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Simulation of hybrid solar ejector cooling system using TRNSYS and EES for Kuwait climate

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ABSTRACT
Cooling systems in Kuwait are mainly operated by vapor compression chillers. The needs of the electrical power of the cooling system in the state of Kuwait are investigated which shows an average of 50 % of the total annual power consumption account of these needs. Almost 75% of the total power consumption goes to air-conditioning systems during the month of highest power demand by building sector. This high demand could be satisfied from a clean energy resource if solar cooling techniques were adopted especially in commercial buildings. Kuwait's annual solar radiation is predicted to be between 2100 and 2200 kW/m^2, and the range from 7 to 12 is the average daily sunshine hours/year. According to 2015 Kuwait Energy Policy, Laws and Regulations, the solar PV is the most useful RE source for the country because the peak electricity demand and the maximum solar radiation occurs at the same time of the year. Therefore, Kuwait plan to increase the share of RE in future electrical power production. This study describes a simulation program developed on the TRNSYS-EES softwares. This program is used to design the hybrid photovoltaic-thermal (PV-T) solar system components and to evaluate the performance of the solar ejector cooling system with water as a refrigerant. A typical cooling load for a med-size commercial building such as (Kettering Lab) will be used along with Energy Plus Weather (EPW) data for Kuwait. This study aimed to evaluate the prospect of hybrid photovoltaic-thermal (PV-T) solar system in generating electricity as an alternative to decrease dependency on combined cycle gas turbine Kuwait power stations and meet the typical cooling load for a med-size commercial building. The result show that the system will produce 280 kwh of energy. That result is almost meet the required cooling load for the building which is 329 kwh.
Keywords–Ejector, Hybrid Photovoltaic-Thermal, Solar PV, Simulation.

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I. INTRODUCTION

The state of Kuwait has suffered from harsh climatic conditions that originate from the advent of oil production. The atmosphere in Kuwait has been rendered susceptible to spikes in temporal and humidity levels thereby calling for the use of mechanical cooling systems. Before the oil production began, most buildings in the state were kept cool through the use of architectural features that were passive in both their construction and designs be they the underground basements, small windows, thick walls, shading and also the orientation (Alhaddad, Ettouney, & Saqer, 2015). Musings have shown that the first conditioning units used in the state were window type air conditioners with central air conditioner following suit which barely paid any homage to the various rules and regulations used in ensuring for the conservation of energy in building design and construction (Alhaddad, Ettouney, & Saqer, 2015). This has, in turn, caused an influx in the demand for electricity both on the national and capita basis. The overall growth rate has increased by 6% with the national average being determined at 12%.

By geographical definition, Kuwait can be said to be a flat desert terrain with the summer climates being at peak values of 1000 w/m^2. The ambient temperatures during summer are quite high and mechanical systems are needed to counter this. The monthly mean temperatures from May through to September are normally high thereby affecting the power consumption.

A study by Ayash noted that the lowest monthly power consumption in the state occurs in March when there is no heating or cooling required (Ayash, 1983). This backs up the aforementioned theoretical statement that showed that there was extra power consumption needed for cooling and heating needs between December and February. Keynotes can be drawn on the fact that the power needs to be brought forth by the cooling systems not only consume a major share of the electricity generated but also leads to a rise in the shares. The patterns in the solar radiation and the daily temperatures also lead to change in the power consumption and the demand for cooling. The changes in the power demand result in a peak load which is a function of many factors that may include but not limited to the cooling systems used or even the environmental parameters in the state (Ayash, 1983). The peak load is significant as it helps derive measurements of the overall power generation facilities caused by the different environmental parameters. Note that the ambient temperatures in the state not only affect the cooling load and the influx in magnitudes but also affect the power consumed meaning that the systems have an enormous role in the overall size of the facilities used in power generation (Ayash, 1983). Kuwait's annual solar radiation is predicted to be between 2100 and 2200 kW/m^2, and the range from 7 to 12 is the average daily sunshine hours/year (Abdullahi, Asan, & Saud, 2018).

The needs of the electrical power of the cooling system in the state of Kuwait are investigated which shows an average of 50 % of the total annual power consumption account of these needs (Hajiah, 2006). Almost 75% of the total power consumption goes to air-conditioning systems during the month of highest power demandby building sector (Hajiah, 2006) figure 1.Kuwait is considered one of the highest per capita consumption of electrical energy in the world.

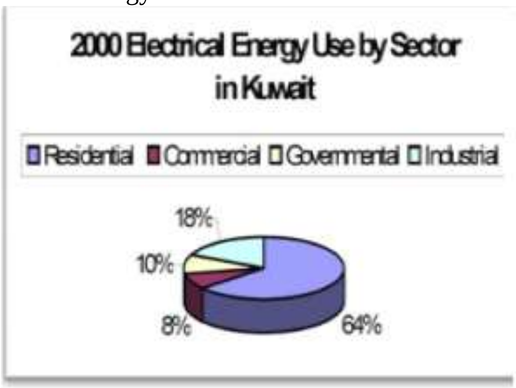

Figure 1: Distribution of Kuwait Electrical Energy Consumption by End-Use Sector

The rapid increase in the energy consumption become the ultimate concern in Kuwait. These concerns are trigger for questioning energy resources' reliability and environmental impact. According to 2015 Kuwait Energy Policy, Laws and Regulations, the solar PV is the most useful RE source for the country because the peak electricity demand and the maximum solar radiation occurs at the same time of the year. Factors that account for unsustainable energy use include but not limited to economic development, increase in energy demand, and environmental pollution. As a result, renewable sources of energy are widely sought after in order to address such challenges. These sources are clean, sustainable, and easy to harness. (Ramos, 2017) examines the role of hybrid photovoltaic-thermal (PV-T) solar systems in power supply as well as combined cooling and heating (p.838). It is an attractive technology that appeared in the recent decades.The affordable deployment of this technology is recognized as a major step towards the integration of renewable sources of energy (Ramos, 2017). PV-T solar systems and solar absorption chillers are poised to bridge the gap between efficiency and cost (Ramos, 2017).

Hybrid PV-T systems generate thermal energy and electricity from the same area. Water based PVT collectors are normally used only during the day for electricity generation and thermal energy production. Depending on the application, the main objective is either the electricity production or the thermal output. Therefore, they can be integrated with energy storage facilities to provide multiple energy outputs, with ease. Solar systems allow for self-consumption, which translates to a reduction in electricity bills. They are also resilient to political instability and oil price fluctuations. The hybrid photovoltaic-thermal (PV-T) collectors can reach overall efficiencies of 70% or higher. It is depending on the conditions, the electrical efficiencies up to 15–20% and thermal efficiencies more than 50% (Ramos, 2017). In addition, hybrid PV-T and solar PV cells are reliable and can operate for over 20 years with little deterioration. Commercial PV-T systems are mostly integrated with solar thermal collectors and existing PV modules.

Ejector is a thermally driven technology that has been used for cooling applications. The first steam ejector refrigeration system was developed by Maurice Leblanc in 1910. The most advantage of the ejector is the capability to produce refrigeration by using waste heat or solar energy as a heat source at temperatures above 80°C(Chunnanond & Aphornratana, 2004). It can produce a refrigeration effect by utilizing low-grade energy sources.

1.0 Description and Approach

The methodology of this study is to simulate hybrid solar ejector cooling system using TRNSYS and EES to meet a typical cooling demand for med-size commercial building. Hybrid solar ejector cooling system cycle includes three different temperatures. The hottest temperature heat flow (T_h) is driven from a heat source. In this case, hybrid photovoltaic-thermal (PV-T) are employed to supply the high temperature fluid needed for the ejector cooling cycle. The lowest temperature heat flow (T_l) goes to the load through heat exchanger. The medium temperature heat flow (T_{mid}) what gets rejected to the Borehole Thermal Energy Storage (BTES) out of the system to prevent the fluctuating of the ambient wet-bulb temperature. The extremely Kuwait hot summer weather will not affect the system when the cooling load at highest, since the ground temperature is constant through the year.

The approach entailed developing a mathematical model of the ejector in the EES software since the ejector is not included in the standard TRNSYS component library. Also, EES has a limitation number of using variables that can be stored, so this lead to use a combination of both programs for this project.

I incorporated the refrigerant properties of Water in the EES data store into the program for coupling with TRNSYS model for simulating the hourly weather data for Kuwait at latitudeof 29.3375° N and longitude of 47.6581° E. I used Energy Plus Weather (EPW) data collected for 1995 on Kuwait airport, which consisted of total solar radiation and ambient temperature. The PV-T model in TRNSYS does not support vapor phase which used in vacuum tubes. Therefore, a heat exchanger model was developed in EES to separate the PV-T model in separate cycle from the refrigerant cycle figure 2. That is one of the main concepts in this project is using vacuum tube to get low boiling point for the refrigerant. Since the main advantage of the vapor jet ejector cycle is that it can produce a refrigeration effect by utilizing low-grade energy sources.

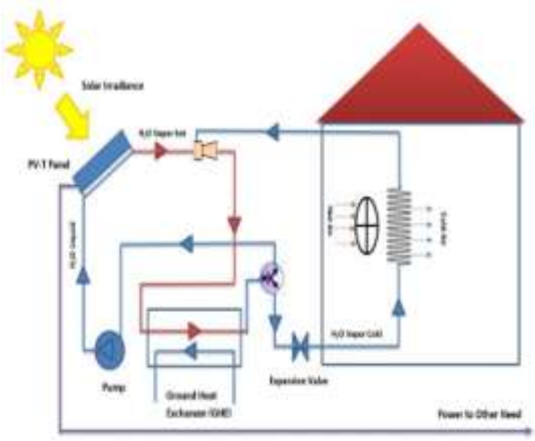

Figure 2: Steam ejector refrigeration cycle

2.0 Input Data

Energy delivered by the hybrid photovoltaic-thermal solar (PV-T) array calculated by using a computer model of the PV-T through TRNSYS for process hot water use as the heat source and electric energy produced and simulate its annual performance on hourly basis. The input data that we need at this study divided into four categories: Site and Building Data, Weather Data, Hybrid Photovoltaic-Thermal Solar Data, and Ejector.

2.1 Site and Building Data

The study is located at one of the college building in Kuwait with latitude 29.3117 ° N and Longitude 47.4818 ° E. The PV-T system will be installed to fit on the rooftop of the building which is assumed similar to the Kettering Lab will simulate the building roof area and load. The available roof area on the Kettering Labs building is about 2750 m2. The total area of the system will be 2749 m2, as shown in Figure 3.

Figure 3: The location of the solar concentrator array system

To calculate the Energy delivered by the system the desired hot water temperature assumed to be 40 C and the water main buried at depth of 1.5 m and the average ground temperature at Kuwait City is 13.1 °C. The Kettering Lab energy cooling load found through Esim which was developed by Dr. Kelly Kissock(Kissock, 1994). In Table 1, a sample result from Esim shows that Kettering Lab cooling load in the column named "Eac (kWh/hr)".

Table 1: Esim Hourly Load (in kWh) Results – Simple

Mo	Dy	Yr	Hr	Toa (F)	Qnet (kBtu/ hr)	NGf (kBtu/ hr)	NGhw (kBtu/ hr)	Ngext (kBtu/ hr)	NG (kBtu/ hr)	Elight (kWh/ hr)	Eplug (kWh/ hr)	Eext (kWh/ hr)	Eac (kWh/ hr)	Efan (kWh/ hr)	E (kWh/ hr)
1	1	1995	1	56	571	0	0	0	0	83.9	83.9	0	433.3	22.8	623.9
1	1	1995	2	55	516	0	0	0	0	83.9	83.9	0	437.3	22.8	627.8
1	1	1995	3	54	480	0	0	0	0	83.9	83.9	0	434.4	22.8	625
1	1	1995	4	53	459	0	0	0	0	83.9	83.9	0	432.3	22.8	622.8
1	1	1995	5	51	446	0	0	0	0	83.9	83.9	0	418.6	22.8	609.1
1	1	1995	6	51	441	0	0	0	0	83.9	83.9	0	420.1	22.8	610.6

2.2 Weather Data

The weather data for most middle eastern countries is difficult to find but the latest weather data for Kuwait City is available in Energy Plus version. The Energy Plus file is an hourly weather data that can be read by TRNSYS and used to simulate the annual hourly energy produce by both systems (solar and thermal). In Table 2 is a sample of the Energy Plus data for Kuwait City. The main factors that used by TRNSYS are Dry Bulb Temperature, and Normal Solar.

Table 2: Energy plus weather data for Kuwait - Simple

Date/Time	Dry Bulb Temperature [C]	Wet Bulb Temperature [C]	Atmospheric Pressure [kPa]	Relative Humidity [%]	Dew Point Temperature [C]	Global Solar [Wh/m2]	Normal Solar [Wh/m2]	Diffuse Solar [Wh/m2]	Wind Speed [m/s]
[illegible]	13.3	12.35	102.33	92	12.06	0	0	0	6
[illegible]	13	11.88	102.37	88	11.09	0	0	0	7
[illegible]	12.4	11.31	102.41	88	10.5	0	0	0	7
[illegible]	11.8	10.91	102.38	90	10.25	0	0	0	5
[illegible]	10.6	10.17	102.36	95	9.66	0	0	0	4
[illegible]	10.6	9.92	102.47	92	9.39	0	0	0	3

2.3 Hybrid Photovoltaic-thermal (PV-T) Solar Data

Hybrid photovoltaic-thermal solar (PV-T) panels generate electric and solar power. These panels are constructed layers. The first layer for the photovoltaic which is generate the electricity from the sun light directly. The second layer for solar thermal which is generate energy by heating the refringent fluid. The efficiency of PV panels is decrease by increase the panels temperature, so, the second benefit of the solar thermal layer is to decrease the PV panels temperature to get the maximum power that can be produce. For this project the PV-T panels that manufactured by DUALSUNWave are used. The following are the panel specification data for the chosen panel:

I. Thermal Data:

- For Insulated BIOV, a = 0.51 (same as FR(τα)n); b = 11.4 W/m2-K (same as FRUL)
- Collector Area = 1.58 m2
- Collector Fluid = 50% propylene glycol
- Collector Length = 1677 mm
- Solar Flux Threshold = 5 w/m2

II. Electrical Data:

- Nominal power = 250 W
- Model efficiency = 15.40%
- NOCT = 49 C
- Efficiency loss = 0.44%/C

In Figure 4, a full demonstration of the PV-T panel dimensions. The number of collectors that was used for this study is 1740 collectors and the total Collector Array Area is (2749 m2).

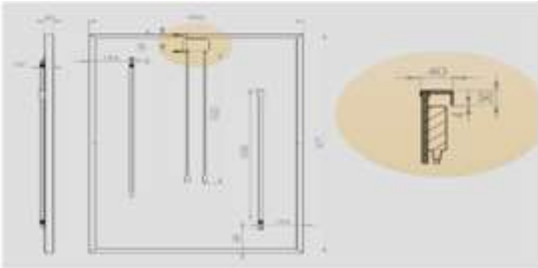

Figure 4: PV-T panel dimensions

2.4 Ejector

Ejector is a thermally driven technology that has been used for cooling applications. The most advantage of the ejector is the capability to produce refrigeration by using waste heat or solar energy as a heat source. In this study ejector is used for this advantage. Operating the system with the ejector should follow couple of steps. First, the working fluid as refrigerant which is water should enter the ejector as steam. Therefore, to boil the water at low temperature the vacuum tube needed which will be the right choice to go with for this project. In this case, the 40 C chosen to be the desire temperature and by looking at Table 3 the pressure needed for the vacuum tube is 73.48 mbar (7.348 kPa).

Table 3: boiling temperature for the water at different vacuum pressure

Absolute pressure				Vacuum (below standard atmospheric pressure)			Water boiling point	
[Microns] [μm Hg]	[in Hg]	[psia]	[mbara] [0.01*Pa]	[in Hg]	[mmHg] [Torr]	[mbar] [0.01*Pa]	[°C]	[°F]
760000	29.92	14.696	1013.3	0	0	0	100	212
635000	25.00	12.279	846.6	4.92	125.0	16661	96	205
525526	20.69	10.162	700.6	9.23	234.4	31256	90	194
500000	19.69	9.668	666.6	10.24	260.1	34677	89	192
355092	13.98	6.866	473.4	15.94	404.9	53979	80	176
233680	9.200	4.519	311.5	20.72	526.3	70166	70	158
200000	7.874	3.867	266.6	22.05	560.1	74670	67	152
149352	5.880	2.888	199.1	24.04	610.6	81409	60	140
100000	3.937	1.934	133.3	25.98	659.9	87978	52	125
92456	3.640	1.788	123.3	26.28	667.5	88994	50	122
55118	2.170	1.066	73.48	27.75	704.9	93972	40	104
31750	1.250	0.614	42.33	28.67	728.2	97088	30	86
25400	1.000	0.491	33.86	28.92	734.6	97934	27	80
22860	0.900	0.442	30.48	29.02	737.1	98273	24	76
20320	0.800	0.393	27.09	29.12	739.6	98612	22	72

Second, the cycle that was used for this project called steam ejector refrigeration cycle which shown in Figure 5 both the system sketch and pressure (P) vs. specific enthalpy (S) plot. The main advantage of the vapor jet ejector cycle is that it can produce a refrigeration effect by utilizing low-grade energy sources.

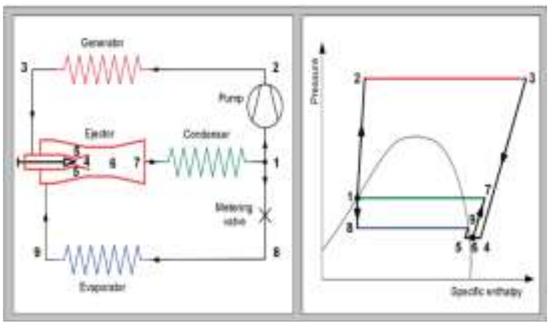

Figure 5: system sketch and pressure (P) vs. specific enthalpy (S) for steam ejector refrigeration cycle

Third, the ejector is one of the main components in the cycle that play very important rule which used as a replacement of a compressor. The main construction and inside components of the ejector shown in Figure 6.

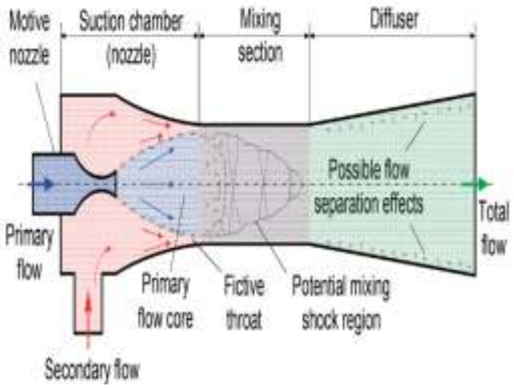

Figure 6: Schematic of a typical two-phase ejector design

II. RESULT AND CONCLUSIONS

After building the TRNSYS diagram which is shown in Figure 8. This diagram includes five EES models which would be calling by TRNSYS. The coded models are Heat Exchanger, Ejector, Condenser, Expansion Valve and Evaporator, and Pump. Unfortunately, when TRNSYS run gives error message which is shown in Figure 7. This message means that there is a problem with the clipboard function that transfer the results to both programs. It seems that the problem from EES and most users who used "calling from EES" component in TRNSYS reported the same problem. Moreover, the calling from EES example in TRNSYS doesn't run and show the same error message. After contacting the TRNSYS support team there was no solid solution for this problem currently but maybe in the future. In this case, another solution was proposed which will be explain in Section 5.1.

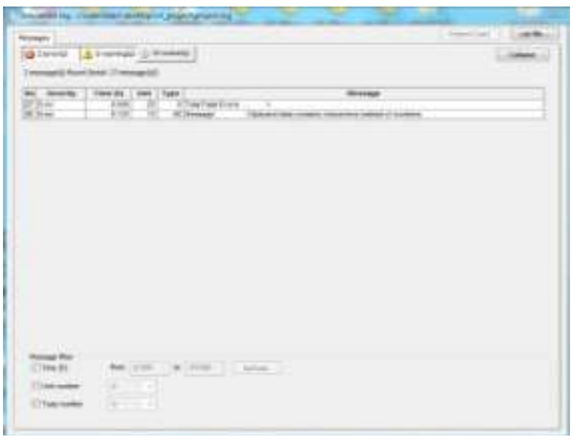

Figure 7: TRNSYS error message

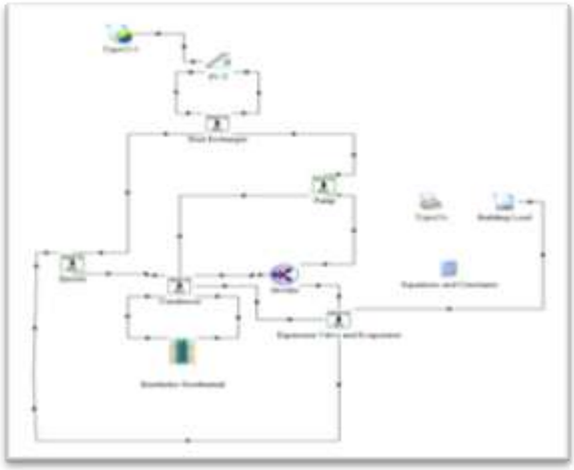

Figure 8: TRNSYS Diagram

a. Output Data

The alternative solution is to run a study state case for one hour in as specific day and month. July 13 at 1pm was chosen to be the study state case because July is the hottest month and around noon is also the hottest hour of the day in Kuwait.

The code and the simulation of the system was only by using EES. Figure 10 shows the whole system results for the simulation but there are some points that should be pointed. First, the Energy produce by the solar panels (PV) without counting for the solar thermal cooling is 311.2 kWh and the efficiency is 12.14 %. On the other hand, by counting for the solar thermal cooling the power increased to reach 334.4 kWh with 13.03 % efficiency. This an approve for something approved before which is the cooling of the PV cells is increase the efficiency and the power produced. Second, the load of the building is 329 kWh and the system able to reach 279.5 kWh which is close to the actual load. Third, in figure 9 shows evaporator process on a T-q diagram. Its clearly shows that the temperature interred the building to cool it is 18 oC and the return temperature from the building as almost 30 C which is losing and gaining energy.

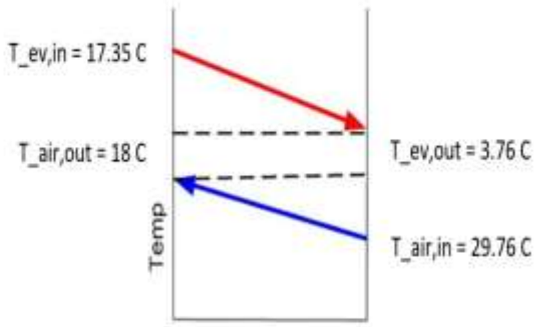

Figure 9: Evaporator process on a T-q diagram

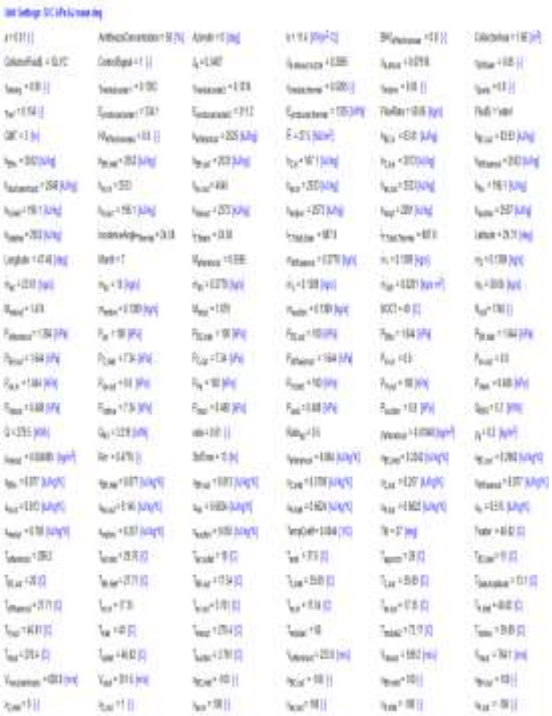

Figure 10: Study state results from EES

There are a few recommendations to improve the design for this project. First, find a solution for “Calling from EES” component in TRNSYS either by an update from the company or another solution that could be devolved. Second, since the medium temperature heat flow (Tmid) what gets rejected to the Borehole Thermal Energy Storage (BTES) out of the system to prevent the fluctuating of the ambient wet-bulb temperature. The Thermal Energy Storage (TES) could be store heat to ensure continuous heat flow, which supply to the system even after the sunset. That will overcome the discontinuous of the hybrid photovoltaic-thermal energy generation. Third, the refrigerant type could be changed to a better type than water to insure the best result. Forth, modify the system to work both ways cooling in the summer season and heating in the winter season for the building. This to make the system usable in all seasons.

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