DESIGN OF RENEWABLE ENERGY POWERED SOLAR COOL RESEARCH CENTRE

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Master of Science Thesis

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Energy Technology EGI-2011-101

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ABSTRACT

Solar cooling research center is being developed on CSEM-UAE outdoor research facility in RAK/UAE. The research center is capable to test system from 1 TR cooling capacity to 10 TR cooling capacity. The source of heat is solar radiation and heat pipe type evacuated tube solar collectors are used to collect the solar energy. Solar station controls and circulates water in solar collectors and helps charge the hot water stratified tank. While in operation of the solar cooling facility, circulation pumps for hot water, chilled water and rejection circuit have to be continuously operated along with fan coil units, solar station, chiller and cooling tower. These all components require continuous electrical power. Currently, the entire electrical power requirement is supplied by a diesel generator.

Since the center is for research activities, most of the time solar cooling center is on no load condition. Thus solar collectors are subjected to saturation. To prevent heat collection during no load conditions solar collectors are covered.

Research project carried out to design of the renewable energy powered system to ensure the electricity availability for all the components so that the facility can be operated continuously without fossil fuel. UAE climate is sunny throughout the year thus Photovoltaic will be most prominent as a renewable source in generating electrical power.

The PV is subjected to UAE harsh hot and dust environment which affect the performance of the PV. Thus the performance variations of PV due to dust deposition and temperature have analyzed. A matlab simulink model has developed to analyze the energy generation in UAE environment with available weather data. Technical and economical analysis has done for different PV technologies and find out the optimum PV design for the solar cooling center.

To prevent the saturation of the solar collectors, a heat rejection unit have designed and installed. The control system for the automatic operation also implemented.
ACKNOWLEDGEMENT

First of all, I would like to thank KTH and CSEM-UAE for providing me an opportunity to do my master thesis project in CSEM-UAE. Also I offer my sincere gratitude to Dr Hamid Kayal providing continuous guidance and facilities to a successful project.

I would like to extend my gratitude to my supervisor/examiner Mr. Peter T Kjaerboe supporting me with useful ideas. I would also like to thank my industrial supervisor Mr Manoj Porkrel, for his guidance and invaluable support throughout the period.

Furthermore, I thank Mr Rajesh Reddy, Mr Venkatachalm Laxshman, Ms Sujatha Dahal the engineering staff members of CSEM-UAE and my master thesis colleagues for providing support, motivation and enjoy during this six month period.

Special thanks to Flexcell and Gulf Solar companies for providing their valuable products free of charge to assist my project installations.

I appreciate and thank my wife Ms Nimesha Herath for her fullest support, encouragement and taking care of all the responsibilities at home during my absence.

Last but not least, I would like express my gratitude to all the individuals who have contributed to carry out this project success.
NOMENCLATURE

CSEM Centre Suisse d'Electronique et de Microtechnique
EES Energy Equation Solver
GCC Gulf Cooperative Council
KTH Kungliga Tekniska Högskolan
kW Kilo Watt
kWh Kilo Watt hours
PV Photovoltaic
RAK Ras Al Khaimah
R&D Research and development
UAE United Arab Emirates
MENA Middle East and North African countries
IV current vs voltage
NOCT Normal operating cell temperature
DC Direct current
AC Alternating Current
CISG Copper Indium Gallium Selenide
PWM Pulse width modulation
MPPT Maximum power point tracking
VRLA Valve regulated lead acid
AGM Absorbed glass mat
TTL Transistor-transistor logic
Voc Open circuit voltage
Vac Voltage – Alternative Current
Isc Short circuit current
Vmp Voltage at maximum power point
Imp Current at maximum power point
CPC Compound Parabolic Concentrator
1. **INTRODUCTION**

1.1. **Background**

Energy is a critical component of socio-economic development causing rapid increase in the energy usage day by day. Major portion of energy is still supplied by fossil fuel and nuclear power. With the disaster of Fukushima nuclear power plant, world has pulled back with the nuclear programs. Thus intensive use of fissile fuels is further pushed higher levels for power generation, heating and transportation but which is believed to be having severe consequences on the earth’s environment. The only solution will be the rapid increase of use of renewable energy. Solar energy is playing a key role in the renewable energy sector having a huge potential of energy supply. Main methods with solar energy are to use as light source, electrical source with photovoltaic (PV) and heat source with heat collectors.

The PV systems become very popular and cost effective. The PV power is increasingly important part of the energy mix around the globe. The global cumulative installed capacities have gone up 16GW, 23GW and 40GW in 2008, 2009 and 2010 respectively [1]. Figure 1-1 presents the evolution of global cumulative installed capacity of PV from 2000 to 2010.

![Figure 1-1: Evolution of global cumulative installed capacity of PV, 2000-2010 [1].](image)

The current share of PV in Middle East and North African countries (MENA) is negligible amount but it has identified as one of best solar energy potential region in the world. Lack of awareness among policy makers, subsidized prices of electricity produced by fossil fuel plants and the lack of regulatory framework have impact on the lack of PV development in the region. With the rapid increase of fossil fuel prices, governments have been introducing the renewable technologies in the region. In, Abu-Dhabi United Arab Emirates (UAE), Masdar city program is being implemented which is claiming to be the first net zero city in the world. Masdar city is being powered by Photovoltaic and Solar thermal technologies.

Due to concentrated development in UAE, especially in Ras Al Kaimah (RAK) emirates the electrical grid is available in very small area. Most of the cases available grid is 11kV high voltage only. Thus huge investment has to be made for small low voltage consumers. With concerning all these and other related reasons RAK government have actively participating on renewable energy programs.
Centre Suisse d’Électronique et de Microtechnique-United Arab Emeritus (CSEM-UAE) Innovation Centre is independent, non-profit joint venture company between CSEM and Ras Al Khaimah Investment Authority (RAKIA) for applied research and development focusing in solar energy and clean technology solutions.

CSEM-UAE is doing intensive applied research activities in photovoltaic and solar cooling activities. PV research center consists of dual axis tracking, single axis tracking mechanisms, online measuring equipments of PV performances, professional weather station system and different types of PV technologies for PV research activities.

CSEM-UAE has developed solar cooling research center in its outdoor research facility in order to analyze the operational performance of different solar cooling technologies. The research center is designed to test system of 1TR cooling capacity and 10TR cooling capacity. Absorption chillers with 1TR and 10TR capacities have been installed.

The absorption chillers’ require a pre-dominant thermal energy source and some parasitic electrical energy to produce chilled water that can be used to maintain comfort condition in air-conditioned space. The source of heat is solar radiation and heat pipe type evacuated tube solar collectors are used to capture the solar energy. A solar station comprising controller, circulating pumps and other accessories controls and circulates water in solar collectors and store the thermal energy in hot water stratified tanks. During operation of the solar cooling facility, circulation pumps for hot water, chilled water and cooling tower water circuits have to be continuously operated along with fan coil units, solar station controller, absorption chiller and cooling tower fan. These all components require continuous electrical power. At present, the entire electrical power requirement is supplied by a diesel generator.

Since the centre is a research facility, and the cooling demand is not continuous, the solar cooling system is operated mainly to cater the need of the research and cooling demand that is intermittent. Thus, most of the time heat storage is in saturation condition. While the buffer/storage is at saturation condition, the collector system should not transfer the collected thermal energy to it. If the collector system is operated even after the saturation of the storage tank, the average fluid operation temperature in the solar collector increases and stagnation may occur. To avoid the stagnation condition and to maintain the temperature level of the storage system not to cross the maximum limit, the energy collector system should bypass or dump the unnecessarily collected thermal energy. Furthermore, adequate control and protection system should be designed and installed so that the system ensures bypassing and rejection of the collected thermal energy and maintain trouble free operation.

When the system operates at low load conditions in clear day, the tank temperature reaches its maximum very fast and the controller switches off the circulation. Consequently, the temperature of the collector rises rapidly and stagnation occurs which is from 220°C to 300°C [8]. The solar collector fluid in the solar collector evaporates and the solar collector empties.

In this context, the main purpose of the proposed research is to identify optimum design and installation of the renewable energy systems to ensure electrical power to operate the entire solar-cooling facility without fossil-fuel-run diesel generator. As, UAE climate is sunny throughout the year direct generation of electricity from PV could be the most cost-effective way to ensure the electrical power for the parasitic electricity needs of the solar cooling facility. Hence, the research considers the optimum PV system design to ensure the renewable powered solar cooling research facility.

Furthermore, to protect the system during no load and low load conditions, a security thermal by-pass or heat rejection system with necessary control sub-system have to be identified, designed and installed in the thermal collector cycle.
1.2. **Objectives**

1) Design and implement of security system for the solar cooling system (including heat rejection unit, control system, PV system to supply power).
2) Mathematical modeling of PV module energy generation.
3) Performance analysis of temperature on PV in UAE environment.
4) Performance analysis due to dust collection on PV in UAE environment.
5) Design of extended PV system to ensure 1 TR solar cooling system renewable operation.
6) Design of extended PV system to ensure 10 TR solar cooling system with renewable electricity power.
7) Design and implement PV system with available solar PV modules for selected operations.
1.3. **Methodology**

1.3.1. **Literature survey**

The project objectives are in several areas of study. Thus literature study is very important so that the critical areas of concerns can be identified in early stages. To this effect, the following sector wise literature survey has been conducted during the thesis project period.

- Stagnation behavior and control methods of the solar hot water collectors
- Heat rejection systems in solar hot water and cooling systems
- Mathematical models of PV modules
- Performance variations with temperature and dust on PV modules
- Standards for Photovoltaic systems design

Literature review on solar absorption cooling system, its operation and control parameters, was necessary. Technical details, operation and maintenance manuals of the existing solar cooling system have also been referred.

1.3.2. **Data Collection**

Following set of data need to be collected,

- Average annual weather data of the CSEM-UAE, RAK.
- Technical and financial data of different types of PV technologies.
- Technical and financial data of the related components of the PV System (e.g. Battery Pack, Inverter).
- Electrical power and energy consumption data of the solar cooling system.
- Measurement and control equipment data for the solar station.

1.3.3. **Data Analysis**

The whole set of weather data consists of beam radiance, global radiance, diffuse radiance, ambient temperature, wind speed and direction. The available weather data were in consistence past four year (2007-2011) with some measurement errors. The set of data was filtered, statistically generated and corrected for making it more consistence and accurate over the period. The collected data have been analyzed to identify the design parameters of the security control system and PV system. Financial analysis has been conducted having referred collected data as first preference and estimated data as second preference.

1.4. **METHOD OF ATTACK**

The methods of attacks have been grouped in five sub-headings viz: security system design, PV performance testing, and mathematical modeling of PV energy generation, PV system design and PV system design for available solar PV modules. The process diagram of the total project is shown in Figure 1-2. The group wise method of attack targets to realize the respective objective of the project. Some results from PV performance testing sub-group will be considered to update the mathematic modeling of the PV energy generation. Similarly, the output from PV energy generation sub group will be considered for PV system design sub group. In overall, design, installation and validation of the security control system and PV system are main areas of the project.
Figure 1-2: Process diagram.
2. LITERATURE REVIEW

Literature reviews in different sectors have been considered to carry out research on the proposed project. The sectors that are focused more are as follows:

I. Stagnation studies of solar thermal collector systems
II. Heat dissipating systems
III. Mathematical models of PV panels
IV. Performance analysis of PV panels with dust collection
V. Solar radiation incident angle calculation

2.1. Stagnation of solar thermal collector system

During power failure and lower load conditions thermal energy absorbed by solar thermal receivers accumulates resulting increase in working fluid temperature. Rapid increase of the temperature forms steam inside the loop. In such conditions solar collectors reach “stagnation” and temperature may rise over critical levels.

To minimize the harmful effects due to stagnation, a mechanism to control the collector loop temperature has to be introduced so that it ensures the normal operating conditions. In principal, temperature rise can be controlled either by reducing the solar energy input to the solar collector or by removing the excessive heat from the solar collector.

Energy input to solar collectors can be reduced by reducing the incidence irradiance. This can be achieved by covering the solar collectors by shades.

Similarly, excessive heat collected by the solar collectors can be rejected by any means to maintain the collector temperature at safer level. This can be done by introducing heat rejection systems in to the collector loop or ventilation system on collectors in the case of flat plate collectors.

Under normal operating conditions energy delivered to the load equals to the energy collected by the solar collectors and heat loss of the system. The heat loss can be identified as heat loss in solar collector and heat collection loop.

\[ Q_{\text{load}} = Q_{\text{abs}} - Q_{\text{loss}} \] \hspace{1cm} \text{-------- Equation 1}

\[ Q_{\text{load}} = Q_{\text{abs}} - Q_{\text{loss,coll}} - Q_{\text{loss,loop}} \] \hspace{1cm} \text{-------- Equation 2}

\( Q_{\text{abs}} \) is directly proportional to the solar collector area (\( A_c \)), transmittance of the cover (\( \tau \)), absorption of the absorber (\( \alpha \)) and solar irradiance (\( G \)).

\[ Q_{\text{abs}} = A_c \ (\tau \alpha) \ G = A_c \ \eta_0 \ G \] \hspace{1cm} \text{-------- Equation 3}

\( Q_{\text{loss,coll}} \) depends on the heat loss coefficients and average temperature of solar collector.

\[ Q_{\text{loss,coll}} := A_c \ [a_1 \ (T_m - T_a) + a_2 \ (T_m - T_a)^2] \] \hspace{1cm} \text{-------- Equation 4}

During the stagnation conditions, no heat delivered to the load. Under this situation to control the temperature, system should dissipate the heat equal to the load.

\[ Q_{\text{reject}} = Q_{\text{abs}} - Q_{\text{loss}} \] \hspace{1cm} \text{-------- Equation 5}
2.2. **Heat dissipating systems**

Heat dissipating systems mean heat exchangers in thermodynamics. In general, heat exchangers are classified according to Figure 2-1.

![Heat exchanger categories diagram](image)

The proposed heat dissipating system should dump unwanted solar thermal energy collected by installed solar collector in solar cooling facility. The installed solar collector system is having close pressurized water loop system; therefore, the heat rejection unit to be proposed should be indirect contact type. Furthermore, the heat transfer will be from collector cycle water to environment air. Thus the unit should be liquid to gas type.

Because of the time limitation of project implementation, detail-designing or modifications of the heat exchangers has not been considered in the scope of the research work. Thus, locally available heat rejection unit that has potential to match the above-mentioned requirements are reviewed. The number of available option further reduces due to operating temperature limitation of 60°C-110° C.

There are several options available for use,

- Heat rejection systems specially designed for solar heat collector systems
- Industrial coolers
- Automobile radiators

### 2.2.1. **Heat rejection systems for solar collectors**

Heat rejection systems specially designed for heat rejection of solar collectors are available commercially. Main limitation of use those systems are over capacity and cost. These systems are designed for large collector areas used for commercial applications. Comparison of available radiators is shown in the Table 2-1.
<table>
<thead>
<tr>
<th>Unit Type</th>
<th>Available Capacity</th>
<th>Power consumption</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiSun heat rejection unit</td>
<td>75kW</td>
<td>500W</td>
<td>Over capacity, High cost</td>
</tr>
<tr>
<td>Industrial Coolers</td>
<td>15-400kW</td>
<td>-</td>
<td>Designed for higher flow rates</td>
</tr>
<tr>
<td>Auto Radiators</td>
<td>70kW</td>
<td>300W</td>
<td>Designed for high air flow rates</td>
</tr>
</tbody>
</table>

Table 2-1: Comparison of commercially available radiators

**Industrial coolers/radiators**

Industrial coolers/radiators are typically designed for very large capacity applications of heat rejections. Also the designed flow rates are in higher ranges compared to solar collector applications.

**Automobile radiators**

Auto radiators are designed to cool the internal combustion engine of automobiles. It operates by passing liquid coolant through radiator to transfer the heat to atmosphere. Auto radiators are also coupled with electrical fan to improve the air flow for better effectiveness. However, the radiator mainly uses the increased air flow when automobile moves. Normally auto radiators are designed for 16km/h air flow rate for fail safe operation. A general physical design specification of the auto radiator of Toyota Camry 2001 model is presented in Table 2-2.

<table>
<thead>
<tr>
<th>Radiator length</th>
<th>rL</th>
<th>0.73m</th>
<th>Radiator height</th>
<th>rH</th>
<th>0.026m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiator width</td>
<td>rW</td>
<td>0.40m</td>
<td>Tube width</td>
<td>rW</td>
<td>0.026m</td>
</tr>
<tr>
<td>Tube height</td>
<td>tH</td>
<td>1.92mm</td>
<td>Fin height</td>
<td>fH</td>
<td>8.4mm</td>
</tr>
<tr>
<td>Fin width</td>
<td>fW</td>
<td>26mm</td>
<td>Fin thickness</td>
<td>fT</td>
<td>0.157mm</td>
</tr>
<tr>
<td>Distance between fins</td>
<td>fD</td>
<td>1.124mm</td>
<td>Louver length</td>
<td>lL</td>
<td>12.78mm</td>
</tr>
<tr>
<td>Louver pitch</td>
<td>lP</td>
<td>1.48mm</td>
<td>Louver angle</td>
<td>θ</td>
<td>28°</td>
</tr>
<tr>
<td>Non louvered inlet and exit</td>
<td>S1</td>
<td>2.4mm</td>
<td>Re-direction length</td>
<td>S2</td>
<td>2.55mm</td>
</tr>
<tr>
<td>fin region</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1 number</td>
<td>2</td>
<td></td>
<td>S2 number</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Number of tubes</td>
<td>nTube</td>
<td>73</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2-2: Physical dimensions of the Toyota Camry 2001 model Radiator [7]
Design information of thermal and fluid flow parameters of the radiator is presented in Table 2-3. According to the table, the maximum heat transfer capacity of the radiator is 70 kW at specified flow condition of air and coolant subjected to automobile operating condition.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant volumetric flow</td>
<td>$v_{fc}$</td>
</tr>
<tr>
<td>Air volumetric flow</td>
<td>$v_{fa}$</td>
</tr>
<tr>
<td>Air velocity</td>
<td>$v_a$</td>
</tr>
<tr>
<td>Heat transfer capacity</td>
<td>Q</td>
</tr>
</tbody>
</table>

Table 2-3: Design thermal and fluid flow parameters of the radiator [9]

From the macro level literature review of heat dissipating system, it is observed that the automobile radiator could have potential to be used as one of the low cost solution for the proposed heat rejection system for solar thermal collector. However, the flow parameters and capacity has to be re-formulated in compliance with actual condition of solar thermal flow and local wind flow condition so that off-design capacity of the radiator can be evaluated to theoretically validate the selection of the auto-radiator as the heat dissipation unit.
2.3. **Mathematical models of a PV Module**

PV is a semiconductor which produces electron movement when subjected to energy in the form of electromagnetic waveform. At the moment crystalline silicon, polycrystalline silicon, amorphous silicon, etc are commonly used for fabricating the PV cells. Voltage generated in a single junction is 0.2-0.7V. Thus series of rows and columns of PV cells have connected to generate large operating voltage and current, which creates a solar PV module.

A mathematical model has to develop in order to analyze and simulate the PV characteristics. There are three types of PV cell modeling viz: single-diode, two-diode and empirical. Most commonly used model is the single-diode model which represents electrical behavior of the PV cell. Two-diode model include recombination process of charge carriers both on surface and bulk material. The empirical model is a goodness of fit model derived from the measure IV curve and has less no of parameters. Usually manufacturer’s datasheet comes with these parameters.

In research literature activities done on PV mathematical model simulations, main three type of mathematical models have discussed. Laurentiu Albotenu, Gheorghe Manolea and Florin Ravigan from university of Craiova [4] have done analysis of three models which single diode mode, two diode model and empirical model.

Tomas Skocil, M.P. Donsion [5] from University of west Bohemia, have used the single diode model during their analysis of Mathematical Modeling and Simulation of Photovoltaic Array.

I. H. Altas, A.M. Sharaf [6] from Karadeniz Technical University and University of Bunswick have developed a Mathlab simulink model using single diode mathematical model.

### 2.3.1. **Single-diode model**

The PV cell is represented by an equivalent circuit containing a current generator, a diode, and two resistances as given in Figure 2-3. PV source is represented by a current source where value depends on incident solar radiation. The diode represents the PV module physical semiconductor properties and two resistances of series and shunt also included.

![Figure 2-3: equivalent circuit diagram of the PV cell](image)

Applying Kirchhoff current law,

\[ I_s = I_{ph} - I_d - I_{sh} \]

\[ \text{----------- Equation 6} \]

The photocurrent is directly depending on the solar irradiance \( G \) and the ambient temperature given by;
\[ I_{ph} = P_1 G \left[ 1 + P_2 (G - G_{ref}) + P_2 (T_f - T_{ref}) \right] \]  

Equation 7

The diode loss current \( I_d \) due to charge carrier recombination is given by,

\[ I_d = I_o \left[ \exp \left( \frac{V + IR_s}{n V_{th}} \right) - 1 \right] \]  

Equation 8

\[ I_{sh} = \frac{V + IR_s}{R_{sh}} \]  

Equation 9

\[ I_o = CT^3 \exp \left( - \frac{V_{go}}{V_{th}} \right) \]  

Equation 10

\[ V_{th} = \frac{kT}{q} \]  

Equation 11

\( P_1, P_2, P_3, V_{go}, \) and \( n \) change with the PV junction material used.

### 2.3.2. Two diode model

The two diode model is derived version of single diode model. Main difference is recombination current \( I_d \) is represented by two separate components \( I_{d1} \) and \( I_{d2} \). First diode represents the natural region of the semiconductor and space-charge recombination effect simulate by second diode.

![Figure 2-4: Equivalent circuit of PV cell two diode model](image)

\[ V_s \]  

\[ I_o \]  

\[ I_{d1} \]  

\[ I_{d2} \]  

\[ I_{sh} \]  

\[ R_s \]  

\[ V_s \]  

\[ R_{sh} \]

\[ V_s \] and \( I_s \) relationship is given by,

\[ I_s = I_o - I_{d1} \left[ \exp \left( \frac{V_s + R_{d1} I_{d1}}{V_{th}} \right) - 1 \right] + I_{d2} \left[ \exp \left( \frac{V_s + R_{d2} I_{d2}}{V_{th}} \right) - 1 \right] - \frac{V_s + R_{sh} I_{sh}}{R_{sh}} \]  

Equation 12

The parameters can be estimated by solving the above equation for open circuit, short circuit and maximum voltage conditions.

For short circuit current \( I_s = I_{sc}; V_s = 0 \);

\[ I_{sc} = I_o - I_{d1} \left[ \exp \left( \frac{R_{d1} I_{d1}}{V_{th}} \right) - 1 \right] + I_{d2} \left[ \exp \left( \frac{R_{d2} I_{d2}}{V_{th}} \right) - 1 \right] - \frac{R_{dsc}}{R_{sh}} \]  

Equation 13

For open circuit condition \( I_s = 0; V_s = V_{oc} \);

\[ 0 = I_o - I_{d1} \left[ \exp \left( \frac{V_s}{V_{th}} \right) - 1 \right] + I_{d2} \left[ \exp \left( \frac{V_s}{V_{th}} \right) - 1 \right] - \frac{V_s}{R_{sh}} \]  

Equation 14

For maximum power point condition \( I_s = I_{mp}; V_s = V_{mp} \);
\[ I_{mp} = I_o - I_{d1} \left[ \exp \left( \frac{V_{mp} + R_s I_{mp}}{V_{th}} \right) - 1 \right] + I_{d2} \left[ \exp \left( \frac{V_{mp} + R_s I_{mp}}{V_{th}} \right) - 1 \right] - \frac{V_{mp} + R_s I_{mp}}{R_{sh}} \]  \text{---Equation 15}

\[ I_o = CT_{std}^3 \exp \left( - \frac{V_{oa}}{V_{th}} \right) \]  \text{---Equation 16}

\[ V_{th} = \frac{kT_{std}}{q} \]  \text{---Equation 17}

\( I_o \) parameters can be found from manufacturer’s datasheet and Gstd and Tstd are standard testing conditions of 1000W/m² and 25°C respectively.

Calculation of module parameters is straight forward in single diode model. Thus in most of the literature for simulation of PV module, single diode model has used. Newton Raphson method or complex equation solvers have to be used. This will lead to time consuming simulations for larger data sets. With the development of technology in computer processing speeds and advanced simulation software modeling of two diode models is possible. The use of two diode model will lead to higher accurate results than single diode model. Thus two diode models have selected to develop the equivalent mathematical model of the PV module.

### 2.3.3. Empirical model for PV module

In single diode and two diode models many parameters have used in the final mathematical model. The empirical model have developed to use with minimal number of parameters for easy of simulations. This model has developed using same single diode model Figure 2-3. The developed equation 18 for numerical simulations

\[ I_{smax} \left[ 1 + \frac{1}{20.7} \left( \frac{l_{smax}}{l_{sc} - l_{smax}} + \ln \left( \frac{l_{smax}}{l_{sc}} \right) \right) \right] - \frac{2P_{max}}{V_{oc}} \]  \text{---Equation 18}

Once \( I_{smax} \) is solved, \( R_s \) is calculated using equation 19.

\[ \frac{P_{max}}{I_{smax}^2} = \frac{V_{oc}}{20.7} \left( \frac{1}{l_{sc} - l_{smax}} \right) - R_s \]  \text{---Equation 19}

Both values are substitute into equation 20 to get the IV curve for the PV module.

\[ U_s = U_{oc} \left[ 1 + \frac{1}{20.7} \ln \left( \frac{l_{smax}}{l_{sc}} \right) \right] - R_s I_s \]  \text{---Equation 20}

Two diode mathematical model have selected for further development in Matlab even though it is the most complex out of discussed three models for better accuracy.
2.4. **Performance analysis of PV modules against dust collection**

As described in above section, solar PV modules current generation is directly proportional to the solar incidence irradiance on the solar cells. All PV modules consist of transparent material layer on top for the protection of PV cell. The transmittance of this protection layer reduces the solar irradiance falling on PV junctions.

Due to high content of dust particles in air, PV surfaces are continuously subjected to dust deposition. Particles accumulate on the solar panel surface reduces current generation hence reduction in energy output of the module.

A number of research projects carried out for the dust deposition effect on PV performance have identified various outcomes depending on site conditions, environmental conditions and tilt angle. In 1978, Sayigh[25] has investigated the sand dust effect on flat-plate collectors in Saudi Arabia and found the reduction of about 30% in the energy collection after 25 days without cleaning cycle. He has done some progress test on same effect in 1979 and experienced 2%, 14% and 30% reduction of power after one, 13 and 32 days respectively without cleaning. Similar studies conducted in Kuwait by Wakim (1981) found a reduction of 17% in PV power after 6 days dust deposition.

Nahar and Guptha [27] carried out a study in the Thar Desert in India, which is one of the dustiest deserts in the world. 30cmx30cmx4mm size glass samples were fixed at 0°, 45° and 90° tilt angles from the horizontal and analyzed the reduction in transmittance due to dust deposition. The annual average reduction in one day cleaning cycle was 4.26%, 2.94% and 1.36% for 0°, 45° and 90° tilt respectively. The annual average reduction in weekly cleaning cycle was 15.06%, 9.88% and 3.23%. The figure Figure 2-5 shows the power output variation with dust deposition after four months and one year.

![Figure 2-5: Power output variation with dust deposition](image)

Mohamed Ibrahim [28] and his team have done some testing on advanced PV Test Park in Egypt. They have observed the power output, solar intensity and reflectance in Figure 2-5, Figure 2-6 and Figure 2-7 respectively.

Monto and Rohit [29] have conducted testing on PV performance reduction with respect to partial sizes of the dust collected in laboratory conditions. The variation of reduction in solar intensity is given in Figure 2-6.
Further they have conducted similar test on reflectance with respect to wavelength of the incident light. According to the Figure 2-7 it can be shown that the reflectance also varies with the wavelength of incident light also. Thus solar PV materials which are more sensitive in 0.3-0.6 um range will be highly affected by the dust deposition.

According to the literature review dust deposition on PV modules will affect its performance severely. Solar research center is in middle of the UAE desert where dust deposition is a common problem. Thus high importance should be given during performance analysis, selecting and designing of Solar PV systems.

Therefore, a sub mathematical module for dust performance effect will be inserted to PV mathematical module.
2.5. **Solar angle calculations**

According to the literature of PV mathematical model, its performance is varying with incidence solar radiation on the panels. PV modules mounted on dual axis trackers, sun angle will be 90° during the day time. Thus the incident radiation is the beam radiation value. But in the case of single axis and fixed PV modules sun angle is varying with sun position. Thus, will have to do a trigonometric transpose of the beam and diffuse radiation in order to get the incident radiation.

In the case of single axis systems PV module follows the sun direction during the day time but it will not adjust according to the seasonal changers of the sun travelling path, while fixed PV modules subjected to continuous directional change of the sun light.

J.M Pinazo, J Canada and F Argo from department of applied thermodynamic of Universidad Politecnica de Valencina in Spain have done a mathematical analysis on “Incident angle of beam radiation of CPC”.

In the case of compound parabolic concentrators (CPC), the accuracy of incident angle is very sensitive compared to PV modules. Thus use of similar set of mathematical model will benefit the PV module simulations.

They have developed a mathematical model for the CPC as shown in Figure 2-8.

![Figure 2-8: Definition of angles reference to CPC face plane](image)

The developed mathematical model,

\[
S_c = [\cos \beta \cos \delta \cos \gamma - \sin \beta \sin \gamma] \cos \sigma - \cos \beta \sin \delta \cos \alpha \\
+ [\cos \beta \cos \delta \sin \gamma + \sin \beta \cos \gamma] \cos \pi
\]

\[
V_c = \sin \delta \cos \gamma \cos \sigma + \cos \delta \cos \alpha + \sin \delta \sin \gamma \cos \pi
\]

\[
E_c = -[\sin \beta \cos \delta \cos \gamma + \cos \beta \sin \gamma] \cos \sigma \\
+ \sin \beta \sin \delta \cos \alpha + [\sin \beta \cos \delta \sin \gamma + \cos \beta \cos \gamma] \cos \pi
\]

Where

- \( \delta \) - slope of the surface with respect to horizon
- \( \gamma \) - orientation in relation to the local meridian
- \( \beta \) - angle between longitudinal axis of the CPC and horizontal line on place of CPC
This model is little bit complicated. John A Duffie and William A Beckman have introduced a simple model in their Solar Engineering of Thermal Processes book.

Solar angles have defined according to the Figure 2.9.

Figure 2.9: Solar angles reference to a PV module

\[
\cos \theta = \sin \delta \sin \emptyset \cos \beta - \sin \delta \cos \emptyset \sin \beta \cos \gamma + \cos \delta \cos \emptyset \cos \beta \cos \omega + \cos \delta \sin \emptyset \sin \beta \cos \gamma \cos \omega + \\
\cos \delta \sin \beta \sin \gamma \sin \omega \quad \text{---------- Equation 21}
\]

Where
\[
\begin{align*}
\delta & \quad \text{Declination angle} \\
\emptyset & \quad \text{Latitude} \\
\beta & \quad \text{Slope of the surface} \\
\gamma & \quad \text{azimuth angle} \\
\omega & \quad \text{hour angle}
\end{align*}
\]

This mathematical model is straight forward equation where it can be solved by single instruction using mathematical software.

Thus the equation 18 will be using in electrical energy generation of PV modules mathematical model.
2.6. **PV System design**

The PV systems can be divided into two major groups as grid tied systems and off grid systems.

**Grid connected PV System**

The electrical power will be directly fed into the local electrical power grid. Solar PV modules are connected to a grid tied type solar charge controller which will invert the DC voltage generated into the AC voltage and make sure the positive power flows by regulating the AC voltage generated.

**Off-grid PV system**

This type of systems is isolated systems where energy generated by the solar PV modules will be consumed by available loads and balance energy is stored in electrical batteries for future requirements.

The solar cooling research centre at CSEM-UAE operates in off grid mode due to non availability of the local grid. Thus, the PV system will be designed as off-grid type PV System.

2.6.1. **PV System components for off-grid systems**

In off-grid system, supply and demand is not matching most of the times. Supply is linearly proportional to the incident global insolation which is varying according to the time and environmental conditions. Demand is depending on the load conditions. Thus whenever the supply is greater than the demand, additional energy has to be stored and when the supply is less than demand, balanced will be used from storage.

**Solar PV modules**

PV modules transform the energy contained in solar waveform to electrical energy. Typical conversion efficiencies are from 4%-20% depending on the technology and manufacturing quality. Table 2-3 presents a summary of the conversion efficiency of the different types of PV technologies.

<table>
<thead>
<tr>
<th>Type of technology</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mono-crystalline Silicone</td>
<td>14-20 %</td>
</tr>
<tr>
<td>Polycrystalline Silicone</td>
<td>10-16 %</td>
</tr>
<tr>
<td>Amorphous Silicone</td>
<td>4-12%</td>
</tr>
<tr>
<td>Copper indium gallium selenide (CIGS)</td>
<td>4-8%</td>
</tr>
<tr>
<td>Triple junction Cells</td>
<td>20-30%</td>
</tr>
</tbody>
</table>

Table 2-4: Efficiencies of different type of PV technologies

For off grid systems, energy supply and demand has to be matched for optimum design not the power requirement of loads.

**Solar Charge controller**

PV module voltage output depends on the incident insolation and current drawing. While the PV modules with battery backup systems is in use, the output voltage of the PV modules should be regulated.
such that battery bank will not overload. The solar charge controller performs this kind of regulation. Therefore, the charge controller is placed in between the battery bank and the solar modules. There are different types of charge controllers available in the market. They can be categorized according to the voltage regulation method.

PWM Charging – In this method, the PV module output voltage modulates in pulse width to match the battery bank voltage. Thus, the module output voltage should be higher than the battery bank voltage in order to carry out the charging process. Whenever the PV module voltage drops lower than the battery bank voltage charging process stops to prevent the reverse power flow.

MPPT Charging – For all PV modules and its states, I-V curve have similar characteristics. For each I-V curve there exists a point where point where PV module can deliver maximum power. In order to capture the maximum amount of energy from the PV modules the charging process should follow this maximum power point. MPPT charge controller consists of voltage buck boost converter, which follows the maximum power point of the connected modules.

**Battery Bank**

Batteries store the additional energy generated by the solar PV modules for the future use. There are various kinds of battery types designed and available for different applications. For solar applications there are three major types of battery type are used in common.

Lead acid Batteries – These types of batteries are commonly available and use in various applications especially in automobile applications and Un-interrupted Power Supply (UPS) system. The same kind of batteries is used in solar applications as well. Due to large quantities of use and simple technology these batteries are cheaper compared to other battery type used in solar applications. Lower conversion efficiencies, lower discharge capacity, lower life time and necessity of regular maintenance are some of the drawback of lead acid battery systems.

GEL Batteries- Hydrogen (H) and Oxygen (O) atoms producing at each terminal are recompiled to generate water (H2O) back in to the system in these types of batteries. There exists an automotive valve to regulate the gas pressure generation during rapid charging and discharging processes which is commonly used as Valve regulated lead acid (VRLA) batteries. Also the acid is impregnated in to a jellified medium. So these types are non maintained batteries which no maintenance is required for long period of time. Long maintenance cycle, higher efficiencies are the main advantages of these types of batteries and higher cost is the limitation in common use.

AGM Batteries – the AGM stands for absorbed glass matt where a glass matt is used to store the acid instead of costly jellified medium in GEL batteries. Thus the cost of AGM batteries is much more competitive with lead acid batteries when considered its higher performance. Therefore, AGM batteries are most commonly used in solar PV applications.

**Inverter**

The voltage generated by solar PV module and battery storage is in Direct Current (DC). But most of the electrical applications are used 120V or 230V system voltage. Also this high voltage use helps to reduce investment cost heavily due to reduction in cable sizes necessary and also reduces the power losses in cables. To convert the DC storage and generated voltage in to high AC voltage an inverter is used. Inverters consist of power electronic devices which boost the voltage and oscillate the voltage waveform in required frequency using different method.
Since the CSEM-UAE research center is not available with grid power, the PV system should be off-grid type PV system. MPPT Charge controller have selected to optimum utilization of sun energy. Other components of the PV system have decided upon the performance and financial considerations.

Literature survey has done throughout the thesis project period for find the best possible and high accurate results of the project considered. Literature in different areas has conducted due to the large scope of the considered thesis project.
3. **SOLAR COOLING FACILITY AND ITS SOLAR THERMAL SYSTEM DESCRIPTION**

CSEM-UAE solar cooling research center consists of 1TR cooling system and being installed a 10TR cooling system. The solar cooling system diagram is shown in Error! Reference source not found. for 1TR system. Hot water storage is shared for 10TR system as well and other components are similar but higher in scale.

Figure 3-1: System diagram of 1TR system in CSEM-UAE research facility

Specifications of the 1TR system components are listed in Table 3-1.

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Capacity/Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar collectors</td>
<td>Evacuated tube heat collectors</td>
<td>36.12 m²</td>
</tr>
<tr>
<td>Heat storage</td>
<td>Stratified tank with inbuilt spherical heat exchanger</td>
<td>1000l</td>
</tr>
<tr>
<td></td>
<td>Backup tank</td>
<td>1000l</td>
</tr>
<tr>
<td>Cold storage</td>
<td>Insulated chilled water storage</td>
<td>1000l</td>
</tr>
<tr>
<td>Condenser</td>
<td>Wet cooling tower</td>
<td></td>
</tr>
<tr>
<td>Chiller</td>
<td>Rotating type absorption chiller</td>
<td>1TR, 70°C min working temp</td>
</tr>
<tr>
<td>Fan coil units</td>
<td>Fan coil units compatible with chilled water</td>
<td>50Wx3 Units</td>
</tr>
<tr>
<td>Solar controller</td>
<td>TiSun solar controller with inbuilt pump</td>
<td>200W</td>
</tr>
<tr>
<td>Circulation pumps</td>
<td>Hot water circulation pump</td>
<td>1100W</td>
</tr>
<tr>
<td></td>
<td>chilled water circulation pump</td>
<td>370W</td>
</tr>
<tr>
<td></td>
<td>Cooling tower circulation pump</td>
<td>550W</td>
</tr>
<tr>
<td></td>
<td>Chilled water distribution pump</td>
<td>370W</td>
</tr>
<tr>
<td>Fan</td>
<td>Cooling tower fan</td>
<td>430W</td>
</tr>
<tr>
<td>Heater</td>
<td>Backup heaters</td>
<td>20kW, 10kW</td>
</tr>
</tbody>
</table>
3.1. **Operational behavior of solar thermal system**

The solar collector controller have inbuilt control functions to maintain proper operations and safety of the devices. Two temperature sensors (PT1000), GDS flow sensor and a hot water pump have connected to the solar controller as shown in Figure 3-2.

![Diagram of sensor connections](image)

**Figure 3-2: Sensor connections**

In the controller, $T_1$ is defined as collector, $T_2$ as tank temperature. In the existing installed system, $T_1$ have installed closer to storage tank due to ease of installation by considering the heat loss of pipe is negligible. But when pump is switched off, $T_1$ does not reflect the collector temperature. The controller has an inbuilt function to circulate the water for 30 sec in each 30 minute period to check the collection temperature in such installations. The tank temperature sensor has placed on top of the storage tank.

The controller had set to operate in the parameters given in Table 3-2. **Table 3-2: Controller parameters**

<table>
<thead>
<tr>
<th>Key parameters of the controller</th>
<th>Value</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Collector temperature</td>
<td>110°C</td>
<td>Start the pump for short time even though the max tank temperature reached</td>
</tr>
<tr>
<td>Maximum tank temperature</td>
<td>90°C</td>
<td>For the protection of the storage tank</td>
</tr>
<tr>
<td>$dT_{\text{min}}$ $(T_1-T_2)$</td>
<td>2°C</td>
<td>Prevent reverse heat flow</td>
</tr>
<tr>
<td>$dT_{\text{max}}$ $(T_1-T_2)$</td>
<td>4°C</td>
<td>To prevent reverse heat flow and fluctuations</td>
</tr>
<tr>
<td>Maximum Flow rate</td>
<td>40l/min</td>
<td>Limited by collectors</td>
</tr>
</tbody>
</table>

According to these settings of the controller, as cooling load reduced tank temperature rise occurs. When it reaches the maximum tank temperature, circulation pump switched off by the controller. This will lead to rapid temperature rise in the solar thermal collector and starts steam generation which will end up in stagnation. Tank temperature setting is also very much important to prevent steam generation inside the storage tank which can be catastrophic.
4. SYSTEM DESIGN AND MODELLING

4.1. Proposed heat rejection system

Requirement of the heat rejection system is to remove the additional heat collected by the solar collectors from the system. This system can be installed in the heat collector cycle and in the heat storage. Whenever, the heat rejection requirement present temperature of the collector outlet is higher than the heat storage. Thus by installing heat rejection unit closer to collector outlet higher temperature difference between heat rejection unit and ambient temperature can be obtained. So the heat rejection unit size can be minimized. Therefore the proposed heat rejection system is given in Figure 4-1. Heat rejection should be done only when it is necessary, so it is not continuous. Rejection unit will activate through a bypass line only. Thus a motorized three port valve is used to change the flow.

During the normal operation, three port valve allow straight line flow (180°) which is given by red arrow. During the heat rejection operation straight flow is blocked and 90° flow is allowed which is shown in blue arrow. This method has couple of advantages over use of two 2-port valve in inlet and outlet of heat rejection unit where it will only use one motorized valve thus need only one output of the controller and most importantly will prevent high temperature contact to the motorized valve.

4.2. Control System Design and Selection

The control system needs to not only ensure anti-stagnation operation in the collector cycle but also consider safety of the components during operation. Table 4-1 includes the parameters and its operating constraints.

The control system of the heat rejection system should be defined precisely so that it will ensure the safety and anti-stagnation operation of the solar collector system and at the same time storing the maximum possible solar thermal energy.
Table 4-1: system parameters, constraints and limitations

Expected performance of the system is shown in Figure 4-2. Maximum collector temperature is 110 °C. The preferable hot water storage temperature is 90 °C at maximum. Thus at the maximum capacity, the heat rejection unit inlet and outlet temperatures will be 110 °C and 90 °C respectively.

The collectors have been using in the research center is evacuated tube collectors (ETC). Thus temperature sensor cannot be placed inside the collector area. Collector temperature sensor needs to be placed just before the collector outlet.

![Graph with labels](image)

Figure 4-2: expected performance curves of system temperatures

Whenever the collector temperature goes more than 95 °C, the three port valve which is shown in Figure 4-1 will operate and pump will start running if it is in idle condition. Three port valve operations will divert the water in collector circuit through the heat rejection unit. Once the flow starts temperature hype is expected because of heat collected inside the collector will come to T1 temperature sensor. In few seconds the flow will completely divert through the heat rejection unit and temperature will drop until steady state condition.

Control logic for proper operation of the above system has been conceived and presented by an electronic block diagram shown in Figure 4-3. The collector temperature and maximum set temperature (∆Tmax) is compared which will set the output. This will switch on the circulation pump (P), bypass valve (M) and heat rejection unit fan (F) by using a relay. The collector temperature and minimum set temperature (∆Tmin) is also being compared and reset the output whenever the collector temperature dropped down to ∆Tmin. Thus the collector cycle come back to normal operating mode.
4.2.1. Controller component selection

In compliance with the control system logic, the requirement of the controller component has been identified. The controller should be capable of following requirements,

- Temperature Input – 1 Nos
- TTL/Relay Output – 1 Nos
- Capability of simple logic controls

Various options have been identified which is capable of implementing the control system. The key features have been compared for each option and are presented in the Table 4-2.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Reliability</th>
<th>Extendibility</th>
<th>Power Consumption (W)</th>
<th>Cost (US$)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiSun Solar Controller</td>
<td>High</td>
<td>No</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Industrial Controller</td>
<td>Temperature</td>
<td>Medium</td>
<td>No</td>
<td>20-30</td>
<td>300</td>
</tr>
<tr>
<td>Microcontroller</td>
<td>Medium</td>
<td>Yes</td>
<td>15-25</td>
<td>~100</td>
<td>Some electronic circuit design is required</td>
</tr>
<tr>
<td>ADAM DAQ 4000 Series</td>
<td>Medium</td>
<td>Yes</td>
<td>150</td>
<td>1000</td>
<td>Computer is required for controlling</td>
</tr>
<tr>
<td>ADAM 6000 Series</td>
<td>Medium</td>
<td>Yes</td>
<td>50-100</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>PLC S7 200 + RTD Module</td>
<td>High</td>
<td>Yes</td>
<td>150</td>
<td>700</td>
<td></td>
</tr>
</tbody>
</table>

Table 4-2: Comparison of possible controllers

A solar controller from TiSun has been installed on the existing solar cooling center to control the solar thermal system. The controller is thermal collector system controller which is designed to control three pumps with five temperature sensor inputs. The controller controls the operation of circulation pump based on collector temperature and tank temperature difference. The device have inbuilt simple control function capability as well. With proper assignment of logics the heat rejection control system can be implemented in the existing TiSun controller.

Since the controller is already in use, no requirement of addition burden of power and investment needed. Therefore, the TiSun Solar controller has been selected as the heat rejection system controller.
4.3. HEAT LOAD CALCULATION

Heat collection cycle in the CSEM-UAE solar cooling center have design to run in isolated condition. The storage facility is having a total of 2000 liter capacity that consists of stratified tank of 1000 liter capacity with an inbuilt spherical heat exchanger and an additional back up tank having 1000 liter capacity. The collector system consists of 4 parallel rows of evacuated tube (heat pipe type) solar collectors with each row having 3 collectors connected in series. The total aperture area of the collector system is 36.12 m². The thermodynamic system boundary for the analyzing application is given in the Figure 4-4.

![Figure 4-4: Thermal system boundary](image)

\[ Q_{\text{storage}} = Q_{\text{collector}} - Q_{\text{loss}} \]

During lower and no load conditions, the storage temperature will rise; therefore temperature should be controlled so that it remains below the recommended safety limits. Thus a heat rejection system have been introduced to the solar collector loop to reject the unnecessary heat during lower and no load condition such that it always maintains the storage temperature at set point. Figure 4-1 shows the introduction of the heat rejection unit in to the system.

To control the flow through heat rejection unit, a motorized three port valve is used. The valve diverts the circulating fluid in the collector circuit through the heat rejection unit when the fluid temperature reaches the defined safety limit by a controller unit.

During no load condition, all thermal energy collected by the collector should be rejected; in other words the storage should not have any thermal energy beyond its capacity calculated at the safety limit of the temperature. Thus, it can be represented by the equation

\[ Q_{\text{storage}} = 0, \]

\[ Q_{\text{rejection}} = Q_{\text{collector}} - Q_{\text{loss}} \]

---------------Equation 22
Since the system is properly insulated $Q_{\text{loss}}$ will be very small value. When comparing with the absorbed heat, losses can be neglected.

\[
Q_{\text{rejection}} = Q_{\text{collector}} \quad \text{--------Equation 23}
\]

For evacuated tube collectors absorbed thermal energy can be expressed as equation

\[
Q_{\text{abs}} = A_c \eta_0 G - A_c [a_1 (T_m - T_a) + a_2 (T_m - T_a)^2] \quad \text{--------Equation 24}
\]

Design parameters are shown in Table 4-3. The presented values are taken from the manufacturer datasheet.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conversion factor</td>
<td>$\eta_0$</td>
<td>0.73</td>
</tr>
<tr>
<td>Loss coefficient</td>
<td>$a_1$</td>
<td>1.5 W/m².K</td>
</tr>
<tr>
<td>Loss coefficient</td>
<td>$a_2$</td>
<td>0.0058 W/m².K²</td>
</tr>
<tr>
<td>Aperture area</td>
<td>$A_{ap}$</td>
<td>3.008 m²</td>
</tr>
<tr>
<td>No of collectors</td>
<td>$N$</td>
<td>12</td>
</tr>
<tr>
<td>Collector input temperature</td>
<td>$T_{in}$</td>
<td>95 °C</td>
</tr>
<tr>
<td>Maximum flow rate</td>
<td>$V$</td>
<td>20 l/min</td>
</tr>
</tbody>
</table>

Table 4-3: Thermal and physical parameters of solar collector

The absorbed heat by the solar collector depends on the global irradiance, ambient temperature and collector input temperature values. When the heat rejection system activates, the collector input temperature almost equals to the heat storage input temperature due to zero heat transfer to storage. Thus the maximum collector input temperature will be the safety limit of the storage tank which is at 90°C.

The heat rejection unit should be capable of rejecting the heat when solar collector is getting maximum amount of heat from the sun. Solar heat collection usually increases with higher solar radiation and lower ambient temperature.

According to the weather database of the site, maximum available global solar radiation on 25° inclined surface is 1050 W/m² and minimum temperature during highest radiation times is 30°C.

The heat load is calculated by Engineering Equation Solver (EES) software. The maximum heat collection from the installed solar evacuated tube collector field in worst case scenario is $23\text{kW}_\text{th}$. The calculation and results are presented in Appendix 1.
4.4. HEAT REJECTION SYSTEM DESIGN

Major requirement of the heat rejection system is to dissipate the unnecessary thermal energy collected by solar collectors. The system has been designed to meet the worst case scenario. The maximum heat collection is 23kWth heat according to the heat load calculations.

With the limited time available for the project completion, design and manufacturing of a dedicated heat rejection system is not possible. Thus a best matching available heat rejection system have selected.

During the literature survey, several types of heat transfer systems have identified as possible options and listed in Table 4-4.

<table>
<thead>
<tr>
<th>Unit Type</th>
<th>Available Capacity</th>
<th>Additional Power consumption</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiSun heat rejection unit</td>
<td>75kW</td>
<td>500W</td>
<td>Over capacity, High cost</td>
</tr>
<tr>
<td>Industrial Coolers</td>
<td>15-400kW</td>
<td>-</td>
<td>Designed for very high flow rates</td>
</tr>
<tr>
<td>Auto Radiators (1.5l gasoline engine)</td>
<td>70kW</td>
<td>200W</td>
<td>Designed for high air flow rates</td>
</tr>
</tbody>
</table>

Table 4-4: Available heat transfer units

The TiSun has developed a heat rejection system unit for large capacity solar collector system. The unit is specifically designed for the concerned application. Furthermore, the rated capacity of the rejection system is 75kWth. Moreover, the cost of the system is too high.

Industrial coolers and radiators are manufactured for used in industrial applications to reject unwanted heat in some processes. Common requirements for the industrial coolers and radiators are in large scale; thus available sizes are in higher capacities and very high flow rates. From the economical aspect also the industrial coolers are in high cost regions.

In this context, there exists a possibility of using automobile radiators as a solution as it is comparatively cheaper compared to other options mentioned above. Most commonly available vehicle type is having automobile engine capacity of 1.5-2.0 l. Thus, Toyota Camry radiator has been selected for the analysis.

Toyota Camry 2001 release model automobile radiator parameters are given in Table 2-2. The designed capacity of the radiators is 70 kW at 110 l/min coolant flow rate and 16 km/h air flow rate. The designed flow rate is considered while the vehicle in moving.

Thus, two important variables viz: coolant and air flow rate have been identified as the critical parameters to be considered for the adaptation of the automobile radiator as heat rejection unit of solar thermal system. For the stationary mode of operation, the radiator fan is assumed to deliver about 1200 cfm of air flow rate. Similarly, the maximum coolant flow rate is assumed to be 20 l/m that is equivalent to the maximum flow rate that the pump can circulate around the solar collector system. These variables and its values are considered as the operational parameters of the radiator.

One of the major issues identified in the analysis of radiator is that it falls under the category of compact heat transfer systems. Furthermore, it is found that radiators are designed to operate under turbulent flow conditions. The main reason to operate it under turbulent conditions is to increase the heat transfer coefficient so that the size and weight of the radiator can be minimized. It helps accommodate the radiator in the very limited space available in automobile.
During the literature survey, it was very difficult to find the thermodynamic models of radiators design considering laminar flow conditions. Therefore, during the analysis the thermodynamic equations given by Yunus A Cengel's Thermodynamic systems and Yu Juei Chang and Chi Chuwan Wang's study on radiators have been used and adapted for the radiators selection validation for heat rejection unit.

For the coolant side,

\[ ReynoldsNum = \frac{\rho v D_H}{\mu} \]  
\[ D_H = \frac{4 A_{min}}{W_P} \]  
\[ A_{min} = t W_{new} \times t H_{new} \]  
\[ W_{Pc} = 2(t W_{new} + t H_{new}) \]

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
Parameter & Result \\
\hline
A_{min} & 0.000039 m^2 \\
W_{Pc} & 0.055 m \\
D_{ij} & 0.00283636 m \\
ReynoldsNum & 452.4 \\
\hline
\end{tabular}
\caption{Table 4-5 : Results of coolant side parameters}
\end{table}

According to result, the coolant side flow condition is laminar. To analyze the thermodynamic system in laminar condition Yunus A Cengel’s internal forced convection fully developed laminar flow for circular tube have been used.

For the fully developed laminar flow conditions,

\[ PrandtlNum = \frac{c_{\mu}}{k} \]  
\[ NusseltNum = \frac{h c D_H}{k} \]

For the air side of the radiator,

\[ A_{min} = simplify(t W_{new} \times t H_{new}) \]  
\[ W_{Pc} = 2(t W_{new} + t H_{new}) \]

Similar to the coolant side, air side of the radiator also works in fully developed laminar flow region even though it is designed to work in turbulent region for higher heat transfer coefficient. The heat transfer coefficient calculation is more complex in air side than in the coolant side due to complex fin structure with louvers.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nusselt number</td>
<td>4.36</td>
</tr>
<tr>
<td>PrandltNum</td>
<td>6.609</td>
</tr>
<tr>
<td>$Hc$</td>
<td>637.93 kg/s$^3$K</td>
</tr>
<tr>
<td>$A_{\text{min,a}}$</td>
<td>0.00000969 m²</td>
</tr>
<tr>
<td>$W_{Pa}$</td>
<td>0.01928 m</td>
</tr>
<tr>
<td>$D_{i,b}$</td>
<td>0.00201037 m</td>
</tr>
<tr>
<td>ReynoldsNum</td>
<td>119.65</td>
</tr>
</tbody>
</table>

Table 4-6: Results of air side parameters

Yu Juei Chang and Chi Chuwan Wang from Energy and Research laboratories, Taiwan have studied about heat transfer coefficient for louver fin geometry and found best matching model. They have estimated the optimized coefficients of terms of Colburn factor equation.

$$ColburnFactor = \frac{0.296725 \cdot 0.27 \cdot \left( \frac{\theta}{T_p} \right)^{0.68}}{\text{ReynoldsNum}^{0.59} \left( \frac{T_p}{T_F} \right)^{0.14} \left( \frac{T_P}{T_F} \right)^{0.29} \left( \frac{T_P}{T_F} \right)^{0.23} \left( \frac{T_P}{T_F} \right)^{0.28} \left( \frac{T_F}{T_F} \right)^{0.05}}$$ \hspace{1cm} \text{Equation 33}

$$ColburnFactor = \frac{nfha \cdot \text{PrandltNum}^{2/3}}{\rho v C_p} \hspace{1cm} \text{Equation 34}$$

Total heat transfer capacity,

$$CR = Cmf r \hspace{1cm} \text{Equation 35}$$

$$mfr = \text{FluidViscosity} \cdot \rho \hspace{1cm} \text{Equation 36}$$

$$ITD = \text{CoolantTemperature} - \text{AirTemperature} \hspace{1cm} \text{Equation 37}$$

$$q = \epsilon \cdot Cmin \cdot ITD \hspace{1cm} \text{Equation 38}$$

$$\epsilon = 1 - e^{-\frac{C_{\text{max}} \left( 1 - e^{-\text{Ratio Ntu}} \right)}{C_{\text{min}}}} \hspace{1cm} \text{Equation 39}$$

$$Ntu = \frac{UA}{C_{\text{min}}} \hspace{1cm} \text{Equation 40}$$

$$\frac{1}{UA} = \frac{1}{hc \cdot Ac} + \frac{1}{nfha \cdot Aa} \hspace{1cm} \text{Equation 41}$$

With the reduced coolant flow rate, reduced air flow rate and increased temperature difference (ITD) the de-rated heat rejection capacity of the radiator under the condition of stationary air and prevailing fluid flow in collector cycle is 17.8kWth. The capacity is slightly less than estimated heat load of 23 kWth in chapter 5. In this context, it has been decided to use two automobile radiators from Toyato Camry 2001 model as the heat rejection system.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Result</th>
<th>Parameter</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colburn Factor</td>
<td>0.0398641</td>
<td>Cmax</td>
<td>1245</td>
</tr>
<tr>
<td>PrandltNum</td>
<td>0.722385</td>
<td>Cratio</td>
<td>0.1836</td>
</tr>
<tr>
<td>h_s</td>
<td>253.157 kg/s°K</td>
<td>ITD</td>
<td>80K</td>
</tr>
<tr>
<td>mf_s</td>
<td>0.2276 kg/s</td>
<td>UA</td>
<td>1406 m² kg/s°K</td>
</tr>
<tr>
<td>mf_i</td>
<td>0.338299 kg/s</td>
<td>Ntu</td>
<td>6.1483</td>
</tr>
<tr>
<td>CR_a</td>
<td>228.73 m² kg/s°K</td>
<td>Enew</td>
<td>0.974898</td>
</tr>
<tr>
<td>CR_c</td>
<td>1245.62 m² kg/s°K</td>
<td>Q</td>
<td>17839 J/s</td>
</tr>
<tr>
<td>Cmin</td>
<td>228</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4-7: Results of heat transfer calculation
4.5. MATHEMATICAL MODELING OF PHOTOVOLTAIC MODULE

One of the project objectives is to find out the best performing PV technology in the RAK-UAE environment. The performance of PV will be subjected to various factors which,

- PV Technology
- Global insolation
- Module temperature
- Transmittance of the glass cover (change due to dust deposition)

In order to evaluate the performance of PV an optimized mathematical model which includes the above factors is necessary. The two diode model have been used for the best fitting of manufacturer’s tests and performance test carried out. The simulation has been done with using MatLab Simulink tool using basic nodes.

4.5.1. Simulink model for solar PV module

A simulink block “PV” in the Figure 4-5 is developed equivalent to the PV module with simulink blocks. The block input parameters are incident radiation to the panel board and module temperature.

The “PV” block gives the PV module key parameters described in literature review and it generates power output curve.

![Simulink model for PV module](image)

Figure 4-5 : Simulink model for PV module
PV module parameters can be defined in “PV” block parameters dialog box as shown in Figure 4-6. The block parameters viz: short circuit current, open circuit voltage, current at maximum power point, voltage at maximum power point and temperature coefficient of short circuit current are set in the “PV” block which can be found in the manufacturer’s datasheet for each module.

![Figure 4-6: PV block parameter settings](image)

Each time a new data is feed to the PV system block it will run its initialization code to generate the basic element parameters Id, Io1, Io2, Vth, Rsh and Rs. The initialization code will use the three conditions of open circuit condition, short circuit condition, and maximum current point condition to solve the mathematical equations.

![Figure 4-7: PV system block](image)
A reference voltage is generated by simulink block which is used to evaluate the mathematical equations and find the matching current value. The product of voltage and current will be the power generation for that voltage. The reference voltage is varying from 0 to Voc thus all the possible power points will be evaluated.

The generated power by the PV block is analyzed by the “Monitor” custom simulink block in order to find the maximum power point for the given input conditions.

In order to evaluate the modeled PV system a solar PV module output and Kyocera KC130GT-1 module manufacturer’s curves have been compared.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Manufacturer’s value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum power</td>
<td>130W</td>
</tr>
<tr>
<td>Voc</td>
<td>21.9V</td>
</tr>
<tr>
<td>Isc</td>
<td>8.02A</td>
</tr>
<tr>
<td>Vmp</td>
<td>17.6V</td>
</tr>
<tr>
<td>Imp</td>
<td>7.39A</td>
</tr>
<tr>
<td>Temperature coefficient of Isc</td>
<td>3.18e-3 A/°C</td>
</tr>
</tbody>
</table>

Table 4-8 : KC130GT-1 PV module parameters at standard testing condition

![Performance graphs of Kyocera KC130GT-1 module](image)

Figure 4-8 : Performance graphs of Kyocera KC130GT-1 module

Most of the manufacturers include parameters as shown in Table 4-8 and performance graphs as shown in Figure 4-8 in module’s datasheet. Variations in I-V curve with temperature at constant irradiance and variations in I-V curve with irradiance at constant module temperature are considered to be standard tests results included in datasheets.
The performances of the mathematical model have been compared with an experimental data set which is shown in Figure 4-11. The x-axis is the time axis for a one day period and y-axis is the module power output in Watt. Yellow color curve is the model power output and pink color curve is the experimental power output.
Both manufacturer’s tests and onsite test at CSEM-UAE test facility results are following the developed simulink model.

4.5.2. Calculation of incident solar radiation on to inclined surfaces

The weather data of the CSEM-UAE has consists of different parameters. The beam radiance is the direct solar radiation. For beam radiation measurement, a sensor always follows the sun position by precise solar tracking system to capture the direct solar radiation. The global and diffused radiations are measured for horizontal plane. The mathematical model needs to feed the incident solar radiation on the inclined PV modules in the developed model.

Therefore, solar radiation incident on an inclined surface have been calculated using the available data in-order to evaluate the performance of PV module mounted on inclined surfaces. The mathematical equations described during literature survey have been used to create a model library which will calculate the incident solar radiation on inclined surface within the simulink model.
The Latitude, Slope angle of the surface and bearing of the surface to the south are the changing parameters of inclined surfaces. These parameters can be assigned in the Function block parameters dialog box of the new simulink sub-model as shown in Figure 4-13.

**4.5.3. Evaluating the photovoltaic module temperature**

The PV performance varies with the module operating temperature. CSEM-UAE not measured module temperature parameter for their solar database; thus the PV module temperature has been evaluated using optimized mathematical model. Most of the PV mathematical modeling literature consists of mathematical expressions to evaluate the PV module operating temperature using ambient temperature, global solar irradiance and wind speed. The models used are different to each other which forced to evaluate and optimize the already developed models with test data.

The model from R Chenni, M. Makhoul [7],

\[ T_m = 0.943T_a + 0.028G_{in} - 1.528W_s + 4.3 \]  \[ \text{---------Equation 42} \]

Optimized model using test values,

\[ T_m = 0.972T_a + 0.025G_{in} - 1.35W_s + 4.3 \]  \[ \text{---------Equation 43} \]

Where,

- \( T_m \) - Module Temperature
- \( T_a \) - Ambient Temperature
- \( G_{in} \) - Global radiance on PV module
- \( W_s \) - Wind speed
Figure 4-14 shows the result comparison of module temperature recoded, optimized model and the model in the literature.

![Temperature vs Time Graph](image)

**Figure 4-14: Module temperature, actual Vs Literature models**

The optimized model for the module temperature has been included in the simulink model as shown in Figure 4-15.

![Simulink Model](image)

**Figure 4-15: Integration of the module temperature sub-model**
5. **PERFORMANCE ANALYSIS OF PV DUE TO DUST**

The effect of the two cleaned surface in helpful to similar to CSEM-UAE tracer analysis is before the testing period. The data logging was started after 45 days of dust deposition due to some technical support issues. The test was carried out for 5 months period. The single axis tracker setup used for dust analysis is shown in Figure 5-1.

CSEM-UAE PV research center is having a single axis tracker which has 6 connections to the PV Multi-tracer analyzer. Multi-tracer can also be connected with pyranometers and temperature sensors.

Three different types of solar PV modules have used to test for the dust performance test. Two identical PV modules installed from each type for comparison. Three PV modules have been cleaned every time before the test carried out and the other set of modules was left for dust deposition over the whole testing period. The data logging was started after 45 days of dust deposition due to some technical support issues. The test was carried out for 5 months period.

![Figure 5-1: Six solar PV modules on single axis tracker for dust performance test](image)

<table>
<thead>
<tr>
<th>PV Module</th>
<th>Technology</th>
<th>P rated (W)</th>
<th>Voc (V)</th>
<th>Isc (A)</th>
<th>Vmp (V)</th>
<th>Imp (A)</th>
<th>Temperature coefficient of Isc (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kyocera</strong></td>
<td>Monocrystalline</td>
<td>130</td>
<td>21</td>
<td>8.02</td>
<td>17.6</td>
<td>7.39</td>
<td>0.0396</td>
</tr>
<tr>
<td><strong>Wurth Solar</strong></td>
<td>Thinfilm</td>
<td>75</td>
<td>44.5</td>
<td>2.36</td>
<td>35</td>
<td>2.15</td>
<td>0.05</td>
</tr>
<tr>
<td><strong>Hyundai</strong></td>
<td>Monocrystalline</td>
<td>200</td>
<td>33.1</td>
<td>8.19</td>
<td>26.4</td>
<td>7.6</td>
<td>0.056</td>
</tr>
</tbody>
</table>

Table 5-1: PV Modules used in dust performance test
PV panels of dusty and clean modules power output ratios have been compared with different product used in order to identify any impact with product type in Figure 5-2, Figure 5-3 and Figure 5-4.

Figure 5-2: Performance ratios of three products of dusty and clean modules after 20 days

Figure 5-3: Performance ratios of three products of dusty and clean modules after 60 days

Figure 5-4: Ratios of three products of dusty and clean modules after 90 days
The results show two Mono-crystalline modules performance is similar and about 2% higher reduction in thinfilm module. But the root cause may be difference in type of glass cover used and may be due to placement in the single axis tracker. Even though there is a small difference in performance ratios, same performance reduction with time can be assumed based on the above graphs.

The performance reduction seems to be linear at first sight. But in long time dust deposition, dust removal by wind forces and deposition of dust will be equal and dust deposition will come to saturation. Thus the performance reduction model cannot be in linear form.

Thus a exponential mathematical model for such applications has used to model the observation.

\[ \text{performance ratio} = C_1 \times e^{-tC_2} \quad \text{Equation 44} \]

Initially, the PV modules are cleaned for start of testing. Thus the performance ratio is unity at \( t=0 \).

\[ \therefore C_1 = 1 \]

Constant \( C_2 \), was found by comparing with the test performances.

The Figure 5-5 shows the actual performance reductions and mathematical model. It gives a common mathematical equation for all module types.

\[ \text{Performance ratio} = e^{-0.0033t} \quad \text{Equation 45} \]

\( t \) : No of days of dust deposition on PV module considered

![Figure 5-5: Performance ration over the testing period](image)

The estimated mathematical model has been included into the simulink mathematical model in order to analyze the performance of PV with dust deposition. The updated system is shown in Figure 5-6 where the performance ratio and cleaning cycle can be set in parameter setting dialog box as shown in Figure 5-7. Also the modeled performance ratios for 6 months period have given in Table 5-2.
Table 5-2: Performance reduction of PV due to dust

<table>
<thead>
<tr>
<th>Dust deposition period</th>
<th>Performance reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Month</td>
<td>8%</td>
</tr>
<tr>
<td>2 Months</td>
<td>16%</td>
</tr>
<tr>
<td>3 Months</td>
<td>25%</td>
</tr>
<tr>
<td>4 Months</td>
<td>33%</td>
</tr>
<tr>
<td>5 Months (extrapolated)</td>
<td>40%</td>
</tr>
<tr>
<td>6 Months (extrapolated)</td>
<td>46%</td>
</tr>
</tbody>
</table>

Figure 5-6: Simulink model with dust performance sub model

Figure 5-7: Parameter dialog box for dust performance settings
6. **PV SYSTEM DESIGN**

6.1. **PV system design for the 1TR solar cooling system**

1TR solar cooling system consists of 36 m² evacuated tube type solar collectors, heat storage tanks, 1TR absorption chiller unit, chilled water tank, cooling tower, fan coil units, solar collector control station and 5 pumps. The rated power consumptions of system components are given in Table 6-1. For a proper and optimum design of a PV system, the power consumption curves and energy consumption is very important which decides the capacities of PV system components.

<table>
<thead>
<tr>
<th>Component</th>
<th>Rated Power (W)</th>
<th>Expected operated duty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar control station</td>
<td>20</td>
<td>24h/day</td>
</tr>
<tr>
<td>Solar collector pump</td>
<td>200</td>
<td>8h/day</td>
</tr>
<tr>
<td>Absorption chiller</td>
<td>200</td>
<td>6h/day</td>
</tr>
<tr>
<td>Heat cycle pump</td>
<td>1100</td>
<td>6h/day</td>
</tr>
<tr>
<td>Chilled water pump</td>
<td>370</td>
<td>6h/day</td>
</tr>
<tr>
<td>Chilled water feeding pump</td>
<td>370</td>
<td>8h/day</td>
</tr>
<tr>
<td>Cooling tower pump</td>
<td>550</td>
<td>6h/day</td>
</tr>
<tr>
<td>Cooling tower fan</td>
<td>430</td>
<td>6h/day</td>
</tr>
<tr>
<td>Fan coil units</td>
<td>3x 35</td>
<td>8h/day</td>
</tr>
</tbody>
</table>

Table 6-1: Rated power consumption and duty of solar cooling system components

According to the rated power of components maximum power demand is 3350W. Figure 6-1 shows a test result of the total system power consumption curve. The storage tank temperature was not in required level to start the absorption chiller. Thus only heat collector cycle was run until noon. Then total system has been started to run and one hour shutdown time was there due to lunch break. The active power is running around 2200W and average apparent power is 3200VA. The maximum apparent power is reaching 5800VA during pump startups due to inrush current.

![Figure 6-1: data of Power and Energy curves of 31/05/2011](image-url)
Figure 6-2: Recorded data of Power and Energy curves of 1/06/2011

From the power and energy graphs shown in Figure 6-1 & Figure 6-2 and predicted operation time design parameter values can be extracted for the PV system design. Extracted design parameter values are shown in Table 6-2.

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent power of the system</td>
<td>3200VA</td>
</tr>
<tr>
<td>Maximum apparent power due to inrush currents</td>
<td>5800VA</td>
</tr>
<tr>
<td>Maximum active power of the system</td>
<td>2200W</td>
</tr>
<tr>
<td>Energy consumption of the system of day time</td>
<td>21kWh</td>
</tr>
</tbody>
</table>

Table 6-2: Extracted design parameter values of 1TR cooling system

Next step of the PV design is to find out the PV module and no of panel required to generate the required 21kWh of energy per day. The developed Mathlab simulink model is fed with weather data from CSEM-UAE to simulate the energy generation from each PV module considered so that performance variations with solar radiation, dust deposition and ambient temperature are considered.

<table>
<thead>
<tr>
<th>PV Module</th>
<th>Technology</th>
<th>Country of origin</th>
<th>Rated power</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV-A</td>
<td>Mono-crystalline</td>
<td>Japan</td>
<td>235W</td>
</tr>
<tr>
<td>PV-B</td>
<td>Thinfilm</td>
<td>Japan</td>
<td>128W</td>
</tr>
<tr>
<td>PV-C</td>
<td>Thinfilm</td>
<td>Switzerland</td>
<td>150W</td>
</tr>
<tr>
<td>PV-D</td>
<td>Mono-crystalline</td>
<td>USA</td>
<td>327W</td>
</tr>
</tbody>
</table>

Table 6-3: Selected PV modules for analysis

Four types of photovoltaic modules given in Table 6-3 have been considered during the analysis for the PV system. The test and analysis carried out is compared with performance, investment comparison; however the PV module brand names are not published in the thesis report.
The roof structure has been fabricated to install PV module to generate power for solar cooling research center. The roof structure’s latitude, slope angle and bearing angle are used as input parameters for incident irradiance block and dust performance block in developed simulink model.

The results of the simulation for each PV module are given in the Table 6-5. Required no of PV modules and required space for PV installation are also calculated and presented.

<table>
<thead>
<tr>
<th>PV Module</th>
<th>Rated Power W/Panel</th>
<th>Energy generated Wh/day/panel</th>
<th>No of Panels required</th>
<th>Mounting Method</th>
<th>Area required m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV-A</td>
<td>235</td>
<td>1102</td>
<td>20</td>
<td>Frame</td>
<td>34</td>
</tr>
<tr>
<td>PV-B</td>
<td>128</td>
<td>576</td>
<td>38</td>
<td>Frame</td>
<td>54</td>
</tr>
<tr>
<td>PV-C</td>
<td>150</td>
<td>745</td>
<td>28</td>
<td>Roof</td>
<td>106</td>
</tr>
<tr>
<td>PV-D</td>
<td>327</td>
<td>1478</td>
<td>15</td>
<td>Frame</td>
<td>33</td>
</tr>
</tbody>
</table>

Table 6-5: PV Power generation

**Battery bank design**

Power generation curve by required no of PV panels is given in the Figure 6-3 with the apparent power of the load (demand curve). It is evident that supply cannot match the demand all the time. Thus a battery bank is necessary for trouble free operation for this system. Started time of system operation is 12 noon of the tested date but the actual operation is starting at 1000 once it is in to continuous operation. Stored energy of the batteries will be used during 1430 to 1500 and 1900 to 0600 periods. Calculated battery bank parameters are shown in Table 6-6.
Based on the results obtained, PV system parameters have been calculated for each case given in Table 6-7.

<table>
<thead>
<tr>
<th>Component</th>
<th>PV-A</th>
<th>PV-B</th>
<th>PV-C</th>
<th>PV-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>235</td>
<td>128</td>
<td>150</td>
<td>327</td>
</tr>
<tr>
<td>No of Panels required</td>
<td>20</td>
<td>38</td>
<td>28</td>
<td>15</td>
</tr>
<tr>
<td>Area</td>
<td>34</td>
<td>54</td>
<td>106</td>
<td>33</td>
</tr>
<tr>
<td>Charge controller</td>
<td>60A 150Voc</td>
<td>45A 150Voc</td>
<td>60A 150Voc</td>
<td>45A 150Voc</td>
</tr>
<tr>
<td>Battery Bank</td>
<td>12V 50Ah x 4</td>
<td>12V 50Ah x 4</td>
<td>12V 50Ah x 4</td>
<td>12V 50Ah x 4</td>
</tr>
<tr>
<td>Inverter</td>
<td>5000AV, 48V</td>
<td>5000AV, 48V</td>
<td>5000AV, 48V</td>
<td>5000AV, 48V</td>
</tr>
</tbody>
</table>

Financial analysis has been done for each case of PV system designs. The life time of the each PV system components and PV module are the same. Therefore detailed economic analysis like Net present value (NPV) or Levelized cost of electricity generation (LCEG) is not required. An optimum PV system for the proposed application can be selected based on total investment cost.
<table>
<thead>
<tr>
<th>Component</th>
<th>PV-A</th>
<th>PV-B</th>
<th>PV-C</th>
<th>PV-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated cost ($/W)</td>
<td>2.3</td>
<td>2.1</td>
<td>3</td>
<td>2.2</td>
</tr>
<tr>
<td>Panel cost ($)</td>
<td>10810</td>
<td>10215</td>
<td>12600</td>
<td>10791</td>
</tr>
<tr>
<td>Structure cost ($)</td>
<td>476</td>
<td>810</td>
<td>1378</td>
<td>462</td>
</tr>
<tr>
<td>Charge controller</td>
<td>800</td>
<td>800</td>
<td>500</td>
<td>400</td>
</tr>
<tr>
<td>Battery Bank</td>
<td>420</td>
<td>420</td>
<td>420</td>
<td>420</td>
</tr>
<tr>
<td>Inverter</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
</tr>
<tr>
<td>Cables</td>
<td>400</td>
<td>550</td>
<td>1042</td>
<td>1095</td>
</tr>
<tr>
<td>Accessories</td>
<td>600</td>
<td>1140</td>
<td>840</td>
<td>420</td>
</tr>
<tr>
<td>Installation &amp; commission</td>
<td>800</td>
<td>820</td>
<td>960</td>
<td>800</td>
</tr>
<tr>
<td><strong>Total Investment</strong></td>
<td><strong>15550</strong></td>
<td><strong>16000</strong></td>
<td><strong>19000</strong></td>
<td><strong>15650</strong></td>
</tr>
</tbody>
</table>

Table 6-8: Investment cost analysis of 1TR PV system
6.2. **PV system design for the 10TR solar cooling system**

The CSEM-UAE is being installing the 10 TR solar cooling system. Thus power and energy consumption is evaluated considering the similar operation and performance of 1 TR solar cooling system.

<table>
<thead>
<tr>
<th>Component</th>
<th>Rated Power (W)</th>
<th>Expected operated duty (h/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar control station</td>
<td>25</td>
<td>24</td>
</tr>
<tr>
<td>Solar collector pump</td>
<td>800</td>
<td>8</td>
</tr>
<tr>
<td>Absorption chiller</td>
<td>200</td>
<td>6</td>
</tr>
<tr>
<td>Heat cycle pump</td>
<td>1500</td>
<td>6</td>
</tr>
<tr>
<td>Chilled water pump</td>
<td>750</td>
<td>6</td>
</tr>
<tr>
<td>Chilled water feeding pump</td>
<td>430</td>
<td>8</td>
</tr>
<tr>
<td>Cooling tower pump</td>
<td>1100</td>
<td>6</td>
</tr>
<tr>
<td>Cooling tower fan</td>
<td>750</td>
<td>6</td>
</tr>
<tr>
<td>Fan coil units</td>
<td>3x 50</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 6-9: 10TR Cooling system components power and expected duty

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent power of the system</td>
<td>5705VA</td>
</tr>
<tr>
<td>Maximum apparent power due to inrush currents</td>
<td>10.8kVA</td>
</tr>
<tr>
<td>Maximum active power of the system</td>
<td>4000W</td>
</tr>
<tr>
<td>Energy consumption of the system of day time</td>
<td>27kWh</td>
</tr>
</tbody>
</table>

Table 6-10: Design parameter values of 10TR PV system

Calculation of PV system parameter is the same as 1TR system calculation. Calculated results of the PV system design parameters are shown in Table 6-11, Table 6-12 and Table 6-13.

<table>
<thead>
<tr>
<th>PV Module</th>
<th>Rated W/Panel</th>
<th>Power No of Panels required</th>
<th>Area required m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV-A</td>
<td>235</td>
<td>26</td>
<td>43</td>
</tr>
<tr>
<td>PV-B</td>
<td>128</td>
<td>38</td>
<td>68</td>
</tr>
<tr>
<td>PV-C</td>
<td>150</td>
<td>28</td>
<td>145</td>
</tr>
<tr>
<td>PV-D</td>
<td>327</td>
<td>20</td>
<td>42</td>
</tr>
</tbody>
</table>

Table 6-11: Required PV modules and area for 10TR System

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy required from the batteries</td>
<td>2kWh</td>
</tr>
<tr>
<td>Battery system voltage</td>
<td>48V</td>
</tr>
<tr>
<td>Battery bank capacity</td>
<td>300Ah</td>
</tr>
</tbody>
</table>
Table 6-12: Battery bank for 10TR system

<table>
<thead>
<tr>
<th>Component</th>
<th>PV-A</th>
<th>PV-B</th>
<th>PV-C</th>
<th>PV-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>235</td>
<td>128</td>
<td>150</td>
<td>327</td>
</tr>
<tr>
<td>No of Panels required</td>
<td>26</td>
<td>48</td>
<td>38</td>
<td>20</td>
</tr>
<tr>
<td>Area</td>
<td>43</td>
<td>68</td>
<td>145</td>
<td>42</td>
</tr>
<tr>
<td>Charge controller</td>
<td>40Ax2 150Voc</td>
<td>45x2A 150Voc</td>
<td>45Ax2 150Voc</td>
<td>45Ax2 150Voc</td>
</tr>
<tr>
<td>Battery Bank</td>
<td>12V 75Ah x 4</td>
<td>12V 75Ah x 4</td>
<td>12V 75Ah x 4</td>
<td>12V 75Ah x 4</td>
</tr>
<tr>
<td>Inverter</td>
<td>5000AV, 48V</td>
<td>5000AV, 48V</td>
<td>5000AV, 48V</td>
<td>5000AV, 48V</td>
</tr>
</tbody>
</table>

Table 6-13: PV system parameters for 10TR system

For the obtained design parameters, cost estimation have done for the complete solar PV system and compared for optimum technology for the application considered.

As shown in Table 6-14 the lowest investment cost is with PV-A module design which is Mono-crystalline type PV modules.

<table>
<thead>
<tr>
<th>Component</th>
<th>PV-A</th>
<th>PV-B</th>
<th>PV-C</th>
<th>PV-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated cost ($/W)</td>
<td>2.3</td>
<td>2.1</td>
<td>3</td>
<td>2.2</td>
</tr>
<tr>
<td>Panel cost ($)</td>
<td>14050</td>
<td>12900</td>
<td>17100</td>
<td>14388</td>
</tr>
<tr>
<td>Structure cost ($)</td>
<td>620</td>
<td>1025</td>
<td>1870</td>
<td>620</td>
</tr>
<tr>
<td>Charge controller</td>
<td>800</td>
<td>800</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td>Battery Bank</td>
<td>570</td>
<td>570</td>
<td>570</td>
<td>570</td>
</tr>
<tr>
<td>Inverter</td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
</tr>
<tr>
<td>Cables</td>
<td>520</td>
<td>700</td>
<td>1420</td>
<td>1460</td>
</tr>
<tr>
<td>Accessories</td>
<td>780</td>
<td>1440</td>
<td>1140</td>
<td>560</td>
</tr>
<tr>
<td>Installation &amp; commission</td>
<td>950</td>
<td>960</td>
<td>1250</td>
<td>1000</td>
</tr>
<tr>
<td>Total Investment</td>
<td>19900</td>
<td>20000</td>
<td>25725</td>
<td>21000</td>
</tr>
</tbody>
</table>

Table 6-14: Financial analysis for 10TR PV system

Thus the optimum PV technology for the 10TR system in CESM-UAE solar research center is high efficient Mono-crystalline modules.
### 6.3. PV system design with available PV modules

CSEM-UAE has received thin film solar PV modules from a Swiss company for installing and testing in UAE climatic condition. A set of modules has allocated to install a PV system to supply power to the solar cooling research center.

In general, PV system design starts by analyzing the load requirements and ends by calculating the solar PV module capacity requirement. But in this scenario, CSEM-UAE has fixed no of solar PV modules, so that the objective is to design the system to utilize the maximum energy generated by the available PV modules.

The received solar PV modules are thin film technology type having rated power of 150W. The modules are from Flexcell Switzerland. For the PV system 14 No of panels are allocated which gives 2.1kW of total rated system power output.

Average daily energy production from the PV system with simulated results is 10.5kWh/day. The expected amount of energy generation is more than sufficient to run the heat rejection system but not enough to run all the components of 1TR cooling system that requires electricity. Thus various options available were considered for optimum utilization and to match the PV system installation budget.

The powering of heat rejection system is mandatory in all cases. A solar assisted air conditioner (AC) has also been installed in the solar cooling research center for testing purposes. The rated electrical power consumption of the system was 1.1kW. Powering up this solar assisted AC has been considered as an option.

Even though the energy generation in a single day is not enough to operate the 1TR cooling system, storing the balanced energy for consecutive days will able to operate 1TR system for a day. Thus operating 1TR system in cyclic pattern with large battery bank capacity has been considered as another option of operation. Third option of operation was to run the both the above equipments alternately.

In addition, 4 no of solar control stations have also been installing in solar cooling facility for the purpose of characterization and solar collector system for 10TR cooling system operations. Powering up all these control stations was selected as the fourth option.

<table>
<thead>
<tr>
<th>Option Tag</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Operating heat rejection system and 1.1kW Solar assisted AC system for PV testing facility.</td>
</tr>
<tr>
<td>B</td>
<td>Operating heat rejection system and the 1TR absorption cooling system cyclic days by capturing energy of consecutive days</td>
</tr>
<tr>
<td>C</td>
<td>Operating options A &amp; B alternatively</td>
</tr>
<tr>
<td>D</td>
<td>Operating heat rejection system and all solar control stations of CSEM-UAE solar cooling research center.</td>
</tr>
</tbody>
</table>

Table 6-15: Options available for PV power utilization

Main parameters of the PV system requirement for each option considered have been calculated to do investment cost estimation.
<table>
<thead>
<tr>
<th>Option</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Demand (VA)</td>
<td>2100</td>
<td>4800</td>
<td>4800</td>
<td>1500</td>
</tr>
<tr>
<td>Cooling system electrical demand (W)</td>
<td>1100</td>
<td>0</td>
<td>1100</td>
<td>0</td>
</tr>
<tr>
<td>Equipments electrical demand (W)</td>
<td>400</td>
<td>3200</td>
<td>3200</td>
<td>1500</td>
</tr>
<tr>
<td>AC energy demand (kWh)</td>
<td>5.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Equipment energy demand (kWh)</td>
<td>2.8</td>
<td>2.8+18.2</td>
<td>0</td>
<td>8.3</td>
</tr>
<tr>
<td>Total energy demand (kWh)</td>
<td>8.3</td>
<td>21</td>
<td>0</td>
<td>8.3</td>
</tr>
<tr>
<td>Energy should stored (kWh)</td>
<td>2.2</td>
<td>15.4</td>
<td>0</td>
<td>2.2</td>
</tr>
<tr>
<td>Battery bank size (Ah)</td>
<td>400</td>
<td>1400</td>
<td>1400</td>
<td>400</td>
</tr>
<tr>
<td>Inverter capacity (VA)</td>
<td>2500</td>
<td>4800</td>
<td>4800</td>
<td>4800</td>
</tr>
</tbody>
</table>

Table 6-16: Calculated PV system parameters for four options considered

| COST                                                                 |
|---------------------------------------------------------------------|-------|-------|-------|-------|
| Option                  | A     | B     | C     | D     |
| Battery Lead Acid       | 1200  | 2400  | 2400  | 1200  |
| Inverter                | 900   | 1100  | 1100  | 1100  |
| Charge Controller       | 500   | 500   | 500   | 500   |
| Installation and other accessories | 520   | 720   | 720   | 690   |
| Total                   | 3120  | 4720  | 4720  | 4490  |

Table 6-17: Investment cost for each option

According to the results in Table 6-17, CSEM-UAE management has decided to go with the option D for installation. Thus all of their solar charge controllers can be run using solar PV power which is their major requirement.

A PV system has been designed according to the selected requirement so that it reduces the installation cost and losses. The single line diagram of the PV system is in annexure 10.4.
7. IMPLEMENTATION AND TESTING

After completing the designs of heat rejection system and PV system, next phase was the implementation and testing. Since, the CSEM-UAE Innovation center is a subsidiary of a governmental body, general ordering and purchasing procedure has been practiced for the component procurement. Furthermore, all the installation and testing work has been executed solely by the researcher as part of the thesis without the involvement of any subcontractors or technical support.

7.1. Heat rejection unit

Heat rejection unit has been installed by breaking the return hot water line of the collector cycle. The three port motorized valve has maximum operating temperature of 110°C. While in operation, the collector temperature may rise more than 110 °C. Therefore, the flow diversion method is used such that 3 port valve is not exposed to its maximum temperature. By using slotted angle iron bars, a support structure has been made to mount the radiator, fan & motor. Figure 7-1 shows the completed installation of the heat rejection unit.

![Figure 7-1: Installed heat rejection unit](image)

![Figure 7-2: Temperature and Flow sensor positions](image)
A fair amount of wind is usually available during the noon time. It is validated from the analysis of the weather data available at the CSEM-UAE research center. As such, optimum wind direction for 2 hours early and after the noon time has been identified. In accordance with the optimum direction of wind, the orientation of the radiator is fixed on the support structure, so that natural wind flow dominates on the radiator operation.

Control unit of the solar heat collector and heat rejection system is installed inside the shelter area closer to the solar collector circulation pump. Temperature and flow sensors have been placed as shown in the Figure 7-2 and connected to the controller.

7.2. Photovoltaic system

CSEM-UAE Innovation center received 2.1kW capacity thin film photovoltaic modules from Flexcell, Switzerland for the installation and testing purposes. CSEM-UAE has decided allocate these modules for solar PV installation. Additional components required to implement the PV system according to the desired operating condition and design, were procured from local companies.

The Flexcell solar PV modules is thin film type and larger than conventional PV modules. It requires a metallic roof structure for the mounting and support. A 50m² has been constructed to the existing solar cooling research center for PV module mounting. The installed modules have been connected two in series and wired to the PV combiner box separately. All the incoming PV strings have been connected together by using DC circuit breaker, DC fuse and a diode for each string. The combined output is feed to the charge controller which will regulate the charging voltage of the battery bank such that the PV modules operate at maximum power point. A single phase inverter is connected to the battery bank to generate the stored DC energy in to 230VAC power.

The PV system design and its installation have been conducted according the National Electrical code for Photovoltaic systems of USA.

The PV combiner box, battery bank and inverter have been installed inside the solar cooling research cabin. Figure 7-3 and Figure 7-4 shows the complete PV system installation and Figure 7-5 shows modified electrical panel board for synchronizing the grid and PV power.
The 230Vac power generated by the inverter is fed in to the existing power panel board and installed a change over switch for power source selection.

The installed PV system installation has been commissioned and operated successfully from 2nd of October 2011.
8. RESULT AND DISCUSSION

After completing the installation continuous tests has been carried out for couple of days and logged the data. Figure 8-1 shows the recorded graph of the heat rejection system.

Key control parameters of the control system are collector temperature (T₁ <110°C) and the tank temperature (T₂ <90°C). During the first two days of operation the maximum collector temperature was set to 110°C, maximum tank temperature was set for 88°C and tank temperature sensor was placed to the top of the tank. Thus, the anti-stagnation control parameters limited to small band. This makes high frequent operation cycles creating non stable system.

In order to increase the anti-stagnation operation band, the tank temperature sensor was placed on the bottom of the tank and the maximum tank temperature was set to 76°C. This gives ability to set anti-stagnation operation in between 98°C starting and 84°C stopping. This large span temperature setting increases the operating cycle period and increase the stability of the system.

The last two days operation shows the modified control technique. The collector temperature never crossed the 100°C limit and tank bottom temperature could be maintained steadily at 76°C, consequently help maintained tank top temperature around 90°C. The temperature profile of 5th of October 2011 has shown in Figure 8-2.

During the night time period bottom tank temperature drops by 20°C because of thermal loss of the tank and temperature stabilization in the tank. The solar collector cycle charge the storage tank until 13:00 to increase the T₂ to 76°C set temperature. There exists 2-5°C temperature drop (T₁-T₃) due to heat losses in pipes during charging.

When T₂ reach set temperature the pump P₁ stops. Then T₁ starts to rise slowly due to continuous heat collection of collectors. As T₁ crosses the anti-stagnation starting temperature 98°C both pump P1 and output 3 activates. Output 3 will powered the motorized valve and radiator fan. The output 3 and P1 will stop when T₁ drops to 84°C. Again T₁ starts to increase and wait until 98°C to start anti-stagnation operation. During the operation of anti-stagnation, the temperature difference across radiator unit is
maintaining 10-20°C. This verifies the heat rejection system thermal calculation. Switch on period of output 3 is changing depending on the available solar radiation. If the solar radiation is high the heat rejection system will operate for longer time and vice versa.

One of the major objectives of the project was to design and implement a heat rejection system which is economically sound. According to the results, the temperature difference of the radiator reaches 20°C which shows better performance than the design condition. This over performance is due to the utilization of the natural wind available to assist the heat rejection. Also the radiator system is capable of rejecting the heat before the collector temperature reaches its maximum at 110°C provided that tank temperature is maintained at required set value. The temperature fluctuation of the tank temperature was only 2°C.

The automobile radiators consist of pressure regulated and air release cap on its top side, which is also used for refilling purpose in case of its application in automobile. The cap is designed to release the pressure in the system once it reaches 1.5bar. The cap is not suitable for the proposed application where pressure may go beyond 2 bar in the solar collector circuit. Also, it is experienced that the sealing of the cap is difficult with operating pressure over 2 bar. Therefore, it is recommended to use Cu or Brass cover radiators so that top water filling cap can be brazed and sealed. These types of radiators are available in the market for heavy duty vehicles.

Figure 8-2: Temperature profile of 5th October 2011
9. **CONCLUSION**

Once of the main objective of the project was to analyze possibility of using automobile radiator as heat rejection units in solar thermal systems. According to the results obtained, the use of automobile radiator is successful.

In literatures, the mathematical models of PV with two diode model are usually discussed but single diode model is practiced for modeling and simulation due to complexity in parameter calculation. By using the integration method for initial condition evaluation and Matlab simulink fsolve function to calculate the actual parameters for each mode, two diode model methods has been successfully developed and executed. The simulation results are matching the manufacturer’s graphs and measured outputs in the UAE weather conditions.

Solar incident radiation calculation model on inclined surfaces give more flexibility to analyze the performance of PV modules with custom weather data available. This gives the same flexibility as professional PV software and possibility of using custom weather data in the analysis for higher accurate results.

The dust deposition on the PV modules is affecting the power generation severely than expected. It is experienced the performance can decrease by 50% in six months period if PV panels are not cleaned. Thus, the cleaning of PV modules is very important part of the PV system designs in UAE environments. A proper cleaning mechanism or maintenance plan at least once a month is recommended. It is very important to carry out research activities in dust deposition reduction methods for optimum utilization of resources. It was experienced that cleaning of dust collected on the PV modules on the installed thin film PV modules installed at CSEM-UAE solar cooling center is easier with simple water jet cleaning. This has removed about 90% of the deposited dust. The other PV module that usually consists of conventional glazing cover gives more resistance to removing the dust. Usually, it requires rubbing using a cloth or brush. It is experienced that the overall performance of the thin film PV will be higher even though the transmittance of such material is lower than conventional glass covers.

The effect on performance due to dust collection has also been included in the developed model that results in more accurate values during design and practical installations. Since the impact due to dust is higher, the actual values and simulated performance may vary in higher ratios.

In the case of technology of the PV modules, the optimum efficient technology available is Mono-crystalline type PV modules for the considered application of 1TR and 10TR solar cooling center power requirements. This higher economical viability of the Mono-crystalline modules is achieved due to the recent price reductions of these modules compared to thin film modules. Even though the thin film modules are cheaper compared to crystalline panels, structure cost is higher due to large space utilization. Thus the cost of overall project have to analyzed during feasibility studies rather than just considering the $/W value of PV modules in selecting PV module technology for installations.
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[20]. J.M Pinazo, J Canada and F Argo from department of applied thermodynamic of Universidad Politecnica de Valencina in Spain
[23]. Estimating solar radiation on tilted surfaces with various orientations: a study case in Karaj by Gh. A. Kamali, I. Moradi, A Khalili
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10. ANNEXURE

10.1. Annexure I: Heat load calculation of evacuated type solar thermal collectors using EES.

\[ G = 1000 \text{ [W/m}^2\text{]} \]
\[ T_a = 30 \text{ [C]} \]
\[ T_{in} = 95 \text{ [C]} \]
\[ T_m = (T_{in} + T_{out})/2 \]
\[ n = 12 \]
\[ A_{ap} = 3.008 \text{ [m}^2\text{]} \]
\[ A = n \times A_{ap} \]
\[ P_c = 202.6 \text{ [k.Pa]} \]
\[ V_{dot} = 20/60/1000 \text{ [m}^3\text{/s]} \]
\[ \eta_0 = 0.73 \]
\[ a_1 = 1.5 \]
\[ a_2 = 0.0058 \]
\[ \rho = \text{Density(Water,} T=T_m, P=P_c) \]
\[ m_{dot} = V_{dot} \times \rho \]
\[ C_p = \text{Cp(Water,} T=T_m, P=P_c) \]
\[ \eta = \eta_0 - a_1 \times X - a_2 \times G \times X^2 \]
\[ X = (T_m - T_a)/G \]
\[ Q_{dot} = A \times G \times \eta \]
\[ Q_{dot} = m_{dot} \times C_p \times 1000 \times (T_{out} - T_{in}) \]
### Radiator Operating Conditions

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
<th>Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant Volumetric Flow ( \left( v_{\text{cn}} \right) )</td>
<td>30</td>
<td>m$^3$/s</td>
<td>Use FPS value</td>
</tr>
<tr>
<td></td>
<td>0.0003333</td>
<td>gpm</td>
<td>Use SI value</td>
</tr>
<tr>
<td>Air Volumetric Flow ( \left( v_{\text{an}} \right) )</td>
<td>2349</td>
<td>m$^3$/minute</td>
<td>Use FPS value</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>s</td>
<td>Use SI value</td>
</tr>
<tr>
<td>Air Velocity ( \left( v_{\text{an}} \right) )</td>
<td>10</td>
<td>m/s</td>
<td>Use FPS value</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>h</td>
<td>Use SI value</td>
</tr>
<tr>
<td>Heat Transfer Performance ( \left( q_{\text{cor}} \right) )</td>
<td>4025</td>
<td>Btu/minute</td>
<td>Use FPS value</td>
</tr>
<tr>
<td></td>
<td>70729.3</td>
<td>J/s</td>
<td>Use SI value</td>
</tr>
</tbody>
</table>

Figure 10-1: Components within an automobile cooling system
<table>
<thead>
<tr>
<th>Proposed Radiator Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Radiator length</strong> $(rL_{\text{new}})$:</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Radiator width</strong> $(rW_{\text{new}})$:</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Radiator height</strong> $(rH_{\text{new}})$:</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Tube width</strong> $(tW_{\text{new}})$:</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Tube height</strong> $(tH_{\text{new}})$:</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Tube pitch</strong> $(tP_{\text{new}})$:</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Fin width</strong> $(fW_{\text{new}})$:</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Fin height</strong> $(fH_{\text{new}})$:</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Fin thickness</strong> $(fT_{\text{new}})$:</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Distance Between Fins</strong> $(fD_{\text{new}})$:</td>
</tr>
</tbody>
</table>
Louver length \((l_{l^t_{new}})\): 
- 0.0419291 \(\text{ft}\) 
- 0.01278 \(\text{m}\)

Louver height \((lH_{l^t_{new}})\): 
- 0.0853018 \(\text{ft}\) 
- 0.026 \(\text{m}\)

Louver pitch \((lP_{l^t_{new}})\): 
- 0.00485564 \(\text{ft}\) 
- 0.00148 \(\text{m}\)

Louver angle \((l\theta_{l^t_{new}})\): 
- 28°

Number of tubes \((ntube_{l^t_{new}})\): 
- 73

Coolant and Air Property Tables

The thermal fluid properties for the coolant and air are listed in the following two tables.

**Coolant Properties: 50-50 Glycol-Water**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity ((k_c))</td>
<td>0.239943</td>
<td>(\text{W/m}\cdot\text{K})</td>
</tr>
<tr>
<td>Specific Heat ((C_c))</td>
<td>0.880019</td>
<td>(\text{J/kg}\cdot\text{K})</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity ((k_c))</td>
<td>0.415</td>
<td>(\text{Btu/\text{h}\cdot\text{ft}\cdot\text{deg}\text{F}})</td>
</tr>
<tr>
<td>Specific Heat ((C_c))</td>
<td>3682</td>
<td>(\text{Btu/\text{lb}\cdot\text{deg}\text{F}})</td>
</tr>
</tbody>
</table>

Use FPS value: ☑️
Use SI value: ☐

- Use FPS value: ☑️
- Use SI value: ☐
Heat Transfer Performance of Proposed Radiator Assembly

The $\varepsilon$-Ntu (effectiveness-Ntu) method is used to predict the heat transfer performance of our new system.
The more common equations that are typically used in heat exchange design are listed below.

## Heat Exchange Equations:

**HeatTransferEquation** := \( q = \varepsilon \cdot C_{min} \cdot \Delta T_D \)

**UniversalHeatTransferEquation** := \( \frac{1}{UA} = \frac{1}{h_c \cdot A_c} + \frac{1}{n f a \cdot A_a} \)

**ReynoldsEquation** := **ReynoldsNum**

\[
= \left( \frac{\rho \cdot v \cdot D_H}{\mu} \right)
\]

**HydraulicDiameter** := \( D_H = \frac{4 \cdot A_{min}}{W_{P}} \)

**DittusBoelterEquation**

\[
:= NusseltNum_{Turbulent} = 0.683 
\cdot ReynoldsNum^{0.466} 
\cdot PrandtlNum^{\frac{1}{3}}
\]

**NusseltNumTransient** = 0.116

\[
= \left( \frac{ReynoldsNum^{\frac{2}{3}} - 125}{PrandtlNum^{\frac{1}{3}} \cdot f_0^{0.146}} \right) \left( \frac{d}{L} \right)^{\frac{2}{3}} + 1
\]

**Yunus** := **NusseltNumLaminar** = 4.36

## Definitions:

The rate of conductive heat transfer

The overall thermal resistance present in the system

A dimensionless modulus that represents fluid flow conditions

Parameter used to equate any flow geometry to that of a round pipe

An equation used to calculate the surface coefficient of heat transfer for fluids in turbulent flow

F - Fin ; T - Tube ; L - Louver ;

p - pitch ; l - length ; d - depth
A dimensionless modulus that relates fluid viscosity to the thermal conductivity, a low number indicates high convection.

\[
\text{ColburnFactor} = \text{ReynoldsNum}^{-0.59} \left( \frac{\theta}{90} \right)^{0.27} \cdot \left( \frac{F_L}{L_p} \right)^{-0.14} \cdot \left( \frac{F_t}{L_p} \right)^{-0.29} \cdot \left( \frac{T_d}{L_p} \right)^{-0.23} \cdot \left( \frac{L_t}{L_p} \right)^{0.68} \cdot \left( \frac{T_p}{L_p} \right)^{-0.28} \cdot \left( \frac{\delta_t}{L_p} \right)^{-0.05}
\]

\[
\text{HeatTransferAirSide} := \text{ColburnFactor} = \frac{n_{ha}}{\rho \cdot v \cdot C_p} \cdot \text{PrandtlNum}^{\frac{2}{3}}
\]

\[
\text{PrandtlNum} := \frac{C \cdot \mu}{k}
\]

A dimensionless modulus that relates surface convection heat transfer to fluid conduction heat transfer.

\[
\text{NusseltNum} := \frac{h \cdot c \cdot D_h}{k}
\]

A dimensionless modulus that defines the number of transferred units.

\[
\text{Nu} := \text{Nu} = \frac{UA}{C_{min}}
\]

\[
\text{eNu} := \epsilon = 1 - e^{-\frac{C_{max}}{C_{min}}} \cdot \left( 1 - e^{-\text{Cratio} \cdot \text{Nu}} \right)
\]

A mathematical expression of heat exchange effectiveness vs. the number of heat transfer units.

\[
\text{ITD} := \text{ITD} = \text{CoolantTemperature} - \text{AirTemperature}
\]

Measure of the initial temperature difference.
First calculate the overall heat transfer coefficient $UA_{\text{new}}$ of the smaller radiator before we can determine it's heat transfer performance.

Solve for $UA_{\text{new}}$

The Universal Heat Transfer Equation is defined in (1)

$$\frac{1}{UA} = \frac{1}{hc Ac} + \frac{1}{nfha Aa}$$

The next several steps will take us through the process for solving for the unknown values of $Ac, Aa, hc$ and $nfha$

Solve for $Ac_{\text{new}}$ & $Aa_{\text{new}}$

$$CoolantSurfaceArea := Ac = \text{NumberOfTubes} \cdot (2 \cdot (\text{TubeHeight} \cdot \text{RadiatorLength}) + 2 \cdot (\text{TubeWidth} \cdot \text{RadiatorLength})) :$$

$$AirSurfaceArea := Aa = \text{TotalNumberOfAirPassages} \cdot (2 \cdot (\text{FinDistance} \cdot \text{FinHeight}) + 2 \cdot (\text{FinHeight} \cdot \text{FinWidth})) :$$

where

$$\text{TotNumAirPassages} := \text{TotalNumberofAirPassages}$$

$$= \text{NumRowsOfFins} \cdot \left( \frac{\text{RadiatorLength}}{\text{FinDistance}} \right) :$$

Figure 10-2: Expanded view of tubes

Figure 10-3: Expanded view of fins

Solving the unknown values leads to the following values for the $Total\text{NumberOfAirPassages}$, $Ac$, and $Aa$, and
Solve for $hc$

The value of $hc$ depends on the physical and thermal fluid properties, fluid velocity and fluid geometry.

The *ReynoldsEquation* defined below can be used to determine the flow characteristics of the coolant as it passes through the tubes.

$$ReynoldsEquation$$

$$ReynoldsNum = \frac{\rho \nu D_H}{\mu}$$

The value $D_H$ is found from the *HydraulicDiameter* equation:

$$HydraulicDiameter$$

$$D_H = \frac{4 A_{min}}{WP}$$

where

$$A_{min} := simplify(iW_{new} \cdot iH_{new})$$
The velocity of the coolant as it flows through the tubes is:

\[ v_c := \text{simplify} \left( \frac{v_{en}}{n_{tube_{new}} \cdot A_{min_c}} \right) \]

\[ v_c = 0.117071 \left[ \frac{m}{s} \right] \]

ReynoldsNum := simplify(solve(subs([D_H = D_{He}, \nu = v_c, \rho = \rho_c, \mu = \mu_c], ReynoldsEquation), ReynoldsNum))

\[ ReynoldsNum_c := 452.397 \]

Yunus

\[ NusseltNumLaminar = 4.36 \]

PrandtlEquation

\[ PrandtlNum = \frac{C \mu}{k} \]

NusseltEquation

\[ NusseltNum = \frac{hc D_H}{k} \]

PrandtlNum_c := simplify(solve(subs([C = C_c, \mu = \mu_c, k = k_c], PrandtlEquation), PrandtlNum))

\[ PrandtlNum_c = 6.60982 \]

NusseltNum_c := solve(Yunus)

\[ NusseltNum_c = 4.36000 \]

Knowing the NusseltNumber we can now solve for \( h_{c_{new}} \)

\[ h_{c_{new}} := \text{simplify} \left( \text{solve} \left( \left\{ k = k_c, D_H = D_{He}, NusseltNum = NusseltNum_c \right\}, h_c \right) \right) \]
Determine \( nfha_{new} \)

Solve for \( ha_{new} \) in a similar manner as we did for \( hc_{new} \) (by determining the ReynoldsNum for air)

\[
\begin{align*}
A_{min, a} &:= \text{simplify}(fH_{new} \cdot fD_{new}) \\
0.00009690 \, [m^2] \\
WP_a &:= 2 \cdot \text{simplify}(fD_{new} + fH_{new}) \\
0.01928 \, [m] \\
D_{Ha} &:= \text{simplify}\left(\text{solve}\left(\left[ A_{min} = A_{min, a}, \text{WP} = WP_a \right], \text{HydraulicDiameter}, D_{Ha}\right)\right) \\
0.00201037 \, [m] \\
ReynoldsNum_{a} &:= \text{simplify}\left(\text{solve}\left(\left[ D_{Ha} = D_{Ha}, \nu = \nu_{an}, \rho = \rho_a, \mu = \mu_a \right], \text{ReynoldsEquation}, ReynoldsNum\right)\right) \\
119.656
\end{align*}
\]

The ReynoldsNum for air indicates that the air flow is laminar (that is, \( ReynoldsNum_{a} < 2100 \) -- LaminarFlow). As a result, cannot use the DittusBoelterEquation to relate the ReynoldsNum to the NusseltNum and hence determine the value for \( ha_{new} \). Another approach to determining the value of \( ha_{new} \) is to solve for the value of \( ha_{cur} \) since the value of \( ha_{new} = ha_{cur} \). In the next section, we will show how the value of \( ha_{cur} \) is calculated by first obtaining the heat transfer coefficient for the original radiator \( (UA_{cur}) \).

ChangAndWangEquation

\[
\begin{align*}
\text{ColburnFactor} &= \left(0.296725 \theta^{0.27} \left(\frac{L_I}{L_p}\right)^{0.68}\right) / \\
&\left(\text{ReynoldsNum}^{0.59} \left(\frac{F_p}{L_p}\right)^{0.14} \left(\frac{F_I}{L_p}\right)^{0.29} \left(\frac{T_d}{L_p}\right)^{0.23} \left(\frac{T_p}{L_p}\right)^{0.28}ight) \\
&\left(\frac{\delta_I}{L_p}\right)^{0.05}
\end{align*}
\]
Solve for

The equation, which relates Number of Transferred Units \( (Ntu) \) to Universal Heat Transfer, will be used to determine the Universal Heat Transfer Coefficient \( (UA_{cur}) \) of the current model.

\[ Ntu = \frac{UA}{C_{min}} \]

\( C_{min} \) is obtained by comparing the thermal capacity rate \( (CR) \) for the coolant and air.

\[ CR = C \cdot mfr, \]

\[ mfr = FluidViscosity \cdot \rho; \]

\[ mfr = FluidViscosity \cdot \rho \]

The Mass Flow Rate for the coolant and air are:

\[ m_{f,c}^a := simplify(solve(subs([FluidViscosity = \rho_a, \rho = \rho_a], MassFlowRate, mfr))] \]

\[ 0.227600 \left[ \frac{kg}{s} \right] \]

\[ m_{f,c}^a := simplify(solve(subs([FluidViscosity = \rho_c, \rho = \rho_c], MassFlowRate, mfr))] \]
The Thermal Capacity Rates for the coolant and air are:

\[
CR_a := \text{solve}\left(\text{subs}\left(\left[mfr = mf_a, C = C_a\right], \text{ThermalCapacityRate}, CR\right)\right)
\]

\[
228.738 \left[ \frac{m^2 \text{ kg}}{s^3 \text{ K}} \right]
\]

\[
CR_c := \text{solve}\left(\text{subs}\left(\left[mfr = mf_c, C = C_c\right], \text{ThermalCapacityRate}, CR\right)\right)
\]

\[
1245.62 \left[ \frac{m^2 \text{ kg}}{s^3 \text{ K}} \right]
\]

Since \( CR_a < CR_c \):

\[
C_{\text{min\_new}} := CR_a, \quad C_{\text{max\_new}} := CR_c
\]

\[
228.738 \left[ \frac{m^2 \text{ kg}}{s^3 \text{ K}} \right]
\]

\[
1245.62 \left[ \frac{m^2 \text{ kg}}{s^3 \text{ K}} \right]
\]

and

\[
Cratio_{\text{new}} := \frac{CR_a}{CR_c}
\]

0.183634

Next, need to calculate the Number of Transfer Units \((N_{\text{Nu}})\) of the original radiator assembly. To do this we for \( ITD_{\text{cur}}, \varepsilon_{\text{cur}}\) and \( q_{\text{cur}}\) from the \(e_{\text{NuEquation}}\ \text{HeatTransferEquation}\), and \( ITDEquation\), respectively. \(ITDEquation\)

\[
ITD = \text{CoolantTemperature} - \text{AirTemperature}
\]

\[
ITD_{\text{value}} := \text{solve}\left(\text{evalf}(T_c - T_a)\right) = 80. \left[ \text{K} \right]
\]

Solve for \( q_{\text{new}}\)

Determine the heat transfer performance \((q_{\text{new}})\) of the new radiator assembly by using the \(\text{HeatTransferEquation}\):

\[
q = \varepsilon C_{\text{min ITD}}
\]
determine the value of $\varepsilon_{\text{new}}$ from the $\varepsilon_{\text{NuEquation}}$.

\[
\varepsilon_{\text{NuEquation}} = \frac{C_{\text{max}} \left(1 - \frac{\text{Cratio} \times \text{Nu}}{C_{\text{min}}}\right)}{C_{\text{min}}}
\]

$\varepsilon = 1 - \frac{\varepsilon_{\text{new}}}{C_{\text{min}}}$

The unknown value for $N_{\text{u,new}}$ can be determined using the $N_{\text{uEquation}}$:

\[
N_{\text{u}} = \frac{UA}{C_{\text{min}}}
\]

Finally the value of $UA_{\text{new}}$ can be determined from the $UniversalHeatTransferEquation$:

\[
\frac{1}{UA} = \frac{1}{hc \cdot Ac} + \frac{1}{n_{\text{ha}} \cdot Aa}
\]

Solving for $UA_{\text{new}}, N_{\text{u,new}},$ and $\varepsilon_{\text{new}}$ yields the following:

$$UA_{\text{new}} := \text{simplify}\left(\text{solve}\left(\{hc = hc_{\text{new}}, n_{\text{ha}} = n_{\text{ha,new}}, Aa = Aa_{\text{new}}, Ac = Ac_{\text{new}}\}, \text{UniversalHeatTransferEquation}, UA\right)\right)$$

$$1406.35 \text{ } \left[\frac{m^2 \cdot \text{kg}}{s^3 \cdot \text{K}}\right]$$

$$N_{\text{u,new}} := \text{solve}\left(\{UA = UA_{\text{new}}, C_{\text{min}} = C_{\text{min,new}}, N_{\text{uEquation}}\}, N_{\text{u}}\right)$$

$$6.14830$$

$$\varepsilon_{\text{new}} := \text{solve}\left(\{C_{\text{max}} = C_{\text{max,new}}, C_{\text{min}} = C_{\text{min,new}}, N_{\text{u,new}}, \text{Cratio} = \text{Cratio_{new}}\}, \varepsilon_{\text{NuEquation}}\right)$$

$$0.974898$$

The heat transfer performance $q_{\text{new}}$ of our smaller radiator design can be found by substituting the value of $\varepsilon_{\text{new}}$ and $C_{\text{min}}$ into the $HeatTransferEquation$:

$$q_{\text{new}} := \text{simplify}\left(\text{solve}\left(\{\varepsilon = \varepsilon_{\text{new}}, C_{\text{min}} = C_{\text{min,new}}\}, \text{HeatTransferEquation}, q\right)\right)$$

$$17839.7 \text{ } \left[\frac{J}{s}\right]$$
10.3. **Annexure III: Solar cooling center PV System single line diagram**