

## Preliminary thermal analysis of a solar assisted micro-cogeneration system

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**ABSTRACT:** In this work, three solar assisted thermodynamic cycles for a micro-cogeneration system are studied. The thermodynamic cycles are based on the organic Rankine cycle (ORC) and the operating temperatures of solar thermal collectors are 80°C, 100°C-150°C and 200°-250°C, for cycles 1, 2 and 3, respectively. Several researchers have investigated the application and performance of ORCs. They have shown that organic fluids can be used to generate power using low-temperature energy sources (solar or waste heat). The main work objective is the modelling of the selected cycles for optimisation according to the temperature range.

Micro-cogeneration, or micro-CHP, is the combination of micro-generation of electricity with useful heat. In this case, the micro-CHP system under analysis uses a micro-turbine and an electric generator with a power output of 5 kW. The turbine inlet temperatures are 80°C, 120°C and 230°C, respectively for cycles 1, 2 and 3.

The performance of several fluids was evaluated from a thermal and an economical point of view, taking into account also fluid toxicity. The integration of the micro-CHP system with solar thermal collectors was evaluated and the solar fraction was obtained for climatic conditions of Almeria (Spain), Tunis (Tunis) and Cairo (Egypt).

**Keywords:** micro-cogeneration, solar energy, organic Rankine cycle, solar fraction

### NOMENCLATURE

|           |                                                              |
|-----------|--------------------------------------------------------------|
| $A$       | area [m <sup>2</sup> ]                                       |
| $c_p$     | fluid specific heat [kJ/kg/K]                                |
| $f$       | solar fraction [-]                                           |
| $k$       | incidence angle modifier [°]                                 |
| $I$       | incident radiation on collector surface [W/m <sup>2</sup> ]. |
| $\dot{m}$ | water mass flow rate [kg/s]                                  |
| $Q$       | thermal energy [J, kWh]                                      |
| $\dot{Q}$ | thermal power [kW]                                           |

|           |                       |
|-----------|-----------------------|
| $T$       | temperature [°C]      |
| $\dot{W}$ | electrical power [kW] |

#### Greek letters

|          |                        |
|----------|------------------------|
| $\eta$   | efficiency [-]         |
| $\eta_0$ | optical efficiency [-] |

#### Subscripts

|               |           |
|---------------|-----------|
| <i>amb</i>    | ambient   |
| <i>annual</i> | annual    |
| <i>boiler</i> | boiler    |
| <i>col</i>    | collector |
| <i>cond</i>   | condenser |

|              |                                       |
|--------------|---------------------------------------|
| <i>elect</i> | electrical                            |
| <i>in</i>    | inlet                                 |
| <i>input</i> | heat from the solar system and boiler |
| <i>HX</i>    | heat exchanger                        |
| <i>out</i>   | outlet                                |
| <i>pump</i>  | pump                                  |
| <i>solar</i> | solar                                 |
| <i>tank</i>  | thermal storage                       |
| <i>water</i> | water                                 |

## 1. INTRODUCTION

Existing large-scale plants for power generation are usually located far away from centres of population. This prevents efficient utilization of a reasonable proportion of the waste heat produced. Moreover, current technology limits these power stations to a maximum efficiency of about 40%, which, after the transportation of electricity through the grid, is reduced to about 30% [1]. This means that vast quantities of fossil fuels are burnt with unwanted pollutants entering the atmosphere.

Solar radiation availability in the Mediterranean area (Europe and North Africa) is excellent when compared with other regions of the World. However, this resource has been poorly utilised. The utilisation of solar energy with conventional energy sources, for combined heat and power for buildings, reduces pollutant emissions and offers energy savings.

## 2. DESCRIPTION OF THE SOLAR ASSISTED MICRO - COGENERATION SYSTEM

Micro-generation is the decentralized production of electricity with an electrical power output up to 50 kW. Micro-cogeneration, or micro-CHP, is the combination of micro-generation with useful heat.

The micro-CHP system under analysis uses a micro-turbine and an electric generator with a power output of 5 kW.

Such small turbines are recently available in the market, and have typical overall efficiencies around 70%. The system is composed of two circuits: the primary circuit where the working fluid expands in the turbine, passes in a regenerator and condenses in the condenser, and the secondary circuit with the solar collectors. In the secondary circuit two possibilities were studied: solar collector without thermal storage tank - Figure 1- and solar collector connected to a thermal storage tank -Figure 2. In both cases a boiler is considered for supplying auxiliary energy (gas) when necessary.

A heat exchanger transfers heat between the two circuits. The heat rejected in the condenser can be used for water heating or building heating.

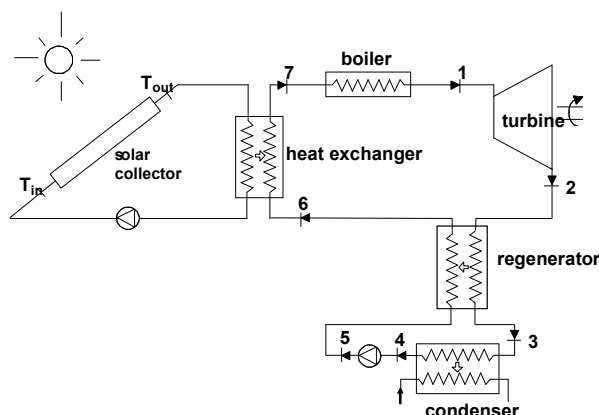


**Figure 1:** Schematic representation of the micro-CHP system without thermal storage.

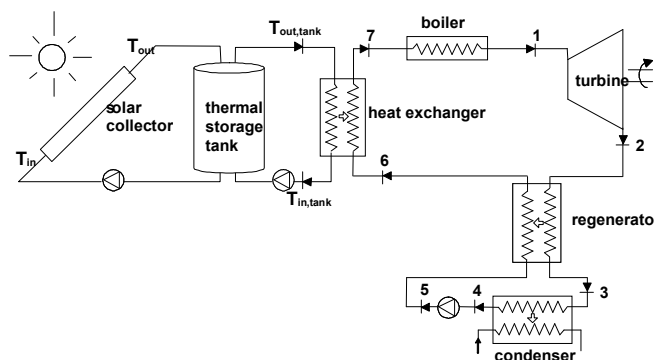


**Figure 2:** Schematic representation of the micro-CHP system with thermal storage tank.

The thermal performance of organic Rankine cycles operated at 3 different inlet turbine temperatures was simulated. Organic fluids are desirable for low temperature applications, due to their high molecular weight and positive slope of the saturated vapour curve in the temperature-entropy plane, both attributes simplifying the design of the expander [2].

The inlet temperatures, point 1 in Figure 1, were 80°C, 120°C and 230°C, respectively for cycles 1, 2 and 3. At condenser outlet the fluid is at 45°C (saturated liquid). The heat rejected in the condenser can be used for water heating or building heating or cooling. Several fluids were analysed for the power circuit: ammonia, n-pentane, HFE7100, methanol, cyclohexane, toluene, R245fa and water.

In the solar system, solar collector areas between 10 m<sup>2</sup> to 100 m<sup>2</sup> were studied. The fluid flowing in the collectors was water. When the thermal storage tank was used, it was modelled as a fully-mixed tank which does not include thermal stratification.

### 3. MODELLING OF THE SYSTEM

#### 3.1 Micro-CHP system (primary circuit).

The micro-CHP system and its components were modelled with EES software [3]. A micro-turbine of 5 kW and an overall efficiency equal to 70% was considered.

The efficiency of electricity production was calculated through equation 1. This efficiency represents the relation between the electrical power obtained from the micro-CHP system ( $\dot{W}_{elect} - \dot{W}_{pump}$ ) and the thermal power obtained from the boiler and solar system through the heat exchanger ( $\dot{Q}_{input}$ ).

$$\eta = \frac{\dot{W}_{elect} - \dot{W}_{pump}}{\dot{Q}_{input}} \quad (1)$$

The regeneration was considered if the outlet turbine temperature (point 2) was higher than outlet pump temperature (point

5). A regenerator efficiency of 80% was considered. The turbine inlet pressure was optimised to maximise the electrical efficiency (equation 1).

#### 3.2 Solar system (secondary circuit).

The solar system circuit and its components were modelled with EES software and TRNSYS simulation program, [4].

The solar behaviour of the 2 cycles (cycle 1 and cycle 2) was simulated for: Almeria (Spain), Tunis (Tunis) and Cairo (Egypt). The collectors were associated in parallel and tilted 31° for Almeria and Tunis and 25° for Cairo. The climatic data were obtained through Meteonorm, provided by TRNSYS.

For the solar collectors, a water flow rate of 0.02 kg/s/m<sup>2</sup> was used and a storage volume equal to  $50 \cdot A_{col}$  (in litres) was considered. A control system activates the circulation pump, so that water is circulated in the collectors only when the outlet temperature is higher than the storage temperature.

Flat plate collectors were considered for cycle 1, with efficiency parameters supplied by AES company [5]. For cycle 2, a compound parabolic concentrator (CPC) was selected and the efficiency parameters were supplied by AO SOL company [6].

For cycle 1, solar collector efficiency (see eq. 2) depends on the incidence angle modifier ( $k$ , see eq. 3), angle of incidence ( $i$ ), ambient temperature ( $T_{amb}$ ), inlet water temperature ( $T_{in}$ ) and incident radiation on collector surface ( $I$ ).

$$\eta = k \cdot 0.8 - 2.5 \cdot \left( \frac{T_{in} - T_{amb}}{I} \right) \quad (2)$$

$$k = 1 - 0.136 \cdot \left( \frac{1}{\cos i} - 1 \right) \quad (3)$$

For incidence angles higher than 80°, solar contribution was set to zero.

For cycle 2, solar collector efficiency was calculated through:

$$\eta = \eta_0 - 1 \cdot \left( \frac{T_{in} - T_{amb}}{I} \right) \quad (4)$$

In this case, the dependence of optical efficiency ( $\eta_0$ ) with incidence angle ( $i$ ) is expressed by:

$$\begin{cases} \eta_0 = 0.61 + 0.002 \cdot i & \text{for } i \in [0, 35[ \\ \eta_0 = 0.628 - 0.009 \cdot i & \text{for } i \in [35, 67[ \\ 0 & \text{for } i \in [67, 180] \end{cases} \quad (5)$$

## 4. SIMULATION RESULTS

### 4.1 Performance of several fluids for the micro-CHP system.

The primary circuit was studied for the 3 cycles. Table I presents a comparison of different fluids for cycle 1. The required heat to produce 5 kW of electricity ( $\dot{Q}_{\text{input}}$ ), the condenser heat ( $\dot{Q}_{\text{cond}}$ ) and the efficiency ( $\eta$ ) are presented. The simulations were done with EES software.

**Table I:** Thermal performance of several fluids for cycle 1.

| Fluid       | $\dot{Q}_{\text{input}}$ (kW) | $\dot{Q}_{\text{cond}}$ (kW) | $\eta$ (%) |
|-------------|-------------------------------|------------------------------|------------|
| water       | 74.1                          | 69.1                         | 6.74       |
| n-pentane   | 75.3                          | 70.4                         | 6.64       |
| HFE 7100    | 76.1                          | 71.2                         | 6.57       |
| Methanol    | 74.3                          | 70.0                         | 6.73       |
| Cyclohexane | 75.2                          | 70.2                         | 6.65       |
| Ammonia     | 74.9                          | 70.3                         | 6.67       |
| Toluene     | 74.6                          | 74.3                         | 6.70       |
| R245fa      | 76.3                          | 71.6                         | 6.54       |

It was found that wet fluids (water, methanol and ammonia) present the best thermal performances, although differences are not significant. However, the micro-turbine considered doesn't allow the use of wet fluids. Table II shows the prices and risk of the different fluids.

**Table II:** Prices and risk of several fluids.

| Fluid       | Price* (€/litre) | Risk Statements |
|-------------|------------------|-----------------|
| water       | ---              | ---             |
| n-pentane   | 33               | EF and T        |
| HFE 7100    | 151              | NR              |
| Methanol    | 42               | HF and T        |
| Cyclohexane | 65               | HF and T        |
| Ammonia**   | 185 (100gr)      | F and T         |
| Toluene     | 79               | HF and T        |
| R245fa      | n.a.             | NR              |

EF: Extremely Flammable

HF: Highly Flammable

T: Toxic

NR: No Risk statements

\* Prices offered by Sigma-Aldrich Company in March 2008.

\*\* Ammonia solutions have different prices and risk, depending on the solution.

As can be seen in the Tables I and II, within the dry fluids, toluene and cyclohexane present higher efficiencies, but are however toxic and flammable. When price, efficiency and risk are taken into account, cyclohexane can be considered as the best fluid for the power circuit (primary circuit). Figure 3 shows the temperature versus entropy diagram for cyclohexane in cycle 1.

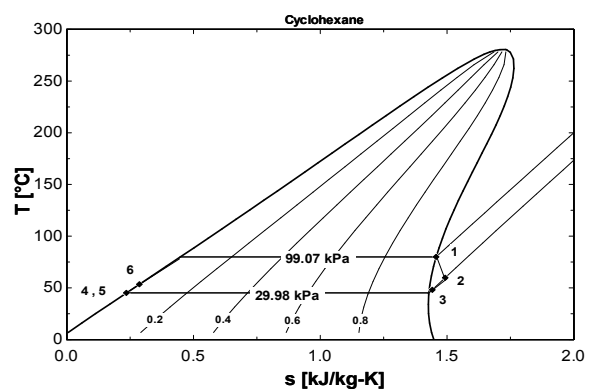


**Figure 3:** Temperature versus entropy diagram for cyclohexane in cycle 1.

When analyzing cycle 2, it was found that cyclohexane still led to the best performance results, for the same reasons of cycle 1, with an electricity generation

efficiency of 12.4% ( $\dot{Q}_{\text{input}}=40.4$  kW and  $\dot{Q}_{\text{cond}}=35.5$  kW).

For cycle 3, where the operating temperatures of solar thermal collectors are 200°-250°C, it is necessary to consider that there are four fluids with critical temperature below 230°C: n-pentane, HFE7100, Ammonia and R245fa. Another constraint was considered, since according to the turbine manufacturer [7], the inlet pressure in point 1 is limited to 2500 kPa. For this cycle, R245fa presents the best performance; however, this is for a high pressure (17670 kPa).

Taking all constraints into consideration (efficiency, toxicity, price, critical temperature and turbine inlet pressure) cyclohexane still led to the best performance results, with an electricity generation efficiency of 22.2% ( $\dot{Q}_{\text{input}}=22.5$  kW and  $\dot{Q}_{\text{cond}}=17.6$  kW).

#### 4.2 Simulation of solar performance.

The solar performance of cycle 1 and cycle 2 was simulated for: Almeria, Tunis and Cairo. The collectors were associated in parallel and tilted 31° for Almeria and Tunis, and 25° for Cairo.

After obtaining the required heat to produce 5 kW of electricity ( $Q_{\text{input}}$ ), it is possible to determine the solar contribution by a thermal balance. Solar fraction ( $f$ ) represents the percentage of energy input in the micro-CHP system that is due to solar energy. The fluid in the primary circuit is cyclohexane with water in the secondary circuit.

Without thermal storage, the monthly average solar fraction is defined by:

$$f = \frac{Q_{\text{solar}}}{Q_{\text{input}}} \quad (6)$$

The useful solar input (instantaneous) is calculated through:

$$\dot{Q}_{\text{solar}} = (\dot{m} c_p)_{\text{water}} (T_{\text{out}} - T_{\text{in}}) \quad (7)$$

When connecting solar collectors to a thermal storage tank, the monthly average solar fraction is defined by:

$$f = \frac{Q_{\text{HX}}}{Q_{\text{input}}} \quad (8)$$

In this case, solar fraction depends on the total heat transfer rate between fluids in the heat exchanger ( $Q_{\text{HX}}$ ).

It was assumed that the heat exchanger thermal efficiency was constant (75%) operating in single-phase or two-phase mode. When using the storage tank, water and cyclohexane flow rates in the heat exchanger are the same.

Figure 4 shows the annual average solar fraction for different collector areas, for the 3 cities and for cycle 1. When the system operates without storage, operation from 9 to 19 h was considered. Due to utilization of the thermal storage tank, the system may operate 24 h/day. In this case, the average solar fraction was calculated for a full year. The results for cycle 2 are shown in Figure 5.

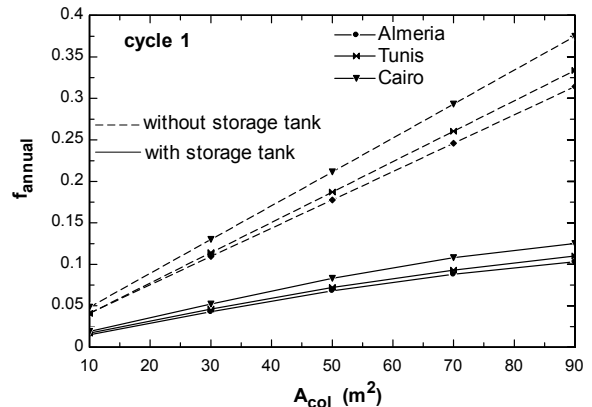


**Figure 4:** Variation of average annual solar fraction with solar collector area for the 3 cities, with and without storage tank, for cycle 1.

Note that the annual solar fraction is higher (about 3 times) when solar collectors are connected directly to the heat exchanger without storage tank. But in this case, the micro-CHP system only operates during part of the day (when solar radiation is available). Thus, the total solar energy output is smaller for lower requirements. The advantage of

using thermal storage is that the system may operate for a longer period, with higher total output.

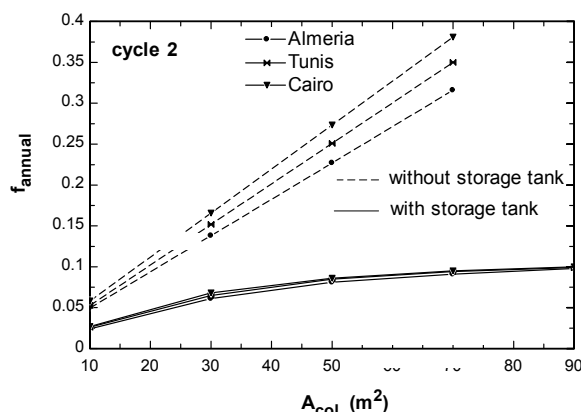


**Figure 5:** Variation of average annual solar fraction with solar collector area for the 3 cities, with and without storage tank, for cycle 2.

For cycle 1 without storage tank, it is possible to have an instantaneous solar fraction of 1, for maximum solar radiation, for a collector area above 100 m<sup>2</sup>, in the 3 cities. For cycle 2 without storage tank, the same maximum solar fraction can be obtained for a collector area above 70 m<sup>2</sup>, in all cities.

Comparing the 3 cities, Cairo has the highest solar fractions for cycle 1 and cycle 2.

## 5. CONCLUSION

The thermal performance of organic Rankine cycles operated at 3 different inlet turbine temperatures was simulated, in order to produce 5 kW of electricity. The performance of several fluids was studied from a thermal and economical point of view, taking also into account fluid toxicity. Cyclohexane presented the best performance for cycles 1, 2 and 3.

The integration of solar collectors with and without storage tank in the micro-CHP system was analyzed. The solar fraction for cycle 1 and cycle 2 was evaluated for Almeria, Tunis and Cairo. Simulation results showed that the annual solar fraction

is higher when the storage tank is not used. Comparing the 3 cities, Cairo presented the highest solar fraction for collector areas between 10 and 90 m<sup>2</sup>. With thermal storage the system may operate for longer periods (up to 24 h/day).

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