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Energy Tri-Generation: Combined Gas Cogeneration/Solar Cooling

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Abstract

The article presents an analysis of a tri-generation system using a solar energy as primary energy to provide a reliable alternative to minimize energy consumption in countries with a large solar field as the MENA region. At the University of Nancy, within the faculty of Sciences and Technologies, we are experimenting energy tri-generation through solar cooling of water for air-conditioning and heat/electricity cogeneration using gas fueled internal combustion engine. The technology used for refrigeration is combined thermal solar-adsorption cooling. The physical principle of an adsorption based refrigerating machine is in some respect similar to the operating principle of a conventional compression based refrigerating machine [1-4]. Both systems rely on a "condenser - expansion valve – evaporator" refrigerant cycle. However, the way the two systems achieve refrigerant's vapor compression is quite different. While the conventional machine provides a "mechanical" compression of the refrigerant's vapor (standard refrigerant), the sorption machine achieves rather a "thermal" compression of the refrigerant's vapor (water) in two steps: in the first stage, the vapor issue from the evaporator is assimilated within a solid adsorbent (silica gel) by rejecting heat; in the second stage, this vapor is restituted back to the system loop at high pressure due to solar heat input through an intermediary fluid (water).

Keywords*: tri-generation, solar cooling, adsorption machine, heating, energy efficiency.*

1. Introduction

Most consumers that need heat need also electricity. These two forms of energy are generally produced separately: (i) heat from a high-efficiency boiler fueled by gas, liquid fuel or biomass; (ii) electricity from an external grid supplied by different power plants. Power plants have conversion efficiency between 35 and 40% for coal plants, nearly 55% for combined cycle plants fueled by natural gas and even less for power plants using heavy fuel oil or diesel. However, during operation, these plants produce heat that is not recovered, i.e. exhaust gas (400-550°C), intercooler (30-80°C), water cooling of the engine block (75-120°C) and the circuit lubricants (75-95°C).

The recovery of waste heat in order to improve the efficiency of conversion of primary energy reflects the purpose of co-generation which consists of the simultaneous production of heat and electricity from the same plant. A circuit with multiple recovery exchangers in series adds value to the available heat in the form of hot water (90-100°C) or sometimes low-pressure steam (2 bar). Several recovery exchangers can also be used to produce heat for different types of applications: domestic hot water (35-45°C), heating (85-95°C) or steam (110-120°C). The choice of the technology is thus driven by the quality of heat required.

Recovered heat during power generation can also be used, in part or in whole, in an absorption or adsorption refrigeration machine. It is the principle of tri-generation which is particularly interesting for tropical countries where air conditioning contributes significantly to peak demand of electricity. In temperate regions, the two modes may alternate (heat in winter and cooling in summer). In order to reduce reliance on fossil fuels, it makes sense to use solar thermal as a renewable primary heat source in order to meet the needs of heating and cooling (through sorption processes). Indeed, the co-generator acts as a booster during the days when there is not enough sunshine.

In this study, a micro tri-generation unit integrated with a solar system is described. A basic micro-cogeneration technology integrating solar collectors, storage tank, co-generator is combined with an adsorption chiller. The heat, cool and electricity are used, respectively, for water heating (floor heating system); water cooling (chilled ceiling) and lighting. The monitoring and evaluation of measures are analyzed in order to evaluate the performance of the tri-generation system. The purpose is to show the interest of such tri-generation system especially in areas with a large solar field.

2. Micro tri-generation unit description

Figure 1 illustrates the schematic diagram of the micro tri-generation unit, driven by solar energy, provided from solar collectors, and the fuel source such as the natural gas. This platform combine cogeneration (by the production of electricity and heating), solar cooling, and sustainable construction (wood structure). Two similar adjacent chambers, with opposite comfort demand, are the users of heating and refrigeration. The

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objective is to: (i) characterize innovative construction and insulation materials, (ii) analyze the performance of each component and of the global tri-generation system, and (iii) investigate measures in order to reduce the thermal load of the building and enhance the global energy efficiency.

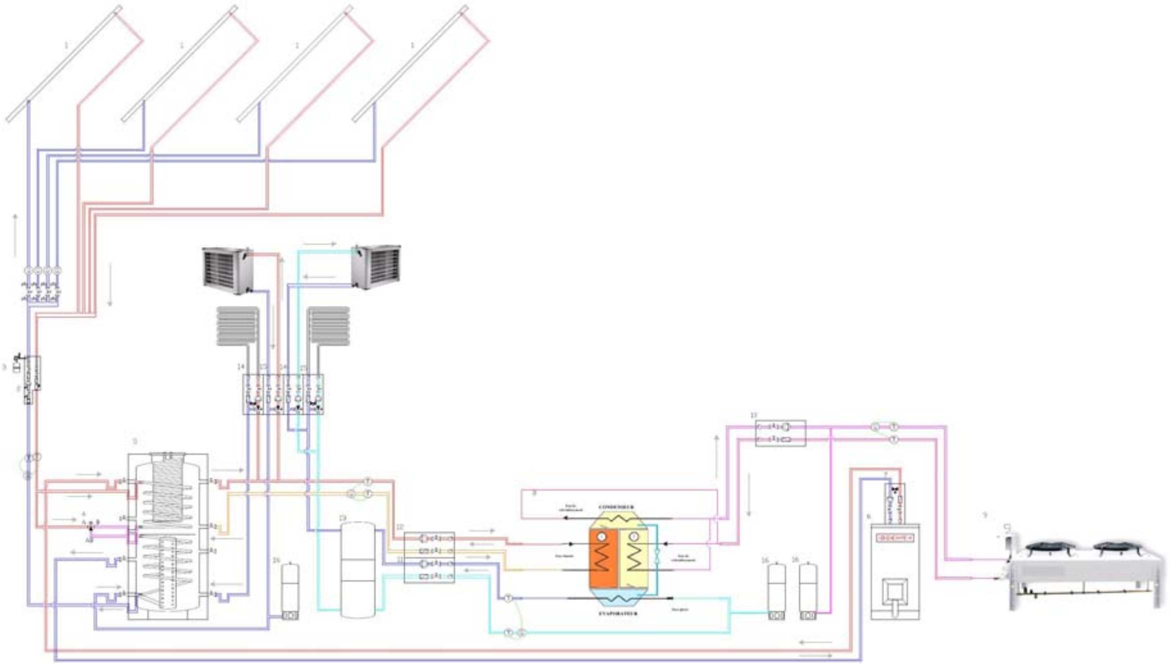


Fig. 1: Schematic diagram of the micro tri-generation unit

1 solar thermal collectors	5 storage tank	9 dry cooler	13 station hydraulic circuit hot water
2 solar primary circuit pump station	6 cogeneration engine	10 primary cooling circuit pump station	14 heating floor pump station
3 solar expansion tank	7 module load back to 60 °C	11 secondary cooling circuit pump station	15 chilled ceiling pump station
4 solar 3-way valve	8 adsorption chiller	12 chilled water circuit pump station	16 expansion tanks

2.1. Solar collectors

On the roof, a solar field (Fig. 2) with 16 solar collectors, 2.4 m² each, is installed. The collector characteristics are given in the following:

- Optical efficiency: η = 0.763;
- $a_1 = 2.437$ W/m^2/K;
- $a_2 = 0.0296$ W/m^2/K^2;
- Output power for an irradiation of 1000 W/m²: 1693 W.

The global efficiency of the solar collector, under European norm, is given by:

$$\eta_g = \eta - a_1.\frac{(T_m - T_a)}{G} - a_2.\frac{(T_m - T_a)^2}{G} \qquad (1)$$

The heat production of the whole solar field, for an irradiation of 1000 W/m² is about 27 kW. This heat production is intended for the storage tank.

Where: a_1 and a_2 represent the thermal losses coefficients due to conduction and convection, respectively;
T_m is the mean temperature between inlet and outlet solar collector, and G is the global irradiation expressed in W/m²

Fig. 2: Solar collectors

2.2. Storage tank

A storage tank of 1500 liters capacity is used to store water at 85°C. Stratification allows the management of temperature levels (Fig.3) in the supply of heat (heating floor and adsorption refrigerating machine). At low solar irradiation conditions, the storage tank is heated by the co-generator.

Fig. 3: Storage tank and its functional scheme.

2.3. Co-generator

The used co-generator (Fig. 4) is an internal combustion engine coupled with electric generator which recovers more than 90 % of heat from coolant, lubricant, and exhaust gas. Thus, it is used as mean of producing electricity (220 V, 50 Hz) and heat (hot water at 85°C). Its electrical and thermal efficiencies are approximately 25 % and 65 %, respectively.

Fig. 4: The cogeneration engine.

2.4. Adsorption chiller

The cooling production is provided by an adsorption chiller (Fig. 5) which feeds on heat to produce refrigeration (as well as low electrical power to operate the pumps). The operating mode of this chiller follows these two steps:

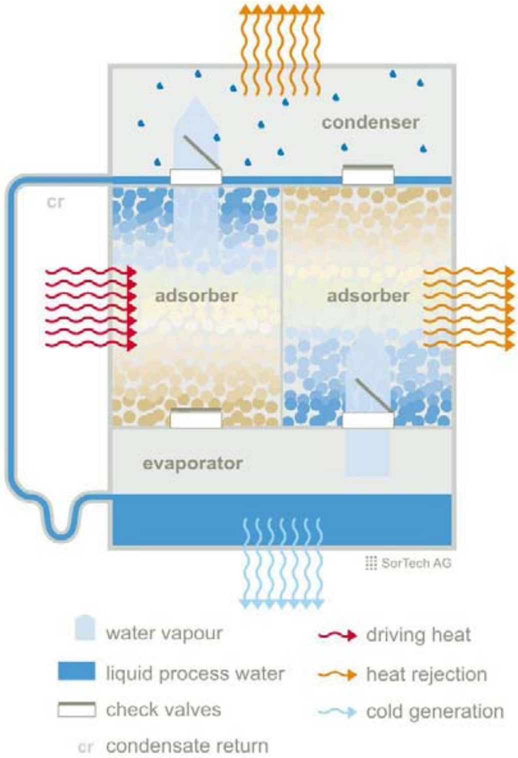


Fig. 5: scheme of the Adsorption chiller

– *Step 1: Desorption (desiccation of the adsorbent)*

The adsorbent (silica gel) is desiccated by means of the heat provided from the coolant. Heating stops when the adsorbent reach a dry state. Subsequently, the generated steam is cooled down and condenses in the condenser, then, the heat produced by this process is evacuated by the coolant to the dry-cooler. The expansion of the condensate is from the condenser (at high pressure) to the evaporator (at low pressure). This liquid water will evaporate at low temperature by absorbing heat from the refrigeration coolant which provides the air conditioning to cool the cold chamber.

– *Step 2: Adsorption (humidification of the adsorbent)*

The adsorbent is cooled by the circulated coolant leading to a pressure drop. The steam water produced by the evaporator is then aspirated by the adsorbent. This process releases heat which is evacuated by the coolant to an external dry-cooler using additionally water spray in order to achieve cooling at hot weather conditions.

These two steps occur simultaneously to ensure the continuity of the production of cold through the use of two adsorbent compartments. The adsorption chiller consumes ≈ 13.5 kW of hot water at 55°C ≤ T ≤ 95°C from the storage tank, rejects ≈ 21 kW of hot water at 22°C ≤ T ≤ 37°C to the dry-cooler (Fig. 6), and produces ≈ 8 kW of cold water at 6°C ≤ T ≤ 20°C supplied to the chilled ceiling or unit cooler (within the experimental room, for the dissipation of excess cold load).

Fig. 6: Dry cooler

2.5. Test building

A small building (Fig. 8), with a volume of 27 m3, is fabricated with solid wood glue-backed. It is divided into two identical chambers of equal size (3 m × 3 m × 1.5 m) and separated by a wall with an opening of 150 cm × 80 cm enabling the testing of innovative construction and insulation materials.

Fig. 8: Test chambers.

The hot chamber

This chamber is equipped with a heating floor (Fig. 9) which is provided by the storage tank. This ensures an inside temperature between 20 °C and 55°C.

(a) (b)

Fig. 9: The hot chamber : (a) Inside the room, (b) Floor heating (before cement screed)

The cold chamber

As depicted in Fig.10, the chamber is equipped by a chilled ceiling provided by the adsorption chiller. The inside temperature is maintained between 10°C and 20°C.

(a) (b)

Fig. 10: The cold chamber (a) Inside the room; (b) Chilled ceiling

2.6. Heat recovery ventilation

The test building is also equipped with a heat recovery ventilation system (Fig. 11) that controls the inside temperature and the relative humidity.

Fig. 11: Heat recovery ventilation

2.7. Data acquisition

The data are acquired and manipulated (Fig. 12) as two dimensional graphs and tabulated. Instrumentation also allows regulation of the tri-generation unit.

Fig. 12: The automaton apparatus.

3. Regulation principles

The pump of the collectors' fluid (glycol-water) starts functioning when the following conditions are satisfied (Fig.13) : (i) the temperature difference between the solar thermal collectors (measured at the last collector's core) and the inlet storage tank is greater than some prescribed fixed value (7°C); (ii) the solar thermal collector temperature is greater than 30°C ; and (iii) the lower level temperature of the storage tank is less than 95 °C.

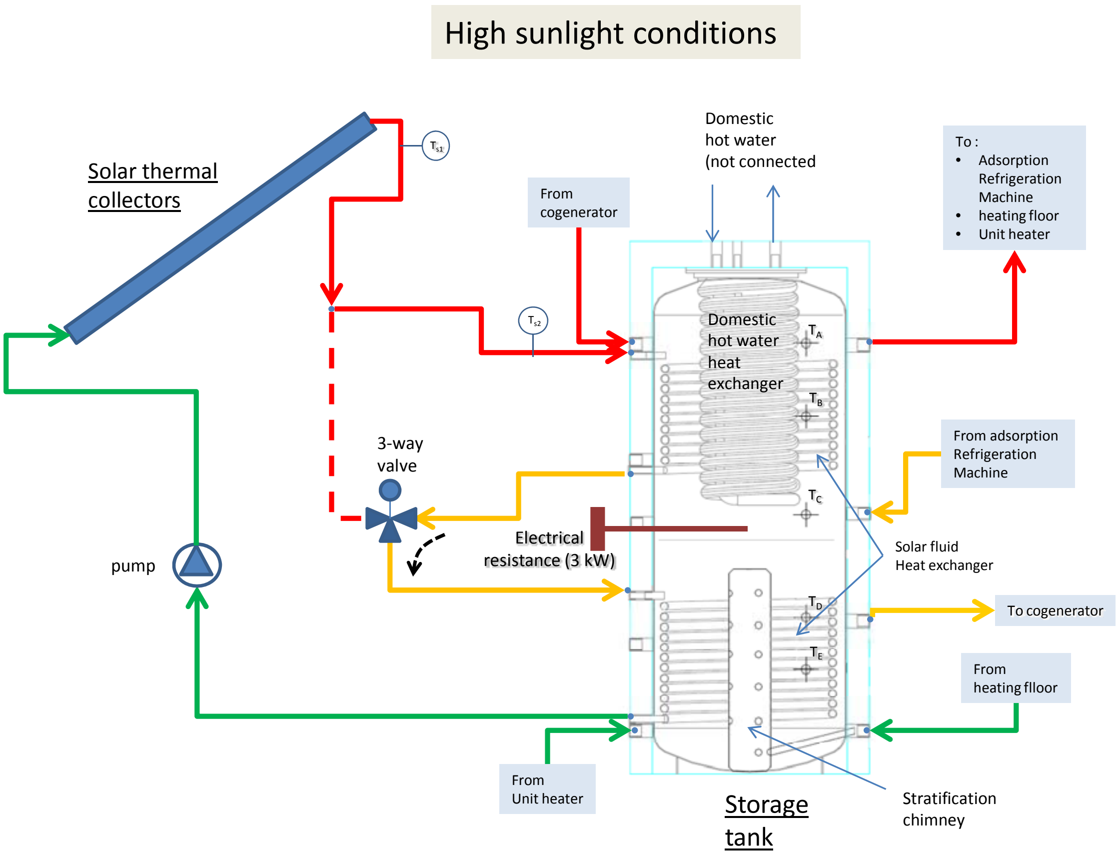


Fig. 13: hydraulic circuit at high sunlight conditions

When the solar thermal energy potential is weak (low solar irradiation - the temperature difference between the solar thermal collectors and the inlet storage tank is less than 4 °C), the solar fluid will circulate only through the bottom heat exchanger (Fig. 14).

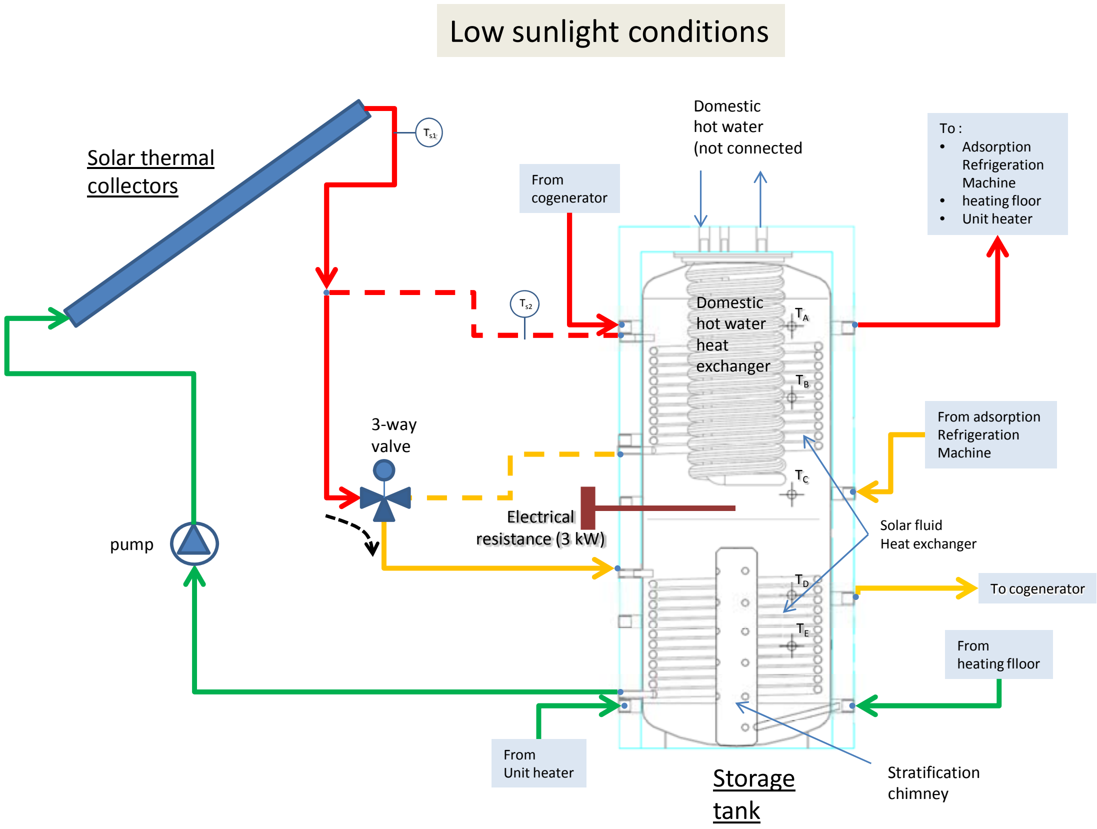


Fig. 14: hydraulic circuit – case (a) and (b)

The generator of the adsorption refrigeration machine operates if the water temperature from the storage tank toward the machine is in the range 75°C to 94°C. For safety purpose, when the tank's lower level temperature is higher than 92°C then the circulation pump feeding the heat discharge heater turns on in order to dissipate the excess heat not used by the installation. The cogeneration engine operates as long as the engine temperature is below 83 °C and stops beyond this limit to cool down.

4. Experimental results

Figure 15 shows the surface temperature of the solar collectors and the temperature at the inlet and outlet of the storage tank during 3 days, from 1st to 3rd October 2011. Almost the same shape of the temperatures was recorded because the global insolation was relatively the same. The difference between the inlet and outlet temperatures of storage tank is about 20°C.

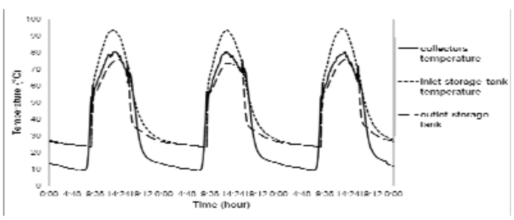


Fig. 15: temperatures of the solar primary fluid at solar collectors (mean temperature) and at inlet/outlet of the storage tank.

The thermal stratification in the storage tank can be seen clearly in Figure 16. We note, especially a harmony between the temperature profile of the different levels and the global insolation as observed in Figure 15. This is due to the fact that, during the monitoring period the co-generation engine, which normally ensures the supply of heat to the storage tank where there is less sunlight or during the night, did not provide his role, because the global insolation is sufficient to allow the storage tank by an appropriate amount of heat. The thermal stratification in the storage tank plays also an important role regarding. During the day however, the heat supply is provided only from the solar collectors. The 1st and 2nd temperature levels are relatively identical because the compartment (where these two temperatures are recorded) is not always supplied on heat, dependent on the management of the operating mode.

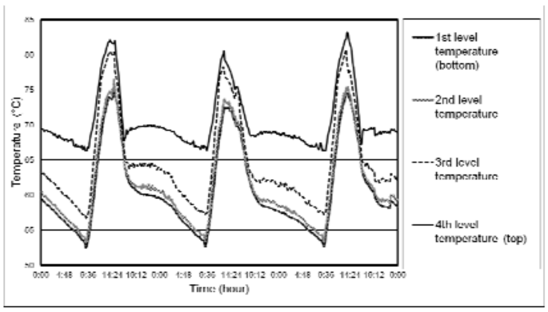
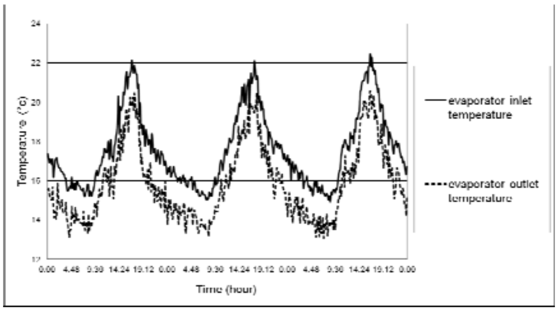
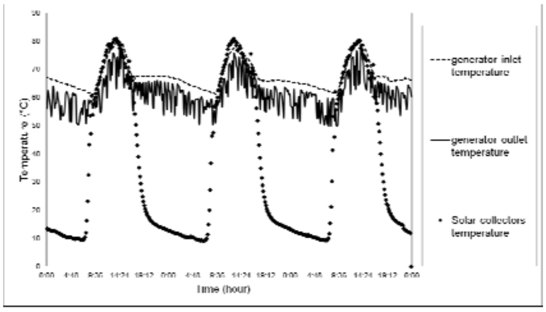


Fig. 16: temperature stratification within the storage tank.

In order to monitor the temperature on the adsorption chiller, different sensors were placed at the inlet and outlet of the evaporator and generator (Fig. 17). The temperature difference is almost constant between the inlet and outlet of the evaporator because the adsorption/desorption cycles are done simultaneously in order to ensure the continuity of the cold production through the use of two adsorbent compartments. Therefore, the supply of cold is provided throughout the whole day. Otherwise, the difference temperature between the inlet and outlet of the generator (Fig. 17b) varies depending on the availability of the sunlight and the need of the building in cold.



(a)



(b)

Fig. 17: temperatures at the adsorption chiller: (a) inlet/outlet of the evaporator; (b) inlet/outlet of the generator.

5. Performances analysis

The performance analysis of the micro tri-generation unit has been performed using the experimental results in nominal and dynamic regimes.

5.1. Nominal regime

Global energy balance is represented by a Sankey diagram (Fig. 18). This diagram shows that the combined solar energy and natural gas energy produce about 39.7 kW of heat and approximately 4.7 kW of electricity. The heat produced is distributed as follows: (i) 18 kW for the unit heater; (ii) 6 kW directed to the floor heating; and (iii) 13.5 kW destined to the adsorption machine. This one produce 8 kW of cold destined to the chilled ceiling (6 kW) and the cooler unit (2 kW). The Coefficient Of Performance (COP) of this machine is about 0.6.

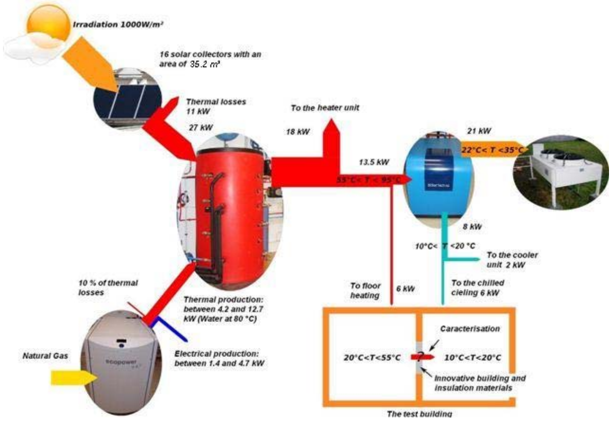


Fig. 18: Sankey diagram of the tri-generation system

5.2. Dynamic regime

The power fluxes of the adsorption chiller are presented in Figure 19. The small amplitude of fluctuations observed in the evaporator power (power produced) is due to the fact that the temperature difference is constant on either side of the evaporator. However, the fluctuations observed in the generator and condenser powers are more important due to the variation of the temperature difference on each component.

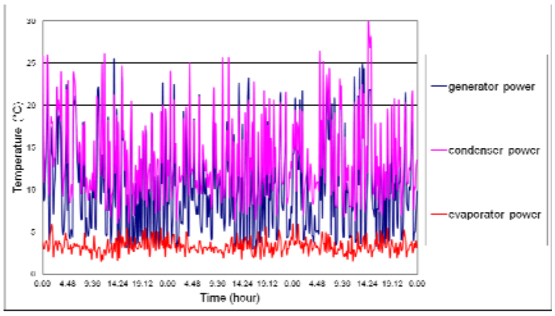


Fig. 19: energy fluxes at the refrigerating machine.

6. Conclusion

One of the promising technologies to meet the criteria for energy efficiency and lower emissions of greenhouse gases is tri-generation, or combined production of electricity, heat and cold. In this work we are experimenting energy tri-generation through solar cooling of water for air-conditioning and heat/electricity cogeneration. The experimental results show the important role of the storage tank in the tri-generation unit allowing us to store energy from the renewable and fossil sources. The thermal stratification in the storage tank plays also an important role regarding the energy distribution management.

The other results highlighted the performance of the adsorption machine. Hot water is provided from solar collectors at temperatures between 55°C and 95°C with an input thermal power about 13 kW. The cooling capacity of the system is about 8 kW with cool water temperature between 6°C and 20°C. Heat rejection through dry-cooler is about 21 kW. This configuration proved to be suitable for Nancy's weather conditions where high summer temperatures are about 25°C to 35°C. For hotter climate, the dry-cooler should be replaced by either cooling towers or geothermal cooling. This later approach is under consideration.

The use of the micro tri-generation unit in the field of scientific research allows, among other findings, the validation of the numerical models corresponding to the building envelope and the energy equipments ([5-7]). The aim is to enhance the energy efficiency of the test building.

In several countries, applications of tri-generation systems in the industrial and service sectors are growing. In African and Asian countries, some food industries have needs for simultaneous heat, cold and electricity and could use tri-generation to reduce their energy cost.

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