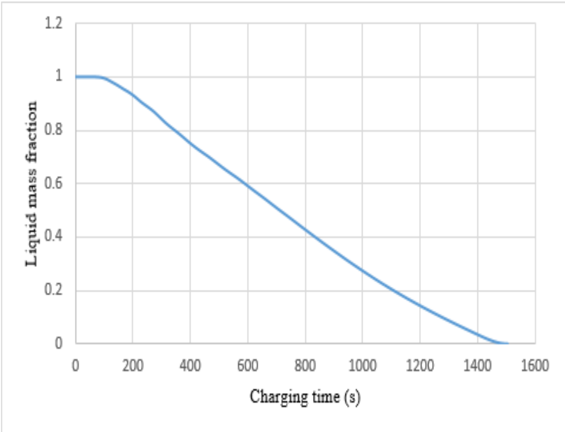


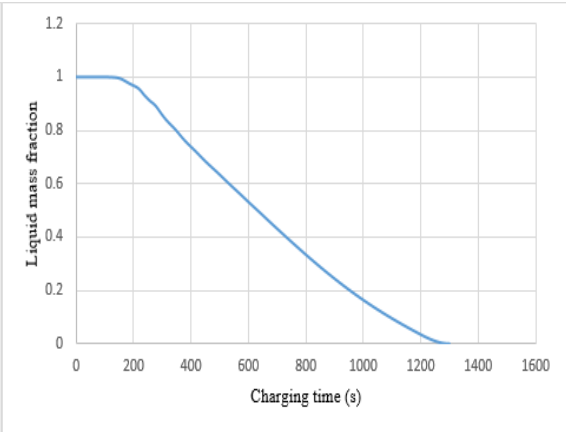
(e) Fin with hole *T=263 K*



(f) One hole *T=263 K*

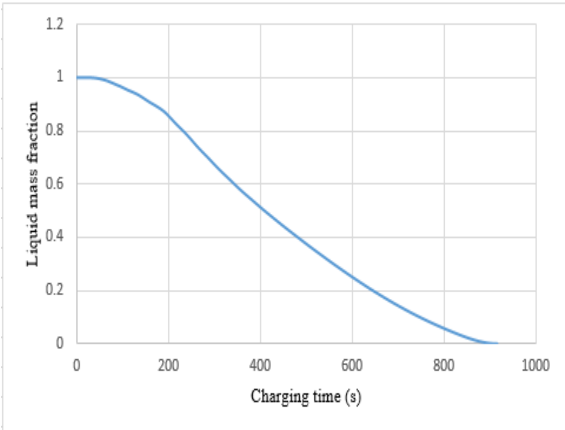
Figure 4.8. Liquid mass fraction for the fastest and the slowest charging time at $Q2$ = $3.675\times10^{-3}\ m^3/s$.

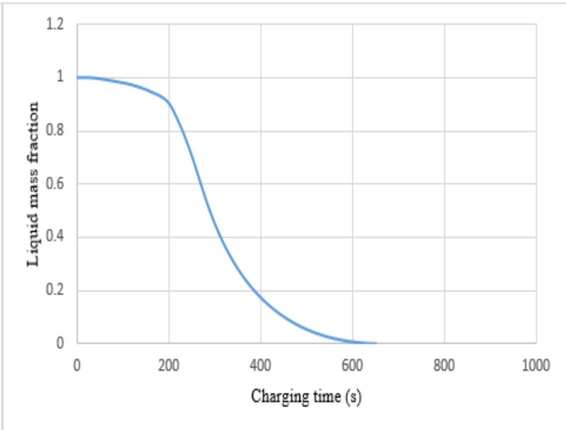




(a) Fin with hole *T=270 K*

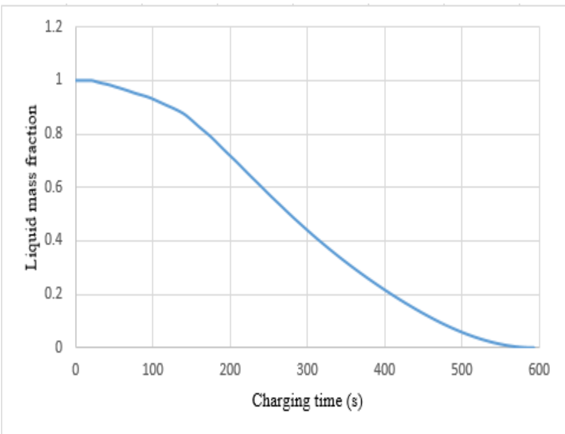
(b) One hole *T=270 K*

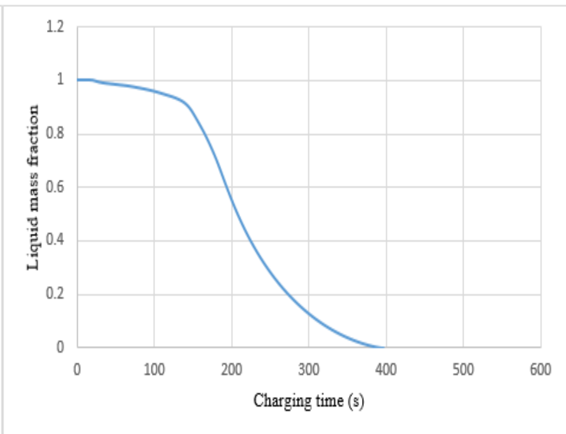




(c) Fin with hole *T=267 K*

(d) Reversed fin *T=267 K*





(e) Fin with hole *T=263 K*

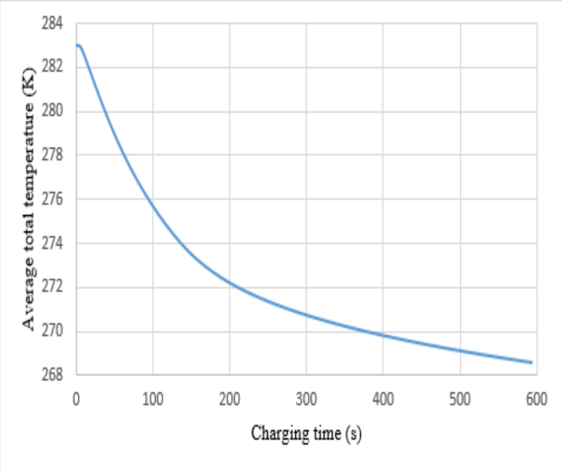
(f) Reversed fin *T=263 K*

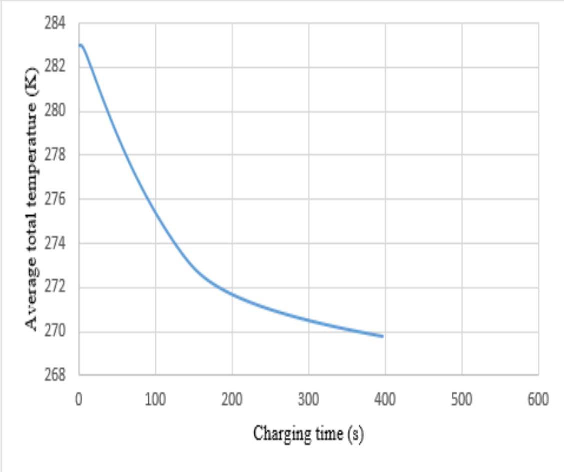
Figure 4.9. Liquid mass fraction for the fastest and the slowest charging time at $Q3 = 6.125 \times 10^{-3}\ m^3/s$

During the process it is noticed that for all capsules, the liquid mass fraction decreases as the charging time increases. Also, for a certain charging time, the magnitude of the liquid mass fraction decreases by increasing the flow rate or decreasing the inlet temperature of the HTF. All of which capsule take a period of time at first to acquire the sensible heat and turn into the latent heat. For further exploration, the duration to reach this point depends on the surface area and the shape of the capsule. Whereas The higher the surface area, the shorter duration to access the turning point except in the reversed fin capsule. Where it is noticed that the reversed fin capsule in low flow rate despite the large surface area it owns, it reaches late to this point. The reason for that is the reversed fins where they act as dead zones that do not allow the HTF to pass through and thus do not cause heat transfer. Conversely, at high flow rates these reversed fins work to increase turbulent effects over the capsule by converting the dead zones previously reported to be good areas for heat transfer.

In inspection of figures, it can be inferred that the decreasing rate of mass fraction changes more appropriately in capsules which have a hole than those that do not have. This is evident when comparing capsules, reversed fin with two holes in the first flow rate. Where the line of continuous change of mass fraction over charging time in the Figure 4.7 (b,d and f) is more straight than in the Figure 4.7 (a,c and e) where the line is wavering and it’s reduction rate at the beginning is faster than that at the end of the solidification process. This can be attributed to the fact that the progressive formed ice layer acts as an insulating material for the rest of the water contained in the center of the capsule while being overcome by the hole in those that it has one.

Furthermore, it is also noticed that at the full charging time the capsule that solidifies late has an average total temperature less than the capsule that solidifies faster. For instance as shown in Figure 4.10, at 263 K inlet temperature for the third flow rate, the average total temperature in the full charging time for fin with hole capsule and fined capsule are 268.5 K and 269.8 K, respectively. This means that the ice layers in the fin with hole capsule absorbed the cold thermal energy as a sensible heat instead of being transferred to the rest of water in the capsule to turn into ice.





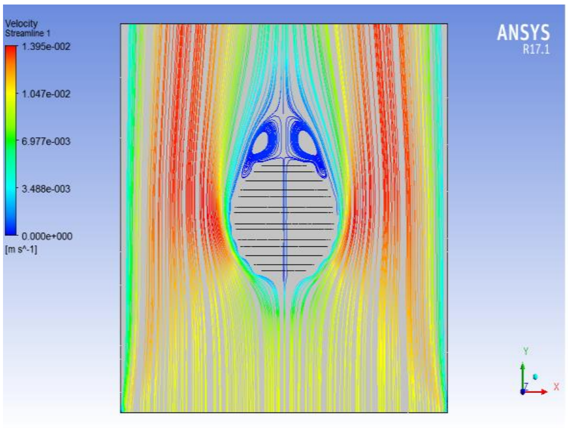
(e) Fin with hole *T=263 K* (f) Reversed fin *T=263 K*

Fig 4.10. Average total temperature at *Q3* = $6.125\times10^{-3}\ m^3/_s$

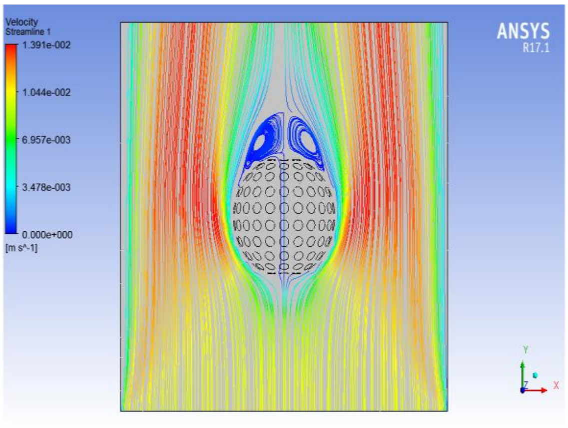
4.6. Velocity Analysis

The velocity analysis is the basis for all other subsequent analysis in this study. The variations in velocity are the prime determinant of changing properties like temperature and pressure throughout the control volumes. Since the water is contained in a closed capsule without moving parts, the velocity of HTF is only analyzed. For each flow rate, velocity streamlines for HTF are compared as shown in Fig 4.11, 4.12, and 4.13. From the figures, it can be observed that the velocity of HTF increases when it approaches the capsule and decreases when it passes the capsule. It may be due to, the reduction in area that occurs when the HTF approaches the capsule and the subsequent reduction in pressure. As the flow area increases the velocity of HTF decreases correspondingly.

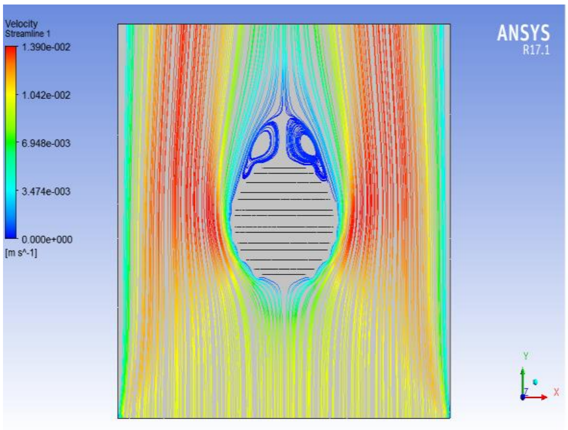
Also, it shows that the velocity of the HTF directly below the capsule is almost zero even in capsules in which a hole is existing. For capsules that do not have a hole, this behavior may occur due to the near stagnation condition that arises at that region. This is mainly because of the fact that the particular layer of HTF has less chance to escape due to the obstruction created by the capsule and the continuous collision with fresh HTF which nearly impedes its motion. Thus, there is less chance of fresh HTF interaction with capsule wall at this region. Where the hole was originally made to overcome this problem. But there was another problem appeared that didn't allow the hole to do its job properly at high flow rates especially and this will explain in the next lines.



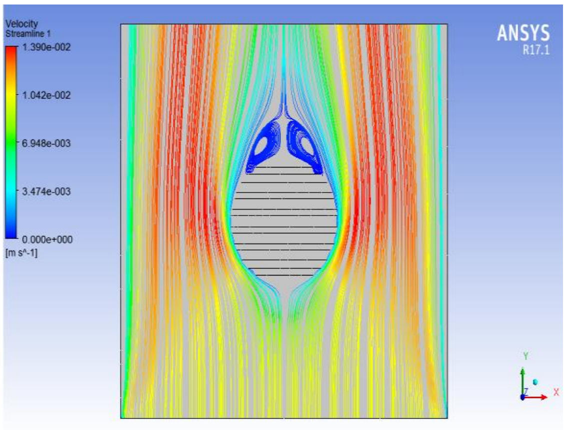
(a) Fin with hole



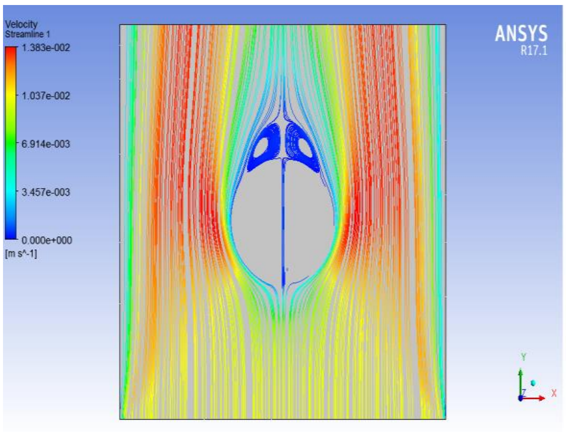
(b) Fingered with hole



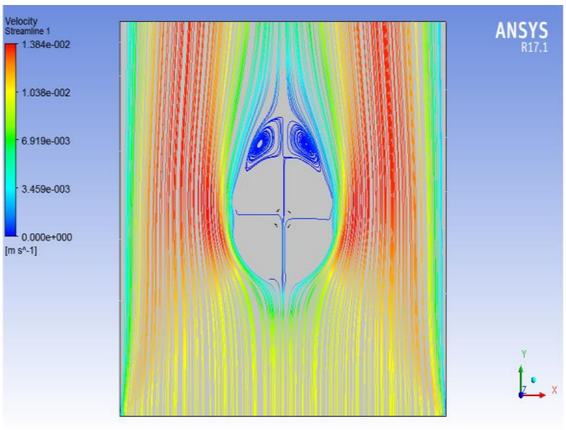
(c) Finned



(d) Reversed fin

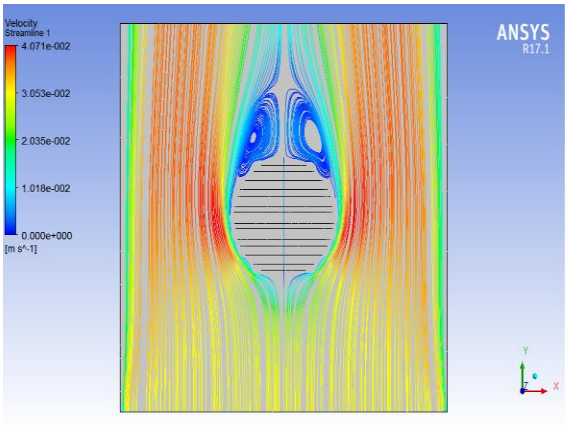


(e) One hole

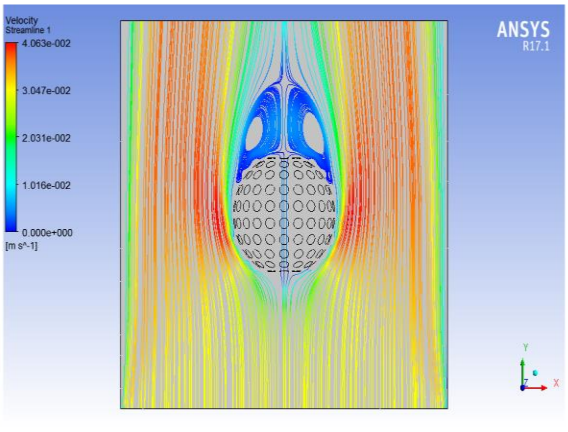


(f) Two holes

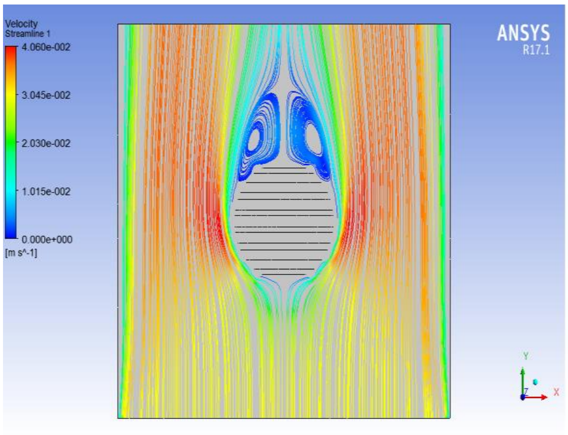
Figure 4.11. Velocity streamlines for capsules at $Q1 = 1.225\times10^{-3}\ {m^3}/{s}$



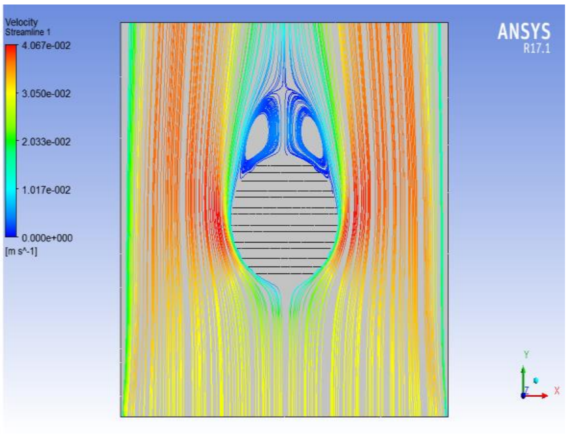
(a) Fin with hole



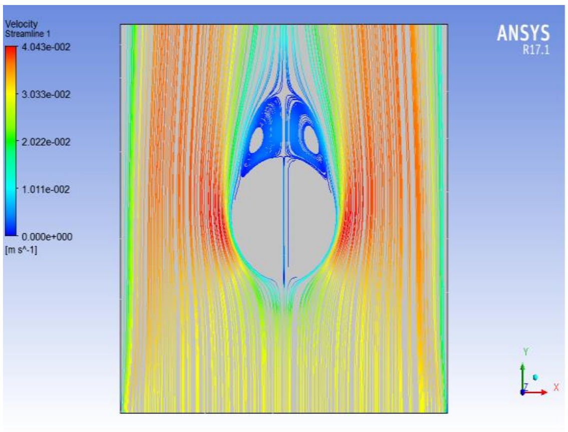
(b) Fingered with hole



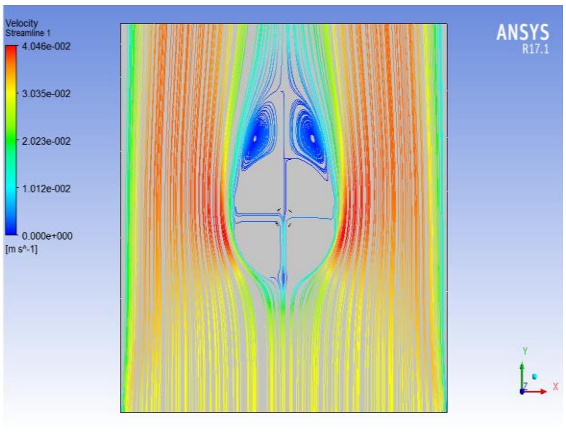
(c) Finned



(d) Reversed fin

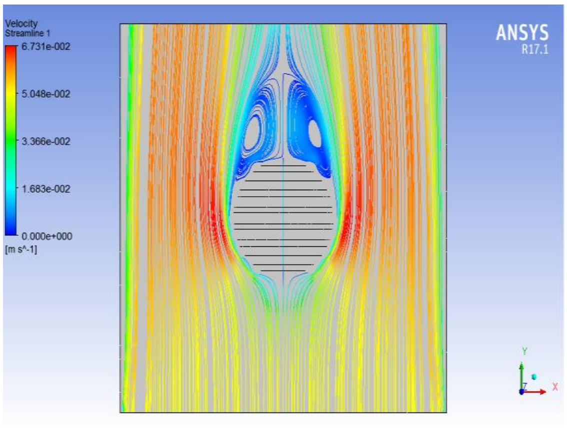


(e) One hole

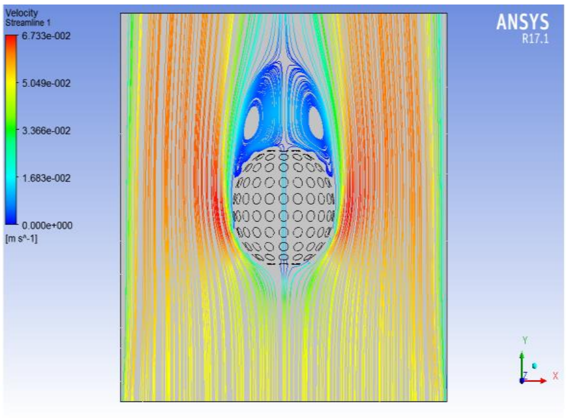


(f) Two holes

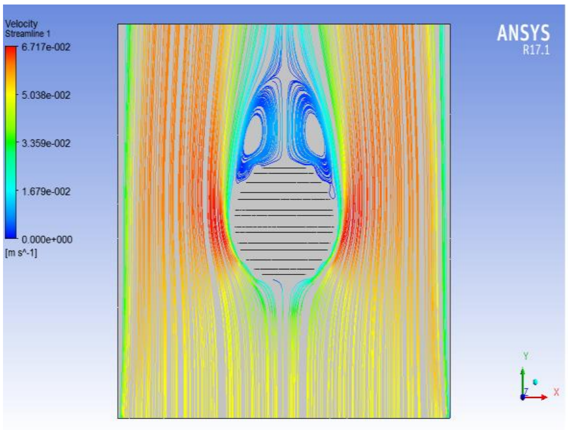
Figure 4.12. Velocity streamlines for HTF at $Q2$ = $3.675\times10^{-3}\ {m^3}/{s}$



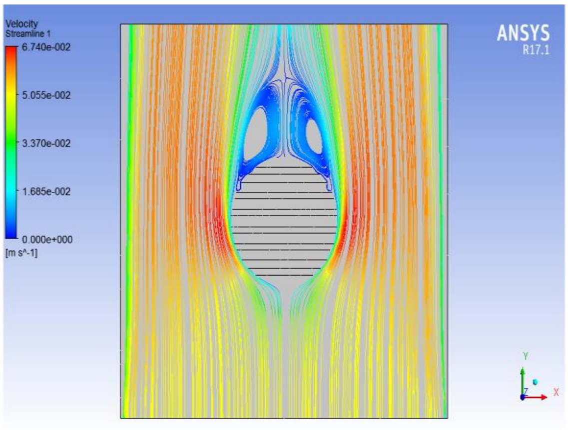
(a) Fin with hole



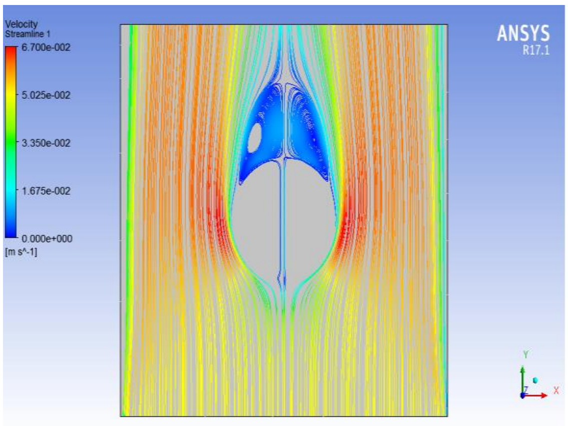
(b) Fingered with hole



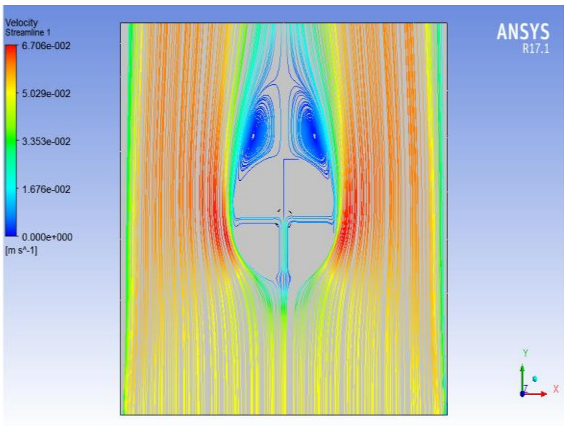
(c) Finned



(d) Reversed fin



(e) One hole



(f) Two holes

Figure 4.13. Velocity streamlines for HTF at $Q3 = 6.125\times10^{-3}\ m^3/_s$

Figure 4.14 shows the vertices of velocity for HTF past a sphere with hole at high flow rate. As the HTF flows past the capsule, which was set to no slip at the wall, the HTF decelerates near the capsule surface and creates a thin layer, called the boundary layer, due to viscous effects. HTF is attached to the capsule surface until the formation of a wake, evident to the rear of the capsule, where some of the fluid is flowing backward against the main flow. The maximum velocity occurs at θ = 180º. Near θ = 90º, the velocity is at a minimum or zero. This is where the circulation happens. Where a very strong recirculation region that is attached to the aft of the capsule impedes HTF to pass through the hole causing the flow to stop. For that aspect at high flow rates, capsules that do not have a hole introduce the lowest full charging time, while the capsules that have a hole produce the highest one.

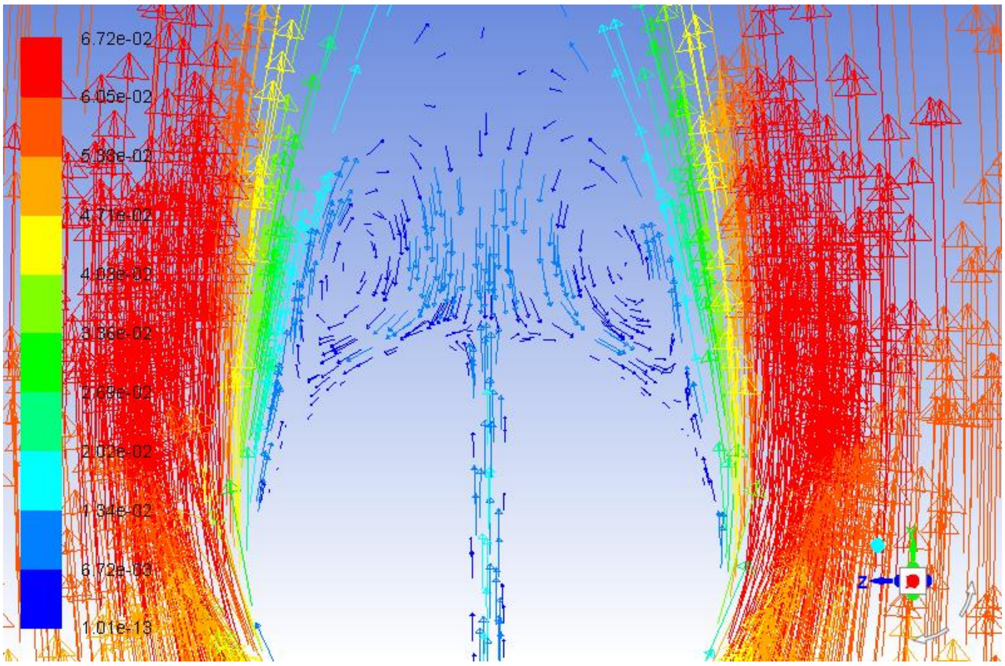


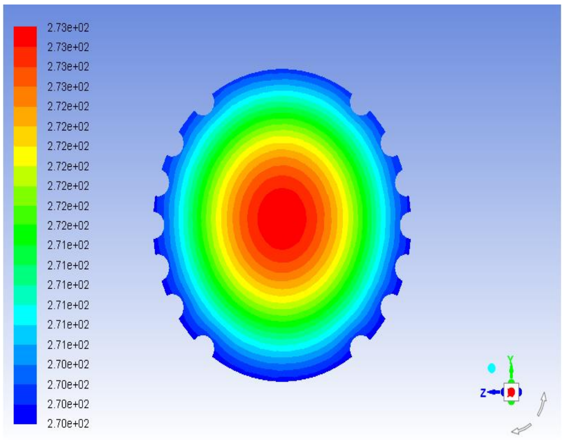
Figure 4.14. Velocity vertices for HTF at the top of one hole capsule

It is also observed that as the value of flow rate is increased, the wake becomes, longer and wider, and its point of attachment on the capsule moves forward. As seen from Figures 4.11, 4.12 and 4.13 there is appearance of a weak, long period of oscillation increases as the flow rate increases, but the wake remains attached to the capsule. For a certain capsule, the flow separation, which occurs when the wall shear stress of contact region for capsule wall is zero, from the capsule surface occurs earlier as the flow rate is increased. It is due to the fact that the flow has difficulty to attach more longer to the capsule as the velocity increases. For further exploring, capsules that have properties in the form, like fins or fingers, have a higher separation angle than capsules that do not contain these properties. This is because these properties in the capsule form create turbulence, or mixed flow, making the flow layer clings to the capsule as long as possible, in which leads to less vulnerable to separation.

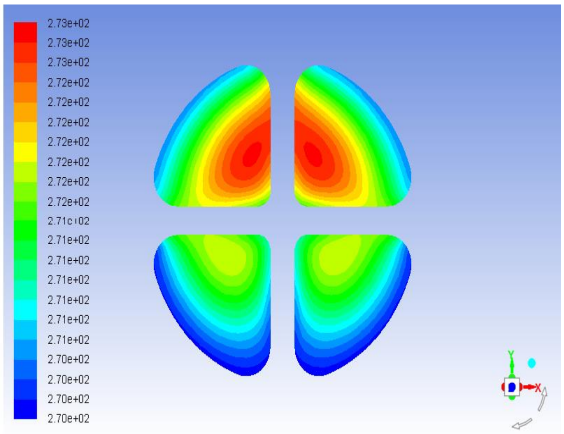
4.7. Temperature Analysis:

Temperature analysis is carried out by considering only the PCM at full charging time. This is because HTF in all cases exhibit same behavior. Figures 4.15, 4.16 and 4.17 show the temperature contours inside capsules for the best and worst performance of each case. From the figures, we can see for all cases that the peripheral layers of capsules show a lower temperature than the inner layers. Also, the bottom layer of capsules shows lower temperature than the top layer or any other layer. It may be due to the collision region created by the flow, so that HTF molecules hits the bottom surface of capsule. This causes lower temperature of bottom surface than any other surface. Temperature of the bottom surface is almost same as HTF temperature. It is through the wall of the capsule heat passes to HTF around the capsule.

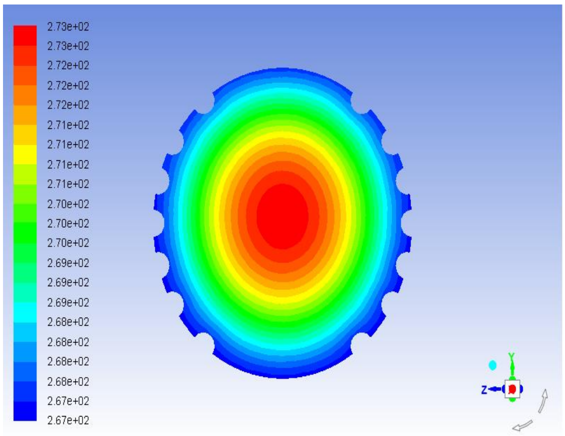
Furthermore, as the value of flow rate is increased, the peripheral layer, which has temperatures close to the temperature of HTF, becomes thinner. On other hand, the inner layer that has temperatures close to the solidification temperature of water, becomes thicker. In addition, the inner layer with high temperature is observed to be larger in high-performance capsules than in low-performance capsules.



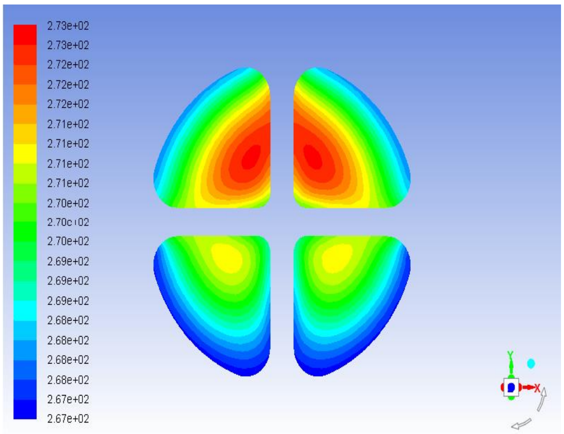
(a) Reversed fin *T=270 K*



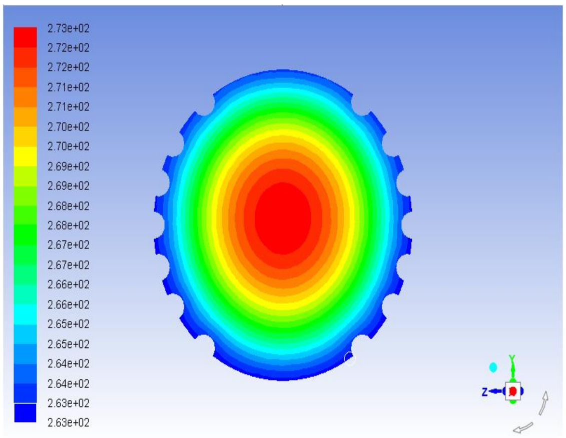
(b) Two holes *T=270 K*



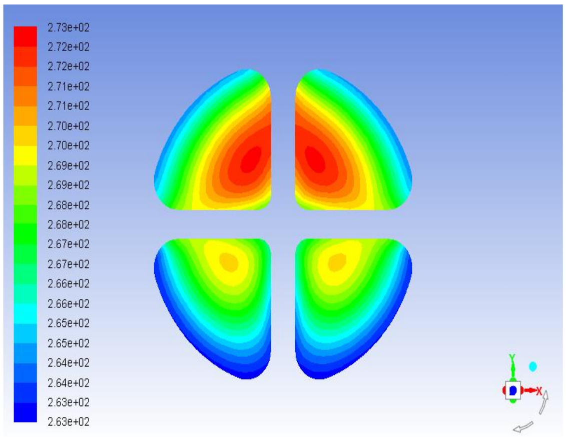
(c) Reversed fin *T=267 K*



(d) Two holes *T=267 K*

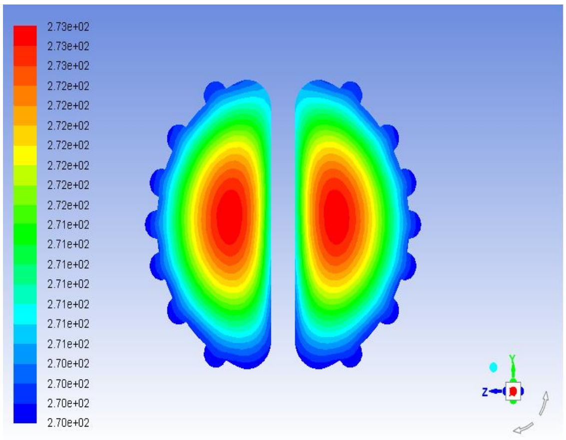


(e) Reversed fin *T=263 K*

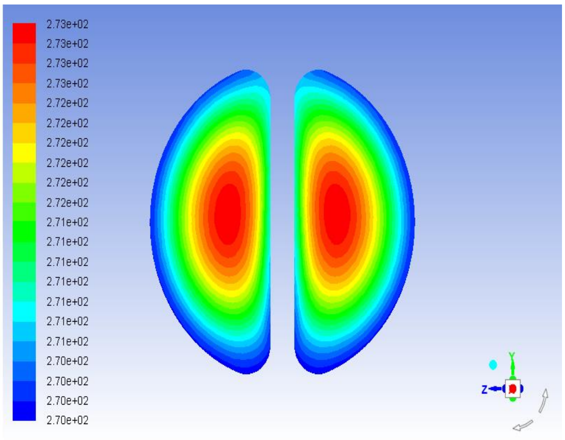


(f) Two holes *T=263 K*

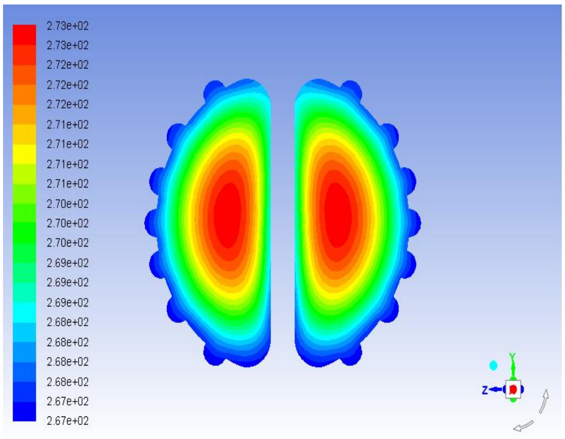
Figure 4.15. Temperature contour inside capsules for the fastest and the slowest charging time at $Q1 = 1.225\times10^{-3}\ {m^3}/{s}$



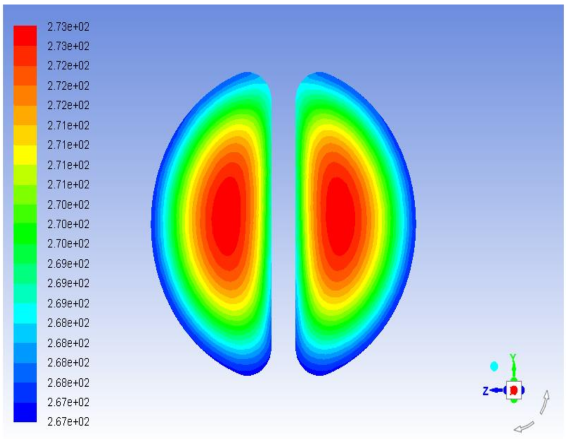
(a) Fin with hole *T=270 K*



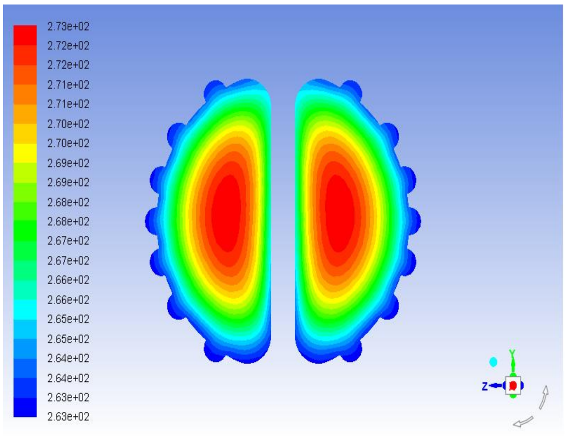
(b) One hole *T=270 K*



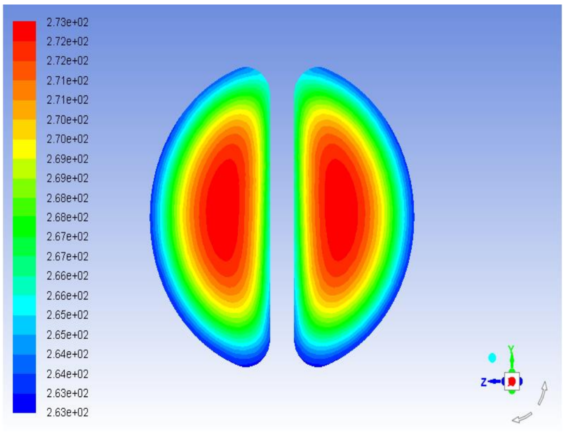
(c) Fin with hole *T=267 K*



(d) One hole *T=267 K*

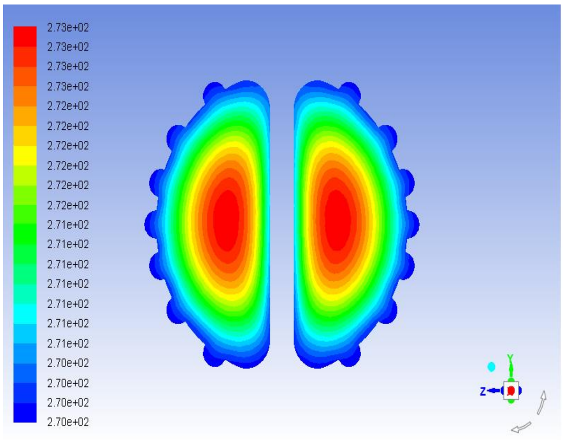


(e) Fin with hole *T=263 K*

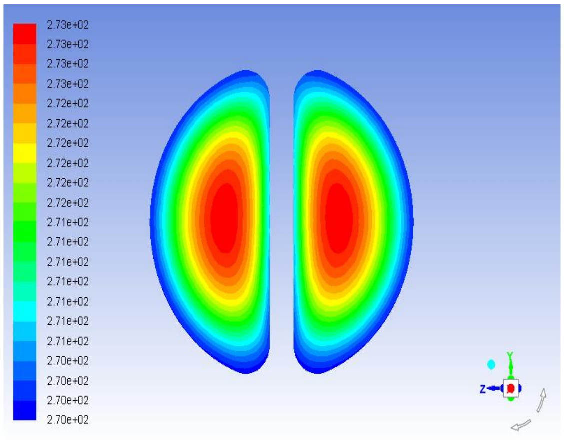


(f) One hole *T=263 K*

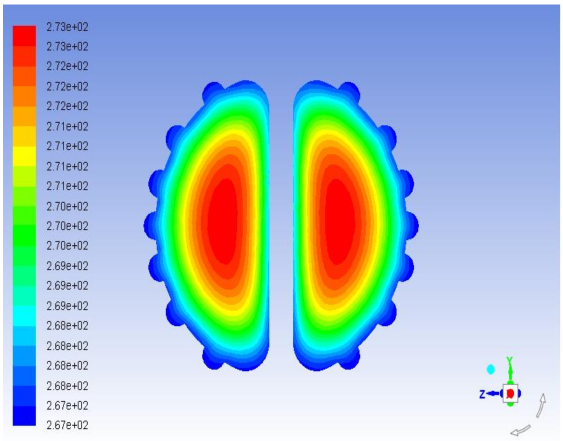
Figure 4.16. Temperature contour inside capsules for the fastest and the slowest charging time at *Q2* = $3.675\times10^{-3}\ m^3/s$



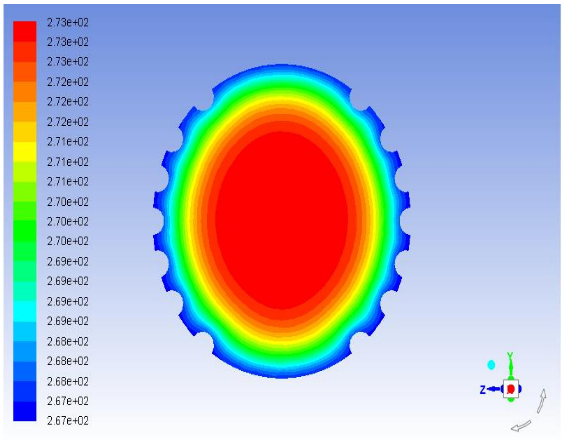
(a) Fin with hole *T=270 K*



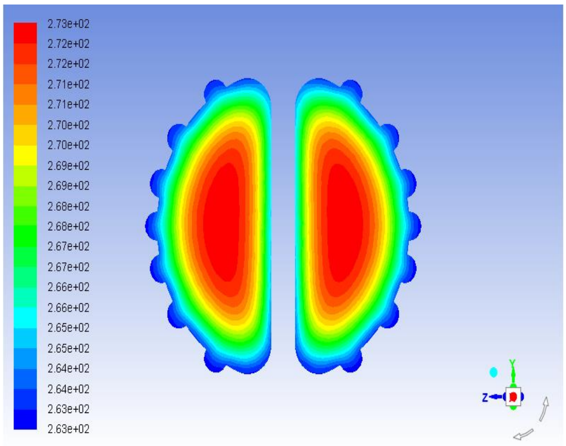
(b) One hole *T=270 K*



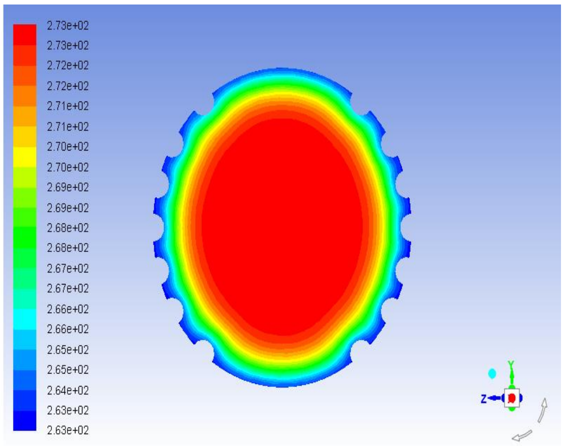
(c) Fin with hole *T=267 K*



(d) Reversed fin *T=267 K*



(e) Fin with hole *T=263 K*



(f) Reversed fin *T=263 K*

Figure 4.17. Temperature contour inside capsules for the fastest and the slowest charging time at *Q3* = $6.125\times10^{-3}\ m^3/s$

CHAPTER 5

CONCLUSIONS

Thermal energy storage TES is one of the most important and effective methods of storing energy. it has different ways to store large amounts of heat. One of the most promising concepts in this area is the concept of phase changing materials (PCM). These materials are able to hold large amounts of energy when changing from one phase into another. Such TES systems play an important role as a support system for cooling applications to solve the mismatch between supply and demand of electricity, and reduce peak load when electricity use is heavy and expensive. Ice thermal energy storage (ITES) systems are widely used to store cold capacity in many commercial applications. Ice storage systems are divided into static or dynamic , according to the way ice is delivered to the storage tank. As a static system, encapsulated ITES system has investigated in many researches due to a number of advantages, including its environmental and attractive economic benefits.

The solidification process of some common spherical encapsulated ice TES capsules is performed here using commercially available FLUENT 18.0 software for heat transfer and computational fluid mechanics. Six spherical capsules, including features in their respective form, are modeled to be in a test domain considering the test domain of the experimental study of ElGhnam et al. [29]. After extensive time step, grid size, and far-field boundary condition independence tests, the model was validated and found to be fully consistent with experimental results. Following this validation, simulations were performed while varying the flow rate and inlet heat transfer fluid (HTF) temperature. For all cases, the initial temperatures of the capsules were set at 283*K*. While the inlet HTF temperature was changed between 263*K*, 267*K* and 270*K*. Since the three flow rates, which were selected to be similar to real-world scenarios, were also studied, their impact on the charging processes was also recorded. In total, near 130 simulations were achieved on different computers with a set of computing speeds, and the arithmetic time exceeded 2800 hours to carry out all experiments.

Once these experiments were carried out, processes were inspected from thermodynamic principles to introduce a more factual look to the performance of each capsule. Detailed velocity and temperature analyses were studied to the processes in full, and gave a significant look into the overall performance of capsules. With these analyzes, a number of results can be drawn with respect to the effect of changes in capsule form on charging time, liquid mass fraction, and separation angle of HTF

For all cases, it was observed that solidification process was achieved faster by reducing the inlet HTF temperatures. Due to the large temperature gradients that exist between the HTF and capsule when the inlet temperature is reduced. Also, the flow rate had a significant impact on the charging times. As the volume flow rate increases, the full charging time is reduced. This is because of the convection heat transfer between the PCM and HTF would increase dramatically. Moreover, the full charging times varied significantly when the spherical capsule was changed. but it was surprising that no capsule has achieved the best heat transfer characteristics or the worst in all the cases. where at the low flow rates, the best heat transfer characteristics was appeared by the two holes capsule followed by the one hole capsule, fingered and fined with hole, and lastly the finned and reversed fin capsules which were the worst. Sequentially, as the HTF flow rate was increased, finned and reversed fin capsules were taken steps to provide better heat transfer properties

In studying the liquid mass fraction of PCM, it was first noticed that the average liquid mass fraction for capsules which have a hole changed more appropriately. While for the one that do not have a hole, the liquid mass fraction at the beginning was faster than that at the end of the solidification process. Due to the progressive ice layer formed as a buffer for the rest of the water contained in the center of the capsule while being overcome by a hole in the capsule that has one. In other words, the ice layers absorb the cold thermal energy as a sensible heat instead of being transferred to the rest of water to turn into ice. For that aspect, the capsule that solidifies late had an average total temperature less than the capsule that solidifies faster at the same operating conditions.

In terms of velocity and temperature analysis, since the water is contained in a closed capsule, the velocity of HTF was only considered. the velocity of the HTF directly below the capsule was almost zero. This is mainly due to the fact that a particular layer of HTF has a lower chance of escape due to obstruction created by the capsule wall and continuous collision with a new flow which almost hinders its movement. Also, as the flow rate increased, HTF separated early from capsule wall. Furthermore, fins or fingers made HTF to hang on the capsule wall as long as possible leading a higher separation angle. Temperature analysis was carried out for PCM only. The lower layer of capsules showed lower temperature than the upper layer or any other layer, as well as the peripheral layers of the capsules showed a lower temperature than the inner layers.

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