The Non-Tracking Solar Collectors for Solar Air Conditioning System using a Single Effect NH_3-H_2O Absorption Chiller

Dilawer Ali

A Thesis Submitted in Fulfillment of the Requirements for the Degree of Master of Science in Sustainable Energy Management
Prince of Songkla University
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I hereby certify that this work has not been accepted in substance for any degree and is not being currently submitted in candidature for any degree.

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ABSTRACT

The novel non-tracking solar collectors are used to operate 17.6 kW single effect NH_3-H_2O absorption chiller. This solar collector uses a wet metal-to-water contact which can increase the heat transfer capability and can operate efficiently under cloudy condition. The heating system is comprised of 10 solar collectors with total area of 38.4 m2. From the experiment, the outlet temperature of the solar collectors at 120 ºC can produce cool water of -3.2 ºC. The coefficient of performance (COP) of the absorption chiller was evaluated and found to be 0.40. A comparative performance analysis of the non-tracking solar collectors and commercially available non-concentrating assembly of evacuated tubes also made. The experimental results show the efficiencies based on gross area have no significant difference and the non-tracking solar collector yields higher temperature which is suitable for operating NH_3-H_2O absorption chiller for air-conditioning as well as refrigerating systems.

Keywords: Non-tracking solar collector, coefficient of performance, solar air-conditioning.

DEDICATION

This thesis is dedicated to my beloved parents and my schoolteacher.

ACKNOWLEDGEMENT

My deepest gratitude goes to Allah Almighty who has provided all that was needed to complete this project and the program for which it was undertaken.

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Dilawer Ali

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LIST OF ABBREVIATIONS

IEA	International energy agency
NTC	Non-tracking solar collectors
ETC	Evacuated tube solar collector
FPC	Flat plate collector
AHP	Absorption heat pump
DHW	Domestic heat water
GAX	Generator absorber exchanger
COP	Coefficient of performance
HTF	Heat transfer fluid
UA	Heat loss coefficient
η	Collector Efficiency
η_o	Efficiency without heat loss
a_1, a_2	Heat loss coefficient constants (W/m^2K)

C_p	Specific heat capacity (J/kg K)
M	Mass of the hot water tank (l)
Q_c	Heat abstracted from collector
$Q_{chiller}$	Heat abstracted from chiller
Q_{loss}	Heat loss in tank
Q_{load}	Heat abstracted due to load
T_i	Inlet temperature (ºC)
T_e	Outlet temperature (ºC)
T_a	Ambient temperature (ºC)
T_{sim}	Simulated temp of water tank (ºC)
T_{exp}	Experimental temp of water tank (ºC)
$\dot{m}$	Flow rate of heat transfer fluid (kg/s)

LIST OF APPENDICES

LIST OF PUBLICATIONS

1. Wattana Ratismith, **Dilawer Ali**, and John Briggs* . The semi-circular trough solar collector. Solar Energy (ISI Web of Science; IF 4.67) (Under Review)
2. **Dilawer Ali**, Shahida Batool, Montri Suklueng & Kuaanan Techato* (2019). GIS-MCDM approach to determine forest plantation areas in U-tapao river basin, Songkhla Thailand.. International Journal of Integrated Engineering (IJIE). (SCOPUS) (Accepted)
3. Ismail Kamdar, **Dilawer Ali**, Juntakan Taweekun*, Warangkana Jutidamrongphan & Kuaanan Techato (2019). A review study on municipal solid waste management and waste to energy technologies. International Journal of Integrated Engineering (IJIE). (SCOPUS) (Accepted)
4. **Dilawer Ali***, Fida Ali & Ismail Kamdar (2019). A review of efficient and economically viable self-starting Darrieus vertical axis wind turbines. Journal of Environmental Management and Energy System (JEMES). (Under Review)

CHAPTER 1

INTRODUCTION

1.1. Background

Rising environmental concerns subject to the excessive emissions of CO_2, has a direct nexus with conventional energy utilizations (Ali, Taweekun, Techato, Waewsak, & Gyawali, 2019) . Use of fossil fuels result in greenhouse gas emissions due to which world's concern towards use of fossil fuels are mounting day by day. In last two decades, growing anxiety and concerns over environmental pollution issue has served to focus attention towards use of environment friendly renewable energy sources. The pollution free and environment friendly green energy resources are available in abundance and can be utilized to produce energy (Trygg & Amiri, 2007).

Among renewable energies currently in use, solar energy is one of the most widely used energy resources and their contribution in total worlds energy consumption are increasing day by day. Solar thermal technologies dominate the solar energy market globally with the total installed capacity of 667 GWth in contrast to 227 GWth in photovoltaic by 2015 (Li et al., 2017). IEA (International Energy Agency) Solar Heating & Cooling Programme published report on global solar thermal capacity in operation and energy yielded by 2017 as shown in Fig. 1.1.

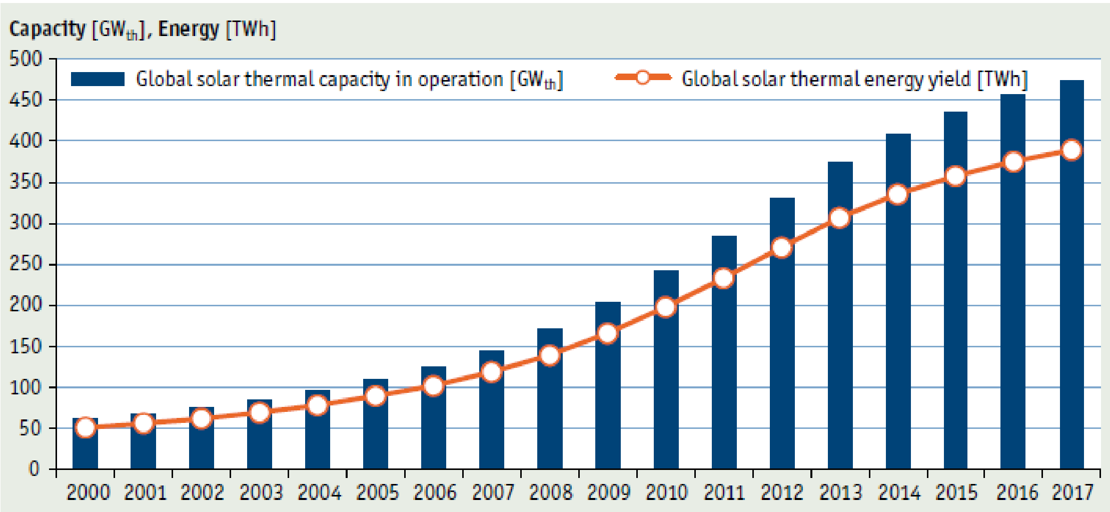


Fig. 1.1 Global solar thermal capacity in operation vs solar thermal energy yield by 2017 (Werner Weiss, 2018)

The exploitation of solar energy in building is one of the significant contributions for the reduction of fossil fuel consumption and hazardous emissions to the environment and can significantly reduce a severe growth in conventional energy utilization for cooling and related CO_2 emissions and can also contribute to meet the heating demands, i.e., domestic heat water (DHW), and solar air conditioning for commercial, industrial and office buildings (Mateus & Oliveira, 2009; Sultana, Morrison, & Rosengarten, 2012). The International Institute of Refrigeration stated that almost 15% of the world generated electricity is consumed by refrigeration and air conditioning systems (Kalkan, Young, & Celiktas, 2012). Air conditioning systems consume almost half (45%) of the total residential energy (Choudhury, Chatterjee, & Sarkar, 2010). The electrically driven compressor chillers used in refrigeration and air conditioning systems uses chloroflurocarbons (CFCs) and hydroflurocarbon (HFC) refrigerants cause the depletion of ozone layer at stratosphere (McCulloch, 2003). To avoid using such refrigerants, the usage of environment friendly refrigerants associated with renewable energy sources become important. An alternative solution to avoid hazardous refrigerants is to use solar energy as solar cooling is likely to reduce the greenhouse gas emission by using environmentally friendly refrigerants in air cooled absorption system and play a pivotal role in meeting the required energy demand (Aman, Ting, & Henshaw, 2014; Nkwetta & Smyth, 2012a, 2012c).

Researchers have studied and developed technologies to harness solar energy and are still investigating different techniques to enhance the collection and exploitation of solar energy (Wei, 2010). Effective collection and storage of solar energy are few challenges currently facing by researchers as solar radiation is available during daytime only, therefore it seems to be a daunting task to collect and store solar energy effectively during daylight hours. Currently, solar thermal collectors are used to capture solar radiation which is converted to thermal energy and then transferred to working fluid simultaneously (Singh, Kumar, Hasan, Khan, & Tiwari, 2013).

Considering the importance of solar collector in solar cooling system numerous compound parabolic troughs were considered and analyzed. In particular, solar collector troughs designed by (Ratismith, Inthongkhum, & Briggs, 2014) were investigated in detail focusing mainly the troughs shape and their power concentration factor. Extensive research in solar trough designing led to the formation of a novel non-tracking solar collector with the ability to capture solar intensity in sunny as well as cloudy conditions. Simple in design and lesser heat loss at higher temperature make non-tracking solar collector commercially competitive. As an application of the non-tracking concentrator, a modular system installed on the roof of an 8-storey building at Prince of Songkla University in HatYai, Thailand is connected to an NH_3-H_2O absorption chiller to operate an air conditioning unit. In this way we show that the non-tracking solar collector is capable of achieving required output temperatures and power necessary for residential and small scale industrial applications. Fig. 1.2 shows the monthly temperature detail of HatYai for a whole year.

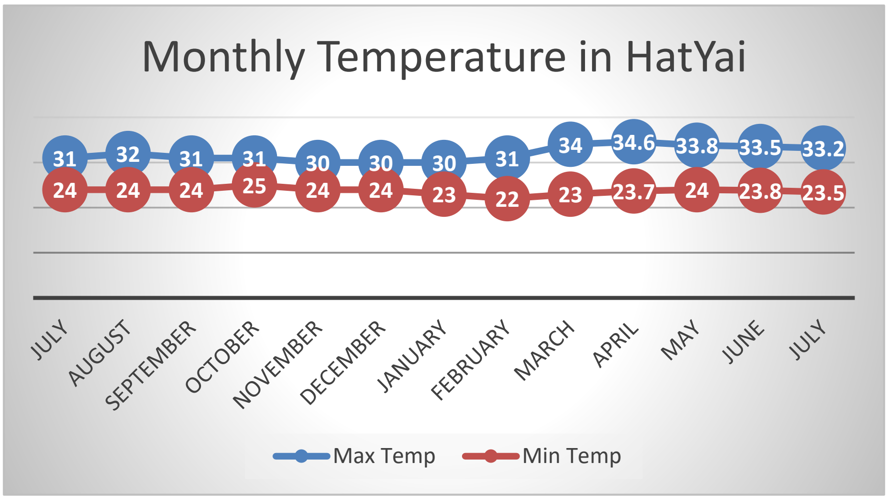


Fig. 1.2 Monthly temperature detail of HatYai from July 2018 to July 2019 (Source: Weather Atlas)

1.2. Statement of problem

Currently, the world is facing two vital problems in the form of energy scarcity and environment pollution (Ali et al., 2019). Energy demand for cooling is expected to increase rapidly over the century due to global warming with 1.1 °C – 6.4 °C rise in surface temperatures if emissions are not curbed. Conventional air conditioning and refrigerating systems are the main sources of energy consumption and CO_2 emissions in office and residential buildings. Air conditioning systems consume almost half (45%) of the total residential energy (Choudhury et al., 2010). The electrically driven compressor chillers used in refrigeration and air conditioning systems uses chlorofluorocarbons (CFCs) and hydrofluorocarbons' (HFC) refrigerants cause the depletion of ozone layer at stratosphere (McCulloch, 2003). Therefore, researches about sustainable energy utilization and environment friendly technologies are essential.

Solar collector is the most critical component of solar absorption system; thus, the selection of solar collectors plays an important role in driving sorption system. Many researchers have studied different types and applications of solar collectors (Kabeel, Dawood, & Shehata, 2017). Among solar thermal collectors evacuated tube solar collectors dominate the solar thermal collector technology with a global share of 71.6% followed by flat plate, glazed and unglazed collectors' share of 22.1%, 6.1% and 0.3% respectively. Flat plat collectors perform well at low temperature and provides maximum output only at mid-day, however evacuated tubes can track and capture solar radiation throughout the day due to its cylindrical shape and perform better in high temperature applications like air conditioning, building heating and refrigerating (Budihardjo, Morrison, & Behnia, 2003; Mangal, Lamba, Gupta, & Jhamb, 2010). Conduction and convection losses are higher in flat plat collectors compared to evacuated tube collectors since the absorber surface in evacuated tubes are enclosed by vacuum. However, evacuated tubes augmented with non-tracking solar collector have the potential to further reduce heat losses.

The newly design non-tracking solar collector driven sorption air conditioning and refrigerating systems combine the solar utilization and thermally driven refrigeration technologies which can be good solutions to curb energy crisis and environment pollution.

1.3. Research objectives

The objectives of our study have been described below;

1. To test the performance of newly designed non-tracking solar collector by comparing it with the commercially available non-concentrated evacuated tube solar collectors.

2. To test the performance non-tracking solar collectors for solar air conditioning system.
3. To analyze data from the experimental result.

1.4. Research questions

This study seeks an answer to the following questions.

1. Thailand has diffused light up to 60%. Can NTC receive diffused light efficiently?
2. Single effect NH3 H2O absorption chiller require temperature from 80- 120 ºC. Can NTC operate this chiller?
3. Using NTC, can NH3-H2O absorption chiller attain temperature below 0 ºC?
4. Is the newly designed non-tracking solar collector effective suitable to use for solar air conditioning system?

1.5 Research significance

The aim of our study is to utilize the newly designed non-tracking solar collectors in solar cooling and heating applications like; air conditioning and refrigerating systems, preheating systems in factories, etc.

The newly designed concentrator can operate in both clear and cloudy conditions. This dual feature of the concentrator become significant to utilize in tropical regions where most of the solar radiation is diffused in cloudy conditions, for example in Thailand almost 60% of the solar irradiation is diffuse in humid and cloudy conditions. More importantly, capturing solar radiation from different directions is possible without tracking due to specially designed trough which can give a large acceptance angle. Evacuated tube augmented with the concentrator can produce temperature higher than non-concentrating collectors due to the concentration of solar flux incident on the absorber (Nkwetta & Smyth, 2012b). Moreover, reduction in the number of evacuated tubes needed to gain higher temperature as well as reduction in greenhouse gases are both economically and environmentally attractive.

1.6. Research scopes

The present study is focused on the utilization of the newly designed non-tracking solar collectors in solar cooling and heating applications like; air conditioning and refrigerating systems, preheating systems in factories, etc. The experiment was performed at the Solar Energy Research Unit at Prince of Songkla University, HatYai using NH_3-H_2O absorption chiller augmented with 10 non-tracking solar collectors. The experimental data is then proven by numerical analysis validating the authenticity of the results.

CHAPTER 2

LITERATURE REVIEWS

Renewable energies exploitation such as solar cooling may extinct CO_2 emissions significantly, which are the basis for global warming (Nkwetta & Smyth, 2012c). The advanced research in solar technology has led to the possible use of solar energy as the main heat input for cooling system, thus providing various prospects to study different cooling technologies by using simulation approaches as well as experimental analysis.

2.1 Solar collectors and their types

Many researcher have studied different types and applications of solar collectors as the importance of solar collector in solar cooling is indispensable (Kabeel et al., 2017). Among solar thermal collectors evacuated tube solar collectors dominate the solar thermal collector technology with a global share of 71.6% followed by flat plate, glazed and unglazed collectors' share of 22.1%, 6.1% and 0.3% respectively (Werner Weiss, 2018). Flat plate collectors (FPCs) perform well at low temperatures which limit their applications to domestic water heating and space heating (Ghoneim). Lower cost as well as heat loss compared to conventional FPCs make evacuated tube solar collectors applicable for domestic as well as industrial purpose (Kalogirou, 2003; Schmid, Collins, & Mannik, 2006). Ayompe et.al (Ayompe, Duffy, Mc Keever, Conlon, & McCormack, 2011) analyzed the performance of solar heater with FPCs and heat pipe evacuated tube collectors (ETCs) considering solar insolation, heat energy, solar fractions and collector and system efficiencies and concluded that the heat pipe ETCs performed better as compared to FPCs. According to Sabiha et.al. (Sabiha, Saidur, Mekhilef, & Mahian, 2015), ETCs can capture both direct and diffused radiations, likewise ETCs can be easily installed and is transportable as well. ETCs perform better as compare to FPCs in high temperature applications like air-conditioning, building heating and refrigeration (Budihardjo et al., 2003). FPCs provide maximum energy output only at mid-day, however ETCs have the ability to track and capture solar radiation throughout the day due to its cylindrical shape (Mangal et al., 2010). Additionally, the maintenance of an ETC is simple and cheap. For ETCs, if tube is damaged, then it is possible to replace it with a new one without shutting down the whole system, however, in case of FPC, to replace the damaged collector the whole system needs to be shut down, demanding higher maintenance and cost as compared to ETCs.

Evacuated tube solar collectors can be used to operate medium temperature applications likewise single effect (75-90 ℃) and double effect (90-120 ℃) absorption refrigeration system, however these operational temperature ranges are unfavorable and uneconomical (Nkwetta & Smyth, 2012b). The combined use of compound parabolic concentrators and evacuated tube solar collectors assist in gaining medium temperature used for solar cooling, however using non-tracking low concentrated evacuated tube heat pipe solar collectors improve their efficiency and make them operational for solar heating and medium to high temperature applications (Nkwetta & Smyth, 2012a, 2012c).

2.2 Absorption Chiller

One of the most widely used applications of solar energy is the thermally driven sorption cooling comprises of both adsorption and absorption. Adsorption is the process during which solid is used for adhering ions and molecules of another substance onto its surface while in absorption, a substance is absorbed into another substance of a different phase (Deng, Wang, & Han, 2011) In sorption cooling, thermally driven compressor is used instead of electrically driven mechanical compressor.

2.3 Absorption Working Fluids

In absorption cycle, a refrigerant and an absorbent operate parallelly. Lithium bromide-water (LiBr-H_2O) and NH_3-H_2O are the most commonly used absorption working fluids (Al-Zubaydi, 2011; Herold, Radermacher, & Klein, 2016), with the former being more widely used when temperature around 5 to 10 ℃ are required, while the latter is mostly used when the evaporation temperature below 0 ℃ is required such as small size air conditioning and industrial applications (Abdulateef, Sopian, & Alghoul, 2008). Although Lithium bromide-water is widely used absorption working fluid due to its higher efficiency, however there are several critical limitations that restrain its use in residential scale applications.

Lithium-bromide-water absorption heat pump (AHP) uses water as a refrigerant, thus it cannot operate at an evaporation temperature below 0 ℃ as the freezing point of the water is 0 ℃ which hamper its use in subfreezing refrigeration (Karamangil, Coskun, Kaynakli, & Yamankaradeniz, 2010; Muthu, Saravanan, & Renganarayanan, 2008) as well as domestic hot water supplementation in cold regions. Maintenance of high vacuum condition is a challenging task for the LiBr-H_2O system to be work efficiently otherwise its efficiency would be degraded to large extent (Yan, Shi, & Tian, 2010). Crystallization is another common issue in Lithium bromide-water solution and is formed when the absorption temperature is high, or evaporation temperature is relatively low which render it unsuitable for air cooled applications (Izquierdo, Venegas, Rodríguez, & Lecuona, 2004; K. Wang, Abdelaziz, Kisari, & Vineyard, 2011).

2.4 NH_3-H_2O Absorption Chiller

Ammonia has the advantage of low freezing point (-77.7 ℃) which does not crystallize at low evaporating temperature, thus helps the condenser and the absorber units of absorption chiller to cool with direct air cooling (Aman et al., 2014). These factors render ammonia-based solution more suitable for implementation absorption heat pipe working fluids in situations involving subfreezing refrigeration, air cooled AHPs, and Domestic heating water (DHW), etc. Absence of crystallization and vacuum issues has also gained attention of the researchers (Wu, Wang, Shi, & Li, 2014). For many decades, the advancement in water-ammonia chillers halted due to the lower efficiency however in recent years, the employment of generator-absorber exchanger (GAX) concept has enhanced the efficiency of water-ammonia chillers. In GAX absorption cycle, the higher difference of ammonia concentration in rich and weak solution increases the efficiency of the chiller (R. Wang, Ge, Chen, Ma, & Xiong, 2009). The Robur Company of Italy for the first time introduced the GAX technology in a NH_3-H_2O absorption chiller with cooling capacity of 17.7 kW and a coefficient of performance (COP) of 0.71 (Häberle et al., 2007). High driving temperature is needed to operate GAX technology which can be consider as its drawback: 160 ℃ is required to reach a COP of 0.75 (Sabatelli, Fiorenza, & Marano, 2005). With same cooling capacity, the COP of an NH_3-H_2O cycle is lower as compared to LiBr-H_2O due to addition of rectifier and lower vaporization heat of ammonia (Gomri, 2010).

After a thorough literature review, it can be concluded that although NH_3-H_2O absorption chillers have low COP as compared to LiBr-H_2O chillers, however, the former requires low maintenance and absence of crystallization enables the former to achieve low cooling temperature. The addition of solar collectors with high energy collection rates will improve the COP of the NH_3-H_2O absorption chillers.

2.5 The Absorption Chiller's Working Principle

Single effect NH_3-H_2O absorption chiller is used in the experiment. The chiller has a cooling capacity of 17.6 kW with dimension (length = 1500 mm, width = 600 mm, height = 600 mm and weight = 0.7 Ton). Fig. 2.1 is a schematic flow diagram of the absorption chiller. The flow diagram illustrates heat exchanger components, pumps, pipes and valve devices. The cooling unit uses ammonia as a refrigerant and water as an absorbent. The concentrated ammonia solution is heated in the generator using the heat captured by solar collectors, ammonia evaporates and leaves a dilute solution in the generator (Aman et al., 2014). The high pressure ammonia vapor in generator is condensed to high pressure liquid ammonia in the condenser which is then passed through the throttle valve after reducing its pressure, where the low pressure ammonia evaporates in the evaporator and cooling effect occurs. From the evaporator the low pressure ammonia vapor is absorbed by dilute solution in the absorber and become concentrated water ammonia solution, where it is pumped back to the generator by the solution pump, after which the whole process keeps on repeating. During this whole process, a rectifier is used to purify the ammonia as ammonia vapor may contain water vapor which could form ice in the condenser as well as the water vapor may freeze in the pipeline and block the throttling valve (Raghuvanshi & Maheshwari, 2011). Additionally, the presence of water content in the evaporator results in rising the evaporating temperature, thus lower the cooling effect of the evaporator (Aman et al., 2014). It is important to be noted that in absorption chiller system, the part which utilizes power input is the pump, however the pump in chiller system use much lesser power as compared to compressor in a vapor compression cycle system (Cengel & Boles, 2002).

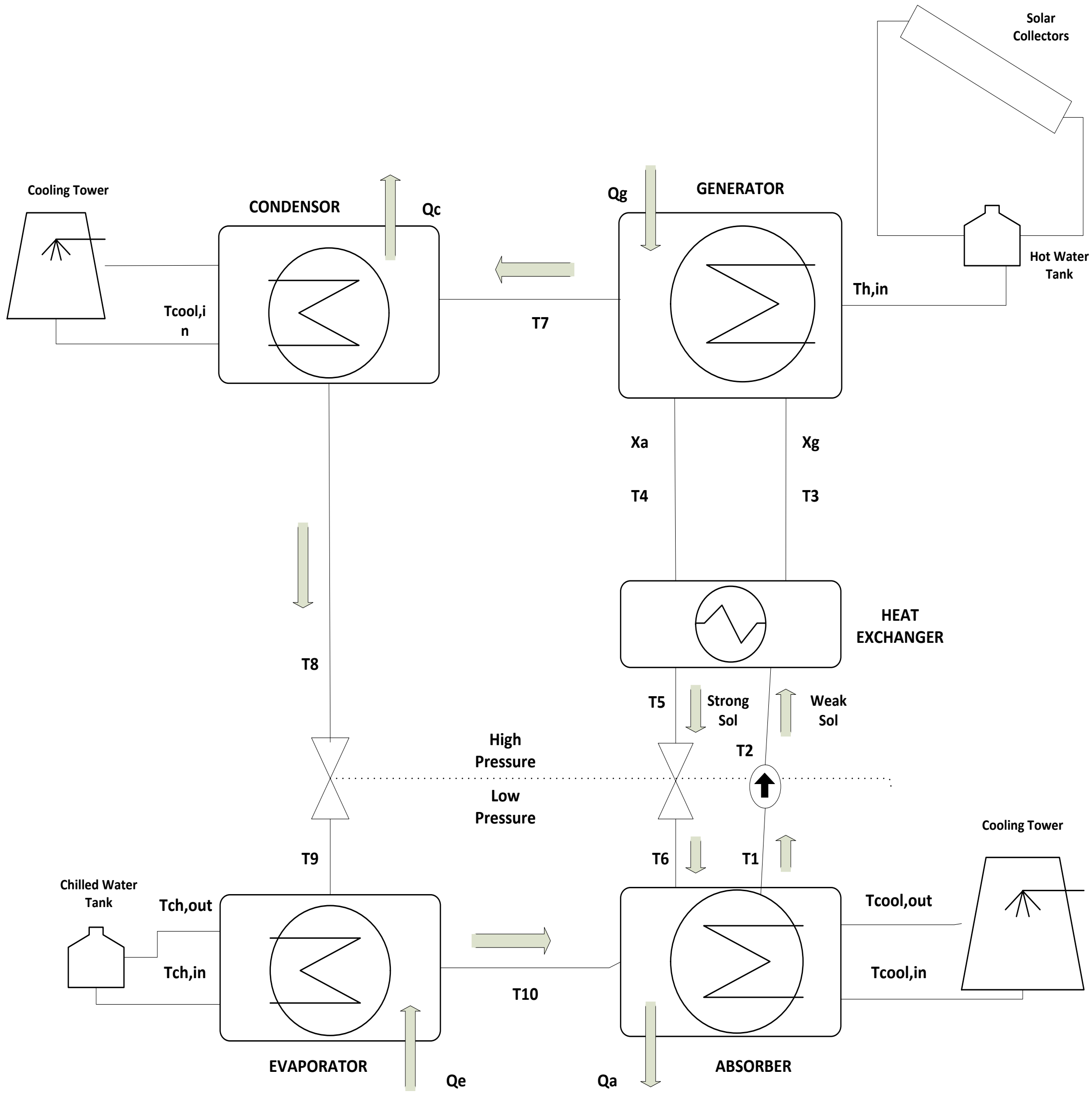


Fig. 2.1 illustrates the schematic diagram of the absorption chiller system and shows the inlet and outlet temperatures of different parts of chiller.

After a detail literature review of various solar collectors and absorption chiller systems, it can be concluded that the combined use of compound parabolic concentrators and evacuated tube solar collectors assist in gaining medium temperature used for solar cooling, however using non-tracking low concentrated evacuated tube heat pipe solar collectors improve their efficiency and make them operational for solar heating and medium to high temperature applications.

Among various absorption chillers, NH_3-H_2O absorption chillers have low COP as compared to LiBr-H_2O chillers, however, the former requires low maintenance and absence of crystallization enables the former to achieve low cooling temperature. The addition of solar collectors with high energy collection rates will improve the COP of the NH_3-H_2O absorption chillers.

In the next chapter , the research methodology is discussed in detail which highlights the instrumentation and measurements of testing configuration. The experimental setup of the solar cooling pilot plant installs at the roof top of 8-storey building at Faculty of Environmental Management is discussed.

CHAPTER 3

RESEARCH METHODOLOGY

This chapter includes the methodology used to carry out the research during experimentation. In first section, instrumentations and measurements of the testing configuration are discussed. In second section, the whole experimental setup of the solar power plant with detail measurement of different parts of the power plant is discussed.

3.1 Instrumentation and Measurements of Testing Configuration

The testing configuration is consisting of 3 modules (see Fig. 3.1(a) with 8 non-tracking concentrated collector tubes (NTC) and 8 and 16 non-concentrated evacuated tubes (ETC). NTC has a gross area of 3.837 m^2 while ETC has gross area of 2.11 m^2 and 4.13 m^2 for 8 and 16 tubes respectively. The concentrator assembly is directly connected with the working fluid (wet connection) flowing through manifold, thus increases the efficiency of heat transfer to the fluid. The performance of NTC is compared with both 8 tubes and 16 tubes of ETC as shown in Fig. 4.9 - 4.11.

Thermocouples with sensitivity of 41 µV/°C measures the inlet and outlet temperatures across the solar collectors and ambient temperature as well. The ambient temperature sensor was placed away from the direct solar radiation and heating system to avoid any heating effect. The pyranometer is used to measure the incoming solar irradiance during sunny and cloudy weathers. A pyranometer was fixed near solar collector with same inclination as that of collectors without any obstacles and shading.

Water is used as the heat transfer fluid (HTF) and 3-5 bar pressure is kept constant to avoid steam generation. Two flow meters are used to measure the fluid flow rate through the solar collectors, one flow meter is fixed at the inlet end of the non-tracking solar collectors while the second one is installed at the inlet end of the commercially available non-concentrating collectors comprising of same number of tubes.

An acquisition data system is linked with solar collectors and pyranometer to record the inlet and outlet temperatures of the solar collectors, ambient temperature and solar irradiance. Some parameters are recorded every second while some of them are recorded every minute by the data loggers (data acquisition system). Ultrasonic flow meter was used to measure the flow rate for hot and chilled water.

In this case of solar collectors' performance testing, standard operating procedures were followed during operation and the arrangement of the test can be summarized as;

- All collectors are covered with sheet first.
- All sensors checked.
- Flow rate across the solar collectors checked.
- Removed the sheet placed across all the solar collectors.
- Data acquisition systems started working properly and sampled data for inlet and outlet temperature across solar collectors, ambient temperature and solar irradiance after every minute. Data loggers connected with PC recorded all the data by sampling the data every second and averaged every 1 minute.
- The whole experimental setup operates for 6-9 hours for several weeks in sunny, cloudy and partial cloudy conditions. System performance is monitored after every 20 minutes to ensure whether the system is functioning properly or not.
- Solar collectors shielded by sheet and valves are closed soon after test period over.
- Logger stopped, and the data retrieves and then logged via PC.

Table 3.1

Characteristics and specification of instrumentation and measurements

Parameter and instrument	Measurement and characteristics
Fluid flow	Water
Pump	Type CDXIA 120/07, EBARA pump, Italy.
Pressurization	3 bar
Temperature measurement	K-type, sensitivity 41 µV/°C
Data logging	HIOKI LR8500, voltage and temperature measurement accuracy; ±100 mV and ±0.6 °C
Pyranometer	SR20-T1, sensitivity 13.58 x 10^{-6} Vm^2W^{-1}
Flow meter	Siemens Pt 500, WFN21

(a)

(b)

(c)

Fig. 3.1 (a) Testing of NTC and ETC collectors, (b) Pyranometer, (c) Data Logger

3.2 Experimental Setup of Solar Cooling Pilot Plant

The solar power plant is running at the roof of the 8-storey building at Faculty of Environmental Management building comprising of 38.4 m^2 non-tracking solar collectors, a 17.6 kW single effect NH_3-H_2O absorption chiller coupled with a cooling tower, two tanks for storage of hot and chilled water, a refrigerator and fan-coils installed in the office at the rooftop to be conditioned. A schematic detail of the experimental setup is demonstrated in Fig. 3.2 and the system parameters are detailed in Table 3.1.

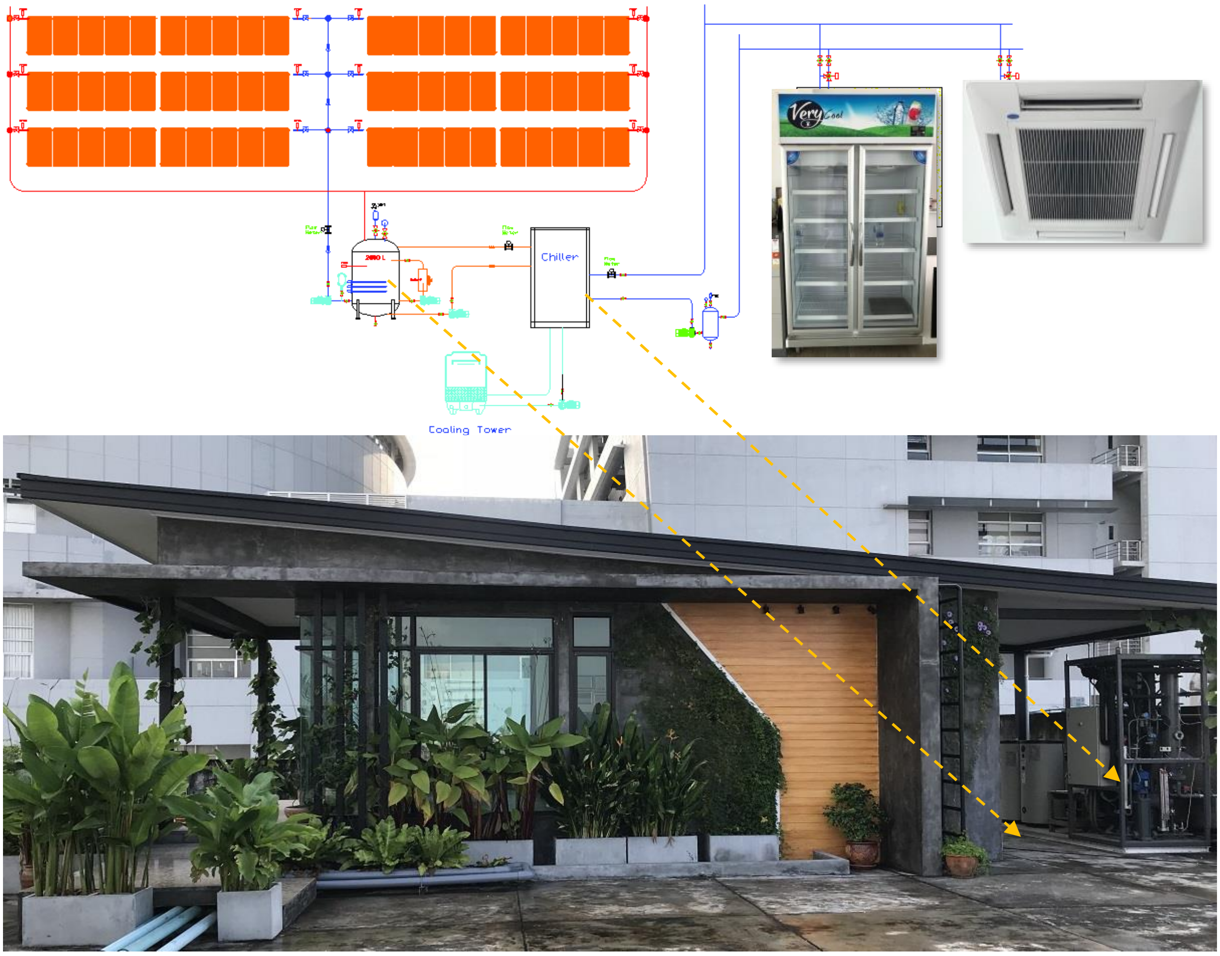


Fig. 3.2 Cooling system installed at roof top of Prince of Songkla University, showing fan coil, refrigerator, an assembly of solar collectors, hot and chilled water tanks and absorption chiller .

The alignment of the non-tracking concentrating solar collector was made in north- south direction. The concentrator is composed of 10 modules (see Fig. 3.3) having eight tubes in each module, accumulate to form eighty tubes in total. Each module is expanded to a width of around 1.75 m.

The concentrator assembly is directly connected with the working fluid (wet connection) flowing through manifold, thus increases the heat transfer efficiency of the fluid. Water is used as the heat transfer fluid (HTF) with two storage tanks. The installed system is designed to be monitored automatically.

Fig. 3.3 Demonstration of Solar Cooling system at Solar Energy Research Unit, Prince of Songkla University, HatYai, Thailand.

Two acquisition data systems are used with the installation components. The first logger, integrated with the control system measures series of parameters including, inlet and outlet temperatures at different points of the absorption chiller and air conditioning system, pressures at different point of chiller system, controls the operational conditions such as start-up and shutdown, safety parameters and the operating time of different parts of the solar power plant as well. The second acquisition data system is linked with solar collectors and pyranometer to record the inlet and outlet temperatures of the solar collectors, ambient temperature and solar radiation intensities. Some parameters are recorded every second while some of them are recorded every minute by the data loggers (data acquisition system). Ultrasonic flow meter was used to measure the flow rate for hot and chilled water.

Solar testing accomplished NTC (8 tubes)with wet connections and ETC (8 and 16 tubes) with dry connections (Ratismith, Favre, Canaff, & Briggs, 2017). Outdoor testing of these collectors was based on ISO 9806.

The outdoor experiments related to solar collector testing principally dependent on weather conditions, making the data collection time consuming. Test period varies from 6-9 hours to depending on sunny, cloudy and partially cloudy conditions.

Table 3.2

Physical and geometric characteristics of the non-tracking solar collector.

Characterization	Profile Values
Glass material	Borosilicate glass
Absorber Area (m^2)	1.375
Outer glass diameter (mm)	100 mm
Inner glass diameter (mm)	94 mm
Wall thickness (mm)	3 mm
Absorber area	1.38 m^2
Aperture area	1.51 m^2
Absorptance	0.95±0.02
Emittance	0.05±0.02
Transmittance	>0.91
Reflectivity	0.899

Considering Thailand general climatic condition, the cooling loads are more important than the heating loads. Since, the focus of the study is to air condition the office built at the roof top of Faculty of Environmental Management at Prince of Songkla University, therefore a significant measure was taken to reduce the office temperature prior using solar energy for solar cooling. The cooling load of the office is minimized by planting green walls and thermal insulated curtains which can be considered as significant steps towards energy preservation and environmental safety. The office to be air conditioned requires cooling for the whole year, so it can be taken as a testing platform.

The next chapter which is the most important section of the study discusses result taken out from the experiment. The chapter highlights the performance of non-tracking solar collector and NH_3-H_2O absorption chiller by considering the efficiency, the coefficient of performance (COP), comparing output power of NTC and ETC and analyzing the air-conditioning capability of the chiller.

CHAPTER 4

RESULT AND DISCUSSIONS

4.1 Ray Tracing Analysis of Non-Tracking Solar Collectors

The evacuated tube with a non-tracking trough with vertical absorber plate have been used to extract heat from the cusp of non-tracking solar collector profile. The behavior of the non-tracking collector reflector was analyzed in detail by using a two dimensional ray tracing analysis on the basis of optical performances, acceptance angles, reflection characteristics, intercept factor and flux distribution at different incident angles. Concentrator is used to increase the amount of solar radiation entering the absorber plate placed in the trough. The enhanced solar radiation considering with and without concentrator is represented in terms of concentration ratio and it depends upon the dimensions of the trough as well as shape and size of the absorber (Ratismith et al., 2017). The geometrical and physical characteristics of the non-tracking solar collectors are given in Table 3.1.

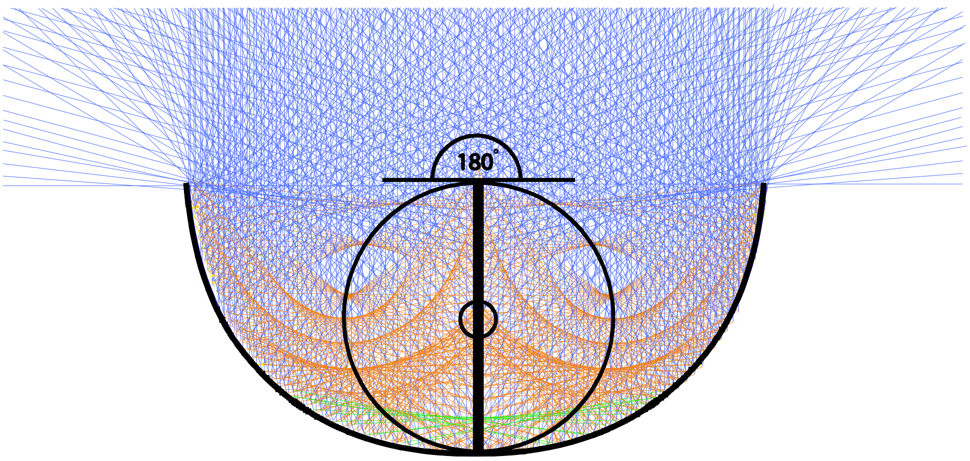


Fig. 4.1 Ray-tracing diagram represents non-tracking solar collector having acceptance angle of 180˚.

A unique trough is developed with the ability to capture almost 100% of the light incident on the trough which is achieved due to specifically designed trough bottom creating a tea-cup cusp in reflection (Ratismith et al., 2017). This cusp divides into two symmetrical parts when light is incident from finite angle. Since the newly designed trough looks like semi-circle as shown in Fig. 4.1, therefore the incident angle from 0˚to 180˚will almost pass through the absorber plate making intercept factor close to 100%. Ray-tracing diagrams at different time instants with blue, orange and green lines representing incident, 1st reflected and 2nd reflected rays respectively are shown in Fig. 4.2.

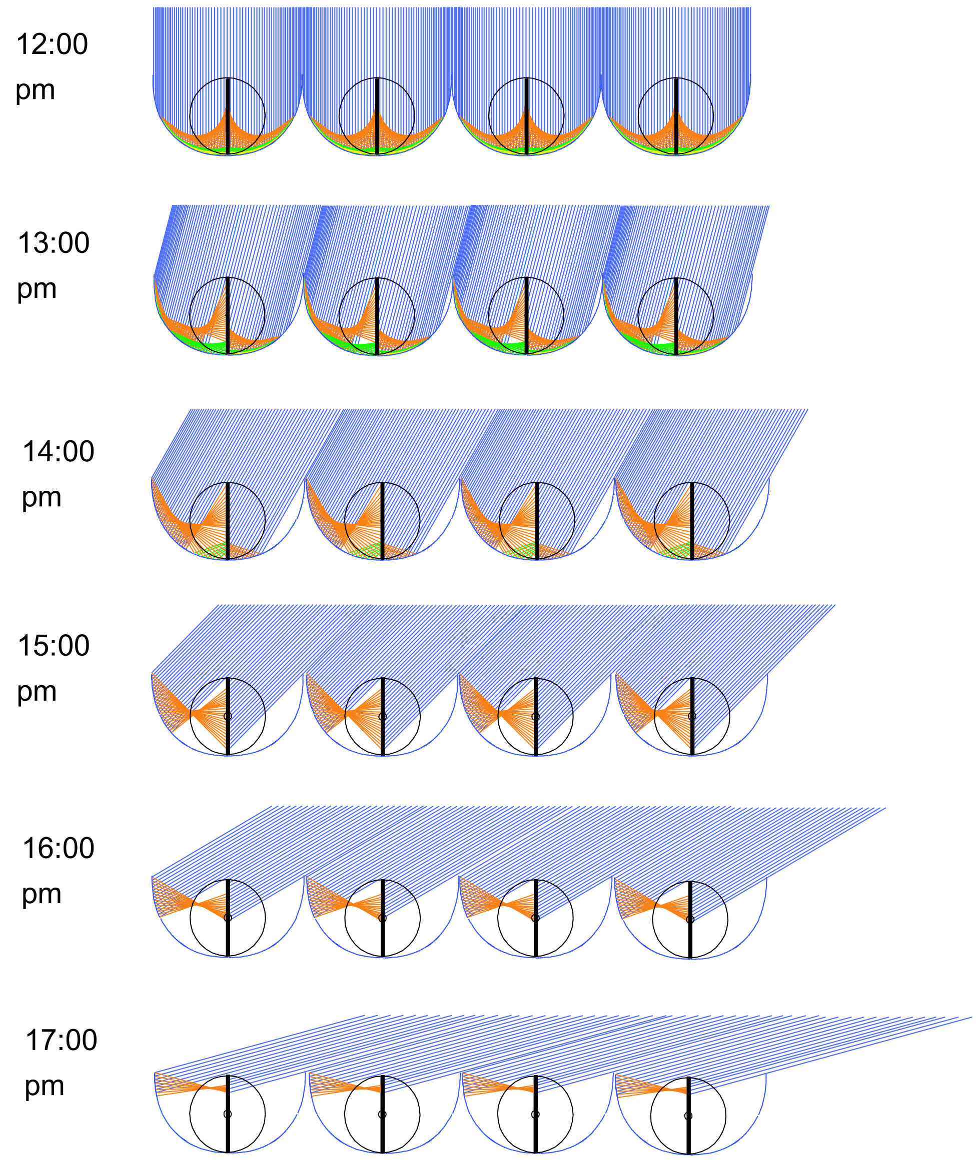


Fig. 4.2 Ray-tracing diagrams at different time instants with blue, orange and green lines representing incident, 1st reflected and 2nd reflected rays respectively. The circle shows the absorber tube and the vertical thick line presents flat plat absorber.

Ray tracing analysis of non-tracking solar collector at different time instants show its capability to capture 100% of the incident light without use of any tracking device, making intercept factor close to 100% and is economical too.

4.2 Comparison of Non-tracking and Evacuated tube solar collectors (NTC and ETC)

In this study, comparisons have been made between non-tracking solar collector (NTC) and evacuated tube solar collector (ETC) based on same number of tubes as well as considering the same area of the collectors. In section 4.2.1 comparisons of NTC and ETC based on the efficiency have been discussed and in section 4.2.2 the performance of solar collectors of both NTC and ETC have been discussed.

4.2.1 Efficiency Tests of NTC and ETC

In this study, the efficiency characteristics of newly designed non-tracking concentrated solar collector is discussed. The tests were conducted with 3 modules of solar collectors NTC (8 tubes) and ETC (8 and 16 tubes) installed at the roof top of 8-storey building at Prince of Songkla University, Thailand. The solar collector module used for testing is shown in Fig 3.1.

For measurement of efficiency, the setup and procedure is close to that of (Nkwetta & Smyth, 2012b) which follows the guidelines of test standards of ANSI/ASHRAE Standard Both NTC and ETC modules (8 and 16 tubes) were configured in parallel connection and tilted to the sun at an angle of approximately 20º and aligned in north-south direction. Water is flowed continuously to the collector by 0.55 kW pump. The flow rate across NTC module was higher (almost double) compared with ETC because the header in NTC is made up of stainless steel which requires high flow rate to transfer heat. Heat sensors were fixed at the inlet and outlet point of the collectors to measure the difference in temperatures of the fluid flowing through it. Radiator was used to control the temperature. The whole testing process is executed by varying inlet temperature from 90 ºC to 40 ºC keeping 10 ºC difference. At each measured temperature (90 ºC, 80 ºC, 70 ºC …) the difference in temperature was measured for at least 15 minutes with the help of radiator to get constant and reliable values.

4.2.1.1 Thermal Efficiencies of NTC and ETC (8 tubes) Solar Collectors

The efficiencies of the two solar collectors (NTC and ETC) were evaluated using the data retrieved during the experiment to generate efficiency curves obtained by calculating the fluid flow rates, and inlet and outlet fluid temperatures, ambient temperatures and the varying solar irradiance. The block diagram of testing system of NTC (8 tubes) with ETC (8 tubes) is shown in Fig. 4.3.

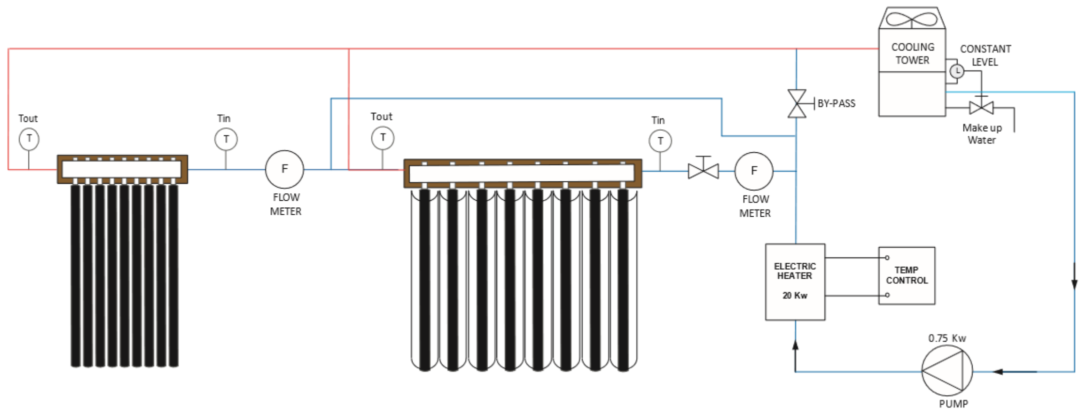


Fig. 4.3 Block diagram of testing system of NTC (8 tubes) with ETC (8 tubes)

The efficiencies and heat loss coefficients of the solar collectors were determined by using equation Eq (3). The thermal performances of NTC and ETC collectors in real outdoor conditions evaluated by using graphs of efficiency against x=((Ti-Ta)/G) are illustrated in Fig. 4.4 and 4.5 and are detailed in Table 4.1.

$$\eta = \frac{\dot{m}\, C_p (T_e - T_i)}{GA} \quad (2)$$

$$\eta = \eta_\circ - \frac{a_1 (T_i - T_a)}{GA} - \left(\frac{a_2 (T_i - T_a)^2}{GA}\right) \quad (3)$$

$$\eta = \eta_o - a_1 x - a_2 x^2 \quad (4)$$

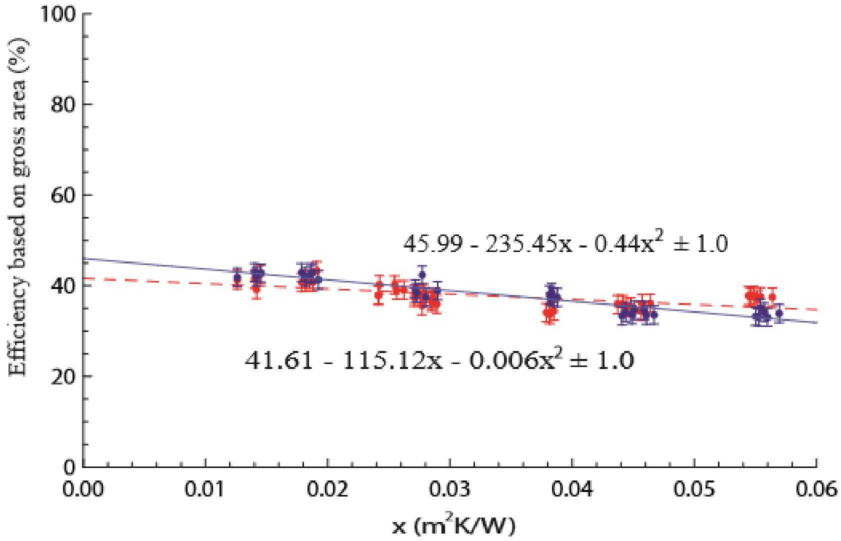


Fig. 4.4 Thermal efficiency (based on gross area), dashed curve (red): ETC module with 8 tubes, continuous curve (blue): NTC module with 8 tubes.

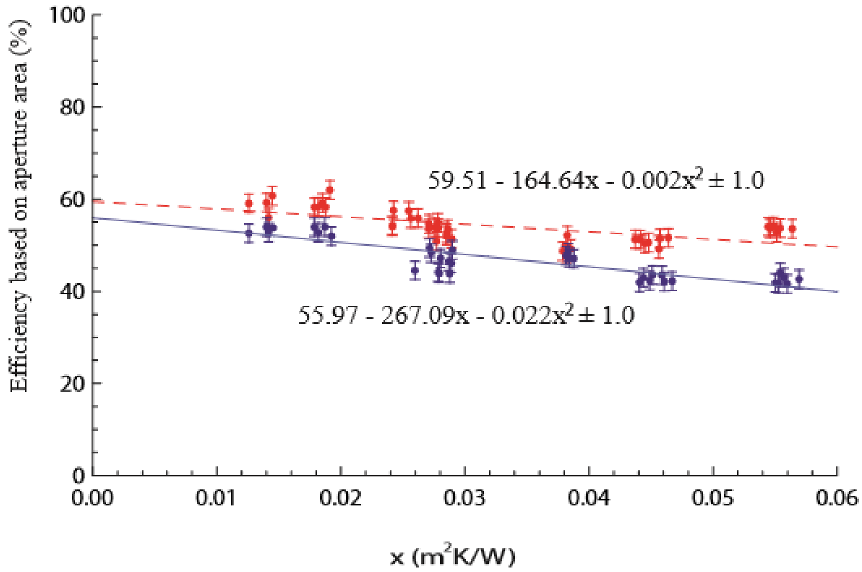


Fig. 4.5 Thermal efficiency (based on aperture area), dashed curve (red): ETC module with 8 tubes, continuous curve (blue): NTC module with 8 tubes.

Based on aperture area, efficiencies of ETC and NTC collectors were found to be 0.5951 (with heat loss coefficients a_1=1.65 W/m^{2}K and a_2=0.00002 W/m^{2}K) and 0.559 (with heat loss coefficients a_1=2.67 W/m^{2}K and a_2=0.00022 W/m^{2}K) respectively were gained. Considering gross area, the optical efficiency values of ETC and NTC collectors were 0.416 (with heat loss coefficients a_1=1.15 W/m^{2}K and a_2=0.00006 W/m^{2}K) and 0.459 ((with heat loss coefficients a_1=2.35 W/m^{2}K and a_2=0.0044 W/m^{2}K) respectively.

Table 4.1

Characterization of NTC and ETC (8 tubes) based on aperture and gross area

Solar collectors	Characteristic equation base on aperture area	Performance		Characteristic equation base on gross area	Performance	
		Optical efficiencies	Heat loss coefficients (Wm^{-2}K^{-1})		Optical efficiencies	Heat loss coefficients (Wm^{-2}K^{-1})
NTC	η = 0.5597-2.6709x-0.00022x^2	0.5597	a_1=2.67 a_2=0.00022	η = 0.4599-2.3545x-0.004363x^2	0.4599	a_1=2.35 a_2=0.0044
ETC	η=0.5951-1.6464x-0.00002x^2	0.6531	a_1=1.64 a_2=0.00002	η = 0.4161-1.1512x-0.00006 x^2	0.4678	a_1=1.15 a_2=0.00006

4.2.1.2 Thermal Efficiencies of NTC and ETC (16 tubes) Solar Collectors

The efficiencies of the two solar collectors (NTC and ETC) were evaluated using the data retrieved during the experiment to generate efficiency curves obtained by calculating the fluid flow rates, and inlet and outlet fluid temperatures, ambient temperatures and the varying solar irradiance. Block diagram of testing system of NTC (8 tubes) with ETC (16 tubes) is shown in Fig 4.6.

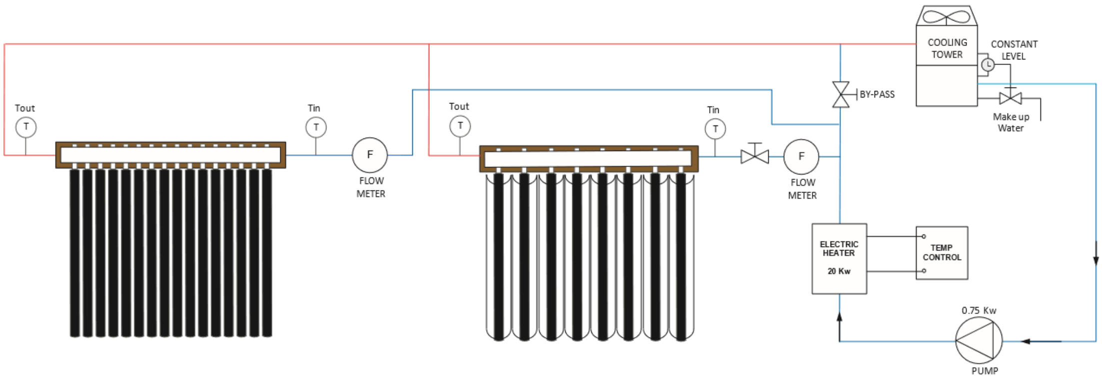


Fig. 4.6 Block diagram of testing system of NTC (8 tubes) with ETC (16 tubes)

The efficiencies and heat loss coefficients of the solar collectors were determined by using equation Eq (3). The thermal performances of NTC and ETC collectors in real outdoor conditions evaluated by using graphs of efficiency against x=((Ti-Ta)/G) are illustrated in Fig. 4.7 and 4.8 and are detailed in Table 4.2.

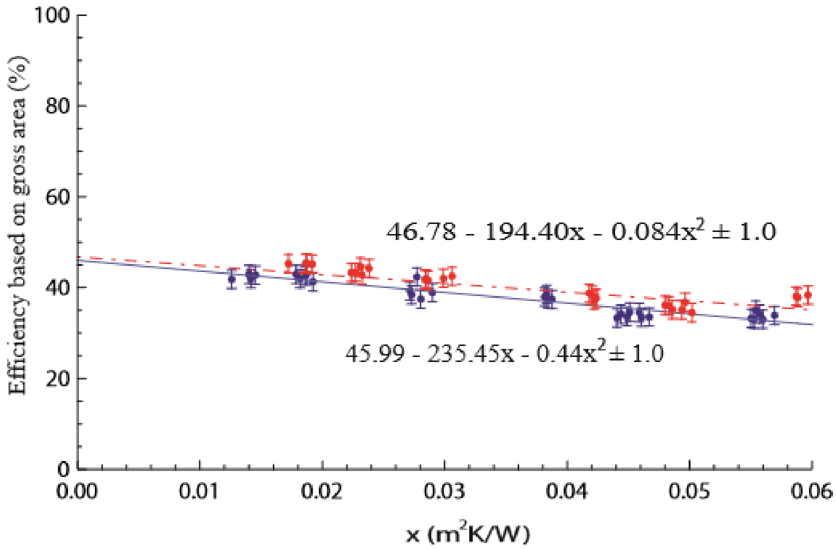


Fig. 4.7 Thermal efficiency (based on gross area), dashed curve (red): ETC module with 16 tubes, continuous curve (blue): NTC module with 8 tubes.

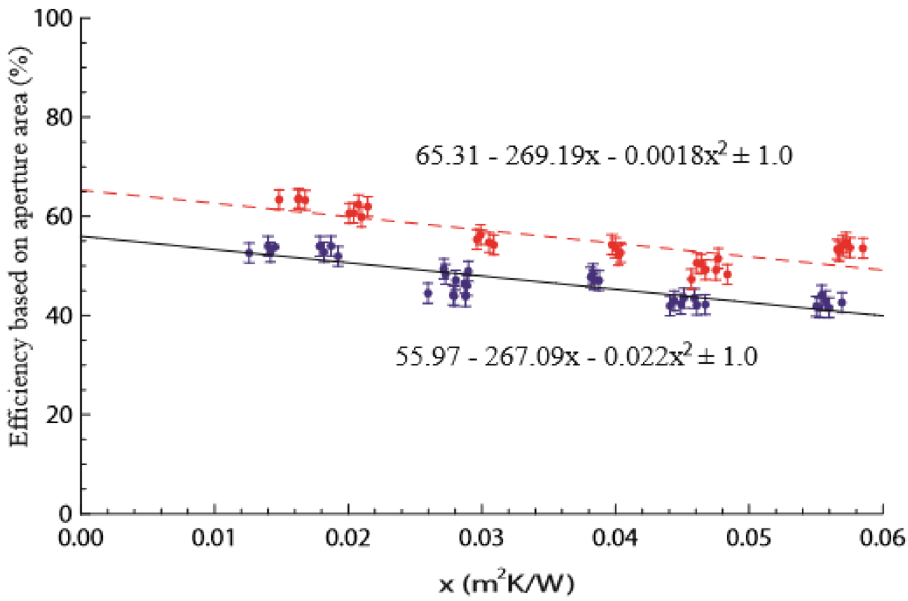


Fig. 4.8 Thermal efficiency (based on aperture area), dashed curve (red): ETC module with 16 tubes, continuous curve (blue): NTC module with 8 tubes.

Based on aperture area, efficiencies of NTC and ETC collectors were found to be 0.653 (with heat loss coefficients a_1=2.69 W/m^{2}K and a_2=0.000018 W/m^{2}K) and 0.559 (with heat loss coefficients a_1=2.67 W/m^{2}K and a_2=0.00022 W/m^{2}K) respectively were gained. Considering gross area, the optical efficiency values of NTC and ETC collectors were 0.468 (with heat loss coefficients a_1=1.94 W/m^{2}K and a_2=0.000084 W/m^{2}K) and 0.459 ((with heat loss coefficients a_1=2.35 W/m^{2}K and a_2=0.0044 W/m^{2}K) respectively.

Table 4.2

Characterization of NTC and ETC (16 tubes) based on aperture and gross area

Solar collectors	Characteristic equation base on aperture area	Performance		Characteristic equation base on gross area	Performance	
		Optical efficiencies	Heat loss coefficients (Wm^{-2}K^{-1})		Optical efficiencies	Heat loss coefficients (Wm^{-2}K^{-1})
NTC	η = 0.5597-2.6709x-0.00022x^2	0.5597	a_1=2.67 a_2=0.00022	η = 0.4599-2.3545x-0.004363x^2	0.4599	a_1=2.35 a_2=0.0044
ETC	η=0.6531-2.6919x-0.000018x^2	0.6531	a_1=2.69 a_2=0.000018	η = 0.4678-1.9440x-0.00084 x^2	0.4678	a_1=1.94 a_2=0.00084

4.2.2 Performance Analysis of Solar Collectors

To analyze the thermal performance of the non-tracking solar collectors (NTC) and the non-concentrated evacuated tube solar collectors (ETC), inlet and outlet temperature differential, differences in mean collector fluid temperature and ambient temperatures were evaluated.). Fig. 9-11, illustrates the output power of a collector of NTC (8 tubes) and ETC (8 & 16 tubes) along with the measured global irradiance G (W/m^2).

The energy storage capacity of a water (or other liquid) storage unit at uniform temperature (i.e., fully mixed or unstratified) operating over a finite temperature difference is given by

$$\boldsymbol{Q_c} = \dot{m}\, \boldsymbol{C_p}(\boldsymbol{T_e} - \boldsymbol{T_i}) \qquad (5)$$

where,

$\dot{m}$ is the flow rate of the heat transfer fluid, $\boldsymbol{C_p}$ is the specific heat capacity (J/kg K), $\boldsymbol{T_e}$ is the outlet temperature and $\boldsymbol{T_i}$ is the inlet temperature of the solar collectors.

4.2.2.1 Comparison of Output Power of NTC and ETC under Clear Condition

Considering the output power of 8 tubes of non-tracking solar collectors with 8 & 16 tubes of non-concentrated ETC under clear condition, it was found that heat generated by NTC was 1.5 times higher than ETC (8 tubes). Fig. 4.9 illustrates that as the solar power drops, ETC power drops more rapidly than NTC which shows that NTC retain the heat for longer period of time and works efficiently than ETC. The consistent output power from start till the end of operation demonstrates that the novel non-tracking solar collectors effectively distribute the radiations.

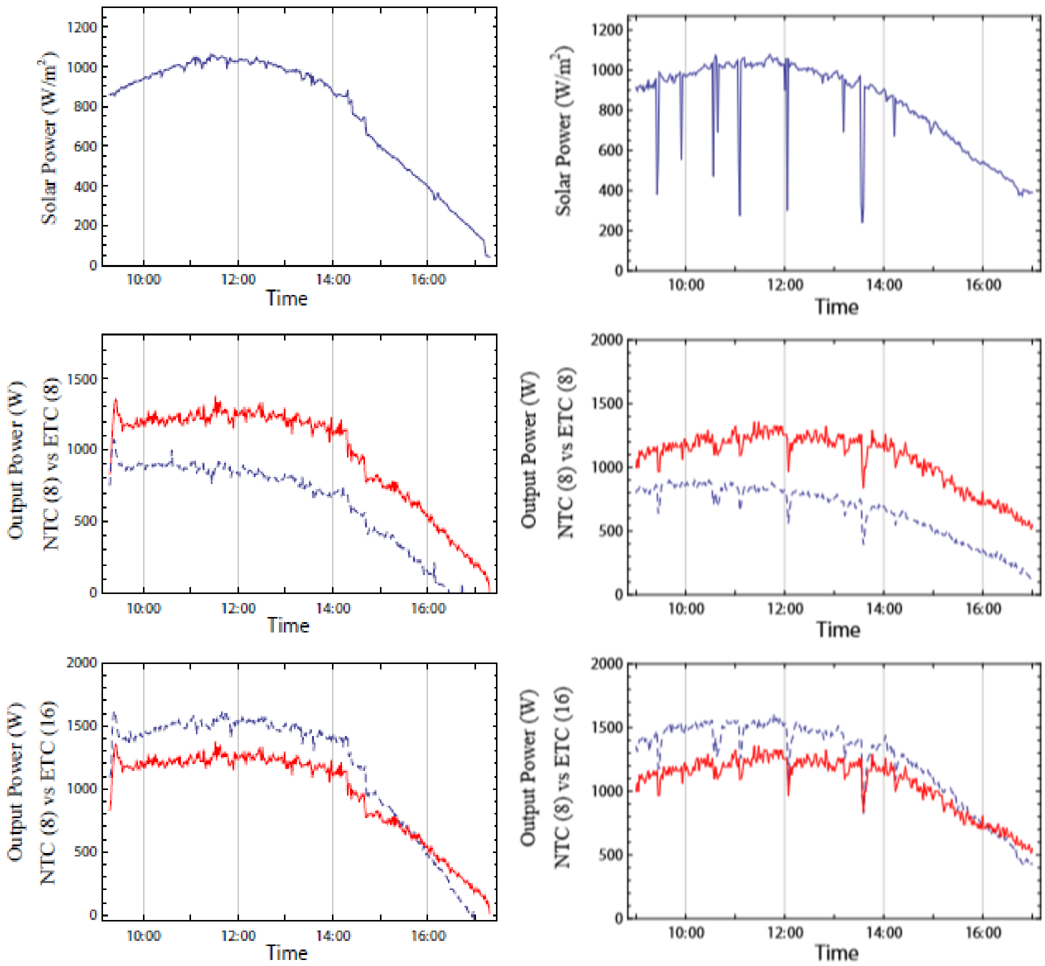


Fig. 4.9 Output power comparisons of NTC (continuous curve) and ETC (dashed curve) collectors in accordance with solar irradiance on clear sunny days

4.2.2.2 Comparison of Output Power of NTC and ETC under Partial Cloudy Condition

By comparing the output power of 8 tubes of NTC with 8 & 16 tubes of ETC under partial cloudy condition, it was found that heat generated by NTC was 1.4 -1.6 times higher than ETC (8 tubes). Fig. 4.10 shows that NTC retained the higher output power at the start of the operation till the end, however it can be observed that in case of ETC 16 tubes, the heat drops suddenly to large degree as the solar power drops. This shows that NTC perform well even in cloudy conditions.

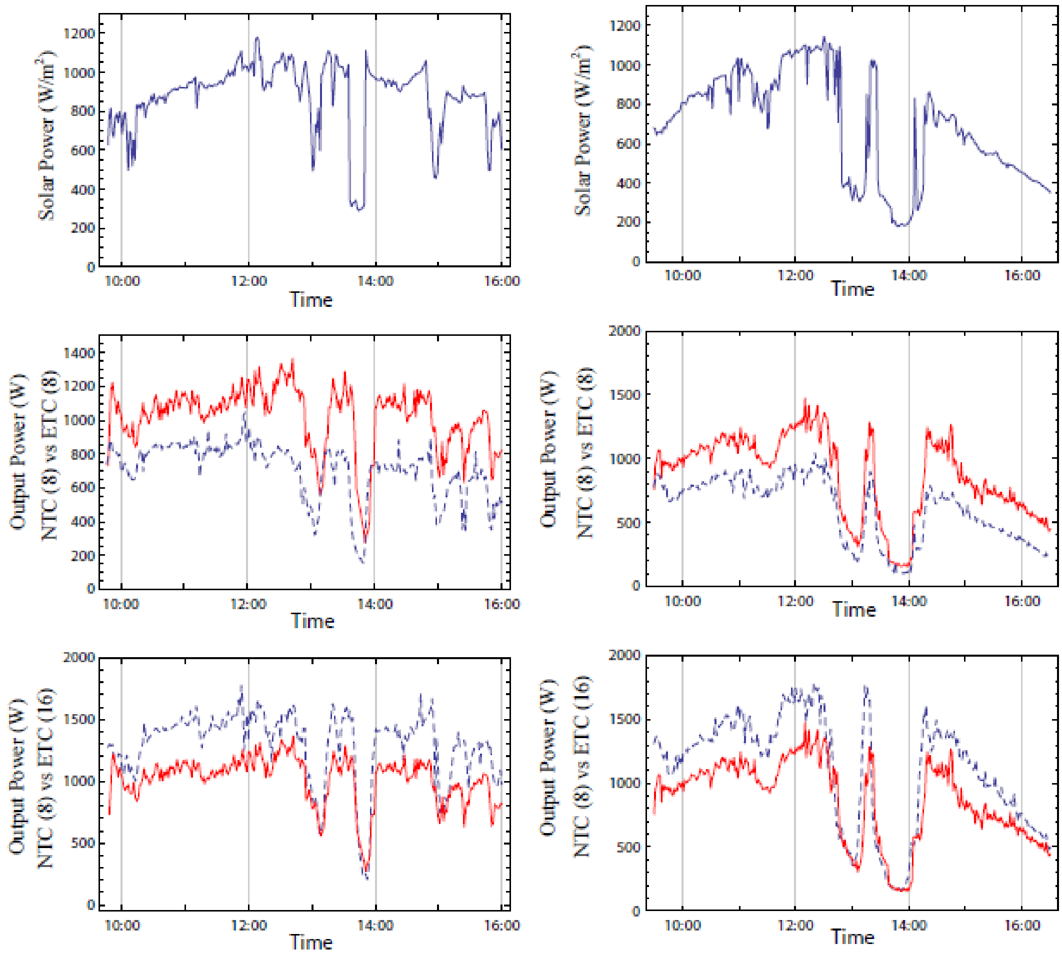


Fig. 4.10 Output power comparisons of NTC (continuous curve) and ETC (dashed curve) collectors in accordance with solar irradiance during partial cloudy conditions

4.2.2.3 Comparison of Output Power of NTC and ETC under Cloudy Condition

When the output power of 8 tubes of non-tracking solar collectors with 8 & 16 tubes of non-concentrated ETC were compared under cloudy condition, NTC retained a maximum power output of 1.5 times higher than ETC (8 tubes). Fig. 4.11 shows that ETC 16 tubes lost heat to large extent when it was raining, however, NTC retained the heat. It can be concluded that NTC perform well even in partial cloudy conditions due to its ability to capture heat more efficiently than ETC.

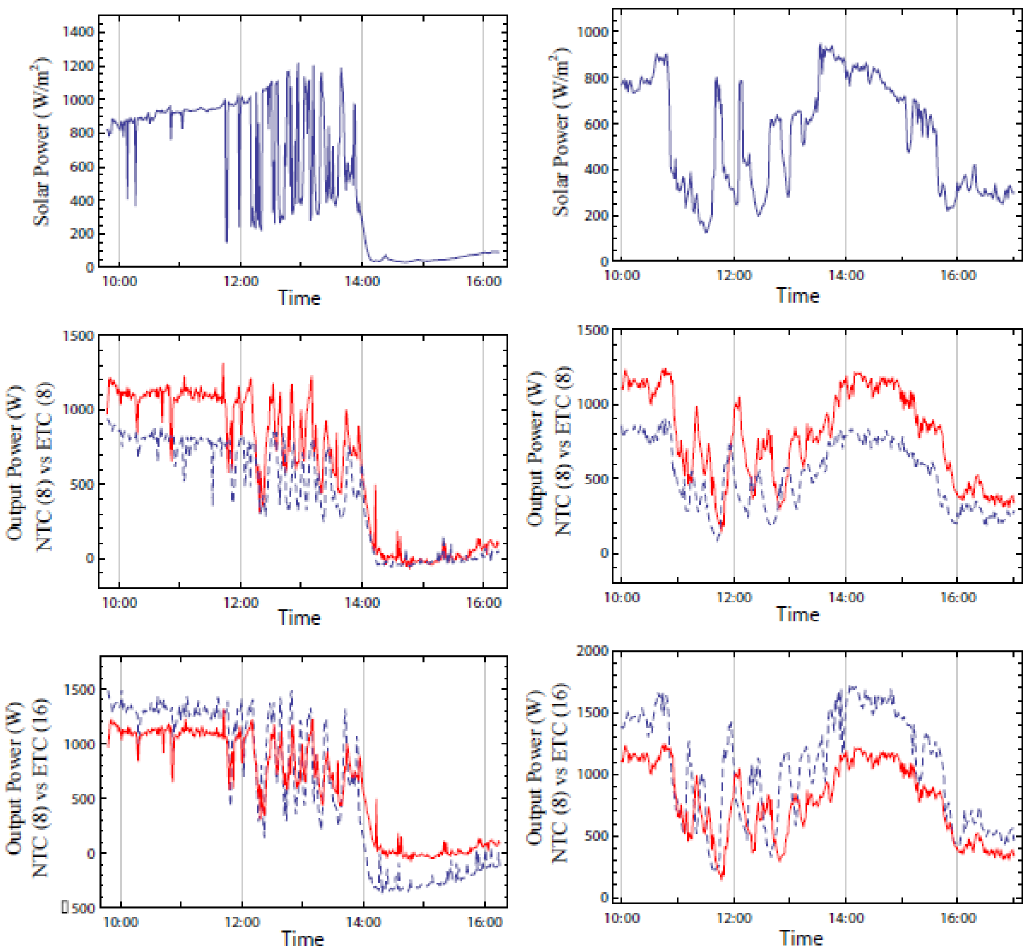


Fig. 4.11 Output power comparisons of NTC (continuous curve) and ETC (dashed curve) collectors in accordance with solar irradiance in cloudy conditions

Considering the output power comparison of NTC and ETC in clear, cloudy and partial cloudy conditions, it clearly shows that with same number of tubes (8 tubes each), NTC gives as an average of 1.5 times more power output than ETC, however when compared with 16 ETC tubes there is not significant difference in power output. The heat storage capacity of NTC is also much better than ETC whether it's clear or cloudy conditions.

4.3 Numerical Analysis of the Experimental Data

To analyze and validate the experimental data, numerical analysis is a convenient way. In this study, the performance analysis of non-tracking solar collectors for solar air conditioning system using a single effect NH_3-H_2O absorption chiller has been studied considering heating and cooling parts of the system.

4.3.1 Numerical Analysis of Absorption Chiller (Heating Part)

The real and simulated value of the absorption chiller system can be analyzed in two parts; 1). time period before absorption chiller starts working, and 2). the time after absorption chiller starts operation. While solving the numerical analysis of the heating part, the time period before operation of absorption chiller is considered. At first, the solar energy absorbed by the non-tracking solar thermal collector is used to heat up the hot water tank. The real experiment was performed under cloudy condition; therefore, the operating temperature of the chiller system was setup at 93 ºC. The temperature of the hot water tank increases gradually until it crosses 90 ºC. $Ts_{(t+dt)}$ calculated using eq. (5). By comparing real temperature of hot water tank Ts_{hot} with simulated value of T_{sim}, the result found is shown in Fig. It can be concluded from the graph that the both real and simulated values are overlying each other which validates the experimental value.

4.3.2 Heat Loss Coefficient (UA)

To find out heat loss coefficient UA, the temperature of hot water tank and ambient temperature were measured for 14 hours from 7:30 pm in the evening to 9:30 am the next morning. Analyzing this data using differential equation in Mathematica, the UA value found to be 2.02 W/K. Energy balance equation for UA is

$$MC\frac{dT_s}{dt} + (UA)(T_s - T_a) = 0$$

Where,

M is the mass of the hot water tank, C is the specific heat of water (J/kg ºC), T_s is the temperature of the water inside the tank, T_a is the ambient temperature.

$$MC\frac{dT_s}{dt} = -(UA)(T_s - T_a)$$

By taking initial temperature of the hot water tank $T_s[0]$ = 81.95 ºC, M = 300 liters, C = 4187 J/kg ºC, Ta = 27.70 ºC, the solution to above differential equation is

$$T_s[x] = e^{-7.96115\times 10^{-7}\, UA\, x}\left(54.25 + 27.7\, e^{7.96115\times 10^{-7}\, UA\, x}\right)$$

Fig 4.12 shows the state of the temperature in the tank which is decreasing gradually with the passage of time.

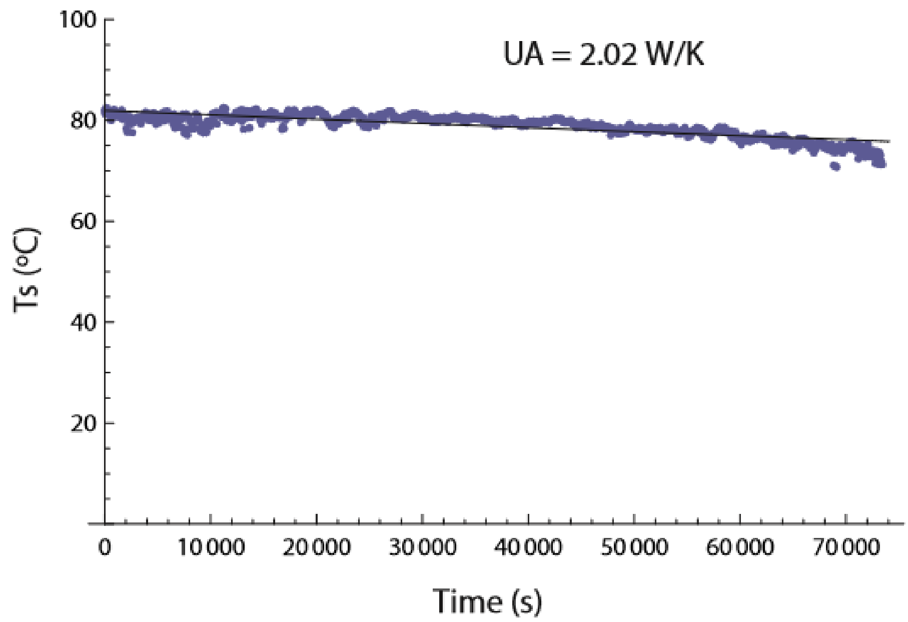


Fig. 4.12 Heat loss coefficient of hot water tank.

Low value of heat loss coefficient UA = 2.02 W/K indicates better insulation of the tank, thus reduces heat loss to large extent.

4.3.3 Energy Balance Equation

Energy balance equation for the hot water tank can be written as

$$MC\,\frac{dTs}{dt} = Q_c - Q_{loss} - Q_{load}$$

Where,

$$Q_{cn} = m_h\, C\,(T_n - T_{n-1}) = A\,((F_R(\tau\alpha))_n\, G - (F_R U_L)_n\,(T_{n-1} - T_a))$$

Where,

$$m_h = 1.05\ kg/s,\ C = 4187\ J/kgC,\ UA = 2.02\ W/K$$

$$(F_R(\tau\alpha))_n = F_R(\tau\alpha)_e\left[\frac{1-(1-K)^\wedge n}{nK}\right]$$

$$(F_R U_L)_n = F_R U_L\left[\frac{1-(1-K)^\wedge n}{nK}\right]$$

$$K = \frac{A\,F_R U_L}{m\,C}$$

Here, n is the total number of solar collectors used,

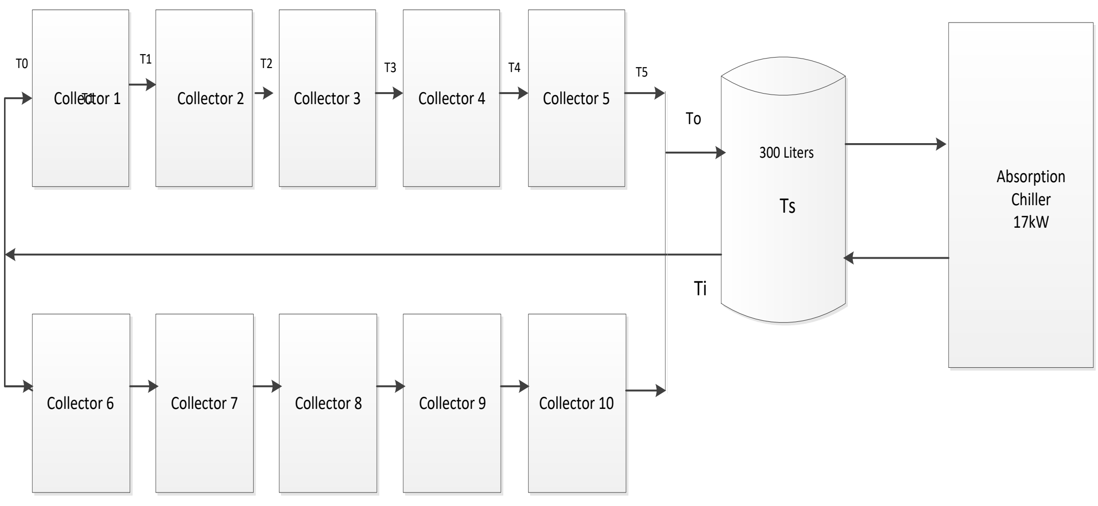


Fig. 4.13 Solar collectors connected in series with hot water tank and absorption chiller.

The temperature of water flowing through the first collector is

$$T_1 = T_o + \frac{A}{m\,C}((F_R(\tau\alpha))_1\,G - (F_RU_L)_1\,(T_0 - T_a))$$

Similarly, temperature of water flowing through collectors 2,3,4 and 5 connected in series can be calculated as;

$$T_2 = T_1 + \frac{A}{m\,C}((F_R(\tau\alpha))_2\,G - (F_RU_L)_2\,(T_1 - T_a))$$

$$T_3 = T_2 + \frac{A}{m\,C}((F_R(\tau\alpha))_3\,G - (F_RU_L)_3\,(T_2 - T_a))$$

$$T_4 = T_3 + \frac{A}{m\,C}((F_R(\tau\alpha))_4\,G - (F_RU_L)_4\,(T_3 - T_a))$$

$$T_5 = T_4 + \frac{A}{m\,C}((F_R(\tau\alpha))_5\,G - (F_RU_L)_5\,(T_4 - T_a))$$

In parallel connection, the performance of solar collector is not changed, so the combined heat in 2 rows (each row consists of 5 collectors connected in series) is calculated as

$$Q_C = 2 \text{ x } m_h\,C\,(T_5 - T_0)$$

Energy balance equation in hot water tank can be written as

$$MC\,\frac{dTs}{dt} = Q_C - Q_{loss} - Q_{load}$$

Where,

$$Q_{loss} = (UA)_s\,(T_s - T_a)$$

$$Q_{load} = m_h\,C\,(T_{Lo} - T_{Li})$$

Or

$$Q_{load} = m_h\,C\,(T_{ho} - T_{hi})$$

The temperature in the tank after an interval is;

$$T_s^{t+dt} = T_s + \frac{dt}{MC}\,(Q_c - (UA)_s\,(T_s - T_a) - m_h\,C\,(T_{ho} - T_{hi}))$$

In case of heating part, Q_{load} = 0, until the chiller system is not turned on.

$$T_s^{t+dt} = T_s + \frac{dt}{MC}\,(Q_c - (UA)_s\,(T_s - T_a) - m_h\,C\,(T_{ho} - T_{hi}))$$

$$T_s^{t+dt} = T_s + \frac{dt}{MC}(Q_c - (UA)_s (T_s - T_a)) \qquad (1)$$

Temperature of the tank Ts before chiller start running is shown in Fig. 4.14.

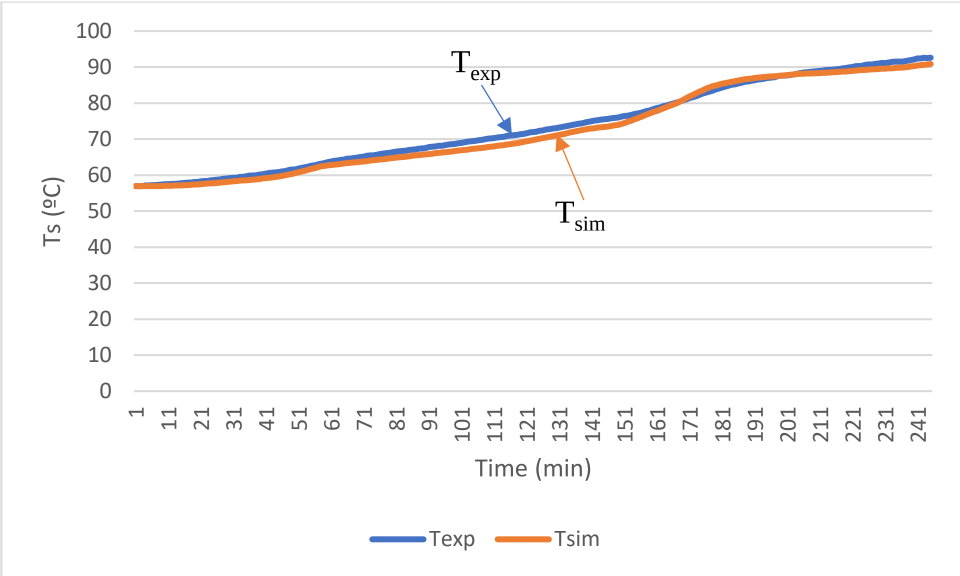


Fig. 4.14 Experimental value T_{exp} and simulated value T_{sim} of the hot water tank

Flow rate of hot water m_h calculated manually and through simulation match each other. For example, the flow rate calculated manually was 1.1 kg/s and through simulation m_h value found to be 1.05 kg/s.

Gaining temperature more than 90 ºC in fully cloudy conditions proves the potential of the NTC, therefore NTC can be utilize effectively in varying weather conditions.

4.4 Performance Tests of NTC driven Absorption Chiller

The performance of the cooling system was tested for whole year from July 2018 to July 2019. These tests were conducted in both sunny, cloudy and partial cloudy conditions. Figures 4.19 - 4.21 show a typical and cloudy day's performance and illustrate the power provided by the sun, hot return temperature from the solar collectors' arrays as well as inlet and outlet temperatures for the hot and cool water tanks.

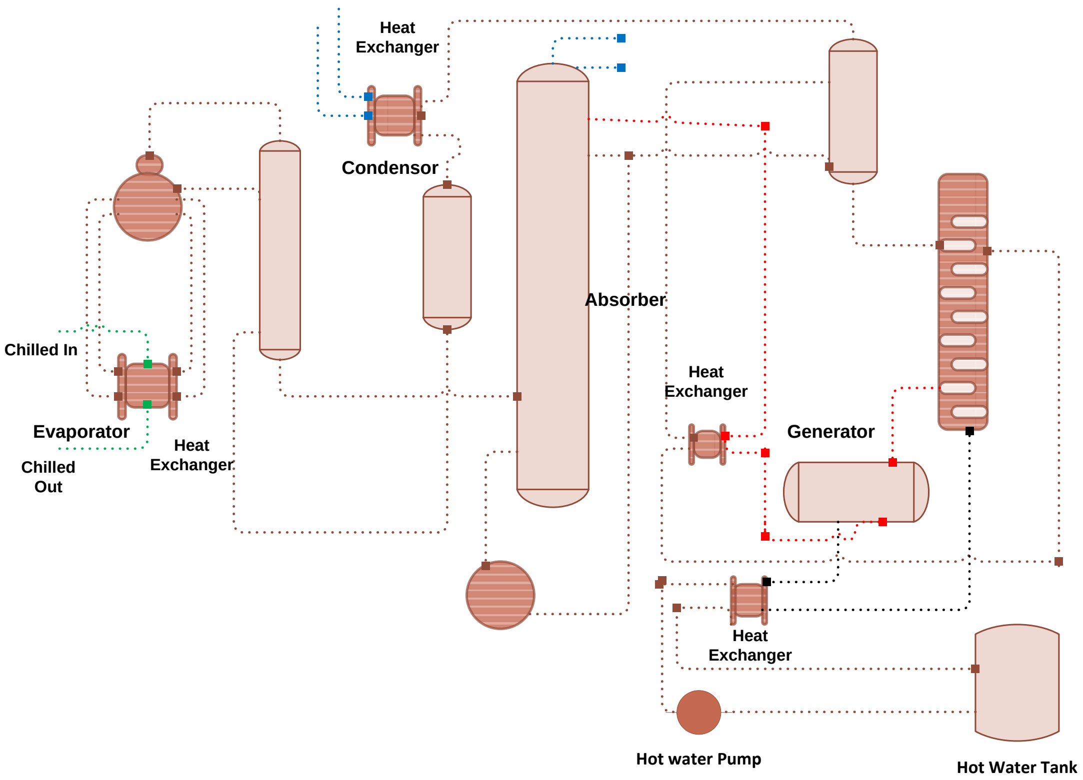


Fig. 4.15 Schematic diagram shows the absorption chiller system.

During experimentations, the collector received solar energy and intermediate glycol loops were circulated for about 3 hours until the temperature was high enough to drive the single effect absorption chiller. Being a standalone system, no auxiliary heats were provided to power the chiller during experimentation, this resulted a delay between when the collector start losing temperature and when the chiller starts producing cooling. The delay occurred as the thermal fluid takes time to warm up the generator inside the chiller to reach up to the required operating temperature from the ambient temperature. Fig. 4.21 shows the chilled inlet and outlet temperature with delay and it can be noted that 3-6 °C is lost in warming up the generator inside the chiller. However, by operating the electrical and absorption chiller in parallel till the generator gain the required operating temperature can eliminate this delay and constrain the collector from losing the temperature, thus lengthens the cooling time. Fig. 4.19 and Fig. 4.20 illustrate the chilled inlet and outlet temperature without further delay and losing the temperature and gives the optimum result. The chiller gives the cooling effect until the hot return temperature drops down to 70 °C. Once the hot return temperature reaches 70 ℃, the chilled inlet and outlet temperatures' difference nears to zero and no cooling occurs.

4.5 Numerical Analysis of Absorption Chiller (Cooling Part)

The method to analyze cooling part of the absorption chiller system is same as that of heating part with a slight change. Instead of considering the temperature of hot water tank T_s, here the temperature of cold water tank T_{exp} is to be compared with the simulated value T_{sim}. The value of T_{exp} and T_{sim} after the chiller started working is shown in Fig. 4.16. The overlapping of T_{exp} and T_{sim} validates the authenticity of experimental data.

The temperature of the hot water tank increases continuously and reaches 90 ºC. thus, enables the absorption chiller to start operating. $Q_{chiller}$ has to be considered once the absorption chiller start working.

Energy balance equation for the cold water tank can be written as

$$MC\frac{dTs}{dt} = Q_{chiller} - Q_{loss}$$

Where,

$M = 320$ liters, $C = 3980$ J/kg ºC, $UA = 2.02$ W/K,

$m_C = 0.58$ kg/s

$$Q_{loss} = (UA)_s\,(T_s - T_a)$$

$$Q_{chiller} = m_C\,C\,(T_{Lo} - T_{Li})$$

Or;

$$Q_{chiller} = m_C\,C\,(T_{ci} - T_{co})$$

The temperature of the cold water tank after absorption chiller started working can be calculated as;

$$T_s^{t+dt} = T_s - \frac{dt}{MC}\left(m_C\,C\,(T_{ci} - T_{co}) + (UA)_s\,(T_s - T_a)\right)$$

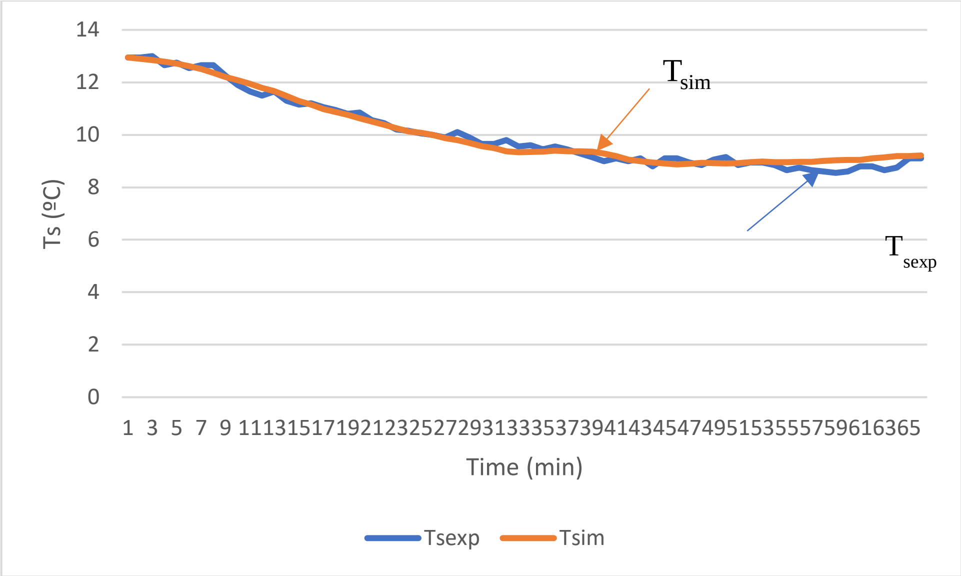


Fig. 4.16 Experimental value $Ts_{chilled}$ and simulated value T_{sim} of the hot water tank

Flow rate of chilled water m_c calculated using ultrasonic flow meter was 0.46 kg/s, however the simulated value of m_c was 0.58 kg/s, thus simulated value is not differing significantly with the real value.

The Fig. 4.16 illustrates that even operating at 90 ºC, chilled water of around 9 ºC has achieved, thus proved that NTC is suitable for solar air-conditioning not only during clear condition but also during cloudy condition.

4.5.1 Cooling System with 100% Solar Power

During the operation of absorption chiller, it was found that without using auxiliary heating, the non-tracking solar collectors produce hot water around 120 °C. With this heat, the coolant can produce cool water around -3.2 °C as shown in Fig. 4.17.

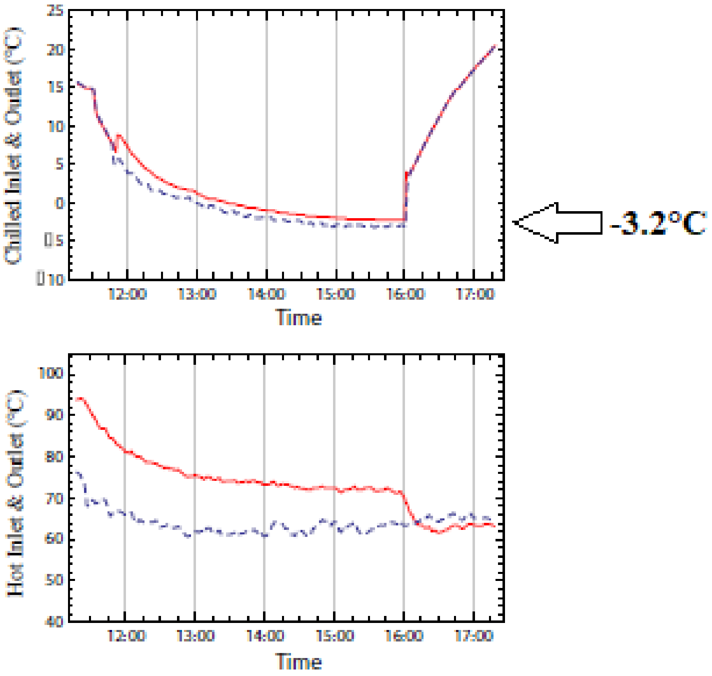


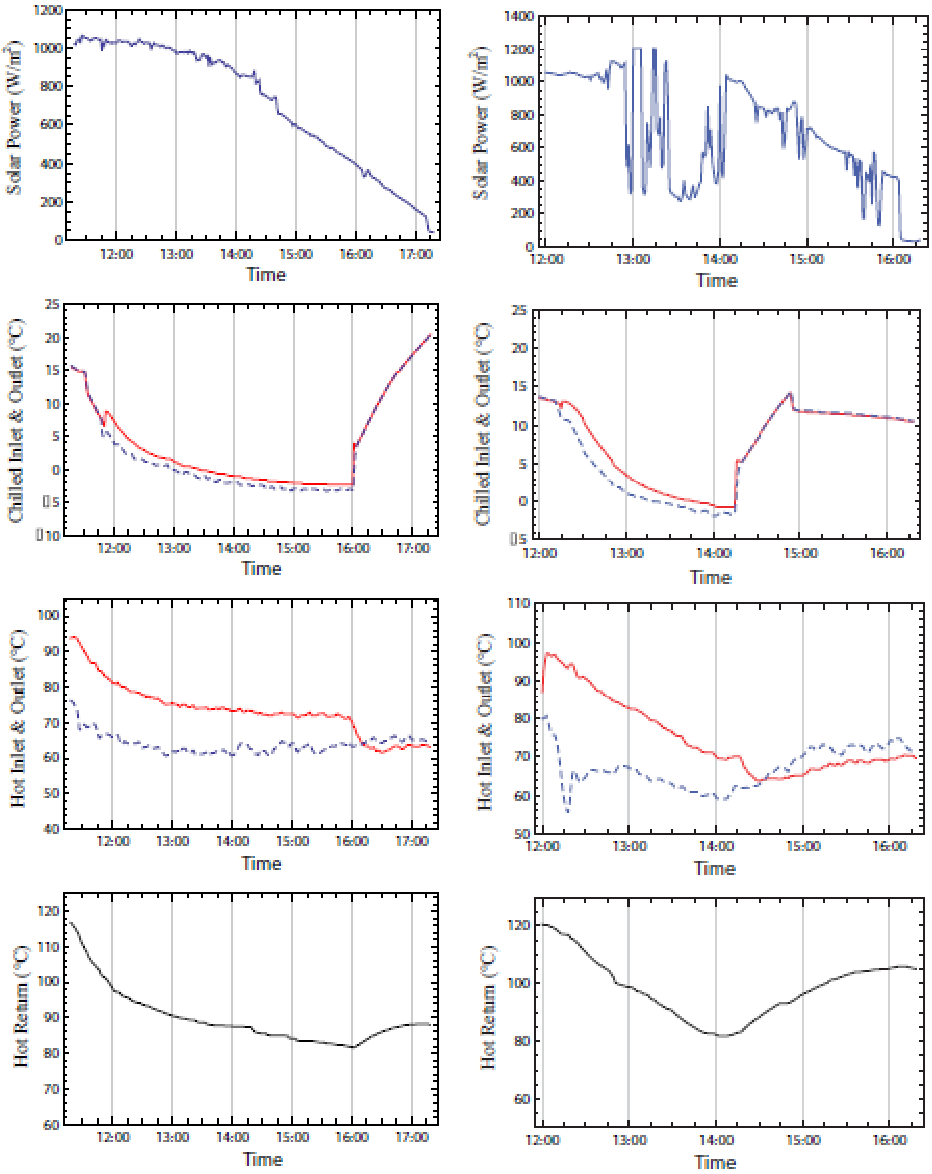
Fig. 4.17 The lowest chilled out temperature -3.2°C achieved during testing.

The ice formed on the chilled water pump during the cooling process is shown in Fig. 4.18.

Fig. 4.18 Ice formed on chilled water pump during cooling process

4.5.2 Cooling system below 0 °C

Temperature below 0 °C can be attained during clear and sunny days. Fig. 4.19 (a) illustrates the performance of absorption chiller under clear and sunny conditions and it can be observed that cooled water of around -3.2 °C was achieved when hot water of 118 °C attained. Attaining -3.2 °C without auxiliary heating is a proof that the novel non-tracking solar collectors can operate efficiently and help single effect NH_3-H_2O absorption chiller to yield the temperature below 0 °C. The cooled water then used to cool the office from 16.00 to 17.00. Fig. 4.19 (b) shows the partial cloudy conditions with cooled temperature of -1.9 °C. It is to be noticed that both electrical and absorption chillers were running in parallel while generator inside the chiller was warming up. This helps in maintaining the temperature in hot water tank, thus lengthens the cooling time.

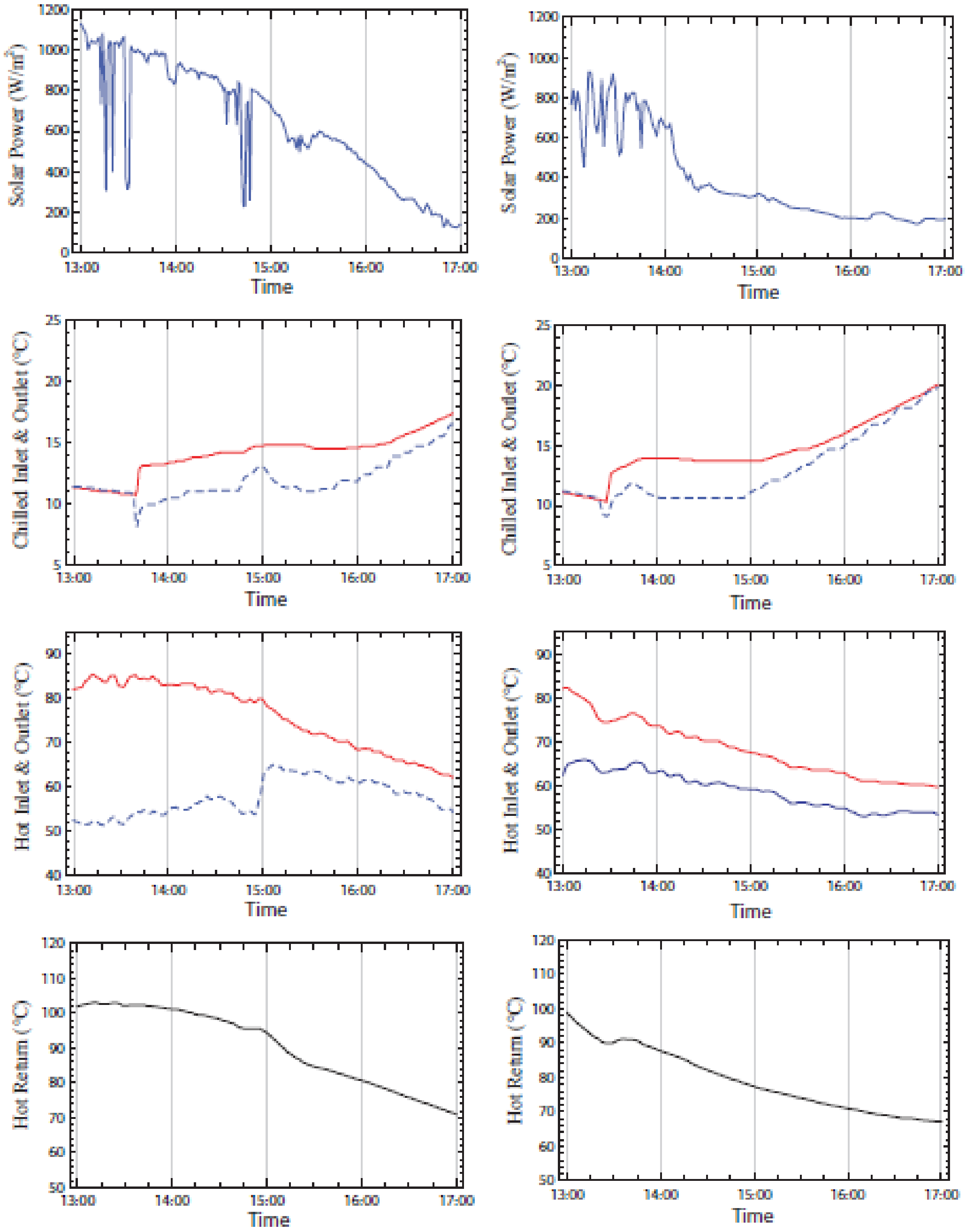


(a) (b)

Fig. 4.19 (a, b). Solar power (W/m^2), Chilled Inlet and Outlet temperature in the cool water tank, temperature of hot water tank (Hot Inlet/Outlet and outlet from solar collectors 'arrays (Hot Return))

4.5.3 Cooling System below 15 °C under Partial Cloudy Condition

During partial cloudy days, the outlet temperature of the solar collectors 'arrays (Hot Return) reaches to 100 °C after 3 hours of operation and start cooling. The chiller yields a cooled water in the range of 7-15 °C for long period of time which necessitates the cooling demand to large extent. Fig. 4.20 (a,b) shows the temperature details of the chiller at different instant of time.

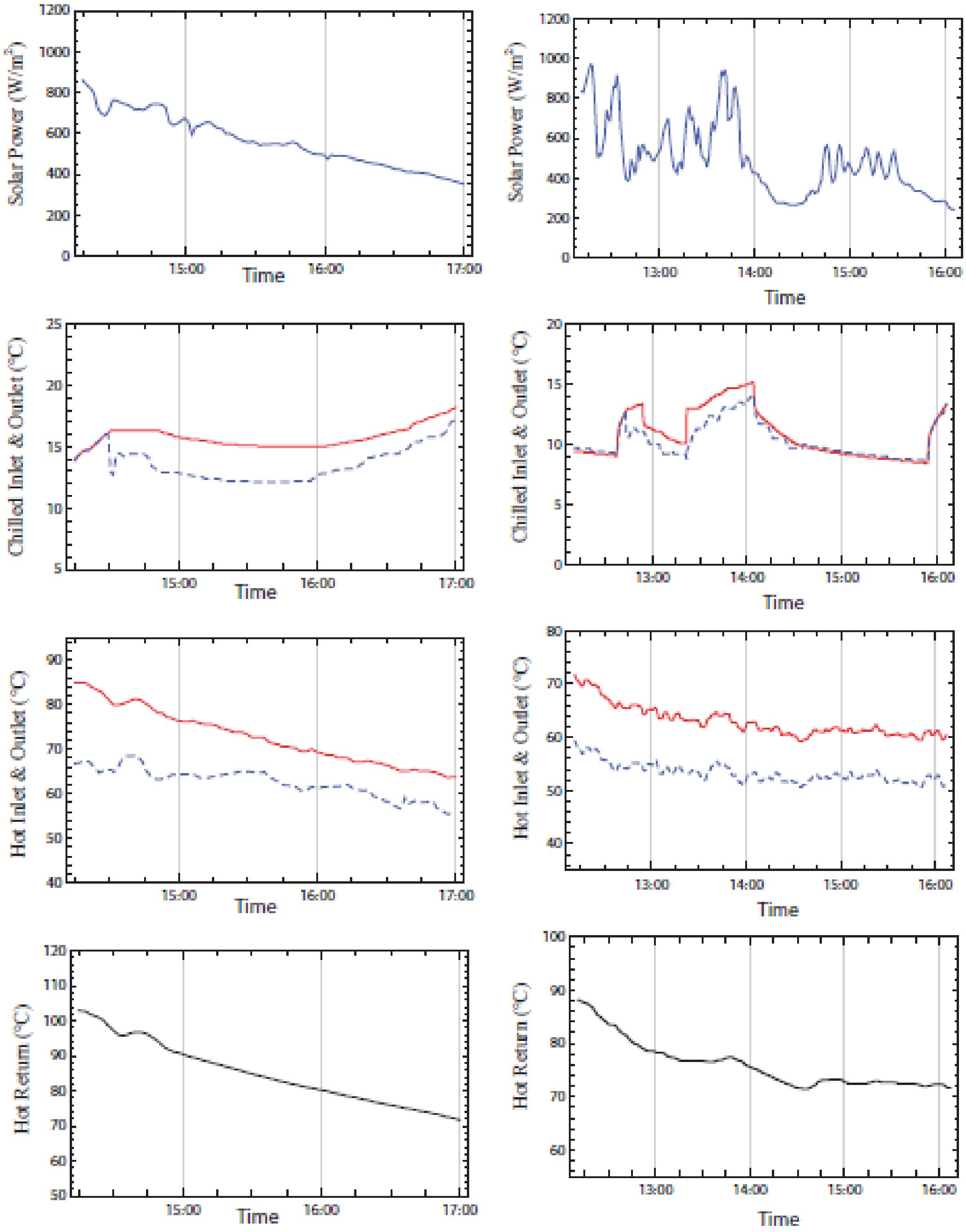


(a) (b)

Fig. 4.20 (a, b) Solar power (W/m^2), Chilled Inlet and Outlet temperature in the cool water tank, temperature of hot water tank (Hot Inlet/Outlet and outlet from solar collectors ‘arrays (Hot Return)) in partial cloudy conditions

4.5.4 Cooling System below 15 °C under Cloudy Condition

During partial cloudy days, the outlet temperature of the solar collectors ‘arrays (Hot Return) reaches to 100 °C after 3-4 hours of operation and start cooling. Unlike sunny days, attaining temperature below 0 °C is quite difficult during cloudy days, however the chiller yields a cooled water in the range of 9 -15 °C for long period of time which necessitates the cooling demand to large extent. Fig. 4.21 demonstrates that the chilled inlet and outlet temperature with delay and it can be noted that 3 - 5 ℃ is lost in warming up the generator inside the chiller. However, by operating the electrical and absorption chiller in parallel till the generator gain the required operating temperature can eliminate this delay and constrain the collector from losing the temperature, thus lengthens the cooling time.



(a) (b)

Fig. 4.21 (a, b). Solar power (W/m^2), Chilled Inlet and Outlet temperature in the cool water tank, temperature of hot water tank (Hot Inlet/Outlet and outlet from solar collectors ‘arrays (Hot Return)) during cloudy days

4.5.5 Coefficient of Performance (COP) of the Absorption Chiller

COP of the chiller is defined as the useful $Q_{chilled}$ produced per unit driving heat *(Q_{heat})* and gives a measure of the system's ability to produce cooling from heat (Widyolar, Winston, Jiang, & Poiry, 2014) .

$$COP_{chiller} = \frac{COP_{chilled}}{COP_{heat}} = \frac{\dot{m}_c Cp_c \Delta T_{chilled}}{\dot{m}_h Cp_h \Delta T_{heat}} \quad (4)$$

The experimental analysis illustrates that COP of the NH_3-H_2O absorption chiller is 0.40.

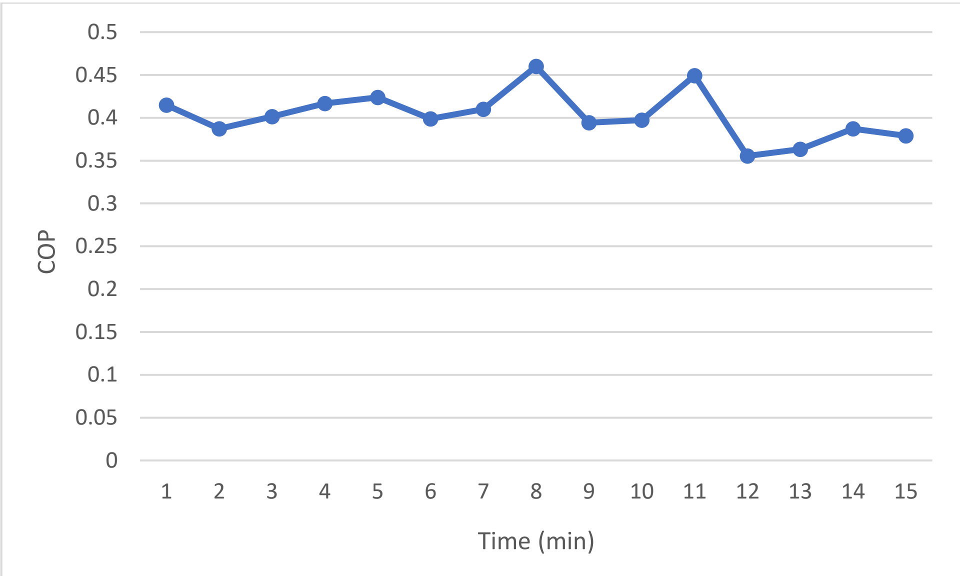


Fig. 4.22 Coefficient of the performance of NH_3-H_2O absorption chiller

To evaluate the temperature at which the absorption chiller system operates efficiently, temperature of the hot water tank T_s is compared with COP. It can be observed from the graph that as Ts drops down to 80 °C , the COP falls too. Thus, it can be concluded that the chiller works better above 80 °C.

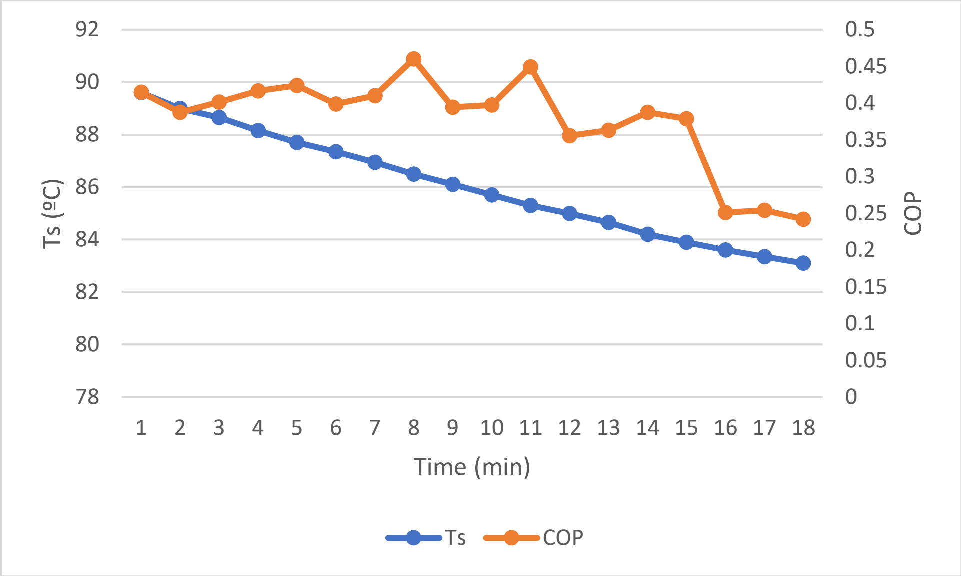


Fig. 4.23 Graph showing the varying COP value against Ts

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

In this study, the design and performance of a solar cooling system using a novel non-tracking solar collector is presented and analyzed. Ray tracing analysis shows that the newly designed non-tracking solar collector captures almost 100% of the light incident on the trough which is achieved due to specifically designed trough bottom creating a tea-cup cusp in reflection. A comparative analysis of non-tracking solar collectors and evacuated tube collectors in terms of energy collection rates and efficiencies are also performed and reported. NTC gains almost the same output power by using half number of tubes compared to ETC. Based on aperture and gross area, the efficiencies of NTC and ETC (16 tubes) are 0.559 and 0.653 and 0.459 and 0.468 respectively. However, on the basis of aperture and gross area for ETC with 8 tubes, the values found to be 0.595 and 0.416 respectively. Without auxiliary heating, the minimum chilled outlet temperature recorded was -3.2 ℃ after attaining hot return temperature of 118 ℃. The experimental result shows that the temperature around 10-15 ℃ achieved when fan coil was turned on in an office of 35 m^2 in clear, cloudy or partial cloudy conditions, which is suitable for air-conditioning. NTC can receive diffused light efficiently , thus suitable for use in any weather conditions. Additionally, to validate the authenticity of experimental results, the numerical analysis was also performed, and the results were quite similar. This study implies that NTC augmented with single effect NH_3-H_2O absorption chiller proved to be feasible and a better alternative to integrate renewable energy in medium temperature applications like air conditioning systems in buildings as NTC produces temperature above 100 ℃ compared to non-concentrated evacuated tube solar collectors. It has been proved that NTC can be used to operate NH_3-H_2O absorption chiller and get temp below 0 ℃ which is not only suitable for air conditioning but for freezing too, especially its use in sea food industry. Thus, NTC associated with NH_3-H_2O absorption chiller can be used as process heat and cooling applications in industries.

REFERENCES

Abdulateef, JM, Sopian, Kamaruzzaman, & Alghoul, MA. (2008). Optimum design for solar absorption refrigeration systems and comparison of the performances using ammonia-water, ammonia-lithium nitrate and ammonia-sodium thiocyanate solutions. *International Journal of Mechanical and Materials Engineering, 3*(1), 17-24.

Al-Zubaydi, Ahmed Y Taha. (2011). Solar air conditioning and refrigeration with absorption chillers technology in Australia–an overview on researches and applications. *Journal of Advanced Science and Engineering Research, 1*(1), 23-41.

Ali, Shahid, Taweekun, Juntakan, Techato, Kuaanan, Waewsak, Jompob, & Gyawali, Saroj. (2019). GIS based site suitability assessment for wind and solar farms in Songkhla, Thailand. *Renewable energy, 132*, 1360-1372.

Aman, Julia, Ting, DS-K, & Henshaw, Paul. (2014). Residential solar air conditioning: Energy and exergy analyses of an ammonia–water absorption cooling system. *Applied Thermal Engineering, 62*(2), 424-432.

Ayompe, LM, Duffy, Aidan, Mc Keever, M, Conlon, Michael, & McCormack, SJ. (2011). Comparative field performance study of flat plate and heat pipe evacuated tube collectors (ETCs) for domestic water heating systems in a temperate climate. *Energy, 36*(5), 3370-3378.

Budihardjo, I, Morrison, GL, & Behnia, M. (2003). *Development of TRNSYS models for predicting the performance of water-in-glass evacuated tube solar water heaters in Australia.* Paper presented at the Destination Renewables-ANZSES 2003 Conference. New South Wales. Australia.

Cengel, Yunus A, & Boles, Michael A. (2002). Thermodynamics: an engineering approach. *Sea, 1000*, 8862.

Choudhury, B, Chatterjee, PK, & Sarkar, JP. (2010). Review paper on solar-powered air-conditioning through adsorption route. *Renewable and sustainable energy reviews, 14*(8), 2189-2195.

Deng, J, Wang, RZ, & Han, GY. (2011). A review of thermally activated cooling technologies for combined cooling, heating and power systems. *Progress in Energy and Combustion Science, 37*(2), 172-203.

Ghoneim, Adel A. OPTIMIZATION OF EVACUATED TUBE COLLECTOR PARAMETERS FOR SOLAR INDUSTRIAL PROCESS HEAT.

Gomri, Rabah. (2010). Investigation of the potential of application of single effect and multiple effect absorption cooling systems. *Energy Conversion and Management, 51*(8), 1629-1636.

Häberle, A, Luginsland, F, Zahler, C, Berger, M, Rommel, M, Henning, HM, . . . Aprile, Marcello. (2007). *A linear concentrating Fresnel collector driving a NH3-H2O absorption chiller.* Paper presented at the Proceedings of the 2nd International Conference Solar Air-Conditioning, Tarragona.

Herold, Keith E, Radermacher, Reinhard, & Klein, Sanford A. (2016). *Absorption chillers and heat pumps*: CRC press.

Izquierdo, M, Venegas, M, Rodríguez, P, & Lecuona, A. (2004). Crystallization as a limit to develop solar air-cooled LiBr–H2O absorption systems using low-grade heat. *Solar energy materials and solar cells, 81*(2), 205-216.

Kabeel, AE, Dawood, Mohamed M Khairat, & Shehata, Ali I. (2017). Augmentation of thermal efficiency of the glass evacuated solar tube collector with coaxial heat pipe with different refrigerants and filling ratio. *Energy conversion and management, 138*, 286-298.

Kalkan, Naci, Young, EA, & Celiktas, Ahmet. (2012). Solar thermal air conditioning technology reducing the footprint of solar thermal air conditioning. *Renewable and Sustainable Energy Reviews, 16*(8), 6352-6383.

Kalogirou, Soteris. (2003). The potential of solar industrial process heat applications. *Applied Energy, 76*(4), 337-361.

Karamangil, MI, Coskun, S, Kaynakli, O, & Yamankaradeniz, N. (2010). A simulation study of performance evaluation of single-stage absorption refrigeration system using conventional working fluids and alternatives. *Renewable and Sustainable Energy Reviews, 14*(7), 1969-1978.

Li, Qiyuan, Zheng, Cheng, Shirazi, Ali, Mousa, Osama Bany, Moscia, Fabio, Scott, Jason A, & Taylor, Robert A. (2017). Design and analysis of a medium-temperature, concentrated solar thermal collector for air-conditioning applications. *Applied Energy, 190*, 1159-1173.

Mangal, Dharamvir, Lamba, Devander Kumar, Gupta, Tarun, & Jhamb, Kiran. (2010). Acknowledgement of evacuated tube solar water heater over flat plate solar water heater. *International Journal of Engineering (IJE), 4*(4), 279.

Mateus, Tiago, & Oliveira, Armando C. (2009). Energy and economic analysis of an integrated solar absorption cooling and heating system in different building types and climates. *Applied Energy, 86*(6), 949-957.

McCulloch, Archie. (2003). Fluorocarbons in the global environment: a review of the important interactions with atmospheric chemistry and physics. *Journal of fluorine chemistry, 123*(1), 21-29.

Muthu, V, Saravanan, R, & Renganarayanan, S. (2008). Experimental studies on R134a-DMAC hot water based vapour absorption refrigeration systems. *International Journal of Thermal Sciences, 47*(2), 175-181.

Nkwetta, Dan Nchelatebe, & Smyth, Mervyn. (2012a). Comparative field performance study of concentrator augmented array with two system configurations. *Applied energy, 92*, 800-808.

Nkwetta, Dan Nchelatebe, & Smyth, Mervyn. (2012b). Performance analysis and comparison of concentrated evacuated tube heat pipe solar collectors. *Applied energy, 98*, 22-32.

Nkwetta, Dan Nchelatebe, & Smyth, Mervyn. (2012c). The potential applications and advantages of powering solar air-conditioning systems using concentrator augmented solar collectors. *Applied energy, 89*(1), 380-386.

Raghuvanshi, Satish, & Maheshwari, Govind. (2011). Analysis of ammonia–water (NH3-H2O) vapor absorption refrigeration system based on first law of thermodynamics. *International Journal of Scientific & Engineering Research, 2*(8), 1-7.

Ratismith, Wattana, Favre, Yann, Canaff, Maxime, & Briggs, John. (2017). A non-tracking concentrating collector for solar thermal applications. *Applied energy, 200*, 39-46.

Ratismith, Wattana, Inthongkhum, Anusorn, & Briggs, John. (2014). Two non-tracking solar collectors: Design criteria and performance analysis. *Applied energy, 131*, 201-210.

Sabatelli, V, Fiorenza, G, & Marano, D. (2005). Technical status report on solar desalination and solar cooling. *NEGST– new generation of solar thermal systems is a project financed by the European Commission DGTREN within FP6*.

Sabiha, MA, Saidur, R, Mekhilef, Saad, & Mahian, Omid. (2015). Progress and latest developments of evacuated tube solar collectors. *Renewable and sustainable energy reviews, 51*, 1038-1054.

Schmid, R, Collins, RE, & Mannik, E. (2006). Performance comparison of flat plate and evacuated tubular collectors used in the Sydney University solar cooling and heating project. *University of Sydney, Australia*.

Singh, Ragh Vendra, Kumar, Shiv, Hasan, MM, Khan, M Emran, & Tiwari, GN. (2013). Performance of a solar still integrated with evacuated tube collector in natural mode. *Desalination, 318*, 25-33.

Sultana, Tanzeen, Morrison, Graham L, & Rosengarten, Gary. (2012). Thermal performance of a novel rooftop solar micro-concentrating collector. *Solar Energy, 86*(7), 1992-2000.

Trygg, Louise, & Amiri, Shahnaz. (2007). European perspective on absorption cooling in a combined heat and power system–a case study of energy utility and industries in Sweden. *Applied Energy, 84*(12), 1319-1337.

Wang, Kai, Abdelaziz, Omar, Kisari, Padmaja, & Vineyard, Edward A. (2011). State-of-the-art review on crystallization control technologies for water/LiBr absorption heat pumps. *International Journal of Refrigeration, 34*(6), 1325-1337.

Wang, RZ, Ge, TS, Chen, CJ, Ma, Q, & Xiong, ZQ. (2009). Solar sorption cooling systems for residential applications: options and guidelines. *International Journal of refrigeration, 32*(4), 638-660.

Wei, Xialu. (2010). *Evaluation of the efficiency of evacuated tube solar thermal collector based on finite element analysis*: Southeastern Louisiana University.

Werner Weiss, Monika Spörk-Dür. (2018). Solar Heat Worldwide (Global Market Development and Trends in 2017). In A.-I. f. S. Technologies (Ed.), (pp. 94). Austria: STEINHUBER INFODESIGN, Graz, Austria.

Widyolar, Bennett, Winston, Roland, Jiang, Lun, & Poiry, Heather. (2014). Performance of the Merced demonstration XCPC collector and double effect chiller. *Journal of Solar Energy Engineering, 136*(4), 041009.

Wu, WEI, Wang, Baolong, Shi, Wenxing, & Li, Xianting. (2014). An overview of ammonia-based absorption chillers and heat pumps. *Renewable and Sustainable Energy Reviews, 31*, 681-707.

Yan, QS, Shi, WX, & Tian, CQ. (2010). Refrigeration technology for air conditioning. *China Building Industry Press, China*, 32.

APPENDICES

APPENDIX A

Conference certificate

CERTIFICATION OF ATTENDANCE

This certifcate is awarded to

Dilawer Ali

for presentation on

"Experimental study on Efficient, Environmental and Economically viable low speed Darrieus - Savonius vertical axis wind turbine using Wind Boosters"

in ASSURING SUSTAINABILITY via University with Research: Towards a sustainable development (ASSURE 2018) International Conference

23th January 2018
Ranong Room Siam Oriental Hotel
Hatyai, Songkhla, Thailand

Assoc. Prof. Dr. Banchong Witthayawirasak
Dean, Faculty of Environmental Management
Prince of Songkla University

VITAE

Name Mr. DILAWER ALI

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Scholarship Awards during Enrollment

Interdisciplinary Graduate School (IGS) Contract no. IGS-Energy 2017/04

Awarded Scholarship for Bachelor’s study in Electrical Engineering at University of Engineering and Technology Peshawar, Pakistan. │ 2011 – 2015.

Work – Position and Address

Project Coordinator at Huawei Technologies Private Limited, Islamabad November 2017 – May 2018.

List of Publication and Proceeding

<u>Journal Publications</u>

Wattana Ratismith, **Dilawer Ali** & John Briggs* (2019). A non-tracking semi-circular trough solar concentrator. Solar Energy (ISI Web of Science; IF 4.8) (Under Review)

Dilawer Ali, Shahida Batool, Kuaanan Techato*, Saroj Gyawali & Montri Suklueng (2018). GIS-MCDM approach to determine forest plantation areas in U-tapao river basin, Songkhla, Thailand. International Journal of Integrated Engineering (IJIE). (SCOPUS) (Accepted)

Ismail Kamdar, **Dilawer Ali**, Juntakan Taweekun*, Warangkana Jutidamrongphan & Kuaanan Techato (2019). A review study on municipal solid waste management and waste to energy technologies. International Journal of Integrated Engineering (IJIE). (SCOPUS) (Accepted)

D**ilawer Ali***, Fida Ali & Ismail Kamdar (2019). A review of efficient and economically viable self-starting Darrieus vertical axis wind turbines. Journal of Environmental Management and Energy System (JEMES). (Under Review)

Fida Ali*, **Dilawer Ali** & Ismail Kamdar (2019). A review of Ultra-low head hydro turbines and their application in Thailand. Journal of Environmental Management and Energy System (JEMES). (Under Review)

Conference proceedings

Dilawer Ali, Khamphe Phoungthong, Montri Suklueng & Kuaanan Techato: "Title: Experimental study on Efficient, Environmental and Economically viable low speed Darrieus – Savonius vertical axis wind turbine using Wind" at Assuring Sustainability via University with Research: Towards a sustainable development (ASSURE 2018) International Conference, 23 January, Ranong Room Siam Oriental Hotel, Hat Yai, Songkhla, Thailand.

Dilawer Ali: Attended International Conference on Energy Systems and Environmental Management (ESEM 2018) on 22nd June 2018, Golden Crown Grand Hotel Hat Yai, Songkhla, Thailand