Experimental and Numerical Study on Heat Pipe Assisted PCM Storage System

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Master of Science Thesis 2015
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# Experimental & Numerical Study on Heat Pipe Assisted PCM Storage System

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Abstract

In this study, thermal performance, energy storage and cooling capacity of a heat pipe assisted Phase Change Material (PCM) storage system have been investigated experimentally and numerically. The heat pipe assisted PCM storage system can store and release energy efficiently. Heat pipe as a two-phase heat transfer device with very high thermal conductivity can be employed to transfer heat at a high rate and very low-temperature difference. The core idea referred to this system is to improve the capability of storing and releasing energy at PCM storage system by using heat pipe.

In order to study the effect of using heat pipe on energy storage system performance and miniature cooling applications, two different test rigs were built to investigate melting and solidification processes. In addition, a numerical analysis of a heat pipe assisted PCM storage system has been performed. The two systems were modeled using Gambit and Fluent software and validated by experimental results.

Results of case I indicate that it is beneficial for the energy storage system to use heat pipe to increase the heat transfer rate significantly. In other words, the charging and discharging (heat absorption/release) of the storage system can happen faster with a higher power.

Considering the case II, which is designed for the miniature cooling applications, it is found that the system can contribute to cooling process up to 86.7%.

Keywords: heat pipe; phase change materials; heat transfer; melting and solidification
Thesis organization

Chapter 1: Introduction

Chapter 2: Literature review of the thermal energy storage, Phase Change Material, and heat pipe technology

Chapter 3: Experimental setups for case I and case II

Chapter 4: Numerical modeling

Chapter 5: Experimental results and discussion for the case I

Chapter 6: Experimental results and discussion for case II

Chapter 7: Electronics cooling application

Chapter 8: Experimental results compare with numerical ones for cases I and II

Chapter 9: Conclusion and future works
Acknowledgement

First of all, thanks God to assist me during the whole life to accomplish this thesis. I would like to express my appreciation for individuals who have helped me during my master thesis research. I have achieved valuable knowledge in science and engineering through the pursuit of this work, which could not be possible without the assistance of the people around me.

I would like to appreciate Dr. Rahmatollah Khodabandeh and PhD student Morteza Ghanarpour, who is my major supervisors, for great support to provide me such opportunity to accomplish this research in the fields of thermal energy storage, phase change material and heat pipe technology. I would also like to express my deepest thanks to Ph.D. student Mohammadreza Behi for great assistance during this work.

Hamidreza Behi

4th of Apr 2015
## Abbreviations and Nomenclature

### Symbols

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<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>$C_p$</td>
<td>Specific heat capacity</td>
<td>J/(K.kg)</td>
</tr>
<tr>
<td>$D_t$</td>
<td>Phase change half temperature range</td>
<td>K</td>
</tr>
<tr>
<td>$D_x$</td>
<td>Dimension range</td>
<td>m</td>
</tr>
<tr>
<td>$Q$</td>
<td>Heat transfer rate</td>
<td>W</td>
</tr>
<tr>
<td>$K$</td>
<td>Thermal conductivity</td>
<td>W/(m.K)</td>
</tr>
<tr>
<td>$A$</td>
<td>Unit of area</td>
<td>m$^2$</td>
</tr>
<tr>
<td>$H$</td>
<td>Enthalpy</td>
<td>J/kg</td>
</tr>
<tr>
<td>$T_f$</td>
<td>Fluid temperature</td>
<td>K</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Solid temperature</td>
<td>K</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>The Stefan-Boltzmann Constant</td>
<td>W/(m$^2$.K$^4$)</td>
</tr>
<tr>
<td>$L$</td>
<td>Latent heat</td>
<td>J/kg</td>
</tr>
<tr>
<td>$m_i$</td>
<td>Mass flow rate</td>
<td>kg/s</td>
</tr>
<tr>
<td>$M$</td>
<td>Mass</td>
<td>kg</td>
</tr>
<tr>
<td>$P$</td>
<td>Power</td>
<td>W</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
<td>ºC</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>Temperature difference</td>
<td>ºC</td>
</tr>
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### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>GHG</td>
<td>Greenhouse gas emission</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td>LHTES</td>
<td>Latent heat thermal energy storage</td>
</tr>
<tr>
<td>PCM</td>
<td>Phase Change Material</td>
</tr>
<tr>
<td>TES</td>
<td>Thermal Energy Storage</td>
</tr>
<tr>
<td>RT42</td>
<td>RUBITHERM® RT</td>
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1. Introduction

Energy is a basic source for all human activities on the earth. Recently, energy demand has increased very fast due to the high energy consumption in various fields. For a long time, fossil fuels have supplied all human requirements. These fossil fuels have created enormous problems such as CO₂ & GHG emissions that led to environmental problems, like global warming and ice melting in north and south poles. Moreover, the cost of fossil fuels rose in last decades, and it is assumed to continue in future years because of increasing energy demand. Thus, in order to decrease the dependency on fossil fuels another source of energy must be improved. It is expected renewable energies participate the significant role for energy supply in the coming future years. Renewable energies are almost sustainable and decrease tremendously CO₂ & GHG emissions rather than fossil fuels. More or less all kind of renewable energies are hold up by their high capital costs and their availability. Another important point to these types of energy sources are large fluctuations (on the daytime scale), i.e. and big differences in energy availability [2,3]. This flashing and fluctuation issue can be solved by the energy storage system. Furthermore, in order to increase the efficiency of heat transfer in an energy storage system utilizing devices like a heat pipe can be feasible. The energy storage system that embedded in the heat-transfer device in useable manner can be converted into the practical form of a new idea. In fact, Energy storage diminishes the maladjustment between supply and demand and gets better performance, efficiency and reliability of systems and has a significant point in conserving energy. Moreover, utilizing the energy storage and heat transfer devices can save the fuels and makes the system more cost effective by reducing the waste of energy and cost.

Phase Change Materials (PCMs) are known as latent heat storage materials that are utilizing in thermal energy storage systems. Latent Heat based Thermal Energy Storages (LHTESs) have tremendous advantages like high storage density, non-hazardousness to the environment, commercial availability, cost effectiveness and small temperature fluctuation. In the first case, PCM storage system embedded with vertical heat pipe was built. For case I thermal performance and heat storage capacity enhancement utilizing heat pipe is investigated experimentally and numerically. Contours of melting and solidification, melting, and solidification rates and PCM energy storage are described.

In the second case, PCM storage system embedded with horizontal heat pipe was built. Thermal performance and heat storage capacity enhancement of phase change material and feasibility of electronic cooling have been considered. The adiabatic section of the heat pipe is covered by a plastic tube as storage container filled with phase change material (RT42). It can store and release thermal energy depending upon the heating powers of evaporator and water circulation of the condenser. Experimental investigations are conducted to achieve the distributions of system temperature from melting performance test. The parameters in this study include the different range of temperature and heat flux for the first and second case respectively.
1.1 Aim

This thesis is built upon that heat pipe assisted PCM storage system can be useful for thermal energy storage and heat transfer cooling. Relevant research questions should be considered to evaluate the report as follows:

- How much can heat pipe assisted PCM storage system contribute to sustainable development and thermal energy storage?
- How could heat pipe-assisted PCM storage system enhance heat transfer cooling influence?
- What kind of equipment and methodologies could help to achieve mentioned aims?

1.2 Objectives

Thermal energy storage enhancement plays a significant role to improve the overall energy system efficiency and achieve a sustainable future. Utilizing energy storage increases the energy security of the system. The thermal energy storage attributes to system optimization through peak and periodic energy saving. For instance, it can influence on industry energy peak saving, electronic cooling and building energy saving. The energy charge/discharge rate is one of the most crucial factors to consider the required cooling and heating demand. Therefore, the overall goals of this thesis are as follows:

- Utilizing Heat Pipe-PCM storage system to improve the capability of storing and releasing energy
- Applying the Heat Pipe-PCM storage system to harness the periodic waste heat
- Using the Heat Pipe-PCM technology for electronic cooling application
- prediction of thermal energy storage enhancement and electronic cooling by accurate numerical modeling
1.3 Energy Sources

In thermodynamic energy is the capacity of a physical system to do work. Totally, the sources of energy have classified into two main groups; renewable and non-renewable. The non-renewable energy sources because of replenish rate are categorized in "limited resources" that will slowly decrease. Therefore, because of consumption and replenish rate they are going down, and their prices increase. Also, most of the non-renewable energy sources are environmentally damaging due to a large amount of CO₂ and GHG emission [4]. The major nonrenewable sources to produce heat and electricity are fossil fuels and uranium for nuclear power generation.

Renewable resources are a natural resource that time of replenishing is lower than the time of usage. Solar, wind, biomass, hydropower and geothermal are some examples of renewable energy. The main renewable sources to produce heat and electricity are hydropower, solar and biomass. However, renewable energy sources are not available anytime. For example, solar energy is not available at night or wind energy can be stopped in some part of day or night. Therefore, it is necessary to store the energy when it’s available and use it in peak demand time. This kind of energies can be stored as electricity, potential or heat.

Basically, heat is a kind of energy in transfer rather than as work or transfer of matter, which is related to the vibration of atoms and molecules in any material. When the speeds of the atoms/molecules increase in a material, it is getting warmer. This heat is related to the heat capacity of materials. Sometimes, phase change happens in an energy content of a material in a constant temperature. It can be clearly seen in the Fig. 1 that when phase change occurs through a material like water, it releases or absorbs energy as heat. Therefore, water vapor can be condensed which releases energy with higher quality compared to liquid water [5].

Figure 1. Latent heat exchanges of energy involved with the phase changes of water [5]
The energy can be transferred through heat flow in different ways namely conduction, convection, radiation and most cases by a combination of them.

1.4 Heat Transfer and Energy Storage

Heat is a form of energy that transfers between two systems with a temperature difference. According to the first law of thermodynamic the internal energy of both systems changes during the heat transfer. In General, heat transfer classified in three major mechanisms including Conduction, Convection, and Radiation. In energy storage systems conduction and natural convection are most common heat transfer mechanism. Different mechanisms of heat transfer are shown in Fig. 2.

![Figure 2. Different mechanism of heat transfer](image)

**1.4.1 Conduction**

The energy that is transported due to molecular motion and interaction is named Conduction heat transfer. Conduction heat transfer is based on molecular vibration through solids. The conduction heat transfer process can be calculated based on the heat transfer per unit area (W/m²), which is proportional to the temperature gradient dT/dx and the constant of proportionality that is called thermal conductivity k (W/m. K) [7].

\[
\frac{Q}{A} = -k \frac{dT}{dx}
\]  

Eq- 1.1

The thermal conductivity k (W/m. K) depends on the substance and temperature of a material. Thermal conductivity of some typical materials are shown in Table 1.
Table 1. Thermal conductivity of typical materials [7]

<table>
<thead>
<tr>
<th>Substance</th>
<th>Thermal conductivity (W/m. K)</th>
</tr>
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<tbody>
<tr>
<td>Copper</td>
<td>400</td>
</tr>
<tr>
<td>Aluminum</td>
<td>240</td>
</tr>
<tr>
<td>Cast Iron</td>
<td>80</td>
</tr>
<tr>
<td>Water</td>
<td>0.61</td>
</tr>
<tr>
<td>Air</td>
<td>0.026</td>
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</table>

1.4.2 Convection

The energy that is transported due to bulk fluid motion is named Convection heat transfer. Generally, Convection heat transfer happens due to fluid motion along the surface through gasses and liquids from a solid boundary. In order to calculate the convection heat transfer, Newton determined the heat transfer effect on the area (W/m²) and \( T_s - T_f \) (K) the fluid-solid temperature difference. Frequently, the temperature difference happens across a thin layer of fluid adjacent to the solid surface that named boundary layer. The \( h \) (W/K.m²) is constant proportionality is called the heat transfer coefficient [7].

\[
\frac{Q}{A} = h(T_s - T_f) \quad \text{Eq- 1.2}
\]

Type of fluid and the fluid velocity is two most significant items that influenced heat transfer coefficient.

1.4.3 Radiation

The energy that is transported due to the emission of electromagnetic waves or photons from a surface or volume of materials is named Radiation heat transfer. One of the specific features of radiation is occurring in a vacuum. According to the radiation formula, the heat transfer by radiation is proportional to the fourth power of the surface or volume temperature. The \( \sigma \) is a constant coefficient that is named Stefan-Boltzman, and it is equal to 5.67×10⁻⁸ (W/m².K⁴)[7].

\[
\frac{Q}{A} = \varepsilon.\sigma.T^4 \quad \text{Eq- 1.3}
\]

1.5 Low-grade Energy Storage

By more precise view, lots of low-grade energy can be found all around us. The solar energy, wind energy and waste heat are the most common forms of low-grade energies found surroundings. Moreover, in most factory, industry process, electric devices, and vehicles low-grade energy stream can be seen. Almost, these kinds of energies are flowing as a sensible heat
that can appear as hot exhaust gasses. Totally, a number of exhausted gasses contain \( \text{CO}_2 \) and GHG that have a distractive effect on the environment and lead to global warming. Therefore, because of energy sources importance the field of waste energy is a significant issue and must be considered by researchers [8].

Normally, a process like fuel combustion or chemical reaction have produced waste heat that mostly have not harnessed and released to the atmosphere with little or no attempt to utilize it for useful and economic function. Thus, by harness waste heat in different applications, a considerable amount of non-renewable energy sources could be saved. One of the most important items that should be considered for exhausted heat is the temperature. Waste heat is classified into three major groups as follows in Table 2:

Table 2. Classification of waste heat by temperature [9]

<table>
<thead>
<tr>
<th>Application</th>
<th>Temperature range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-grade energy</td>
<td>30 °C – 250 °C</td>
</tr>
<tr>
<td>Medium grade energy</td>
<td>250 °C – 650 °C</td>
</tr>
<tr>
<td>High-grade energy</td>
<td>650 °C -1650 °C</td>
</tr>
</tbody>
</table>

In this work is tried to focus on the low-grade energy that have the temperature range between 30 °C to 250 °C. A number of methods have been using to recover energy from low-grade heat streams, but their efficiency is not impressive. However, here, utilizing a new idea and method is tried to recover low-grade energy for different application with high efficiency.

1.6 Introduction to energy storage technology

As the energy recovery and energy efficiency became a significant issue on the global stage, thermal storage is becoming more popular. A long time ago, the invention of refrigeration systems and the thermal storage capacity had been utilized to kept food and ice cool during the summer in root cellars and ice houses. PCMs have created an impressive effect on energy storage technology. Impregnated wallboard or concrete, seasonal thermal storage and regulation of facility temperatures are typical usages of thermal energy storage. In the construction of buildings, in order to absorb and save the thermal energy during the day, PCM impregnated wallboard and concrete can be utilized.

In fact, the phase change material melts during the daytime and keeps buildings warm at night through the solidification of the phase change material. This technique can be feasible by filling hollow spaces inside the concrete with small storage of phase change material. The application of seasonal thermal energy storage has its own difficulties. In fact, in order to absorb the summer thermal energy for winter consumption needs equipment in a large scale and high cost to store seasonal energy. One of the most important reasons to use thermal storage is energy efficiency
improvement. Comfort and convenience are also other interesting usages of thermal energy storage which can guaranty the continuous cooling/heating. Another good idea for thermal energy storage is designing clothes that could keep soldiers and worker more comfortable and efficient in work. A number of companies suggest clothing that filled with phase change materials to keep the worker at a constant temperature. The thermal storage in phase change materials can be used for short-term protection of goods, food, medical and electronics industries as well. In order to shelter and staying cool during a primary power outage for expensive back-up generators and sensitive electronics installations in electronics industries, phase change materials can be embedded in the enclosure to guarantee thermal protection for a given period. A phase change material thermal storage system can also be utilized to produce cooling during the day. In fact, nighttime cold is used as a cooling storage material in free cooling systems. Base on high storage density, PCMs can be used for cooling purposes. According to the free cooling system, the cold air at night is used to solidify the PCM and use it in a warm day. The same technology can be used for protection of food and medical products based on their optimum temperature during transport to prevent spoilage. Energy storage technology mainly can categorize as following in Table 3 [11].

Table 3. Classification of Energy storage technologies [10]

<table>
<thead>
<tr>
<th>Mechanical storage systems</th>
<th>Electrochemical storage systems</th>
<th>Chemical energy storage</th>
<th>Electrical storage systems</th>
<th>Thermal storage systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumped hydro storage (PHS)</td>
<td>Secondary batteries</td>
<td>Hydrogen</td>
<td>Double-layer capacitors (DLC)</td>
<td>Sensible heat storage</td>
</tr>
<tr>
<td>Compressed air energy storage (CAES)</td>
<td>Flow batteries</td>
<td>Synthetic nat\44egvDural gas (SNG)</td>
<td>Superconducting magnetic energy storage (SMES)</td>
<td>Latent heat storage</td>
</tr>
<tr>
<td>Flywheel energy storage (FES)</td>
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2. Thermal energy storage

Utilizing latent heat storage system with phase change materials is an efficient way of accumulating and preserving the thermal energy. It has benefits of high-energy storage density and an isothermal nature of a storage process. A great amount of energy is capable of absorbing and releasing in thermal energy storage through PCMs. As an example, processes like melting, solidifying or evaporation need a lot of energies. In fact, when the PCMs changed like solid to liquid and vice versa heat is absorbed or released.
Thus, PCMs unavoidably change their phase with a specific amount of energy and release this energy at a later time. The main difference between the storage of sensible and latent heat is that there is no temperature change in the latent heat storage. In phase change, a huge amount of energy can be stored or released at a constant temperature. Thermal energy can be stored as a change in internal energy of materials like sensible heat, latent heat and thermochemical. A schematic summary of different kind of thermal energy storage is illustrated in Fig. 3 [11].

Figure 3. Different kind of thermal energy storage [11]
2.1 Sensible heat storage

According to the definition of Sensible heat storage, the thermal energy is stored by increasing the temperature of a substance especially a solid or liquid. The amount of sensible heat storage is dependent on the specific heat, temperature change and the quantity of storage material [6]. It can be clearly seen in Fig. 4 the heat transferred to the storage leads to a temperature increase of the storage.

\[ Q = \int_{T_1}^{T_f} m \cdot Cp \cdot dt \]  
Eq- 2.1

\[ Q = m \cdot cp \cdot \Delta t \]  
Eq- 2.2

Because of very low volumetric heat capacity of gasses, they are not utilized for sensible heat (or cold) storage. Water is known as one of the best sensible heat storage because of high specific heat capacity and low price. However, in the temperature range more than 100 °C because of low heat capacity of the vapor is not feasible. Therefore, oils, molten salts, and liquid metals, etc. are utilized at temperatures more than the boiling point of water [13].

2.2 Latent heat storage

Latent heat storage is another method in order to store thermal energy. Latent heat happens with the phase change of materials. The latent heat is the amount of heat that stored throughout the phase change process. Latent heat storage materials or PCMs materials with a solid-liquid phase change are appropriate for heat or cold storage.
When a PCM changes from solid to liquid and liquid to gas, a specific amount of heat is stored. Then, this materials release the absorbed energy when they have the reverse phase change. It is necessary to note that, in this study we have mainly focused on the solid-liquid and liquid–solid phase change [13]. The latent heat of a thermodynamic system can be calculated based on the mass of material (kg), the specific latent heat (J/kg), as follows [14]:

\[ Q = m \cdot L_f \]  \hspace{1cm} \text{Eq-2.3}

There are a number of advantages to using latent heat instead of sensible heat including higher storage density per degree and larger volumetric energy storage capacity. Another significant advantage is related to absorption and release of the energy that store at a constant temperature which makes easier the choice of material to use in the variety of purposes [15]. The schematic graph of latent heat transfer shows in Fig. 5 as follows:

![Figure 5. Heat storage as latent heat [16]](image-url)
2.3 Phase Change Material (PCM)

Utilizing of PCMs is an effective means of thermal energy storage application. Commonly, PCM is named any substance that has ability to reverse solid-liquid transformation and store/release a tremendous amount of energy at a constant temperature or in slight temperature range during the transformation process. In fact, PCM is a material with a capability of storing and releasing a huge amount of energy and high heat of fusion that can be melted and solidified at a particular temperature. The phase of materials change from solid to liquid or vice versa due to chemical bonds breaks in molecular structure [17-18]

Even though utilizing the PCMs as water and ice storages come back into a long time ago, usage of these kinds of materials has increased in recent few decades. First PCM references were introduced by Abt and Lane in 1983[18]. Nowadays, information about PCMs is almost massive containing the results gotten from different fields of material studies. There are two significant features of phase change materials follows: (I) Constant or very small temperature range for phase change (II) High heat of fusion.

According to the figure 3 Phase Change Materials (PCMs) can store vast amounts of heat /cold at very small temperature change. Thus, Phase Change Materials (PCMs) can be functional to design heat or cold storages with high storage density, for instance in the industry, domestic heating, and Vehicles.

2.3.1 PCMs properties

A number of characteristic like thermal, physical, kinetic, chemical and economic properties should be considered to evaluate the thermal performance of phase change materials. Also, a heat of fusion and melting temperature should be considered [20], [21]. The desired thermal properties of phase change materials are perfect to cover proper phase-transition temperature for different application. For instance, high latent heat in order to occupy the minimum possible volume, high thermal conductivity to supply minimum temperature gradients and simplify the charge and discharge of heat. The physical properties should include the small volume changes, high density, and low vapor pressure to prevent high stress on containers and heat exchangers. The most significant item for kinetic properties is no supercooling in the materials because it is hard to control heat transfer and to make sure melting and solidification process happen at the same temperature. The chemical properties are classified as long-term chemical stability, reversible melting and solidification process. Moreover, high adaptability with construction material and high recyclability with environmental and economic issues. Also, it should be non-toxic, non-flammable and non-explosive for safety reasons. Finally, for economic properties the materials should be available and low cost in order to utilize for storage system [22].
2.3.2 PCMs classification

Generally, PCMs have classified into three major groups such as organic materials, inorganic materials, and eutectics. It is interesting to note that most materials do not respect all the properties that mentioned before. It has to be compensated with the system design and variety enhancement methods like utilizing the fins or heat pipe or composite materials in the form of matrixes.

The organic materials are divided into two main groups such as paraffin compounds and non-paraffin compounds. The paraffin consisted of saturated hydrocarbons with the general formula of \( C_nH_{2n+2} \). The most familiar PCM material that utilized in this group is Paraffin wax that is a combination of different hydrocarbons. Esters, fatty acids, and glycols are different elements of the non-paraffin group. According to the variety of properties, each of materials, can be used in different applications. The organic materials also are divided into two main groups such as salt hydrate and metallic. One of inorganic alloys salts and water is salt hydrate that has a general formula of \( AB\cdot nH_2O \). Melting metals and metal eutectics are significant items of the metallic group. It is interesting to note that because of their high weight they are not considered as PCM. Regardless of this, they have a number of useful features such as high thermal conductivity and heat of fusion and low vapor pressure. The third group is eutectics group that related to a mixture of materials (in fixed proportions) that melts and solidifies at a specific temperature. The eutectic group classified into three different groups such as organic-organic, inorganic-inorganic and inorganic-organic that is related to the nature of the components in a composition [15].
2.4 Heat Pipe

The heat pipe is a two-phase heat transfer device in which a large amount of heat can be transferred with a very low-temperature difference. In fact, the heat pipe is a device that plays a role of "superconductor" to transfer the heat in the different application without or the least heat loss. There are two primary benefits to using heat pipe as following:

- There is no need for any external device to circulate the working fluid inside the heat pipe
- Heat pipe is two-phase heat transfer device that has much greater heat transfer coefficient compare to single heat transfer device

A heat pipe as can be shown in Fig. 7 consists of a tubular metal structure that is closed from both sides. Generally, it consists of three major parts such as evaporator, adiabatic part and, condenser. Moreover, inside the heat pipe working fluid is circulating in the liquid and the vapor phases. When a temperature source influences the evaporator part, the liquid vaporizes, therefore, absorb and store a large amount of heat. Then, the working fluid that shows by red arrows travels through the pipe towards the condenser section with increasing the vapor pressure. In condenser section, the vapor transforms back into liquid and releases the latent heat as a heat. Heat sink extracts this heat from the heat pipe. In fact, in the condenser section, heat is taken away by cooling a circuit that could be water or air based. The condensate liquid returns to its original place by capillary force in the wick structure that is indicated in gray [22], [23].

![Diagram of the heat pipe](image)

*Figure 7. Diagram of the heat pipe [24]*

By more precise view in Fig. 7 vapor pressure changes due to friction, inertia, evaporation and condensation effects along the heat pipe. On the other side the liquid pressure changes mainly as a result of friction. According to the zero local pressure gradients at very low vapor flow rates, the liquid–vapor interface is flat near the condenser end cap. The liquid and vapor pressures for moderate vapor flow rates is shown in Figs.8. The maximum local pressure difference occurs near the evaporator end cap. The sum of the pressure drops in the vapor and the liquid across the heat pipe in the absence of body forces should be equal to maximum local capillary pressure. When body forces are present like an adverse gravitational force, the liquid pressure drop is
greater, that shows the capillary pressure must be higher in order to return the liquid to the evaporator for a given heat input. Dynamic effects cause the vapor pressure drop and recovery along the condenser section at moderate vapor flow rates, as it can be seen in Fig. 8 [25].

![Figure 8. Vapor and liquid pressure distribution along the heat pipe (Le, La and Lc are Length of evaporator, adiabatic part and condenser sections) [25]](image)

In Fig.9 the thermal resistance of conventional heat pipe is shown. The transient modeling of the heat pipe operation during startup from the frozen state is highly dependent on thermal processes such as solidification and liquefaction, and those related to rarefied gases. Basically, first and second laws of thermodynamics play a role to analyze the internal thermal processes of a heat pipe as a thermodynamic cycle [26, 27]. Transient heat pipe performance by utilizing a simple thermal resistance model predicted by Zuo and Faghri [26] in the Fig.9.
2.4.1 Heat Pipe advantages and disadvantages

A number of heat pipe advantages are as follows:

- A superconductor to transfer the heat to different applications without or the least heat loss with stable heat delivery
- Better performance in transferring thermal energy compare with copper rod, the best-known conductor [28]
- Very low maintenance
- Transferring a large amount of thermal energy with a low-temperature gradient on the surface of the heat pipe

A number of heat pipes negative aspects are as follows:

Despite unique advantages of the heat pipe, there are a number of negative characteristics that decrease utilizing of the conventional heat pipe. A number of them are like the flooding limit, and some of them have more effect on the performance of a heat pipe [29].
3. Experimental procedure

In this project, thermal performance, heat storage capacity enhancement, and electronic cooling of a heat pipe-PCM storage system have considered experimentally and numerically for melting and solidification purposes in two different test rigs. The heat pipe-PCM storage system is a kind of system that covered by a storage container with PCM. It can store and release heating and cooling energy of any energy source. The core idea referred to this system is to improve the capability of storing and releasing energy at PCM storage system utilizing heat pipe. In order to record the melting, solidification, and phase change data and also the feasibility of this idea two different test rigs were built as follows:

1- PCM storage system embedded with vertical heat pipe

2- PCM storage system embedded with horizontal heat pipe

3.1 Experimental setup for case 1

In order to consider the heat storage capacity enhancement of the PCM, an experimental test rig was built. The schematic of the setup and the illustration of the actual structure is shown in Fig. 10. This setup is consisted of an Aluminum block as a holder, a heat pipe, a plastic tube as PCM storage, a low temperature water bath that can provide hot and cold water, a data logger, T type thermocouples and a personal computer. The heat pipe is made of Cu with a length of 290 mm and diameter of 6 mm. The shape of the heat pipe is tubular. Working fluid inside the heat pipe is water. In order to record the temperature at a different location of PCM storage and heat pipe, nine thermocouples in two different radiiuses and three different heights have attached to the test rig. All the thermocouples are cautiously calibrated, and the expected error of temperature is 0.2 °C.

In order to build the test rig, first of all, a plastic tube have attached to the aluminum block. To avoid the leakage of PCM a washer has been used in the joint of tube and block. Utilizing the three screws and a lid, the tube entirely attached to the block. Inside the block was empty, and heat pipe could through it in order to transfer the heat from the heat source. A water bath selected as a heating/cooling source.
Figure 10. Schematic diagram and setup of the experimental system. (1) water bath; (2) test rig; (3) data logger; (4) personal computer

The melting process has been measured for 50 °C, 60 °C, and 70 °C temperatures. RT42 from Rubitherm Company have been chosen as a PCM. RT 42 is commercial paraffin that is stable chemically. A number of important properties of Rubitherm products and scheme of RT42 are provided in Table 5 and Fig. 11.

![Table 5 and Fig. 11](image)

Figure 11. Picture and important properties of RT42 [30]

<table>
<thead>
<tr>
<th>The most important data:</th>
<th>Typical Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting area</td>
<td>38-43 [°C]</td>
</tr>
<tr>
<td>Congealing area</td>
<td>43-37 [°C]</td>
</tr>
<tr>
<td>Heat storage capacity ± 7,5%</td>
<td>174 [kJ/kg]</td>
</tr>
<tr>
<td>Combination of latent and sensible heat in a temperature range of 35°C to 50°C.</td>
<td>48 [Wh/kg]</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>2 [kJ/kg·K]</td>
</tr>
<tr>
<td>Density solid at 15 °C</td>
<td>0.88 [kg/l]</td>
</tr>
<tr>
<td>Density liquid at 80 °C</td>
<td>0.76 [kg/l]</td>
</tr>
<tr>
<td>Heat conductivity (both phases)</td>
<td>0.2 [W/(m·K)]</td>
</tr>
<tr>
<td>Volume expansion</td>
<td>12.5 [%]</td>
</tr>
<tr>
<td>Flash point (PCM)</td>
<td>186 [°C]</td>
</tr>
<tr>
<td>Max. operation temperature</td>
<td>72 [°C]</td>
</tr>
</tbody>
</table>
It is necessary to write because of PCM impurities the melting point is located between 38 °C to 43 °C.

*Table 5. Important properties of Rubitherm company [30]*

<table>
<thead>
<tr>
<th>RUBITHERM product properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>high thermal energy storage capacity</td>
</tr>
<tr>
<td>heat storage and release take place at a constant temperature</td>
</tr>
<tr>
<td>long-life product</td>
</tr>
<tr>
<td>constant performance over several ten thousands of cycles</td>
</tr>
<tr>
<td>melting temperature range between approx. -10 °C and 90 °C</td>
</tr>
<tr>
<td>easy handling</td>
</tr>
<tr>
<td>ecologically</td>
</tr>
<tr>
<td>harmless non-toxic</td>
</tr>
<tr>
<td>100 % recyclable</td>
</tr>
</tbody>
</table>

In Fig. 10 the systematic configuration of a heat pipe, latent heat thermal storage (plastic tube), thermocouples and aluminum block (holder) can be seen. As it shows in Fig. 10 the heat pipe divided into two parts. One part located inside the holder (down) and the rest of it located in PCM storage (up). The down part plays the role of evaporator and condenser in melting and solidification processes respectively. The melting process happens when evaporator section of the heat pipe placed in the thermal bath and had a direct connection with hot water. Thus, heat is transferred by heat pipe to the PCM and melts it. In the melting process, the upper section of the heat pipe plays the role of the condenser. The solidification happened when the holder placed in the cooling bath. In this process, heat is extracted from the PCM storage by the heat pipe and transferred to the cooling bath. In solidification process, the upper part of the heat pipe plays the role of the evaporator and the down part of the heat pipe play the role of the condenser. In table 6 the main parameter of the heat pipe can be seen.

*Table 6. Main parameter of the heat pipe*

<table>
<thead>
<tr>
<th>Main Parameter of Heat Pipe</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>Thermacore CO.</td>
</tr>
<tr>
<td>Pipe Material</td>
<td>Copper</td>
</tr>
<tr>
<td>Pipe Diameter</td>
<td>6 mm</td>
</tr>
<tr>
<td>Pipe Wall Thickness</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>Pipe Height</td>
<td>290 mm</td>
</tr>
<tr>
<td>Working Fluid</td>
<td>Water</td>
</tr>
</tbody>
</table>
3.2 Physical model of case I

According to the Fig. 8 the physical geometry of the model is consist of an aluminum holder that fixed down a section of the heat pipe and PCM cylinder storage that covered the upper part of the heat pipe. The storage part is filled with RT42 as PCM. Fig. 12 shows the 2D axisymmetric configuration of the system.

The inner radius and length of storage are 18mm ($r_s$) and 190mm ($l_s$) respectively. Also, the radius and length of the heat pipe are 3mm ($r_h$) and 290 mm ($l_h$) respectively.

![Diagram of physical configuration](image)

*Figure 12. The physical configuration of PCM storage system embedded with vertical heat pipe*

3.3 Charging and discharging processes for case I

The melting process recorded for heat source temperatures of 50 °C, 60 °C, and 70 °C. In this step, the holder putted in a thermal bath. According to the Fig. 13 during the beginning of melting process, heat that is transferred from the thermal bath to the heat pipe is mainly used to
warm the heat pipe wall. Afterward, as soon as wall temperature of the heat pipe getting more than the PCM temperature, heat is transferred to the PCM around the heat pipe. Therefore, this process continues until the hole of PCM melted. It is interesting to note that in the beginning heat is transferred as form of sensible until a thin layer of PCM melted. In this step, the form of heat transfer has changed to conduction/convection. By increasing the thickness of melted PCM the effect of convection became more dominant.

At the end of melting process, solidification process has started. The solidification operation is a process for PCM that results from the heat pipe cooling. Therefore, the holder putted in the cooling bath with a temperature of 23 °C. At beginning because of high efficiency of the heat pipe, heat transfer is mainly used to decrease the temperature of heat pipe surface. Then, when
wall temperature of the heat pipe is getting less than the PCM temperature, heat transfer started to cool bath by the heat pipe. Therefore, this process continues until the hole of PCM solidified. It is interesting to note that at the beginning of heat transfer, the natural convection is more dominant. When the thin layer of solid PCM cover the surface of the heat pipe, the mechanism of heat transfer has changed to convection/conduction. By increasing the thickness of solid PCM, the effect of conduction becomes more dominant. The solodification process can be seen in Fig.14.

![Scheme of discharging process, T= 23 ºC](image)

**Figure 14. Scheme of discharging process, T= 23 ºC**

### 3.4 Experimental setup for case II

In order to consider the heat storage enhancement and heat transfer performance in electronic cooling, an experimental test rig was built. This test rig is consisted of two copper blocks as
evaporator and condenser that provide enough heating and cooling power. It is also comprised of a heat pipe, a plastic tube as PCM storage, a data logger, T type thermocouples and a personal computer. In order to record the temperature at a different location of PCM storage, heat pipe, evaporator and condenser eleven thermocouples were attached to test rig and data logger. According to the position of thermocouples temperatures of the heat pipe, PCM, evaporator and condenser were recorded. Six thermocouples located in two different radiiuses of storage (7mm, 18mm) and five thermocouples attached on the surface of the heat pipe. All the thermocouples are cautiously calibrated, and the expected error of temperature is 0.2 °C. A plastic tube (PCM storage) covered the adiabatic section of the heat pipe. To avoid the leakage of PCM two lids were attached to the PCM storage. Utilizing the three screws and two lids, the tube perfectly sealed. The evaporator section of the heat pipe is covered with a copper block that embedded with a cartridge and a power supply. Power supply could afford the enough heating power for evaporator section. The condenser part of the heat pipe was covered with a copper block, which was connected to a loop equipped with a pump that could circulate water with mass flow of 0.0027 (lit/h) to the condenser. The flow rate of circulation water is measured by flow meters with high precision. The schematic of the test rig and the illustration of the actual setup shown in Fig. 15.

Moreover, Two thermocouples were measured the input and output temperature of condenser water. Utilizing the water input and output temperature, heat capacity and mass flow of water the heat transfer by heat pipe was calculated. The melting process has been measured for 50W, 60W, 70W and 80W heat flux. RT42 from Rubitherm Company was chosen as a phase change material. It is also interesting to note that during the entire process, the temperature gradient on the surface of the heat pipe is minuscule. It confirms the usual features of heat pipes and demonstrates its excellent temperature leveling capability and fast transient thermal response.

![Figure 15. Schematic of the test rig and diagram of the experimental system. (1) Power supplier; (2) cartridge; (3) copper block; (4) PCM storage; (5) heat pipe; (6) circulation pump; (7) flow meter (8) data logger and (9) personal computer](image-url)
3.5 Physical model of case II

According to the Fig. 15 the physical geometry of the model is consist of a heat pipe that two copper blocks covered the evaporator, condenser section of heat pipe, and PCM cylinder storage that covered adiabatic part of heat pipe. The evaporator and condenser parts are separated from the PCM storage part and are connected to the power supply and water loop respectively. The storage part is filled with RT42 as PCM. Fig. 16 shows the 2D axisymmetric configuration of the system.

The inner radius and length of storage are 23mm ($r_s$) and 115mm ($l_s$) respectively. The copper blocks for evaporator and condenser section both have a dimension of 60mm*35mm*15mm. The radius and length of the heat pipe are 4mm ($r_h$) and 290mm ($l_h$) respectively.

![Diagram of the physical model](image)

*Fig 16. The physical configuration of PCM assisted heat pipe system, left side: evaporator and right side: heat sink*

The evaporator received the heat from the power supply and heated the storage and heat sink. Heat is absorbed by the storage and heat sink that is connected to a water loop. The PCM will melt (during the charging mode) and absorb some part of the evaporator heat.
3.6 Charging processes for case II

The melting process recorded for different heat flux between 50W to 80W. For melting process enough heat supply in evaporator by power supplier that is connected with a cartridge. On the other side, condenser connected to a water loop that can receive some part of the evaporator heat. According to the Fig. 17 during the beginning of melting process, heat that is transferred from the evaporator to the heat pipe is absorbed by the condenser and the rest used to warm the heat pipe wall. Afterward, as soon as wall temperature of the heat pipe getting more than the PCM temperature, heat is transferred to the PCM around the heat pipe. Therefore, this process continues until the hole of PCM melted. It is necessary to mention that in the beginning the form of heat transfer is conduction until a thin layer of PCM melted. In this step, the form of heat transfer has changed to conduction/convection. By increasing the amount of melting PCM the effect of convection became more dominant.

Figure 17. Scheme of charging process, \( Q = 70 \) W
4. Numerical modeling

This section is based on heat pipe assisted PCM storage system design and its experimental verification. In order to prepare a numerical model, the geometry and mesh are drawn in Gambit software. Then, it is exported to Fluent software to run the calculation and finally got the results. The liquid fraction and temperature distributions of PCM have been reported during the charging and discharging process at different input temperature and heating power source. The model is validated by using the measurements data obtained from the experimental setup.

According to the numerical method, the goal has been to enhance a model to predict accurately the thermal storage performance and electronic cooling application. A conduction only model is proposed for assessment solid form of PCM, whereas a conduction/convection model is
proposed for the evaluation of the mushy zone and liquid form of PCM. In the conduction/convection model, the governing equations are the continuity equation, the momentum equation, and the energy equation [30].

4.1 Error Analysis

The experimental error of the independent variables like temperature and output power (electricity) is specified by the accuracy of the corresponding instrument. Also, the experimental error of the dependent variables like the overall system heat gain/transfer can be considered by experimental error of the independent variables based on the theory of error propagation. The relative error (RE) of the dependent variable \( y \) is calculated as follows [31]:

\[
RE = \frac{dy}{y} = \frac{\partial f}{\partial x_1} + \frac{\partial f}{\partial x_2} \ldots + \frac{\partial f}{\partial x_n}
\]

\[\text{Eq- 4.1}\]

\[
\int (X1 + X2 + \ldots + Xn)
\]

\[\text{Eq- 4.2}\]

According to the above equations the “\( X_i \)” is variable of dependent variable of “\( y \)”. Moreover, the “\( \frac{\partial f}{\partial x} \)” is error of transferring coefficient of variables. The “RME” during the test period can be calculated as bellow [24]:

\[
RME = \frac{\sum_{i=1}^{N} \text{Rel}}{N}
\]

\[\text{Eq- 4.3}\]

According to the above calculation the RME different application is mentioned in table 7.

Table 7. Experimental RME of different variables

<table>
<thead>
<tr>
<th>Independent variable</th>
<th>T (°C)</th>
<th>m (g)</th>
<th>k (W/m k)</th>
<th>( \dot{m} ) (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pm 0.2 )</td>
<td>( \pm 0.01 )</td>
<td>( \pm % 2 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RME</td>
<td>( \pm 0.05 )</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5. Experimental result discussion for case 1

The schematic Dimension of setup is shown in Fig. 19. As mentioned earlier, in order to record the temperature at a different location of PCM and heat pipe, nine thermocouples in two different radiuses and three different heights have attached to the test rig. The temperature variation of the heat pipe and charging curves in a different radius of PCM can be seen in Figs of 21 and 23.

![Figure 19. Dimension of case I test rig with location of thermocouples](image)

5.1 performance of heat pipe

Heat pipe as a superconductor can transfer heat properly and with high efficiency. Based on the experiments the heat pipe that used in the storage system functioned properly. According to the Fig. 20 during the primary stage of the melting process the heat transferred from the thermal bath to the heat pipe is mainly used to heat the wall of the heat pipe and increase the temperature of the heat pipe. Thus, it can clarify the rapid rise of the heat pipe wall temperature during this step. However, as soon as wall temperature of the heat pipe getting more than the PCM temperature, heat is transferred to the PCM around the heat pipe.
Figure 20. Wall temperature profile along the heat pipe length at various times, $T=70\, ^\circ\mathrm{C}$

### 5.2 Charging curves and phase change interfaces

Broad experiments were performed to test the performance of the PCM storage system embedded with vertical heat pipe for the melting operation mode. Therefore, many melting curves of the PCM were obtained. The group of the melting curves at a different height ($h=50, 100, 150\, \text{mm}$) and radius ($r=6, 13\, \text{mm}$) can be seen in Fig. 21.
Throughout of primary time in melting process, PCM storage absorbs the heat transferred by the heat pipe from the thermal bath in the form of sensible heat. Utilizing this heat the temperature of PCM gradually increased to the melting point. The melting process starts once the wall temperature of the heat pipe is equal or higher than the melting point of PCM.

The heat transferred to the PCM by pure conduction before melting takes place, and the temperature increases almost linearly with time. The temperature surrounding the heat pipe rises very quickly due to the low thermal conductivity of the PCM. However, when the PCM reaches melting point and the melting process starts, the raising temperature of the PCM became almost constant. Energy is stored as latent heat and heat transferred to its neighbor region same as with heat absorbed by the phase change interface. This mechanism causes the different trends of temperature variations at the different locations. In measured cases (Fig. 21) the trend of temperature versus time in the radius of 6mm and 13mm compared with each other. It can be clearly seen that the trend in both radiiuses is almost similar, however, in radius 6mm because of its vicinity to the heat pipe compare with a radius of 13mm temperature is a little more.

Figure 21. Scheme of PCM temperature variation for melting process in vertical and radius variation, $T=70^\circ C$, $h=50,100,150 \text{ mm}$, $r=6,13 \text{ mm}$
Fig. 22 shows the temperature distribution of the PCM for charging process at 20 min under the experimental conditions as follows.

I) Water bath temperature: 70 °C
II) Initial PCM temperature: 23 °C

According to the graph it can be seen that temperature variation along the axial direction of heat pipe is less than 1.5 °C that is obviously smaller than that along the radial direction (more than 3 °C), which demonstrate high efficiency and ability of heat pipe to heat transfer. Moreover, because of heat pipe influence region the form of the temperature surface along the radial direction (r = 6 and 13 mm) and the axial direction of heat pipe are more uniform compared with other regions. This phenomenon shows that the heat pipe effective in enhancing the heat transfer process.

5.3 Influences of increasing temperature heat source

It is obvious the bath water temperature had an impressive effect on the melting operation processes. Therefore, significant number of experiments was done to study this effect. Fig. 23 illustrates the effect of bath water temperature on the heat pipe surface temperature and the PCM storage temperature variation, respectively. It is necessary to say that results of different temperature on the radius of 6 mm and 13 mm in the height of 50 mm have chosen to consider the effect of bath water temperature. It can be clearly seen that increasing bath water temperature had a significant and direct influence. According to the test, initial temperature and conditions were same as different water temperature.
Figure 23. Influences of the heat source temperature on the charging process, $T=50 \, ^\circ C$, $60 \, ^\circ C$ and $70 \, ^\circ C$

Since the initial PCM temperature is same in these experiments, therefore increasing the bath water temperature had a direct effect to rise the inlet temperature of the evaporator and a great extent on PCM temperature. It is obvious that phase change time for the temperature of $70 \, ^\circ C$ has decreased tremendously for both radiuses. Our experimental results demonstrate that phase change time for inlet temperature of $60 \, ^\circ C$ is less than 2000 S which is reduced to 1000 S for $70 \, ^\circ C$, this value is. On the other hand, phase change time for temperature of $50 \, ^\circ C$ is more than 2000 S.

5.4 Discharging curves and phase change interfaces

The solidification process is an application of the PCM that results from the heat pipe cooling. The group of solidification curves at a different height (h=50, 100, 150 mm) and radius (r=6, 13mm) can be seen in Fig. 24. According to the Fig. 24, PCM was cooled from the liquid to the solid state. Based on the solidification curves it divided into three different regions. In the first region, heat is being extracted from heat pipe from liquid PCM in the form of sensible and the heat recovered by the cold water. Because heat storage capacity in sensible heat is really smaller than the latent heat, the diminishing rate of the PCM temperature is quicker in this period than in the other periods. Afterward, in solidification point and when it takes place, the process enters into the second period, and the temperature of the PCM diminishes really slower than in the initial period and getting almost constant because of the latent heat effect. Finally, when the solidification of the PCM is complete, again the heat is extracted as sensible heat from the PCM, and this speeds up the declining of the PCM temperature.
Figure 24. Comparison of PCM temperature variation for solidification process in vertical and radius variation, T= 23 °C, h=50,100,150 mm, r=6, 13 mm

In the last three cases (Fig. 24) the trend of temperature versus time in the radius of 6mm and 13mm compared with each other. It can be clearly seen that the trend in both radiuses is almost
similar, however, in radius 6mm because of its vicinity to the heat pipe compare to the radius of 13mm temperature is decreased more quickly.

6. Experimental result and discussion for case II

The schematic Dimension of setup and location of thermocouples is shown in Fig. 25. As it mentioned earlier, in order to record the temperature at different location of PCM, heat pipe, evaporator and condenser eleven thermocouples in two different radius and three different horizontal axis have attached to the test rig.

![Location of thermocouples](image)

Figure 25. Scheme of case II test rig with location of thermocouples

6.1 Performance of Heat Pipe

The wall temperature variation of the heat pipe can be seen in Fig 26. Fig 26 shows the temperature variation of heat pipe in a wide range of time span (0-3000 s). Due to high thermal conductivity of heat pipe, the temperature rose very fast and reached the heat source temperature. Fig 26.b illustrates the primary stage of the PCM melting process, the heat transferred from the evaporator to the heat pipe is mainly used to heat the wall of the heat pipe and increase the temperature of the heat pipe. Therefore, it can clarify the rapid rise of the heat pipe wall temperature during this step. However, as soon as wall temperature of the heat pipe getting more than the PCM temperature, heat is transferred to the condenser section and the PCM storage around the heat pipe. Therefore, this process continues until the hole of PCM is melted.
Figure 26. Wall temperature profile along the heat pipe length at various times, $Q = 70$ W a) by position b) by time

6.2 Charging curves and phase change interfaces

A number of experiments were accomplished to test the performance of the PCM storage system embedded with horizontal heat pipe for the melting operation. Therefore, many melting curves of the PCM and heat pipe were obtained. The charging curves in different radius ($r=7, 18$ mm) of PCM storage shows in Fig. 27 along the horizontal direction ($Z=24, 53, 87$ mm) of the heat pipe.
Throughout of beginning time in melting process, PCM absorbs the heat transferred by the heat pipe from the evaporator in the form of sensible heat. Utilizing this heat the temperature of PCM gradually increased. However, this temperature grow was not significant due to the effect of the condenser. The melting process starts once the wall temperature of the heat pipe is equal or higher than the melting point of PCM. As it can be seen in the Fig.27 the heat transferred to the PCM by pure conduction before melting takes place but as soon as melting process start the heat transferred by conduction/convection form. By accelerating the melting process, the effect of convection also is increased.

The temperature surrounding the heat pipe rises very quickly due to the low thermal conductivity of the PCM. However, when the PCM reaches melting point and the melting process starts, the raising temperature of the PCM are tremendously getting slow. Energy is stored as latent heat and heat transferred to its neighbor region same as with heat absorbed by the phase change.
interface. This mechanism causes the different trends of temperature variations at the different locations. In measured cases (Fig. 27) the pattern of temperature versus time in radiuses of 7mm and 18mm compared with each other. It can be seen that the trend in both radiuses is almost similar, however, in radius 7mm because of its vicinity to the heat pipe compare to the radius of 13mm temperature is more.

![Temperature distribution diagram](image)

**Figure 28. Temperature distribution of the PCM at 20 min. Charging mode, Q = 70 W**

Fig. 28 shows the temperature distribution of the PCM for charging process at 20 min under the experimental conditions as follows.

I) Heating power of power supply: 70 W  
II) Initial PCM temperature: 23 °C

According to the graph, it can be clearly seen that temperature variation along the axial direction of heat pipe that starts by blue color and ends in red color is almost 2 °C that is apparently smaller than radial direction (more than 7 °C), which demonstrate high heat transfer ability of the heat pipe. It is also obvious that because of heat pipe influence, form of the temperature surface along the radial direction (r = 7 and 18 mm) and the axial direction of graph are more uniform compared with other regions. This phenomenon shows that the heat pipe effective in enhancing the heat transfer process.

**6.3 Influences of the increasing heating power**

As it is expected, the inlet heating power on evaporator should have a very strong influence on the charging operation processes. Therefore, significant number of experiments was done to study this effect. Fig. 29 illustrates the effect of inlet heating power on the PCM storage temperature variation. It is necessary to say that results of different heating power on the radius
of 7 mm and 18 mm on a horizontal axis of 24 mm have chosen to consider the effect of heating power inlet. It can be clearly seen that the inlet heating power had a significant and direct influence. According to the test, initial temperature and conditions were same for different heating power.

Figure 29. Influences of the inlet heating power on the charging process, $Q=50W, 60W, 70W$ and $80W$

Since the initial PCM temperature is same in these experiments, therefore the heating power had a direct influence to increase the inlet temperature of the evaporator and a great extent on PCM temperature. It is obvious that phase change time for the heating power of 80 W and 70 W has decreased for both radiuses. Our experimental results demonstrate that phase change time for inlet heating power of 70 W is less than 2500 S, and for 80 W, this value is reduced to 2000 S. On the other hand, phase change time for 60 W and 50 W heating power are more than 3000 S.

7. Heat transfer performance in electronic cooling

Thermal energy storage combined heat pipe system can store latent heat during the off-peak period and releases heat during peak load, which can alter power consumption and decrease the system capacity. These types of energy storage units also have a significant role in the enhancement of electronic cooling in devices such as personal computing, cell phones, digital electronic devices and so on. By the aim of enhancing the performance of electric cooling, a number of researchers have widely investigated the PCM characteristics. However, most PCMs have a significant disadvantage as their thermal conductivity is lower than metal material. In order to improve PCM performance, some ways of utilizing fibers, fins and so on have been used. However, one of the most effective ways is utilizing the heat pipe. In order to estimate the role of case II in electronic cooling applications, following calculation has done as below:
Energy balance equation of the PCM-assisted heat pipe system during a time interval $\Delta t$, from initial time $t_i$ to final time $t_e$, can be expressed as:

$$Q_E = Q_{EAC} + Q_{ESP} + Q_{LOSS}$$  \hspace{1cm} \text{Eq-7.1}$$

Eq-7.1 represent the energy balance between heat supplied ($Q_E$), energy absorbed by condenser ($Q_{EAC}$), energy stored in PCM ($Q_{ESP}$) and heat loss parameter ($Q_{LOSS}$). The value of different components can be calculated from experimental conditions. The energy input by power supply ($Q_E$) is equal to the summation of energy storage in the PCM ($Q_{ESP}$), the energy absorbed by condenser ($Q_{EAC}$) and the total heat loss ($Q_{LOSS}$). Here, the heat loss ($Q_{LOSS}$) mainly assumed the heat loss to ambient at the evaporator and the PCM storage. The energy storage in the PCM is related to the mass and the temperature difference in solid zone, mushy zone and liquid zone. It can be shown as follows:

$$Q_{ESP} = Q_S + Q_m + Q_l$$  \hspace{1cm} \text{Eq-7.2}$$

where

$$Q_S = mc\Delta(t_m - t_i)$$  \hspace{1cm} \text{Eq-7.3}$$

$$Q_m = mL_f$$  \hspace{1cm} \text{Eq-7.4}$$

$$Q_l = mc\Delta(t_f - t_m)$$  \hspace{1cm} \text{Eq-7.5}$$

To have a clearer picture of the system performance and PCM cooling contribution, the balance of energy for one of cases is elaborated (input nominal power is 70W)

According to the PCM mass, PCM heat capacity and temperature difference in solid zone and liquid zone the amount of stored energy is as follows:

$$Q_{ESP} = Q_S + Q_m + Q_l = 92612 \frac{J}{3947 \text{s}} = 7.73 \text{ W}$$

Therefore, based on real input of power supply which was, the amount of absorbed energy by PCM can be calculate as follows:

Absorbed energy by PCM $= \frac{7.73}{66.01} = 11.7 \%$

The energy absorbed by condenser can be calculated based on mass of circulation water, heat capacity and input and out of water temperature.

$$Q_{EAC} = mc\Delta(t_{out} - t_{in}) = 49.73 \text{ W}$$

Absorbed energy by condenser $= \frac{49.73}{66.01} = 75 \%$
Thus:

Absorbed energy by condenser + Absorbed energy by PCM = 86.7 %

PCM storage system embedded with horizontal heat pipe test rig shows that the system can contribute up to 86.7% in the cooling application, and 13.3% is lost to the ambient from the test rig. Moreover, the contribution of the PCM in cooling process could be calculated as follows:

\[
\% \text{ PCM assistance} = \frac{Q_{ESP}}{Q_{ESP} + Q_{EAC}} \times 100
\]

This percentage shows the ratio of heat absorbed by the PCM to the entire transferred heat through the system (except the heat loss). In the discussed case, the PCM could assist about 13.5% the heat pipe for cooling the heat source. Utilizing this arrangement, the size of cooling system and operation of the cooling fan can be decreased.
8. Experimental results compare with numerical for case I and II

8.1 Experimental charging measurement Compare with Numerical curves

The temperature profile of PCM in different radius (r=6, 13mm) and height (h=50, 100, 150 mm) of storage shows in Fig. 30 along the vertical direction of the heat pipe. The continuous lines represent the numerical results while the dashed lines represent the experimental results. By comparing numerical and experimental for the charging process, it is obvious that the results are very similar.
Figure 30. Experimental measurement Compare with Numerical for melting process in vertical and radius variation, T= 70 ºC, h=50,100,150 mm, r=6, 13 mm

Also, it appears that the experimental and numerical curves shapes are almost similar, which indicates that the phenomena are numerically well represented. However, the small difference between the simulation and experiment in some cases can be explained by the fact of conduction/convention influence during the melting process. The maximum deviation for the charging process is calculated 14.8%.

8.1.1 Temperature profile during charging process

Temperature contour of the PCM during melting process (T=70 ºC) can be seen in Fig. 31. Following contours related to the PCM storage embedded with vertical heat pipe. The vertical axis of counters is heat pipe wall (right side), and the horizontal axis is the radius of PCM storage. Temperatures contours show the melting process for six different time periods (10 min, 30 min, 50 min, 70 min, 90 min and 110 min). According to the colors, the melted, and solidified parts are defined from the red to blue areas in melting contours. Thermal transport is happening between the thermal bath and the liquid surface of the PCM. Throughout of primary time in melting process, PCM storage absorbs the heat transferred by the heat pipe from the thermal bath in the form of sensible heat. Utilizing this heat the temperature of PCM gradually increased to the melting point. The melting process starts once the wall temperature of the heat pipe is equal or higher than the melting point of PCM. The heat transferred to the PCM by pure conduction before melting takes place, and the temperature increases almost linearly with time.
Figure 3. Temperature distribution for case I, charging process, $T = 70 \, ^\circ C$
According to the contours in primary time, due to the high efficiency of the heat pipe and low thermal conductivity of PCM the temperature of heat pipe increase very fast and heat transferred to PCM. It is obvious temperature rise inside the PCM storage by increasing the time and solidified layer thickness of PCM storage decrease. It can be seen that after 50 minutes the 50% of PCM temperature is more than melting point and finally at 110 minutes total of PCM storage temperature is more than the melting point.
8.1.2 Liquid fraction profile during charging process

Liquid fraction contour of the PCM during the melting process (T=70 °C) can be seen in Fig. 32. Below contours related to the PCM storage embedded with vertical heat pipe. The vertical axis of counters is heat pipe wall (right side), and the horizontal axis is the radius of PCM storage. The contours of the liquid fraction show the melting process for six different time periods (10 min, 30 min, 50 min, 70 min, 90 min and 110 min). The solidified and melted parts are the blue and red areas respectively in melting contours. Between the solid and liquid area, a mushy zone is observed, the area where phase change is occurring. Thermal transport is happening between the thermal bath and the liquid surface of the PCM. The heat transferred to the PCM by pure conduction before melting takes place, and the temperature increases almost linearly with time. The temperature surrounding the heat pipe rises very quickly due to the low thermal conductivity of the PCM. However, when the PCM reaches melting the point, and the melting process starts, the raising temperature of the PCM is getting slow, and heat transferred mechanism to the PCM is convection/conduction.

According to the contours with increasing the time, the solidified layer thickness of PCM storage decrease and the liquid fraction increase. It can be seen that after 50 minutes more than 50% of PCM storage is melted and finally at 110 minutes total of PCM storage is melted.
Figure 32. Liquid fraction distribution for case I, charging process, T= 70 °C

8.2 Experimental discharging measurement Compare with Numerical

In discharging data, the numerical results are still similar with the experimental ones. As it mentioned for charging process the temperature of PCM in different radiuses (r=6, 13mm) and heights (h=50, 100, 150 mm) of storage along the vertical direction of the heat pipe is presented.
The temperature profile along the vertical direction during the discharging process with water bath is plotted in Fig. 33. The continuous lines represent the numerical results, and the dashed lines represent the experimental results. It can be clearly seen that numerical and experimental curves for the discharging process are very similar. In fact, it indicates that the phenomena are numerically well represented. In some curves in Fig. 33 because of convection effect there is a small difference between experimental and numerical data. The maximum deviation for the discharging process is calculated 16%.

**8.2.1 Temperature profile during discharging process**

Temperature contour of the PCM during the solidification process (T=23 °C) can be seen in Fig. 34. Following contours related to the PCM storage embedded with vertical heat pipe. The vertical axis of counters is heat pipe wall (right side), and the horizontal axis is the radius of PCM storage. Temperatures contours show the solidification process for seven different time periods (10 min, 30 min, 50 min, 70 min, 90 min, 110 min and 130 min). According to the colors, the solidified, and melted parts are defined from the blue to red areas in solidification
contours. Thermal transport is happening at the interface of the liquid surface of the PCM and cooling water bath.
According to the Fig. 34, PCM was cooled from the liquid to the solid state. Utilizing heat pipe the temperature of PCM decreased to the solidification point. The solidification process starts once the wall temperature of the heat pipe is equal or less than the phase change temperature of PCM. In primary time, the heat transferred from the PCM to cooling bath by convection before solidification takes place, and the temperature decreases almost linearly with time. As soon as solidification starts the PCM is solidified surround the heat pipe wall, and heat transfer mechanism has changed to convection/conduction. According to the contours in primary time, due to the high efficiency of the heat pipe and effect of the convection and conduction the temperature of PCM transferred very fast from storage to the cooling water bath. It is obvious temperature decrease inside the PCM storage by increasing the time and solidified layer thickness of PCM increase. It can be seen that more than 50% of PCM is solidified after 70 minutes and finally at 130 minutes total of PCM temperature is less than phase change temperature.

**8.2.2 Liquid fraction profile during discharging process**

Liquid fraction contour of the PCM during the solidification process (T=23 ℃) can be seen in Fig. 35. Below contours related to the PCM storage embedded with vertical heat pipe. The vertical axis of counters is heat pipe wall (right side), and the horizontal axis is the radius of PCM storage. The contours of liquid fraction show the solidification process for seven different time periods (10 min, 30 min, 50 min, 70 min, 90 min, 110 min and 130 min). The solidified and melted parts are the blue and red areas respectively in solidification contours. Between the solid
and liquid area, a mushy zone is observed, the area where phase change is occurring. Thermal transport is happening at the interface of the liquid surface of the PCM and cooling water bath.
In primary time, the heat transferred from the PCM to cooling bath by convection before solidification takes place, and the temperature decreases almost linearly with time. As soon as solidification starts the PCM is solidified surround the heat pipe wall, and heat transfer mechanism has changed to convection/conduction. According to the illustrated contours, initially, due to the high efficiency of heat pipe and influence of convection and conduction in liquid PCM the temperature of heat pipe decrease very fast and heat transferred from PCM to the cooling water bath. It is obvious temperature decrease inside the PCM by increasing the time and solidified layer thickness of PCM increase. It can be seen that after 70 minutes more than 50% of PCM storage temperature is solidified and finally at 130 minutes total of PCM is solidified.

8.3 Experimental charging measurement Compare with Numerical curves

The temperature of PCM in different radius (r=7, 18mm) and horizontal axis (Z=24, 53, 87 mm) of storage shows in Fig. 36 along the horizontal direction of the heat pipe. The continues lines represent the numerical results while the dashed line represent the experimental results. By comparing numerical and experimental data for the charging process, it can be seen that the results have a similar tendency.

Figure 35. Liquid fraction distribution for case I, discharging process, T= 23 °C
Figure 36. Experimental measurement Compare with numerical for charging process in horizontal axis and radius variation, $Q=70$ W, $Z=24, 53, 87$ mm, $r=7, 18$ mm

In fact, it indicates that the phenomena are numerically well represented. However, the difference between the simulation and experiment after phase change temperature in some cases can be explained by the fact of conduction/convention influence especially in a radius of 18 mm
during the melting process. The maximum deviation for the charging process is calculated 16.4%.

### 8.3.1 Temperature profile during melting process

Temperature contour of the PCM during melting process (Q=70 W) can be seen in Fig. 37. Downward contours related to the PCM storage embedded with horizontal heat pipe. The horizontal axis of counters is heat pipe wall (downside), and the vertical axis is the radius of PCM storage. Temperatures contours show the melting process for six different time periods (10 min, 30 min, 50 min, 70 min, 90 min and 110 min). According to the colors, the melted, and solidified parts are defined from the red to blue areas in melting contours. Thermal transport is happening between the power supply and the liquid surface of the PCM. Throughout of primary time in the melting process, PCM absorbs the heat transferred by the heat pipe from the evaporator in the form of sensible heat. Also, some part of the heat is absorbed by the condenser.
Figure 37. Temperature distribution for case II, charging process, $Q = 70W$
Utilizing this heat the temperature of PCM gradually increased to the melting point. The melting process starts once the wall temperature of the heat pipe is equal or higher than the melting point of PCM. The heat transferred to the PCM by pure conduction before melting takes place. However, in phase change time and after that heat transfer mechanism is Conduction/convection. According to the contours in primary time, due to the high efficiency of the heat pipe and low thermal conductivity of PCM the temperature of heat pipe increase very fast and heat transferred to PCM storage. It is obvious temperature increase inside the PCM storage by increasing the time and solidified layer thickness of PCM storage decrease. It can be seen that after 50 minutes the 50% of PCM storage temperature is more than the melting point and finally at 110 minutes total of PCM storage temperature is more than the melting point.

8.3.2 Liquid fraction profile during melting process

Liquid fraction contour of the PCM during the melting process (Q=70 W) can be seen in Fig. 38. Following contours related to the PCM storage embedded with horizontal heat pipe. The horizontal axis of counters is heat pipe wall (downside), and the vertical axis is the radius of PCM storage. The contours of the liquid fraction show the melting process for six different time periods (10 min, 30 min, 50 min, 70 min, 90 min and 110 min). The solidified and melted parts are the blue and red areas respectively in melting contours. Between the solid and liquid area, there is an area where phase change is occurring and called a mushy zone. Thermal transport is happening between the power supply and the liquid surface of the PCM. The heat transferred to the PCM by pure conduction before melting takes place. The temperature surrounding the heat pipe rises very quickly due to the low thermal conductivity of the PCM. Therefore, as it mentioned, heat transfers to the PCM via conduction. However, in phase change time heat transferred mechanism to the PCM is convection/conduction.
According to the contours with increasing the time, the solidified layer thickness of PCM storage decrease and the liquid fraction increase. It is obvious that more than 50% of PCM storage is melted after 50 minutes and total of PCM is melted at 110 minutes.

9. Concluding discussion

Heat pipe assisted PCM storage system is one of the technologies that maybe lead to energy conservation. The thermal energy storage combined with heat pipe attribute to system optimization through peak and periodic energy saving. The work presented here has contributed to the science of Latent heat thermal energy storage (LHTES) as follows:

- Assessment and validation of Heat Pipe-PCM storage system to improve the capability of storing and releasing energy
- Optimization of system integration and evaluation for electronic cooling application and harnessing periodic waste heat
- Prediction of thermal energy storage enhancement and electronic cooling by accurate numerical modeling

9.1 Concluding

A major disadvantage referred to phase change materials (PCMs) is low thermal conductivity. This problem has a negative influence on the rate of energy storage (charging/discharging) in PCM. A number of methods have been proposed by many researchers to cope with this problem in energy storage. In order to enhance the heat transfer rate of an LHTES and electronic cooling unit, the effect of the heat pipe was studied. It is shown that thermal conductivity and heat transfer rate of PCM utilizing heat pipe has been improved. The concept consists of using heat pipe inside the PCM storage in difference temperature and heating power to reach higher charge/discharge rate.

Simulation of a PCM storage embedded with vertical heat pipe demonstrates the wonderful performance improvement of melting and solidification process. In this application, full charge
and full discharge to different heat source temperature were measured. Here, three different heat sources for charge and discharge cycles were performed. The results indicate similar melting and solidification performance trend however by increasing the source temperature, the time of the melting process decreased. To improve the cooling application in electronic devices, a PCM storage embedded with horizontal heat pipe was proposed. Simulation of this application demonstrates peak cooling performance by 86.7% and 13.5% PCM contribution for electronic cooling. In this case, four different heating power sources for charge cycle were performed. The results indicate similar melting performance trend however by increasing the heating power the time of the melting process decreased.

### 9.2 Future works

Numerical simulation with the experimental measurement has here been established as adequate tools for designing of PCM storage embedded in heat pipe system. However, utilizing metal balls and mesh inside the PCM are yet a property that has to be accounted for the model to improve further thermal conductivity performance. Also, under the same operating conditions, Nano-PCM storage can enhance the heat transfer. These enhancements can decrease the time of charging/discharging process. Further research in enhancing mentioned configuration shall be addressed in case specific studies, especially in continuous charge/discharge storage cycling process.
PCM-assisted heat pipe system for electronic cooling

PCM and heat pipe can serve an important role in the enhancement of electronic cooling. This paper investigates experimentally and numerically thermal performance and cooling capacity of PCM-assisted heat pipe system for electronic cooling. An experimental setup consisting of a heat pipe, a cartridge connected to power supply and a cooling water loop has been built. The evaporator section of the heat pipe is embedded in a cartridge supplying heating power. The condenser section is being cooled with water which is circulating in the loop. Moreover, the adiabatic section of the heat pipe is covered with PCM that can absorb part of the thermal energy released in the evaporator. In addition, a validated model of the system is built in Ansys-Fluent for numerical consideration. The model is validated by using the measurements data obtained from the experimental setup. The full charging process of the embedded PCM has been evaluated by the numerical simulation. Experimental and numerical investigations are performed to determine the effectiveness of PCM-assisted heat pipe in electronic cooling. The liquid fraction and temperature distributions of PCM have been reported during the charging (cooling process) at different input powers. The results show that the PCM-assisted heat pipe system can contribute to cooling application in the working range of 50 W to 80 W up to 86.7%. Utilizing the proposed system, size of electronic cooling device and operation of cooling fan can be decreased. The overall efficiency of the system has been improved by using PCM-assisted heat pipe for cooling application.
2. Abstract

Experimental and numerical study on heat pipe assisted PCM storage system

One of the most common disadvantages referred to PCM is low thermal conductivity. This issue affects the rate of energy storage (charging/discharging) in PCM. Different methods have been proposed by many researchers to cope with this problem in energy storage. In this paper, a heat pipe assisted PCM for latent heat storage is experimentally and numerically investigated. The temperature of PCM, liquid fraction observations, and charging and discharging rates are reported. Heat pipe effectiveness is defined and used to quantify the relative performance of heat pipe assisted PCM storage system. Both experimental and numerical investigations are performed to determine the effectiveness of heat pipe-assisted PCM storage system in thermal storage enhancement. While charging or discharging, the heat pipe-assisted PCM storage system could improve the energy transfer between a water bath and the PCM in the working range of 50 ºC to 70 ºC significantly.
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