DESIGN AND CFD ANALYSIS OF THERMAL ENERGY STORAGE USING PCM FOR COOKING APPLICATION

A thesis submitted to the school of Mechanical and Industrial engineering in partial fulfillment of the requirement for the Degree of Master of Science in Mechanical Engineering (Thermal Engineering Stream)

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Declaration

I declare that the work in this thesis has been composed by me and this thesis entitled "Design and CFD Analysis of Thermal Energy Storage Using PCM for Cooking Application" is original work of my own, has not been presented for a degree or qualification of this or any other university or other institute of learning and all sources of information of this thesis have been acknowledged.

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APPROVAL SHEET

The thesis titled “DESIGN AND CFD ANALYSIS OF THERMAL ENERGY STORAGE USING PCM FOR COOKING APPLICATION” by Mr. Mengesha Alemu is approved for the degree of Master of Science in mechanical engineering (thermal Stream).

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Abstract

Nowadays there is a serious need for the development of the alternative, appropriate, cheap method of energy use of cooking. In Ethiopia, the majority of the population depends on biomass for cooking applications. However, to avoid this drawback, alternative energy is needed. Hence,the overall purpose of this paper deals with the design and analysis of thermal energy storage using solar salt combnation of 60%$NaNO_3$ and 40%KNO so as to avoid enrgy demand and supply problem. It provides a high energy storage density at a constant temperature which corresponds to the phase transition of phase change material (PCM). At the time of energy available from the solar source, a PCM energy storage technology is selected and designed which will be used for later cooking application.The basic design of the study was using steel materials as a tank (shell) for thermal energy sorage, copper tube encapsulated with PCM material. Heat transfer fluid(air) was selected for the model. In addition, two-dimensional Governing equations like continuity, momentum, and energy were discretized by using the finite volume method (FVM). Thus, all the transient 2D numerical simulations during the charging and discharging process were carried out using the commercial software CFDANSYS Fluent 17.2.As a result,a charging efficiency (70.1%) and discharging efficiency(36.9 %) was obtaind during simulation of thermal energy storage unit by using different mass flow rate. It was observed that the energy stored during charging (30096.47 KJ) and the discharged energy(83454.83KJ) were possibliy used for cooking.This energies were found to be a suitablel design for an indoor cooking application.

Nomenclature

A_{d1} area of air pipe (m^2)

A_{cs} cross sectional area of storage (m^2)

C_{ps} specific heats in the solid phases (KJ/Kg.^{0}c)

C_{pl} specific heats in liquid phases (KJ/Kg.^{0}c)

D_1 diameter of air pipe (m)

D_f diameter of void volume (m)

D_i inner diameter of storage tank (m)

D_{os} outer diameter of storage tank (m)

D_t diameter of total volume of fluid (m)

D_S diameter of storage (m)

dT change of temperature along storage (^{0}c)

dt change of time (s)

d_x distance step in along flow storage (m)

E_{dema} energy demand from stove (J)

$E_{in,flow}$ energy in flow during charging(J)

E_{store} energy during charging and discharging (J)

E_{loss} energy loss from stove (J)

$Eu(_{dema})$ energy demand per day(j)

g gravitational acceleration(m/s^2)

H total volumetric enthalpy (KJ/Kg)

h sensible heat (KJ/Kg)

ΔH specific enthalpy (KJ/Kg)

K thermal conductivity(w/mk)

Lpcm latent heat of pcm (KJ/Kg)

L,H_L length of storage (m)

m mass (Kg)

m_{pcm} mass of P_{pcm} (Kg)

$\dot{m}_a$ mass flow rate of air (kg/s)

n number of tube

P pressure (N/m^2)

Pr Prandtl Number

ΔP Pressure drop (N/m^2)

Q the quantity of heat stored (J)

R_F radius of void volume (m)

T_f final temperature in℃

T_i initial temperature in℃

T_{in} initial temperature (℃)

T_l temperature of the liquid (℃)

T_m melting temperature (℃)

T_s temperature of the solid (℃)

T_{htf} heat transfer tempreture (℃)

V_{a1} velocity of air in pipe (m/s)

V_{a2} velocity of air in storage (m/s)

V_{pcm} volume of pcm (m^3)

V_r velocity along radial(m/s)

V_z velocity along axial(m/s)

Greeks symbols

β liquid fraction

ρ_{a1} density of air in pipe (kg/m^3)

ρ_{a2} density of air in storage (kg/m^3)

ρ_{pcm} density of Pcm (Kg/m^3)

μ fluid viscosity ($N.S/m^2$)

ε void fraction (porosity)

Abbreviations

CFD Computational fluid dynamics

HTF Heat Transfer Fluid

LHS Latent Heat Storage

LHTES Latent Heat Thermal Energy Storage

PCM Phase Change Material

SHS Sensible heat storage

TES Thermal Energy Storage

Subscripts

cs cross section

f final

F fluid

htf Heat transfer fluid

i Initial

l Liquid

m melt

pcm PCM

S Storage

s sol

Chapter One

1. Introduction

Day to day the rapid increasing depletion of fossil fuel and collection of fire wood for house hold cooking purposes are one of majority problem like Ethiopia. This reducing the problem other alternative technology needed.Renewable energy is free and intermittent energy used but it is seasonal. Those problem reduce thermal energy storage the vital one. This chapter included such as background of over all the research, statement of problem, objectives of research, significance of the study, scope of research and limitation of research work. In addition to methodology of over all the research work that is theoretical calculation and design of the total storage unit, and numerical modeling simulation analysis.

1.1. Background of Study

Thermal energy storage is a technique used to balance the mismatch between energy demand and supply. From day to day, the ongoing and rapid increase in economic development worldwide is accompanied by strong demand for an uninterrupted supply of energy. Fossil energy sources are restricted and serious limited related with their stable supply and demand continue. Moreover,un wise use of fossil fuels is associated to be the release of harmful gases that in turn are responsible for climate change and environmental contamination.These greatest problem utilize different source of energy but Some experts and engineers all over the world are in search of new technologies that will lead to greater adoption of renewable energy sources **[1].** However, an important part of this question is un balance between energy source and demand. The main problem is not the lack of energy but rather it is to find ways of supplying sufficient amounts, in a usable form, when and where it is required **[2].**

As it is known to demand and supply mismatch are the greater problem, especially in developing countries like Ethiopia, which have nearly three-fourths of Ethiopia̓s population around 87 million depends on biomass fuel **[3].** But, till now 89.6% of Ethiopia’s energy demand was met from biomass fuels, with only 10.4% coming from modern energy sources (The biomass are mainly obtained from firewood, charcoal, cow dung and crop residues that mainly depend on the surrounding forest resources and agricultural residues. In such way using biomass energy for cooking and baking, to fulfill the gap between demand energy and supply**[4].**

Solar energy is available is seseonal, but its need non seseonal requires or thermal energy storage to collected excess heat during sunshine hours may be stored for later use during the night and cloudy day. Thermal energy storage can be classified as sensible heat storage (SHS), latent heat thermal energy storage (LHTES) and thermochemical storage. In sensible heat storage (SHS), the thermal energy is stored by raising the temperature of the storage material without undergoing phase transformation and therefore, the amount of energy stored is a function of the specific heat of the material, the temperature change, and the amount of storage material **[4]**. On the other LHTES involves phase transformation of the storage material from one state to another such as solid-liquid,solid-solid or liquid-gas and vise-versa when heated to the transformation temperature. A liquid-gas transition requires a large volume of material conduit while a solid-solid transition involves low energy storage density per unit volume of material.Therefore, the solid-liquid transition as applied to latent heat storage applications is more efficient compared with the other transformations and hence, is the most widely used. The third method of energy storage is the thermochemical storage, which involves reversible physicochemicall phenomena to store the thermal energy chemically and recovers the energy upon Supplying heat **[4, 5]**.On the other hand, some litreture tries to done thermal storage important for reduce energy fluctuating between supplay and demand, but mony technical problem associated to thermal energy storage for cooking purpose .These According to **Asfafaw et al [26]** made of experimental investigation and numerical simulation of thermal storage for injera baking purpose by using mixture of 60% $NaNO_3$ and 40% KNO_3 .Howaver,its technical problem for cooking like low thermal conductivity material using storage such as alminium and steam for heat transfer fluid.Due to this,mony problem come up using alminium thermal storage unit like less heat transfer (heat exchange) between phase change material (PCM) and steam for heat transfer fluid its corrosion the storage unit, low thermal stability and need large pipe due to high volume change.It consiquntly reducing thermal efficiency of storege.

Further more,this paper deals with designing and CFD analysis of thermal energy storege using phase change material (PCM) for cooking application.This research contribute to masimazing of thermal efficiency and reliability thermal energy storage using copper pipe serves as encapsulation matrial of pcm due to high thermal conductivity,mechanical stability and high corrosion resistance.Again using steel serves as shell material due to low thermal conductivity and air (hot) heat transfer fluid its easy avaliblity,thermal stability,need less pipe and less corrosion of storage material.Therfore, Using $NaNO_3$ – KNO_3 (60: 40. Mol %) or solar salt uses as one of the promising latent thermal heat storage at middle (23-220^{0}C) temperature for cooking application and the energy model in this work is analyzed with CFD ANSYS Fluent, due to its advantages when it comes to handling more than one variable with quite wide ranges of study. It has created as a simulation model with input parameters that execute calculations to eventually achieve the requested results as output parameters and contour graphs.

1.2. Problem Statement

Nowadays, Ethiopians have used energy like solar, geothermal,wind,biomass,fossil fuel, and electrical energy for different applications. Of these, biomass, fossil fuel, and electrical energy are used for cooking purposes. and 89.6% of Ethiopia's energy demand was met from biomass fuels, with only 10.4% coming from modern energy sources (The biomass is mainly obtained from firewood, charcoal, cow dung and crop residues that mainly depend on the surrounding forest resources and agricultural residues) **[6]**. In addition, lack of distribution electricity in urban and rural areas increase the price of fossil fuel which is one of major problem for cooking purpose in Ethiopia**.** However, due to this reason, an alternative way to find a renewable source of energy is the best solution most of application such as solar energy which is freely available source of renewable energy. On the other hand,in Ethiopia 0.004% of energy use is covered by solar thermal cooking mechanism even if the amount of user this technology in very low its comper to other types of energy sources**[7].** This source of energy technology is limited during the rainy and night time. And, during the applications, the out - door cooking has been applied to solve this problem, a thermal energy storage which is used in indoor application could be modeled and simulated.

1.3. Objectives

1.3.1 General Objective

The main objective of this research is to design and CFD analysis of thermal energy storage using PCM for cooking application.

1.3.2. Specific Objectives

To achieve the main objectives of research,work the following specific objectives are carefully carried out;

- Determine the amount of energy required/demand
- Identify heat transfer fluid (HTF)
- Select phase change material
- Identify thermal energy storage mechanism
- Modeling thermal storage unit

- Analytical design and CFD simulation of heat transfer within the storage during charging and discharging

1.4. Significance of the Study

The following are some of the significance of the study.

- To reduce collecting of firewood for the house hold
- To reduce the rate of desertification in our country
- To improve the living standard of society by using thermal storage cooker
- To reduce the cost of fuel by using thermal storage cooker
- Use the cooking during cloudy weather and night day
- To reduce the environmental pollution.
- To reduce the limitation of energy used

1.5. Scope of the project

Cooking application can have different form such as solar energy based and thermal energy storge using phase change material(PCM).The first one is working in the availability of sun's ray energy. But it does not cook in clouds and evenings. However,in thermal heat storage use store energy at day time using, it possible to cook both in cloudy and night day.Specifically, this research tries to do adesign and analysis of thermal storage for cooking application.It does not touch the solar design part. But it concerned on storage part.

The methodology of the research begins from searching the literature of its short comings.Base on the information gathered there comes the research gap that needed solution.This research work got complation by simulating 2D transient heat transfer analysis in CFD ANSYS Fluent software and the results will be discussed clearly.Therefor,the research focuse on thermal energy storage for cooking in the Ethiopia region.

1.6. Limitations of the study

The design and CFD analysis of thermal storage has been completed with certain limitations that come up in the actual activity included:

1. It was that the research has not tested experimental work since it is directed towards designing and analysis
2. The design is not geographically limited.The purpose was in order not to use solar data

3. It was the use of only CFD ANSYS Fluent software.It does not employ other software can simulating the storegy sufficiently
4. It does not design of solar part.It was design of storeg part

1.7. Methodology

The main research methodology of this thesis work generally followed literature survey. Besides the idea generated was supported by assessing different international journals, textbooks, and reports.After investigation these materials,the back up ideas of thermal energy storage was identified. Then mandatory statements and equations were collected.

In general thesis work is performed with two respective design and analysis methods:

1. Theoretical calculation and design of the total storage unit.In this analysis it is expected to reach the thesis objective.The storage materials such as phase change material, heat transfer fluid,storage tank,pipe or PCM encapsulate materials were chosen according to appropriate design criterial in ordre that it can possible to fullfil thermal heat storage unit.

2. Numerical modeling simulation analysis. In this governing 2D differential equations were desicretizing by finite volume method and time dependent transient simulation analysis of geometrical thermal heat storage using suitable CFD ANSYS Fluent software.

This thermal storage design important for Ethiopian population for cooking application.Its advantage cost free energy,use off sun shine cooking possible,non-envaromental impact and non-emssion gas.But the main dis advantage temporary store energy and not cost-effective in areas which have long periods of cloudy.

1.8. Outline of thesis structure

This thesis is composed of five parts. First it tries to introduce the role of back ground information thermal energy storage using phase change material for cooking purpose and over all research objective, scope and limitation of the research. In addition, the chapter explains the research and the methodology used.

Secondly, the studys introduce theoretical points on thermal energy storage concepts,detail discussion of different types of thermal energy storage and identification of thermal storage phase change materials(PCM).Among detail explanation of different litreture review technicals work on thermal energy storage.Finally at the end of the chapter discussion for selection phase change material (PCM) advantade and dis advantage presented.

Thirdly, the design and analysis of thermal storage for cooking application are discussed. This part focuses on design material selection,energy demand demand determination, quantifing amount of phase change material and modeling of thermal energy storage.Finally using CFD ANSYS fluent software simulation of the storage and detail calculation of charging/discharging efficiency of thermal storage.

The fourth part presents the different simulation results of thermal energy storage for cooking application. Discussion of these results and analysis of different mass flow ret brings contour graphs.

Finally, the brief summary of the whole process of the study, the main findings and conclusions, and the possible reccomendations for futue activities are listed.

Chapter Two

Literature Review

This chapter discuss different litreture review related thermal energy for cooking purpose.Those thermal energy storeg consept and type such as sensible heat storage,latent heat storage and thermo chemical heat storage. On the other hand,detail explanation of phase change material (PCM) for appropriat thermal energy storage system like organic PCM, inorganic PCM and eutectic mixture PCM. Finally,discussion of advantage and dis advantage of phase change material for this thesis design of thermal storage for cooking purpose.

2.1. Thermal Energy Storage Concepts

Energy storage can be reduce the time or rate of mismatch between energy supply and energy demand, it plays an important role in energy conservation.On the other hund, Developing efficient and inexpensive energy storage devices was important developing new sources of energy. Thermal energy storage (TES) is defined temporary storage of energy at high or low temperatures and not a new concept, it has been used for centuries.Howaver, technology of thermal energy storage has been developed to a point were it can have a significant effect on modern life for house holde for cooking.These variety of new techniques of thermal energy storage have become possible in the past such as Heat storage at power plants typically is in the form of steam or hot water.Threfore, major advantage of thermal energy storage was to maintain a constant temperature in dwelling, to keep it warm during cold winter nights,large energy densty with smaller volume change,non-emission gas,reducing limitation of energy used and need small space for store energy any cooking purpose **[8].**

2.2. Types of Thermal Energy Storage

2.2.1. Sensible Heat Storage (SHS)

Sensible heat storage is the most frequently used method for thermal energy storage. The heat is only stored by changing the storage medium temperature from an initial temperature (T_i) to a final temperature (T_f) without a phase change. Therefore, the amount of energy stored (Qs) depends on the mass of the medium (m), its specific heat capacity (C_p) and temperature variation (dT) as **[9,10,11]**:

$$Q = \int_{Tin}^{Tf} mCpdT \qquad (1)$$

Sensible heat storage may be classified in to two on the basis of heat storage medium liquid and solid medium storage depending on the application.Sensible storage systems can be Characteristics high thermal conductivity,high specific heat, high thermal stability, and low cost.Common sensible storage systems include cold or hot water storage, concrete slabs, molten salts, and certain synthetic oils.Moreover,advantages of SHS is that charging and discharging operations can be expected to be completely reversible for a limited number of cycles **[9, 10, 12, 13]**.

Liquid Sensible Heat Storage Media

With it may note that water has the highest specific heat capacity when compared to the other Materials. This property together with its wide availability and low price makes water as one of the most commonly used sensible heat storage materials. Besides its high heat capacity, water is non-toxic and non-flammable, and it allows for the possibility of simultaneous charging and discharging of the storage tank **[13, 14]**. In case of this, Liquids have several benefits including convective heat transfer and the ability to use the same fluid as a heat transfer fluid (HTF) and a storage medium **[13]**.

Solid Sensible Heat Storage Media

One of the most energy storage solid Media are rock, concrete, brick, metal and other storage material. In this case, rock or pebble bed storages are used for higher temperature sensible heat storage up to 1000℃ heat store. On the other hand Magnesium oxide (magnesia), aluminum oxide (alumina) and silicon oxide are refractory materials, and they are also suitable for high-temperature sensible heat storage. Bricks made of magnesia have been used in many countries for many years for storing heat **[14, 15]**. However, both solid and liquid systems tend to be prohibitively large. Some oils can have dangerously high vapor pressures and molten salts can be very reactive, expensive and containment **[13].**

2.2.2. Latent Heat Storage

Latent heat storage makes use of the latent heat of a material to store (or release) energy when the storage medium undergoes a phase change process **[9,13,16,17].** The latent heat storage can be subdivided into three main groups based on the type of phase transition utilized: solid-liquid,

liquid-vapor, and in a few instances solid-solid. Liquid-vapor storage is sometimes used by storing high-pressure high-temperature steam but is generally undesirable because of the dangers associated with storing high-temperature vapors under extremely high pressures and technical difficulties on the tank design (large volumetric variation).On the other hand, it would require significantly larger equipment because of the low density of the materials in the vapor phase **[12,13,16].** Solid-solid PCM do offer some advantages over solid-liquids including smaller volume changes, no leakage, and even lower potential for erosion, but have not been researched near as much as solid-liquid PCM and have not seen significant applications **[13].** Consequently, from the technical and financial point of view, the solid-liquid phase change is more interesting for heat storage purposes **[18].** The total amount of heat stored (Q_{LHS}) is equal to the enthalpy difference (ΔH) between the beginning and end of the phase change. Assuming a non-isothermal process, it can be expressed as follows **[9,11,12]**:

$$Q_{LHT} = \int_{\mathrm{Tin}}^{\mathrm{Ts}} mCps\, dT \; + \; ma_m h_m \; + \; \int_{Ts}^{\mathrm{T}m} mCpl\, dT \qquad (\mathbf{2})$$

T_i, and T_f represent the initial, phase change and final temperature of the storage medium, respectively. Cs represents the specific heat of the material in solid-phase while C_l corresponds to the specific heat in liquid phase.h_m is the latent heat of phase transition **[9.12].** Additionally, latent heat storage has the advantage of storing and releasing heat at nearly constant temperatures. Because sensible heat is stored in a temperature difference, the storage or release occurs over a broad temperature spectrum. But the nature of most phase changes allows heat to be stored or released at a nearly constant temperature. The most challenging design of Latent heat TES most classes of pure PCMs exhibit a low thermal conductivity, although the inorganic PCMs have relatively higher conductivity when compared to organic ones. Consequently, the low thermal conductivity leads to poor heat exchange between the PCMs and the heat transfer fluid (HTF).In addition, low thermal conductivities limit the rate of heat transfer in and out of storage, requiring special heat transfer enhancement or large, complicated, or expensive storage systems and heat exchanger designs **[13]**.

2.2.3. Thermo Chemical Energy Storage (TCS)

Thermochemical energy storage is the newest and least research from of thermal energy storage, offering the highest storage densities: up to ten times the storage densities of even latent heat storage reversible thermochemical storage involves storing energy in the endothermic formation of intermolecular bonds, and extracting that energy when the bonds are broken exothermically This type of storage can have extremely high storage densities **[9,13,18]**. The amount of energy stored (QTHC) depends on the amount of storage material (m), reaction heat (Δhr) and extent of conversion (ζ**) [9]**:

$$Q_{THC} = \zeta \, . \, m. \, \Delta hr \qquad \textbf{(3)}$$

Additionally, thermal energy can be stored in a THCS system for longer periods of time at ambient temperature or transported from one place to another without losses. Despite these advantages THCS systems are still under development state,no commercial applications are available. Advantages of TCS systems are still under development state, no commercial applications are available **[9,13]**.but has significant disadvantages. Most require storage of gases at dangerously high pressures and temperatures, some require potentially dangerous, flammable, or corrosive chemicals, and most require very high temperatures and the facilitation complex chemical reaction pathways **[13]**.

2.3. Phase Change Material (PCM) For Thermal Storage System

Different phase change material used for thermal energy storage In order to assess the potential of latent heat storage applications, a comprehensive review of the PCM physical properties during a phase change is critical. For comparative economic evaluation, market prices for industrial grade materials were used to provide a common approach. Of these, PCM can be classified into different groups and subgroups based on their composition. The most common division of PCMs is into organics, inorganics, and eutectic mixtures.

Organic PCM

Organic compounds, characterized by having carbon atoms in their structure, generally Subgroups of organic compounds include paraffin and no paraffin organics. Organic compounds present several advantages such as non-corrosiveness, low or no undercooling, possess chemical and thermal stability, the ability of Congruent melting, self-nucleating properties and compatibility with conventional materials of construction **[16,19]**. Technical grade paraffin has been widely used as heat storage materials due to wide melting and solidification temperature ranges and has a comparatively high latent heat volume. They are chemically stable, non-toxic and non-corrosive widely heat storage materials.Such using materials are lauric, myristic, palmitic and stearic acid.

Their advantages are opportunity for melting and solidification behavior and slight or no sub-cooling effects. Disadvantages of organic compounds consist of lower phase-change enthalpy, low thermal conductivity(from0.1to 0.7W/m K) and inflammability **[20]**.

Table 1: Organic materials possible of phase change material **[20]:**

Compound	Tm ℃	ΔH_m KJ/Kg	C_{ps} KJ/Kg k	C_{pl} KJ/Kg k	K_s W/ mk	K_l W/ mk	ρ_s Kg/ m³	$E_{density}$ Kwh/m³
Formic acid	8	277	1	1.17	0.3	0.27	1227	96
Acetic acid	17	192	1.33	2.04	0.26	0.19	1214	71
Lauric acid	44	212	2.02	2.15	0.22	0.15	1007	66
Stearic acid	54	157	1.76	2.27	0.29	0.17	940	49
Palmitic acid	61	222	1.69	2.2	0.21	0.17	989	67
Paraffin wax	0-90	150-250	3	2	0.2	-	280-950	50-50
Aceta mide	82	260	2	3	0.4	0.25	1660	93
Oxalic acid	105	356	1.62	2.73	-	-	1900	211
Eryhritol	117	340	2.52	2.61	0.73	0.33	1450	148
HYDPE	130	255	2.6	2.15	0.48	0.44	952	80
Phthalic anhydride	131	160	1.85	2.2	-	-	1530	85
Urea	134	250	1.8	2.11	0.8	0.6	1320	97
Maleic acid	141	385	1.17	2.08	-	-	1590	184
Adipic acid	152	275	1.87	2.72	-	-	1544	109
d-mannitol	165	300	1.31	2.36	0.19	0.11	1490	139
hydroquinone	172	258	1.59	1.64	-		1300	105

Inorganic Phase Change Material (PCM)

Inorganic materials are easily defined as materials that are not based carbon atoms. Mostly used in high temperature solar application. This includes salts, salt mixtures, salt hydrates, metals and alloy. The most advantages of inorganic compounds are a high volumetric latent heat storage capacity, frequently double the capacity of organic compounds and high thermal conductivity occasionaliy lower costs, higher temperature applications, and larger choices **[21]**. Also, Major problems with most of the salt hydrates are super cooling, phase segregation, corrosion and lack of thermal stability.in addition; super cooling in several salt hydrates has been prevented by adding nucleating agents, rotating storage devices and direct contact heat transfer have been used **[20]**.

Table 2: Inorgani serve as phase change materials **[20].**

compound	**Tm** ℃	**ΔH_m KJ/Kg**	**C_{ps} KJ/Kg k**	**C_{pl} KJ/Kg k**	**K_s W/mk**	**K_l W/mk**	**ρ_s Kg/m^3**	**$E_{density}$ Kwh/m^3**
Water	0	333	3.30	4.2	1.60	0.61	920	109
Calcium chloride hex hydrate	30	125	1.42	2.20	1.09	0.53	1710	64
Sodium sulphate delahydrat	32	180	1.93	2.80	0.56	0.45	1485	82
Sodium thiosulfat pentahydrate	46	210	1.46	2.39	0.76	0.38	1666	103
Sodium acetate trihydrate	58	266	1.68	2.37	0.43	0.34	1450	113
Barium hydroxide octahydrate	78	280	1.34	2.44	1.26	0.66	2180	171
Magnesium nitrat hexahydrat	89	140	2.50	3.10	0.65	0.50	1640	74
Oxalic acid dihydrate	105	264	2.11	2.89	0.90	0.70	1653	133
Magnesium chlor-de hexahydrat	117	150	2.00	0.70	0.70	0.58	1570	72

Eutectic Mixture

A eutectic mixture of two (“binary” mixtures) or three (“tertiary” mixtures) different components is the mixture that results in the lowest possible melting point, each of which melts and freezes congruently forming a mixture of the component crystals during crystallization.Of these, nearly always melts and freezes with out separation since they freeze to a close mixture of crystals, leaving little opportunity for the components toseparate.On melting, both components liquefy simultaneously, again with separation unlikely **[13,17,23].** But this alleviates the problems many salts, salt hydrate, and metallic mixtures have with segregation and incongruent melting. However, eutectic mixtures can be costly, need to be perfectly mixed, and still carry many of the other disadvantages of salts, salt hydrates, and metallic **[13].**

Table 3: Eutectic mixture possible phase change materials **[20].**

Eutectic compounds	Mass ratio	Tm ℃	ΔH_m KJ/Kg	C_{ps} KJ/Kg k	C_{pl} KJ/Kg k	K_s W/ mk	K_l W/ mk	ρ_s Kg/m^3	$E_{density}$ Kwh/m^3
$CaCl_2$(H2O)6$MgCl_2$(H2O)6	67-33	25	127	1620	2270	930	550	1661	157
Urea CH3COONa(H2O)3	60-40	30	200	1750	2210	630	480	1370	74
Urea-acetamide	38-62	53	224	1920	2660	510	340	1216	73
Stearic acid palmitic acid	36-64	53	182	1720	2230	234	169	971	46
LiNO3MgNO3(H2O)6	14-86	72	180	2380	2900	700	510	1713	84
LiNO3–KNO3	34-66	133	150	1170	1350	960	520	2018	82
KNO3–NaNO2	56-44	141	97	1180	1740	730	570	1994	52
KNO2–NaNO3	48-52	149	124	1050	11630	580	520	2080	70
LiNO3–NaNO2	62-38	156	233	1570	1910	1120	660	2296	143
LiNO3–KCl	58-42	160	272	1260	1350	1310	590	2196	161
HCOONa–HCOOK	45-55	176	175	1150	930	630	430	1913	92
LiOH–LiNO3	19-81	183	352	1600	2000	1330	690	2124	202
LiNO3–NaNO3	49-51	194	262	1350	1720	870	590	2317	165
LiNO3–NaCl	87-13	208	369	1540	1560	1350	630	2350	235

KNO3–KOH	80-20	214	83	1030	1350	880	540	1905	43
KNO3–NaNO3	55-45	222	110	1010	1490	730	510	2028	61
LiBr–LiNO3	27-73	228	297	1340	1380	1140	570	2603	196
NaNO2–NaNO3	55-45	233	163	1310	2130	590	640	2210	97
CaCl2–LiNO3	13-87	238	317	1500	1530	1370	690	2362	204
LiCl–LiNO3	9-91	244	342	1580	1610	1370	640	2351	218
NaNO3–NaOH	86-14	250	160	1190	1860	660	600	2241	97

2.4. A phase Change Material Used For Cooking;

Buddhi and Sahoo [22] designed and tested a box-type solar cooker by using commercial grade stearic acid (melting temperature 55.1℃; latent heat of fusion 160kJ/kg; thermal conductivity 0.172 W/m℃ for liquid; Density847kg/m^3) as a PCM to store latent heat because of its low cost and large availability in the market. The made of aluminum absorbing plate‘A’ of dimensions 0.28 x 0.28 m at the bottom, 0.40 x 0.40 m at the top for the double glass lid, and the vertical depth of the tray is 0.08 m, the thickness of the aluminum sheet was 0.006 m. In the center of the absorbing plate, a cylindrical container of 0.165 m diameter and 0.02 m in depth has been welded. Moreover, aluminum fins were also provided at the inner side of the tray and cylindrical container and the outer tray ‘B’ of size 0.40 x 0.40 x 0.108 m is also made from the same aluminum sheet. With 3.5 kg Phase, change material was filled below the absorber plate.These two trays were encased in an aluminum box of dimensions 0.5 x 0.5 x 0.14 m.In experimental procedure with cooking load and without cooking load were recorded by using calibrated copper thermocouples. The experimental result shows that late evening cooking can be possible and result compared with the conventional type of solar cooker.The main problem of this research selection of storage materialand low tempreture rang of PCM.On the other hand,**Sharma et.al [23]** designed, developed and evaluated storage performance of box solar cookers with a latent heat storage units for evening cooking. He used commercial grade acetamide (melting point 82℃; latent heat of fusion 263kJ/kg; Specific heat 1.94 kJ/kg℃ ;thermal conductivity 0.5 W/m℃; density of solid 1159 998 kg/m^3; density of solid 998 kg/m^3) and designed concentric cylindrical vessel for thermal energy storage unit.It was design two hollow concentric aluminum cylinders of diameter 18 cm and 25 cm and 8 cm deep of 2 mm thickness and the space between the cylinders were filled with PCM. In deed,8 fins (1x3) were welded at the inner wall of the PCM to heat transfer between the PCM and the inner wall of the PCM container.To experiments were conducted using performance with the PCM cooker compared with a Reference solar cooker the Cooking by different loading times. He showed that cooking food can be possible in the evening with phase change material (PCM) storage unit and the storage of solar energy does not affect the performance of the solar cooker for noon cooking .The main problem of this research selection of suitable thermal storge material,low rang tempreture range of PCM and geometry of storage. According to **Yakoob Kolipak et.al [24]** Development Solar cookers with latent heat storage system using phase change materials (PCM). He used Paraffin wax (the melting point between about 46 and 68 ℃, latent heat of fusion 200-220kJ/kg, the density of 900 kg/m^3) Phase change Material (PCM).It was made cross-section of iron box 420mm x 420mm x 100mm, and the thickness of the iron is 1 mm. The result obtained of temperature 156℃ with a range of around 95℃ to 170℃. Finally,cam up using Paraffin wax the night cooking also can be possible. The main problem of this research chosen of phase change material(PCM), low thermal condectivity material and appropriet geometry of thermal storage.

Saxena et.al [25] investigated different PCMs to find out their suitability as thermal energy storage (TES) for cooking purposes using a box-type solar cooker.Two similar design solar cookers were considered (cookers A & B), they consist of a double-walled box and made of Al sheet. The specific dimensions of the outer and inner box were approximately 540 × 540 ×160 mm^3 and 455 × 435 × 65 mm^3. The space between the outer tray and outer box was filled with glass wool.Due to this ,the inner tray and outer boxes were painted dull black to absorb maximum solar energy. The leakage from the box to the surroundings was minimized by having a rubber gasket (1.5 mm thick) in between the double glass cover (10 mm glazing) and the box. The absorber trays of both cookers were painted black on both sides and designed to be kept at least two cooking vessels of Al alloy of 16 cm diameter (with a height of 9 cm & 0.5 mm thickness) inside the cookers for cooking. Stearic acid was selected as an appropriate phase change material and used in solar box cooker.The experiments, with and without the heat storage. Finally, suggested that cooker with heat storage showed good performance of cooking like rice, beans, pulses, and fish with a good possibility. The main problem of this research chosen coteiner pcm material , lack of heat transfer fluid and geometry of storage.

Asfafaw et al [26] made of experimental investigation and numerical simulation of thermal storage for injera baking purpose by using mixture of 60% $NaNO_3$ and 40% KNO_3 (melting point

222℃; latent heat of fusion 108 kJ/kg; thermal conductivity 0.8 W/m℃; The density of the PCM varies from 1800 to 1700 [kg/m^3] in the course of phase change from solid to liquid) phase change material and Steam serves heat transfer fluid (HTF). Due to this, the storage unity was made of aluminum block serves fin and container and storage unit 10 salt cavity the same size 0.032 m diameter and 0.15 m height were provided, which is coupled to parabolic dish collector of 1.2 m diameter, 0.48 m focus length and a mirror reflector. He used for the experiment carried out the thermal storage loaded with 2 Kg of solar salt for 4.5 hours charged and numerically simulated by COMSOL.Results showed that the experimental and COMSOL charging of the storage gave a similar result. Finally, injera baking requires temperature of 135 -160℃ well cooked.The main problem of this research chosen appropriate heat transfer fliud and low thermal conductivity at phase change material (PCM). **Cheew who Foong [27]** has done numerical investigation of a small scale direct solar thermal energy storage system. He also interesting to known that nitrate salt (mixture of 60% NaNO3 and 40% KNO3) phase change material for utilizing thermal energy storage cooking purpose as melting temperature is in suitable range.In addition,the storage unit consists of a container of 0.19 m internal diameter, 0,2 m height, thickness 0.005 made of stainless steel and aluminum fin.In case of this, performance of storage experiment carried out by variation gaps between consecutive aluminum fin with in phase change material, and thermal behavior of salts was studied with differential scanning calorimeter (DSC).Moreover, numerical simulated based on effective heat capacity method used comsol.He comes up result showed that the effective of convection heat transfer with in the PCM can be neglected when the volume of PCM in between the fin is small and increase of efficiency of storage medium.The main problem of this research chosen low thermal conductivity material used in PCM side and effective heat capacity method in stead of enthalpy method for boundar condition. **According to Sulaiman and Inambao [28]** based on their studies on development of thermal energy storage and cooker module by using mixture of (60 % sodium nitrate and 40 % potassium nitrate) phase change materials (PCM) which at melting point 224 °C .Due to this, the storage unit was constructed from steel cylindrical heat storage pipe using diferent diametr, height and stainless steel was used for experiment. For this heat storage system the oil was heat transfer fluid and rock wool insulation material.The experments were made different quantity PCM and being twelve J-type in different positions.Finally,come up with the conclusion that the results of heat charge/discharge experiments using vertical heat exchange unit showed that the available enthalpy bounding the phase conversion temperature range was not quantitatively affected by the way the temperature of the thermal medium varied during heat charge and discharge.To permit passable heat flow during fast cycles of heat charging and discharging the heat transfer coefficient between the thermal medium and phase change material wantes to be increased.The main problem of this research appropriate heat transfer material and heat transfer fluid(HTF)chosen.**According to J.Vogel etal [29]**made Experimental investigation and numerical model study of flat plate latent thermal energy storage system using a mixtureof solar salt 46%NaNO3-54%KNO_3 (melting point 222℃; latent heat of fusion 108 kJ/kg; thermal conductivity 0.46 W/m℃; The density of the PCM 1959 kg/m^3 and heat capacity 1492J/kgk) phase change material.Due to this, thermal oil serves heat transfer fluid (HTF) and steel serve container material. Moreover, boundaries condition top and bottom of container are adiabatic as heat losses are minimized with a sufficient insulation.It was study various width and heights of flat plate influence of rectangular enclosures were compered to each other. Finally, observe at smallest width heat transfer high and at smallest height heat transfer high by using simulation of ANSYS fluent. The main problem of this research appropriate heat transfer material and heat transfer fluid(HTF) chosen and geometry.in addition to relatively high cost of PCM. **Sebastian Kuboth etal [30]** made Numerical Analysis of Shell-and-Tube Type Latent Thermal Energy Storage Performance with Different Arrangements of Circular Fins using phase change material of RT42 (melting point solid to liquid 40-44℃; latent heat of fusion 176 kJ/kg; The liquid density of the PCM 760 kg/m^3 and heat capacity 2 J/kg k) and water serves heat transfer fluid (HTF). In this storage elements of one-meter length, outer storage element diameter of 40 mm, inner tube diameter of 10 mm, the pipe wall thickness 1mm and the width of the fins was 1mm its was made of copper block act as find and container. Moreover, fins can be included into the storage unit to improve the charge and discharge power.Due to this, the storage could be simulated using a 2D model and all material possessions were established in conformity by the MATLAB Simulink model.The boundary conditions of both the ANSYS Fluent and the MATLAB Simulink model were set adiabatic to ensure heat loss independency. Result observe vary using different storage types mass flow rates, heat transfer coefficient between the fluid and the tube might and the effect of fin arrangement modification which have impact of result.Finally, in order to validate the results, appropriate thermal energy storage was set up in ANSYS Fluent and latent thermal storage show that fin allocation affects storage performance. The main problem of this research appropriate heat transfer material(container) and water serve heat transfer fluid(HTF) chosen and low tempreture range of

PCM.**According to Elias Wagari Gabisa etal [31]** investigated characterization and experimental investigation of NaNO3:KNO_3 as solar thermal energy storage for possible cooking application. In this study 60% $NaNO_3$ and 40% KNO_3 as using different mass ratio are going to be examined to know at which mass ratio of the top thermal characteristics will found those mass ratio.He prepared salt mixture were 12g: 8g $NaNO_3$:KNO_3, 10g: 10g $NaNO_3$:$KNO_{3,}$ 8g: 12g $NaNO_3$:$KNO_{3,}$ 4g: 16g $NaNO_3$:KNO_3 and 16g: 4g $NaNO_3$:$KNO_{3.}$ analysis was performed using PerkinElmer DSC 8000 instrument with an accuracy of 0.01mw and 0.05℃ respectively, with temperature rang 0f 100- 500℃ and density of liquid $NaNO_3$:KNO_3 mature was determined using pycnometer (ASTM-148-02 92007).In order to know the solar thermal energy charging and discharging was conducted in the research grade laboratory of facility of chemical and food engineering and the PCM 99.9% purity using. Final result showed that the experimental and ANSYS charging of the storage gave a similar result of those sample of solar salt. But, it is indicated that the melting point of the sample 60:40 ratio is of solar salt 225.38℃, the heat absorbed per gram of the sample as a latent heat is 120.9100J/g, and specific heat capacity of the sample in the solid area is around 6J/g ℃. The specific heat increases with the temperature in the liquid region and it is around 10J/g℃ in the required temperature range (200–300℃) for cooking application; it makes it more better and highly favorable for thermal energy storage.The main proble of this research no chosen of appropriate software for simulation of PCM.

Ftwi Y. Hagos etal[32] design and investigation heat loading process of thermal energy storage of a transient simulation on heat energy distribution for cooking application by used mixture of $NaNO_3$ and KNO_3 PCM and he designed cylindrical shape of Thermal Energy storage units are 0.25 length of copper tube, 0.015 diameter of copper tube,0.3 diameter and 0.35 length of stainless steel stored tank.in this case, XCELTHERM MK1 serve the heat transfer fluid flow through the PCM medium in the tank. The mechanism of heat exchange and the melting distribution of PCM Numerical 3D simulation were performed using ANSYS FLUENT software in a transient state. Finally come up The PCM usage in medium range heat energy storage have a great potential in solar cooking applications.The main problem of this research heat transfer material selection(HTF)

Regarding litreture survey appropriat thermal storage phase change materials are organic,in organic and eutectic its own advanteg and dis advantage.Moreover,organic phase change material are advantage low cost,chemical stable,non-corrosion and dis advantages are low thermal condectivity,not sharp melting and flammebl.In contrast in organic phase change materials are adevantege high thermal condectivity,high energy storage with small volum change and dis advantage corrosion,no thermal stable,high cost. However,Eutectic PCM suitable thermal storage like solar salt that is a combination of 60% $NANO_3$ and 40% KNO_3 and the major advntege over other PCMs are high thermal condectivity,high energy density storage with small volum change, low envairomantal impact and sharp melting.But,dis advantage corrosion,no thermal stable, high cost comper to organic.Among based on advantage and dis advantage chosen better PCM as 60% $NANO_3$ and 40% KNO_3 for this work.

Chapter Three

3. Design And Analysis Of Thermal Storage For Cooking

The following different techniques are applied to achieve the specific objectives which is mentioned before.Among this technique, the first and most methodology that used to do the research is information that was gathered from different literature about thermal energy storage technologies. Study on mechanisms of thermal heat storages using PCM materials using air as heat transfer fluid.Design and analysis thermal heat storage system for cooking application and the numerical simulations during charging-discharging were performed using CFDANSYS Fluent software.

3.1. Design And Material Selection

3.1.1. The Heat Transfer Fluid Selection Criterial

Water is cheap and readily available. It does exhibit excellent heat transfer properties. But it is unsuitable at high temperature like, 200°C -300°C the heat transfer fluid in this range because it vaporizes at 100 ºC at atmospheric pressure, although it has a high specific heat, non-toxicity and easy availability. Pressurizing the system will increase the boiling point but even increasing the pressure to 15 bar will only raise the boiling point to 200 °C. Furthermore, high pressure piping and tanks would be required, which are expensive **[28].** Also, many molten salt used industrial heat transfer fluid purpose like concentric power plant because effective heat transfer to the plant up to temperatures 500 ºC, but most of salts are unstable and corrosion.On the other hand, some of the oils heat transfer fluid used, but oils is tend to degrade with time. Its degradation is particularly serious if they are used above their recommended temperature limit. It disadvantages the use of oils also presents safety problems since there is a possibility of ignition above their flash point **[32].** However, air is cheap, easly available, Stability and no handling complexity Due to this reason air is the best heat transfer fluid.therefore, choice of heat transfer fluid will be based on the following principles**[33]** :

- Availability: this principle decides the commercial foundation of HTF.
- Stability:this principle shows the stability of the heat transfer fluid at working temperature over the lifetime

- Handling complexity: this principle detects the handling of the HTF in the system and wither its likely or not.
- Phase change temperatures & vapor pressure: this principle indicates wither the HTF sets the system working temperature and pressure.

3.1.2. Suitable Selection For Phase Change Material (PCM)

One of the most presently used thermal energy storage mixture consists of 60%$NaNO_3$ (sodium nitrate) and 40%KNO_3 (potassium nitrate). Moreover, the selection of PCM to be used in Latent storage materials integrated in the TES system should be chosen by series under several needed constraints to maximize the amount of energy stored and to obtain the best efficiency. Regarding melting point temperatures, solar salt (nitrate salt mixture 40% KNO_3 and 60% $NaNO_3$). Different PCM will be chosen to match different HTF temperatures **[11, 27,33 34,35]**:

Thermo-physical Properties

- High latent heat of fusion: represent the need of high variation in the enthalpy produced when heat is applied to change the material phase at a constant pressure.
- Melting temperature in the desired operating temperature range: it characterize wanted melting point with out degradation of materials.
- High thermal conductivity of both solid and liquid phases to assist the charging and Discharging of energy of the storage systems : Its indicate the material fast rate in conducting the heat to other substances.
- High specific heat:it represent provide for additional significant sensible heat storage absorve during melting prosess.
- Low volume change due to the phase change: to fulfil high energy density store with somall volume change.
- Congruent melting: to ensure that the PCM will melt and solidify in equal and uniform compositions.

Kinetic Properties

- High nucleation rate to avoid super cooling of the liquid phase: the criteria of avoiding liquefying below its boiling point.
- Avoid super-cooling: the criteria of avoiding to solidify above the meting point

Chemical Properties

- No chemical decomposition, so that TES system life is assured: represents avoiding to be destroyed during the process of phase change.
- Non-corrosiveness to construction material: this insures that the material will not damage or destroy other substances that are in contact with along high temperature and high-pressure cycles.
- Long term chemical stability: represent of how stable is the material when exposed to different chemical variations in its surrounded environment.
- Nonpoisonous; Non-toxic: represent the requirement of not causing harm on the environment society and organism.
- Non-flammable: to ensure that the material doesn't burn or cause combustion.
- Compatible: represents the ability of the material to exist with used design materials without any problems.

Physical properties:

- Density : Density and the change in density during phase transition are two serious physical properties forphase change materials. High density is preferable to allow a smaller size of storage container. However, lower hydrates, with fewer water molecules coordinated to the PCM, are more dense than materials with higher hydration levels, yet they have lower heats of fusion, i.e.,less storage capacity. The two factors must be balanced in choosing a storage material.PCM heat storage systems encounter difficulties when there is density change during phase transition**[28].**

Economic properties:

- Availability: this principle determines the commercial availability of components and material.
- Commercially available at low cost Cost effectiveness: this principle studies the cost of benefits in terms of money and examines either it is needed or not

3.1.3. Thermal Storage Material

Tubes or Pipes Material

Thermal storage Pipes are in contact with both HTF and PCMs so the compatibility with both materials should be considered. Moreover, to maximize heat transfer between HTF and PCM, pipes material should have high thermal conductivity,mechanical stability and corrosion resistance must be considered to handle HTF pressure as well as thermal expansion since the system operates at high temperature. The commercially available pipes that satisfy these properties used are copper due to high thermal conductivity satisfy TES systems for accelerating the charging and discharging processes **[33,36]**.

3.1.4. Thermal Heat Storage Insulation Material

Shell of heat storage should be well insulated to avoid heat losses to the surroundings.There are many types of insulation material with different properties.For high temperature systems, a material that has high melting temperature, low thermal conductivity and efficient cost must be selected. Many of these insulation materials have own characteristics. As a result, determining which insulation material needed or which material shoud work the best in your condition. Its have considered widely commercial available and manufactured in different forms such as rolls, rigid slabs and mastic.Moreover, they are environmentally friendly,inflammable and does not melt **[37].** Reggarding the maximum operating temperature fiber glass insulations were used to insulate the storage.The insulations maximum working temperature is about 540℃ and the design thickness of 30mm for the heat storage and pipe and The insulations thermal conductivity is 0.04W/Km **[37,38, 39]**.

Table 4: Thermo -physical property of the $NaNO_3$ - KNO_3 eutectic salt (60 : 40 mol %) **[26, 27]**

Parameter	Values	Units
Thermal conductivity	0.8	W/m k
Density >220^0c	1700	Kg/m^3
Density <220^0c	1800	Kg/m^3
Enthalpy of fusion	108.67	KJ/Kg
Phase transition Enthalpy	31.91	KJ/Kg

The Amount of energy required for 10 people per day per household used for cooking can be calculated as follows. And depending on the energy demand, the design of thermal storage has been carried-out.

3.2. Energy Demand Determination

Energy demand for each house hold can be calculated as

$$Q_1 = mC_p(\Delta T) \quad (4)$$

$$Q = mC_p(T_f - T_i) \quad (5)$$

Where, C_p=specific heat in KJ/Kg℃

m=mass in Kg

T_i= initial temperature in℃

T_f = final temperature in℃

The amount of water to be boiled is16 liters

Initial temperature of water can be Ti = 25℃

Final temperature of the required boiling water T_f = 100℃

Specific heat capacity of water C_p = 4.2 KJ/Kg℃

Then, calculate the amount of heat needed in house hold for boiling water;

$$Q_1 = mC_p(100℃ - T_i)$$

$$= m\,[C_p(100℃ - T_i)]$$

$$= 16\,kg\ \ [4.2\,KJ/Kg℃\ (100℃ - 25℃)]$$

$$= 16\,kg\ \ [4.2\,KJ/Kg℃\ (75℃)]$$

= **5.1MJ**

The amount of cooking pea required in house hold can be 2 kg

Initial temperature of water Ti = 25℃

Final temperature required for cooking pea split T_f = 170℃

Specific heat capacity of pea split C_p = 1.17 KJ/Kg℃

Then, calculate the amount of heat needed for cooking pea;

$$Q_2 = mC_p(170℃ - T_i)$$

$$= m\,[C_p(170℃ - T_i)]$$

= 2 kg [1.17KJ/Kg℃ (170℃ − 25℃)]

= 2 kg [1.17KJ/Kg℃ (145℃)]

= 0.344 MJ

The amount of baking bread required for each house hold is 20 Initial temperature of the water Ti = 25℃

Final temperature required for baking bread T_f = 180℃

Specific heat capacity of flour C_p = 1.59 KJ/Kg℃

Calculate the amount of heat needed in house hold for baking bread can be;

$$Q_3 = mC_p(180℃ - T_i)$$

$$= mC_p(180℃ - T_i)$$

$$= 0.2x20kg \ [1.59KJ/Kg℃ \ (180℃ - 25℃ \ )]$$

$$= 4kg \ [1.59KJ/Kg℃ \ (155℃ \ )]$$

$$= 1.00MJ$$

Table 5: Energy demand for 10 people per day

No	Item	Amount	Temperature	Energy
1	Boiling water	16 litter	25 to 100^{0}c	5.1 MJ
2	Cooking pea	2 kg	25 to 170^{0}c	0.344 MJ
3	Baking bread	20 bread	25 to 180^{0}c	1.00 MJ
4	Other spaice	-	25 to 100^{0}c	3.456 MJ
5	Total	-	-	10MJ

From traditional mirt stove considering during cooking food energy has an efficiency of of 10 to 50% **[40]**. Therefore, considering 40% efficiency, the total energy demand ($E_{t(dema)}$) can be calculated as follows.

$$E_{loss} = \frac{10 \ MJ \ x \ 0.6}{0.4}$$

$$= 14 \ MJ$$

Total energy demand ($E_{t(dema)}$)

$$E_{t(dema)} = E_{u(perday)} + E_{loss}$$

$$= 10MJ + 14MJ$$

$$= 24MJ$$

Where, E_{loss} = energy loss from stove

$Eu_{(dema)}$ = energy demand per day

E_{dema} = energy demand from stove

3.3. Quantifying the Amount Of PCM

The PCM melting temperature is 220℃ and it has 108.67 KJ/Kg heat of fusion **[9]**. The amount of PCM is determined based on house hold energy demand. For, Q = 24MJ of energy, the mass of PCM required can be given as **[26]**:

$$Q = \int_{Ti}^{Ts} mC_{ps}\, dT + m_{am}h_m + \int_{Ts}^{Tm} mC_{pl}\, dT + \int_{Tm}^{Tl} mC_{pl}\, dT + \int_{Tl}^{Tf} mC_{pl}\, dT \quad \textbf{(6)}$$

$$Q = m\,[C_p(T_m - T_i) + m_{am}h_m + C_{lp}(T_f - T_m)] \quad \textbf{(7)}$$

In general $Q = \int_{Tin}^{Tf} mC_p\, dT$ (**8)**

$$C_p = \text{KJ/Kg} \begin{cases} 0.75 & \text{if } T < 110℃ \\ 4.2 & \text{if } 110℃ \le T \le 120℃ \\ 1.4 & \text{if } 120℃ < T < 210℃ \\ 12 & \text{if } 210℃ \le T \le 220℃ \\ 1.6 & \text{if } T > 220℃ \end{cases} \quad \textbf{(9)}$$

$$Q = \int_{23}^{109} mC_{ps}\, dT + ma_m h_m + \int_{110}^{120} mC_{pl}\, dT + \int_{121}^{209} mC_{pl}\, dT + \int_{210}^{220} mC_{pl}\, dT \quad \textbf{(10)}$$

$Q = m_{pcm}[0.75(109- 23) + 4.2(120 -110) + 1.4(208-121) + 12(220-210) + 1\times108.67]$

$= m_{pcm} [64.5 + 42 + 121.8 + 120 + 108.67]$

$= m_{pcm} [456.97]$

Where Q = 24MJ of energy required

$24MJ = m_{pcm} [456.97]$

Rearranging the equation and gets the mass of PCM.

$$m_{pcm} = \frac{24000kj}{456.97kj/Kg} = 52.52 \text{ Kg}$$

$$V_{pcm} = \frac{mpcm}{\rho pcm} = \frac{\mathbf{52.52\ kg}}{\mathbf{1700kg/m3}}$$

$V_{pcm} = 0.03089\ m^3 = 30.89$ liter

Where,

Q = the quantity of heat stored (J)

m_{pcm} = mass of P_{pcm} (Kg)

V_{pcm} = volume of P_{pcm} (m^3)

C_{ps} = specific heats in the solid phases (KJ/Kg.^{0}c)

C_{pl} = specific heats in liquid phases (KJ/Kg.^{0}c)

h = enthalpy of phase fusion (KJ/Kg)

T_m = melting temperature, (℃)

T_s = temperature of the solid (℃)

T_l = temperature of the liquid (℃)

T_{in} = initial temperature (℃), and

ρ_{pcm} = density of P_{pcm} (Kg/m^3)

3.4. Encapsulation Of Phase Change Material

The PCM is encapsulated in cylindrical tube which are ensure a best heat exchange between the surrounding heat transfer medium and the PCM.Due to this, Inside the storage tank copper will be encapsulation material a mixture of sodium and potassium salt of phase change material. It will be holding solid and liquid of salt during charging and discharging. Moreover, during charging (melting of PCM) volume is expanded in case ten percent (10%) clearance volume was needed **[26]**.

Total volume of PCM during charging (melting) clearance volume 0.1;

$V_{total} = V_{pcm} \times 0.1 + V_{pcm}$

$= 30.89$ liter $\times 0.1 + 30.89$ liter $= 33.98$ liter

$= 0.03398 m^3$

Table 6: Standard size of copper tube **[41].**

Nominal or standard size inch	Outside diameter		In side diameter		Well thickness	
	inch	mm	inch		inch	mm
1/4	.375	9.525	.315	8.255	.030	0.71
3/8	.500	12.7	.430	10.922	.035	0.9
1/2	.625	15.875	.545	13.843	.040	1
5/8	.750	19.05	.666	16.9164	.042	1
3/4	.875	22.225	.785	19.939	.0.45	1.1
1	1.125	28.575	.1.025	26.035	.050	1.3

1 1/4	1.375	34.925	1.265	32.131	.055	1.4
1 1/2	1.625	41.275	1.505	38.227	.060	1.4
2	2.125	53.975	1.985	50.419	.070	1.5
2 1/2	2.625	66.675	2.465	62.611	.080	2
3	3.125	79.375	2.945	74.803	.090	2.3
3 1/2	3.625	92.075	3.425	86.995	.100	2.5
4	4.125	104.775	3.905	99.187	.110	2.8
5	4.125	130.175	4.875	123.825	.125	3.2
6	5.125	155.575	5.845	148.463	.140	3.5
8	6.125	206.375	7.725	196.215	.200	5.1
10	8.125	257.175	9.685	244.475	.250	
12	12.125	307.975	11.565	293.751	2.7	

3.5. Size of Copper Tube

For ¾ inch of nominal size of copper tube for the given volume of PCM + Clearance for expansion;

V_{total} = 33.98 litter = 0.03398m^3

$V_{pcm} = n \times V_{pipe}$

V_{pipe} for the selected data **[42]**:

$V_{pipe} = \frac{\pi Di^2}{4} \times L$ L = 0.25m

$V_{pipe} = \frac{\pi (0.019939m)^2}{4} \times 0.25m = 0.00007806145\ m^3$

Number of tube (n);

$$n = \frac{Vpcm}{Vpipe} = \frac{0.03398\ m^3}{0.00007806145\ m^3}$$

= 435 copper pipe needed

By considering 0.4 void fraction and calculate the total volume of tank

$V_{pipe,out} = \frac{\pi Do^2}{4} \times L$ L = 0.25m

$= \frac{\pi (0.02225m)^2}{4} \times 0.25m = 0.000096938\ m^3$

$V_{pipe,total} = n \times V_{pipe,out}$

$= 435 \times 0.000096938\ m^3 = 0.04216803\ m^3$

Add void volume

$V_{total,tank} = 1.4 \times V_{pipe,total}$

$= 1.4 \times 0.04216803\ m^3 = 0.059035242 m^3$

For 1 inch copper tube; Di = 0.026035 m and Do = 0.028575 m

V_{pipe} for the selected data

$V_{pipe} = \frac{\pi Di^2}{4} \times L$ L = 0.25m

$V_{pipe} = \frac{\pi(0.026035m)^2}{4} \times 0.25m = 0.0001330898863\ m^3$

Number of tube (n);

$$n = \frac{Vpcm}{Vpipe} = \frac{0.03398\ m^3}{0.0001330898863\ m^3}$$

$= 255$ copper pipe needed

By considering 0.4 void fraction and calculate the total volume of tank

$V_{pipe,out} = \frac{\pi Do^2}{4} \times L$ L = 0.25m

$= \frac{\pi(0.028575m)^2}{4} \times 0.25m = 0.0001603254133\ m^3$

$V_{pipe,total} = n \times V_{pipe,out}$

$= 255 \times 0.0001603254133\ m^3 = 0.04088298\ m^3$

Add void volume

$V_{total,tank} = 1.4 \times V_{pipe,total}$

$= 1.4 * 0.04088298 m^3 = 0.057236172 m^3$

For 2 inch copper tube; Di = 0.050419 m and Do = 0.053975 m

V_{pipe} for the selected data

$V_{pipe} = \frac{\pi Di^2}{4} \times L$ L = 0.25m

$V_{pipe} = \frac{\pi(0.050419)^2}{4} \times 0.25m = 0.0004991353692\ m^3$

Number of tube (n);

$$n = \frac{Vpcm}{Vpipe} = \frac{0.03398\ m^3}{0.0004991353692\ m^3}$$

$= 68$ copper pipe needed

By considering 0.4 void fraction and calculate the total volume of tank

$V_{pipe,out} = \frac{\pi Do^2}{4} \times L$ L = 0.25m

$= \frac{\pi (0.053975m)^2}{4} \times 0.25m = 0.0005720252401\ m^3$

$V_{pipe,total} = n \times V_{pipe,out}$

$= 68 \times 0.0005720252401\ m^3 = 0.038897716\ m^3$

Add void volume

$V_{total,tank} = 1.4 \times V_{pipe,total}$

$= 1.4 \times 0.038897716\ m^3 = 0.054456802\ m^3$

For $2^1/_2$ inch copper tube; Di = 0.062611 m and Do = 0.066675 m

V_{pipe} for the selected data

$V_{pipe} = \frac{\pi Di^2}{4} \times L$ L = 0.25m

$V_{pipe} = \frac{\pi (0.062611\ m)^2}{4} \times 0.25m = 0.000769717163\ m^3$

Number of tube (n);

$n = \frac{Vpcm}{Vpipe} = \frac{0.03398\ m^3}{0.000769717163\ m^3}$

$44.15 \cong 44$ copper pipe needed

By considering 0.4 void fraction and calculate the total volume of tank

$V_{pipe,out} = \frac{\pi Do^2}{4} \times L$ L = 0.25m

$= \frac{\pi (0.066675\ m)^2}{4} \times 0.25m = 0.0008728828058m^3$

$V_{pipe,total} = n \times V_{pipe,out}$

$= 44 \times 0.0008728828058m^3 = 0.038406843\ m^3$

Add void volume

$V_{total,tank} = 1.4 \times V_{pipe,total}$

$= 1.4 \times 0.038406843\ m^3 = 0.05376958m^3$

From above calculation taking 2 inch copper pipe because less thickness than $2\ ^1/_2$ inch copper pipe

$V_{storeg} = \frac{\pi Dos^2}{4} \times L$

$D_{ost}^2 = \frac{0.054456802m^3}{0.25\ m\ x\pi} \times 4 = 0.277346215m^2$

D_{os} = 0.54m

Dis = 0.525m

Area of the cylindrical storage tank (container)

$$A_s = \frac{\pi Dos^2}{4}$$

$$= \frac{\pi(0.54\text{m})^2}{4} = 0.23\text{m}^2$$

Where; D_{os} = outside diameter of storage

Dis = inside diameter of storage

A_s = area of storage

The total height of the storage tank is calculated as the summation of the space left on the top of the storage for the pot (80% of the height of the pot), the storage height and the space left at the bottom of the storage. Therefor, the size of storage tank to be modeled as;

Total storage length (L_{tls}) = 80% of pan length pan+length of storage+length left at bottom +20% of $L_{potleft}$ **(11)**

= 80% of L_{pot} + $L_{storage}$ + L_{bottom} +20% of $L_{pot\ hnd\ left}$

Where, L_{pot} = 15cm

L_{bottom} = 8cm

L_{TSL} = 0.8 x 15cm + 25cm + 8cm +0.2 x 15cm

= 12cm + 25 +8cm + 3cm

= 48 cm

= 480 mm

3.6. Modeling Of Thermal Storage System

Modeling of shell and tube main thermal heat storage unit is used for cooking application**.** This is due to the point that most engineering systems service cylindrical pipes and also heat loss from the shell and tube system is minimal **[42,43].** Suppose geometry model of thermal storage are consists of a shell (container) of 0.54 m outer diameter, 0.53m inner diameter and 0.485 m height made of steel the wall thickness 0.0015m were used. Moreover, for heat storage unit encapsulate eutectic solar salt of $NaNO_3$ and KNO_3 are copper tube with 0.0515m inner diameter and 0.053m outside diameter and 0.0015m thickness.In additional using total length of storage 0.485 m and number of copper tube are 68 used in thermal heat storage geometer as shown below in **figure 1**;

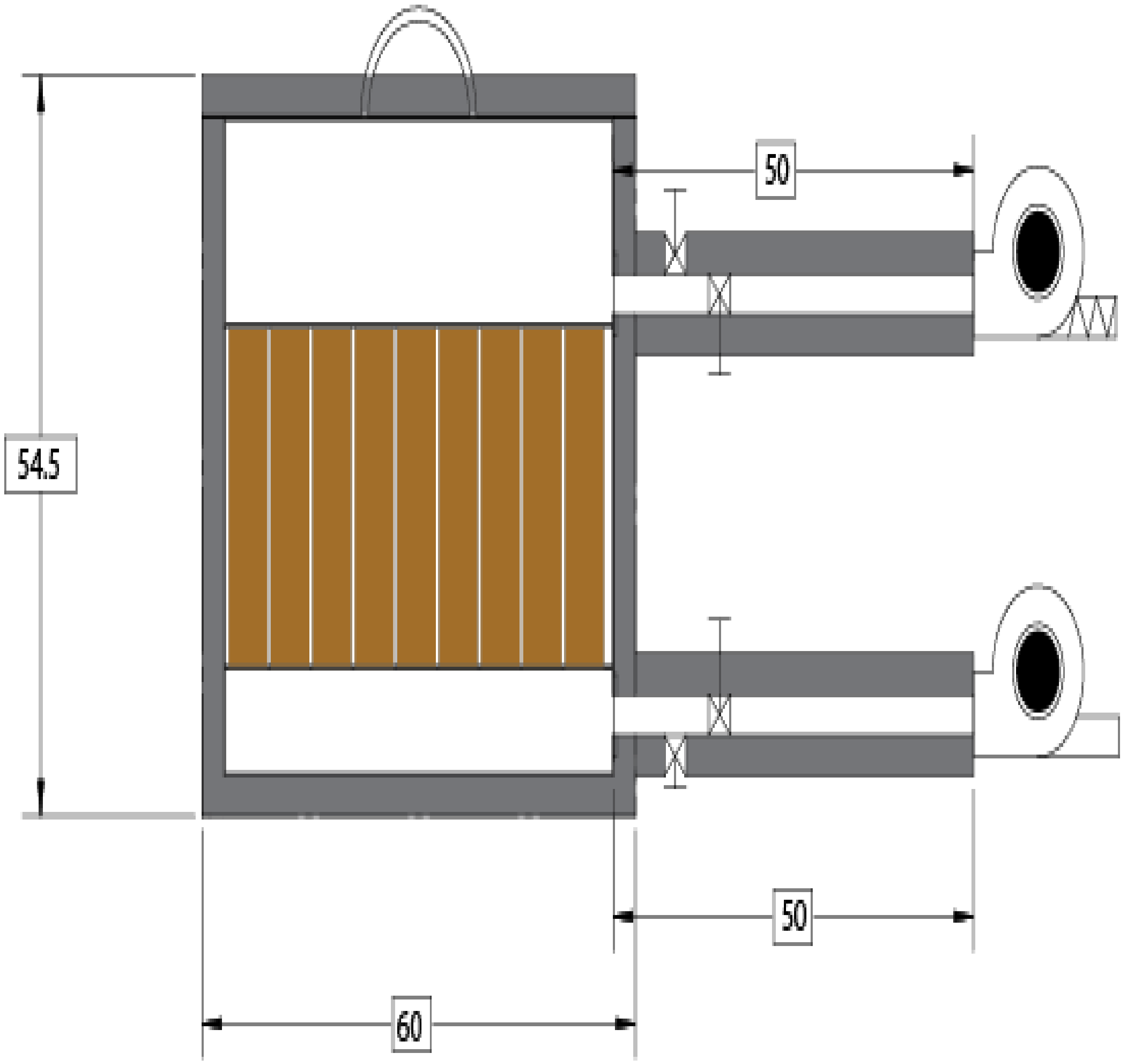


Figure 1 : thermal storage Geometry

Not; all the dimensions are given in cm

Working mechanism of thermal storage shown above figure during charging poried from axial blower pumped HTF (hot air) pass through the pipe inters at top of storage. Due to this contact HTF encapsulation of PCM coper pipe while heat exchange between copper pipe and PCM its became PCM temperature raised (melted) through top to bottom and HTF decrease temperature and exit to the bottom of storage through open valve.Among this process constant inter temperature latent heat stored (charging).in contrast axial blower pumped air and discharged stored latent heat to pass through top during cooking purpose and air pass out to open valve.so for these reason in order to increase the heat transfer rate into the PCM must be all surfaces of the container are thermal insulated using 30mm fiberglass thermal insulation material. Again from Appendix, using standard specification AC axial blower pump according to maximum volume flow rate of air at 0.65m^3/min which model code **CB60B4** has selected to increasing efficiency for this purpose.

Mathematical Method

Table 7: Thermo physical Properties of Gases at Atmospheric Pressure **[42].**

T (K)	ρ (kg/m^3)	C_p (kJ/kg.k)	$\mu.10^7$ (N.s/m^2)	ν. 10^6 m^2/s	k.10^3 w/m.k	α.10^6 m^2/s	P_r
Air							
100	3.5562	1.032	71.1	2.00	9.34	2.54	0.786
150	2.3364	1.012	103.4	4.426	13.8	5.84	0.758
200	1.7458	1.007	132.5	7.590	18.1	10.3	0.737
250	1.3947	1.006	159.6	11.44	22.3	15.9	0.720
300	1.1614	1.007	184.6	15.89	26.3	22.5	0.707
350	0.9950	1.009	208.2	20.92	30.0	29.9	0.700
400	0.8711	1.014	230.1	26.41	33.8	38.3	0.690
450	0.7740	1.021	250.7	32.39	37.3	47.2	0.686
500	0.6964	1.030	270.1	38.79	40.7	56.7	0.684
550	0.6329	1.040	288.4	45.57	43.9	66.7	0.683
600	0.5804	1.051	305.8	52.69	46.9	76.9	0.685
650	0.5356	1.063	322.5	60.21	49.7	87.3	0.690
700	0.4975	1.075	338.8	68.10	52.4	98.0	0.695
750	0.4643	1.087	354.6	76.37	54.9	109	0.702
800	0.4354	1.099	369.8	84.93	57.3	120	0.709

Calculate the mass flow rate of air ($\dot{m}$) for appropriate charging time of 5 hours .The physical properties of air can be calculated using interpolation from the above table.

From table 7 at 1 atmosphere pressure:

ρ_a (kg/m^3)	C_{pa} (kJ/kg.k)	k (w/m.k)
450 $\rightarrow$ 0.7740	450 $\rightarrow$ 1.021	450 $\rightarrow$ 0.0373

$493 \rightarrow x$ | $493 \rightarrow x$ | $493 \rightarrow x$

$500 \rightarrow 0.6964$ | $500 \rightarrow 1.030$ | $500 \rightarrow 0.0407$

by interpolation we get | by interpolation we get | by interpolation we get

$\rho_{a2} = 0.7072$ kg/m^3 | $C_{pa} = 1.028$ kJ/kg.k) | k = 0.0423 (w/m.k)

$\mu. 10^{-7}$ (N.s/m^2) | ν. 10^{-6} (m^2/s) | P_r

$450 \rightarrow 250.7$ | $450 \rightarrow 32.39$ | $450 \rightarrow 0.686$

$493 \rightarrow x$ | $493 \rightarrow x$ | $493 \rightarrow x$

$500 \rightarrow 270.1$ | $500 \rightarrow 38.79$ | $500 \rightarrow 0.684$

by interpolation we get | by interpolation we get | by interpolation we get

$\mu = 267.387\, x10^{-7}$ (N.s/m^2) | ν = 30759 x 10^{-6} (m^2/s) | $P_r = 0.68 \cong 0.7$

Mass flow rate ($\dot{m}$) of air in storage

$$\frac{Q}{t} = \dot{m} C_{pa} \Delta T \qquad \textbf{(12)}$$

Power = $\dot{Q}$

$$\frac{Q}{t} = \dot{m} C_{pa}(T_{pcm} - T_{ab})$$

$$\dot{m} = \frac{Q}{t\, C_{pa}(T_{pcm} - T_{ab})}$$

$$= \frac{24000\text{kJ}}{5 \text{ x } 3600\text{s x } 1.0066\text{kJ/kg.k } (493k - 298k)}$$

= 0.0066kg/s

Calculate velocity (V_{a1}) of air tube

$D_1 = 0.03$m

$$A_1 = \frac{\pi D1^2}{4}$$

$$= \frac{\pi (0.03m)^2}{4} = 0.00071\text{m}^2$$

Where:

D_1 = diameter of air duct

A_{d1} = area of air duct

V_{a1} = velocity of air in duct

From table 7 at 1 atmosphere pressure:

ρ_a (kg/m^3) | C_{pa} (kJ/kg.k) | k (w/m.k)

$550 \rightarrow 0.6329$ | $550 \rightarrow 1.040$ | $550 \rightarrow 0.0439$

573 → x | 573 → x | 573 → x

600 → 0.5804 | 600 → 1.051 | 600 → 0.0469

by interpolation we get | by interpolation we get | by interpolation we get

$\rho_a = 0.60875$ kg/m^3 | $C_{pa} = 1.045$ kJ/kg.k) | k = 0.04528 (w/m.k)

$\mu . 10^{-7}$ (N.s/m^2) | $\nu . 10^{-6}$ (m^2/s) | P_r

550 → 288.4 | 550 → 45.57 | 550 → 0.683

573 → x | 573 → x | 573 → x

600 → 305.8 | 600 → 52.69 | 600 → 0.682

by interpolation we get | by interpolation we get | by interpolation we get

$\mu = 8.004\ x10^{-7}$ (N.s/m^2) | $\nu = 48.84$ x 10^{-6} (m^2/s) | $P_r = 0.684 \cong 0.7$

From this mass flow rate ($\dot{m}$) of air constant

$$\dot{m} = \rho_{a1} A_{d1} V_{a1}$$

$$V_{a1} = \frac{\dot{m}}{\rho_{a1} A_{d1}}$$

$$= \frac{0.0066\ kg/s}{0.60875\ x\ kg/m^3\ x\ 0.00071 m^2} = 15.3 \text{ m/s}$$

From compressible flow continuity equation

$$\rho_{a2} A_{s2} V_{s2} = \rho_{a1} A_{d1} V_{a1} \quad \textbf{(13)}$$

$$V_{s2} = \frac{\rho_{a1} A_{d1} V_{d1}}{\rho_{a2} A_{s2}}$$

$$= \frac{0.60875 kg/m^3\ x 0.00071 m^2 x\ 15.3 m/s}{0.7073\ x\ kg/m^3\ x\ 0.23\ m^2} = 0.041 \text{ m/s}$$

Calculate volume flow rate of air (v)

$$V = \frac{\dot{m}}{\rho_{a1}}$$

$$= \frac{0.0066 kg/s}{0.6088 kg/m^3}$$

$$= 0.011 \text{m}^3/\text{s}$$

$$= 0.011 \text{m}^3/\text{s x } \frac{60s}{min}$$

$$= 0.65 \text{ m}^3/\text{min}$$

Calculate the inlet Reynolds number (R_{eD})

$$R_{eD} = \frac{V_{S2L_P}}{v}$$

$$= \frac{0.041 m/s\ x 0.25 m}{30759 \text{ x } 10^{-6} m^2/s}$$

= 0.325 The flow is laminar

Calculate diameter of fluid container (D_F)

$$\varepsilon = \frac{void\ volume\ (V_f)}{total\ volume\ \ (V_{tot})} \quad \Rightarrow V_f = \varepsilon V_{tot} \qquad \textbf{(14)}$$

$V_{tot} = V_f + V_p$

$V_{tot} = \varepsilon V_{tot} + V_p$

$V_{tot} = \frac{V_p}{1-\varepsilon}$

$= \frac{0.0005720252401 m^3}{1-0.4}$

$= 0.0009533754\ m^3$

$V_{tot} = \frac{\pi Dt^2 L_p}{4}$

$Dt^2 = \frac{4\ x\ V_{tot}}{L_p\ \pi}$

$Dt^2 = \frac{4\ x\ 0.0009533754\ m^3}{0.25m\ x\ \pi}$

$= 0.004855\ m^2$

$D_t = 0.07m$

$D_t = D_{pip} + D_f$

$D_f = D_t - D_{pip}$

$= 0.07m - 0.053m$

$= 0.017m$

$R_f = \frac{0.017m}{2}$

$= 0.0085m$

Where, D_f = diameter of void volume

D_t = diameter of total volume of fluid

R_f = radius of void volume

Governing Equations Used in ANSYS Fluent

Governing equations used in CFD ANSYS Fluent Modelling of the thermal energy storage (TES) system has been performed using CFDANSYS Fluent 17.2 and is based on enthalpy-porosity formulation. In its place the liquid fraction, which shows the fraction of the cell volume that is in a liquid form related with each cell domain is followed. This liquid fraction is partsipate at each iteration, based on the enthalpy balance **[45]**.The Navier-Stokes equations are solved with superior conducts to include the latent heat transfer and phase change in the mushy area, and nil velocity in the solid region **[46].** In the mushy region, liquid fraction lies between 0 to 1 and it generally decreases from 1 to 0 as the material solidifies **[45]**.2D continuity, momentum, and energy equations are given below **[45.47,48];**

Continuity Equation:

$$\frac{\partial \rho}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(\rho r v_r) + \frac{1}{r}\frac{\partial}{\partial z}(\rho r v_z) = 0 \quad \textbf{(15)}$$

Momentum Equation:

Radial momentum along (r) direction;

$$\frac{\partial \rho v_r}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(\rho r v_r) + \frac{1}{r}\frac{\partial}{\partial z}(\rho r v_r) = -\frac{\partial p}{\partial r} + \mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial (r v_r)}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 v_r}{\partial z^2} + \frac{1}{r^2}\frac{\partial v_z}{\partial z}\right] + \rho g - s_i \quad \textbf{(16)}$$

Axial momentum along (z) direction;

$$\frac{\partial \rho v_z}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(\rho r v_z) + \frac{1}{r}\frac{\partial}{\partial z}(\rho v_z) = -\frac{1}{r}\frac{\partial p}{\partial z} + \mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial (r v_z)}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 v_r}{\partial z^2} - \frac{2}{r^2}\frac{\partial v_z}{\partial z}\right] - \rho g - s_i \quad \textbf{(17)}$$

The source term in the momentum equation is define as; $s_i = \frac{(1-\beta)^2}{\beta^3+\varepsilon} c v_i$

Where ;

ρ = density,

μ = dynamic viscosity,

P = pressure,

g = gravitational acceleration,

Si = momentum source term,

C = a constant term to reflect mushy zone morphology and determines the rate of velocity reduction 0 to 1. The value is varied from 10^4 to 10^7 according to the phase change materials property

ε =a small number using (0.001)

β = liquid fraction

V_r =velocity along radial

V_z =velocity along axial

Energy Equation;

$$\frac{\partial \rho}{\partial t}+\frac{1}{r}\frac{\partial(\rho r v_r H)}{\partial r}+\frac{1}{r}\frac{\partial \rho v_z H}{\partial z}=\frac{K}{C_p}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{r\partial H}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 H}{\partial z^2}\right]-s_h \qquad \textbf{(18)}$$

Where; the enthalpy source term is

$$s_h=\frac{\partial \rho \Delta H}{\partial t}+\frac{1}{r}\frac{\partial(\rho r v_r \Delta H)}{\partial r}+\frac{1}{r}\frac{\partial \rho v_z \Delta H}{\partial z}$$

ΔH is the specific enthalpy

Solving of Phase Change Problem

Phase change processes exhibit a transient and non-linear phenomenon with a moving liquid-solid interface and involve flow problems associated with HTF.Consequently, expecting the behavior of phase change procedures is interesting.Two numerical process are broadly used to model the phase change: effective heat capacity process and enthalpy formulation process **[45, 49]**. In addition to these methods, the temperature-transforming model is also used to simulate the phase change process **[45]**.

Moving Boundary Problems

The heat transfer problem in melting and solidification processes is called moving boundary problems. It is especially complicated due to the fact that the solid-liquid boundary moves depending on the speed at which the latent heat is absorbed or lost at the boundary. While in theory phase change occurs at one defined temperature, in practice it happens over a temperature range, forming a so-called mushy zone (two-phase zone) between liquid and solid. Hence, it becomes more relevant to solve the problem by enthalpy formulation method. Enthalpy method treats the enthalpy as a temperature-dependent variable and builds the latent heat flow through the volume integration with the use of enthalpy of the system **[45]**.

Enthalpy Method

The enthalpy method is used in solving non-linear heat equations in phase change problems which involve a moving boundary. Using the enthalpy formulation method, the enthalpy is considered as a temperature dependent variable and the flow of the latent heat is expressed in terms of volumetric enthalpy as a function of a temperature of the PCM, This relationship between temperature and enthalpy is used to solve the phase change problem. The enthalpy method was developed by Voller (1997) and it is one of the most utilized methods for the treatment of phase change boundary **[45, 48]**.

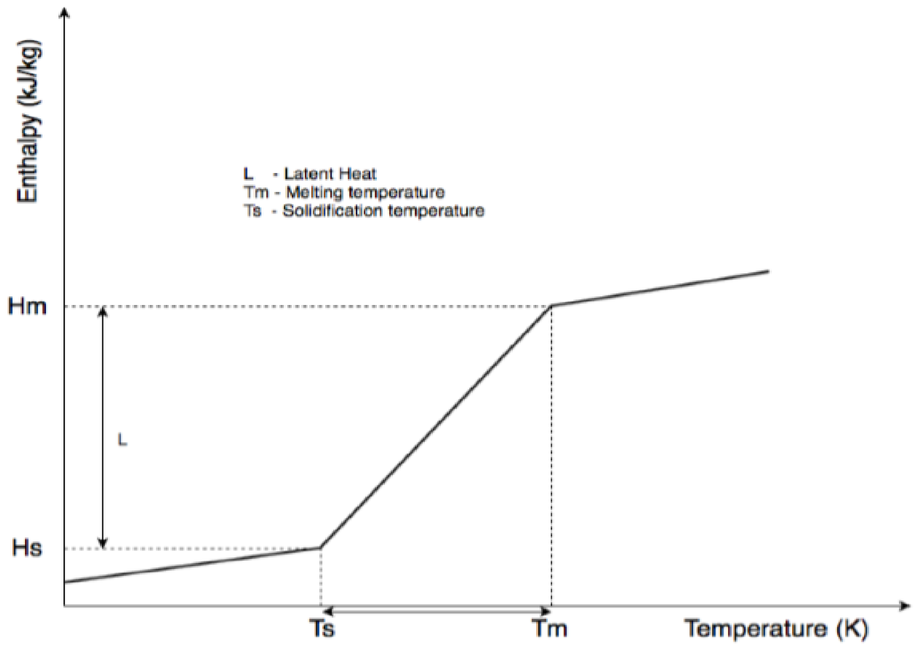


Figure 2: enthalpy formulation system **[45]**

The enthalpy method assumes the enthalpy into the energy equation of sensible and latent heat. Enthalpy is the summation of the sensible heat and latent heat of the phase change as shown in Equation blow **[45, 49]**;

H (T) = sensible heat + latent heat **(19)**

H (T) = h (T) + L β(T)

Where H = total volumetric enthalpy

h = sensible heat

L = latent heat

β = liquid fraction

$$h(T) = \int_{Ts}^{Tl} C_p dT \quad \textbf{(20)}$$

Liquid fraction is given as;

$$\beta = \begin{cases} 0, & \text{if } T \le Ts \\ \frac{T-Ts}{Tl-Ts}, & \text{if } Tl \le T \le Ts \\ 1 & \text{if } T \ge Tl \end{cases} \quad \textbf{(21)}$$

Where, T = local temperature

T_s =solid temperature

T_l = liquid temperature

The liquid fraction represents the state of the PCM at the nodes based on the temperature of the PCM change along storeg that meas pcm tempreture chande from intal state to final or up to liquid.Therefor,liquid fraction represent shown phase transion from solid-liquid ;

if material is solid $\beta = 0$

Mushy region $0 \leq \beta \leq 1$

Material is liquid $\beta = 1$

3.7. Numerical Solution

There are different profitable soft wares for numerical solution of the melting and solidification process. ANSYS fluent is the most commonly utilized software. In addition The CFD software provides ability to modeling objects, mesh them, give suitable boundary conditions and simulating them with real world condition to get results **[47,50]**.However, unsteady **2-D** symmetric transient differential equation **15--18** are numerical problem solved by finite volume method using ANSYS fluent software was utilized to solve phase change equation by applying SIMPLE(Semi-implicitly method for pressure-linked equation) scheme for pressure-velocity coupling while second order up wind discretized continuity, momentum and energy governing equation.Since step-by-step ANSYS work bench space analysis cannot be proceed if the previous step is not complete **[47,51]**.Therefore,the geometrical used to simulate the melting and solidification mechanism modular shown blow;**Figure 3 shows the geometrical parameters of the model used in numerical analysis;**

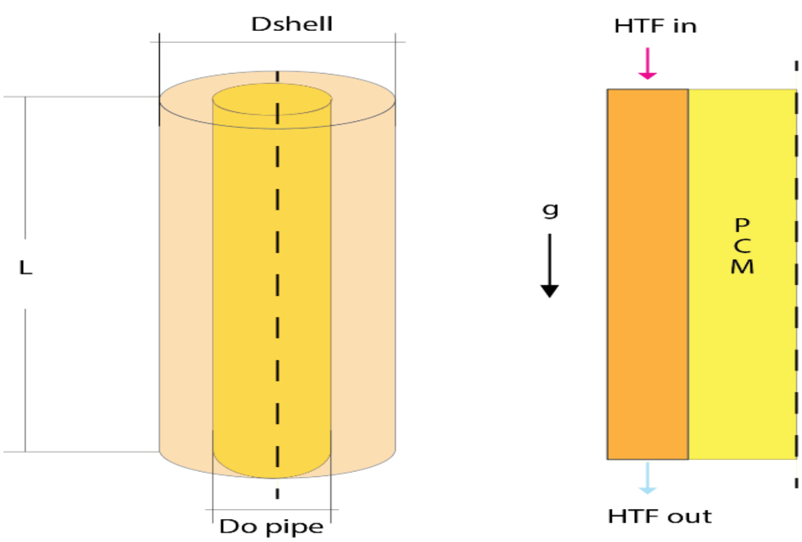


Figure 3: Geometry of the thermal storage model

For this simulation the heat losses to the environment were negligible since the storage unit is well insulated at right and left side.

Initial And Boundary Conditions

Initial and boundary conditions of the problem studied are necessary to perform a numerical simulation for ANSYS Fluent. Such conditions are inserted in the software used for the problem modeling, in other words, the software used to define the physical conditions of the problem **[45, 48,36]**.

Initial Conditions For Charging

Table 8 : Boundary conditions for charging

Intial condition	Radial coordinate	Axial coordinet	Bounder condition
t=0s	$r = r_i$	Z= 0	$T_{pcm} = 298K$ $T_{htf} = 0$
	$V_r = 0$	$V_z = 0$	$T_i = T_{pcm}$
t >0s	$r = r_0$	Vr,Vz 0.041m/s	$T_i = T_{htf}$
	$r = r_0$	Z= 0	$\frac{\partial V_r}{\partial z} = 0$ $V_z = 0$

Initial Conditions For Discharging

Table 9: Boundary conditions for discharging

Intial condition	Radial coordinate	Axial coordinet	Bounder condition
t=0s	$r , r_i = 0$	L= 0	$T_{pcm} = 298K$ $T_{htf} = 0$
	$V_r = 0$	$V_z = 0$	$T_i = T_{pcm}$
t >0s	$r = r_0$	Vr,Vz 0.041m/s	$T_i = T_{htf}$ $T_{pcm} < T_{htf}$
	$r = r_0$	$L = H_s$	$T_{pcm} = T_s$

Mesh Specification

The computational mesh is constructed by FLEUNT based on the triangular grid.The grid spaceused in this simulation is 0.01m. While solving a numerical solution the quality of the mesh plays a vital role as it directly affects the accuracy and stability of the numerical computation. Hence, a closer look was made to have a sufficient mesh quality. First, it was made sure that the important to check the orthogonal quality of the mesh and is advisable that the value should be close to one **[45]**.In addition to, variation of mesh grid sizes has major control charging and discharging in numerical results of the model blow mesh geometry.

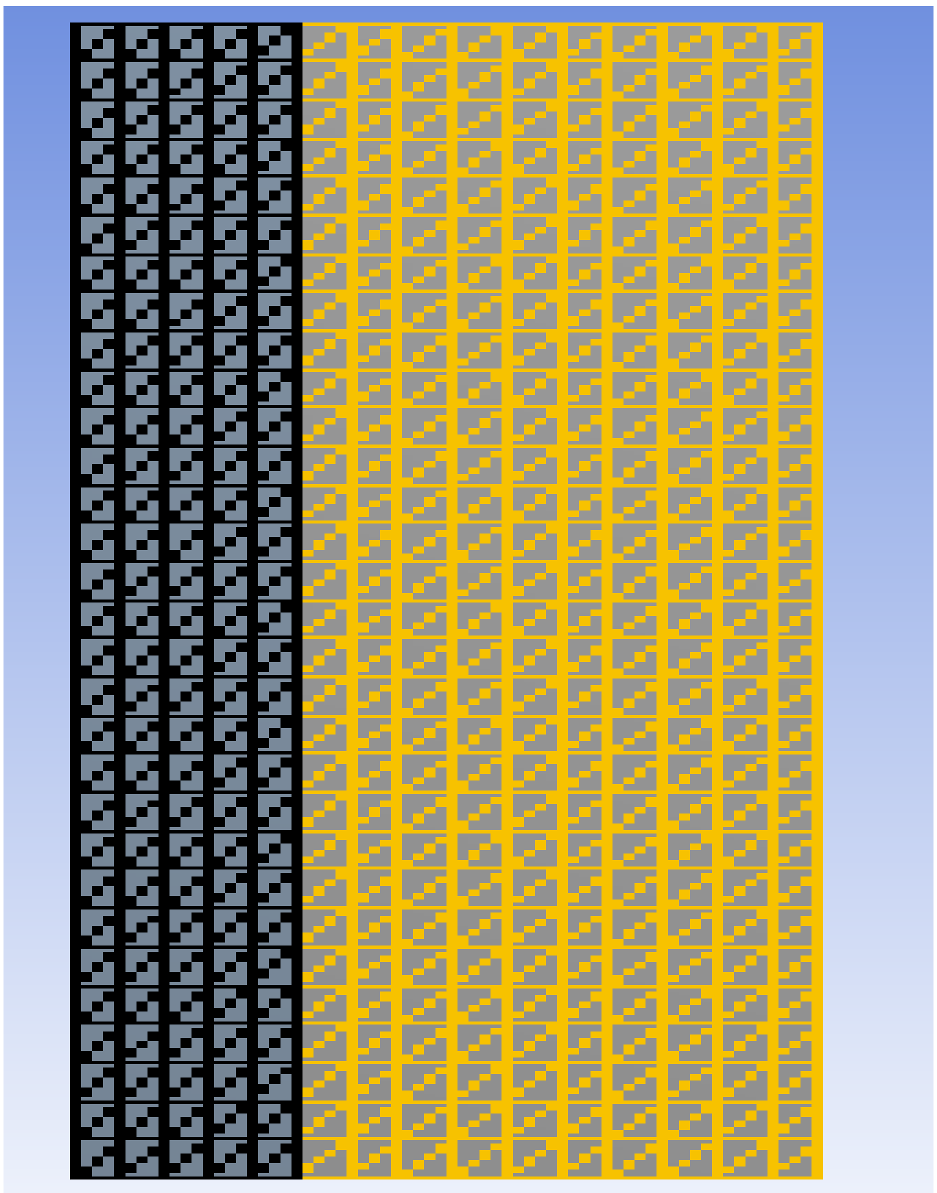


Figure 4: Mesh model

Mesh parameters of the model

This mesh parameter shows mesh elements and nodes which are used to see the effect run for charging and discharging process.After further observation the accuracy of results with 25200 elements are used for chargingand and 19200 elements for discharging.

3.8. Charging And Discharging Efficiency Of Thermal Energy Storage System

Thermal energy storage unit system performance must be analyzed important such as;

- ✓ Geometry of the PCM container
- ✓ Thermal and geometric parameters of the container required for a given amount of PCM
- ✓ Heat transfer mechanism like, charging and discharging time

Each of these factors has a direct influence on the heat transfer characteristics in the PCM and ultimately affects the melt time and the performance of the PCM storage unit **[52, 53]**.

Charging Time Of Thermal Energy Storage

Charging time starts with respect to heat transfer fluid flow rise the temperature of PCM. The TES prototype is said to be fully charged when the entire PCM is melted. Moreover, TES prototype should be designed and optimized in such a way that, the melting fraction reaches a value of unity. This occurs during day time **[52,54]**.

Energy Stored During Charging

Energy stored in the phase change material in two methods during Charging. These are, SHS and LHS.Initialy, when the phase change material is in the solid state, the rate of sensible heat energy storage would be greater than the rate of latent heat storege due to the higher temperature difference between the initial temperature and solidus temperature of PCM. Once the PCM starts melting, the rate of latent heat energy storage would become larger.Therefore,energy inflow, energy stored, and thermal efficiency during charging process can be calculated blow **[55,56, 57]**:

The numerical calculation of energy inflow and stored energy can be given as follows

$$E_{in\ flow} = \int_0^{T_{end}} \int_0^{T_{a(t)}} \dot{m}_a C_p dT dt \qquad \textbf{(22)}$$

$$= \dot{m}_a C_p \int_0^{T_{end}} (T_a - T_0) dt$$

$$= \dot{m}_a C_p \int_0^{T_{end}} (573k - 298k) dt$$

$= \dot{m}_a C_p 275[T_{end} - T_0]$

= 0.0066kg/s x 1.045kJ/kg.k x 275k [5x3600s]

= 34140.15 kJ

$$E_{store} = \int_0^L \rho_{pcm}\, C_p A_{cs}\,(T_{pcm(x)} - T_0)dx \quad \textbf{(23)}$$

$= \rho_{pcm} C_p A_{cs}\,(T_{pcm(x)} - T_0)\Delta x$

Length of storage = 0.25m

$\Delta x = \frac{0.25m}{7}$

= 0.0354m

T_i = 298k

T_s = 493k

$E_{1(\mathbf{store})} = \int_0^L \rho_{pcm}\, C_p A_{cs}\,(T_{pcm(x)} - T_0)dx$

$= \rho_{pcm} C_p$ (1-0.4) x $A_{cs}\,(T_{pcm(x)} - T_0)\Delta x$

=1800kg/m^3 x 12 kJ/kgk x (1-0.4) x 0.23m^2 x (493k-298k) x 0.0354m

= 20576.46KJ

$E_{2(\mathbf{store})} = \int_0^L \rho_{pcm}\, C_p A_{cs}\,(T_{pcm(x)} - T_0)dx$

$= \rho_{pcm} C_p$(1-0.4) $A_{cs}\,(T_{pcm(x)} - T_0)\Delta x$

= 1800kg/m^3 x 1.4 kJ/kg.k x (1-0.4) x 0.23m^2 x (481k-298k) x 0.0354m

= 2252.85KJ

$E_{3(\mathbf{store})} = \int_0^{\mathbf{L}} \boldsymbol{\rho}_{\mathbf{pcm}}\, C_p A_{cs}\,(T_{pcm(x)} - T_0)dx$

$= \rho_{pcm} C_p$(1-0.4)$A_{cs}\,(T_{pcm(x)} - T_0)\Delta x$

= 1800kg/m^3 x 1.4 kJ/kg.k x (1-0.4) x 0.23m^2 x (451k-298k) x 0.0354m

= 1883.53KJ

$E_{4(\mathbf{store})} = \int_0^L \rho_{pcm\, C_p} A_{cs}\,(T_{pcm(x)} - T_0)dx$

$= \rho_{pcm} C_p$ (1-0.4)$A_{cs}\,(T_{pcm(x)} - T_0)\Delta x$

= 1800kg/m^3 x 1.4 kJ/kg.k x (1-0.4) x0.23m^2 x (420k-298k) x 0.0354m

= 1378.79KJ

$E_{5(\mathbf{store})} = \int_0^L \rho_{pcm}\, C_p A_{cs}\,(T_{pcm(x)} - T_0)dx$

$= \rho_{pcm} C_p$(1-0.4)$A_{cs}\,(T_{pcm(x)} - T_0)\Delta x$

= 1800kg/m^3 x 4.2 kJ/kg.k x (1-0.4) x 0.23m^2 x (390k-298k) x 0.0354m

= 3397.75KJ

$E_{6(\mathbf{store})} = \int_0^L \rho_{pcm} C_p A_{cs} (T_{pcm(x)} - T_0) dx$

$= \rho_{pcm} C_p (1-0.4) A_{cs} (T_{pcm(x)} - T_0) \Delta x$

= 1800kg/m^3 x0.75kJ/kg.k x (1-0.4) x0.23m^2 x (359k-298k) x 0.0354m

= 402.29KJ

$E_{7(\mathbf{store})} = \int_0^L \rho_{pcm} C_p A_{cs} (T_{pcm(x)} - T_0) dx$

$= \rho_{pcm} C_p (1-0.4) A_{cs} (T_{pcm(x)} - T_0) \Delta x$

= 1800kg/m^3 x 0.75kJ/kg.k x (1-0.4) x0.23m^2 x (329k-298k) x 0.0354m

= 204.5KJ

$E_{(\mathbf{store})} = E_{1(\mathbf{store})} + E_{2(\mathbf{store})} + E_{3(\mathbf{store})} + E_{4(\mathbf{store})} + E_{5(\mathbf{store})} + E_{6(\mathbf{store})} + E_{7(\mathbf{store})}$

= 20576.46KJ +2252.85 KJ+1883.53 KJ+1378.79 KJ +3397.75 KJ +402.29 +204.5 KJ

= 30096.47KJ

Ergun equation various pressure drop along storage which is valid for a wide range of laminar and turbulent flow conditions **[56, 58]:**

$$\frac{\Delta P}{L} = \frac{150\,(1-\varepsilon)^2 \mu\, V}{\varepsilon^3 D_s^2} + \frac{1.75(1-\varepsilon)\rho_{a2} V^2}{\varepsilon^3 D_s} \quad \textbf{(24)}$$

Pressure dropped along storage

$$\frac{\Delta P}{L} = \frac{150\,(1-\varepsilon)^2 \mu\, V}{\varepsilon^3 D_s^2} + \frac{1.75(1-\varepsilon)\rho_{a2} V^2}{\varepsilon^3 D_s}$$

$$\frac{\Delta P}{L} = \left[\frac{150\,(1-0.4)^2 267.387\ x10^{-7} N.S/m^4 x0.041 m/s}{(0.4)^3 x\,(0.54m)^2} + \frac{1.75(1-0.4)0.7072 kg/m^3 x(0.041 m/s)^2}{(0.4)^3 x\ 0.54m} \right]$$

$$\Delta P = 0.25m \left[\frac{150\,(1-0.4)^2 267.387\ x10^{-7} N.S/m^4 x0.0044 m/s}{(0.4)^3 x\,(0.54m)^2} + \frac{1.75(1-0.4)0.7072 kg/m^3 x(0.0044 m/s)^2}{(0.4)^3 x\ 0.54m} \right]$$

= 0.25[0.031715528 + 0.020638944]N/m^2

ΔP = 0.01308818N/m^2

Where ΔP = pressure drop

V_{a2} = velocity of air in storage

ρ_{a2} = Density of air in storage

D_s = diameter of storage

μ = fluid viscosity

ε = void fraction (porosity)

Pressure dropped along in air pipe

$$\frac{\Delta P}{L} = \frac{150\ (1-\varepsilon)^2 \mu\ V}{\varepsilon^3 D_a^2} + \frac{1.75(1-\varepsilon)\rho_{a2} V^2}{\varepsilon^3 D_a}$$

$$\frac{\Delta P1}{L} = \left[\frac{150\ (1-0.4)^2 8.004\ x10^{-7} N.S/m^4 x15.3m/s}{(0.4)^3 x\ (0.03m)^2} + \frac{1.75(1-0.4)0.7072kg/m^3 x(15.3/s)^2}{(0.4)^3 x\ 0.03m} \right]$$

$$\Delta P = 0.5m \left[\frac{150\ (1-0.4)^2 267.387\ x10^{-7} N.S/m^4 x15.3m/s}{(0.4)^3 x\ (0.03m)^2} + \frac{1.75(1-0.4)0.7072kg/m^3 x(15.3m/s)^2}{(0.4)^3 x\ 0.03m} \right]$$

$= 0.5[0.750375 + 90534.3075] N/m^2$

$\Delta P1 = 45267.52894\ N/m^2$

$\Delta P = \Delta P2 + \Delta P1$

$= [\ 0.013088618 + 45267.52894]\ N/m^2$

$= 45267.54203 N/m^2$

$= 45.26754203 KN/m^2$

Where $\Delta P1$ = pressure drop in air pipe

V_{a1} = velocity of air in air pipe

ρ_{a1} = density of air in pipe

D_{a1} = diameter of air pipe

μ = fluid viscosity

Energy required for the pumping of fluid in storage can be calculated the following **[55, 58]**:

$$E_{pump} = \int_0^{t_{end}} \frac{\dot{m}_a}{\rho_{a1}} \Delta P dt \quad \textbf{(25)}$$

$$= \frac{\dot{m}_a}{\rho_{a1}} \Delta P [T_{end} - T_0]$$

$$= \frac{0.0066 kg/s}{0.60875 kg/m^3} 45.26752938k\ N/m^2\ [5\ x\ 3600s]$$

$= 8834.15KJ$

Where ΔP = Total pressure drop in storage

$\dot{m}_a$ = mass flow rate of air

3.9. Efficiency Of Charging Thermal Energy Storage

$$\boldsymbol{\eta_{char}} = \frac{E_{store}}{\boldsymbol{E_{inflow}} + \boldsymbol{E_{pump}}} \quad \textbf{(26)}$$

$$= \frac{30096.47KJ}{(34140.15+8834.13)KJ}$$

$= \frac{30096.47KJ}{42974.28KJ}$

$= 0.7004 \rightarrow$ **70.1%**

Discharging Time

Discharging time TES starts having giving HTF temperature smoler than phase change temperature.When thermal energy storage to be completely discharged the entire PCM is solidified that means the melting fraction reaches to value of 0.This mode ends with complete solidification of phase change material.It can be sensible, latent heat total heat discharge from PCM and it can be discharged efficiency calculate blow **[55, 57]**:

$$E_{out,\ flow} = \int_0^{T_{end}} \int_0^{T_{a(t)}} \dot{m}_a C_p dTdt \quad \textbf{(27)}$$

$= \dot{m}_a C_p \int_0^{T_{end}} (T_a - T_0)dt$

$= \dot{m}_a C_p \int_0^{T_{end}} (573k - 298k)dt$

$= \dot{m}_a C_p 275[T_{end} - T_0]$

$= 0.0066kg/s \times 1.045kJ/kg.k \times 275k\ [5 \times 3600s]$

= 34140.15 kJ

$$E_{(store)} = \int_0^L \rho_{pcm} C_p A_{cs} (T_{pcm(x)} - T_0)dx \quad \textbf{(28)}$$

$= \rho_{pcm} C_p (1\text{-}0.4) A_{cs} (T_{pcm(x)} - T_0)\Delta x$

$E_{9(store)} = \int_0^L \rho_{pcm} C_p A_{cs} (T_{pcm(x)} - T_0)dx$

$= \rho_{pcm} C_p (1\text{-}0.4) A_{cs} (T_{pcm(x)} - T_0)\Delta x$

$= 1800kg/m^3 \times 12kJ/kg.k \times (1\text{-}0.4) \times 0.23m^2 \times (493k\text{-}298k) \times 0.028m$

= 16275.17KJ

$E_{8(store)} = \int_0^L \rho_{pcm} C_p A_{cs} (T_{pcm(x)} - T_0)dx$

$= \rho_{pcm} C_p (1\text{-}0.4) A_{cs} (T_{pcm(x)} - T_0)\Delta x$

$= 1800kg/m^3 \times 1.4kJ/kg.k \times (1\text{-}0.4) \times 0.23m^2 \times (471k\text{-}298k) \times 0.028m$

= 60162.48KJ

$E_{7(store)} = \int_0^L \rho_{pcm} C_p A_{cs} (T_{pcm(x)} - T_0)dx$

$= \rho_{pcm} C_p (1\text{-}0.4) A_{cs} (T_{pcm(x)} - T_0)\Delta x$

$= 1800kg/m^3 \times 1.4kJ/kg.k \times (1\text{-}0.4) \times 0.23m^2 \times (450k\text{-}298k) \times 0.028m$

= 1480.1KJ

$E_{6(store)} = \int_0^L \rho_{pcm} C_p A_{cs} (T_{pcm(x)} - T_0) dx$

$= \rho_{pcm} C_p (1-0.4) A_{cs} (T_{pcm(x)} - T_0) \Delta x$

= 1800kg/m^3 x1.4kJ/kg.k x (1-0.4) x 0.23m^2 x (428k-298k) x 0.028m

= 1265.85KJ

$E_{5(store)} = \int_0^L \rho_{pcm} C_p A_{cs} (T_{pcm(x)} - T_0) dx$

$= \rho_{pcm} C_p (1-0.4) A_{cs} (T_{pcm(x)} - T_0) \Delta x$

= 1800kg/m^3 x1.4kJ/kg.k x (1-0.4) x 0.23m^2 x (406k-298k) x 0.028m

= 1051.63KJ

$E_{4(store)} = \int_0^L \rho_{pcm} C_p A_{cs} (T_{pcm(x)} - T_0) dx$

$= \rho_{pcm} C_p (1-0.4) A_{cs} (T_{pcm(x)} - T_0) \Delta x$

= 1800kg/m^3 x 4.2kJ/kg.k x (1-0.4) x 0.23m^2 x (385k-298k) x 0.028m

= 2541.43KJ

$E_{3(store)} = \int_0^L \rho_{pcm} C_p A_{cs} (T_{pcm(x)} - T_0) dx$

$= \rho_{pcm} C_p (1-0.4) A_{cs} (T_{pcm(x)} - T_0) \Delta x$

= 1800kg/m^3 x 0.75kJ/kg.k x (1-0.4) x 0.23m^2 x (363k-298k) x 0.028m

= 339.1KJ

$E_{2(store)} = \int_0^L \rho_{pcm} C_p A_{cs} (T_{pcm(x)} - T_0) dx$

$= \rho_{pcm} C_p (1-0.4) A_{cs} (T_{pcm(x)} - T_0) \Delta x$

= 1800kg/m^3 x 0.75kJ/kg.k x(1-0.4) x 0.23m^2 x (341k-298k) x 0.028m

= 224.31KJ

$E_{1(store)} = \int_0^L \rho_{pcm} C_p A_{cs} (T_{pcm(x)} - T_0) dx$

$= \rho_{pcm} C_p (1-0.4) A_{cs} (T_{pcm(x)} - T_0) \Delta x$

= 1800kg/m^3 x 0.75kJ/kg.k x (1-0.4) x 0.23m^2 x (341k-298k) x 0.028m

= 114.76KJ

$E_{(store)} = E_{9(store)} + E_{8(store)} + E_{7(store)} + E_{6(store)} + E_{5(store)} + E_{4(store)} + E_{3(store)} + E_{2(store)} + E_{1(store)}$

= 16275.17KJ +60162.48KJ + 1480.1KJ + 1265.85KJ + 1051.63KJ + 2541.43KJ

339.1KJ + 224.31KJ+ 114.76KJ

= 83454.83KJ

Where, E_{pump} = 8834.15KJ

$$\eta_{dischar} = \frac{E_{outflow}}{E_{store} + E_{pump}} \quad \textbf{(29)}$$

$$= \frac{34140.15KJ}{83454.83KJ + 8834.15\text{KJ}}$$

= 0.369 → 36.9%

Chapter Four

Results And Discussions

In this illustration, the detailed description of the charging and discharging results have been discussed.The numerical simulations using CFDANSYS Fluent Software results have discussed the characterization of thermal heat storage for cooking application. Moreover this method obtained numerical simulation is better due to sufficient got energy for cooking becouse the material of using for encapsulations were high thermal conductivity and store outer part using low thermal conductivity due to this reason got simulation results high efficients in order to sufficiently cooking purpose.

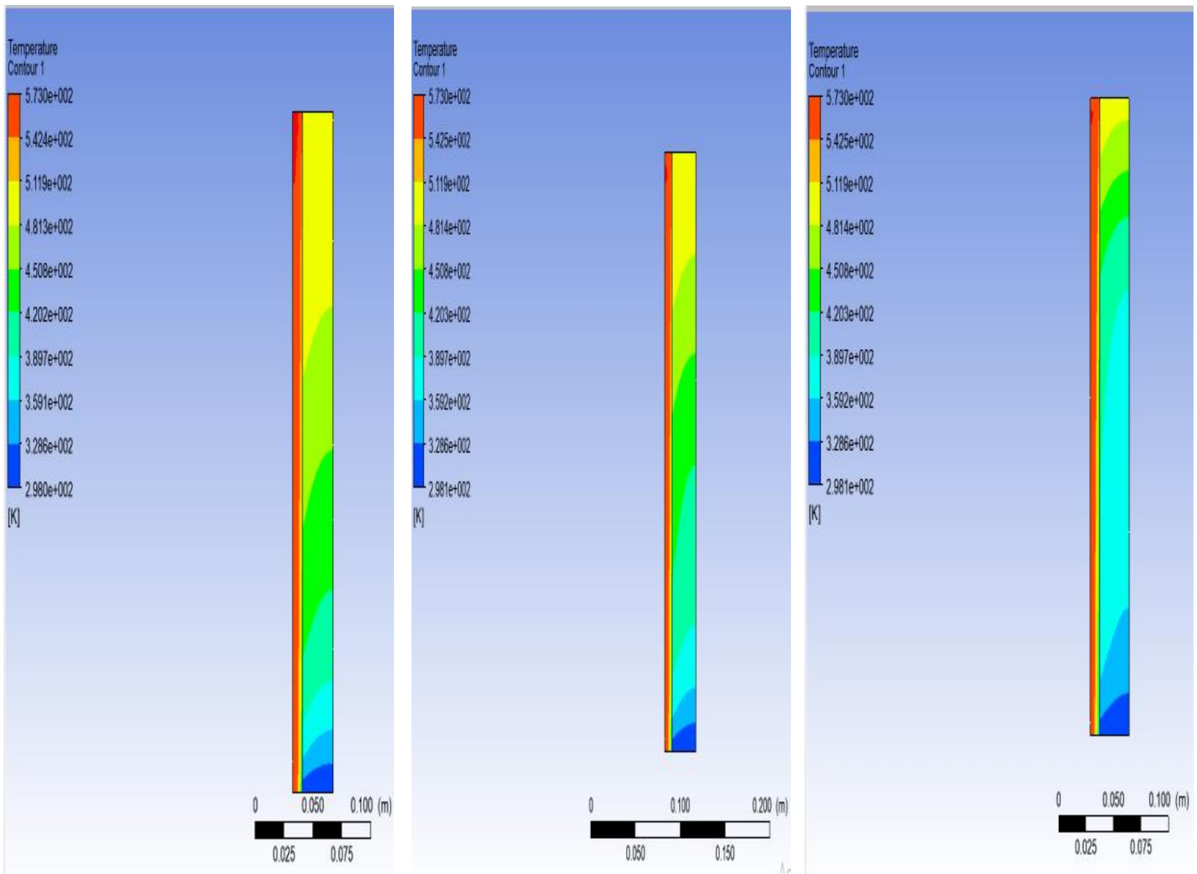
4.1. Mesh independency test

In any computational analysis mesh independency can be considered as the most critical and important process.The quality of the mesh is strongly related to the result of simulation**[59].**So using the same time step size for all and three different mash element size shown table blow;

Table 10 Effect of mesh independency test.

No of horizontal division	No of vertical division	No of elements	No of node
50	100	1000	5252
55	100	11000	5757
70	180	25200	13032

Figure 5 shewn mesh independency test of all three simulation of thermal storage at constant inlet tempreture.But to observe three case results of contoure graph or simple divetion was small at 9%. Therefor,the present simulation thermal storage was chosen number of element 25200 and number of node 13032.In general the mesh fine increase the accuracy of the results increase.



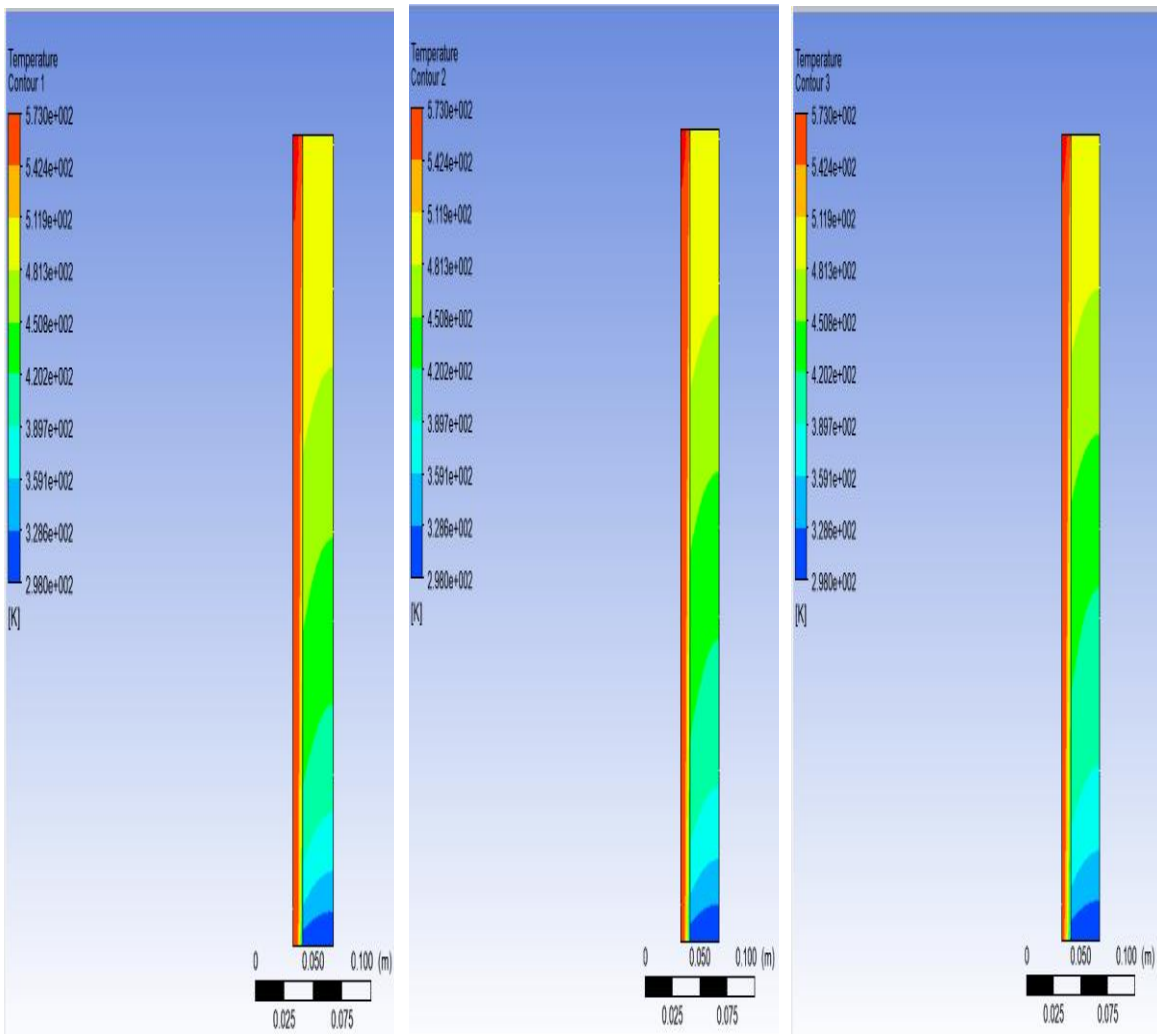
A, $\dot{m}_a$=0.0066kg/s (5 hour) B, $\dot{m}_a$=0.0048kg/s (4hour) C, $\dot{m}_a$=0.0037kg/s (2hour)

Figure 5: Transient tempearture contour of thermal storage for same mass flow rate charging for different hours.

4.2. Charging Conditions

Temperature of PCM Contour

Figure 6 shows the temperature contour during charging time when the inlet temperature is 573k.The temperature of the inflow heat transfer fluid starts to fall during charging down ward in contrast PCM temperature rise from top to bottom flow pattern.For same charging time, the temperature contour have been observed and the increasing of the stored energy is analyzed. Moreover, from contour graph the yello zone indicates the melting region and the blue zone represent slightly solid region the transition zone denotes the solid-liquid interface.Since,by varying mass flow rate,velocity and fixed time observe the results comparasion blow at fig a, iteration for 5hours and mass flow rate 0.0066kg/s more latent heat store than storage of fig b,c,over kept time. By contrast at fig b,iteration for 5hours and mass flow rate 0.0048kg/s observe that more latent heat store than fig c.In generally,the more the iteration or long time charging more accurate heat storage would be achieved.

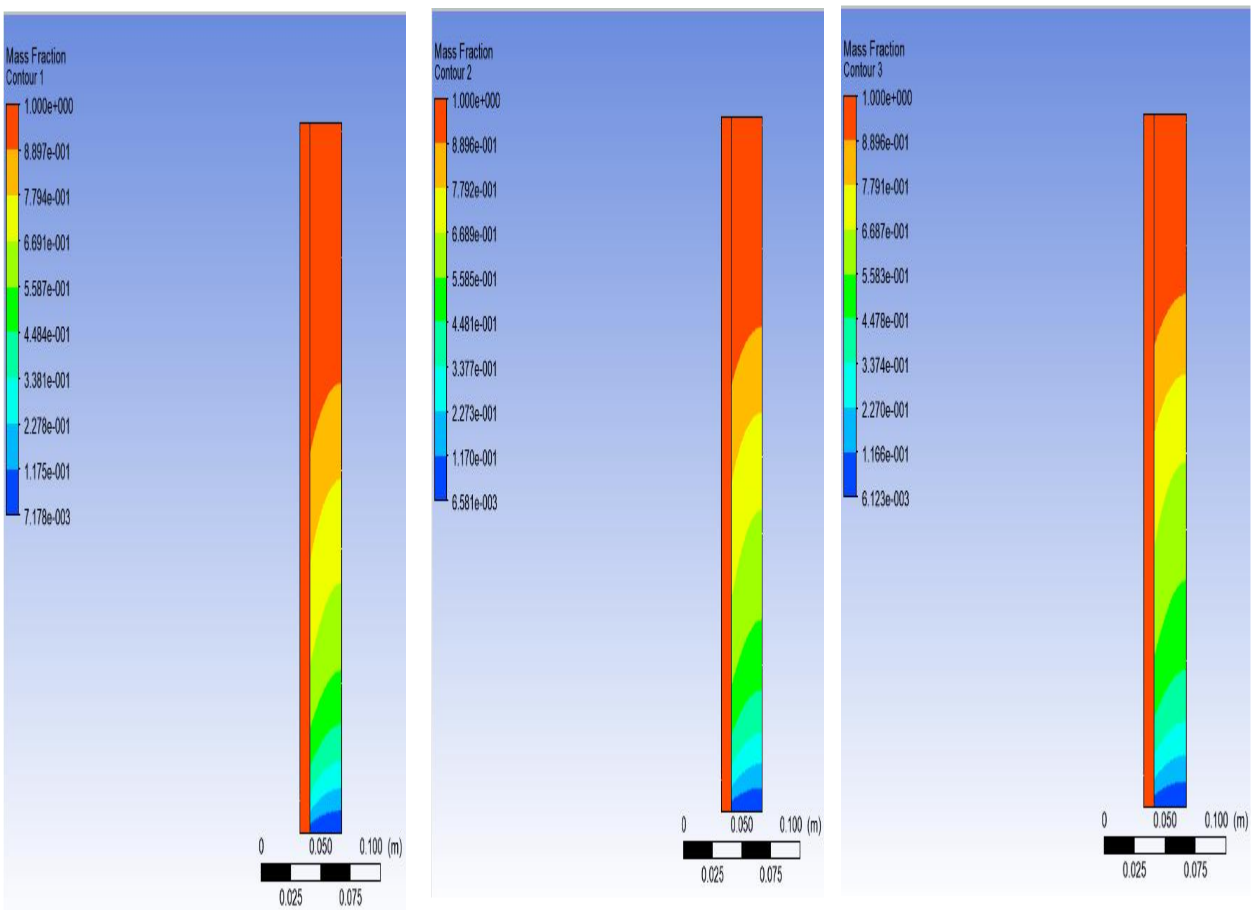


a, $\dot{m}_a$=0.0066kg/s (5 hour) b, $\dot{m}_a$=0.0048kg/s (5hour) c, $\dot{m}_a$=0.0037kg/s (5hour)

Figure 6: Transient tempearture contour of thermal storage for different mass flow rate after charging for 5 hours.

Liquid fraction results

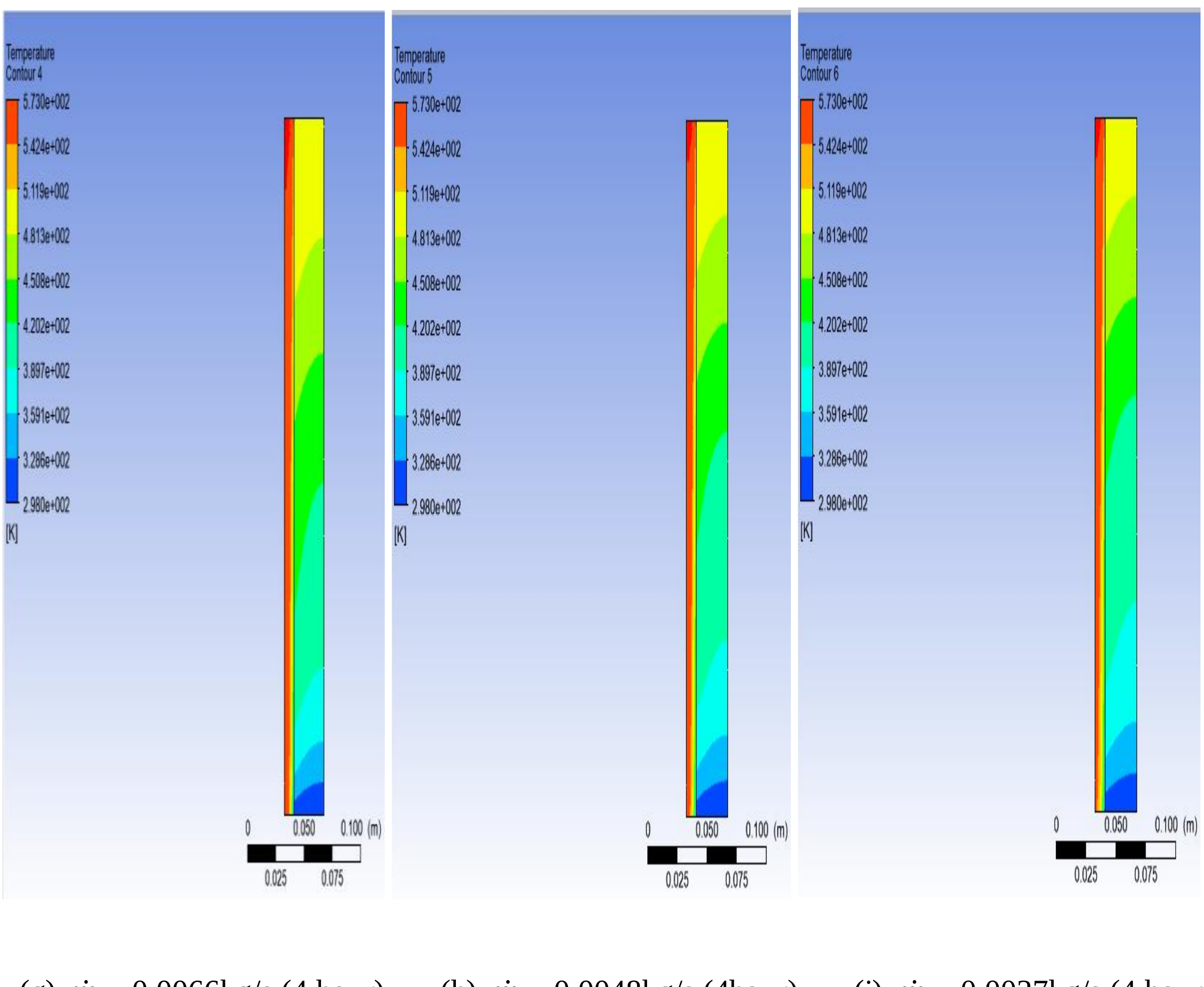
Figure 7 shows that the variation of liquid fraction contour within fixed time for thermal storage. However, the variation of liquid fraction indicates that the PCM is completely liquid at inlet (top) 1 and solid slightly (sensible heat) 0 at bottom of storage. but, change gradually liquid fraction from 0 to 1 that means latent heat storage formed. By comparing melting of PCM with different mass flow rate, velocities of pump and fixed time that means at iteration 18000(5hours) and mass flow rate 0.0066kg/s it more melting liquid fraction and more latent heat store than Fig f,g,. Again at iteration 18000(5hour) and mass flow rate 0.0048kg/s this more melted and more heat storage than Fig g, unfortunately due to the change mass and velocities of pump result get different. A among more mass flow rate has better latent heat energy storage than small mass flow rate.in addition to completely melt PCM more time is required close to the bottom wall.



(d), $\dot{m}_a$=0.0066kg/s (5 hour)   (e), $\dot{m}_a$=0.0048kg/s (5 hour)   (f), $\dot{m}_a$=0.0037kg/s (5 hour)

Figure 7: Transient melting fraction contour for different mass flow rates after charging for 5 hours.

Figure 8 shows temperature contour during charging at constant inlet temperature of 573k. Repeating the same procedure like figure 7, figure 8 have generated as it is shown in blow. When heat transfer fluid is made pass through the outer copper pipe the PCM contain in pipe which is adjacent to the pipe takes heat transfer by conduction and start melting PCM but, to avoid loss heat transfer fluid adiabatic half of top and pipe for this simulation. Through this proses copper materials are used 2mm thickness in order to increase heat transfer rate and reduce resistance influence of melting rate. Because thickness increase heat resistance to heat transfer.The melting heat transfer temperature start to fall axial during and radial charging in contrast PCM temperature rise from top to bottom flow pattern.Through different time contour graph can observe that increasing more and more stored heat from start to end.Moreover, from contour graph the red zone indicates the melting region and the blue zone represent slightly solid region the transition zone denotes the solid-liquid interface.Based on during charging storage different mass flow rate and velocity of pump used.Hence,by varying mass flow rate,velocity and fixed time shows the results blow at fig g iteration 14400(4hours) and mass flow rate 0.0066kg/s relatively slightly change is observe in the heat storage of fig h,I,kept time.By contrast at fig h iteration 14400(4hours) and mass flow rate 0.0048kg/s seen that more heat store than fig i.In generally,the more the iteration time and mass flow rate more accurate heat storage.So the best after 4hours melting time more store heat.

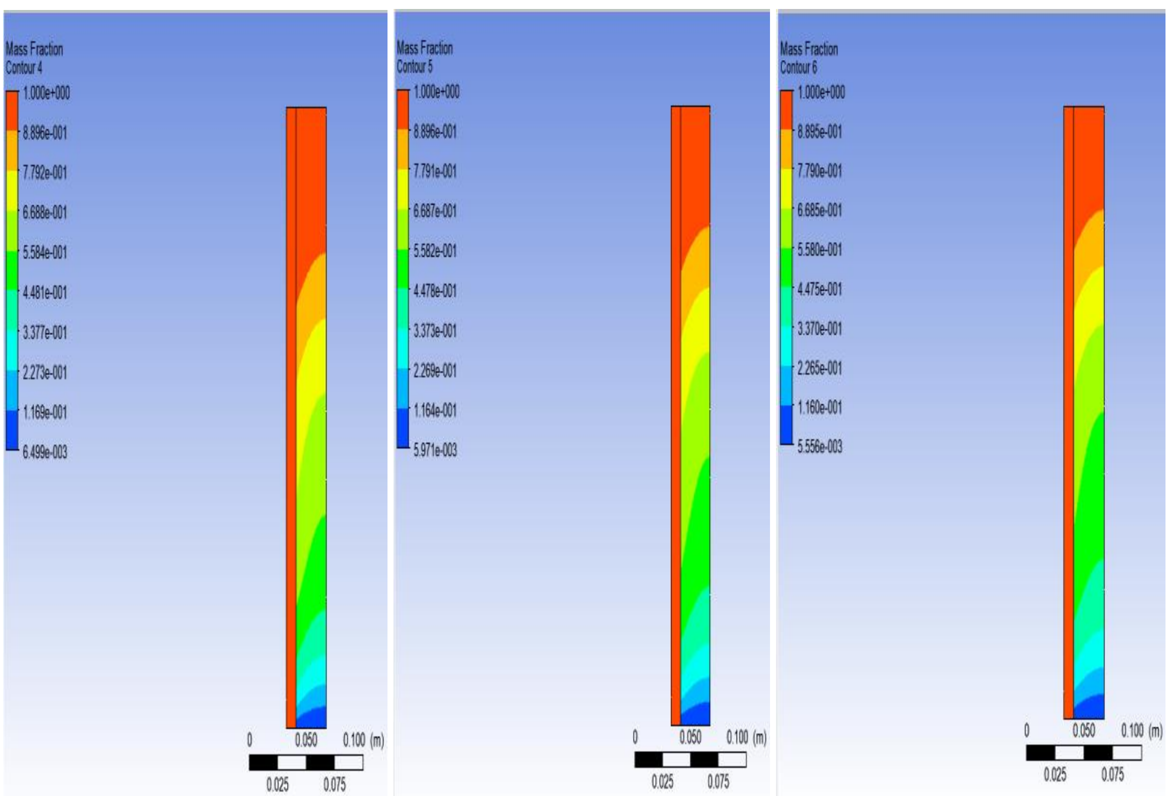


(g), $\dot{m}_a$=0.0066kg/s (4 hour) (h), $\dot{m}_a$=0.0048kg/s (4hour) (i), $\dot{m}_a$=0.0037kg/s (4 hour*)*

Figure 8: Transient temperature contours of thermal sorage for different mass flow rates after charging for 4 hours

Liquid fraction results

Figure 9 shows the variations of liquid fraction contour with in fixed time and constant melting temperatures at 573k. However the variation of liquid fraction indicated that the PCM is completely liquid at inlet (top) 1 and solid slightly (sensible heat) 0 but, change gradually liquid fraction from 0 to 1 that means latent heat storage formed. By comparing melting of PCM with different mass flow rate, velocities of pump and fixed time that means at fig j iteration 18000(4hour) and mass flow rate 0.0066kg/s it can observe that more melting liquid than fig k,l but much time is required to melt the PCM close to the bottom wall. Again at iteration 14400(4hour) and mass flow rate 0.0048kg/s this more melted and more heat storage than fig,8 unfortunately due to the change mass and velocities of pump result get different due to more mass flow rate has better latent heat energy storage than small mass flow rate.in addition to completely liquid fraction get more time needed. Among the more the iteration time and mass flow rate more accurate heat storage melting 4 hours and below variation in total heat storage time so the best after 4hours melting time more store heat.



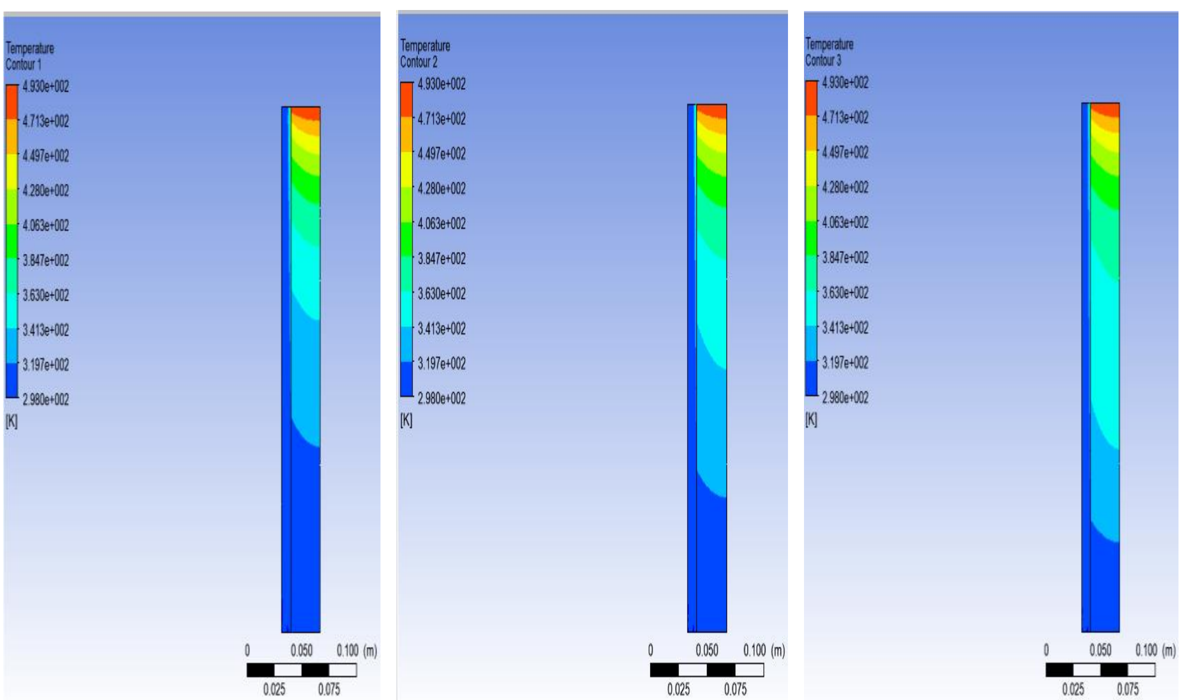
(j),$\dot{m}_a$=0.0066kg/s(4hour) (k),$\dot{m}_a$=0.0048kg/s(4hour) (l),$\dot{m}_a$=0.0037kg/s(4hour)

Figure 9: Transient melting fraction contours of thermal sorage for different mass flow rates after charging for 4 hours

4.3. Discharging thermal storage conditions

During charging there is a considerable temperatures variation throughout the storage until the phase transition is completed.But during discharging the storage temperature decreases at very small difference phase change temperature and heat transfer fluid.

In **Figure 10** discharging contour graphs show that the temperature of the PCM starts to fall from the bottom of the container to the initial temperatures of PCM up to 298k. The PCM starts to losses their heat and the air temperature start to slightly rise. Moreover, at flow time of about iteration 18000(5hours) and mass flow rate, 0.0066kg/s the PCM temperatures gradually decreases original shows fig 10, A this was losses of heat in terms of the stored energy as it could be extracted out of heat from PCM.further illustrated by the contour graph at Fig9, B **i**teration 14400(4hours) and mass flow rate 0.0066kg/s that flow time fail less solidification and more latent contain. Again to shows Fig9, C at iteration 10800(3hours) and mass flow rate 0.0066kg/s the discharging proses decrease solidification by decrease time and better latent heat for cooking purpose. Among from three cases at mass flow rate constant and time varies causes PCM to start to reals heat energy than the other at small-time when time increase solidification increases.

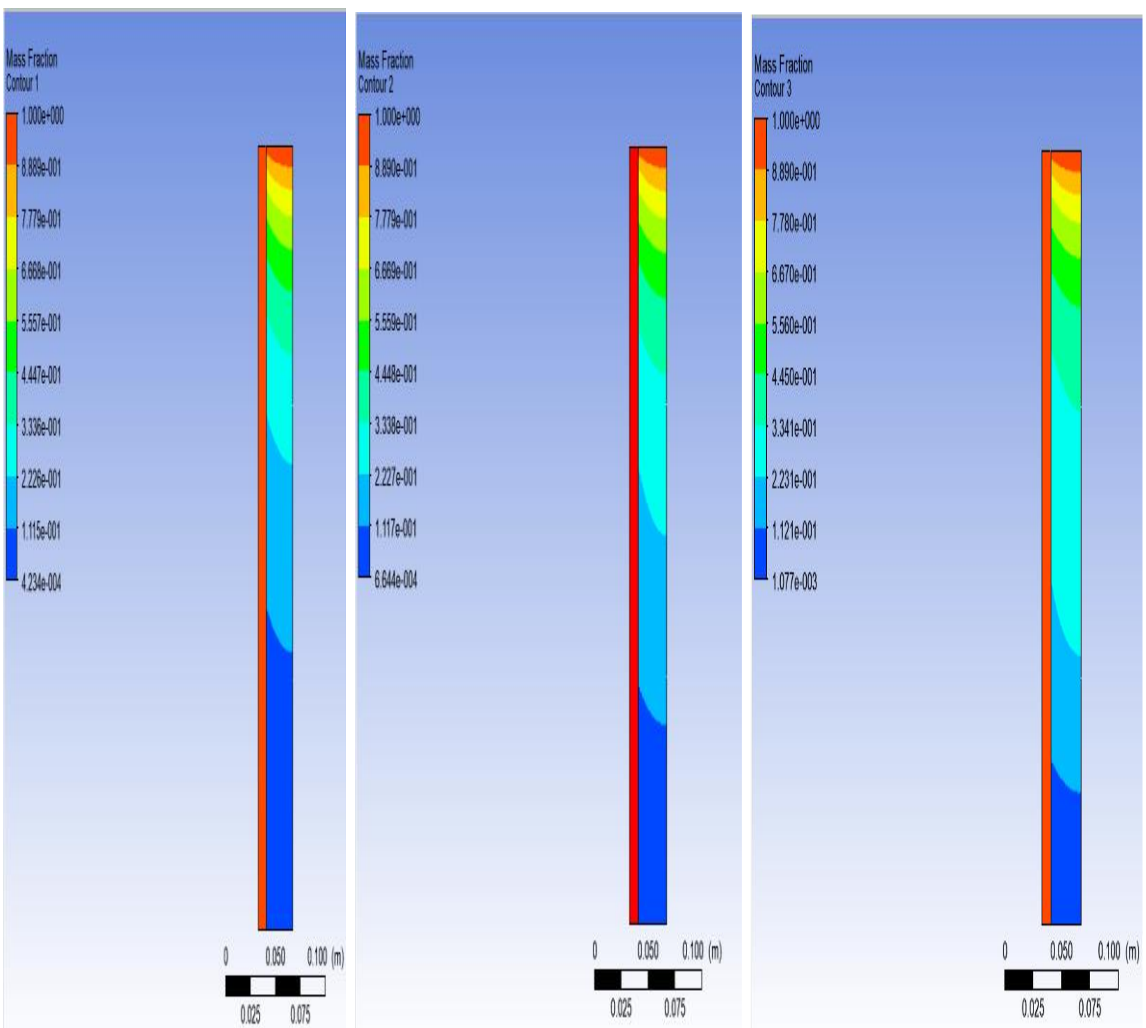


(A),$\dot{m}_a$=0.0066kg/s(5hour) (B),$\dot{m}_a$=0.0066kg/s(4hour) (C),$\dot{m}_a$=0.0066kg/s(3hour)

Figure 10: Transient temperature contours at different discharging time for the constant mass flow rate.

Liquid fraction results

In **Figure11** analysis shows that during discharging mode as melting fraction decrease from bottom to top of container due to releases of heat from PCM. At bottom of container approximately melt fraction blue zero and at the top almost 1. Indeed when the iteration 18000(5hours) and mass flow rate 0.0066kg/s at Fig11, D its more solidified. In contrast at the iteration 14400(4hours) and mass flow rate 0.0066kg/s at Fig11, F less solidified than fig11, D its more latent heat storage. Again iteration 10800(3hours) and mass flow rate 0.0066kg/s at Fig11, E its better latent heat storage than the other two cases. Therefore, the flow rate constant and discharging time varies got results in different graphs.

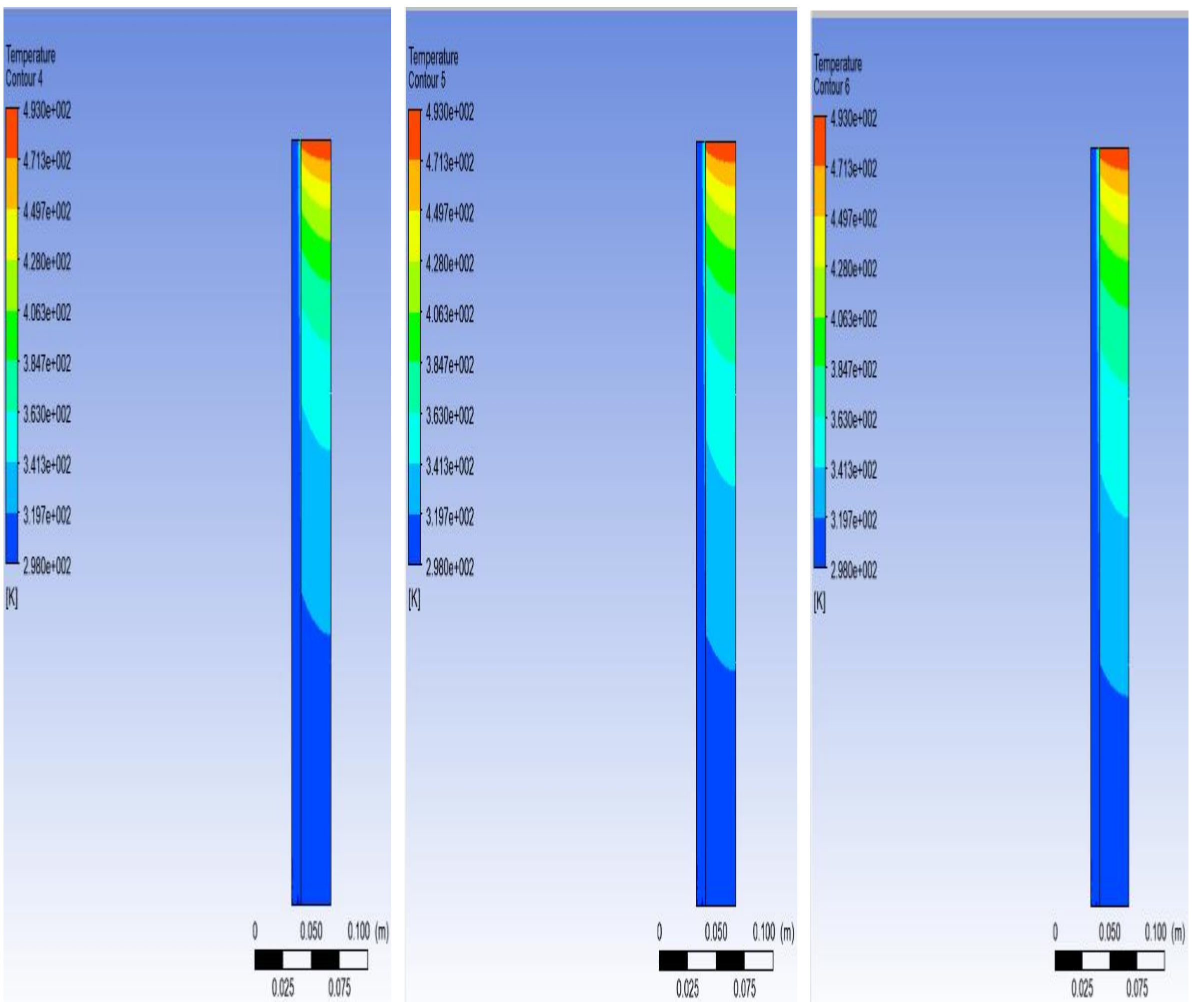


(D),$\dot{m}_a$=0.0066kg/s(5hour) (F),$\dot{m}_a$=0.0066kg/s(5hour) (E),$\dot{m}_a$=0.0066kg/s(5hour)

Figure 11: Melting fraction contours for the same mass flow rates at different discharging time.

Discharging thermal storage effect for varying mass flow rate

This can be attributed to latent heat reals during solidification. However, reals of its latent heat **figure 12** show a similar pattern of all figure blow. But, from fig12 blue 298k PCM and red 493k and the storage discharged at different mass flow rate pump velocity and time fig12,G for the flow rate 0.0066kg/s the thermal storage was discharged rapidly due to high velocity and mass flow rate, while at fig11, H flow rate of 0.0048kg/s medium solidified than previous but different flow rate, pump velocity and time.by contrast at fig11,I for mass flow rate 0.0037kg/s less solidification than previous 2 cases. In general, in range of mass flow rate 0.0066kg/s – 0.0078kg/s the PCM not fully solidified and more flow rate rapid solidified.



(G),$\dot{m}_a$=0.0066kg/s(5hour) (H),$\dot{m}_a$=0.0048kg/s(5hour) (I),$\dot{m}_a$=0.0037kg/s(5hour)

Figure 12: Temperature transient along the length of storage for different mass flow rates after discharging for 5 hours.

Chapter Five

Conclusion and Recommendation

5.1. Conclusion

Design and analysis of the thermal energy storage (TES) with a chemical composition of solar salts containing 60%$NaNO_3$ and 40%KNO_3 have been carried out.The phase change material (PCM) melts at 220℃, which is suitable for cooking applications, and the components, materials and material types have been chosen on the set of design criteria in order to achieve the less cost-effectiveness and maximum longest storage duration.Moreover, charging and discharging analyses at different mass flow rates have been obtained numerically. While the governing equations and boundary conditions have discretized by using the finite volume method (FVM) to analyze the model in ANSYS Fluent workbench.

Furthermore, the 2D transient numerical simulations were performed by using CFD ANSYS Fluent and the cylindrical shell and tube consisting of the phase change material (PCM) was modeled. The PCM is encapsulated in the cylindrical tube which is ensure a good heat exchanger between the surrounding heat transfer medium and the PCM.The transient temperature and molten fractions during charging and discharging conditions at various mass flowrate were contour graghs obtained. For both conditions, 5 hours charging and discharging times were taken and 573 K inflow constant temperature has been considered during charging and 298 K has considered as input for discharging conditions.While at 5 houre by calculating charging efficiency 70.1% and discharging efficiency36.9% has been obtained.Therefore, it is possible to obtain the maximum energy which is 30096.47KJ during charging, and 83454.83KJ during discharging. It is sufficient energy in cooking for a family of ten members used at night as well as a cloudy day.

5.1. Recommendation

Based on the finding and conclusions of the study,the research recommendation the following points to be considered:

1. It is beneficial to consider experimental analysis of the solar thermal storage integrated to solar concentrator.
2. The energy obtained through simulation which is used for cooking can also be used for other household activities.
3. This research does not include cost analysis due to certain limitations.Therefore,any one interested can use the cost analysis part for further study.

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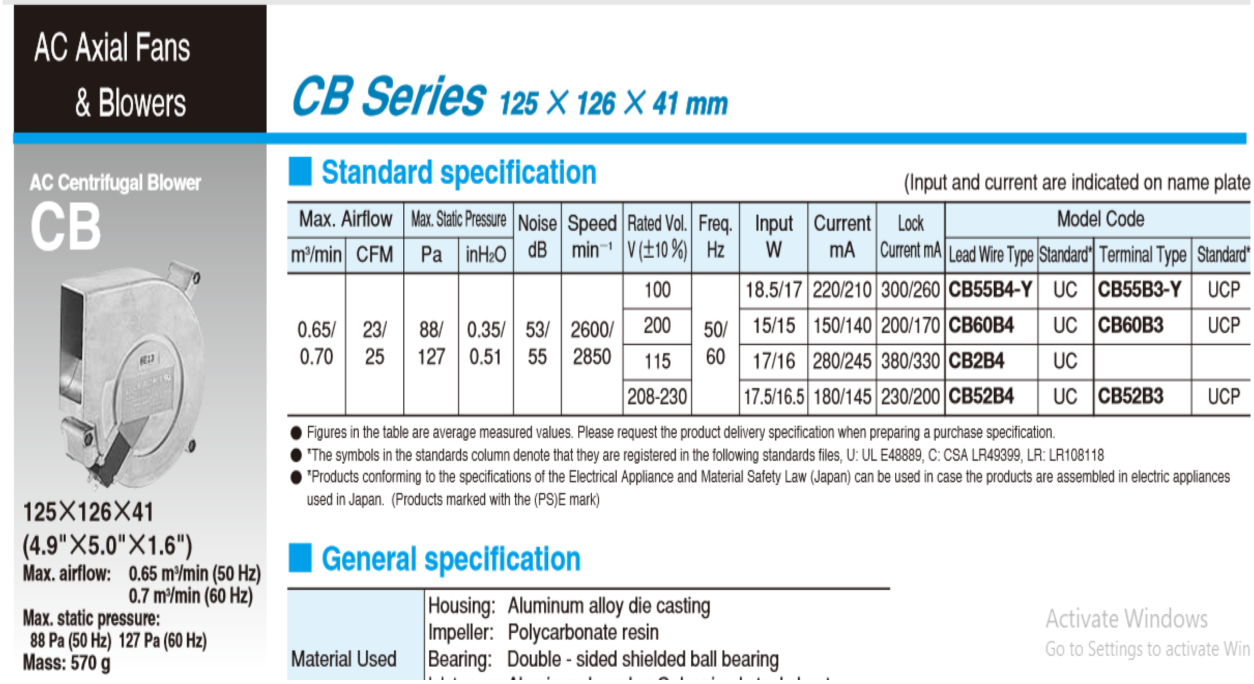
Appendix

Standard catalog of a blower



AC Axial Fans & Blowers

CB Series 125 X 126 X 41 mm

AC Centrifugal Blower

CB

125X126X41 (4.9"X5.0"X1.6")

Max. airflow: 0.65 m³/min (50 Hz) 0.7 m³/min (60 Hz)

Max. static pressure: 88 Pa (50 Hz) 127 Pa (60 Hz)

Mass: 570 g

Standard specification

(Input and current are indicated on name plate

Max. Airflow		Max. Static Pressure		Noise	Speed	Rated Vol.	Freq.	Input	Current	Lock	Model Code			
m³/min	CFM	Pa	inH₂O	dB	min⁻¹	V (±10 %)	Hz	W	mA	Current mA	Lead Wire Type	Standard*	Terminal Type	Standard*
0.65/ 0.70	23/ 25	88/ 127	0.35/ 0.51	53/ 55	2600/ 2850	100	50/ 60	18.5/17	220/210	300/260	**CB55B4-Y**	UC	**CB55B3-Y**	UCP
						200		15/15	150/140	200/170	**CB60B4**	UC	**CB60B3**	UCP
						115		17/16	280/245	380/330	**CB2B4**	UC		
						208-230		17.5/16.5	180/145	230/200	**CB52B4**	UC	**CB52B3**	UCP

- Figures in the table are average measured values. Please request the product delivery specification when preparing a purchase specification.
- *The symbols in the standards column denote that they are registered in the following standards files, U: UL E48889, C: CSA LR49399, LR: LR108118
- *Products conforming to the specifications of the Electrical Appliance and Material Safety Law (Japan) can be used in case the products are assembled in electric appliances used in Japan. (Products marked with the (PS)E mark)

General specification

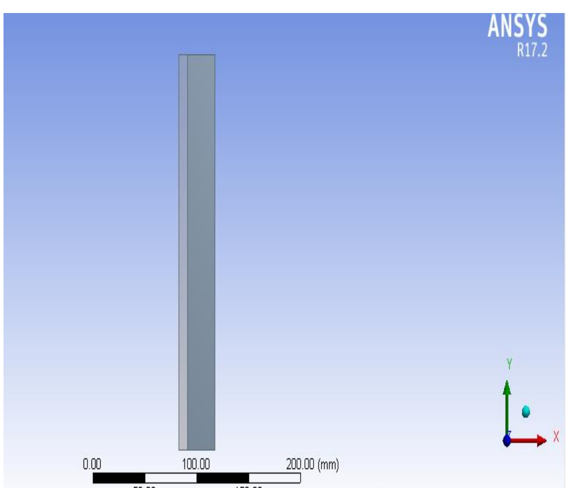
Material Used	Housing: Aluminum alloy die casting Impeller: Polycarbonate resin Bearing: Double - sided shielded ball bearing

ANSYS simulation steps

Charging

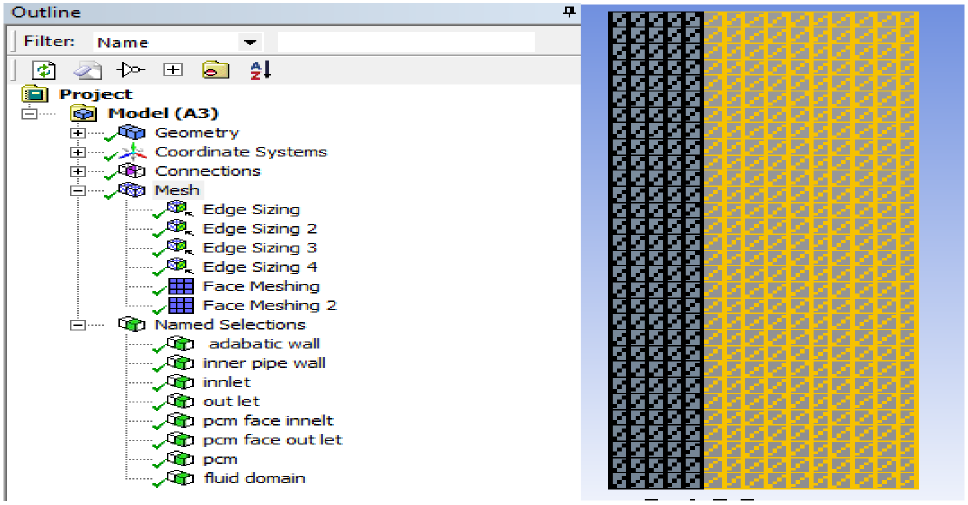
Geometry

The ANSYS Fluid Flow Design modeler was used to first build the geometry. Half HTF and PCM was sketched generated with the different dimensions as 8.5mm and 26.5mm of HTF, PCM, respectively;



Mash

The sizing function was chosen as adaptive with medium smoothing and slow transition to get efficient and smooth mesh. The element size 0.01m with the number of nodes and elements 13032 and 25200, respectively.



Set up

Choosing to put correct materials, boundary condition and iterating solution and results will be generated. Each illustration below;

General

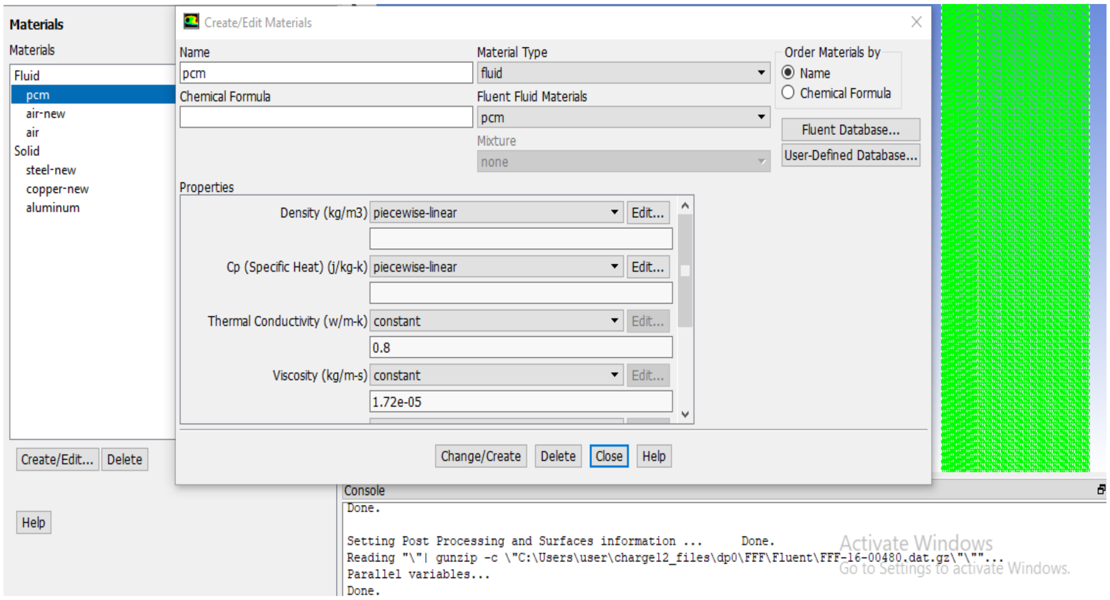
The solver type is pressure based, the time is set as transient, the velocity formulation is absolute velocity and Gravity is setup.

Model

The energy on, Laminar, Solidification and melting on

Materials

Material defined as fluid and solid. The materials considered as fluids were the HTF (air) and PCM. In contrast, the solid materials were steel and copper pipe. Each material was inputted according some of the properties for PCM like the density, specific heat capacity, and temperature were inputted as piecewise-linear.



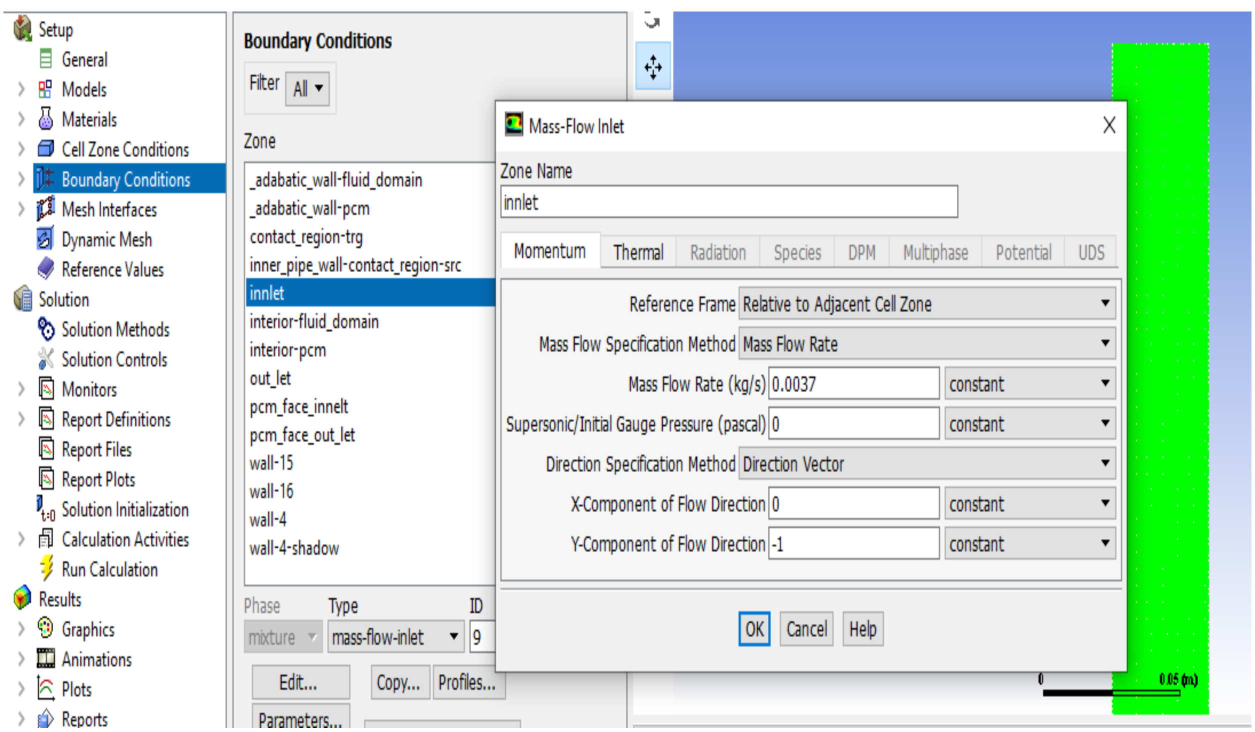
Cell zone conditions

The cell zones are the fluid domain and pcm.

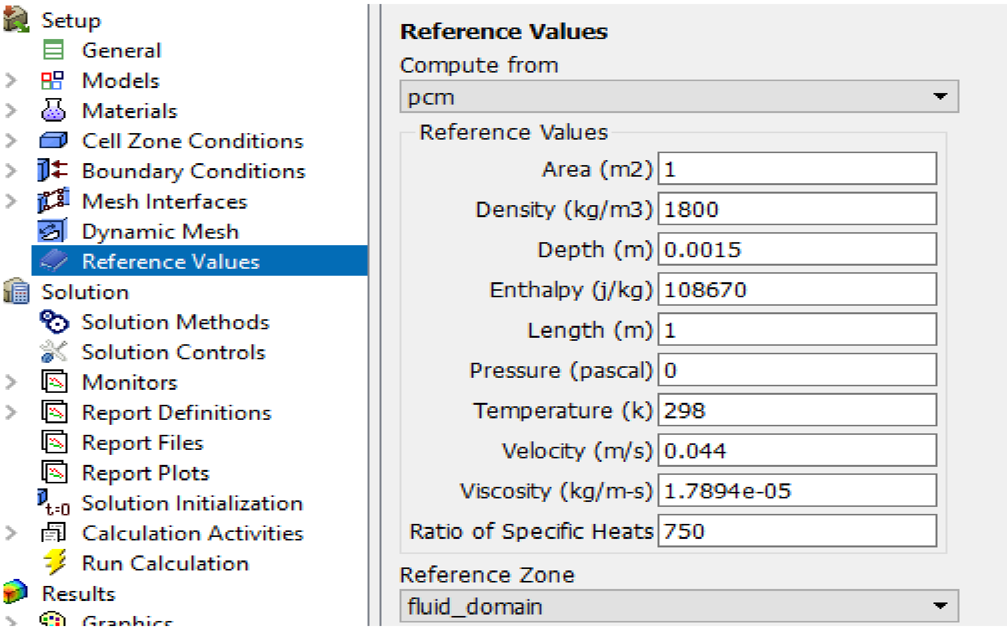
Boundary conditions

For the inlet it was chosen as a temperature 573k, step by step different mass flow

for outlet it was temperature 298k mass flow ret outflow.



Reference values



Solution methods

Solver Pressure velocity coupling

1. Scheme was SIMPLE

2. Spatial discretization gradient

-pressure PRESTO

- Least square cell based

- Momentum second order upwind

-Energy second order upwind

3. Transient formulation second order implicitly

Solution Initialization

The method used is standard initialization of a reference frame that is Relative to Cell Zone and The initial values were a pressure of 1 bar,velocity 0.041m/s temperature of 298k.

Run calculation

The time is used to be transient fixed (30) time step size was chosen and putting different number of time step like,600,480.

For discharging

Since the same step is repeated but some procedure change like;

Mash model

The sizing function was chosen as adaptive with medium smoothing and slow transition to get efficient and smooth mesh. The element size 0.01m with the number of nodes and elements 9982 and 19200, respectively.

Boundary conditions

1. For the PCM inlet (bottom of tank) it was chosen as a temperature 298k, step by step different mass flow rate iteration
2. PCM out let it was temperature 493k.
3. For the HTF inlet (bottom of tank) it was putting as a temperature 298k
4. HTF Out let it putting out flow mass flow rate