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Thermodynamic Simulation Modelling of Low-Temperature Geothermal Source Located in Arid-Zone Area North Africa

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Abstract

This paper presents a thermodynamic modelling study of the utilization of an existing geothermal low-temperature heat source (114 kg/s and 73 °C) situated at Waddan city in Libya. Six models have been built and simulated using both IPSEpro refrigeration and power plant modelling libraries. All the models were validated in accordance to published literature and relevant fundamental thermodynamic tables and graphs. Results of five models have shown that the community in Waddan city could benefit from the geothermal source. For instance these models could provide 1284 ton of refrigeration at 5 °C, for air-conditioning use, or 835 ton of refrigeration at 0°C or 1324 kW of direct generated electricity. The sixth model has proved that this sustainable geothermal source could support a local electrical power station consisting of a natural gas fired turbine unit combined with an organic Rankin cycle. This station will provide Waddan city and surrounding villages with their demand of electrical and thermal energy of about 128MW (GT 85MW, ORC 18MW and District heating 25 MW at 75 °C).

Keywords: Arid-zone; low-temperature geothermal heat source; LiBr absorption chillers; air-conditioning; organic Rankin cycle; IPSEpro.

1. Introduction

In recent years, research has been devoted to improvement of absorption refrigeration systems. Mechanical vapour compression refrigerators require high grade energy for their operation. Apart from this, recent studies have shown that the conventional working fluids of vapour compression systems are causing ozone layer depletion and green house effect [1]. Absorption chillers powered by heat energy can be utilized. Since the temperature requirements for the cycle fell into the low to moderate temperature range, the water/air cooled lithium bromide water mixture single/half effect absorption chillers seem to be good prospect for geothermal application where heat inputs are at low temperatures. However most of these types of chillers, as mentioned by many researchers, were directly powered by low input mass flow rates of high or low temperature heat sources such as steam or hot water.

The most economical way to utilize geothermal source of energy is to use it as a powering source of single/half effect water/air cooled absorption chillers to produce air-conditioning, heating and hot water supply [2]. Many theoretical and experimental studies have been carried out on LiBr-H_2O absorption chillers powered by low heat sources. For instance, A.Kececiler et al. [3] performed experiments on LiBr-H_2O system in lab conditions used low temperature geothermal energy as a powering source. The obtained results showed that the maximum COP was gained when mass concentration of strong and weak solution in the generator and absorber were 0.44 and 0.48 respectively. They showed experimentally that the low-heat geothermal sources can not be used inefficiently in electricity generation, however could be used economically for refrigeration storing of fruits and vegetables at 4-10 °C as well as air conditioning. K. Sumathy et al. [4] developed prototype (cooling capacity = 100 kW) half effect LiBr-H_2O chiller powered by low temperature hot water source ranging from 60 to 75 °C. Test results indicated that the two-stage chiller could be powered by solar hot water system. Da-Wen Sun [5] simulated LiBr-H_2O absorption refrigeration systems. Detailed thermodynamic design data and optimum design maps were produced as a source of reference for developing new cycles and searching for new absorbent/refrigeration pairs. The derived tabulated thermodynamic design data showed that for low heat powering source at about 70 °C, the COP was 0.83 and the mass concentration of weak and strong solutions of LiBr were between 0.516 and 0.579 respectively when both condenser and absorber temperatures run at 30 °C. Figure 1 shows existing geothermal source at high potential and low-temperature heat situated at Waddan city 265 Km south of Libyan North coast.

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The well No. is T/2D/0013/0/88 at coordinates of X = 16 ° 09' 46'' ,Y = 29° 07' 06'' and at an elevation of 291 meters above sea level [6]. This existing sustainable freely available geothermal source was simulated using two IPSEpro power plant and refrigeration modelling libraries. Six schematic models, powered by this artesian hot water 12'' diameter well (1600 m deep) at constant flow rate of 114 kg/s and temperature of 73 °C, are presented in figures 5-10 respectively and they are namely as follows:

1- Water-cooled single effect LiBr-H_2O chiller.
2- Air-cooled single effect LiBr-H_2O chiller.
3- Water-cooled half effect LiBr-H_2O chiller.
4- Water-cooled half effect cascaded with CO_2 conventional compression cycle chiller.
5- Direct electrical generation organic Rankin cycle.
6- Water-cooled half effect cascaded with electrical generation gas turbine and R-245fa organic Rankin cycle.

Figures 2-4, show validation of simulated basic standalone models (single and half effect chillers), in accordance to the well known DÜhring temperature-pressure diagram [7]. The main state points of chillers cycle parameters were plotted at their state point locations on this diagram.

Figure 1. Well head of existing geothermal source

2. Modelling

The fundamental thermodynamic principles of mass and energy conservation were applied on all chiller cycle components. UA types of heat exchanger models were used for all of absorption chiller components except two components; the desorber unit which was modelled as an adiabatic flash drum for two-phase mixture where exiting streams are in equilibrium and exiting vapour is pure water, and in the absorber unit the restored poor solution takes up the occurring gaseous refrigerant mixture and leaves the absorber as a rich solution [8]. For heat exchangers, it is common to use UA formulation along with log-mean temperature difference (LMTD) as follows:

$$Q = UA \ \Delta T_{lm}$$

where Q : heat exchange capacity (w), U : overall heat transfer coefficient (w/m^2 k), A : heat transfer surface area (m^2), ΔTlm : logarithmic mean temperature difference (K)

$$\Delta T_{lm} = \frac{(T_{h,1} - T_{c,2}) - (T_{h,2} - T_{c,1})}{\ln \frac{T_{h,1} - T_{c,2}}{T_{h,2} - T_{c,1}}}$$

where h: hot side, c : cold side, 1 & 2 : either end of heat exchanger.

The maximum possible heat transfer can be calculated from

$$Q_{\max} = (mc_p)_{\min} \Delta T_{inlet}$$

where m : mass flow rate (kg/s), c_p : specific heat at constant pressure (kJ/kg K), ΔT_{inlet} : inlet temperature difference (K).

The energy balance on each of heat exchangers is:

$$Q = \dot{m} \Delta h$$

where $\dot{m}$: mass flow rate (kg/s), Δh : the enthalpy difference between inlet and outlet of heat exchangers (kJ/kg).

The coefficient of performance of absorption chillers can be written as:

$$COP = \frac{Q_{evaporator}}{Q_{generator}}$$

The mass fraction of two-component (binary) mixture of LiBr/H_2O can be, in general, expressed as:

$$x = \frac{mass\ of\ one\ component\ (kg)}{Total\ mass\ of\ both\ components\ (kg)}$$

3. Simulated Models Results and Discussion

3.1 Water-cooled single effect

It can be seen from simulated results in figure 5, that the best obtained COP and refrigeration capacity, at outlet chilled water temperature of 5 °C, were 0.8245 and 563 ton respectively. In addition the useful rejected energy from the desorber was 15739 kW at outlet temperature of 68 °C. These output results achieved when the cycle operated between 0.51 and 0.55 of LiBr-H_2O solution mass fraction and between two low pressure levels of 0.04 and 0.007 bar. The cooling water supply, for removing excess heat from absorber and condenser, was in parallel connection to cycle components at an input mass flow rate of 258 kg/s and at 25 °C.

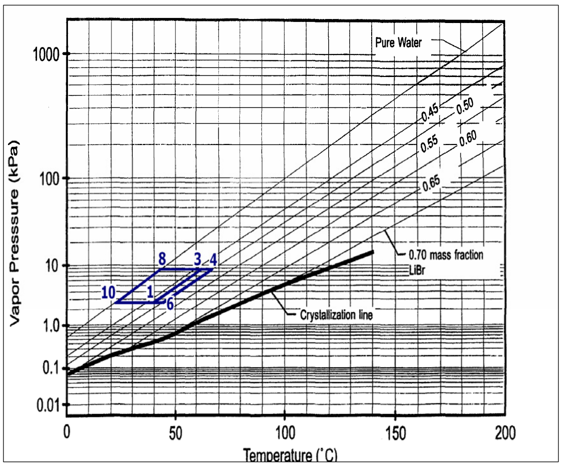


Figure 2. DÜhring plot for validation of Water-cooled single effect model

3.2 Air-cooled single effect

As shown in figure 6, the model was simulated at an outdoor average mean maximum dry bulb temperature of 40 °C (design reference point according to ASHRAE). The range of LiBr-H2O solution mass fraction was between 0.47 and 0.5 which was less than that used in water-cooled single effect cycle due to higher weak solution outlet temperature of the absorber, hence higher heat transfer rate circulated in the cycle. The cycle was performed between two pressure levels 0.026 and 0.0865 bar. The achieved COP and refrigeration capacity were 0.845 and 628 ton respectively. The chilled water outlet temperature of the evaporator was noticeably high (22ºC) but still within the range of air-conditioning use in hot climate conditions such as Waddan city. The utilized output heating energy was roughly equals to that produced from water-cooled single effect chiller.

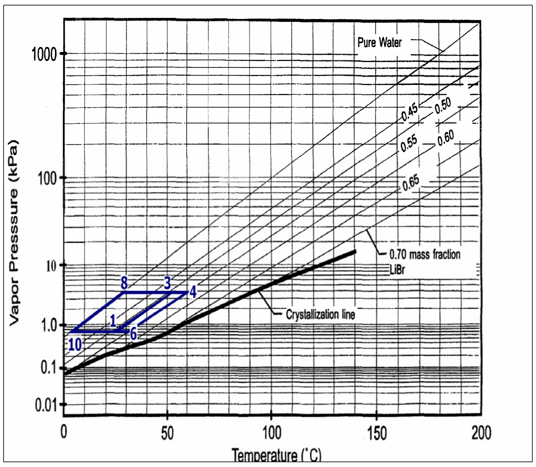


Figure 3. DÜhring plot for validation of Air-cooled single effect model

3.3 Water-cooled half effect

The schematic configuration of this model is shown in figure 7, the model is operated in three-pressure levels (0.07, 0.018 and 0.0071 bar). The high and low pressure levels function in the same way similar to the single effect one. The intermediate pressure level is the new feature of this cycle arrangement, and at this pressure level, the low desorber delivers refrigerant vapour to the high absorber.

The obtained results have shown that a refrigeration capacity of 1284 ton was produced at outlet chilled water temperature of 5 ºC. This higher capacity was roughly double of water/air single effect chillers capacity. In this cycle more heat was extracted from the given powering source, hence no significant economical benefit of heat rejected from the desorber. A penalty must be paid when the cycle produced higher cooling capacity; the COP of the half effect is roughly half (0.424) of COP obtained from single effect chillers (0.8245-0.845). Both lower LiBr H2O mass fraction (0.41-0.44) in high pressure cycle and higher mass fraction (0.52-0.55) in low pressure cycle were circulated within modelled cycle.

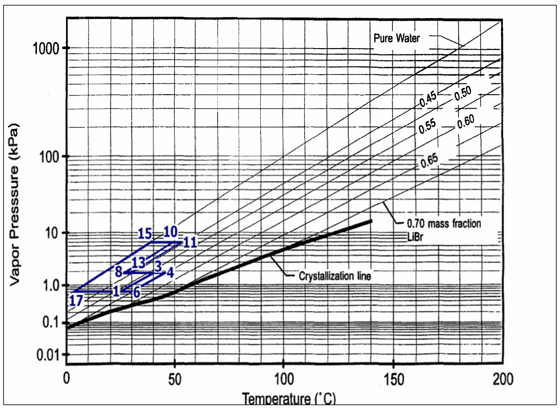


Figure 4. DÜhring plot for validation of Water-cooled half effect model

3.4 water-cooled half effect cascaded with conventional compression cycle CO2 chiller unit

To obtain further reduction of evaporator chilled water outlet temperature (≈ 0 ºC) in hot climate conditions, the half effect simulated absorption chiller model should be cascaded with carbon dioxide CO2 (R744) refrigeration compression cycle chiller model. The Selection of CO_2 as working refrigerant in the low temperature Rankin cycle, was based on the fact that this gas is natural, cheap, cause no damage to the environment, and is not hazardous. The complete schematic diagram for this combined cycle is shown in Figure 8. The results have shown that the refrigeration capacity was 835 ton at chilled temperature of roughly zero degrees centigrade.

3.5 Direct electrical generation organic Rankin cycle

The community in Waddan city could directly benefit from the existing geothermal source by simply installing an organic Rankin cycle (ORC) for direct electricity generation. R-245fa was found to be the most suitable working fluid among other related organic refrigerants, such as R134a. As shown in figure 9, the simulated results have indicted that a net electrical power of 1324 kW was produced at an ORC efficiency of 8.4 %.

3.6 Water-cooled half effect cascaded with gas turbine (GT) and R-245fa organic Rankin cycle (ORC)

Geothermal sources available in hot climate places and near natural gas fields could economically encourage local electrical investment companies to install combined cycle power plant (GT and ORC) to supply Waddan community

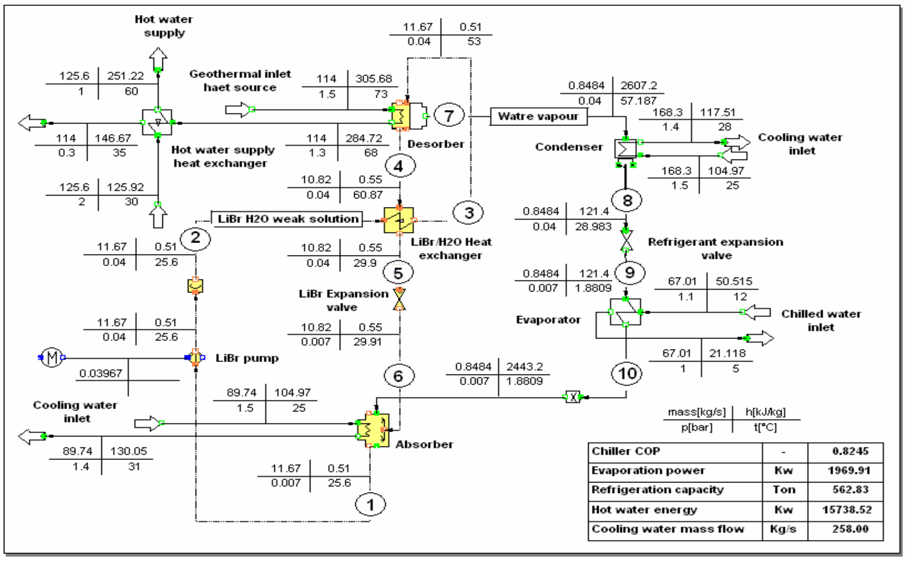


Figure 5. Water-cooled single effect LiBr-H2O absorption chiller

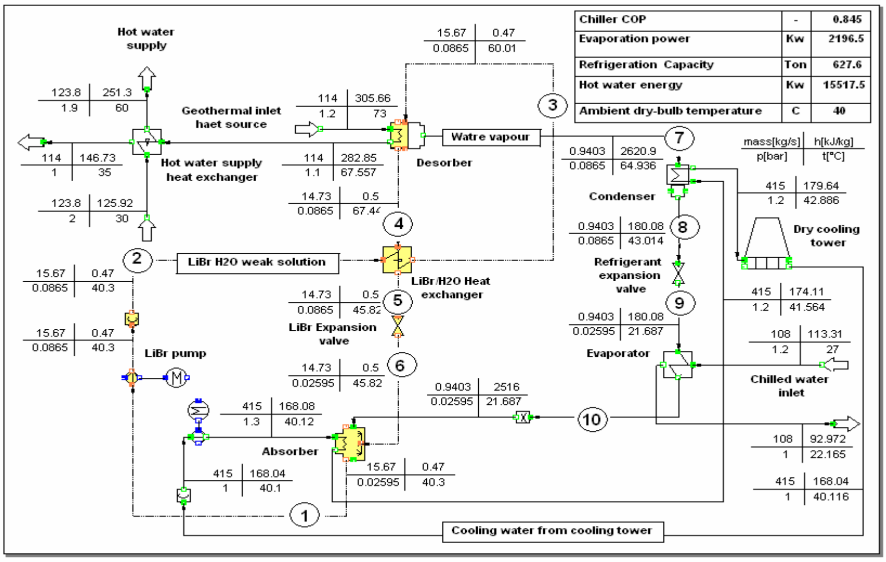


Figure 6. Air-cooled single effect LiBr-H2O absorption chiller

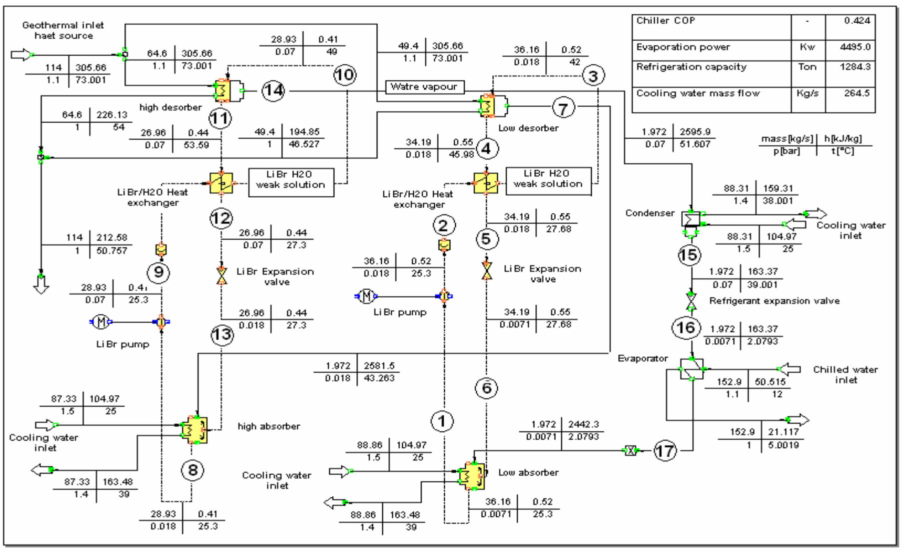


Figure 7. Water-cooled half effect LiBr-H2O absorption chiller.

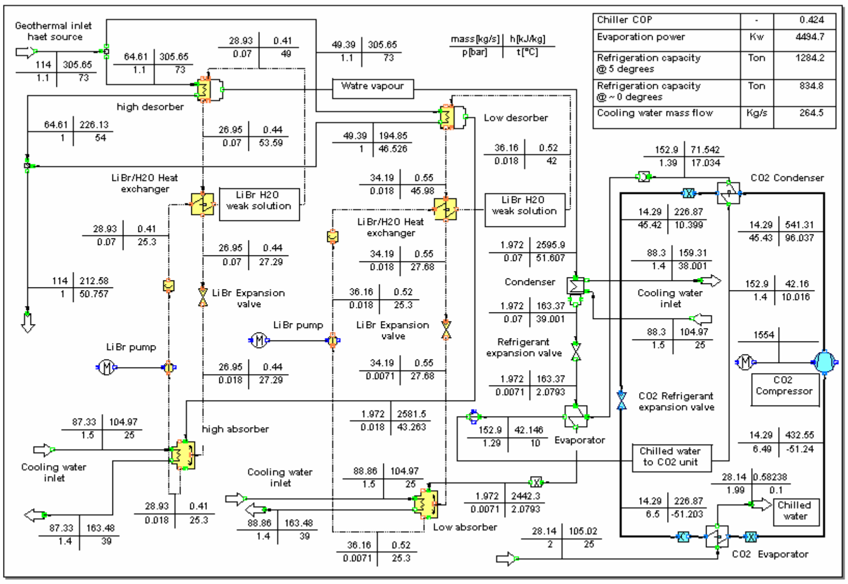


Figure 8. Water-cooled half effect cascaded with CO2 compression cycle chiller

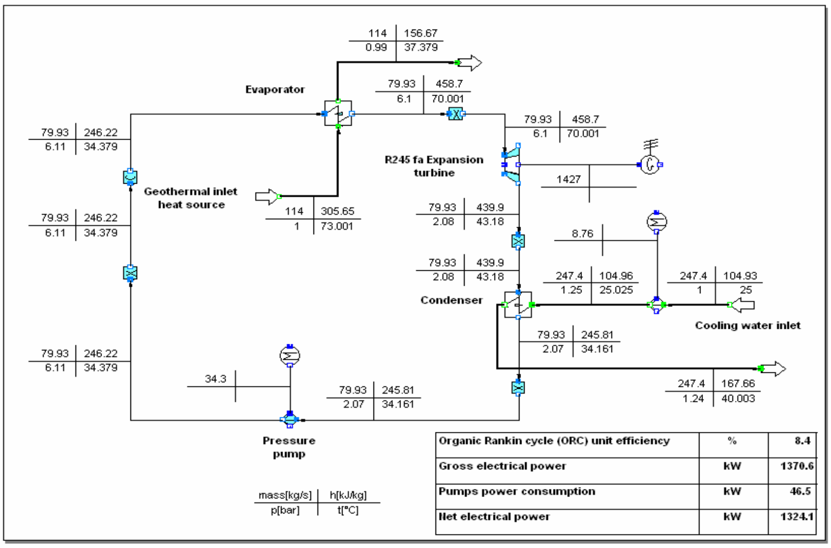


Figure 9. Direct electricity generation by R245fa organic Rankin cycle (ORC)

and surrounding villages with their demand of direct generated electricity and hot water supply. Results obtained in figure 10 have shown that the net output electrical energy and hot water energy were 103 MW and 25 MW respectively. Around 21% (18108 kW) of total produced electricity was from ORC unit. This can be considered as good achieved contribution in saving ozone layers from harmful LNG exhaust emissions.

4. Results summery

The obtained results of the proposed simulated models are displayed in figures 5-10 respectively and also summarized, for clarity, in two tables. Table 1 lists COP, chilled and hot water energies. Table 2 shows produced electrical energy. Graphical presentations for COP and refrigeration capacity are produced in figures 11 and 12 respectively.

5. Conclusion

A- For the stand alone absorption models (water and air cooled single and half effect chillers) the simulated results show, thermodynamically, that this low-temperature geothermal source can be used as heat source for both half and single effect Lithium bromide water mixture absorption chillers. The cooling capacities and coefficients of performance (COP) were found to be within acceptable published limits. The usable chilled water temperature difference a cross the evaporators, of water-cooled single/half effect chillers, was found within the range of air-conditioning use in hot climate conditions. The comparison between the three different models has indicated that the high cooling capacity was produced by water-cooled half effect chiller without any significant economical benefit of the heat rejected from the desorber.

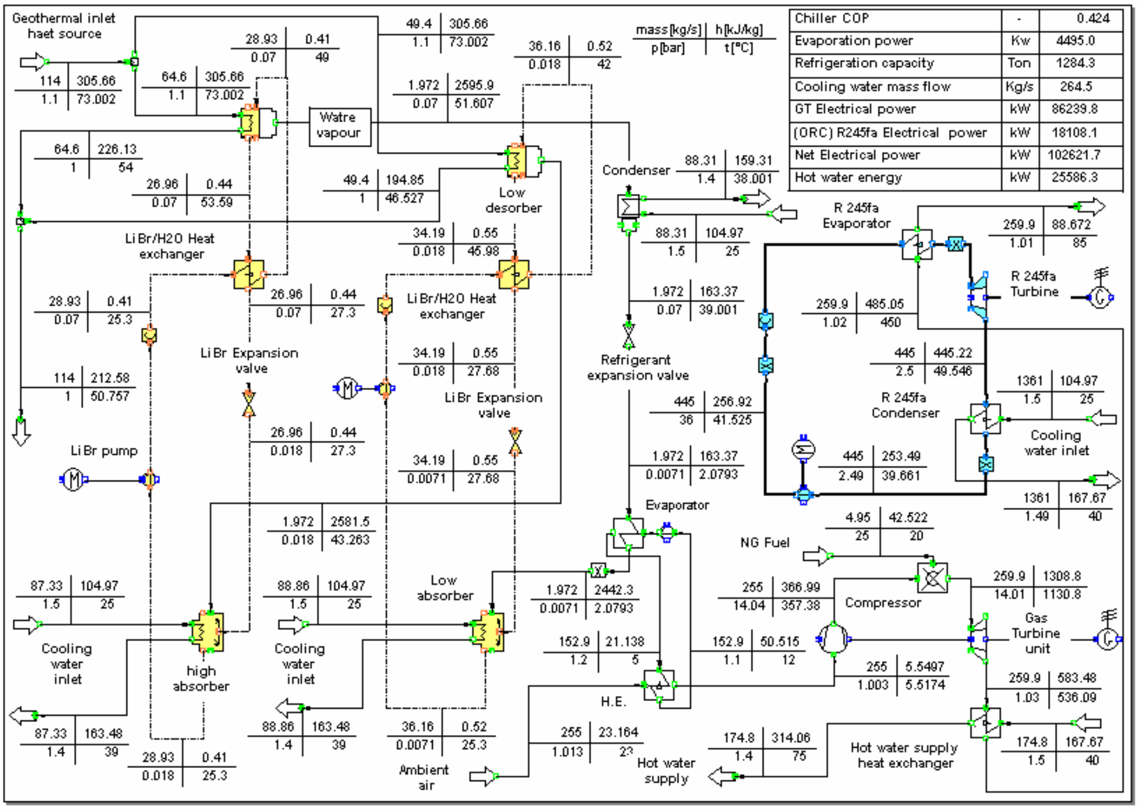


Figure 10. Water-cooled half effect cascaded with gas turbine (GT) and R-245fa organic Rankin cycle (ORC)

Table 1. Outlet results of thermal energy models

Output parameters	Absorption chiller model type			
	Water-cooled Single effect	Air-cooled Single effect	water-cooled Half effect	Water-cooled half effect cascaded with CO chiller
COP	0.8245	0.845	0.424	0.424
Evaporation power (kW)	1970	2197	4495	4495
Refrigeration capacity (ton)	563	628	1284	835
Outlet chilled water temperature (ºC)	5	22	5	0
Hot water supply energy (kW)	15739	15518	-	-
Hot water supply Temperature (ºC)	68	67.5	-	-

Table 2. Outlet results of electricity generation models

Output parameters	Electrical power generation model type	
	R-245fa organic Rankin cycle (ORC) standalone	Water-cooled cascaded with gas turbine and R-245fa organic Rankin cycle (ORC)
ORC Efficiency (%)	8.4	16.74
ORC electrical power (kW)	1,324	18,000
Gas turbine electrical power (kW)	-	85,000
Total electrical power produced (kW)	1,324	103,000
Thermal hot water energy (kW)	-	25,000

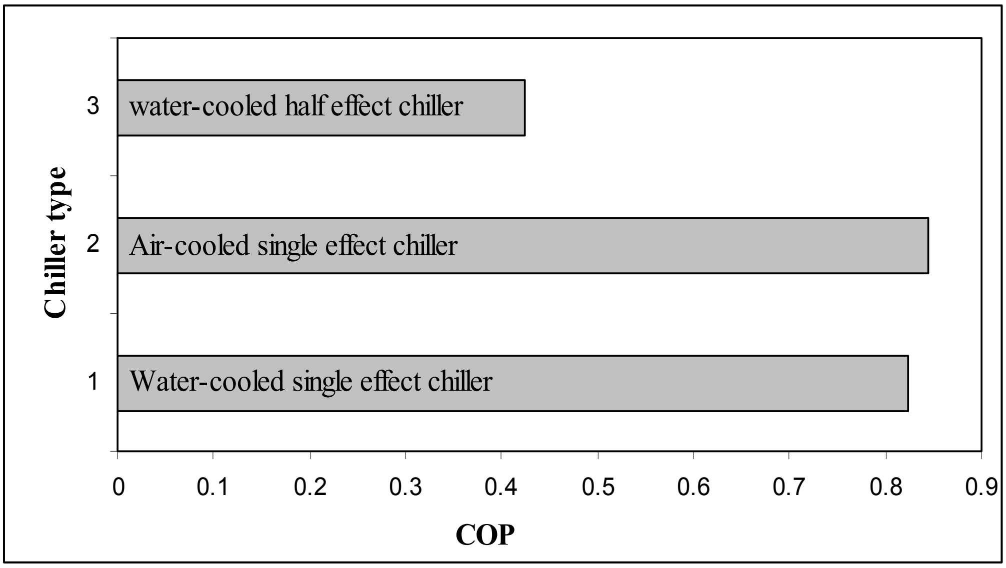
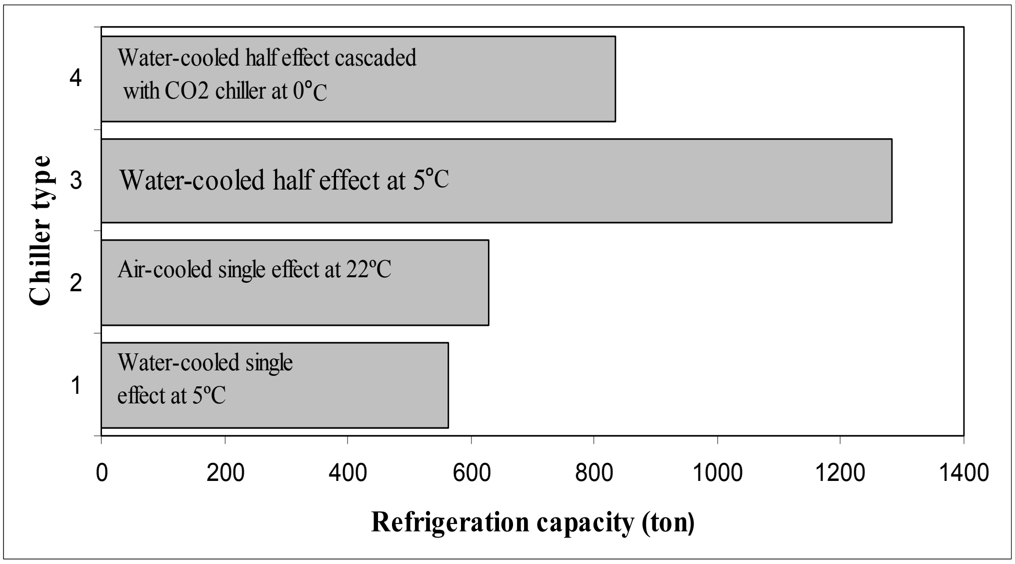


Figure 11. COP for different simulated chillers



Fugure 12. Produced refrigeration capacity for different simulated chillers.

The low cooling capacity was obtained from both air and water-cooled single effect chillers with significant outlet temperatures (about 68 ºC) which can be furtherer used in central heating and domestic hot water supply. For further reduction in the value of evaporator outlet chilled water temperature (0° C or below) the absorption cycles need to be cascaded with conventional compression e.g. CO_2 cycle. If cooling air-conditioning system is decided to be the only suitable choice for Waddan communities, without utilizing hot water energy, then water-cooled half effect chiller is probably the best system to be installed. If air-conditioning and hot water supply systems are desired, in summer and winter seasons, then the water cooled single effect chiller has to be selected instead.

B- Low temperature artesian geothermal sources could be utilized to generate direct electricity using R-245fa organic Rankin cycle (ORC) without any further significant benefit of rejected heat from the evaporator using quite large evaporation surface area. This geothermal source, along with surrounding natural gas fields, seems technically, may be economically and environmentally very attractive to build clean combined power station (GT & ORC).

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