

ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF GRADUATE STUDIES

SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING

"DESIGN AND OPTIMIZATION OF SOLAR POWER MICRO-REFRIGERATOR AT DIRE DAWA SHINILE"

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A thesis submitted to the School of Graduate Studies of Addis Ababa institute of Technology in partial fulfillment of the Masters of Science in Mechanical Engineering (Thermal Engineering Stream)

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This is to certify that the thesis Prepared by Mohammed Abrasha entitled: Design and Optimization of Solar Power Micro-Refrigerator at Dire Dawa Shinile, and submitted in partial fulfillment of the requirements for the degree of Master of sciences (Mechanical and Industrial Engineering) complies with the regulation of the University and meets the accepted standards with to originality and quality.

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DECLARATION

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The undersigned declare that this project report entitled "**Design and Optimization of Solar Power Micro-Refrigerator at Dire Dawa Shinile"** is the result of my own research carried out under the super vision of Dr. Yilm Tadesse. It has not been presented as a thesis in any other university & all source material used for this thesis are duly acknowledged.

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This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

Dr. Yilma Tadesse _____ _____

Date Signature

ABSTRACT

Energy is one of the key factor for development of the country, and it can be gained from different sources, but some of these sources are not environmentally friendly, expensive and difficult to transport; like fossil fuel. The best option to solve these problems is use solar energy, wind energy and etc. Ethiopia has huge potential for solar energy because it is located close to the equator. Refrigerator is one of the essential tools used in daily. Especially refrigerator is very required for the people who live in desert area for cooling water. The people living in grid connected system use electric powered refrigerator for cooling water, but people living in desert off-grid area can't get electric powered refrigerator. Therefore this problem would be solved when they use solar powered refrigerator. In this work Dire Dawa shinile is study area of this thesis and it located at 9.68° latitude and 41.85° Longitude.

One of the major drawbacks of solar refrigerator technology has been the large battery systems that were required to store the sun's energy for use during the night and cloudy periods. These batteries have a relatively short life time and replacements are expensive. In this work solar power refrigerator optimization is eliminates the expensive energy storage batteries and use ice storage tank instead of battery. PV sizing for solar powered refrigerator is depending on power requirement of compressor by using PVsyst software. The Freeze water in ice storage tank by using the sun's energy which operate compressor of refrigerator and then by using these ice storage to cooling water drink, during solar energy couldn't drive compressor. The net capacity of the refrigerator use for cooling water is 33L and an ice storage of 1kg, is able to maintain 6 liter of water drink temperature below 5℃ as comfortable for drink. The initial cost of solar powered refrigerator is 13,266birr and this cost would be obtain after one year. Solar powered refrigerator system can be reliably used at where the local grid is not continuously available where as refrigeration need is critical.

Key words: Solar energy, photovoltaic (PV), cooling water, ice storage, pvsyst.

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NOMENCLATURE

VSDC	Variable Speed Direct Current
AC	Alternating current
DC	Direct current
PV	Photo voltaic
NOCT	Nominal operating cell temperature
EER	Energy efficiency ratio
COP	Coefficient of performance
δ	Declination
γ	Surface azimuth angle
θ	Angle of incidence
α_s	Solar altitude angle
ω	Hour angle
θ_Z	Azimuth angle
η_t	Efficiency
LPG	Liquid petroleum gas
$V_{in,ref}$	Volume of refrigerator
$V_{ic.st}$	Volume of ice storage
V_{pro}	Volume of product
TEV	Thermostatic expansion valve
$\dot{W}_{comp}$	Compressor work
Q_{cond}	Heat Rejection in Condenser
Q_{ref}	Heat Absorbed in Evaporator
m	Mass of product (kg)
c_p	Specific heat of product (kJ/kg-K)
ΔT	Change in product temperature (K)
θ	Time taken (seconds)
PSH	Peak sun hour
R_{eD}	Reynolds number
N_{uD}	Nusselt number
STC	Standard Test Condition

$T_{1,sto}$	Average temperature of storage
$T_{0,sto}$	Ice temperature
$T_{1,cab}$	External cabinet temperature
$T_{0,cab}$	Internal cabinet temperature
$T_{1,load}$	Initial temperature of load (water)
$T_{0,load}$	Final temperature of load (water)
$T_{1,air}$	Initial temperature of air internal temperature
$T_{0,air}$	Final temperature of air internal temperature
IAM	Incidence Angle Modifier
I	The direct irradiation of solar beams (kw/m^2)
A	Surface area of solar panel(m^2)
E	Energy generated by solar panel

CHAPTER ONE

1. INTRODUCTION

Energy is the ability to do work and essential to mankind as he make use of it in his daily life. It is one of the indispensable factors for continuous development and economic growth. The demand of energy is increasing rapidly in the developing countries due to automation, industrialization and urbanization, The growing population and technological developments have shown that the present sources of energy in use are not adequate. The world population has increased at an explosive rate from 1.65 billion to just over 6 billion people in the 20th century, and continues to increase. In the same century, mankind has consumed over 875 billion barrels of oil and it is very likely that even more oil will be consumed in the present century. Annual energy use in developing countries has risen from 55 to 212 kg oil equivalent over the last thirty years, while developed countries use as much as 650 kg oil equivalent per person[1]. Energy is the demand in the world and obtain energy from many source. Several energy source are not environmentally friendly, expensive and difficult to transport; like fossil fuel. some energy sources are friendly with environment like wind energy, solar energy, bio-gas and etc. Ethiopia has huge potential for solar energy because of it located near the equator with an average daily solar radiation of 5.2 kWh/m^2/day [2, 3].

Solar Photo Voltaic (PV) systems, run on direct current electricity provided by solar energy. This energy used for many application, Solar-powered refrigeration equipment is one of this application. Manufacturers of solar arrays generally state that a properly installed system will provide power for the solar refrigerator for over 20 years with no fuel costs and little maintenance. When compared to diesel fuel power generation in particular, PV is a cost-competitive option, especially in the developing world where electricity and diesel prices are often high.

1.1.Background

In the 1980s, solar refrigerators were introduced in areas without electricity as a solution to the problems cited for gas and kerosene refrigerators. However, one of the major draw backs of solar refrigerator technology has been the large battery systems that were required to store the sun's energy for use during the night and cloudy periods. These batteries have a relatively short life time of 3 to 5 years, and replacements are expensive and sometimes unavailable for local

purchase in low-income countries[4]. For these reasons solar refrigerators have often been abandoned when the battery dies well short of the useful life of the refrigerator itself.

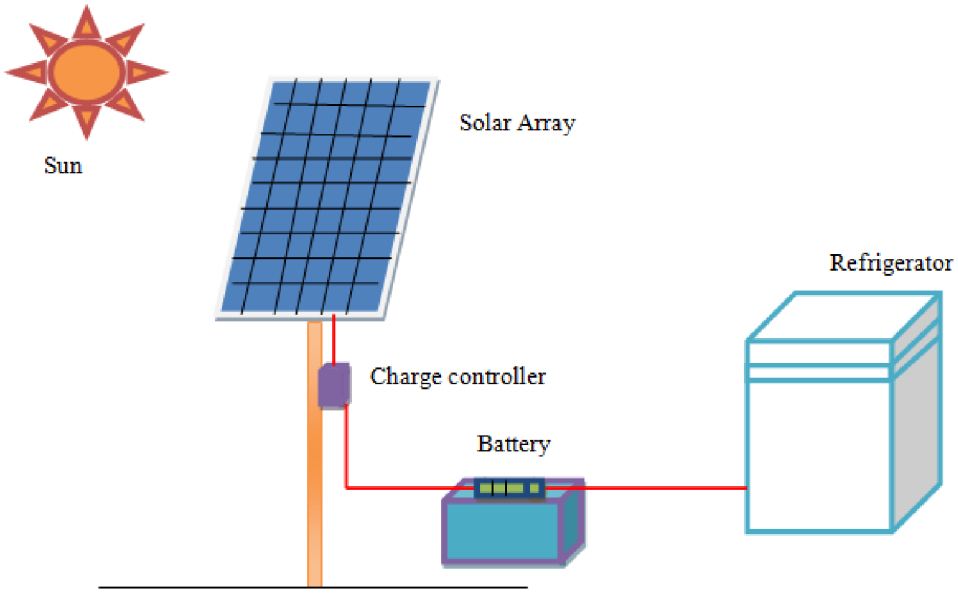


Figure 1- 1: Schematic diagram of solar battery- based refrigerator

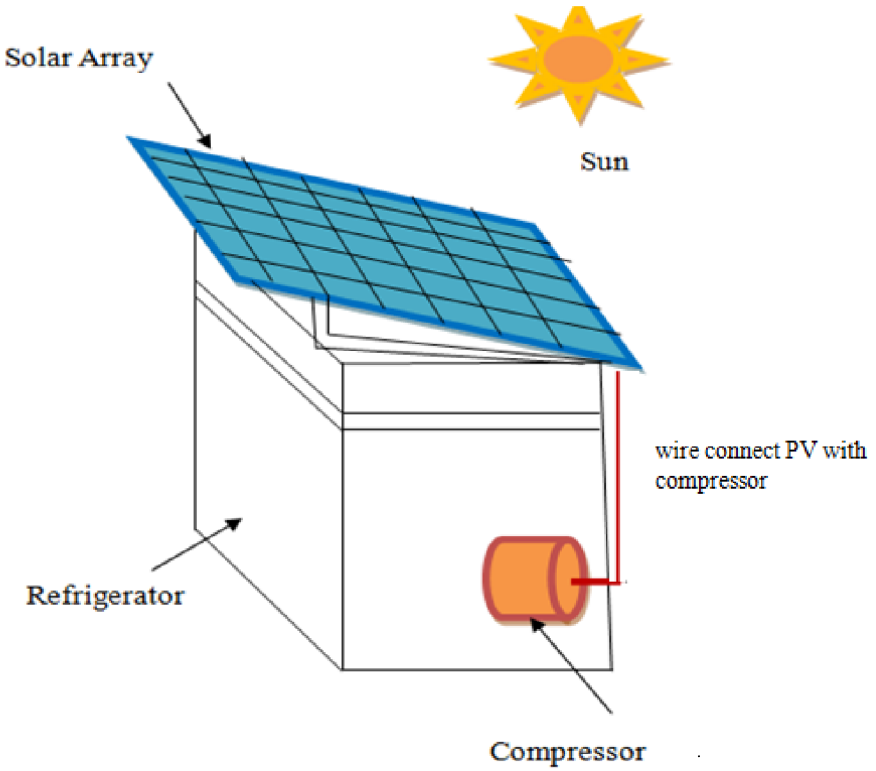


Figure 1- 2: Schematic diagram of solar direct - drive refrigerator.

1.2. System Explanation

The Photo Voltaic refrigerator is based on a compression cycle and is composed of the following elements: A PV module, a DC compressor with a forced air condenser, evaporator immersed in the ice storage tank, ice storage tank, an expansion valve, and the control system.

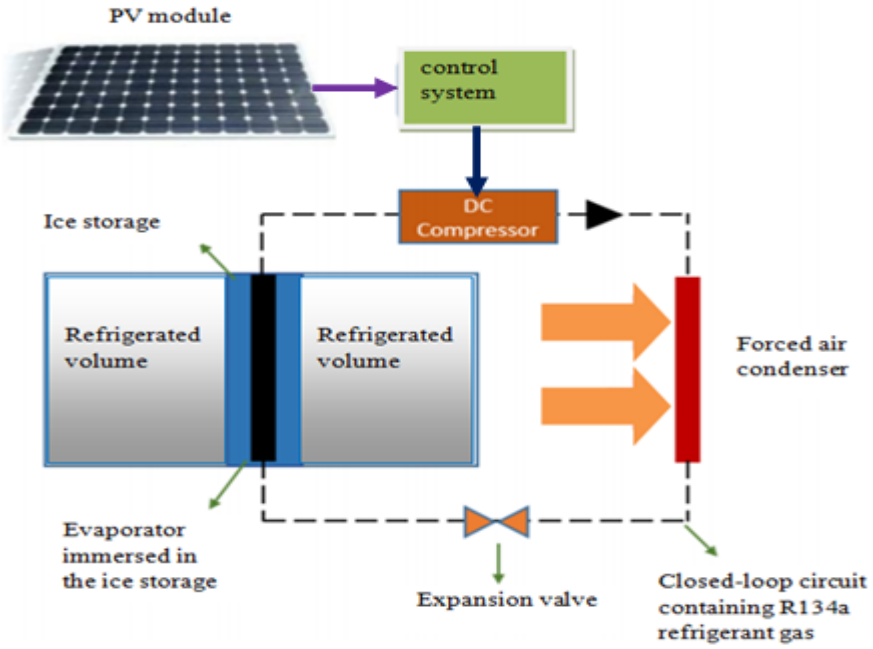


Figure 1- 3: General structure of the system.

In this study, the methodology of converting an AC refrigerator to serve as a DC refrigerator has been explored. A solar powered DC refrigerator operating with a Variable Speed Direct Current (VSDC) compressor has been developed. The design replaces the single speed alternating current (AC) compressor with a VSDC compressor. VSDC compressors are strong candidates to be employed in energy-efficient refrigeration systems, especially for renewable energy technologies, as these compressors do not require power inverters that an alternating current compressor would require. Secondly, these compressors present the option of matching the cooling requirements with refrigerator power consumption there by reducing wastage of energy.

In this thesis study how to eliminates energy storage battery and use storage instead of the expensive energy storage batteries. Direct uses the sun's energy to freeze water or other phase change material and during the night and cloudy days cooling water for drink by using ice storage tank.

1.3. Site Location

Ethiopia is located very close to the equator between $3^0$and 15^0N, receives abundant solar energy potential which can be harnessed and used in the form of both thermal and electrical energy. The average solar radiation of Ethiopia is around 5.2 kWh/m^2/day which is more or less uniform. The value varies seasonally from a minimum of 4.55 kWh/m^2/day in July to a maximum of 5.55 kWh/m^2/day in February and March. With location the radiation varies more widely between 4.25 kWh/m^2/day in extreme western low lands and 6.25 kWh/m^2/day in northern part of the country. Ethiopian Rural Energy Development and Promotion Centre [5] has quantified the technical potentials of solar energy resource use for many applications.

Solar powered refrigerator is essential for different purpose especially in off-grid area. The some part of Ethiopia is desert like Afar, Dire dawa, Borana and etc. Temperature of this area is high, because of hot in that area, people living in this area want cooling water for drink. The people living in grid connecting system use electric powered refrigerator for cooling water, but people exist desert and off-grid area can't get electric powered refrigerator. Therefore this problem would be solve when people exist in desert and off-grid area are use solar power refrigerator. In this work selected site is shinile which locate around Dire dawa. It is locate at 9.68° latitude and 41.85° Longitude.



Figure 1- 4: Map of site location

1.4. Problem Statement

The domestic refrigerator is becoming essential part of life and it is available in different capacities as well as different working models.

Refrigerator is very significant for different function like soft drink, store and keep food, vegetable, fruit, milk, without damage for several period of time and water cooling as appropriate for drink. Some part of Ethiopia is desert and hot environmental climate, due to this case people exist in desert and off-grid area are needs cold water for drinking. But they can't use electric refrigerator as people who exist in urban (grid-connect area). Therefore this problem would be solve when people exist in off-grid area are use solar power refrigerator and also additional advatage is use in area of averge solar radiation is enough to drive the compressor of refrigerator, and in area of low acces to cold water for drinking.

1.5. General Objective

The overall objective of this thesis is study and optimization of solar power refrigerator which is used for cooling water as appropriate for drinking at site location and minimize initial cost of solar powered refrigerator use ice storage instead of battery and also study benefit of solar powered refrigerator.

1.6. Specific Objective

The specific objectives include:

- Collect data of location from different source and compare it;
- Determine energy requirements and other design data;
- study photovoltaic for refrigeration system;
- Design of ice storage;
- Analyze output data and interpret the results;
- Analyze pay back cost;
- Discuss economic and environmental evaluation of the system;

1.7. Delimitation

This research project was intended design and optimization of solar power micro-refrigerator for cooling water drink. In this work not consider huge solar power refrigerator, because of changes of temperature for cold water drinking is low, due to this case power requirement for this refrigerator is also small.

The local limitation: water cooling refrigeration system require in area solar radiation sufficient to drive compressor of refrigerator and not consider for large refrigerator.

1.8. Organization of the Paper

In this thesis describe the background information about solar powered refrigerator in selected site and design and optimization of solar powered micro-refrigerator at dire dawa shinile. This thesis consists of the following chapters:

Chapter 1 ***Introduction***

Introduce the thesis background, problem statement, objectives, delimitations, location site, contributions and organization of paper.

Chapter 2 ***Literature review***

Review the problem of solar powered refrigerator

Chapter 3 *Design and Optimization of solar powered refrigerator*

Solar radiation data analysis, analysis of cooling load, refrigerator component design.

Chapter 4 ***Cost Analysis***

This chapter describes assumptions made to carry out economic analysis of solar powered refrigerator and pay back cost.

Chapter 5 ***Results and discussions***

Summarize the main results achieved in the papers appended to this thesis and high light the main discussions points.

Chapter 6 Conclusions and Recommendations

CHAPTER TWO

2. LITERATURE REVIEW

2.1.1. Solar Terminologies

According to Dan Chiras [6], the solar energy reached each year to the earth's surface is roughly 10k times the total energy consumed by human. As sunlight passes through the earth's atmosphere some of it absorbed, some is scattered and some passes through the molecules in the atmosphere. Solar energy that reaches the earth surface is solar radiation. Nuclear reactions occur in the sun as a result hydrogen is converted into helium with a process called fusion. This reaction caused for the release of large amount of radiation, where its temperature reaches about 15 million degree Celsius [7]. It is part of this energy that strikes the earth's surface. The magnitude of solar irradiance which strike on the surface of the earth depends on latitude, climatologically location parameters like air pressure, cloudiness, etc. Some of the direct applications of solar energy are to heat, to pump, and to desalinate water. Solar energy can be converted in to electricity using different conversion technologies, among which photovoltaic and solar thermal are the basics. Photovoltaic technologies convert the incoming solar insulation directly into electricity. Whereas, solar thermal technologies initially heats water then directs to mechanical systems such as steam turbines to generate electricity. This technology uses mirrors to concentrate the incoming solar energy, it captured in the form of heat. Taking an account for the PV systems and sunshine, it is necessary to take a note of the following important concepts.

Irradiance: It is the power density of the sun, measured in W/m^2. At night and on sunrise times, irradiance is often zero and increases respectively then reaches at its highest value around noon. It again decreases from noon to sunset and dropping to zero at night.

Irradiation: it is the time integral of power density of the sun (irradiance), measured in kWh/m^2.

Air mass: A parameter that influences the quantity of irradiance that is incident on the earth's atmosphere.

Solar constant: The amount of solar radiation incident on the earth's atmosphere at a vertical angle of air mass (AM=0), and its magnitude is about 1367 W/m^2.

Global solar radiation: The total summation of the sunbeam and diffuse radiations. In case of horizontal laid surfaces, global solar radiation is the summation of vertical radiation and diffuse radiation. This is part of the constant solar radiation that hits the ground.

Beam radiation: It is the sunbeam that reaches the earth right from the sun disk.

Diffuse radiation: It is the solar insulation that reaches the ground from the sky where its direction is changed by the atmosphere. The diffuse radiations magnitude depends on solar height, and atmospheric transparency. The higher the cloud in the sky is the higher the dispersed radiation.

Albedo radiation: It is the reflected sunlight from the ground.

Extraterrestrial normal radiation: Is the quantity of solar insulation that arrives on a surface perpendicular to the atmosphere.

Extraterrestrial horizontal radiation: is the quantity of solar radiation reaching on a flat surface positioned on top of the atmosphere. If the entire direct solar radiation source is converted into usable form of energy in the earth, it would be more than enough to supply the energy requirement of the world.

2.1.2. Solar Radiation Model

Solar radiation data provide information on how much of the sun's energy strikes a surface at a location on the Earth during a time period. These data are needed for effective research into solar energy utilization.

2.1.3. Direction of Beam Radiation

The geometric relationships between a plane of any particular orientation relative to the earth at any time (whether that plane is fixed or moving relative to the earth) and the incoming beam solar radiation, that is, the position of the sun relative to that plane, can be described in terms of several angles (Benford and Bock, 1939). Some of the angles are indicated in Figure 2-1. The angles and a set of consistent sign conventions are as follows

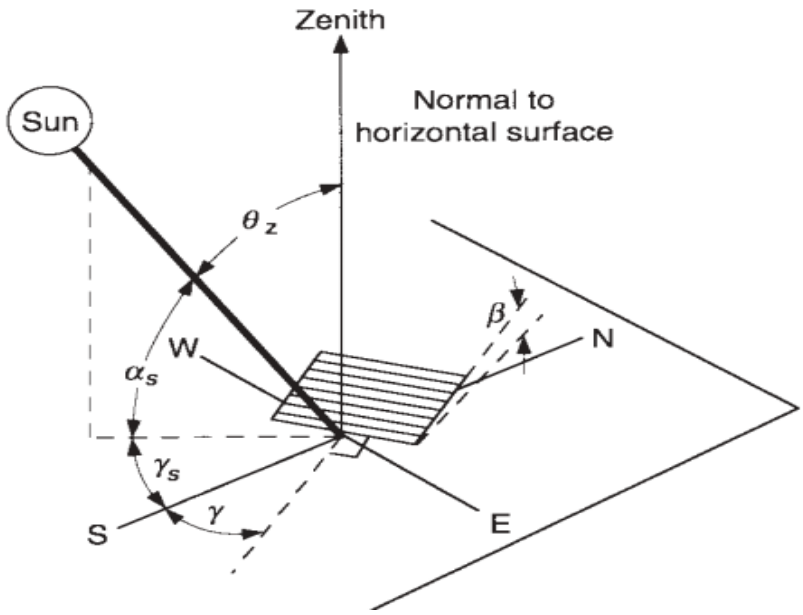


Figure 2- 1: Zenith angle, slope, surface azimuth angle, and solar azimuth angle for a tilted surface (source: solar engineering of thermal processing)

γ Surface azimuth angle, the deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, with zero due south, east negative, and west positive; $-180^{\circ} \leq \gamma \leq 180^{\circ}$.

ω Hour angle, the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour; morning negative, afternoon positive.

θ Angle of incidence, the angle between the beam radiation on a surface and the normal to that surface. Additional angles are defined that describe the position of the sun in the sky:

θ_z Zenith angle, the angle between the vertical and the line to the sun, that is, the angle of incidence of beam radiation on a horizontal surface.

α_s Solar altitude angle, the angle between the horizontal and the line to the sun, that is, the complement of the zenith angle.

γ_s Solar azimuth angle, the angular displacement from south of the projection of beam radiation on the horizontal plane, shown in above Figure. Displacements east of south are negative and west of south are positive.

The sun's declination δ, needed to determine its position, is the angle between the sun's direction at the solar noon and its projection on the equatorial plane (Figure 2-2). It is described by Cooper's equation [8-10]:

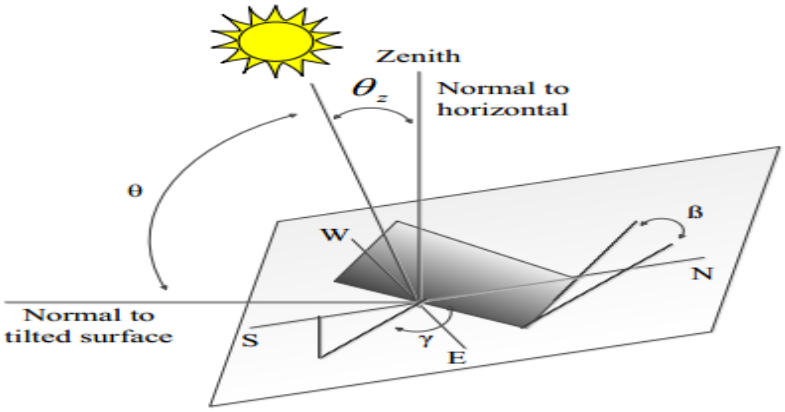


Figure 2- 2: Solar radiation angles

Table 2-1: Recommended Average Days for Months and values of N by Months (Duffie and Beckman, 1991)

Month	N for i^{th} Day of month	For the average day of the month		
		Date	Day of year N	Declination δ
January	I	17	17	-20.9
February	31 + i	16	47	-13
March	59 + i	16	75	-2.4
April	90 + i	15	105	9.4
May	120 + i	15	135	18.8
Jun	151 + i	11	162	23.1
July	181 + i	17	198	21.2
August	212 + i	16	228	13.5
September	243 + i	15	258	2.2
October	273 + i	15	288	-9.6
November	304 + i	14	318	-18.9
December	334 + i	10	344	-23

2.2. Solar Photovoltaic Systems

Photovoltaic system is the most well-known method of converting solar energy directly into electrical energy using semiconductor cells. Today's photovoltaic cells are mainly manufactured from a semiconductor material called crystalline silicon, which is available abundantly in the earth's crust and is free of toxicity. Modules made of by combining crystalline silicon cells are very durable, reliable; noise free and fuel free equipment's to produce electricity. Solar energy is the solitary source to power PV which is infinite. Photovoltaic cells have the capability of transforming 1/6 of solar resources into electric energy. PV systems are free of moving parts and are also environmental friendly. The life time of PV cells can end with greater than 30 years [7]. PV systems provide electricity to remote areas where there is no access to utility grid, thus elevates the life value of the community. In a PV cell there are two doped semiconductor layers, P-type (hole) and N-type layer (electron) which is separated to each other by a junction. A spontaneous electric field is developed at the boundary which defines the direction of the current flow across the junction. In order to get electricity from a PV, the sunlight should penetrate a glass cover and antireflection coating. The model developed to harness solar energy was basically from the western, planed constructing centralized electricity generation and transmitting electricity by transmission wires to the consumers. Energy efficiency of solar photovoltaic is calculated as the power output from the PV divided by the solar radiation emitted to the solar array area.

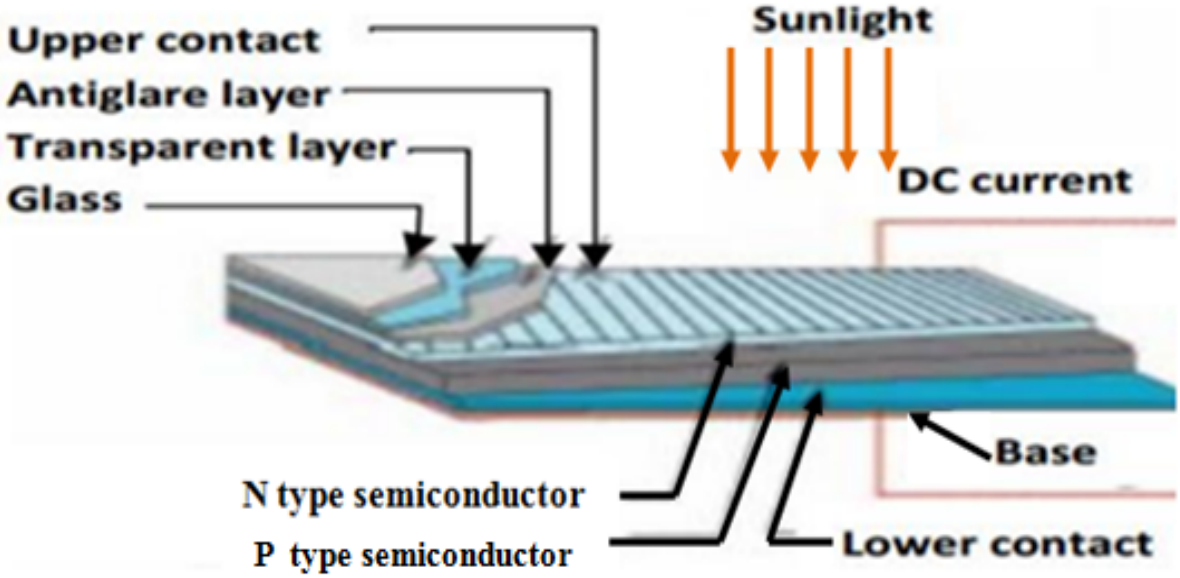


Figure 2- 3: Typical PV cell[11]

2.2.1. Types of Solar PV Cells

Different materials are used to make PV cells, with silicon obtained from sand is being the main material used for and it is available in the earth's crust. The electricity generation depends on the size of the PV cell, the conversion efficiency, and sunlight intensity of the local area. Based on [11] the material from which it is made and the means of manufacturing, PV cells of silicon material are classified into the following.

Mono-crystalline PV Cells: are made from uncontaminated silicon single crystals, cut-off from ingots. It has a dark color and along all its corners is trimmed; this is one clear difference from the poly-crystalline panels. This type of PV cell is the efficient one since it is made from one crystal but the most expensive too. It functions better in areas where low energy sources are required. This technology is the first generation of all PV cells and has high heat resistant ability. The disadvantage with this technology is that it consumes more time to manufacture. The means of production of mono-crystalline silicon is first heating high purity of silicon into super saturated state, second inserting seed crystal into the molten silicon. Then lastly slowly pulling the seed crystal out of the melted mono-crystalline with the aid of Czochralski mechanism to get silicon ingot; moreover, slicing the crystal in to pieces to make the cells then to modules and arrays. This technology has the ability to convert 1000W/m^2 solar radiation to around 140W of electricity in PV cell surface area of 1m^2 [12].

Polycrystalline PV Cells: It is made from combination of smaller quantities of silicon crystal blocks. They are considered as the most widely used cells now a day. Such PV cells are inefficient than the single crystalline cells due to the reason that they are not grown from single crystals but from a combination of many crystals. They perform better than the mono-crystalline in slightly shaded conditions. This technology has the ability to convert 1000W/m^2 solar radiation to around 130W of electricity in PV cell surface area of 1m^2 [12]. The production of this type of cells is more efficient than mono-crystalline. Molten silicon has to be placed into blocks, which are then cut into slabs to make the crystals. Size of poly -crystalline solar panel is larger than mono-crystalline panel to get the same wattage because mono-crystalline is more efficient per area than multi-crystalline. So when comparing the two PV panels in terms of size to get high power output, single crystalline is good in usefulness.

Thin Film PV Cells: These types of cells are not made from real crystals rather the silicon is deposited on stainless steel, plastics or glass to form the solar module. These types of PV cells are much less efficient than the above two but the production process costs less. The inefficiency shows that larger panels of this type required producing same power as the mono or polycrystalline panels. They have efficiency from 5% to 13% and their lifespan is about 15-20 years.

2.2.2. The PV Module and PV Array

Individual PV solar cells are the fundamental building blocks of the solar panel. In general PV cells are smaller in size and produce about one watt power. An individual solar cell produces a voltage of 0.5 to 0.6V. In order to get sufficient output voltage, PV cells are connected in series to form a PV module. PV systems are frequently functioned at multiples of 12 volts; modules are usually designed for optimal operation in these systems. While PV cells are connected in series, the output current remains the same but the output voltage will be the total summation of all cells formed the module. Schematic diagram on how PV cells connect to form module as well as modules to form array is shown in figure 2-4.

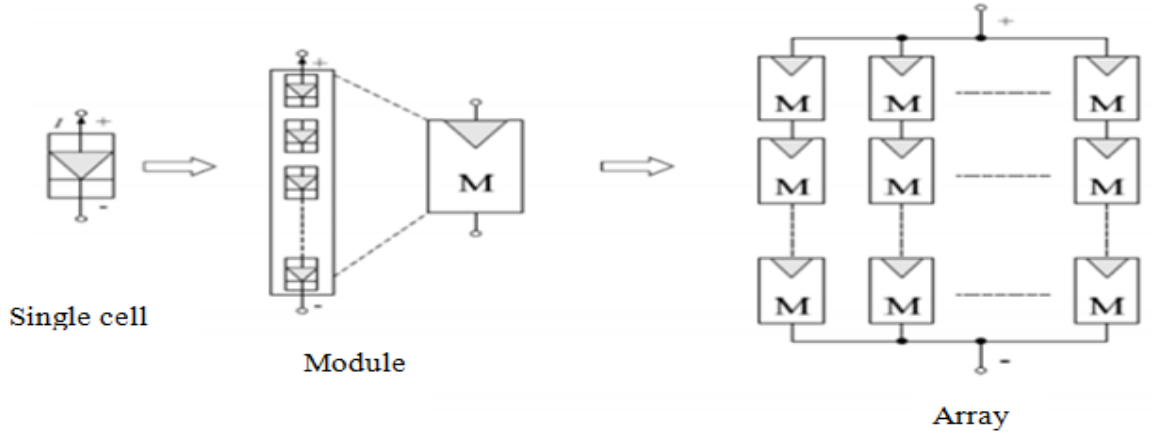


Figure 2- 4: Schematic Diagram for cell, Module and PV array[12]

The power rating of solar panel depends on the number of solar cells and the size of the panel. When the PV cells are assembled as module, they can be illustrated as having a nominal operating cell temperature(NOCT) is the temperature of PV cell when operating at an open circuit at a temperature of 20℃ with air mass of 1.5, irradiance G = 800 W/m^2 and a wind speed less than 1m/s [13, 14]. When large voltages or currents than single module are required, modules have to be connected together to form an array as indicated in figure 2-4. Arrays

connected in series result higher voltages where as the ones connected in parallel has higher current. When modules are connected in parallel they produce large power at the same voltage due to the increment of current, in a similar fashion when modules are connected in series; it is enviable to provide each module maximum power production at the same current due to the increment of voltage.

When deciding to install solar panels, it is important to take into consideration the shading effects faced to the panels during the peak sun hours. The shading effect causes to the reduction of power production and it may even damage the cells. Generally, it is advisable to install PV panels free of trees, buildings, and other obstacles. The second important parameter to consider during solar panel installation is temperature. The heating up of solar panels cause a loss of power because solar cells efficiency is decrease as temperature increases. The mounting system of the panels should allow the air circulation system during the hot sun hour to cool the solar panel.

2.3. Panel Size

Solar Power Required For vapor-Compressor of Refrigerator

The world-wide demand for solar electric power systems has grown steadily over the last 20 years.

Photovoltaic systems provide electricity. When certain semi-conducting materials, such as silicon, are exposed to sunlight, they release small amounts of electricity. The individual PV cells are assembled in series and/or in parallel combination to build a module. The number of cells in series determines the module voltage and the number of cells in parallel determines the module current capability. In general, the larger the area of a module or array, the more electricity that will be produced. Photovoltaic modules and arrays produce direct current (DC) electricity.

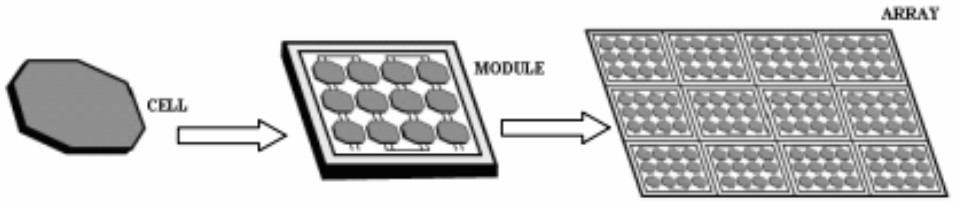


Figure 2- 5: Photovoltaic Cell, Module and Array.

2.3.1. Theoretical Description of the Solar Cell

An illuminated solar cell creates free charge carriers, which allow current to flow through a connected load. Let photocurrent (I_{ph}) be the current which is internally generated in the solar cell. An ideal solar cell can be represented by a simplified equivalent circuit as shown in Figure 2-6. It consists of the diode created by the P-N junction and a photocurrent source with the magnitude of the current depending on the radiation intensity and an adjustable resistor connected to the solar cell as a load.

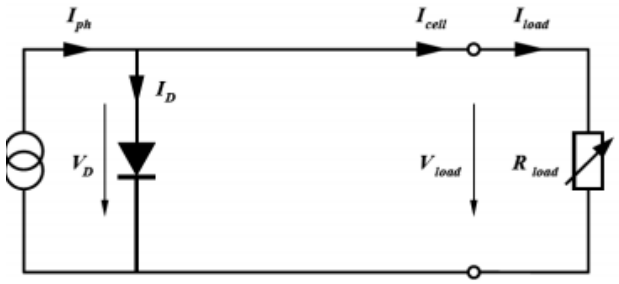


Figure 2- 6: Equivalent Circuit Diagram of an Ideal Solar Cell Connected to Load(source: solar engineering of thermal processing).

The mathematical process of an ideal solar cell leads to the following equation

$$I_{cell} = I_{ph} - I_D = I_{ph} - I_o[e^{(\frac{qv}{KT}} - 1] \quad (2\text{-}1)$$

Where: $I_{cell} = I_{Load}$ = Load current

I_{ph} = current generated in the solar cell

I_o = exp(E_g/KT)

- q = charge on electron [$1.6x10^{-19}C$]
- K= Boltzman constant [$1.38x10^{-23}$J/K]
- T = Absolute temperature of cell [K]
- V = V_{load} = Terminal voltage [V]
- E_g = Energy gap [ev]

The I-V characteristic curve for a certain incident radiation is constructed, point for point as indicated in Figure 2-7:

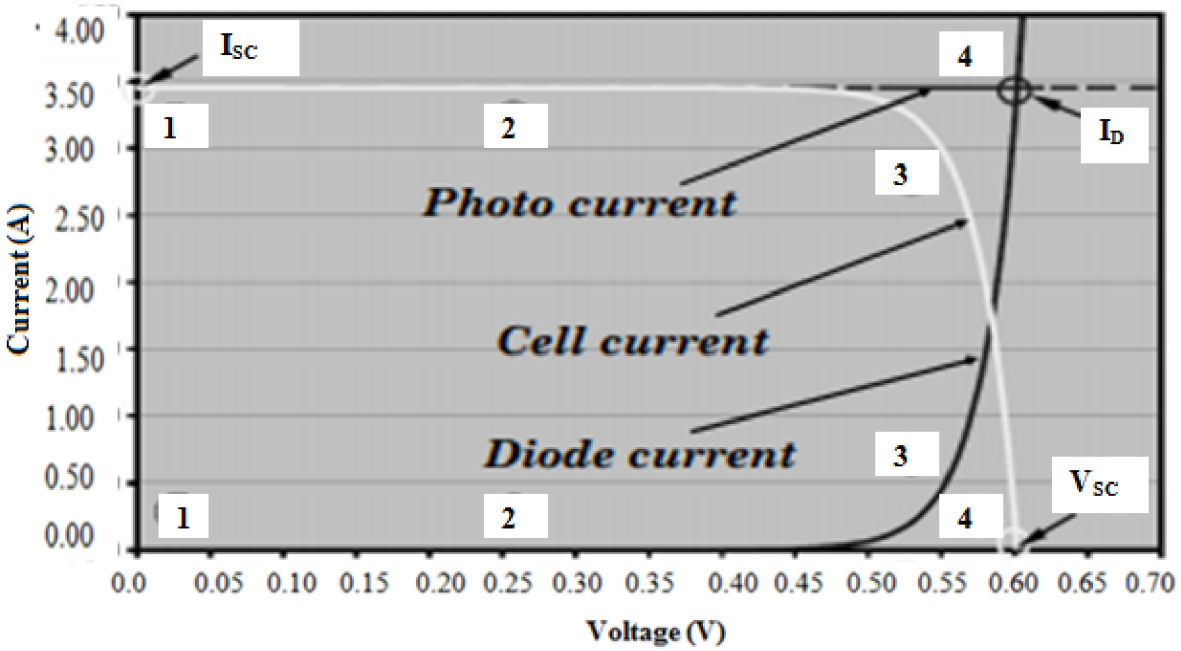


Figure 2- 7: Construction of Solar Cell I – V Curve from the Diode Curve(source: solar engineering of thermal processing)

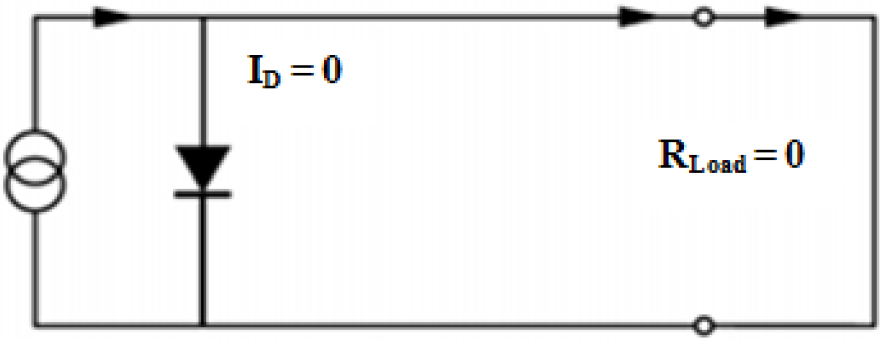


Figure 2- 8: Equivalent circuit diagram of solar cell-short circuit current(source: solar engineering of thermal processing)

when the terminals are short -circuited ($R_{load} = 0$) (figure 2-8) the output voltage across the diode is zero. since V=0, no current I_D flows (point 1in figure 2-7).

Therefore the entire photocurrent I_{ph} generated from the radiation flows to the output. Thus the cell current has its maximum at this point with a value I_{cell} and is referred as the short-circuit current I_{sc}.

$$I_{cell} = I_{ph} = I_{sc} \tag{2-2}$$

If the load resistance is now continuously increased, the solar cell voltage also increases whereas the current remains constant. Up to a certain voltage value, the current flowing through the internal diode remains negligible, and the output current continues to remain constant at the photocurrent, I_{ph} (point 2 in Figure 2-7). the sum of the load current and the diode current must be equal to the constant photocurrent I_{ph}, the output current decreases by exactly this amount (point 3 in Figure 2-7). For an infinitely large load resistance (open circuit) as shown in Figure 2-9, the output current is then zero ($I_{cell} = 0$) and thus the entire photocurrent flows through the internal diode (point 4 in Figure 2-7).

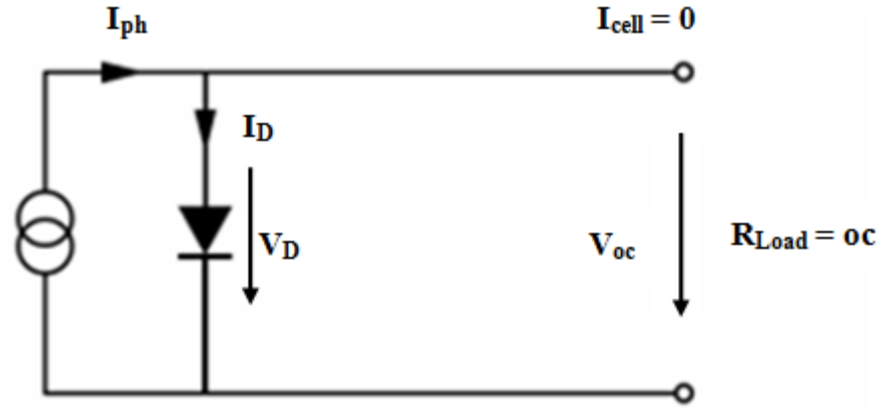


Figure 2- 9: Equivalent circuit diagram of solar cell- open -circuit current(source: solar engineering of thermal processing).

The open-circuit voltage Voc is obtained from:

$$V_{oc} = \frac{KT}{q}.\ln[\frac{I_{ph}}{I_o} + 1] \tag{2-3}$$

Typical values of the open-circuit voltage lie b/n 0.5 – 0.6 V for crystalline cells and 0.6 – 0.9 V for amorphous cells. the current has its maximum at the short circuit point, the voltage is zero and thus the power is also zero. The situation for current and voltage is reversed at the open-circuit point, so again the power here is zero.

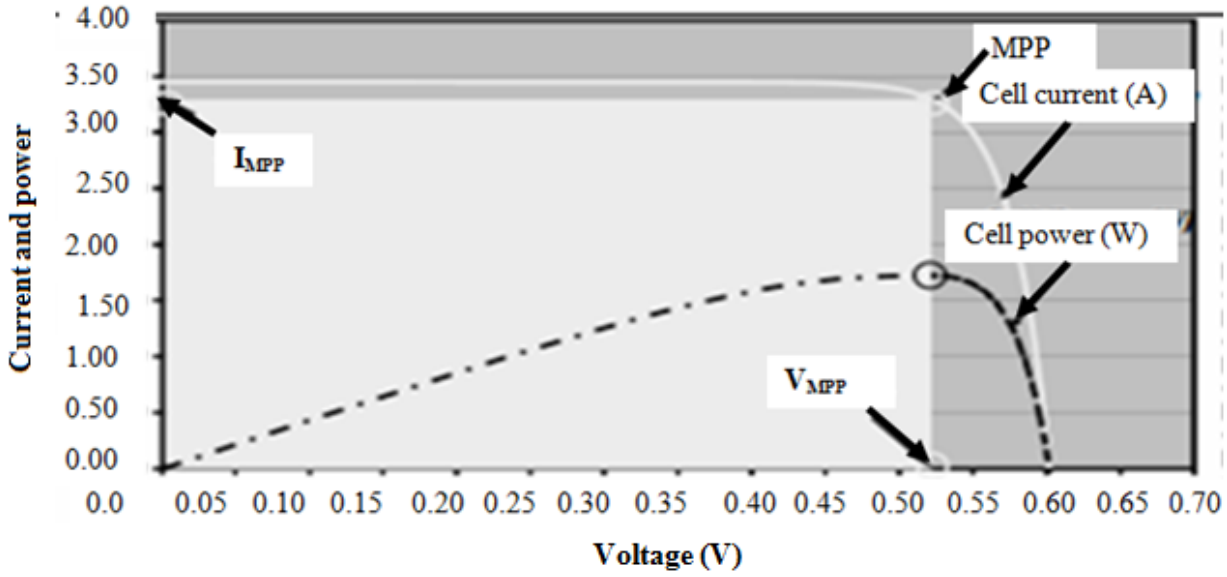


Figure 2- 10: power curve and maximum power point (MPP) (source: solar engineering of thermal processing)

Maximum Power Point (MPP) represents the working point, at which the solar cell can deliver maximum power for a given radiation intensity. It is situated near the bend of the I-V characteristic curve. The corresponding values of V_{MPP} and I_{MPP} can be estimated from V_{OC} and I_{SC} as follows:

$$V_{MPP} = (0.75\text{-}0.9)\,V_{OC}$$

$$I_{MPP} = (0.85\text{-}0.95)\,I_{SC} \qquad (2\text{-}4)$$

The quantity:

$$FF = \frac{(V_{MPP} \cdot I_{MPP})}{V_{OC} \cdot I_{SC}} = \frac{P_{MPP}}{V_{OC} \cdot I_{SC}} \qquad (2\text{-}5)$$

FF is called Fill Factor represents the measure for the quality of the solar cell. The Fill Factor FF indicates how far the I-V characteristic curve approximates to a rectangle. For crystalline solar cells Fill Factor FF is about 0.7-0.8. The maximum output power P_{MPP} of the cell is given by: $P_{MPP} = V_{MPP} \cdot I_{MPP}$ $\qquad FF = V_{OC} \cdot I_{SC}$ (2-6)

The efficiency of the solar cell, which refers to the ratio of the output electrical energy to the input solar radiation (P_{in}), is defined by the relation.

$$\eta_{cell} = \frac{FF.V_{OC} \cdot I_{SC}}{P_{in}} \qquad (2\text{-}7)$$

Efficiencies of the silicon solar cells vary between 10 and 15%

2.4. System-Sizing

Correctly sizing a solar PV system requires careful attention to detail and critical planning. Solar system sizing is a step-by-step process that accounts for facility energy needs and the local solar resource in order to determine the necessary size (in kWp) of the solar array. Photovoltaic panels, also called PV modules, are the basic building block of a PV system. The array of solar panels are normally sized to ensure that enough power is supplied to the photovoltaic solar refrigeration systems. The power consumption varies by storage capacity and model. Countries experience varying weather conditions and solar radiation levels at different periods of the year depending on where they are located globally. Even within a country, different solar radiations, temperature and altitudes vary. These factors and elements influence the overall exercise of calculating the size of the solar array and the battery bank for optimum operation of the solar powered system.

Limiting Factors to System Sizing

Availability of radiation/temperature data is usually limited to main cities and towns already connected to the national power grid. If the national grid power is available for at least 8 hours per 24 hours, it is currently not cost effective/justifiable to use solar powered refrigeration systems in these locations due to the relatively high initial capital investment. However, solar powered systems are used in locations without power grid connection and where the meteorological data is non-existent or very scanty. Reasonable solar data analysis of the regions has to be considered in order to present appropriately sized systems for the requested areas/locations.

System sizing of solar arrays

Solar array size affects battery autonomy. A larger solar array will reduce the number of batteries required for a system. A system sizing template in tropical locations has been prepared as one method of use. It includes information extracted from various data sources on temperature and radiation which are very important parameters for system sizing of a solar array for refrigerators.

Default System Size Categories

Three value categories of 3.5, 4.5 and 5.5 KWh/m^2/day have been identified as fitting the typical locations where these systems find application[15]. A default minimum ambient temperature of 32°C is used as basic parameter to facilitate calculations, amongst others. As indicated above, a small solar array could suffice in one location and perform intermittently in another with the consequence of short battery life. Based on this rationale, and the constraints summarized above, the worst case situation (scenario) for insulation (radiation) and temperature data collected for site is used as an average default value for system sizing as displayed in the Solar Insulation.
ratio of the cooling capacity to the total electrical power required

2.4.1. Solar PV Installation Methods

Solar energy exploitation depends on the tracking system that mounts the PV panel. The tracking system is basically applied to direct the panel to the direction of the sun light which enhances the radiation that strikes the surface of the PV module. Most PV arrays are typically mounted with no tracking systems. There is possibility to track the radiation of the sun for the power output maximization. Solar tracking systems are basically categorized according the number of axes of tracking and the time with which the adjustment is to be made. Below are the techniques to be considered during the design of the PV system [16, 17].

No tracking: Photovoltaic Panels are mounted at a fixed slope and azimuth; moreover it is the simplest and cheapest method. Preferable to orient the panel to the equator (south in the northern hemisphere) usually the angle of tilt is equal to the latitude of the specific site under study. A small increase and decrease from the latitude will be better for the winter and summer sun tracking respectively.

Horizontal axis monthly adjustment: This type of tracking system, it rotates horizontally from east to west direction. The angle of inclination of the PV is adjusted on the beginning of every month so that the beam strikes at 90 to the PV panel when sun is overhead.

Horizontal axis weekly adjustment: This type of mounting system, its axis of rotation is from east to west direction. The PV angle of tracking (slope) is adjusted on the first day of the week, thus solar radiation is at 90 to PV at noon of the corresponding day. The PV module slanted towards parallel the ground.

Horizontal axis daily adjustment: Axis of rotation is about a horizontal east-west direction to track the solar radiation. The slope is adjusted each day so that the sun's rays are at 90 degree to PV at noon of the corresponding day.

Horizontal axis continuous adjustment: It is a type of PV mounting system in which slope of photovoltaic is adjusted continuously and rotation is about a horizontal east-west axis. The slope is adjusted continually in order to minimize the angle on incidence.

Vertical axis continuous adjustment: PV axis of rotation is about a vertical with respect to the ground surface. The slope is fixed, but the azimuth is continually adjusted to minimize the angle of incidence.

Two axes: The panels are rotated about both to east-west and from north-south having two pivots to rotate. However, it is the most expensive method.

2.5. Solar Powered Refrigerator Systems

The choice of solar powered equipment for use in a country programme requires careful analysis and evaluation. The products are appropriate for cooling water and settings as below:

- Hard to reach and remote areas
- In region where there are low acces to cold water for drinking
- This typical design has additional advatage in the area of averge solar radiation is enough to drive the compressor of refrigerator.
- Areas area of with limited/intermittent power supply, i.e. availability of national power supply for less than 8 hours per day.

2.6. Solar Photovoltaic to Operate Refrigeration Cycle

Photo voltaic (PV) involve the direct conversion of solar radiation to direct current (DC) electricity using semi conducting materials. by this concept, the operation of a PV-powered solar refrigeration cycle is simple. Solar photovoltaic panels produce DC electrical power that can be used to operate a DC motor, which is coupled to the compressor of a vapor compression refrigeration system. The major considerations in designing a PV-refrigeration cycle involve appropriately matching the electrical characteristics of the motor driving the compressor with the available current and voltage being produced by the PV array.

- Vapor compression cycle with power input from photovoltaic cells.
- DC electric power output from PV runs the compressor of a conventional cycle considerations.

- Must be match voltage imposed on PV array to the motor characteristics and power requirements of the refrigeration cycle.

- For given operating condition (solar radiation and module temperature), single voltage provides maximum power output.
- Must find compressor motor closely matched to the electric characteristics of the PV module.

2.7. Vapor Compression of solar power Refrigeration

Previous to discussing how solar energy could potentially provide refrigeration, it is appropriate to review the basic principles of operation for vapor compression refrigeration cycles that form the foundation for nearly all conventional refrigeration[4]. A schematic of the vapor compression cycle is shown in Figure 2-11 and a corresponding enthalpy-pressure diagram for the refrigerant is shown in Figure 2-12. In the vapor compression cycle, cooling is provided in the evaporator as low temperature refrigerant entering the evaporator as a mixture of liquid and vapor at State 4 is vaporized by thermal input from the load. The remaining equipment in the system reclaims the refrigerant and restores it to a condition in which it can be used again to provide cooling. The vapor exiting the evaporator at State 1 in a saturated (1a) or slightly superheated (1b) condition enters a compressor that raises the pressure and, consequently, the temperature of the refrigerant. The high pressure hot refrigerant at State 2 enters a condenser heat exchanger that uses ambient air or water to cool the refrigerant to its saturation temperature prior to fully condensing to a liquid at State 3.The high-pressure liquid is then throttled to a lower pressure, which causes some of the refrigerant to vaporize as its temperature is reduced. The low temperature liquid that remains is available to produce useful refrigeration. The major energy input to a vapor compression refrigeration system is the mechanical power needed to drive the compressor.

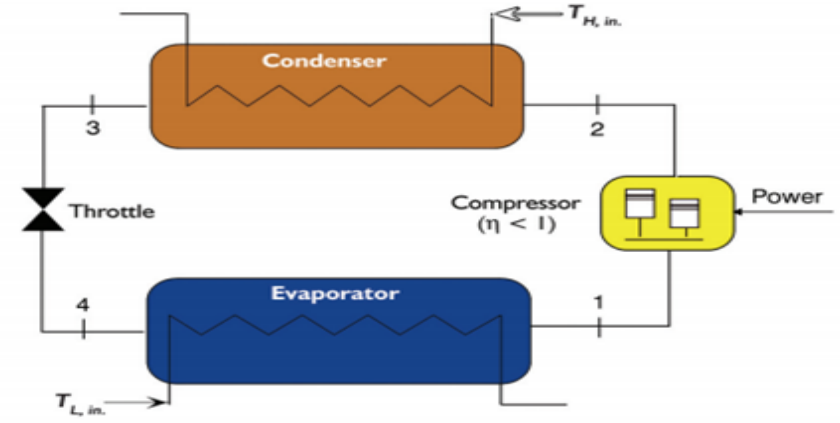


Figure 2- 11: Schematic of a vapor compression refrigeration system[4].

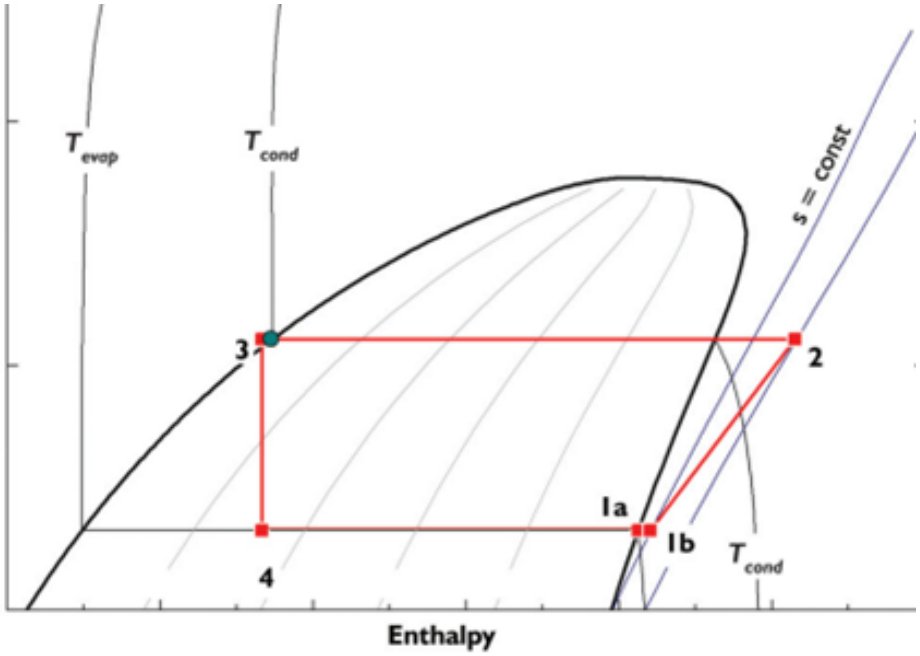


Figure 2- 12: Pressure- Enthalpy diagram for the cycle[4]

2.7.1. Procedure work of Vapor Compression Refrigeration Cycles

The purpose of the compressor is to draw the low pressure refrigerant vapor from the evaporator and compress it to a higher pressure. Refrigerant entering the compressor is a low pressure, superheated vapor. Superheated suction gas prevents liquid refrigerant from potentially causing damage to the compressor.

- High pressure, high temperature vapor leaving the compressor is known as discharge gas.
- The changing of vapor to a liquid at a particular pressure and temperature by removing heat is known as condensation.
- Compression raises the temperature and pressure of the refrigerant and the result in temperature increase is superheat.
- Heat is removed from high temperature, high pressure refrigerant vapor in the condenser. Refrigerant leaves the condenser as a high pressure, sub-cooled liquid.
- Refrigerant absorbs heat in the evaporator and releases it in the condenser.
- The component of the refrigeration cycle that absorbs heat is the evaporator. Refrigerant leaving the evaporator will be low pressure, superheated vapor.
- The evaporator is the element of the refrigerating circuit through which heat is absorbed from the environment that is being cooled.

- The temperature of liquid refrigerant cooled below its saturated pressure-temperature is called sub-cooling. Sub-cooled liquid from condenser reaches the metering device through the liquid line.
- A thermostatic expansion valve is a type of metering device. As refrigerant passes through the metering device, it becomes a mixture of 75% liquid, 25% vapor.

2.8. Solar Powered DC Refrigerator

The solar powered DC refrigerator was developed from an identical AC refrigerator with technical specifications. The refrigerator operates on direct current supplied by the solar PV system. This was possible due to the replacement of the AC compressor with a VSDC compressor. No other components were modified; the DC refrigerator, therefore has the same components as before the conversion, though the system now operates on R134a.

R134a, which is a substance of the ethane group with the formula CH2FCF3 and has a normal boiling point of –26.1 °C. Its thermodynamic properties make it suitable as a refrigerant for medium temperature applications such as domestic refrigerators[danfoss].

Since 1 watt = 3.41 Btu/hr

Energy efficiency ratio(EER) = COP X 3.41

Knowing the EER of a system makes it convenient to calculate the cost of operation once the cooling load is specified in US units. Note that COP is a ratio of the useful energy output of a system versus the amount of work or energy in put to the system as determined by using the same energy equivalents for energy in and out. It is equal to the energy efficiency ratio (EER) divided by 3.412. The higher the COP, the more efficient shall be the device.

2.8.1. Selection of Solar Powered Refrigerator

When comparing solar refrigerators qualified by performance, quality, and safety (PQS), some of the differentiating factors include; purchase price; life time cost; presence of ancillary batteries; climate zone; and autonomy, which is the number of consecutive cloudy days that a solar refrigerator can maintain cooling performance, Need refrigeration in areas not connected to power grid, Need to minimize environmental impact and fuel cost and Evaluate potential of solar energy to meet these needs.

2.9.Refrigeration Systems and Components

There are four main components in a vapor compression refrigeration system:

1) **Evaporator**- Heat is absorbed to boil the liquid at a low temperature, therefore a low pressure must be maintained in this section.

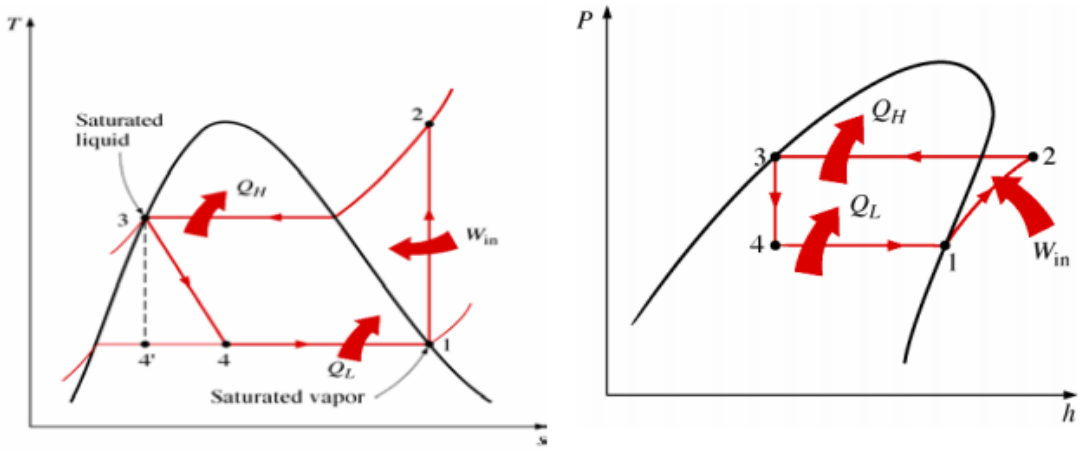
2) **Compressor**- The compressor does work on the system increasing the pressure from that existing in the evaporator (drawing in low- pressure, low-temperature saturated vapor) and to that existing in the condenser (i.e., delivering high pressure and high temperature vapor to the condenser.

3) **Condenser**- The high pressure, high temperature (superheated or saturated) vapor that enters the condenser has heat removed from it and as a result it is condensed back into a liquid phase.

4) **Expansion valve**- The high pressure liquid from the condenser is expanded through this valve,

2.9.1. Theoretical Analysis of Vapor Compression Systems

The refrigerant undergoes four main changes during the cycle: evaporation (4-1), compression (1-2), condensation (2-3) and expansion (3-4). To identify the thermodynamic changes of the refrigerant during a cycle, the properties; temperature (T), pressure (p), enthalpy (h) and entropy (s) are used. These four processes alter the properties of the refrigerant in different ways. To conduct an energy analysis on a typical vapor compression system, the enthalpy values at all four state points are required. Enthalpy values are conveniently read from the appropriate refrigerant tables by using the pressure and temperature values obtained from the refrigerator.



a. Temperature- entropy diagram

b. Pressure – Enthalpy diagram

Source: (Cengel & Boles, 2006)

Figure 2- 13: T-s and P-h diagram of Vapour compression refrigeration system

2.9.2. Compressor Power Requirement

The minimum compressor power is given in Equation 2-8. The compressor power requirement is the product of mass flow rate of refrigerant and changes of enthalpy.

$$\dot{w} = \dot{m}(h_2 - h_1) \quad (2\text{-}8)$$

The coefficient of performance(COP) vapor compression refrigeration system is defined as the ratio of the cooling capacity to the total electrical power required.

2.9.3. Compressor of Refrigerator

A compressor of refrigerator is a combination of mechanical compression part and an electrical motor. The electrical motor converts electrical energy to mechanical energy in a refrigeration compressor. The mechanical energy developed by the motor is used by the piston to compress and circulate the refrigerant in the refrigeration cycle. In vapor compression refrigerators, compressors are the main prime movers responsible for providing the motive force for circulating refrigerant throughout the system and for creating a sufficiently high refrigerant pressure differential that allows the transport of heat from spaces or products to the outside environment. A schematic view of a hermetic refrigerator compressor is shown in Figure 2-14.

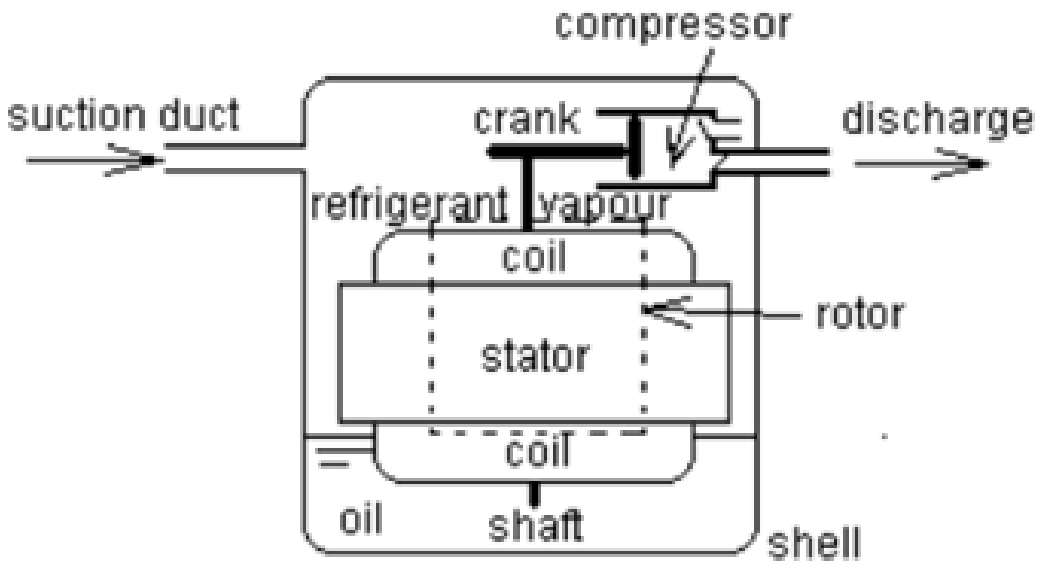


Figure 2- 14: Schematic of hermatic Refrigerator compressor source: (Ekren et al., 2013)

2.9.4. Description of VSDC Compressor (BD 35F) and Electronic Control Unit

In this work mini-compressor was selected for solar power refrigerator because it consume small amount of power which generated from solar array. Therefore the size of solar array required for this compressor is small. Due to this case the cost of solar PV array would be reduce.

The compressor is designed for connection to 12V or 24V DC power supply and for refrigerant R134a (CF3-CH2F). The compressor is suitable for use in mobile applications such as cooling boxes, boats, caravans, trucks, vans and buses. In additions, it can be used in stationary applications powered by photovoltaic solar panels such as used in this thesis due to their low energy consumption and the option for a wide supply voltage range. This is the same type of compressor used on commercially available solar refrigerators. It can be used in refrigerators and freezers designed for capillary tube and thermostatic expansion valve (TEV) as the throttling device[18]. Figure 2-15 shows the selected BD 35 F compressor[Appendix D-1].



Source: (Danfoss, 2007)

Figure 2- 15:Variable Speed Direct Current Compressor (VSDC)

The BD 35F VSDC compressor concept includes an electronic unit which features overload. The compressor has four different speeds of 2000 RPM, 2500 RPM, 3000 RPM, and 3500 RPM. The electronic control unit (shown in Figure 2-16) has internal voltage recording and calibration to the applied voltage [Appendix D-1].



Source: (Danfoss, 2007)

Figure 2- 16: Electronic Control Unit For VSDC Compressor BD 35F

One advantage of this compressor is the ability to connect it directly to a PV or other source of DC energy supply without an inverter. In addition to being quiet in operation, the compressor has a good COP values. Though most household refrigerators operate at -8℃ (Cengel & Boles, 2006), this compressor is capable of reaching storage temperatures down to -30°C.

2.9.5. Ice Storage Versus Batteries

Specific energy of ice storage

A simple calculation shows the interesting result, that the cooling capacity in the ice storage is at similar level as in a lead battery based on both volume and weight. One supplier of lead battery informs, that a 50 Ah, 12 Volts battery has the weight of 13.6 kg. The dimensions are 0.24*0.175*0.175 meters. The energy content of 50 Ah can be calculated as a specific energy content of 0.159 MJ/kg or 294 MJ/m^3.

The cooling system will have a COP-value (coefficient of performance) of about 1.3 (Danfoss BD35F, CECOMAF-data for –15 ºC, 2000 RPM). This will result in a specific cooling capacity of 0.206 MJ/kg or 382 MJ/m^3. For the ice storage: the specific cooling capacity is identical to the melting heat of ice, which is 0.333 MJ/kg or 333 MJ/m^3. The conclusion is, that the specific cooling capacity of ice is 62 % higher compared to lead battery on basis of weight and 13 % smaller compared with lead battery based on volume. In reality, the ice storage outperforms the lead-acid battery, because the allowed daily cycling is less than the nominal 50 Ah, which corresponds to 100% depth of discharge.

If the system includes a battery, the battery voltage will control the operating voltage of the PV module. PV panels can be chosen so that their maximum power voltage is close to the voltage for the battery system. The battery also provides electrical storage so that the system can operate at times when solar radiation is unavailable. However, the addition of a battery increases the weight of the system and reduces its steady-state efficiency. Electrical storage may not be needed in a solar refrigeration system as thermal storage, e.g., ice or other low temperature phase storage medium, may be more efficient and less expensive. A final option for systems that do not use a maximum power tracker or a battery is to select an electric motor having current-voltage characteristics closely matched to the maximum power output of the module.

It has been a wish from the relief organizations to avoid lead batteries as the main source of energy to keep the internal coolers cold during night-time and during periods with minor solar power. Previous experience has shown that additional costs are related to the batteries because frequent discharging results in a fast degradation of the batteries. That is one reason why the solar powered coolers have been more expensive compared to kerosene or LPG-powered absorption refrigerators. In this thesis ice storage have been developed as an alternative source for energy storage, and the Solar power refrigerators use ice storage in different versions.

The conclusion is that the cooling capacity for ice storage of the same order of magnitude as for a lead battery on volumetric and mass basis. The cooling capacity is app. 40% higher (for the ice storage) on weight basis and app. 30% less on volume basis. In this comparison, a 100% discharge of the battery is assumed, which should not be carried out in reality as that would harm the battery. Another point that disfavors lead batteries is the risk of lead pollution at the end of the life time of the battery. Future commercialization of batteries with high energy density for electric vehicles might change the role of battery storage in solar refrigeration. A disadvantage when using ice storage is that the ice has to be stored inside the insulation in the cabinet and therefore part of the volume inside the refrigerator is used.

The ice packs are an alternative to a battery package. The advantage of the ice packs are that they are maintenance free. The ice packs can be an integrated part of the appliance design or can simply be plastic bags that are put into the appliance.

In detail, the work demonstrated that the basic module of the refrigerator, with a net capacity of 250 L and an ice storage of 12.5 kg is able to maintain internal temperature below 10℃ even

after 48 h of no operation of the compressor and with a new thermal load introduced in the refrigerator [19].

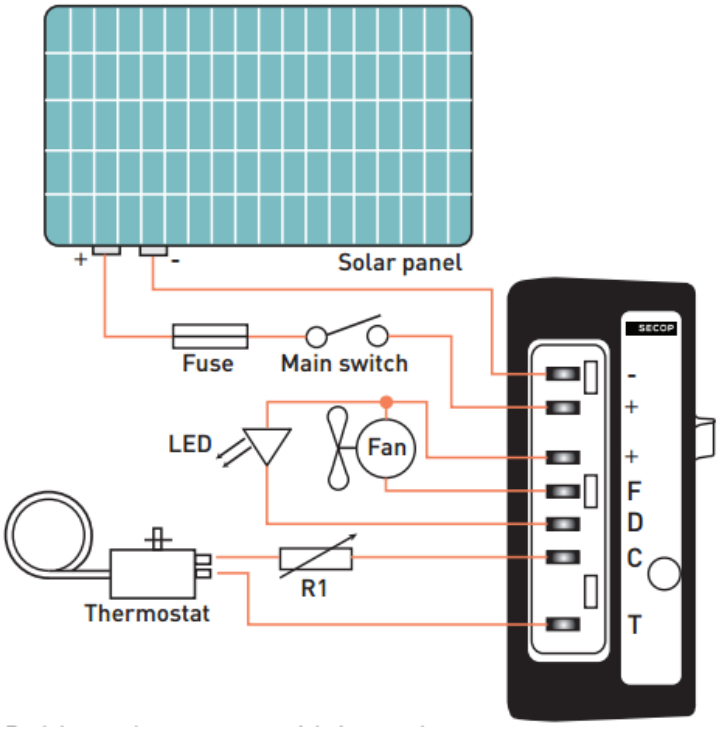


Figure 2- 17: Refrigeration system with icepacks using BD35F

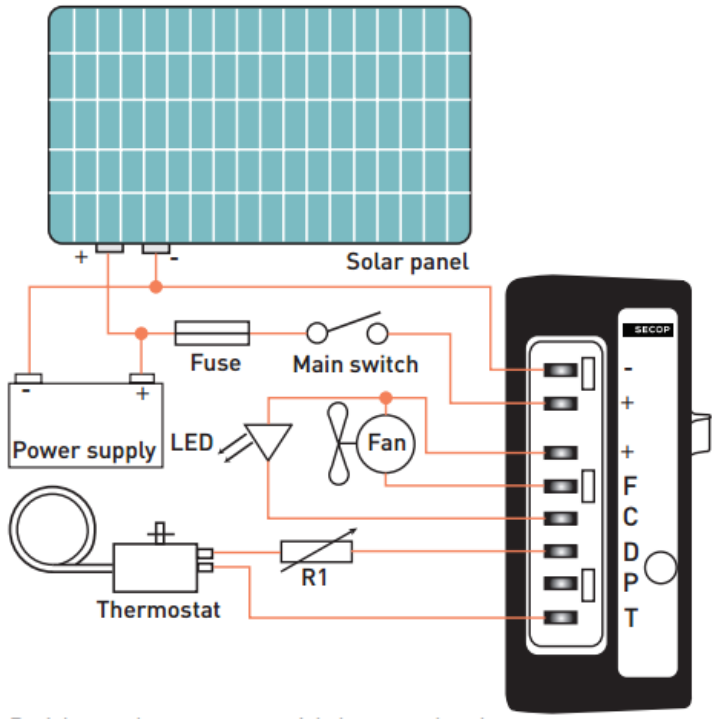


Figure 2- 18: Refrigeration system with battery backup using BD

CHAPTER THREE

3. METHODOLOGY

3.1. Design Procedure of solar powered system

In this section design and optimize the solar power micro-refrigerator at selected site. This design is depends on Collect data of site and desired parameter of the system and design procedure of system is shown in below diagram.

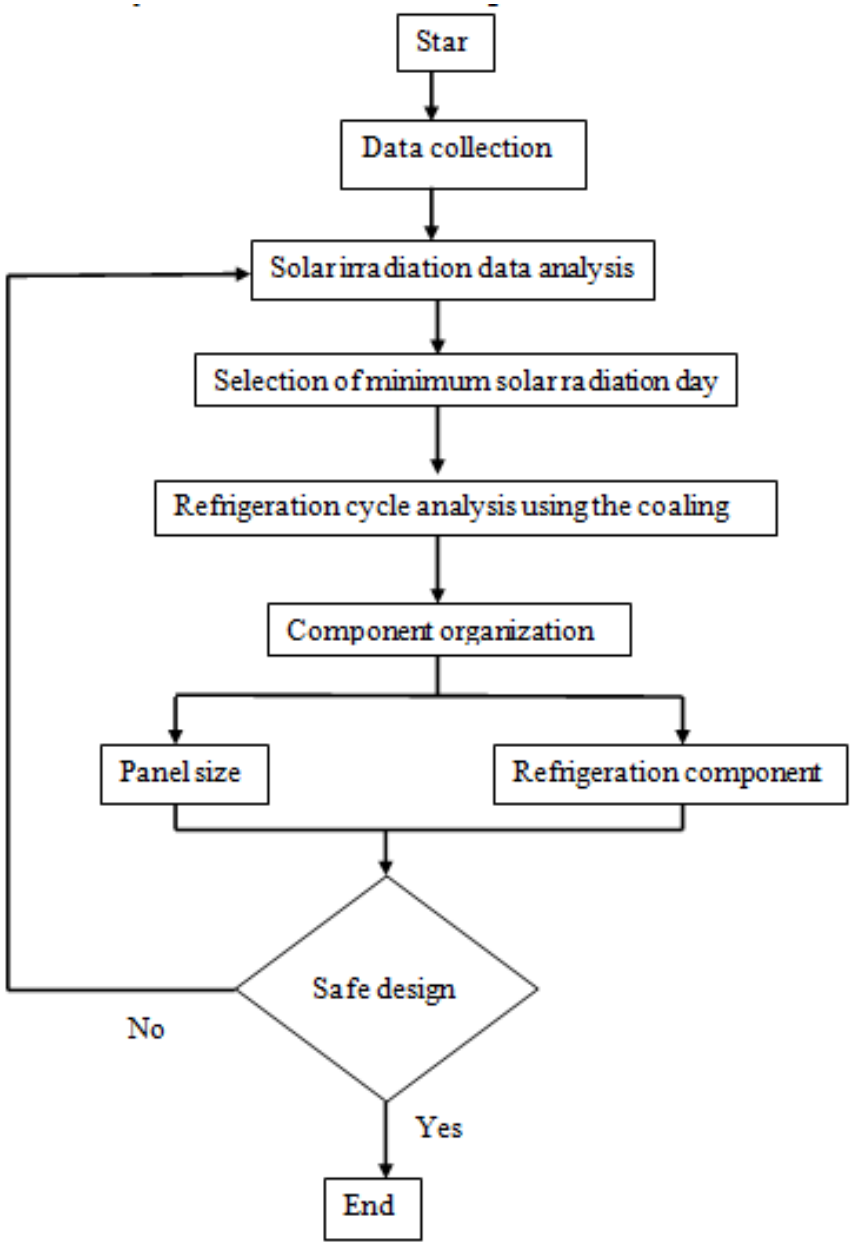


Figure 3- 1: Schematic diagram of design procedure of solar power refrigerator

3.2.Solar Radiation Data Collection and Analysis

3.2.1. Solar Resource Assessment of Selected Site

Data of selected site solar radiation is collected from Photovoltaic Geographical Information System (GPVGIS). In this section solar radiation data is obtain from PVGIS by inserting required parameter as shown in below figure.



Figure 3- 2: Dire Dawa shinile PVGIS Solar radiation data

PVGIS estimates of solar electricity generation

Location: 9.68° North, 41.85° East, Elevation: 1177 m a.s.l.,

Solar radiation database used: PVGIS-CMSAF

Estimated losses due to temperature and low irradiance: 13.2% (using local ambient temperature)

Estimated loss due to angular reflectance effects: 2.5%

Other losses (cables, inverter etc.): 14.0%

Combined PV system losses: 27.2%

Table 3-1: PVGIS estimates of solar electricity generation

Fixed system: inclination=9.6°, orientation=0°				
Month	**E_d**	**E_m**	**H_d**	**H_m**
Jan	5.17	160	7.12	221
Feb	5.44	152	7.56	212
Mar	5.28	164	7.37	228
Apr	4.59	138	6.36	191
May	4.48	139	6.17	191
Jun	4.52	136	6.16	185
Jul	4.43	137	6.04	187
Aug	4.64	144	6.38	198
Sep	4.74	142	6.58	197
Oct	4.85	150	6.76	209
Nov	5.10	153	7.04	211
Dec	5.13	159	7.00	217
Yearly average	**4.86**	**148**	**6.70**	**204**
Total for year		**1770**		**2450**

E_d: Average daily electricity production from the given system (kWh)

E_m: Average monthly electricity production from the given system (kWh)

H_d: Average daily sum of global irradiation per square meter received by the modules of the given system (kWh/m^2)

H_m: Average sum of global irradiation per square meter received by the modules of the given system (kWh/m^2) [Appendix A-1].

Table 3-2: Annual irradiation shortage due to shadowing (horizontal).

Month	Hh	Hopt	H(90)	Iopt
January	6330	7070	5200	39
February	6720	7220	4150	29
March	6620	6750	2530	13
April	6520	6350	939	-4
May	6910	6460	889	-18
Jun	6800	6230	872	-25
July	6570	6090	898	-22
August	6620	6330	911	-10
September	6770	6780	1940	7
October	6710	7060	3510	23
November	6650	7350	5030	36
December	6270	7090	5550	41
Year	6620	6730	2690	12

Hh: Irradiation on horizontal plane (Wh/m2/day)

Hopt: Irradiation on optimally inclined plane (Wh/m2/day)

H(90): Irradiation on plane at angle: 90deg. (Wh/m2/day)

Iopt: Optimal inclination (deg.)

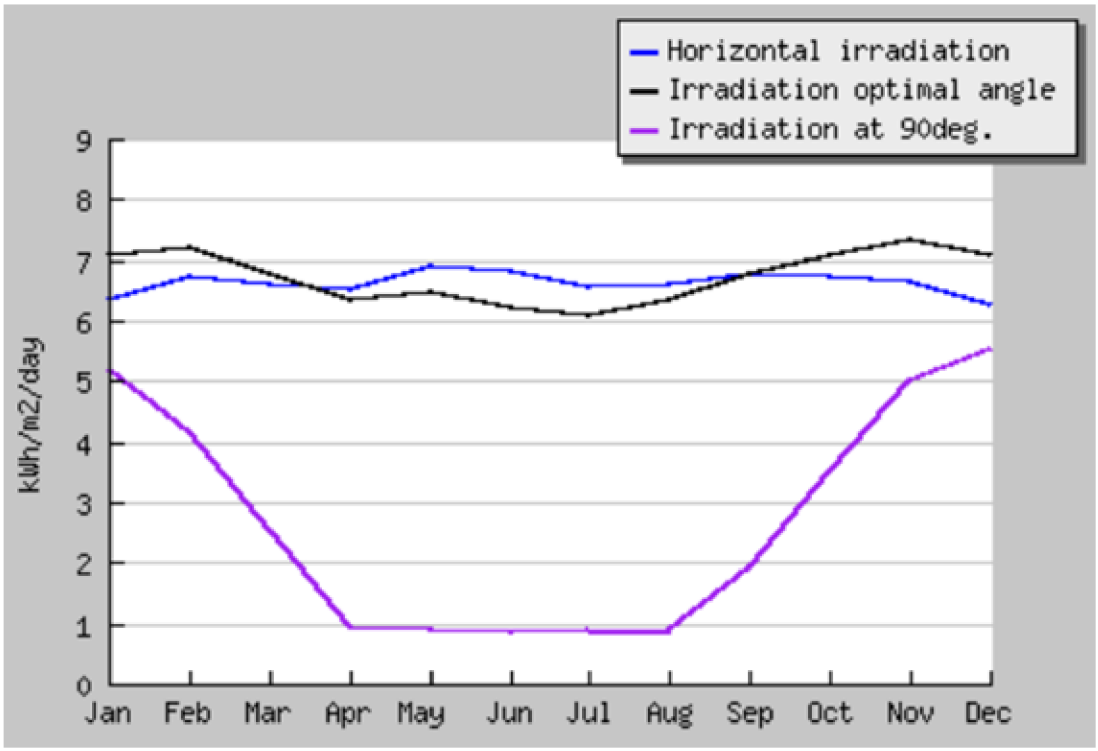


Figure 3- 3: Annual irradiation shortage due to shadowing (horizontal).

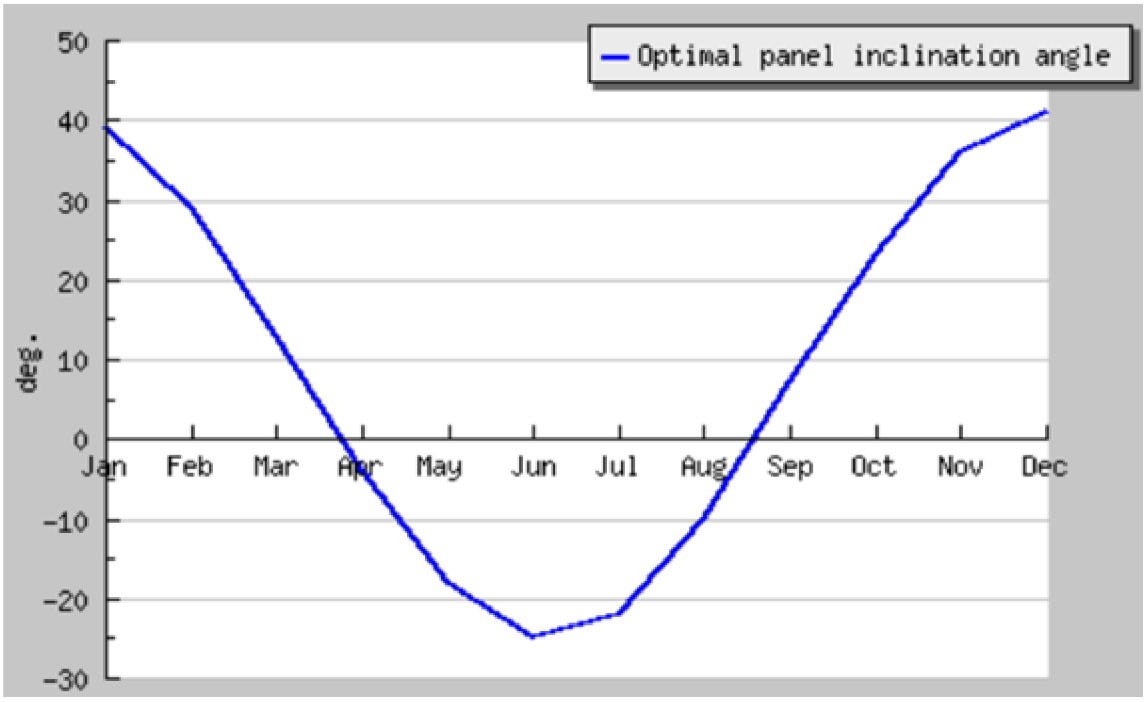


Figure 3- 4: monthly optimal panel inclination angle

3.2.2. Collected site data of from NASA

Latitude 9.68 / Longitude 41.85 was chosen.

Geometry Information

Elevation: **1177** meters
taken from the
NASA GEOS-4
model elevation

Northern boundary
10

Western boundary
41

Center
Latitude **9.68**
Longitude **41.85**

Eastern boundary
42

Southern boundary
9

Table 3-3: Monthly Solar radiation data from NASA

Table Monthly Averaged Clear Sky Insolation Incident On A Horizontal Surface (kWh/m^2/day)

Lat 9.6 Lon 41.85	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
22-year Average	6.43	6.97	7.24	7.20	6.88	6.40	6.35	6.57	6.65	6.68	6.40	6.20

3.3. Method of solar energy determination on the plane of PV panel

The solar radiation is very important in calculating the amount of electricity generated by PV modules. The long term statistical data of solar sunshine hour is also very significant in deriving an equation to calculate the solar radiation, and to know amount energy generate by solar array. However, the solar radiation could be generated by the mathematical model which is developed based on the meteorological sunshine hour data. The analysis follows from extra-terrestrial solar radiation calculation, monthly average terrestrial solar radiation

determination up to daily solar radiation on the plane of solar module for the site. The algorithm used to calculate the radiation on the plane of the solar array would be shown as follows:

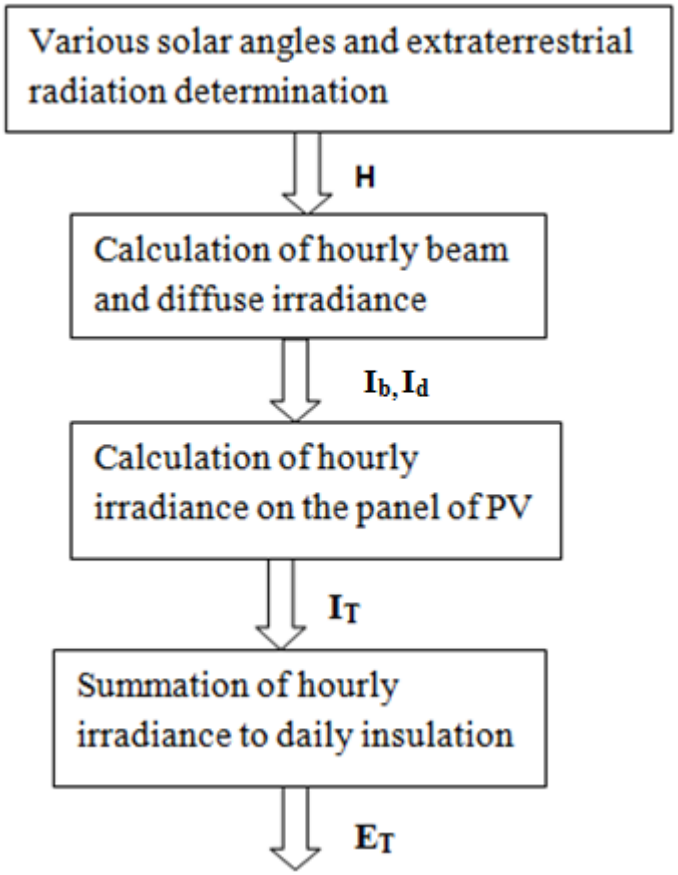


Figure 3- 5: Flow Showing The Determination of Solar Energy on The Plane of PV Panel

3.3.1. Sizing of PV system

Sizing of photovoltaic system is based on the worst operating condition. For the purpose of the solar PV system design, solar data is available but check by numerically analysis in this method use the minimum monthly solar irradiation. since, July month is minimum solar irradiation as shown in table 3-1 assume July17 i.e. N=198 is chosen for PV sizing, and the declination angle can be calculated using equation(3-1).

$$\delta = 23.45\sin[\frac{360}{365}(284+N)] \qquad (3\text{-}1)$$

$\delta = 23.45\sin[\frac{360}{365}(284+198)] = 21.2^0$, as shown in Table 2-2.

Hour angle ω and solar time ST in hour is related as equation(4-2).

Assuming 1:15 PM for the selected site:

$$\omega = (ST - 12) * 15^0 \quad (3\text{-}2)$$

$$\omega = (ST - 12) * 15^0 = 18.75^0$$

For horizontal surface, zenith (θz) can be calculated using equation(3-3).

$$\cos_Z = \cos\varphi \times \cos\delta \times \cos\omega + \sin\delta \times \sin\varphi \quad (3\text{-}3)$$

$$\cos\theta z = \cos 9.68^0 \times \cos 21.2^0 \times \cos 18.75^0 + \sin 21.2^0 \times \sin 9.68^0 = 0.93$$

Where, the latitude ϕ of the site is 9.68^0

$$\theta z = 21^0$$

The relationship for the angle of incidence of surfaces sloped due north or due south can be derived. from the fact that surfaces with slope β to the north or south have the same angular relationship to beam radiation as a horizontal surface at an artificial latitude of (ϕ − β). slope β for all year β = ϕ , for summer β = ϕ - (10^0 - 15^0) and for winter β = ϕ + (10^0 - 15^0). (3-4)

$$\cos\theta = \cos\delta \times \cos\omega \times \cos(\phi - \beta) + \sin\delta \times \sin(\phi - \beta) \quad (3\text{-}5)$$

$$\cos\theta = \cos(21.2) \times \cos 18.75 \times \cos(9.68 - 9.68) + \sin(21.2) \times \sin(9.68 - 9.68)$$

$$\theta = 28^0$$

where: δ is the declination (°) calculated from (3-1) and ϕ is the site's latitude (°)

3.3.2. Estimation of Solar Radiation

The solar radiation passing through the atmosphere and reaching the earth's surface is classified into two components:

- **Beam radiation Ib**: is the solar radiation propagating along the line joining the receiving surface and the sun. It is also referred to as direct radiation.
- **Diffuse radiation Id**: is the solar radiation scattered by aerosols, dust and molecules. It does not have a unique direction.

The total radiation I: is the sum of the beam and diffuse radiation and is sometimes referred to as the global radiation

Estimation of Clear Sky Radiation on Horizontal Surface

Hottel, et. al. (1976) presented a simple model for the estimation of the transmittance of beam radiation in clear sky conditions. The input needed are the altitude of the location A in km above

mean sea level, day number of the year N and the zenith angle (θz). Combined with the Liu and Jordan's model for the transmittance of diffuse radiation through clear sky, the clear sky beam and diffuse radiation can be easily computed.

The clear sky beam radiation on a horizontal surface is:

$$I_b = I_n \tau_b \cos\theta_Z \quad (3\text{-}6a)$$

Where: $I_n = I_{sc}[1.0 + 0.033\cos\left(\frac{360\,N}{365}\right))$

$= 1367 w/m^2[1.0 + 0.033\cos\left(\frac{360\,(198)}{365}\right) = 1323\ w/m^2$

$$\tau_b = a_o + a_1 e^{(-k/\cos\theta_Z)} \quad (3\text{-}6b)$$

$a_o = a_o^* r_o, \quad a_1 = a_1^* r_1, \quad k = k^* r_k$

Where,

$a_o^* = 0.4237 - 0.00821(6 - A)^2$

$a_1^* = 0.5055 + 0.00595(6.5 - A)^2$

$k^* = 0.2711 + 0.01858(2.5 - A)^2$

$r_o = 0.95, r_1 = 0.91, r_k = 1.02$, A= altitude in (1.177km) =1177m

A is altitude of the location in km above mean sea level

$a_o^* = 0.4237 - 0.00821(6 - 1.177)^2 = 0.233$

$a_1^* = 0.5055 + 0.00595(6.5 - 1.177)^2 = 0.674$

$k^* = 0.2711 + 0.01858(2.5 - 1.177)^2 = 0.303$

Therefore,

$a_o = a_o^* r_o = 0.233 \times 0.95 = 0.2213$

$a_1 = a_1^* r_1 = 0.674 \times 0.91 = 0.6133$

$k = k^* r_k = 0.303 \times 1.02 = 0.309$

Substitute the values into equation 3-6(b) gives:

$\tau_b = 0.2213 + 0.6133e^{(-0.309/\cos 22^0)} = 0.660$

Then using equation 3-6(a) to calculate beam radiation

$I_b = 1323 w/m^2 \times 0.660 \times \cos 21^0 = 815 w/m^2$

The transmittance of diffuse radiation through clear sky can be estimated from the beam radiation transmittance based on the study of Liu and Jordan:

$\tau_d = 0.271 - 0.2939\tau_b = 0.271 - 0.2939 \times 0.660 = 0.077$

The clear sky diffuse radiation is:

$I_d = I_n \tau_d \cos\theta_z$ (3-7)

$I_d = 1323 \times 0.077 \times \cos 21^0 = 95 w/m^2$

Therefore, the total clear sky radiation on a horizontal surface could then be estimated as:

$I_T = I_b + I_d$ (3-8)

$I_T = 815 w/m^2 + 95 w/m^2 = 910 w/m^2$

Estimation of Solar Radiation on Inclined Surface

The following formula was given by Liu and Jordan (1962), for evaluating the total radiation on a surface of arbitrary orientation from knowledge of beam and diffuses radiation on horizontal surface.

$I_T = I_b R_b + I_d R_d + r R_r (I_b + I_d)$ (3-9)

Where:

r = reflectivity of the ground = 0.2.

Rb, Rd and Rr are known as conversion factors for beam, diffuse and reflected components respectively.

The expressions for these are as follows:

Rb: is defined as the ratio of flux of beam radiation incident on an inclined surface to that on a horizontal surface. The flux of beam radiation incident on a horizontal surface (R_b) is given by:

$$R_b = \frac{\cos\theta}{\cos\theta_z} = \frac{\cos 28}{\cos 21} = 0.946$$

Rd : is the ratio of the flux of diffuse radiation falling on the tilted surface to that on the horizontal surface. This conversion factor depends on the distribution of diffuse radiation over the sky and on the portion of sky seen by the surface.

$$R_d = (\frac{1+\cos\beta}{2}) = (\frac{1+\cos 9.68^\circ}{2} = 0.993$$

Rr: The reflected component comes mainly from the ground and other surrounding objects.

$$R_r = (\frac{1-\cos\beta}{2}) = (\frac{1-\cos 9.68^\circ}{2} = 7 * 10^{-3}$$

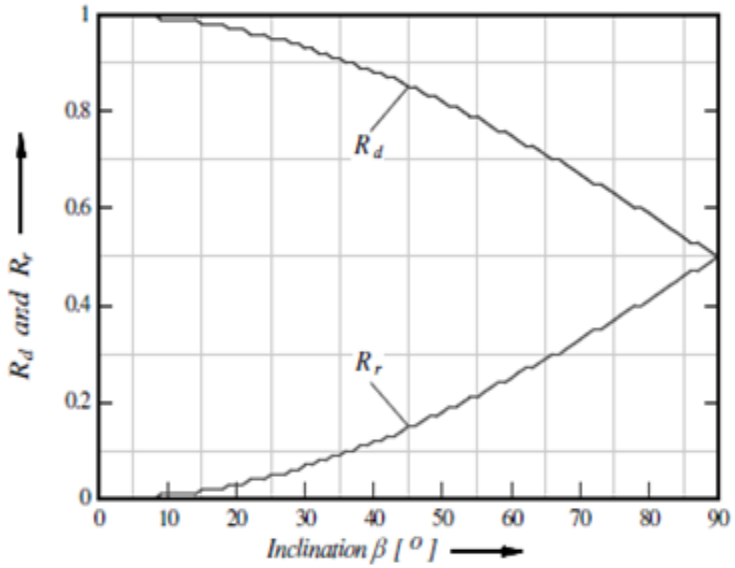


Figure 3- 6: Variation of Rd and Rr with inclination

In this case ($\beta = 9.68^0$), Rd=0.993 and Rr = 7×10^{-3}

This indicates that small slop planes receive little reflected radiation and more deflection radiation. Using equation 3-9 to determine solar radiation on inclined surface:

$I_T = 815 \times 0.946 + 95 \times 0.993 + 0.2 \times 7 \times 10^{-3}(815 + 95)$

I_T =771+94.3+1.274

$I_T = 866\ w/m^2$.

July month is minimum solar radiation in selected site, but the calculated total solar radiation above that taken from data collection. Therefore solar radiation of selected site enough for this system.

3.4.Peak Sun Hours

For the purpose of the solar PV system design, the minimum monthly solar irradiation is used in determining the peak sun shine hours. This approach is usually required for the design of solar PV systems (designing for worst conditions).

Performance of solar PV system depends largely on the peak sun hours of the location of application. The peak sun hour(s) of an area is determined form the available solar irradiance of the location. The peak sun hours and total irradiation are related by Equation 3-10

$$PSH = \frac{\text{Irradiation}[Wh/m^2/day]}{\text{Peak sun}[W/m^2]} \quad (3\text{-}10)$$

After compare collected data of PVGIS and NASA, take minimum solar radiation. Now by definition Peak Sun hour is equivalent to calculated irradiance 866[w/m^2], the number of peak sun hours can be obtained by equation 3-10 using minimum monthly solar irradiation data in July 6.04kwh/m^2 from Table 3-1.

$$PSH = \frac{\text{Irradiation}[Wh/m^2/day]}{\text{Peak sun}[W/m^2]} = \frac{6040}{866}\,h/day = 7.0h/day \quad \text{(This PSH is in July)}$$

3.5. PV Sizing By Pvsyst Software

From the below figure can be observe irradiance of site and describe loss factor of energy on solar array and by using this irradiance can be calculate peak sun hours.

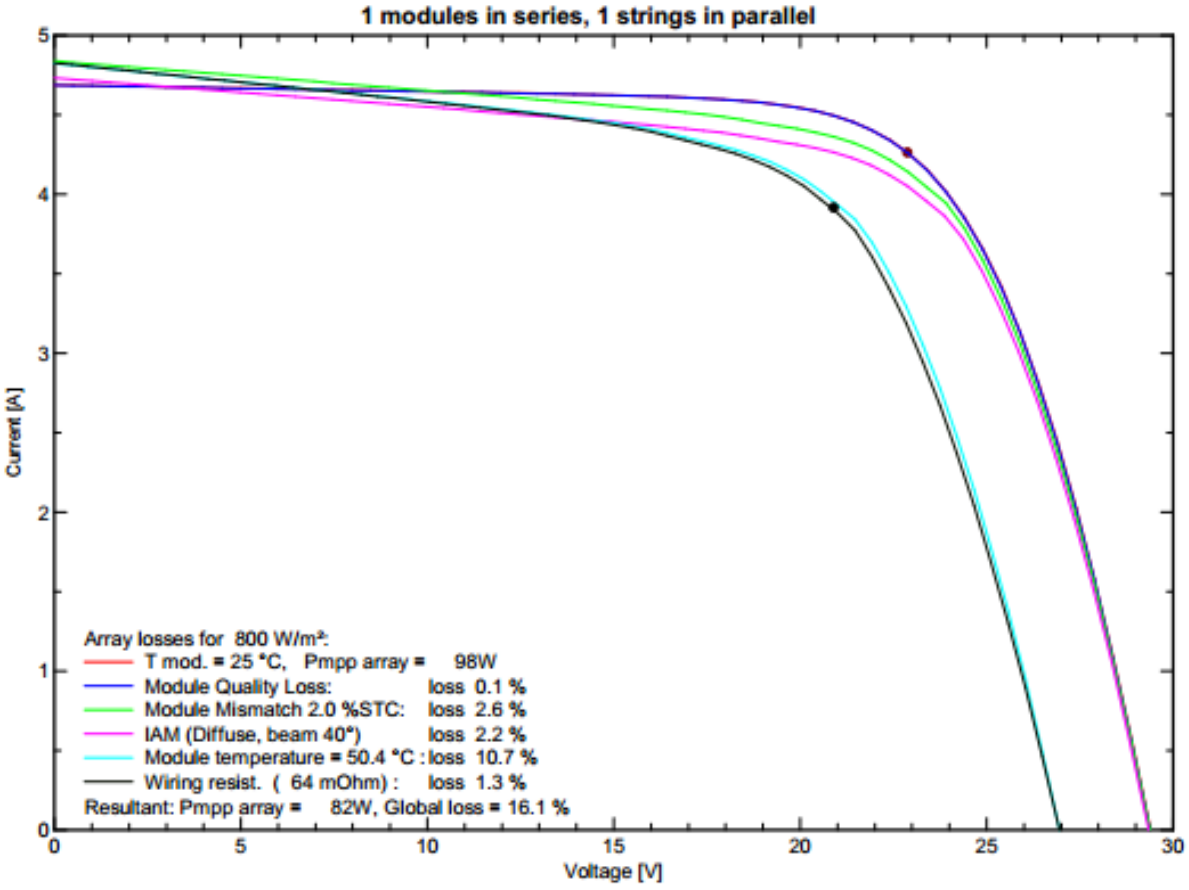


Figure 3- 7: PVsyst I-V curve diagram of PV one Module for 800W/m^2

As shown in figure 3-7 irradiance of site is equivalent to 800[w/m^2], from these irradiance and irradiation of 6040wh/m^2/day, Peak Sun hour is determined.

$$PSH = \frac{\text{Irradiation}[Wh/m^2/day]}{\text{Peak sun}[W/m^2]} = \frac{6040}{800} h/day = 7.6h/day$$

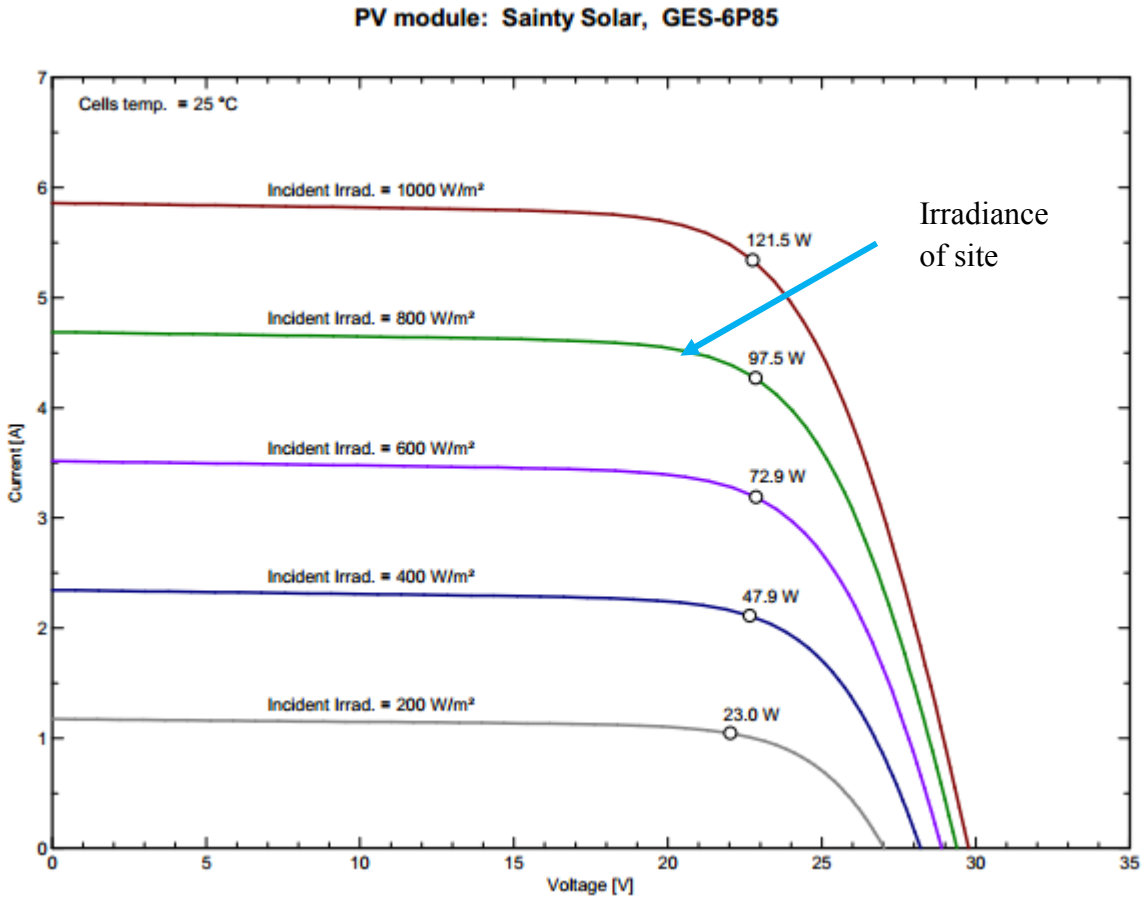


Figure 3- 8: PV power at different irradiance by pvsyst software

The inputs of PVsyst software for this work are latitude, Altitude, Time zone and longitude of site, power requirement types of PV panel and etc. As shown in above figure as irradiance of site increase, power produced by pv panel is increase. The power required for solar powered refrigerator is about 60w can be get these power at irradiance of 800w/m^2. At 800w/m^2 irradiance can be produce power =voltage(V)* Current(A) = 22.5v*4.3A = 97.5w. But these power reduce by different lost like temperature increase, dust, and etc.

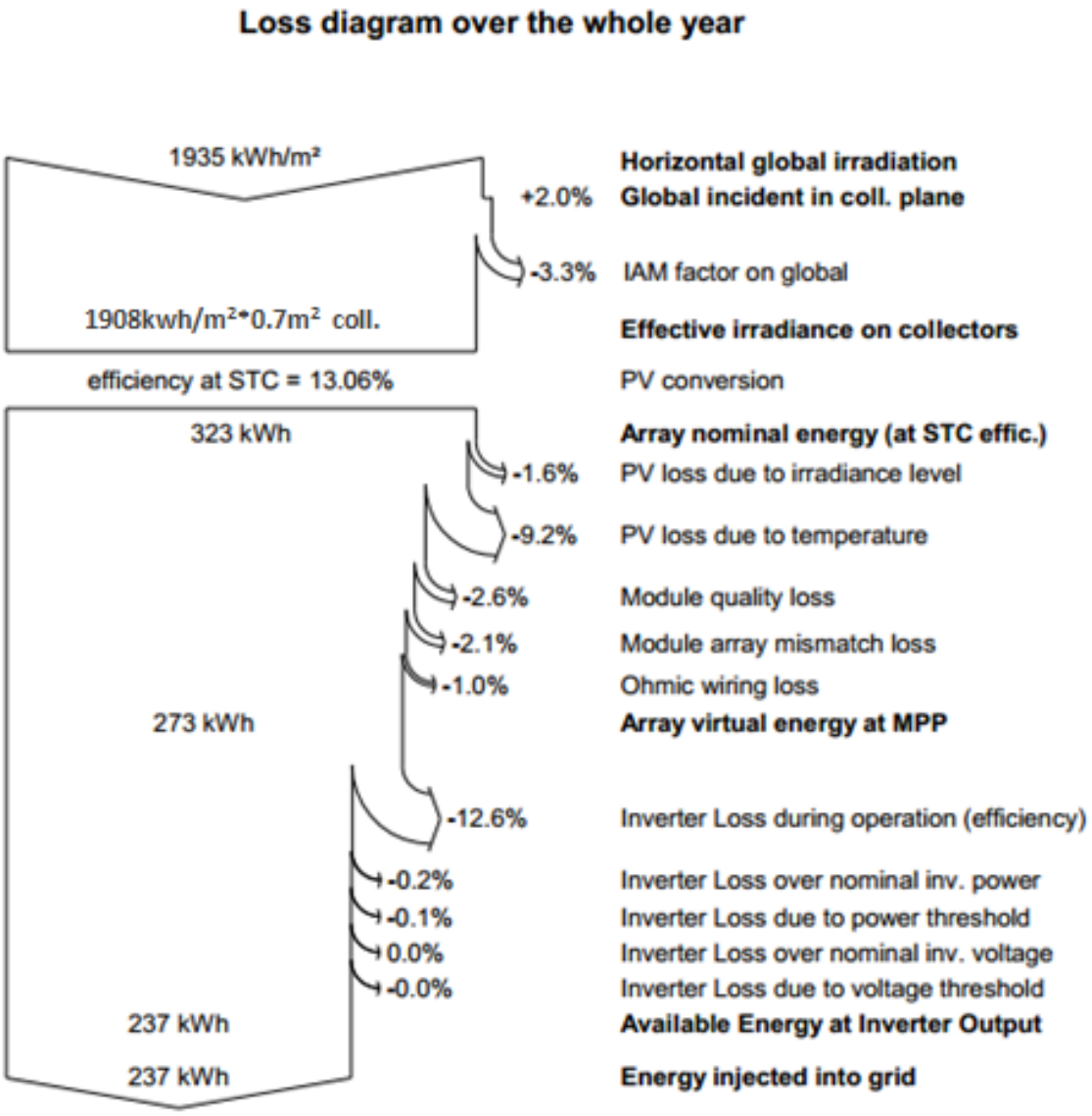


Figure 3- 9: PVsyst loss diagram over the whole year

Power produced from PV panel per year (kwh) = power required per day * day of the year * peak sun hour Power from PV panel per year (kwh) = 0.085kw*365*7.6 h = 237kwh. power output per year is equal with that shown on PVsyst loss diagram over the whole years. Therefore the loss diagram over the whole years is correct.

3.5.1. Sizing of PV Panel

The required power of the solar panel depends on the amount of energy needed for operate refrigerator systems.

Area of solar panel would be calculated as flow:

Power requirement to operate (danfoss/BD35F) compressor is 55Wp and power requirement for fan 5Wp. In this case total power requirement for solar powered refrigerator is 60Wp and the minimum solar radiation of site is 6.04kwh/m^2. The efficiency of maximum power point of module is 13% as shown in Table 3-4 and efficiency of maximum power point of electronic is 80% -90% [19].

Requirement power for compressor(wp)xPSH = Area of PV panel x irradiation(kwh/m^2) xη_{pv} xη_e

$$\text{Area of PV panel } (m^2) = \frac{\text{Requirement power for compressor (WP)} * \text{PSH}}{\text{Irradiation } (KWh/m^2) * \eta_{PV} * \eta_e}$$

$$\text{Area of PV pane } (m^2) = \frac{0.06 * 7}{6.04 * 0.13 * 0.85} = 0.62 m^2$$

Depending on the calculated area, select standard PV panel of 0.65m^2 it can produce 85W [Index B-1] . The selected PV panel can produce above required power. Therefore the design is safe.

Where: PSH is the peak sun hours of the location where the system would be installed.

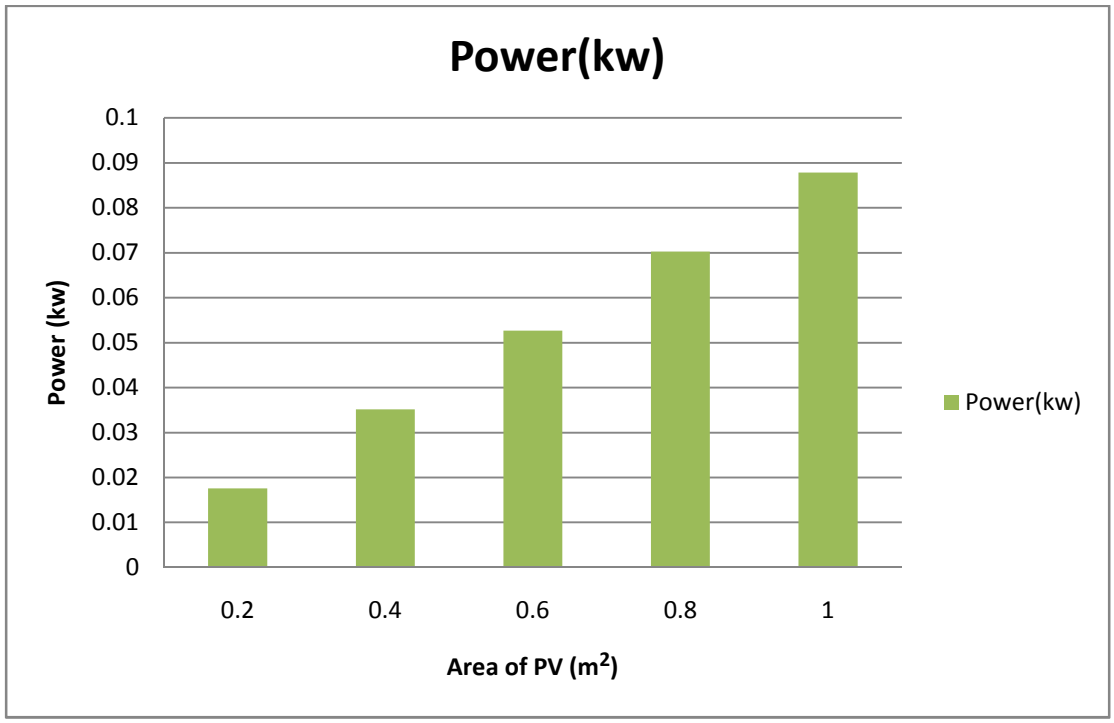
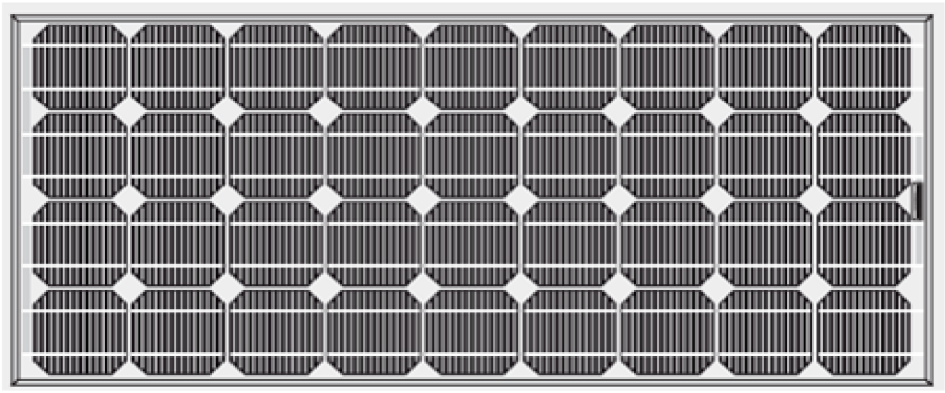
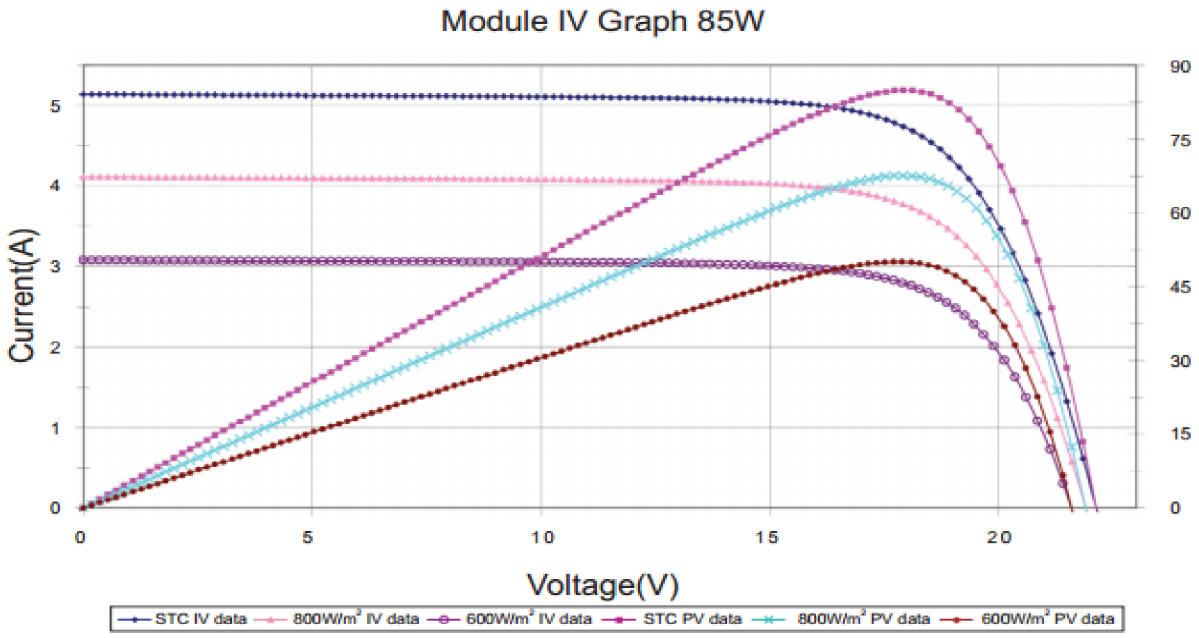


Figure 3- 10: Panel area Vs Power consumption by system

3.5.2. Specifications of the Installed PV Model

The PV model of solar panel selected for this work depends on power requirement is STP085-12/Bb. The selected module Area and power is 0.65m^2 and 85wp respectively. PV model for this system is Suntech's STPBb features total efficiency of 13.1% Which delivers the maximum power output at peak hours. Ideal for off-grid and remote power systems. With a 25 year warranty, the module has high efficiency and long-lasting operating time even in a variety of rigorous conditions. Unique textured cell surface and bypass diode design is critical for the module to fully utilize and absorb sunlight and offer maximum usable power per square meter of solar array. [Appendix B-1]





source: *From manufacturing data (suntech, April 2007)*

Figure 3- 11: Module I-V graph 85W Characteristics

Table3-4: Specifications of the Installed PV Model

Model	Suntech STP085S-12/Bb
Number of cell	36
Open - Circuit Voltage (Voc)	22.2V
Optimum Operating Voltage (Vmp)	17.8V
Short - Circuit Current (Isc	5.15A
Optimum Operating current (Imp)	4.80A
Maximum Power at STC (Pmax)	85Wp
Operating Temperature	-40℃ to +85℃
Maximum system Voltage	715V DC
Total efficiency	13.1%
Maximum Series Fuse Rating	15%
Power Tolerance	±5%
STC: Irradiance 1000W/m^2, Module temperature 25℃, AM =1.5	

Source: (Suntech, 2007)

3.6.Design component of refrigerator

In this work mini-compressor was selected for solar power refrigerator because it consume small amount of power which generated from solar array. Therefore the size of solar array required for this compressor is small. Due to this case the cost of solar PV array would be reduce. The selected compressor for this refrigerator is Danfoss/BD35F and it can be operate by selected PV module. Details of the selected compressor is presented in Table 3-5.

Table 3-5: Technical Specification of Variable Speed DC Compressor

Technical Specification	VSDC Compressor
Manufacturer/model	Danfoss(Escope)/BD35F
Cooling Capacity at ASHARE test condition	33.1 W at 2000 RPM and 50W at 3500 RPM
Compressor type	Hermetic reciprocating
Refrigerant	R134a(max 300g)
Evaporating temperature range	-30℃ to +10℃
Energy source	12/24V DC
Speed (RPM)	Variable speed 2000RPM -3500RPM

Source: (Danfoss, 2007)

VSDC Compressor must be noted that the installed compressor operates at four speeds, thus; 2000 RPM, 2500 RPM, 3000 RPM, and 3500 RPM. To regulate the speed of the compressor, different sizes of resistors were connected to the electronic control unit. (Danfoss, 2007).

The minimum power required to start the compressor of this refrigerator is, equal to approximately 45 W and the average electric power required during the operation is 55 W,

In detail, when the compressor runs, the mean value of 55 W is referred to 3000 revolutions per minute (RPM), Assuming evaporating temperature and condensing temperature is -5℃ and 55℃ respectively[danfoss BD35F]. Such conditions can be considered as a reference for the system and in addition to the 55W needed by the compressor, a 5W supplementary power for the condenser fan has to be considered.

The thermodynamic property of the refrigerant would be obtain From the above explanation. From the Table of Refrigerant (R-134a) obtain enthalpy at different point (h_1,h_2,h_3 and h_4) [Appendix C-1-1, C-1-2 and C-1-3]

The power required by the compressor, $\dot{W}_{comp}$ can be determined as the product of the refrigerant mass flow rate ($\dot{m}$), and the change in specific enthalpy of the refrigerant as it passes through the compressor, this is given in equation 3-12.

$$\dot{W}_{comp} = \dot{m}(h_2 - h_1) \qquad (3\text{-}12)$$

The energy requirement and optimum amount of refrigerant required by the system are yet to be determined.

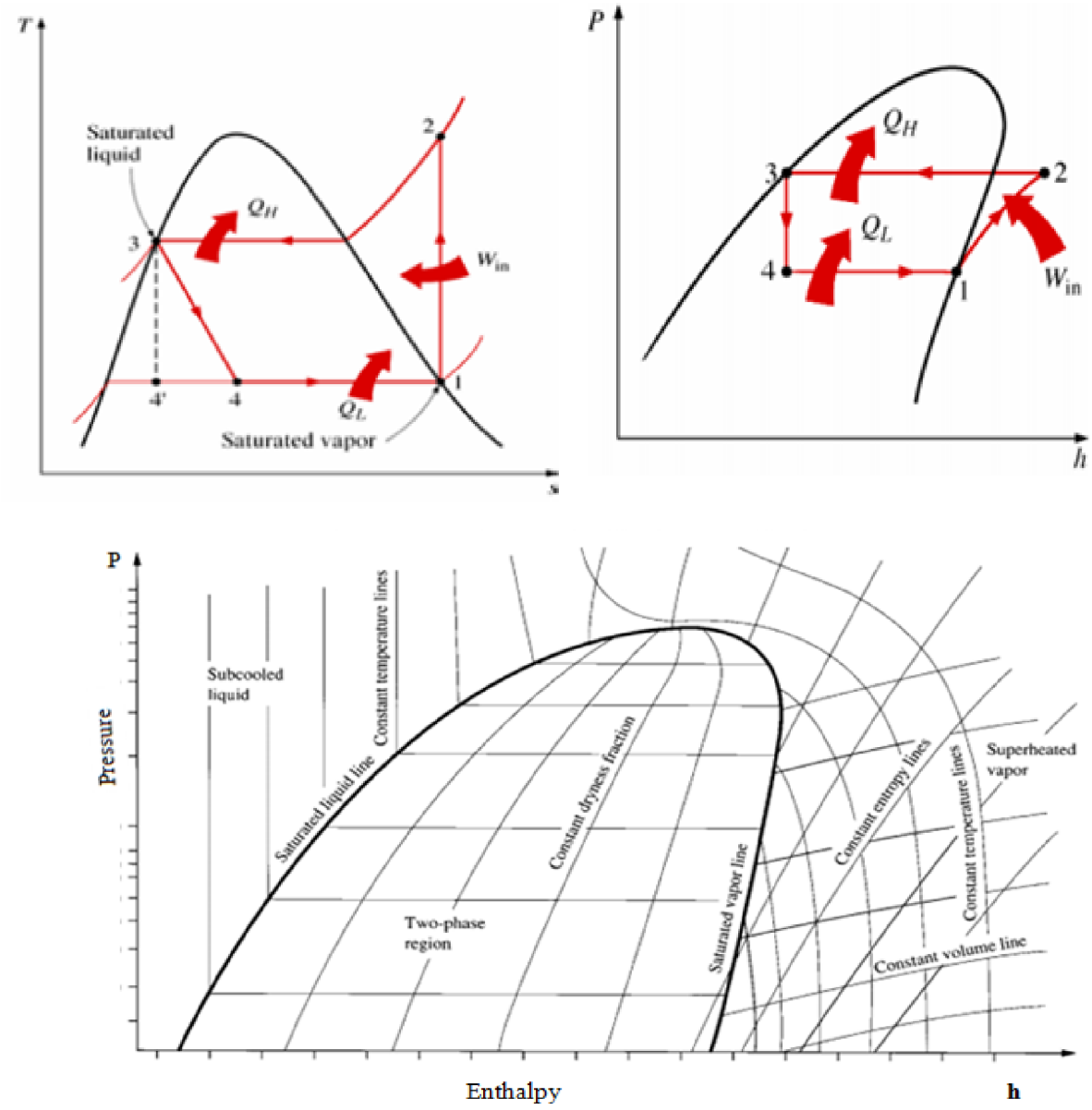


Figure 3- 12: Pressure - Enthalpy and T-S diagram

Table 3-6: Enthalpy at different state from refrigerant (R-134a) table

State	Temperature (°C)	Pressure (Mpa)	Enthalpy (kj/kg)
1	-5	0.24	247
2	61	1.5	284
3	55	1.5	131
4	-5	0.24	131

Mass flow rate of refrigerator can be calculate From equation 3-12.

$$\dot{m} = \frac{W_{Comp}}{h_2 - h_1} = \frac{0.055kW}{284kJ/kg - 247kJ/kg} = 0.0015kg/s$$

Heat Rejection in Condenser

Heat rejected by the refrigerant to the ambient while flowing through the condenser is given by the equation 3-13.

$Q_{cond} = \dot{m}(h_2 - h_3)$ (3-13)

$Q_{cond} = 0.0015kg/s(284kj/kg - 131kJ/kg) = 0.2295kJ/s$

Isenthalpic process

There is no change in enthalpy in the expansion device, this expansion valve for this refrigerator is reduce pressure from1.5Mpa to 0.24Mpa.

$h_3 = h_4 = 131kJ/kg$

Heat Absorbed in Evaporator

The heat gained by the refrigerant or the refrigerating capacity is given by equation 3-14

$Q_{ref} = \dot{m}(h_1 - h_4)$ (3-14)

$Q_{ref} = 0.0015kg/s\ (\ 247kJ/kg - 131kJ/kg) = 0.174kJ/s$

Coefficient of Performance of the Refrigerator

The coefficient of performance (COP) is a dimensionless index used to indicate the performance of a thermodynamic cycle or thermal system. In order to compare different refrigeration systems, a Coefficient of Performance (COP) was defined by Sadi Carnot in 1824. The magnitude of COP can be greater than 1. The COP is defined as shown in equation 3-15.

$$COP = \frac{Q_{ref}}{W_{comp}} = \frac{h_1 - h_4}{h_2 - h_1} \quad (3\text{-}15)$$

$$COP = \frac{247kJ/kg - 131kJ/kg}{284kJ/kg - 247kJ/kg} = 3.13$$

Total system energy balance

$$Q_{cond} = Q_{ref} + W_{comp} = 0.174 kJ/s + 0.055 kJ/s = 0.2295 kJ/s$$

$$W_{comp} = \frac{Q_{ref}}{COP} = \frac{0.174 kJ/s}{3.13} = 0.055 kJ/s \text{ or } 0.055 kW = 55 W$$

The calculated compressor power from the above equation is equal with the taken power. Therefore the design is safe. The overall efficiency of the refrigerator is equal to the product of the efficiency of the PV system and the vapour compression refrigerator.

Efficiency (η_t) = Efficiency of the PV* Efficiency of the refrigerator

$$\text{Efficiency of the PV system} = \frac{E}{I * A}$$

$$\text{Efficiency of the refrigerator} = \frac{Q_{ref}}{E}$$

$$\text{Efficiency}(\eta_t) = \frac{E}{I * A} * \frac{Q_{ref}}{E} = \frac{Q_{ref}}{I * A}$$

I= The direct irradiation of solar beams (kw/m^2)

A=Surface area of solar panel(m^2)

E =Energy generated by solar panel

$$\text{Efficiency } (\eta_t) = \frac{174 J/s}{815 w/m^2 * 0.65 m^2} = 0.3284 = 32.84\%$$

This efficiency is low; because due to reduce temperature of water up to 5℃ as comfortable for drink . Therefore efficiency of refrigerator is depends on application of refrigerator.

3.6.1. Cooling Load of Refrigeration Analysis

Coaling capacity of refrigerator Q_{ref} = 0.174(kJ/s), specific heat of water c_p (kJ/kg-K) is 4.186(kJ/kg-K) and temperature change of cool water as suitable for drink is change from 25℃ (298k) to 5℃ (278k) and amount of water for this purpose is 6Liter ≈ 6kg. Time taken to cool this water is calculate as follow.

$$Q_{ref} = \frac{m * c_p * \Delta T}{\theta} \quad (3\text{-}16)$$

Q_{ref} = cooling capacity of refrigerator (kJ/s)=(kw)

m = mass of product (kg)

c_p= specific heat of product (kJ/kg-K)

ΔT = change in product temperature (K)

θ= Time taken (seconds)

ΔT = 298k-278k = 20k

$$\theta = \frac{m * c_p * \Delta T}{Q_{ref}} = \frac{6kg * 4.186kJ/kg.K * 20K}{0.174kJ/s} = 2{,}887sec = 48min$$

Therefore by this solar powered refrigerator could be cool 6L of water from 25℃ into 5℃ after 48 minute.

The specification of condenser fan

In this work fan is used for cooling condenser tube and it locate between back side of cabinet and condenser tube. The module fan is "Fan wing condenser [Al dia-70mm sucking]" and power requirement of fan is 5W.

3.7. Design of Ice Storage Tank

3.7.1. Energy Balance of internal Refrigerator

The main purpose of this work is study on how to use ice storage instead of battery. Therefore, to design ice storage tank must be determine internal energy balance of refrigerator. This thermal energy balance of ice storage would be defined in the following equation:

$$Q_{sto,0-1} = Q_{cab,0-1} + Q_{Load,0-1} + Q_{air,0-1} + Q_{o,0-1} \quad (3\text{-}17)$$

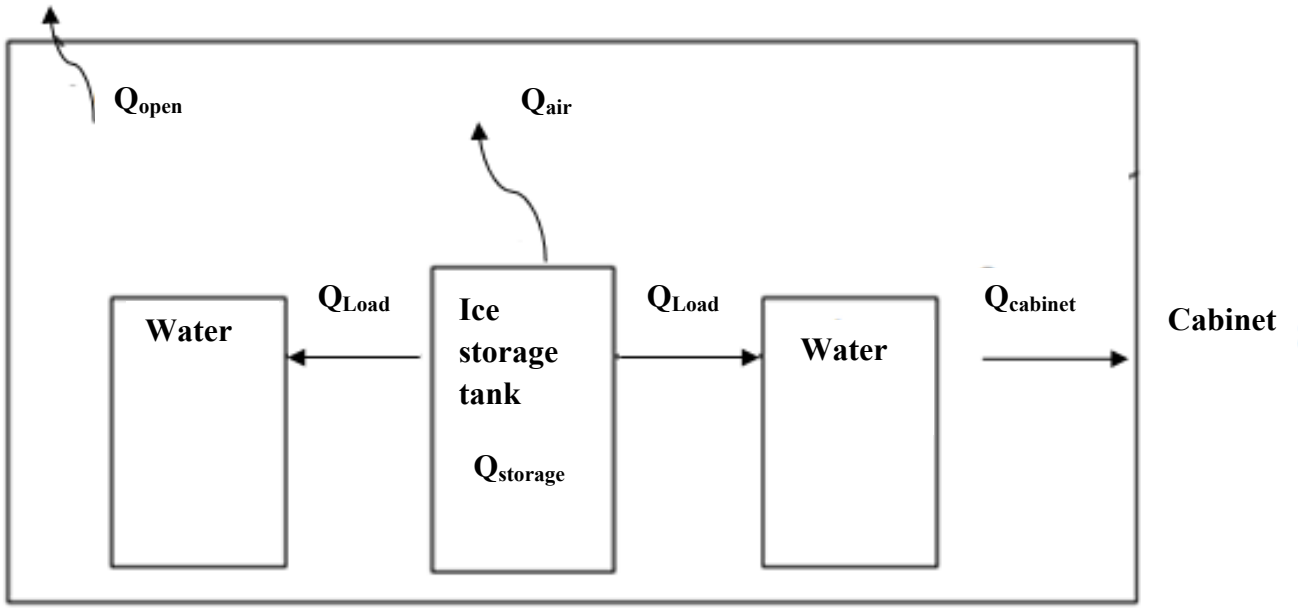


Figure 3- 13: Schematic diagram of internal energy balance of refrigerator

As shown in above figure the amount of energy released by the thermal storage $Q_{sto,\,0-1}$ in the air surrounding the refrigerator is equal to the sum of the heat loss through the envelope $Q_{cab,\,0-1,}$ the thermal energy absorbed by the thermal load inside the refrigerator $Q_{load,\,0-1,}$ the thermal energy absorbed by the air inside the refrigerator $Q_{air,\,0-1}$, and the thermal energy eventually dissipated during the openings of the cover $Q_{o,\,0-1}$. which means that, during a certain time interval $\Delta t = t_1 - t_0$, From above heat loss neglect thermal energy dissipated during the openings of the cover. The time taken to cool water as desired temperature is calculated therefore until calculated time cabinet doesn't open due to this case ($Q_{o,\,0-1}$ =0) and above equation becomes:

$$Q_{sto,0-1} = Q_{cab,0-1} + Q_{Load,0-1} + Q_{air,0-1}$$

$$\left(\frac{K_{al}}{L_{al}} + \frac{K_{ice}}{L_{ice}}\right)A_{sto}(T_{1,sto} - T_{0,sto})\,\Delta t = \frac{K_{st}}{L_{st}}\,A_{cab}(T_{1,cab} - T_{0,cab})\,\Delta t + m_{load} * cp_{load}\left(\frac{T_{1,load} - T_{0,load}}{\Delta t}\right)\Delta t + m_{air} * cp_{air}\left(\frac{T_{1,air} - T_{0,air}}{\Delta t}\right)\Delta t$$

$$\left(\frac{K_{al}}{L_{al}} + \frac{K_{ice}}{L_{ice}}\right)A_{sto}(T_{1,sto} - T_{0,sto})\,\Delta t = \frac{K_{st}}{L_{st}}\,A_{cab}(T_{1,cab} - T_{0,cab})\,\Delta t + m_{load} * cp_{load}(T_{1,load} - T_{0,load}) + m_{air} * cp_{air}(T_{1,air} - T_{0,air})$$

From above equation the known parameters are explain as follow:

Table 3-7: Thermodynamic property

Material	Thermal conductivity (K) w/m.k
Aluminum	237
Steel	14
Ice	1.88

Specific heat of water Cp_{load} = 4186J/kg.k

Specific heat of air Cp_{air} = 1007J/kg.k

mass of water stored in cabinet 6liter ≈ m_{load} = 6kg

Δt = Time taken to cool water is 48min ≈ 1 hour =3600 sec.

The internal volume of refrigerator is 0.35m*0.3m*0.32m =0.0336m^3 =33L and surface area of internal refrigerator A_{cab} =((0.35m*0.3m) + (0.3m*0.32m) +(0.35*0.32))2=0.62m^2

The thickness of cabinet is 0.003m, therefore volume of cabinet is $v_{cab.}$ = 0.62m^2*0.003m = 0.00186m^3. material of cabinet is steel (AISI 304) and it's density is ρ = 7900kg/m^3. Now from this parameter can obtain mass of cabinet as follow:

Mass = density *volume = 7900kg/m^3*0.00186m^3 = 15kg

Density of the air ρ_{air} = 1.22kg/m^3

Mass of the air $m_{air} = \rho_{air} * V_{air}$ = 1.22kg/m^3*0.0336m^3 = 0.04kg

Table 3-8: Temperature of system

Taken temperature of system	Temperature(K)
Average temperature of storage ($T_{1,sto}$)	298K
Ice temperature ($T_{0,sto}$)	273K
External cabinet temperature ($T_{1,cab}$)	301K
Internal cabinet temperature ($T_{0,cab}$)	278K
Initial temperature of load (water) ($T_{1,load}$)	298K
Final temperature of load (water) ($T_{0,load}$)	278K
Initial temperature of air internal temperature($T_{1,air}$)	298K
Final temperature of air internal temperature($T_{0,air}$)	278K

The evaporator is placed inside a mass of water (ice thermal storage). Such water, once frozen, ensures an optimal storage temperature of the refrigerated volume even without solar radiation.

Now to design the size of ice storage substitute known parameter in above original equation and determine the frontal area of ice storage. Assume thickness of ice and aluminum as suitable (fit) with internal size of refrigerator. Due to this case take the thickness of ice and aluminum is 0.05 and 0.002m respectively.

$$\left(\frac{237w/mk}{0.002m} + \frac{1.88w/mk}{0.05m}\right)A_{sto}(298k - 273) * 3600\ sec = \frac{14/mk}{0.003m} * 0.62m^2(301k - 278k) * 3600sec$$

+ 6kg*4186J/kg.k(298k-278k) + 0.04kg*1007J/kg.k(298k-278k)

$A_{sto} = 0.017m^2 = 0.12m*0.14m$

The volume of ice storage is calculated as follow:

$V_{sto} = A_{sto}(2L_{al} + L_{ice}) = 0.0227m^2(2*0.002m+0.05m) = 0.00092m^3 = 0.92L \approx 1L$

Evaporator is pass through in the ice storage tank, therefore voltage of tank is the summation of volume of evaporator and ice.

The size of ice storage tank is fitting with internal volume of refrigerator, therefore the design is safe.

3.7.2. Cooling load of ice storage

Ice storage is one of energy storage as battery in solar powered refrigerator and mass of ice is approximately one kg, because volume of water which used to make ice is 1liter and it is approximately 1kg. The specific heat of water which used for ice is 4186J/kg.k and cooling capacity of evaporator is 174J/s. The time versus changes of temperature for ice storage is shown as below figure by matlab.

$$\Delta t = \frac{m * c_p * \Delta T}{Q}$$

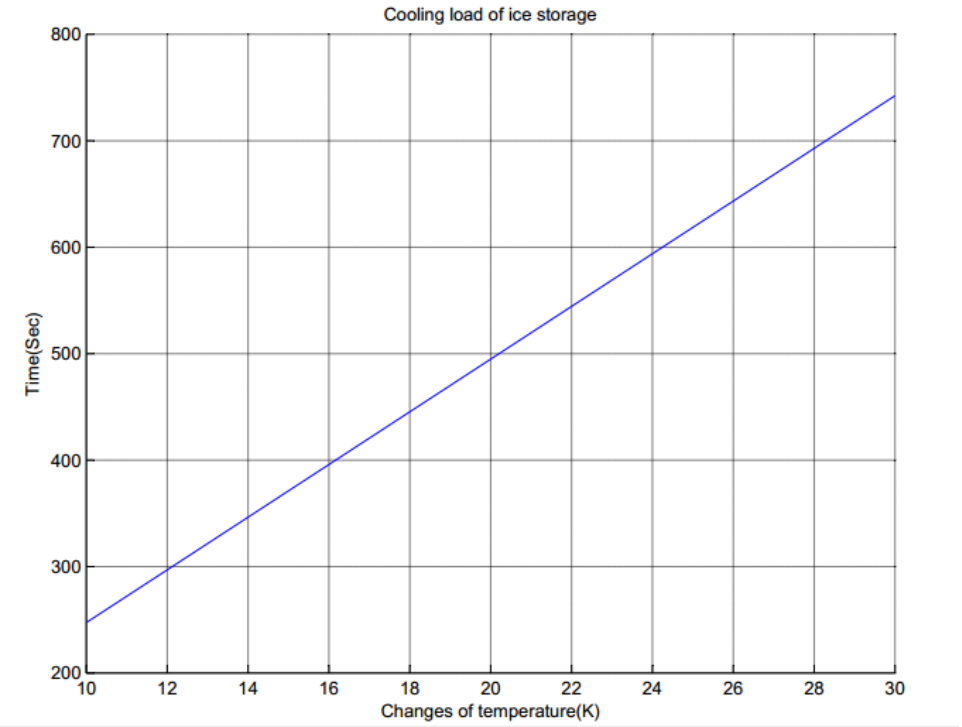


Figure 3- 14: Time(Sec) versus Changes of temperature(k)

3.7.3. Energy Removed by Evaporator

The thermal energy balance of the of solar powered refrigerator in one hour can be described with the following relation:

$Q_{eva} = Q_{sto,\ 0-1} + Q_{cab,\ 0-1} + Q_{load,\ 0-1} + Q_{air,\ 0-1} + Q_{o,\ 0-1}$

As explain in (section 3.7.1) $Q_{o,0-1} = 0$

$Q_{eva} = \left(\frac{K_{al}}{L_{al}} + \frac{K_{ice}}{L_{ice}}\right) A_{sto}(T_{1,sto} - T_{0,sto})\,\Delta t + \frac{K_{st}}{L_{st}} A_{cab}(T_{1,cab} - T_{0,cab})\,\Delta t + m_{load} * cp_{load}(T_{1,load} - T_{0,load}) + m_{air} * cp_{air}(T_{1,air} - T_{0,air})$

$Q_{eva} = \left(\frac{237W/mk}{0.002m} + \frac{1.88W/mk}{0.05m}\right) * 0.00852m^2 * (298k - 273) * 3600\ sec + \frac{14W/mk}{0.003m} * 0.62m^2(301k - 278k) * 3600sec + 6kg * 4186J/kg.k(298k - 278k) + 0.04kg * 1006J/kg.k(298k - 278k)$

$Q_{eva} = 90{,}892{,}800J + 180835200J + 502{,}320J + 804.8J = 272MJ$

But, $\dot{Q}_{eva} = 75kJ/s$

3.8. Design of condenser

Condenser is equipment which Heat rejected by the refrigerant to the ambient and in this device occurs high pressure, high temperature (superheated or saturated) vapor that enters the condenser has heat removed from it and as a result it is condensed back into a liquid phase. The condenser design of this refrigerator is present as follow:

From the selected compressor obtain internal and outer diameter of compressor is 0.005m and 0.007m respectively and heat transfer coefficient of surrounding and refrigerant is 225w/m^2°C and 1200w/m^2 °C respectively. Thermal conductivity of steel tube is 45w/m°C, the maximum temperature of condenser is T_{hi} = 61°C and also mass flow rate of refrigerant is calculated in section 3.6 ($\dot{m}$= 0.0015kg/s). The outlet temperature of condenser is T_{ho} = 35°C, average temperature of site is T_{ci} = 28°C and outlet temperature of air is T_{co} = 32°C.

Now depending on above parameter design the size of condenser.

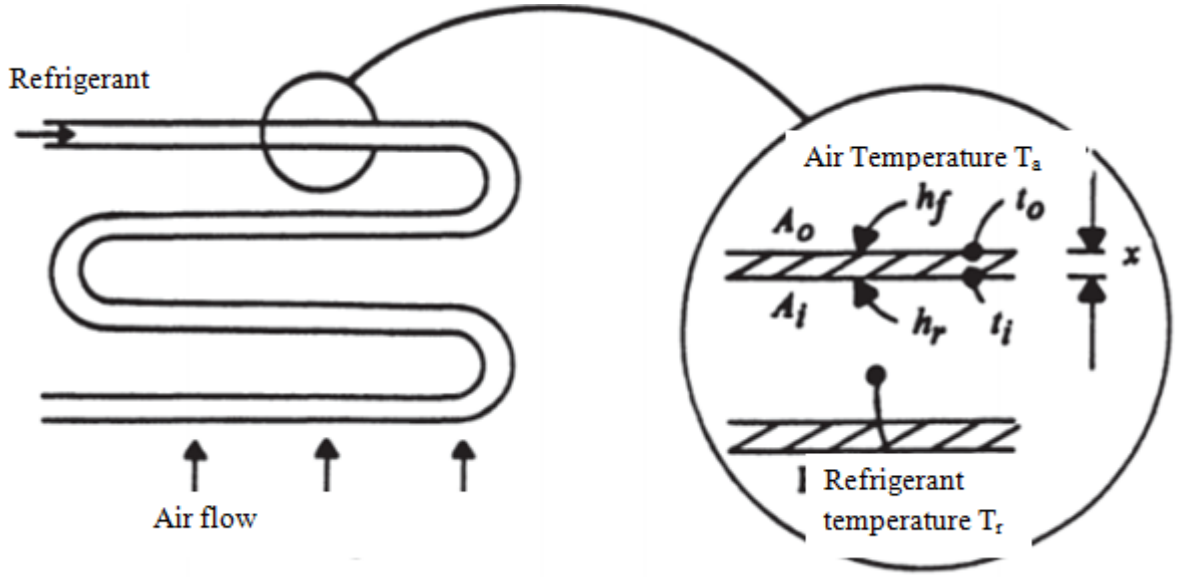


Figure 3- 15: Schematic diagram of condenser

$q = \dot{m}(h_2 - h_3)$ (3-18)

$q = 0.0015kg/s(284kj/kg - 131kj/kg) = 229.5W$

$q = UA\Delta T_m$ (3-19)

Heat transfer from air to outside surface of the tube

$$q = \frac{T_a - T_o}{\frac{1}{h_a A_o}}$$

Heat transfer from outside tube to inside of the tube

$$q = \frac{T_o - T_i}{\frac{x}{kA_{mean}}}$$

Heat transfer from inside tube to refrigerant

$$q = \frac{T_i - T_r}{\frac{1}{h_r A_i}}$$

where A_o = external area of evaporator tube, m^2

A_{mean} = mean cylindrical area of evaporator tube, m^2

A_i = inside area of tube, m^2

h_f = heat-transfer coefficient on fluid side, $W/m^2 \cdot °C$

h_r= heat-transfer coefficient on refrigerant side, $W/m^2 °C$

k= conductivity of the tube, $W/m \cdot °C$

q= rate of heat transfer, W

T_a = fluid temperature, °C

T_o= temperature of outside surface of tube, °C

T_i = temperature of inside surface of tube, °C

T_r = temperature of refrigerant °C

x= thickness of tube, m

Overall heat transfer coefficient

$$\frac{1}{UA} = \frac{1}{h_a A_o} + \frac{X}{KA_{mean}} + \frac{1}{h_r A_i}$$

To compute the U-value based on the inside area,

$$\frac{1}{U_i} = \frac{A_i}{h_a A_o} + \frac{(x)A_i}{\frac{K(A_o + A_i)}{2}} + \frac{1}{h_r}$$

The ratios of the cylindrical areas through which heat flows are the same as the diameter ratios,

$$\frac{A_i}{A_o}=\frac{0.005m}{0.007m}=0.71 \text{ and } \frac{A_i}{(A_o+A_i)/2}=\frac{0.005}{\frac{0.007+0.005}{2}}=0.83$$

$$x=\frac{D_o-D_i}{2}=\frac{0.007-0.005}{2}=0.001m$$

$$\frac{1}{U_i}=\frac{0.71}{225}+\frac{0.001(0.83)}{45}+\frac{1}{1200} \qquad \text{hence,} \qquad U_i=637 w/m.℃$$

$$\Delta T_m=\frac{\Delta T_2-\Delta T_1}{\ln(\Delta T_2/\Delta T_1)}$$

But, $\Delta T_1=T_{hi}-T_{ci}=61-28=33$ $\Delta T_2=T_{ho}-T_{co}=35-32=3$

$$\Delta T_m=\frac{3-33}{\ln(3/33)}=12^\circ c$$

Now determine the length of condenser tube as follow:

$$L=\frac{q}{U_i*\pi*D_i*\Delta T_m}=\frac{229.5W}{637W/m^2{}^\circ c*3.14*0.005m*12^\circ c}=2m$$

Number of turn n= L_{turn}/0.3m. hence 0.3m is length of one turn of compressor this length is fit with back of refrigerator. $n = L_{turn}/0.3m = 2m/0.3m = 6.6 \approx 7$

Surface area of condenser tube is determined as follow:

$A_{cond} = \pi DL = 3.14*0.005m*2.5m = 0.039m^2$ and volume of condenser is $V_{cond.}=0.039m^2*0.002m=0.000078m^3$. Material of condenser steel (ASICI 304) it's density is $\rho = 7900kg/m^3$. mass condenser is calculated as follow:

Mass = density*volume = $7900kg/m^3*0.000078m^3 = 0.616kg$.

3.9. Design of Evaporator

Evaporator is equipment which heat absorb at a low temperature and in this section must be maintain, a low pressure. The evaporator design of this refrigerator is present as follow:

From the selected compressor internal and outer diameter of compressor is 0.005m and 0.007m respectively and heat transfer coefficient of water and refrigerant is 4,211W/m^2℃ and 2200W/m^2℃ respectively. Thermal conductivity of steel tube is 45w/m℃ and temperature range of evaporator for this system is shown in table 3-5 (-30℃ to 10℃), from this interval assume the outlet temperature of evaporator T_{co} = -5℃ also mass flow rate of refrigerant is calculated in section 3.6 ($\dot{m}$= 0.0015kg/s). The evaporator tube is immersed in ice storage tank this tank is contain water until this water change to ice, therefore temperature of water is change from average temperature T_{hi} = 25℃ to ice temperature T_{ho} = 0℃.

$q = \dot{m}(h_1 - h_4) = 0.0015kg/s(247kj/kg - 131kj/kg) = 174W$

$q = UA\Delta T_m$

To compute U-overall heat transfer coefficient

$$\frac{1}{U_i} = \frac{A_i}{h_a A_o} + \frac{(x)A_i}{\frac{K(A_o + A_i)}{2}} + \frac{1}{h_r}$$

The ratios of the cylindrical areas through which heat flows are the same as the diameter ratios,

$$\frac{A_i}{A_o} = \frac{0.005m}{0.007m} = 0.71 \text{ and } \frac{A_i}{(A_o + A_i)/2} = \frac{0.005}{\frac{0.007 + 0.005}{2}} = 0.83$$

$$x = \frac{D_o - D_i}{2} = \frac{0.007 - 0.005}{2} = 0.001m$$

$$\frac{1}{U_i} = \frac{0.71}{4{,}211} + \frac{0.001(0.83)}{45} + \frac{1}{2{,}200} \qquad \text{hence,} \qquad U_i = 1{,}560 W/m.℃$$

$$\Delta T_m = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2 / \Delta T_1)} \qquad \text{But,} \qquad \Delta T_1 = T_{hi} - T_{ci} = 25 - (-20) = 45$$
$$\Delta T_2 = T_{ho} - T_{co} = 0 - (-5) = 5$$

$$\Delta T_m = \frac{5 - 45}{\ln(5/45)} = 18^\circ c$$

Now determine the length of evaporator tube as follow:

$$L = \frac{q}{U_i * \pi * D_i * \Delta T_m} = \frac{174W}{1560 w/m^2 {}^\circ c * 3.14 * 0.005m * 18^\circ c} = 0.4m$$

Now calculate Number of turn n= L/0.13m. hence 0.13m is comfortable (fit) with height of ice storage tank. n = L/0.13m = 0.4m/0.13m =3.08 ≈ 4

Surface area of evaporator tube is determined as follow:

$A_{eva.} = \pi DL = 3.14*0.005m*0.5m = 0.0078m^2$ and volume of evaporator($V_{eva.}$) is $V_{eva.}=0.0078m^2*0.002m=0.0000157m^3$. Material of evaporator is steel (ASICI 304) it's density is $\rho = 7900kg/m^3$. mass of evaporator is calculated as follow:

mass = density*volume = $7900kg/m^3*0.0000157m^3$ =0.124kg.

3.10. Control System of Solar Powered Refrigerator

Control systems of solar powered refrigerator like main switch and fuse. This component is used for control power between solar panel and compressor.

The total mass of solar powered refrigerator is the summation mass of cabinet, solar panel, compressor, ice storage tank, condenser and evaporator.

Table 3-9: Mass of Solar powered refrigerator component

Components of solar refrigerator system	**Mass of component (kg)**
Cabinet	15
Solar PV module	8
Compressor	4.3
Ice storage tank	1
Condenser	0.61
Evaporator	0.124
Total mass of system	29

As shown in above table mass of refrigerator this mass is can be transport in rural area by two people and by animal like donkey, camel and hoarse.

3.11. The System Layout

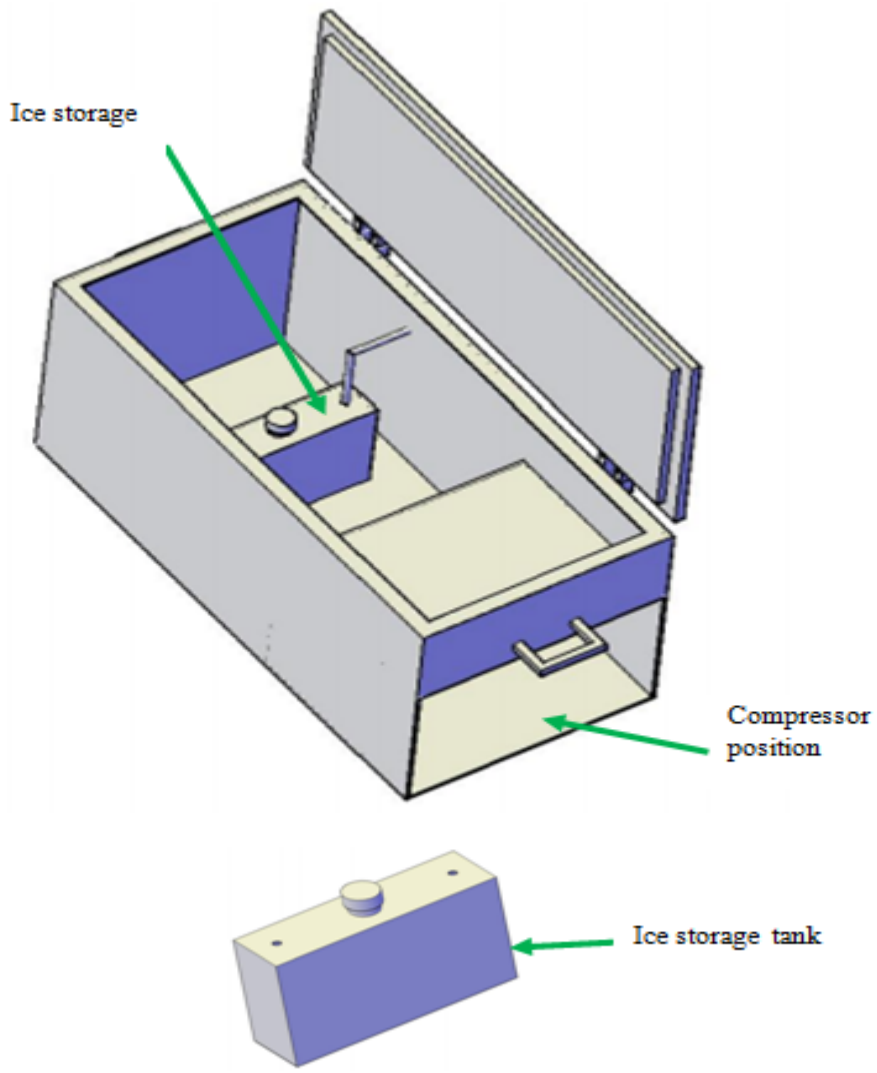


Figure 3- 16: Solar power refrigerator without solar panel and ice storage

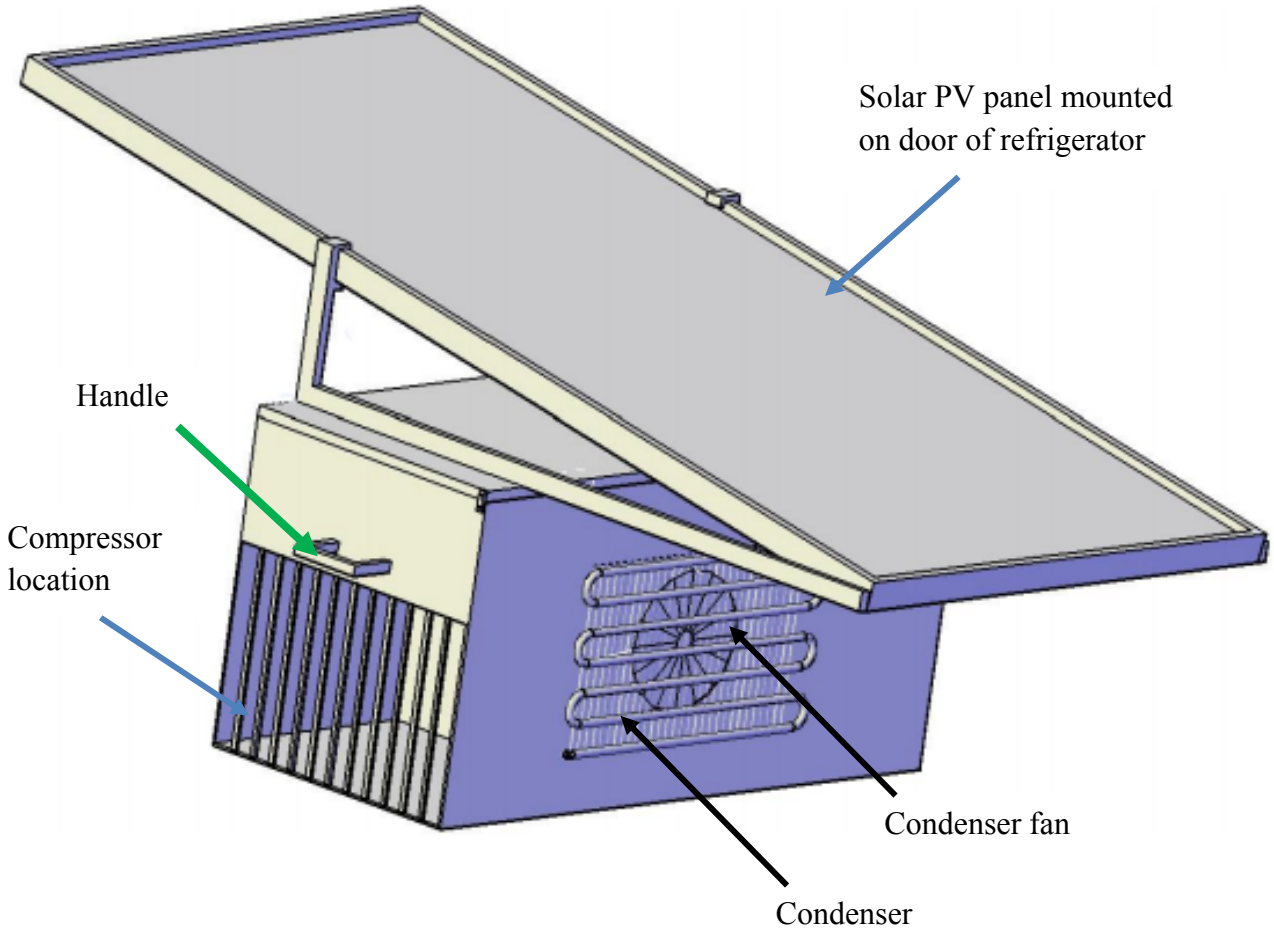


Figure 3- 17: solar powered refrigerator with solar panel

As shown in above figure the angle of panel is tilted to south by site location latitude β= 9.68° and compressor is inside of refrigerator due to this case some heat is transfer into internal refrigerator but this heat is not required for this application. Therefore to solve this problem insert insulate material between compressor and internal of refrigerator for eliminate heat. The solar panel locate above cabinet and it use as shadow for cabinet.

CHAPTER FOUR

4. ECONOMIC ANALYSIS

4.1.Cost Analysis of Solar Powered Refrigerator

4.1.1. Cost of Solar in Africa (<1 Kw)

Solar home systems and grid-connected rooftop solar PV systems can be implemented in Africa not only in rural areas with large non-electrified areas and populations, but also in grid-connected urban areas, which in sub-Saharan Africa are increasingly suffering from frequent power shortages and outages. Solar home systems and grid-connected rooftop solar can help to reduce pressure on the grid by lightening the load of house hold and commercial power demand from the national grid, as well as meet the basic energy services of those without access to electricity today.

The cost range for mini-grid systems (without batteries) that are connected to the grid is somewhat higher than the current range for grid connected utility-scale systems and is around USD 2.5 to USD 2.9/W for projects in sub-Saharan Africa. The data that IRENA has collected for solar PV in off-grid mini-grid systems that do not have batteries are for systems installed in North Africa that have lower installed costs, from USD 1.4 to USD 2.7/W. For mini-grids relying more heavily on solar PV, where a battery is included, the total system cost can be double or triple that of mini-grids without batteries, with a range of between USD 2.5 and USD 10.9/W. This represents the fact that many of these systems are green field in nature and have higher project development costs, in addition to the costs associated with batteries (IRENA (2016), Solar PV in Africa: Costs and Markets)

The cost of solar PV which produce 85W power in off-grid is calculate as follow:

USD2.7*85 = USD229.5 = 5,049birr

4.1.2. Cost of Condenser

Cost of compressor C_{comp} calculated as follow:

$$C_{comp} = \$45.11\left(\frac{EER}{1.5}\right)^{0.5} \quad (4\text{-}1)$$

Energy efficiency ratio EER=COP*3.41= 3.13*3.41=10.53

Cost of compressor c_{comp} =45.11\left(\frac{10.53}{1.5}\right)^{0.5}$ =$119.5 = 2,629 birr

Table4-1: Initial cost of solar powered refrigerator component

Components name of refrigerator	Price (birr)
Compressor	2,629
Cabinet	3,348.54
Thermostat	230.36
Electronic control panel	195.52
Fan compressor	1,884.48
Main switch	160.42
PV module	5,049
Total price	**13,266**

Source: *Manufacturer Specification of solar powered refrigerator*

4.2. Pay Back Cost

The purpose of this Solar power refrigerator is water cooling about 6liter*6hours=36 liter per day. As social Exist in desert area want cold water by adding 1 up to 3 birr per price of one liter. Therefore the profit price of cold water for ten month in a year would be calculate as follow:

when adding 1birr per price of one liter Pc = 1birr/liter*36liter/day*300day = 10,800birr/year

when adding 2birr per price of one liter Pc = 2birr/liter*36liter/day*300day = 21,600birr/year

when adding 3birr per price of one liter Pc = 3birr/liter*36liter/day*300day = 32,400birr/year

The pay back cost is shown in below figure as adding price per liter of water.

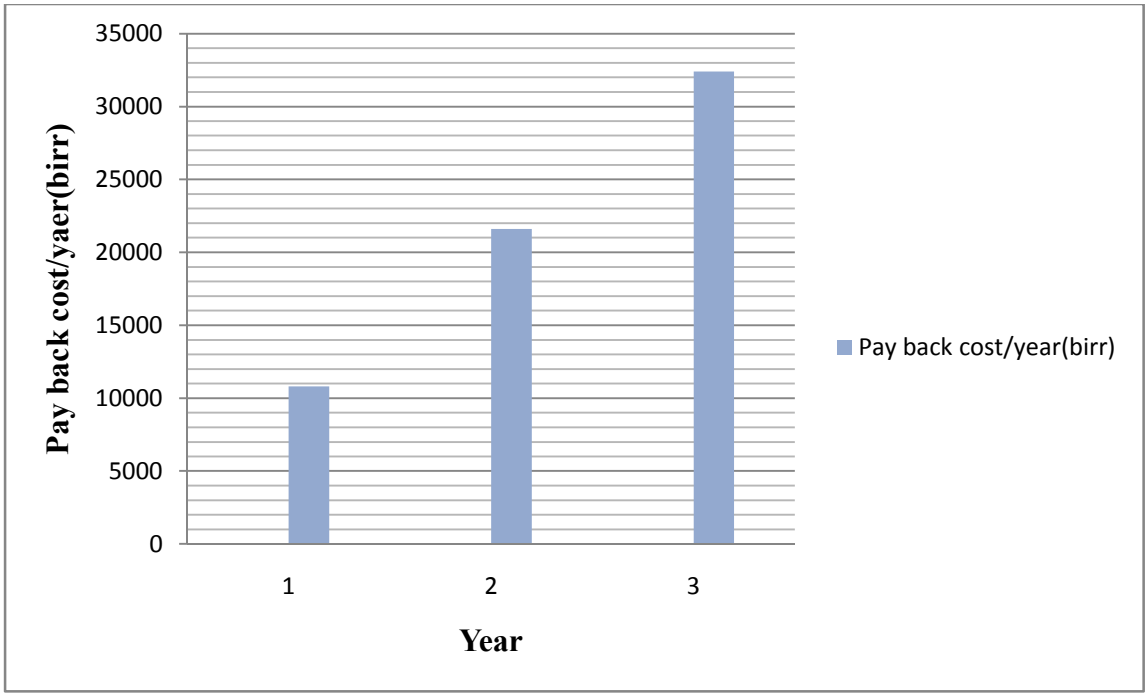


Figure 4- 1: Pay back cost/year versus by adding price/liter

The initial cost of solar powered refrigerator is 13,266 birr. Therefore as shown under pay back cost, the initial cost of the system would be obtain after one to two year from the water which used for drink.

4.3. Pay back Cost up to Ten Years

Product cost in year for ten month during cold water is required by people if adding 1,2 and 3birr per price of one liter is shown in below figure.

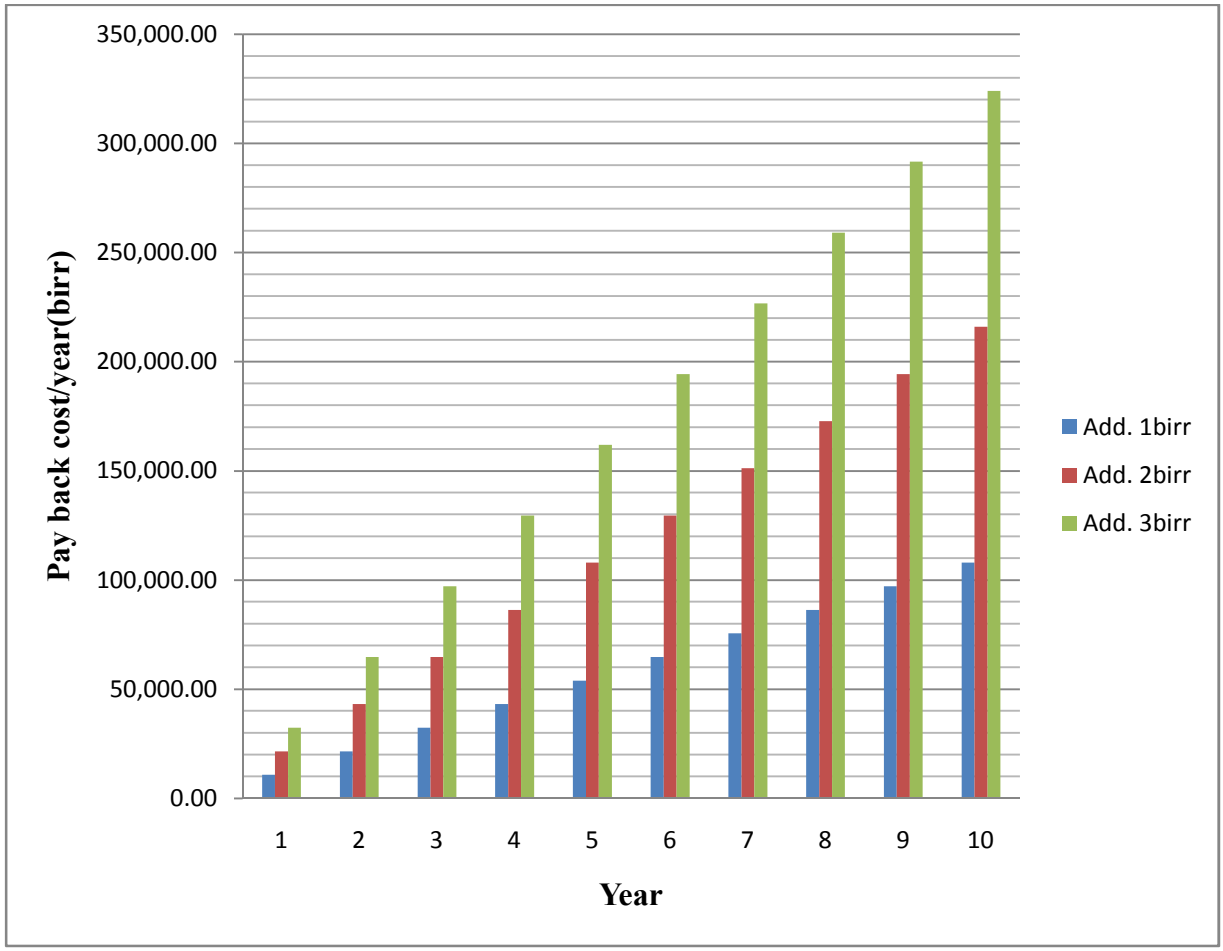


Figure 4- 2: Pay back cost up to ten years

CHAPTER FIVE

5. RESULT AND DISCUSSION

5.1. Data Analysis of Site

Data is one of heart of research and solar radiation data is very necessary for this work. Solar radiation data doesn't constant in all location and it is vary from year to year. Therefore compare data which collected from different source and take minimum solar radiation month from average solar radiation that collected from different years and also checked by manually calculating. Site location of this work is Dire Dawa shinile and solar radiation data of this site is used for design and optimization of solar power refrigerator. Compare the site data which taken from NASA which describe in table 3-3 and PVGIS from table 3-1, then take minimum solar radiation as shown below figure.

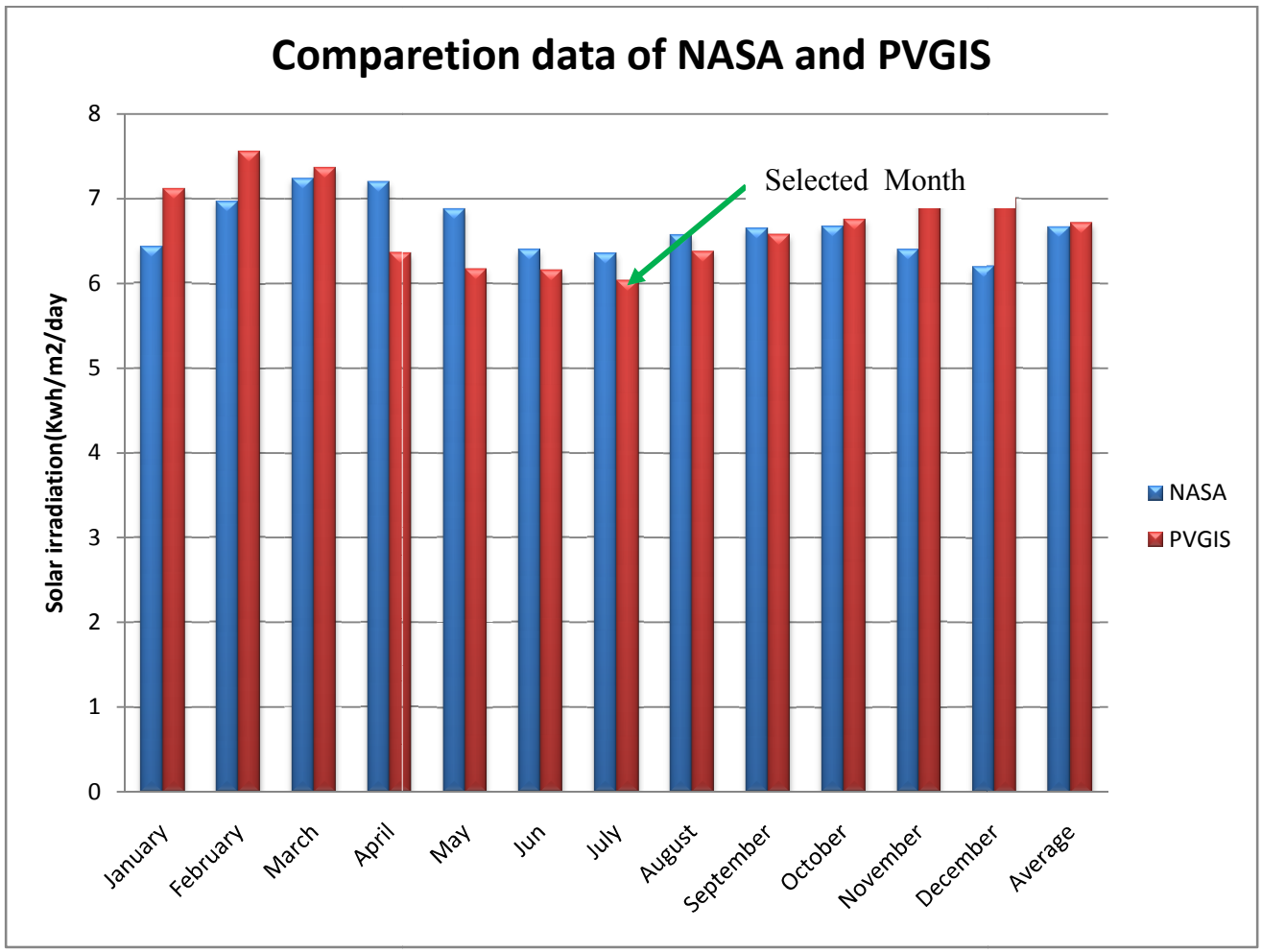


Figure 5- 1: Comparison data of NASA and PVGIS

5.2. Cooling Load

In any refrigerator time to cool material is must be required, also in this refrigerator time taken to cool 6Liter of water from 25℃ into 5℃ is 48minute and temperature of water is reduced to ice (0℃) after one hour. This solar power refrigerator uses for other purpose like pasteurized of milk, vaccine, food store and etc as required temperature for different application.

The changes of temperature is increase as time taken for cool water is increase. In this work solar powered refrigerator is used for cooling water from environmental temperature to as suitable for drink.

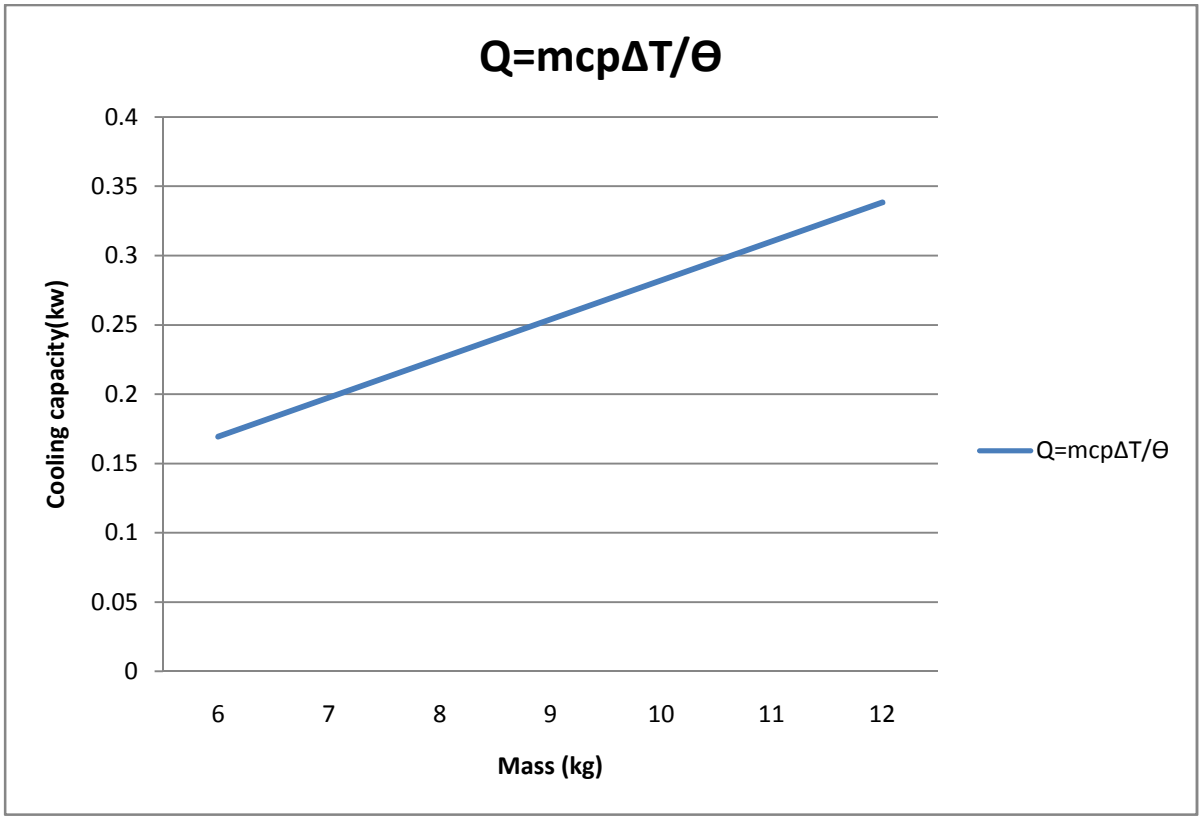


Figure 5- 2: Cooling capacity(kw) versus mass(kg)

As shown in figure 5-2 cooling capacity of refrigerator increase as volume of water for drink increase. The cooling capacity of required for 6 liter of water is 0.174kW in one hour.

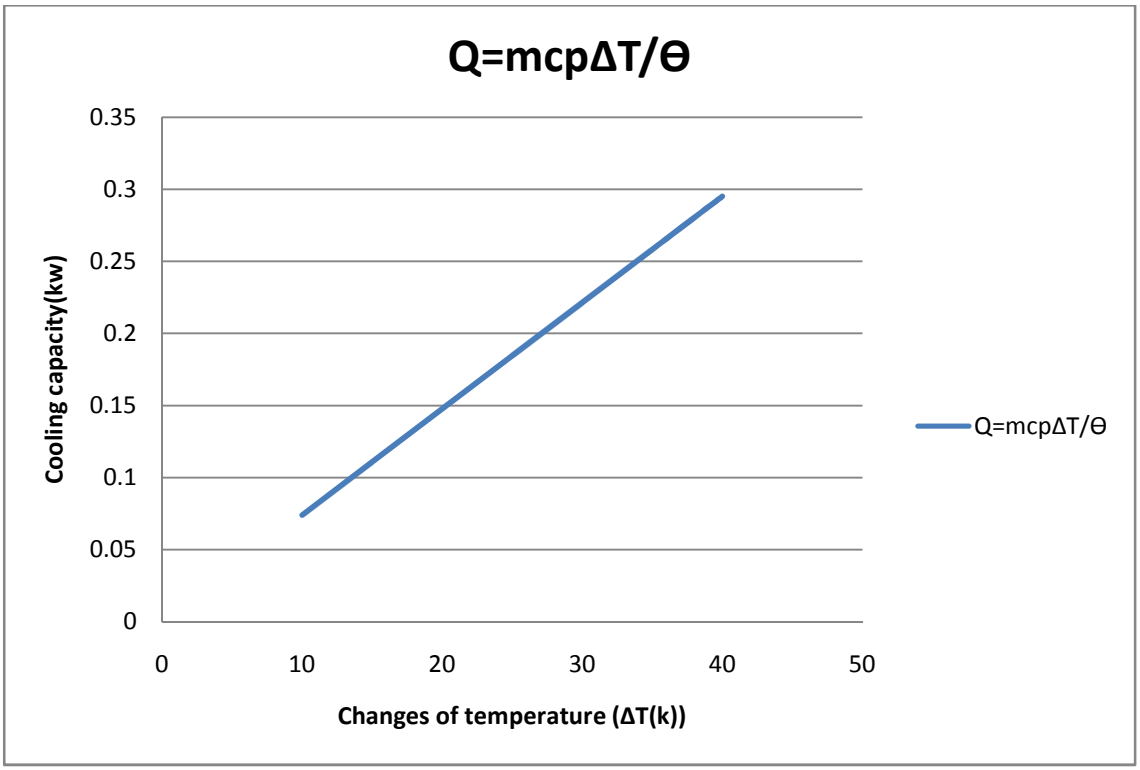


Figure 5- 3: Cooling capacity Vs changes of temperature

As shown in above figure 5-3 cooling capacity is increase as changes of temperature on water increase. At 25k changes of temperature on water for drink cooling capacity is about 0.174kW. when environmental temperature 30℃ =303k and requirement temperature of water as comfortable for drink is 5℃ = 278k, from these temperature; changes of temperature is ΔT = 303k - 278k = 25k. The changes of temperature is vary as environmental temperature is vary.

5.2.1. Thermal ice storage in refrigerator

Thermal ice storage is use as battery storage in solar powered refrigerator. These refrigerator is use solar energy without battery during solar radiation is enough to drive compressor of refrigerator. But, during cloudy day and after sun become to set and solar radiation is can't drive compressor; use ice storage to cool water. The temperature of ice storage is maintain 0℃ until the refrigerator stop work , then temperature of ice become increase. Temperature of water for drink and temperature of ice can be determine during compressor is stop work from energy balance equation as follow:

$$Q_{Sto,0-1} = Q_{cab,0-1} + Q_{Load,0-1} + Q_{air,0-1}$$

$(\frac{K_{al}}{L_{al}} + \frac{K_{ice}}{L_{ice}})A_{sto}(T_{1,sto} - T_{0,sto})\,\Delta t = \frac{K_{st}}{L_{st}} A_{cab}(T_{1,cab} - T_{0,cab})\,\Delta t + m_{load}*cp_{load}(T_{1,load} - T_{0,load}) + m_{air}*cp_{air}(T_{1,air} - T_{0,air})$

$$T_{1,sto} = \frac{1}{\Delta t * A_{sto}(\frac{k_{al}}{L_{al}} + \frac{k_{ice}}{L_{ice}})}(A_{cab} * \frac{k_{st}}{L_{st}} * \Delta T_{cab} * \Delta t + m_{load} * Cp_{load} * \Delta T_{load} + m_{air} * Cp_{air} * \Delta T_{air}) + T_{0,sto}$$

$$T_{1,load} = \frac{1}{m_{load} * Cp_{load}}(\frac{k_{al}}{L_{al}} + \frac{k_{ice}}{L_{ice}})\Delta T_{sto} * A_{sto} * \Delta t - m_{air} * Cp_{air} * \Delta T_{air} - \frac{k_{st}}{L_{st}} * A_{cab} * \Delta t * \Delta T + T_{0,load}$$

The temperature of water and ice can be calculate from above equation.

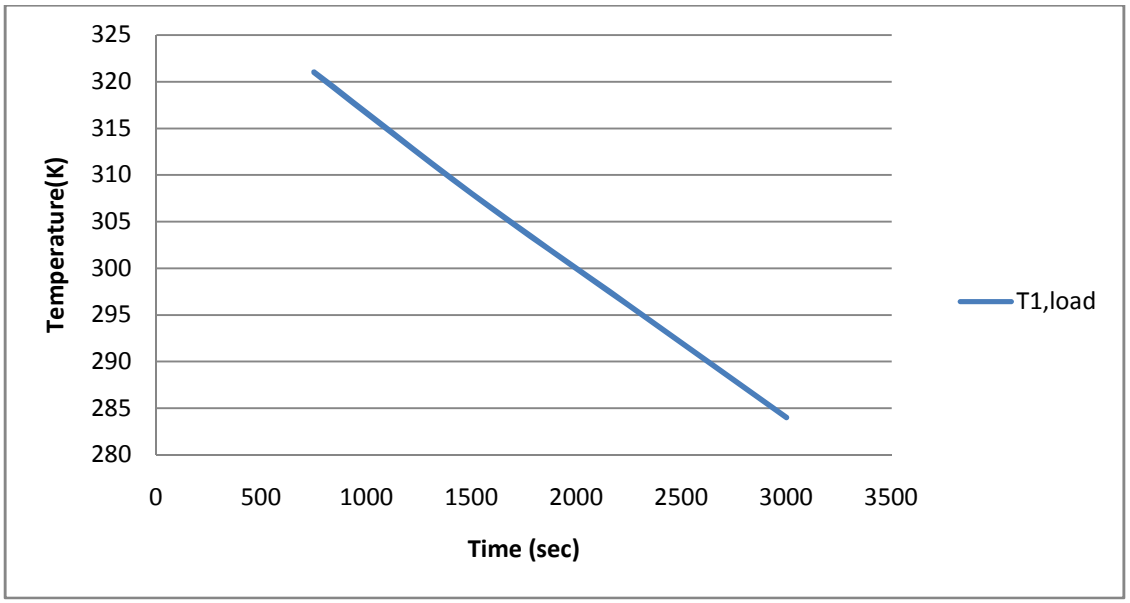


Figure 5- 4:Temperature of water versus time during compressor is stop

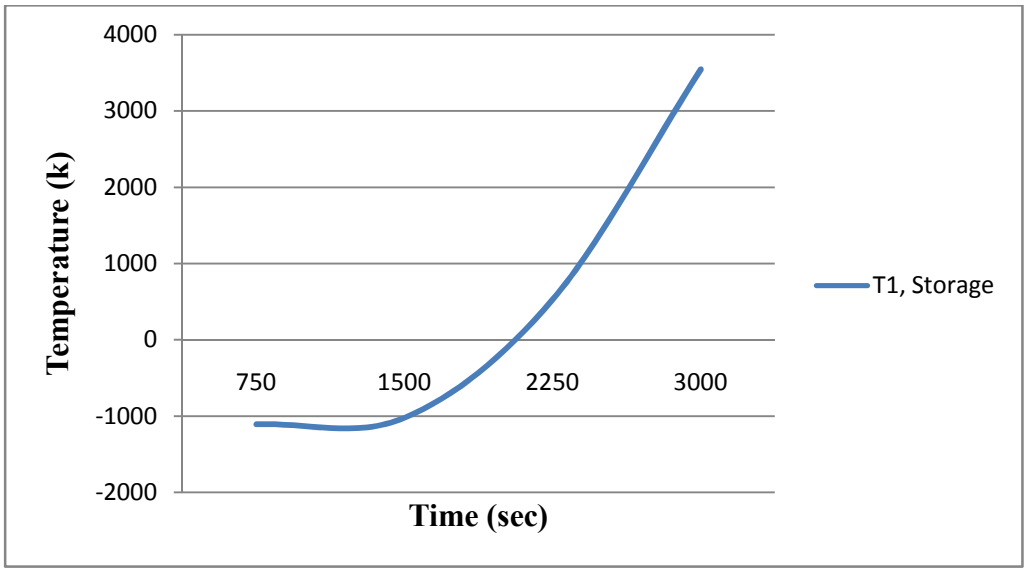


Figure 5- 5: Temperature of ice storage versus time during compressor is stop

As shown in above figures, the temperature of water is reduce for one time to cool 6 liter of water in one hour. These process is repeat on other 6liter which replaced after 6 liter of water is picked and continue until compressor of refrigerator is stop work. After compressor is stop run, water for drink is cool by ice storage; due to this case temperature of ice is increase as temperature of water decrease, the combination both above figures shown in below figure.

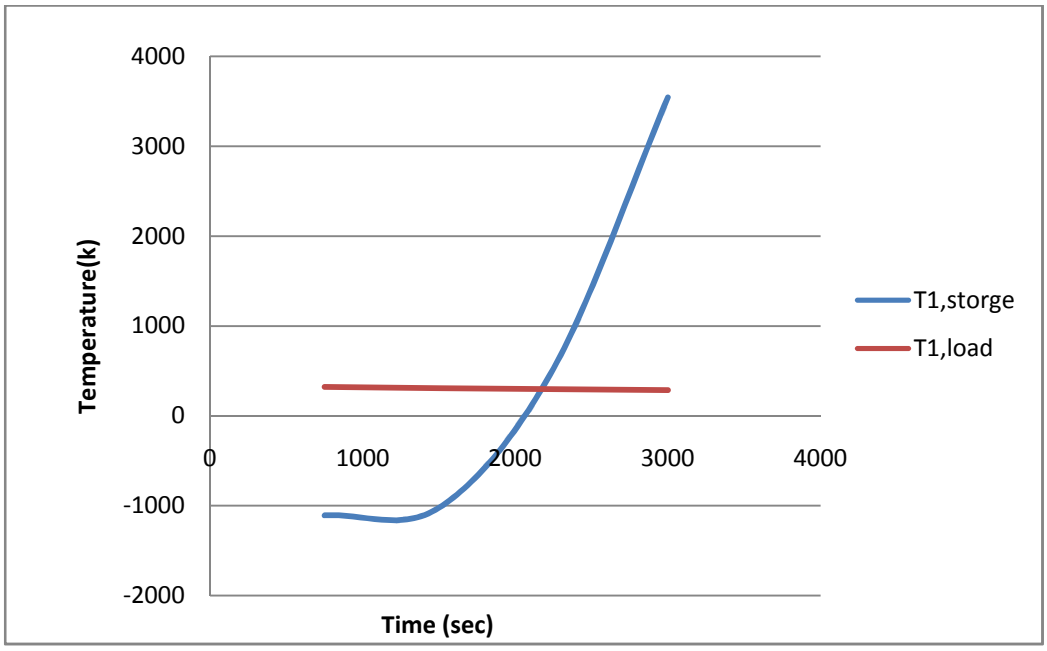


Figure 5- 6: Temperature versus time of cooling water and ice storage

5.3. Detail Drawing of Solar Powered Refrigerator

All dimension in millimeter(mm)

5.3.1. Detail assemble drawing of refrigerator cabinet

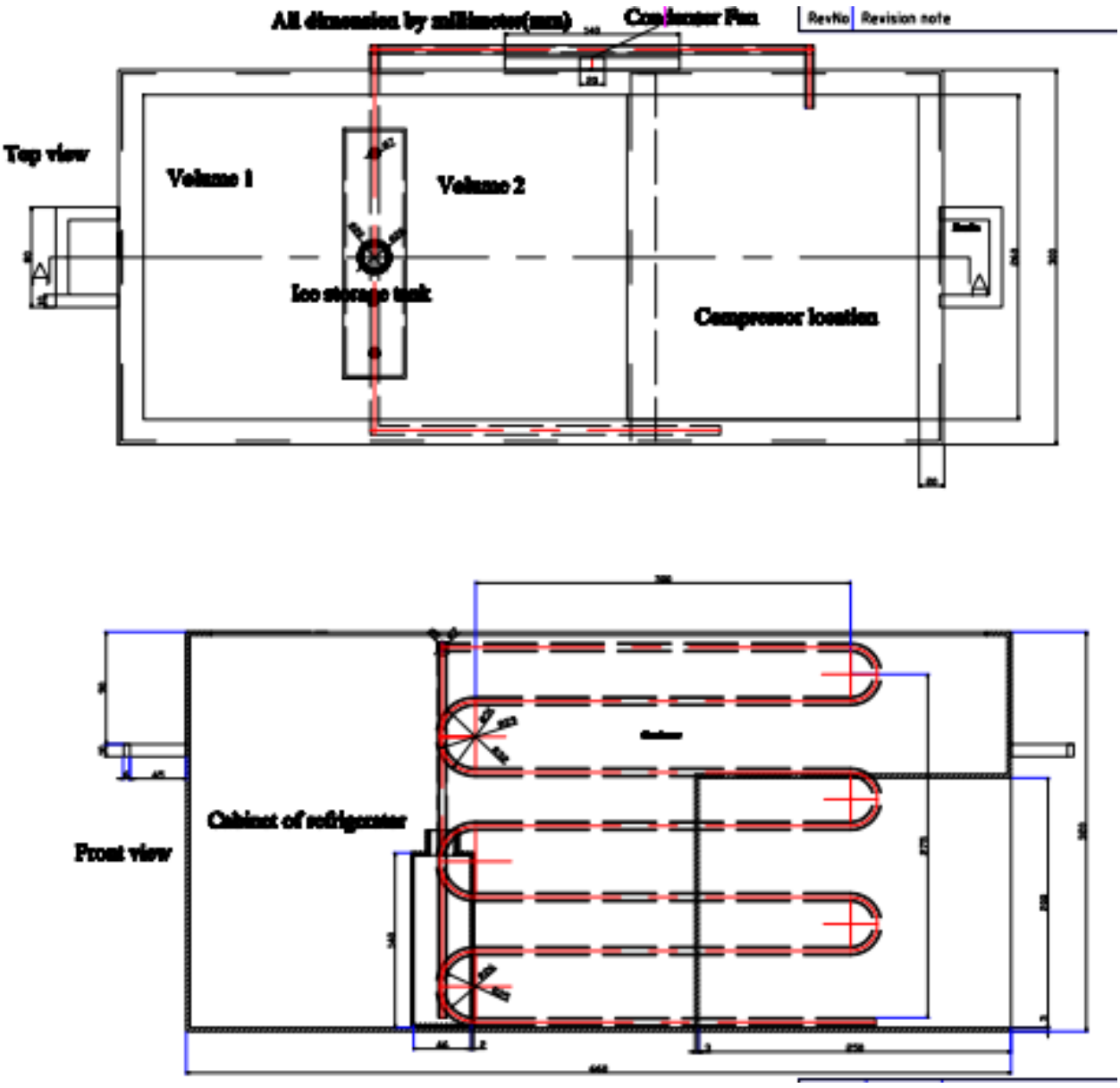


Figure 5- 7: Detail assemble drawing of solar power refrigerator

5.3.2. Detail drawing of door and solar PV panel

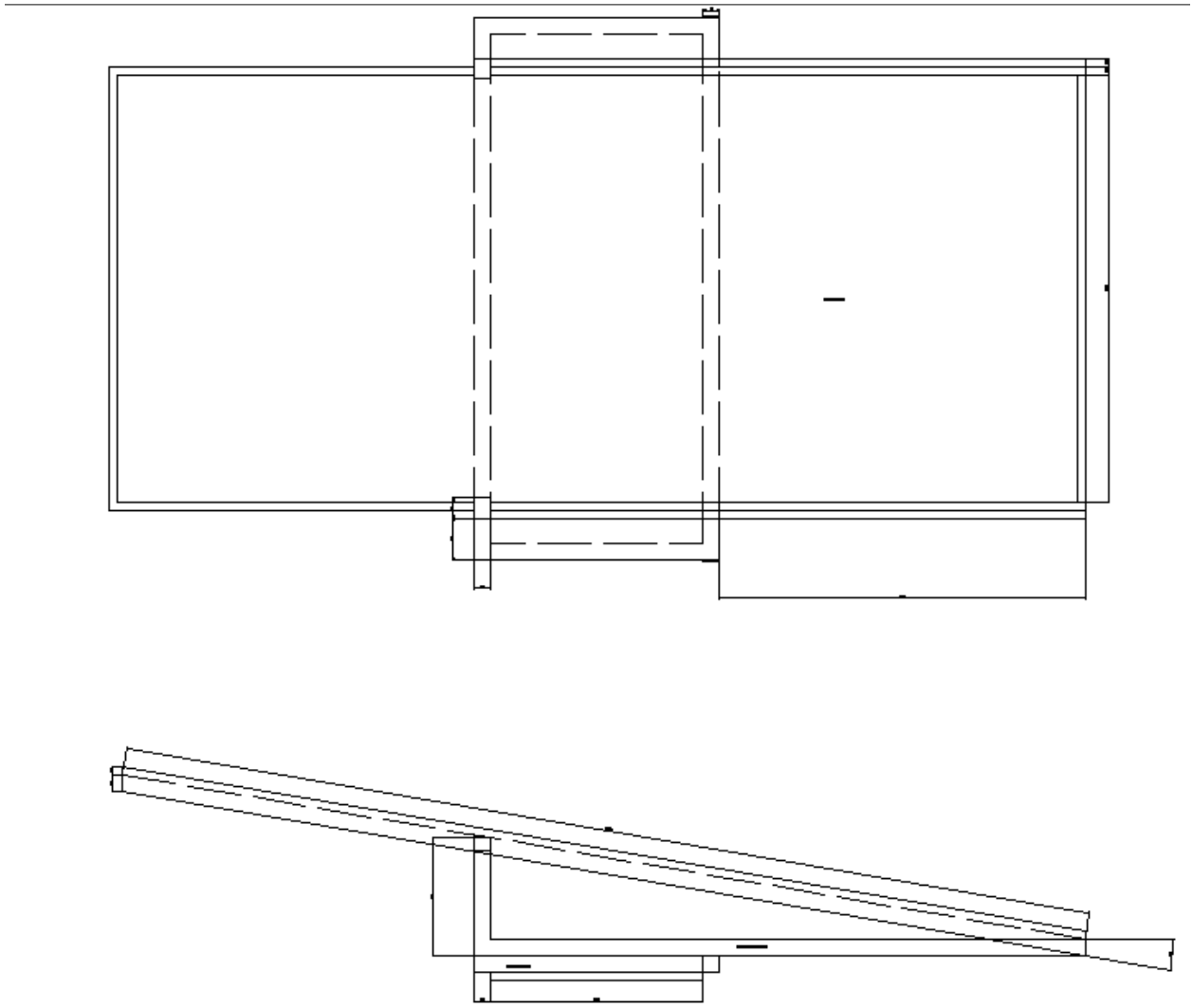


Figure 5- 8: Detail drawing of Door and solar PV panel

5.3.3. Detail drawing of ice storage tank

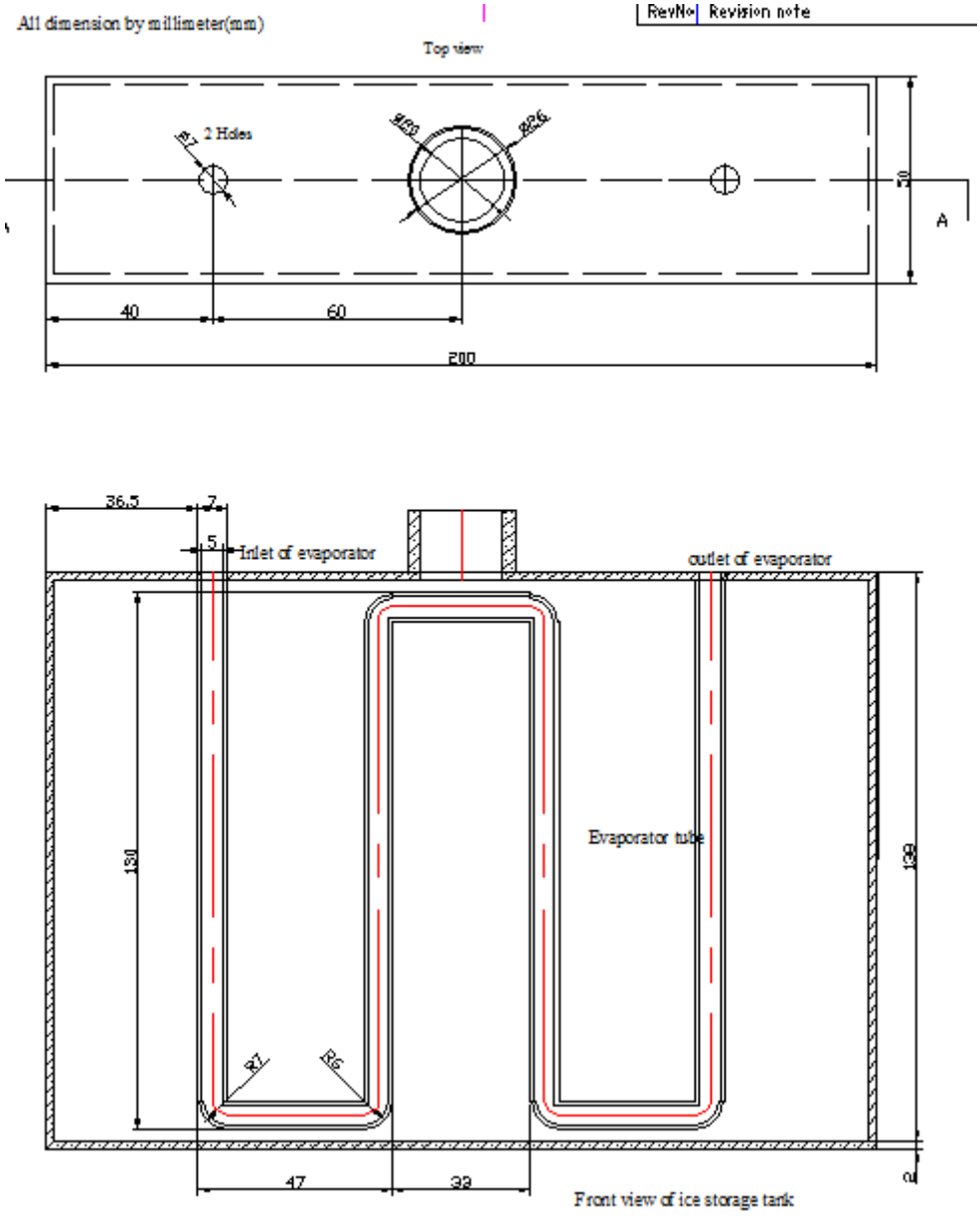


Figure 5- 9: Detail drawing of ice storage tank

5.3.4. Detail drawing of evaporator

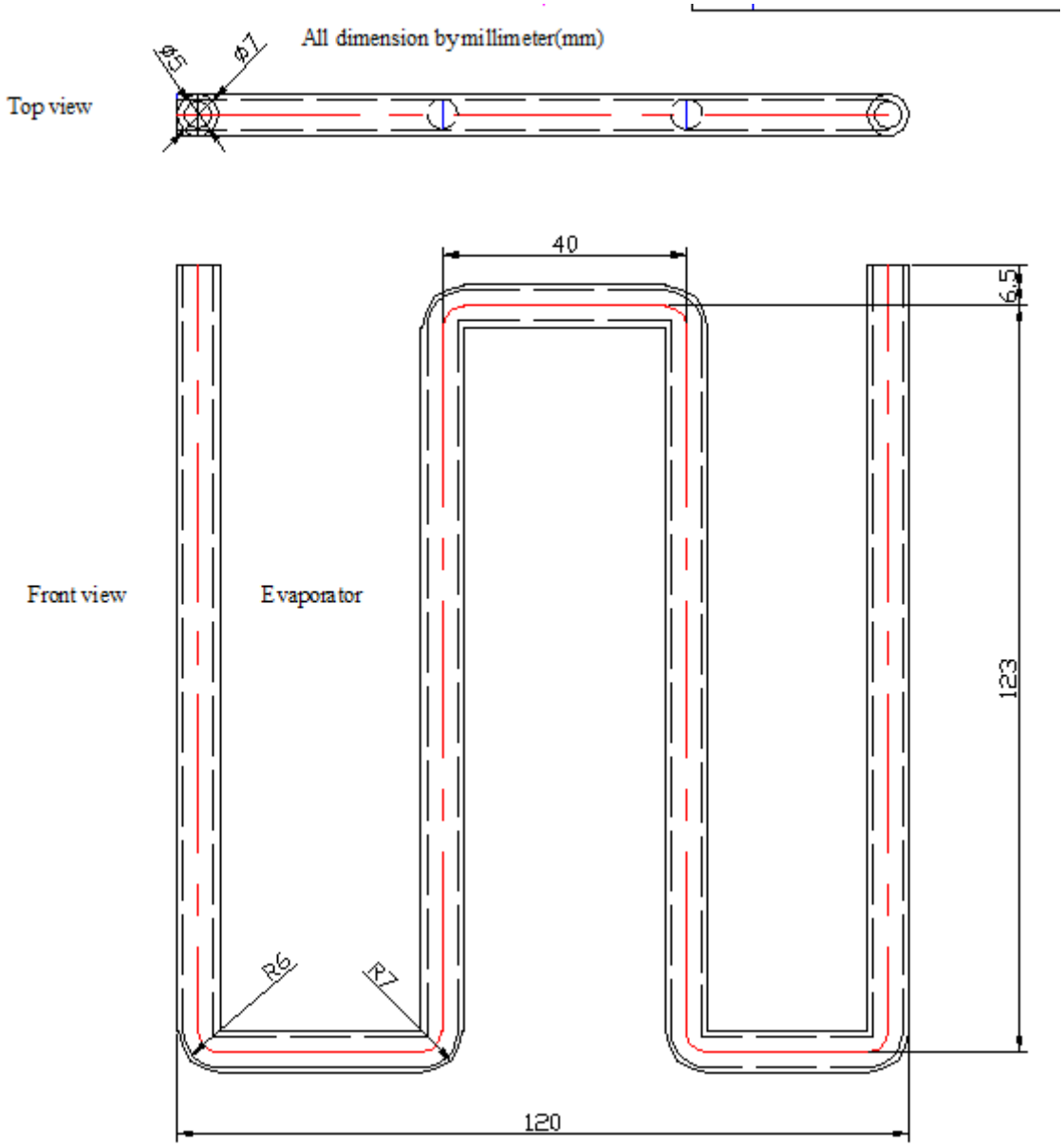


Figure 5- 10: Detail drawing of evaporator

5.3.5. Detail drawing of condenser

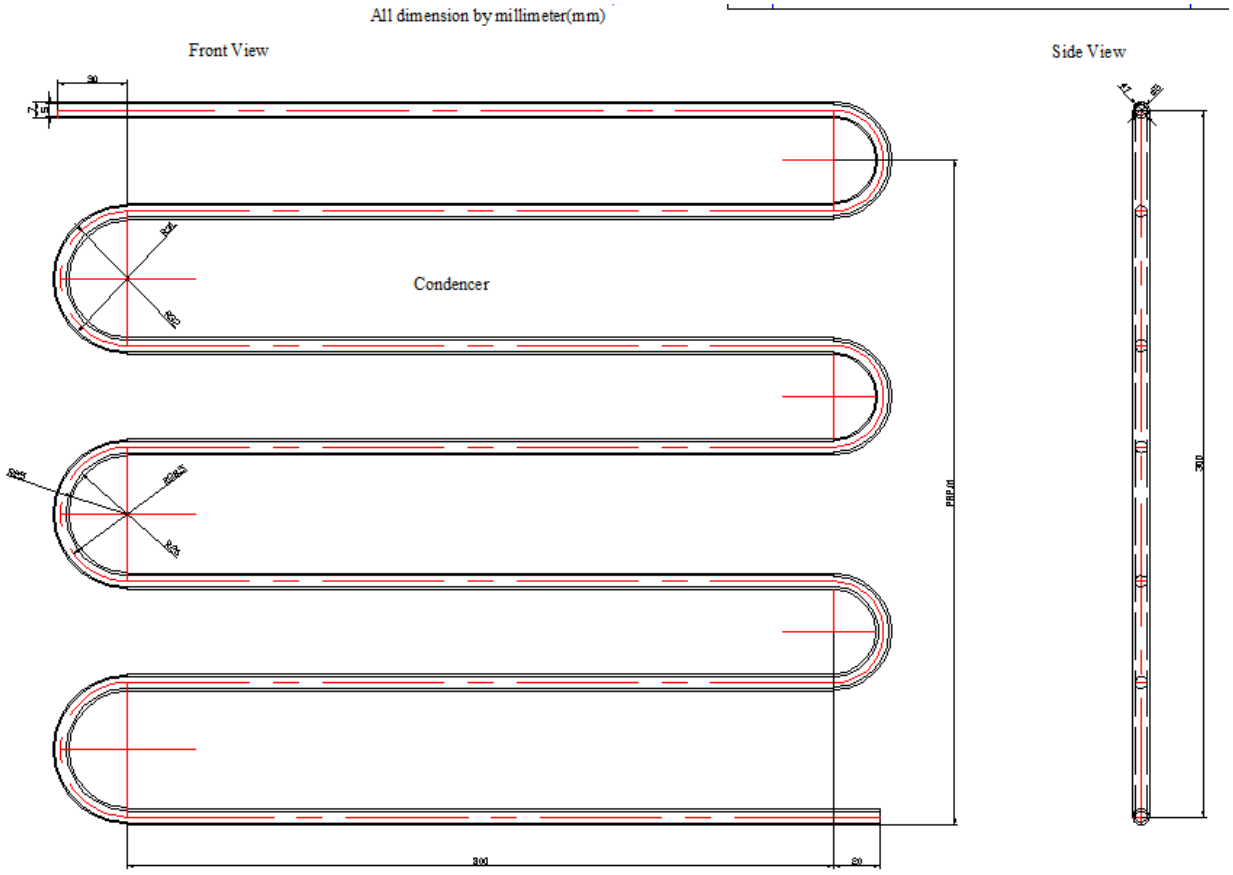


Figure 5- 11: Detail drawing of condenser

5.3.6. Assembly Drawing of solar powered Refrigerator

In below assemble drawing during closed door of refrigerator some external component of solar powered refrigerator can be shown.

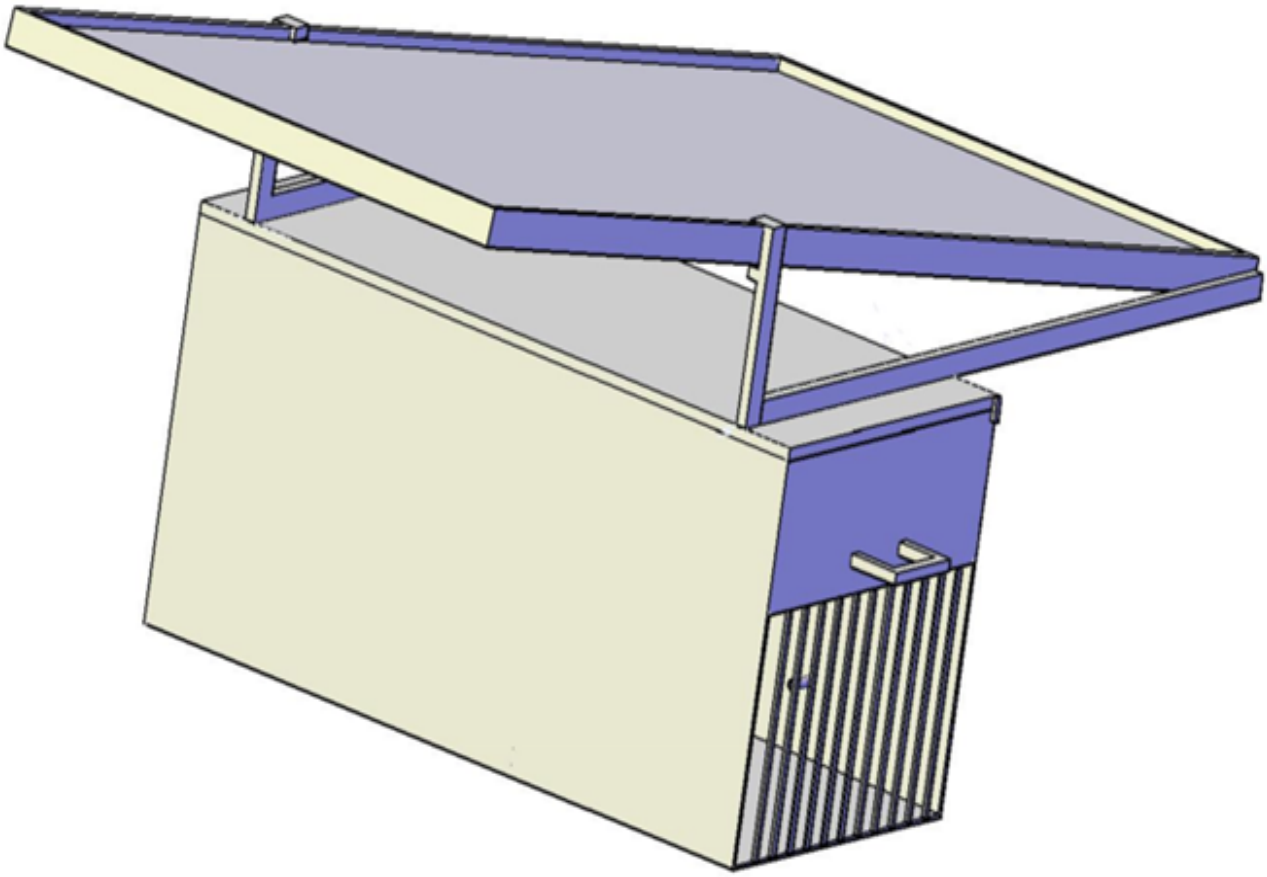


Figure 5- 12: Assemble drawing during closed

5.3.7. Assemble drawing of solar powered refrigerator during open door

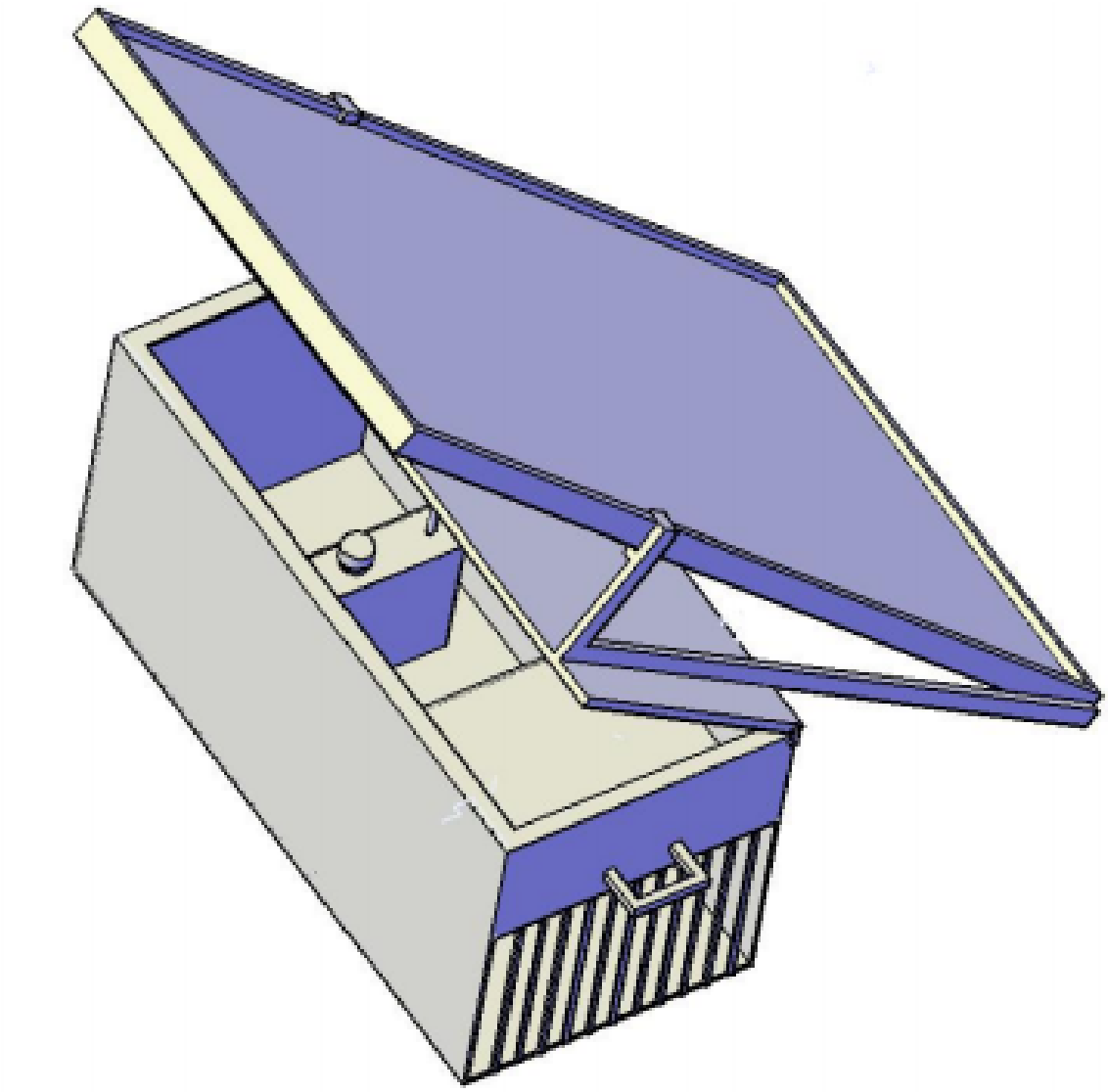


Figure 5- 13: Assemble drawing during open

CHAPTER SIX

6. CONCLUSION AND RECOMMENDATION

6.1. Conclusion

The main purpose of this thesis is to minimize initial cost of solar powered refrigerator by using ice storage instead of battery and also studied the advantage of solar powered micro-refrigerator. The study area of this thesis is Dire Dawa shinile and it locate at 9.68° N and 41.85°E. One of the challenge of solar powered refrigerator is use battery systems to store the sun's energy for use during the night and cloudy periods. These batteries have a relatively short life and replacements are expensive. Due to this case use solar energy without battery to drive compressor refrigerator and uses the sun's energy to freeze water or other phase change material and then uses that ice storage to keep the refrigerator cold during the night and cloudy days. The weight of ice storage for this work is 1kg and it can be maintain an internal temperature below 5℃.

In this work the proposed volume of refrigerator at once to cooling water drink is 6L in one hour and the coefficient of performance (COP) of this refrigerator is 3.13. The PV model of solar panel selected for this work depends on power requirement is STP085-12/Bb. The selected module Area and power is 0.65m^2 and 85wp respectively.

The results in overall reveal that, Photo voltaic powered refrigerator system can be reliably used at where the local grid is not continuously available whereas refrigeration need is critical. The initial cost of solar powered refrigerator system is 13,266birr and The payback cost of solar powered refrigerator by adding 1,2 and 3birr per price of one liter is 10,800birr/year, 21,600birr/year and 32,400birr/year respectively. Therefore the initial cost of the system would be obtain in one to two year from the solar powered refrigerator.

6.2. Recommendation and future work

- Adjustment of Photo voltaic panel to direction of the sun by using sensor mechanism to increase PV power.
- Use solar panel for charging mobile and light during site climate is cool temperature.
- Use solar powered refrigerator for cooling soft drink, milk, store vaccine and etc...
- Study effect on open door of refrigerator at different position.

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APPENDIX A-1

Time	G	Gd	Gc	DNI	DNIc	A	Ad	Ac
06:37	69	44	63	277	323	389	108	421
06:52	118	60	114	387	452	535	140	580
07:07	173	75	172	472	552	641	159	698
07:22	232	88	235	539	630	724	172	789
07:37	291	101	300	592	693	790	182	861
07:52	350	111	365	636	744	842	190	919
08:07	409	121	429	673	787	885	194	966
08:22	465	129	492	704	823	920	197	1000
08:37	520	136	553	730	854	947	199	1040
08:52	572	141	611	753	880	970	199	1060
09:07	620	146	666	772	902	988	198	1080
09:22	666	150	717	788	921	1000	197	1100
09:37	707	153	765	802	938	1010	195	1110
09:52	745	156	808	814	952	1020	193	1120
10:07	780	158	848	825	964	1030	191	1130
10:22	810	159	882	833	974	1040	189	1140
10:37	836	160	912	840	982	1040	186	1140
10:52	858	161	937	846	989	1040	184	1150
11:07	875	161	958	851	995	1040	183	1150
11:22	888	161	973	854	998	1050	181	1150
11:37	897	161	983	856	1000	1050	180	1150
11:52	901	162	988	857	1000	1050	180	1150
12:07	901	162	988	857	1000	1050	180	1150
12:22	897	161	983	856	1000	1050	180	1150
12:37	888	161	973	854	998	1050	181	1150
12:52	875	161	958	851	995	1040	183	1150
13:07	858	161	937	846	989	1040	184	1150
13:22	836	160	912	840	982	1040	186	1140
13:37	810	159	882	833	974	1040	189	1140
13:52	780	158	848	825	964	1030	191	1130
14:07	745	156	808	814	952	1020	193	1120
14:22	707	153	765	802	938	1010	195	1110
14:37	666	150	717	788	921	1000	197	1100
14:52	620	146	666	772	902	988	198	1080
15:07	572	141	611	753	880	970	199	1060
15:22	520	136	553	730	854	947	199	1040
15:37	465	129	492	704	823	920	197	1000
15:52	409	121	429	673	787	885	194	966
16:07	350	111	365	636	744	842	190	919
16:22	291	101	300	592	693	790	182	861
16:37	232	88	235	539	630	724	172	789
16:52	173	75	172	472	552	641	159	698
17:07	118	60	114	387	452	535	140	580
17:22	69	44	63	277	323	389	108	421
17:37	26	26	20	0	0	11	10	9

G: Global irradiance on a fixed plane (W/m2)

Gd: Diffuse irradiance on a fixed plane (W/m2)

Gc: Global clear-sky irradiance on a fixed plane (W/m2)

DNI: Direct normal irradiance (W/m2)

DNIc: Clear-sky direct normal irradiance (W/m2)

A: Global irradiance on 2-axis tracking plane (W/m2)

Ad: Diffuse irradiance on 2-axis tracking plane (W/m2)

Ac: Global clear-sky irradiance on 2-axis tracking plane (W/m2)

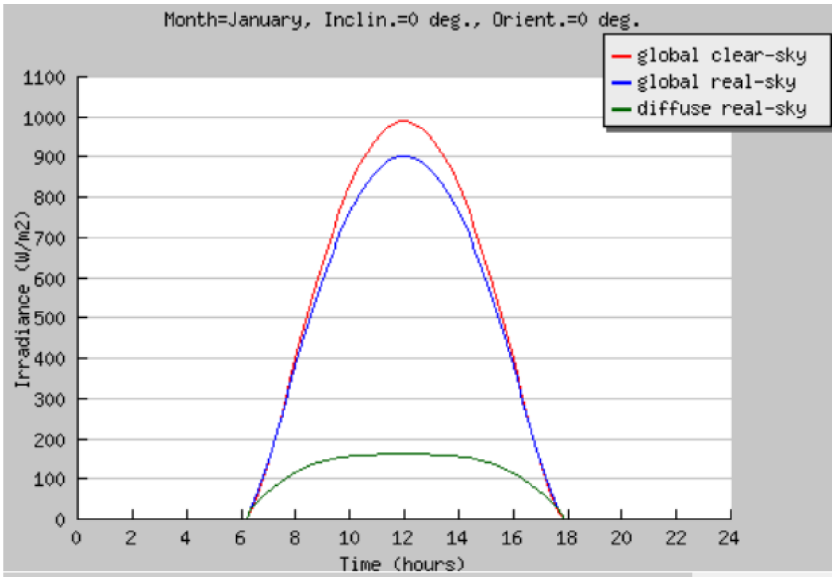


Figure A-1- 1: Daily Irradiance on a fixed plane

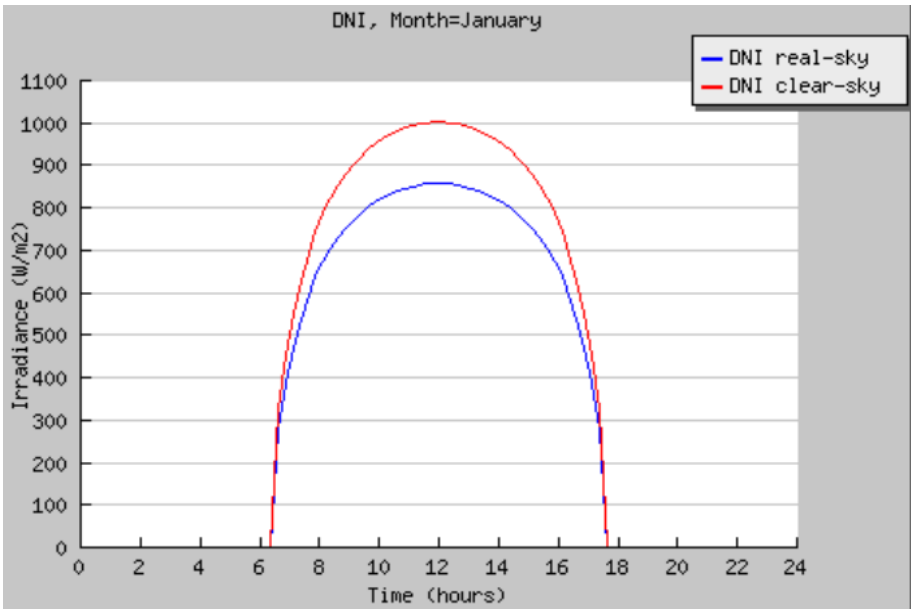


Figure A-1- 2: Direct normal irradiance

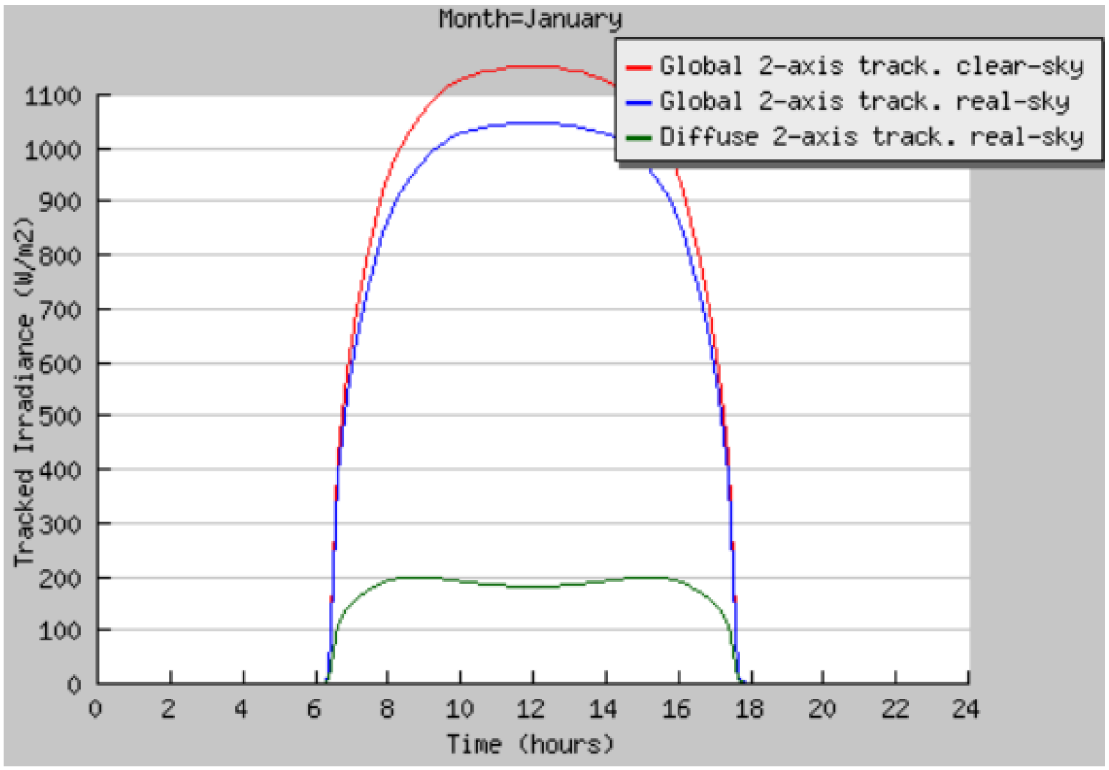


Figure A-1- 3: Daily Irradiance on a 2-axis tracking plane

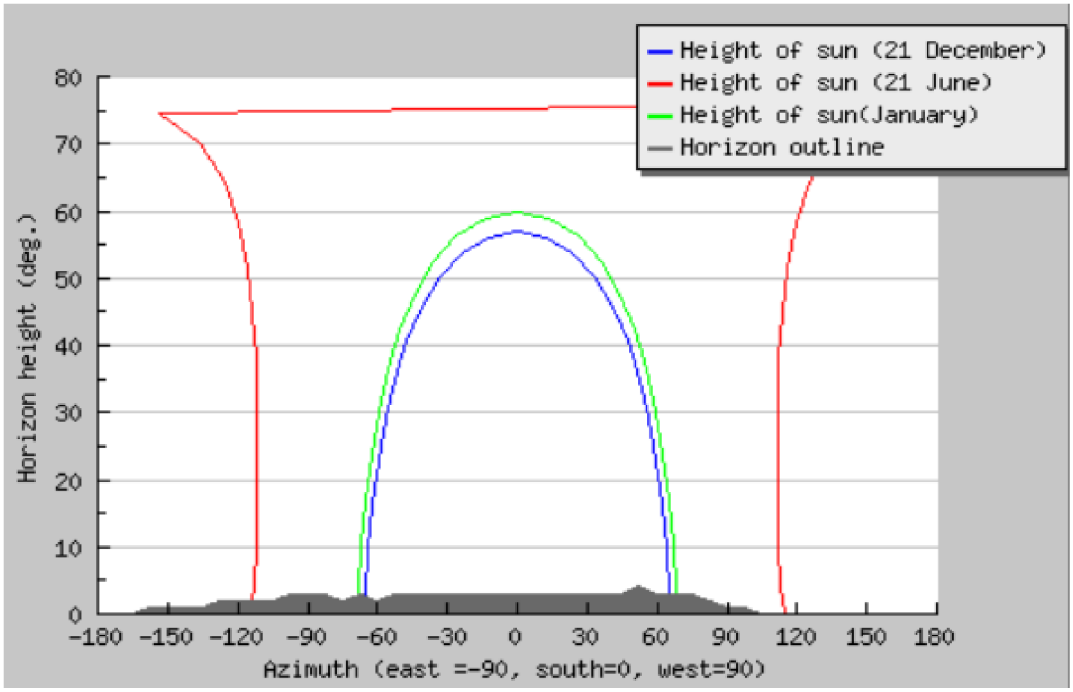


Figure A-1- 4: Outline of horizon with sun path for winter and summer solstice

APPENDIX B-1

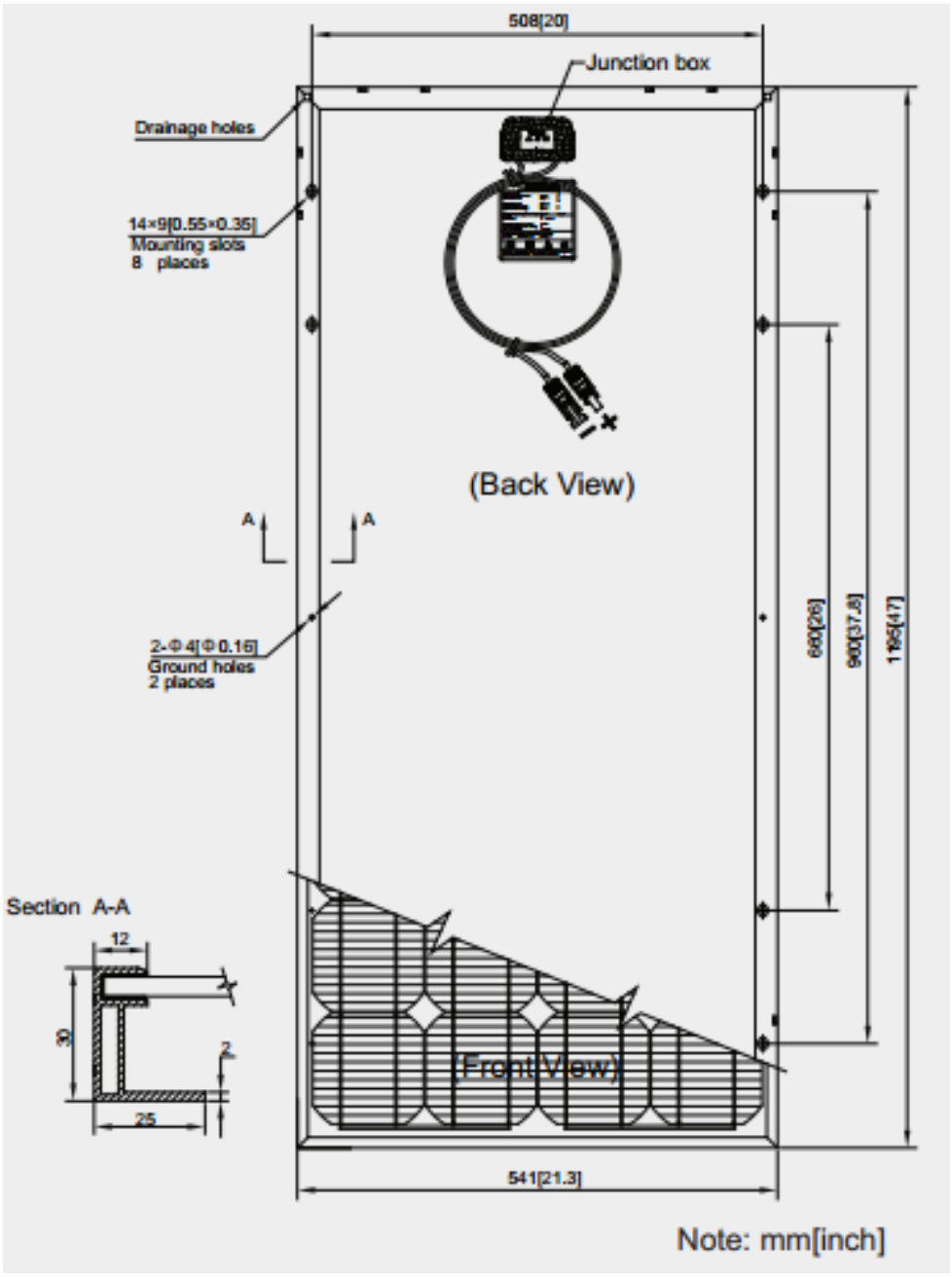


Figure B-1- 1: PV one module panel

APPENDIX C-1

Table C-1- 1: Property of saturated refrigerant-134a Temperature table

Saturated refrigerant-134a—Temperature table

		Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K		
Temp., T °C	Sat. press., P_{sat} kPa	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
−40	51.25	0.0007054	0.36081	−0.036	207.40	207.37	0.000	225.86	225.86	0.00000	0.96866	0.96866
−38	56.86	0.0007083	0.32732	2.475	206.04	208.51	2.515	224.61	227.12	0.01072	0.95511	0.96584
−36	62.95	0.0007112	0.29751	4.992	204.67	209.66	5.037	223.35	228.39	0.02138	0.94176	0.96315
−34	69.56	0.0007142	0.27090	7.517	203.29	210.81	7.566	222.09	229.65	0.03199	0.92859	0.96058
−32	76.71	0.0007172	0.24711	10.05	201.91	211.96	10.10	220.81	230.91	0.04253	0.91560	0.95813
−30	84.43	0.0007203	0.22580	12.59	200.52	213.11	12.65	219.52	232.17	0.05301	0.90278	0.95579
−28	92.76	0.0007234	0.20666	15.13	199.12	214.25	15.20	218.22	233.43	0.06344	0.89012	0.95356
−26	101.73	0.0007265	0.18946	17.69	197.72	215.40	17.76	216.92	234.68	0.07382	0.87762	0.95144
−24	111.37	0.0007297	0.17395	20.25	196.30	216.55	20.33	215.59	235.92	0.08414	0.86527	0.94941
−22	121.72	0.0007329	0.15995	22.82	194.88	217.70	22.91	214.26	s237.17	0.09441	0.85307	0.94748
−20	132.82	0.0007362	0.14729	25.39	193.45	218.84	25.49	212.91	238.41	0.10463	0.84101	0.94564
−18	144.69	0.0007396	0.13583	27.98	192.01	219.98	28.09	211.55	239.64	0.11481	0.82908	0.94389
−16	157.38	0.0007430	0.12542	30.57	190.56	221.13	30.69	210.18	240.87	0.12493	0.81729	0.94222
−14	170.93	0.0007464	0.11597	33.17	189.09	222.27	33.30	208.79	242.09	0.13501	0.80561	0.94063
−12	185.37	0.0007499	0.10736	35.78	187.62	223.40	35.92	207.38	243.30	0.14504	0.79406	0.93911
−10	200.74	0.0007535	0.099516	38.40	186.14	224.54	38.55	205.96	244.51	0.15504	0.78263	0.93766
−8	217.08	0.0007571	0.092352	41.03	184.64	225.67	41.19	204.52	245.72	0.16498	0.77130	0.93629
−6	234.44	0.0007608	0.085802	43.66	183.13	226.80	43.84	203.07	246.91	0.17489	0.76008	0.93497
−4	252.85	0.0007646	0.079804	46.31	181.61	227.92	46.50	201.60	248.10	0.18476	0.74896	0.93372
−2	272.36	0.0007684	0.074304	48.96	180.08	229.04	49.17	200.11	249.28	0.19459	0.73794	0.93253
0	293.01	0.0007723	0.069255	51.63	178.53	230.16	51.86	198.60	250.45	0.20439	0.72701	0.93139
2	314.84	0.0007763	0.064612	54.30	176.97	231.27	54.55	197.07	251.61	0.21415	0.71616	0.93031
4	337.90	0.0007804	0.060338	56.99	175.39	232.38	57.25	195.51	252.77	0.22387	0.70540	0.92927
6	362.23	0.0007845	0.056398	59.68	173.80	233.48	59.97	193.94	253.91	0.23356	0.69471	0.92828
8	387.88	0.0007887	0.052762	62.39	172.19	234.58	62.69	192.35	255.04	0.24323	0.68410	0.92733
10	414.89	0.0007930	0.049403	65.10	170.56	235.67	65.43	190.73	256.16	0.25286	0.67356	0.92641
12	443.31	0.0007975	0.046295	67.83	168.92	236.75	68.18	189.09	257.27	0.26246	0.66308	0.92554
14	473.19	0.0008020	0.043417	70.57	167.26	237.83	70.95	187.42	258.37	0.27204	0.65266	0.92470
16	504.58	0.0008066	0.040748	73.32	165.58	238.90	73.73	185.73	259.46	0.28159	0.64230	0.92389
18	537.52	0.0008113	0.038271	76.08	163.88	239.96	76.52	184.01	260.53	0.29112	0.63198	0.92310

Saturated refrigerant-134a—Temperature table (*Continued*)

		Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K		
Temp., T °C	Sat. press., P_{sat} kPa	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
20	572.07	0.0008161	0.035969	78.86	162.16	241.02	79.32	182.27	261.59	0.30063	0.62172	0.92234
22	608.27	0.0008210	0.033828	81.64	160.42	242.06	82.14	180.49	262.64	0.31011	0.61149	0.92160
24	646.18	0.0008261	0.031834	84.44	158.65	243.10	84.98	178.69	263.67	0.31958	0.60130	0.92088
26	685.84	0.0008313	0.029976	87.26	156.87	244.12	87.83	176.85	264.68	0.32903	0.59115	0.92018
28	727.31	0.0008366	0.028242	90.09	155.05	245.14	90.69	174.99	265.68	0.33846	0.58102	0.91948
30	770.64	0.0008421	0.026622	92.93	153.22	246.14	93.58	173.08	266.66	0.34789	0.57091	0.91879
32	815.89	0.0008478	0.025108	95.79	151.35	247.14	96.48	171.14	267.62	0.35730	0.56082	0.91811
34	863.11	0.0008536	0.023691	98.66	149.46	248.12	99.40	169.17	268.57	0.36670	0.55074	0.91743
36	912.35	0.0008595	0.022364	101.55	147.54	249.08	102.33	167.16	269.49	0.37609	0.54066	0.91675
38	963.68	0.0008657	0.021119	104.45	145.58	250.04	105.29	165.10	270.39	0.38548	0.53058	0.91606
40	1017.1	0.0008720	0.019952	107.38	143.60	250.97	108.26	163.00	271.27	0.39486	0.52049	0.91536
42	1072.8	0.0008786	0.018855	110.32	141.58	251.89	111.26	160.86	272.12	0.40425	0.51039	0.91464
44	1130.7	0.0008854	0.017824	113.28	139.52	252.80	114.28	158.67	272.95	0.41363	0.50027	0.91391
46	1191.0	0.0008924	0.016853	116.26	137.42	253.68	117.32	156.43	273.75	0.42302	0.49012	0.91315
48	1253.6	0.0008996	0.015939	119.26	135.29	254.55	120.39	154.14	274.53	0.43242	0.47993	0.91236
52	1386.2	0.0009150	0.014265	125.33	130.88	256.21	126.59	149.39	275.98	0.45126	0.45941	0.91067
56	1529.1	0.0009317	0.012771	131.49	126.28	257.77	132.91	144.38	277.30	0.47018	0.43863	0.90880
60	1682.8	0.0009498	0.011434	137.76	121.46	259.22	139.36	139.10	278.46	0.48920	0.41749	0.90669
65	1891.0	0.0009750	0.009950	145.77	115.05	260.82	147.62	132.02	279.64	0.51320	0.39039	0.90359
70	2118.2	0.0010037	0.008642	154.01	108.14	262.15	156.13	124.32	280.46	0.53755	0.36227	0.89982
75	2365.8	0.0010372	0.007480	162.53	100.60	263.13	164.98	115.85	280.82	0.56241	0.33272	0.89512
80	2635.3	0.0010772	0.006436	171.40	92.23	263.63	174.24	106.35	280.59	0.58800	0.30111	0.88912
85	2928.2	0.0011270	0.005486	180.77	82.67	263.44	184.07	95.44	279.51	0.61473	0.26644	0.88117
90	3246.9	0.0011932	0.004599	190.89	71.29	262.18	194.76	82.35	277.11	0.64336	0.22674	0.87010
95	3594.1	0.0012933	0.003726	202.40	56.47	258.87	207.05	65.21	272.26	0.67578	0.17711	0.85289
100	3975.1	0.0015269	0.002630	218.72	29.19	247.91	224.79	33.58	258.37	0.72217	0.08999	0.81215

Source: Tables A–11 through A–13 are generated using the Engineering Equation Solver (EES) software developed by S. A. Klein and F. L. Alvarado. The routine used in calculations is the R134a, which is based on the fundamental equation of state developed by R. Tillner-Roth and H.D. Baehr, "An International Standard Formulation for the Thermodynamic Properties of 1,1,1,2-Tetrafluoroethane (HFC-134a) for temperatures from 170 K to 455 K and Pressures up to 70 MPa," *J. Phys. Chem, Ref. Data*, Vol. 23, No. 5, 1994. The enthalpy and entropy values of saturated liquid are set to zero at −40°C (and −40°F).

Table C-1- 2: property of saturated refrigerant-134a; Pressure table

Saturated refrigerant-134a—Pressure table

		Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg - K		
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
60	−36.95	0.0007098	0.31121	3.798	205.32	209.12	3.841	223.95	227.79	0.01634	0.94807	0.96441
70	−33.87	0.0007144	0.26929	7.680	203.20	210.88	7.730	222.00	229.73	0.03267	0.92775	0.96042
80	−31.13	0.0007185	0.23753	11.15	201.30	212.46	11.21	220.25	231.46	0.04711	0.90999	0.95710
90	−28.65	0.0007223	0.21263	14.31	199.57	213.88	14.37	218.65	233.02	0.06008	0.89419	0.95427
100	−26.37	0.0007259	0.19254	17.21	197.98	215.19	17.28	217.16	234.44	0.07188	0.87995	0.95183
120	−22.32	0.0007324	0.16212	22.40	195.11	217.51	22.49	214.48	236.97	0.09275	0.85503	0.94779
140	−18.77	0.0007383	0.14014	26.98	192.57	219.54	27.08	212.08	239.16	0.11087	0.83368	0.94456
160	−15.60	0.0007437	0.12348	31.09	190.27	221.35	31.21	209.90	241.11	0.12693	0.81496	0.94190
180	−12.73	0.0007487	0.11041	34.83	188.16	222.99	34.97	207.90	242.86	0.14139	0.79826	0.93965
200	−10.09	0.0007533	0.099867	38.28	186.21	224.48	38.43	206.03	244.46	0.15457	0.78316	0.93773
240	−5.38	0.0007620	0.083897	44.48	182.67	227.14	44.66	202.62	247.28	0.17794	0.75664	0.93458
280	−1.25	0.0007699	0.072352	49.97	179.50	229.46	50.18	199.54	249.72	0.19829	0.73381	0.93210
320	2.46	0.0007772	0.063604	54.92	176.61	231.52	55.16	196.71	251.88	0.21637	0.71369	0.93006
360	5.82	0.0007841	0.056738	59.44	173.94	233.38	59.72	194.08	253.81	0.23270	0.69566	0.92836
400	8.91	0.0007907	0.051201	63.62	171.45	235.07	63.94	191.62	255.55	0.24761	0.67929	0.92691
450	12.46	0.0007985	0.045619	68.45	168.54	237.00	68.81	188.71	257.53	0.26465	0.66069	0.92535
500	15.71	0.0008059	0.041118	72.93	165.82	238.75	73.33	185.98	259.30	0.28023	0.64377	0.92400
550	18.73	0.0008130	0.037408	77.10	163.25	240.35	77.54	183.38	260.92	0.29461	0.62821	0.92282
600	21.55	0.0008199	0.034295	81.02	160.81	241.83	81.51	180.90	262.40	0.30799	0.61378	0.92177
650	24.20	0.0008266	0.031646	84.72	158.48	243.20	85.26	178.51	263.77	0.32051	0.60030	0.92081
700	26.69	0.0008331	0.029361	88.24	156.24	244.48	88.82	176.21	265.03	0.33230	0.58763	0.91994
750	29.06	0.0008395	0.027371	91.59	154.08	245.67	92.22	173.98	266.20	0.34345	0.57567	0.91912
800	31.31	0.0008458	0.025621	94.79	152.00	246.79	95.47	171.82	267.29	0.35404	0.56431	0.91835
850	33.45	0.0008520	0.024069	97.87	149.98	247.85	98.60	169.71	268.31	0.36413	0.55349	0.91762
900	35.51	0.0008580	0.022683	100.83	148.01	248.85	101.61	167.66	269.26	0.37377	0.54315	0.91692
950	37.48	0.0008641	0.021438	103.69	146.10	249.79	104.51	165.64	270.15	0.38301	0.53323	0.91624
1000	39.37	0.0008700	0.020313	106.45	144.23	250.68	107.32	163.67	270.99	0.39189	0.52368	0.91558
1200	46.29	0.0008934	0.016715	116.70	137.11	253.81	117.77	156.10	273.87	0.42441	0.48863	0.91303
1400	52.40	0.0009166	0.014107	125.94	130.43	256.37	127.22	148.90	276.12	0.45315	0.45734	0.91050
1600	57.88	0.0009400	0.012123	134.43	124.04	258.47	135.93	141.93	277.86	0.47911	0.42873	0.90784
1800	62.87	0.0009639	0.010559	142.33	117.83	260.17	144.07	135.11	279.17	0.50294	0.40204	0.90498
2000	67.45	0.0009886	0.009288	149.78	111.73	261.51	151.76	128.33	280.09	0.52509	0.37675	0.90184
2500	77.54	0.0010566	0.006936	166.99	96.47	263.45	169.63	111.16	280.79	0.57531	0.31695	0.89226
3000	86.16	0.0011406	0.005275	183.04	80.22	263.26	186.46	92.63	279.09	0.62118	0.25776	0.87894

Table C-1- 3: property of super heated refrigerant-134a

Superheated refrigerant-134a

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	P = 0.06 MPa (T_{sat} = −36.95°C)				P = 0.10 MPa (T_{sat} = −26.37°C)				P = 0.14 MPa (T_{sat} = −18.77°C)			
Sat.	0.31121	209.12	227.79	0.9644	0.19254	215.19	234.44	0.9518	0.14014	219.54	239.16	0.9446
−20	0.33608	220.60	240.76	1.0174	0.19841	219.66	239.50	0.9721				
−10	0.35048	227.55	248.58	1.0477	0.20743	226.75	247.49	1.0030	0.14605	225.91	246.36	0.9724
0	0.36476	234.66	256.54	1.0774	0.21630	233.95	255.58	1.0332	0.15263	233.23	254.60	1.0031
10	0.37893	241.92	264.66	1.1066	0.22506	241.30	263.81	1.0628	0.15908	240.66	262.93	1.0331
20	0.39302	249.35	272.94	1.1353	0.23373	248.79	272.17	1.0918	0.16544	248.22	271.38	1.0624
30	0.40705	256.95	281.37	1.1636	0.24233	256.44	280.68	1.1203	0.17172	255.93	279.97	1.0912
40	0.42102	264.71	289.97	1.1915	0.25088	264.25	289.34	1.1484	0.17794	263.79	288.70	1.1195
50	0.43495	272.64	298.74	1.2191	0.25937	272.22	298.16	1.1762	0.18412	271.79	297.57	1.1474
60	0.44883	280.73	307.66	1.2463	0.26783	280.35	307.13	1.2035	0.19025	279.96	306.59	1.1749
70	0.46269	288.99	316.75	1.2732	0.27626	288.64	316.26	1.2305	0.19635	288.28	315.77	1.2020
80	0.47651	297.41	326.00	1.2997	0.28465	297.08	325.55	1.2572	0.20242	296.75	325.09	1.2288
90	0.49032	306.00	335.42	1.3260	0.29303	305.69	334.99	1.2836	0.20847	305.38	334.57	1.2553
100	0.50410	314.74	344.99	1.3520	0.30138	314.46	344.60	1.3096	0.21449	314.17	344.20	1.2814
	P = 0.18 MPa (T_{sat} = −12.73°C)				P = 0.20 MPa (T_{sat} = −10.09°C)				P = 0.24 MPa (T_{sat} = −5.38°C)			
Sat.	0.11041	222.99	242.86	0.9397	0.09987	224.48	244.46	0.9377	0.08390	227.14	247.28	0.9346
−10	0.11189	225.02	245.16	0.9484	0.09991	224.55	244.54	0.9380				
0	0.11722	232.48	253.58	0.9798	0.10481	232.09	253.05	0.9698	0.08617	231.29	251.97	0.9519
10	0.12240	240.00	262.04	1.0102	0.10955	239.67	261.58	1.0004	0.09026	238.98	260.65	0.9831
20	0.12748	247.64	270.59	1.0399	0.11418	247.35	270.18	1.0303	0.09423	246.74	269.36	1.0134
30	0.13248	255.41	279.25	1.0690	0.11874	255.14	278.89	1.0595	0.09812	254.61	278.16	1.0429
40	0.13741	263.31	288.05	1.0975	0.12322	263.08	287.72	1.0882	0.10193	262.59	287.06	1.0718
50	0.14230	271.36	296.98	1.1256	0.12766	271.15	296.68	1.1163	0.10570	270.71	296.08	1.1001
60	0.14715	279.56	306.05	1.1532	0.13206	279.37	305.78	1.1441	0.10942	278.97	305.23	1.1280
70	0.15196	287.91	315.27	1.1805	0.13641	287.73	315.01	1.1714	0.11310	287.36	314.51	1.1554
80	0.15673	296.42	324.63	1.2074	0.14074	296.25	324.40	1.1983	0.11675	295.91	323.93	1.1825
90	0.16149	305.07	334.14	1.2339	0.14504	304.92	333.93	1.2249	0.12038	304.60	333.49	1.2092
100	0.16622	313.88	343.80	1.2602	0.14933	313.74	343.60	1.2512	0.12398	313.44	343.20	1.2356
	P = 0.28 MPa (T_{sat} = −1.25°C)				P = 0.32 MPa (T_{sat} = 2.46°C)				P = 0.40 MPa (T_{sat} = 8.91°C)			
Sat.	0.07235	229.46	249.72	0.9321	0.06360	231.52	251.88	0.9301	0.051201	235.07	255.55	0.9269
0	0.07282	230.44	250.83	0.9362								
10	0.07646	238.27	259.68	0.9680	0.06609	237.54	258.69	0.9544	0.051506	235.97	256.58	0.9305
20	0.07997	246.13	268.52	0.9987	0.06925	245.50	267.66	0.9856	0.054213	244.18	265.86	0.9628
30	0.08338	254.06	277.41	1.0285	0.07231	253.50	276.65	1.0157	0.056796	252.36	275.07	0.9937
40	0.08672	262.10	286.38	1.0576	0.07530	261.60	285.70	1.0451	0.059292	260.58	284.30	1.0236
50	0.09000	270.27	295.47	1.0862	0.07823	269.82	294.85	1.0739	0.061724	268.90	293.59	1.0528
60	0.09324	278.56	304.67	1.1142	0.08111	278.15	304.11	1.1021	0.064104	277.32	302.96	1.0814
70	0.09644	286.99	314.00	1.1418	0.08395	286.62	313.48	1.1298	0.066443	285.86	312.44	1.1094
80	0.09961	295.57	323.46	1.1690	0.08675	295.22	322.98	1.1571	0.068747	294.53	322.02	1.1369
90	0.10275	304.29	333.06	1.1958	0.08953	303.97	332.62	1.1840	0.071023	303.32	331.73	1.1640
100	0.10587	313.15	342.80	1.2222	0.09229	312.86	342.39	1.2105	0.073274	312.26	341.57	1.1907
110	0.10897	322.16	352.68	1.2483	0.09503	321.89	352.30	1.2367	0.075504	321.33	351.53	1.2171
120	0.11205	331.32	362.70	1.2742	0.09775	331.07	362.35	1.2626	0.077717	330.55	361.63	1.2431
130	0.11512	340.63	372.87	1.2997	0.10045	340.39	372.54	1.2882	0.079913	339.90	371.87	1.2688
140	0.11818	350.09	383.18	1.3250	0.10314	349.86	382.87	1.3135	0.082096	349.41	382.24	1.2942

Superheated refrigerant-134a (*Continued*)

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	P = 0.50 MPa (T_{sat} = 15.71°C)				P = 0.60 MPa (T_{sat} = 21.55°C)				P = 0.70 MPa (T_{sat} = 26.69°C)			
Sat.	0.041118	238.75	259.30	0.9240	0.034295	241.83	262.40	0.9218	0.029361	244.48	265.03	0.9199
20	0.042115	242.40	263.46	0.9383								
30	0.044338	250.84	273.01	0.9703	0.035984	249.22	270.81	0.9499	0.029966	247.48	268.45	0.9313
40	0.046456	259.26	282.48	1.0011	0.037865	257.86	280.58	0.9816	0.031696	256.39	278.57	0.9641
50	0.048499	267.72	291.96	1.0309	0.039659	266.48	290.28	1.0121	0.033322	265.20	288.53	0.9954
60	0.050485	276.25	301.50	1.0599	0.041389	275.15	299.98	1.0417	0.034875	274.01	298.42	1.0256
70	0.052427	284.89	311.10	1.0883	0.043069	283.89	309.73	1.0705	0.036373	282.87	308.33	1.0549
80	0.054331	293.64	320.80	1.1162	0.044710	292.73	319.55	1.0987	0.037829	291.80	318.28	1.0835
90	0.056205	302.51	330.61	1.1436	0.046318	301.67	329.46	1.1264	0.039250	300.82	328.29	1.1114
100	0.058053	311.50	340.53	1.1705	0.047900	310.73	339.47	1.1536	0.040642	309.95	338.40	1.1389
110	0.059880	320.63	350.57	1.1971	0.049458	319.91	349.59	1.1803	0.042010	319.19	348.60	1.1658
120	0.061687	329.89	360.73	1.2233	0.050997	329.23	359.82	1.2067	0.043358	328.55	358.90	1.1924
130	0.063479	339.29	371.03	1.2491	0.052519	338.67	370.18	1.2327	0.044688	338.04	369.32	1.2186
140	0.065256	348.83	381.46	1.2747	0.054027	348.25	380.66	1.2584	0.046004	347.66	379.86	1.2444
150	0.067021	358.51	392.02	1.2999	0.055522	357.96	391.27	1.2838	0.047306	357.41	390.52	1.2699
160	0.068775	368.33	402.72	1.3249	0.057006	367.81	402.01	1.3088	0.048597	367.29	401.31	1.2951
	P = 0.80 MPa (T_{sat} = 31.31°C)				P = 0.90 MPa (T_{sat} = 35.51°C)				P = 1.00 MPa (T_{sat} = 39.37°C)			
Sat.	0.025621	246.79	267.29	0.9183	0.022683	248.85	269.26	0.9169	0.020313	250.68	270.99	0.9156
40	0.027035	254.82	276.45	0.9480	0.023375	253.13	274.17	0.9327	0.020406	251.30	271.71	0.9179
50	0.028547	263.86	286.69	0.9802	0.024809	262.44	284.77	0.9660	0.021796	260.94	282.74	0.9525
60	0.029973	272.83	296.81	1.0110	0.026146	271.60	295.13	0.9976	0.023068	270.32	293.38	0.9850
70	0.031340	281.81	306.88	1.0408	0.027413	280.72	305.39	1.0280	0.024261	279.59	303.85	1.0160
80	0.032659	290.84	316.97	1.0698	0.028630	289.86	315.63	1.0574	0.025398	288.86	314.25	1.0458
90	0.033941	299.95	327.10	1.0981	0.029806	299.06	325.89	1.0860	0.026492	298.15	324.64	1.0748
100	0.035193	309.15	337.30	1.1258	0.030951	308.34	336.19	1.1140	0.027552	307.51	335.06	1.1031
110	0.036420	318.45	347.59	1.1530	0.032068	317.70	346.56	1.1414	0.028584	316.94	345.53	1.1308
120	0.037625	327.87	357.97	1.1798	0.033164	327.18	357.02	1.1684	0.029592	326.47	356.06	1.1580
130	0.038813	337.40	368.45	1.2061	0.034241	336.76	367.58	1.1949	0.030581	336.11	366.69	1.1846
140	0.039985	347.06	379.05	1.2321	0.035302	346.46	378.23	1.2210	0.031554	345.85	377.40	1.2109
150	0.041143	356.85	389.76	1.2577	0.036349	356.28	389.00	1.2467	0.032512	355.71	388.22	1.2368
160	0.042290	366.76	400.59	1.2830	0.037384	366.23	399.88	1.2721	0.033457	365.70	399.15	1.2623
170	0.043427	376.81	411.55	1.3080	0.038408	376.31	410.88	1.2972	0.034392	375.81	410.20	1.2875
180	0.044554	386.99	422.64	1.3327	0.039423	386.52	422.00	1.3221	0.035317	386.04	421.36	1.3124
	P = 1.20 MPa (T_{sat} = 46.29°C)				P = 1.40 MPa (T_{sat} = 52.40°C)				P = 1.60 MPa (T_{sat} = 57.88°C)			
Sat.	0.016715	253.81	273.87	0.9130	0.014107	256.37	276.12	0.9105	0.012123	258.47	277.86	0.9078
50	0.017201	257.63	278.27	0.9267								
60	0.018404	267.56	289.64	0.9614	0.015005	264.46	285.47	0.9389	0.012372	260.89	280.69	0.9163
70	0.019502	277.21	300.61	0.9938	0.016060	274.62	297.10	0.9733	0.013430	271.76	293.25	0.9535
80	0.020529	286.75	311.39	1.0248	0.017023	284.51	308.34	1.0056	0.014362	282.09	305.07	0.9875
90	0.021506	296.26	322.07	1.0546	0.017923	294.28	319.37	1.0364	0.015215	292.17	316.52	1.0194
100	0.022442	305.80	332.73	1.0836	0.018778	304.01	330.30	1.0661	0.016014	302.14	327.76	1.0500
110	0.023348	315.38	343.40	1.1118	0.019597	313.76	341.19	1.0949	0.016773	312.07	338.91	1.0795
120	0.024228	325.03	354.11	1.1394	0.020388	323.55	352.09	1.1230	0.017500	322.02	350.02	1.1081
130	0.025086	334.77	364.88	1.1664	0.021155	333.41	363.02	1.1504	0.018201	332.00	361.12	1.1360
140	0.025927	344.61	375.72	1.1930	0.021904	343.34	374.01	1.1773	0.018882	342.05	372.26	1.1632
150	0.026753	354.56	386.66	1.2192	0.022636	353.37	385.07	1.2038	0.019545	352.17	383.44	1.1900
160	0.027566	364.61	397.69	1.2449	0.023355	363.51	396.20	1.2298	0.020194	362.38	394.69	1.2163
170	0.028367	374.78	408.82	1.2703	0.024061	373.75	407.43	1.2554	0.020830	372.69	406.02	1.2421
180	0.029158	385.08	420.07	1.2954	0.024757	384.10	418.76	1.2807	0.021456	383.11	417.44	1.2676

APPENDIX D-1

BD35F Direct Current Compressor R134a, 12-24V DC, 10-45V DC Solar & 100-240V AC 50/60Hz

Application

Application		LBP/MBP/HBP
Evaporating temperature	°C	-30 to 0 (10)
Voltage range (DC & AC)		12-24V DC & 100-240V AC 50/60Hz
		10-45V DC for solar applications
Max. condensing temperature continuous (short)	°C	60 (70)
Max. winding temperature continuous (short)	°C	125 (135)

Motor

Motor type		Variable speed
Resistance, all 3 windings (25°C)	Ω	2.2

Design

Displacement	cm^3	2.00
Oil quantity (type)	cm^3	150 (polyolester)
Maximum refrigerant charge	g	300
Free gas volume in compressor	cm^3	870
Weight - Compressor/Electronic unit	kg	4.3/0.25

Dimensions

Height	mm	A	137
		B	135
		B1	128
		B2	73
Suction connector	location/I.D. mm | angle	C	6.2 | 41.5°
Process connector	location/I.D. mm | angle	D	6.2 | 45°
Discharge connector	location/I.D. mm | angle	E	5.0 | 21°
Connector tolerance	I.D. mm	±0.09, on 5.0 +0.12/+0.20	

Test conditions	EN 12900/CECOMAF	ASHRAE
Condensing temperature	55°C	54.4°C

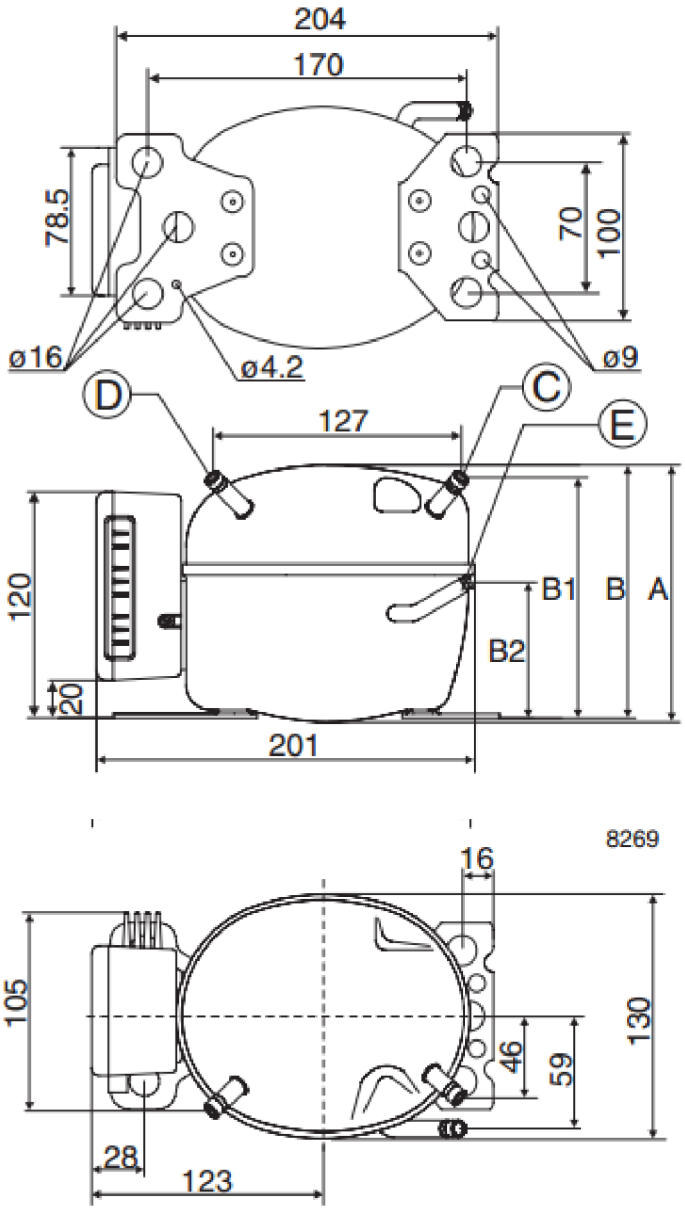


Figure D-1- 1: Detail Drawing of Compressor

APPENDIX -E Matlab code

matlab code of ice storage

```
m=1; %%% mass of ice(kg)
dT=[10 15 20 25 30];  %% Changes of temperature (K)
cp=4186; %% Specific heat of water(J/kg.K)
Q=174;  %% cooling capacity of evaporator(J/s)
t=m*cp*dT/Q;
plot(dT,t);
```

Coaling load of solar powered refrigerator matlab code

```
m=6; %%% mass of ice(kg)
dT=[10 15 20 25 30];  %% Changes of temperature (K)
cp=4186; %% Specific heat of water(J/kg.K)
Q=174;  %% cooling capacity of evaporator(J/s)
t=m*cp*dT/Q;
plot(dT,t);
```