4
Thermodynamic performance of an ORC trigeneration system

4.1.
Motivation

An ORC by itself helps reduce the amount of waste heat of an industrial process by converting it into useful electric energy. The use of this technology in other energy saving systems may be of great interest. The use of an ORC in a trigeneration system can have a positive effect by reducing the fuel consumption and contributing to the electric power generation of the system.

4.2.
Trigeneration System Description

A trigeneration system, also known as combined cooling, heat and power (CCHP), has the capacity to produce heating, cooling and electricity simultaneously from a single heat source.

The schematic diagram of a trigeneration system, shown in Figure 25, presents the different energy flows, and their direction: outgoing (heat and electricity) and incoming (fuel and refrigeration).

Trigeneration systems have been developed in order to supply the needs of heating and cooling, when generating electricity from fuel, by taking advantage of the waste heat. Since an organic Rankine cycle also generates electric power by utilizing waste heat, the introduction of an ORC to a trigeneration system is here proposed in order to augment the electrical power supply to meet a power demand.

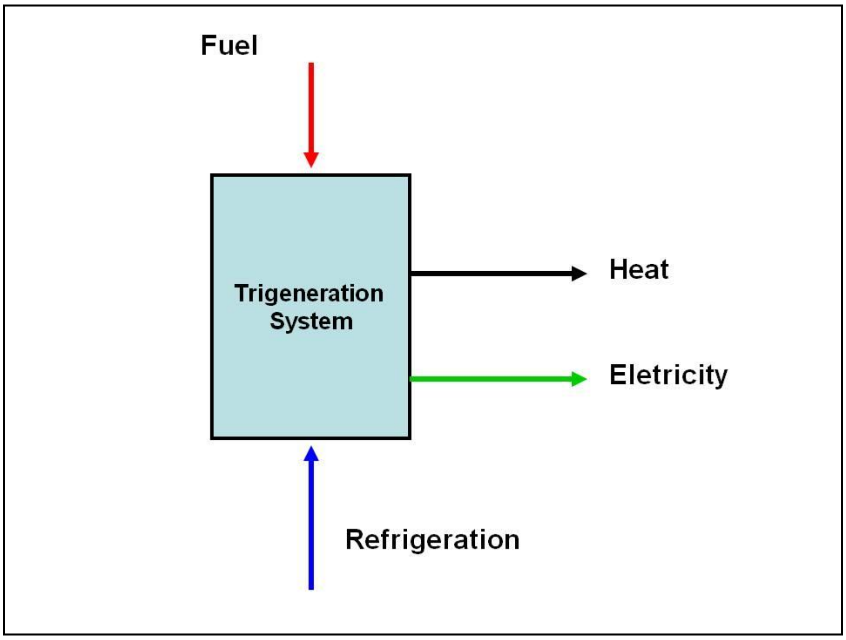

Figure 26. Flow diagram representation of a trigeneration system.

The configuration of the proposed system is shown in Figure 26. The heat engine, powered by the combustion of the incoming fuel, drives an electric generator. The electricity demand is also covered by the ORC, which is driven by the recovered exhaust gases from the heat engine. A percentage of the generated electricity is used to drive the vapor compression chiller, which produces the refrigeration effect, but also rejects heat from the condenser that is utilized to supply part of the heat demand. The heat demand is also met by recovering waste heat from the engine coolant system. In case the total heat recovered from the engine coolant system and chiller condenser does not supply the necessary heat demand, a peak boiler burning the same type of fuel is used as support.

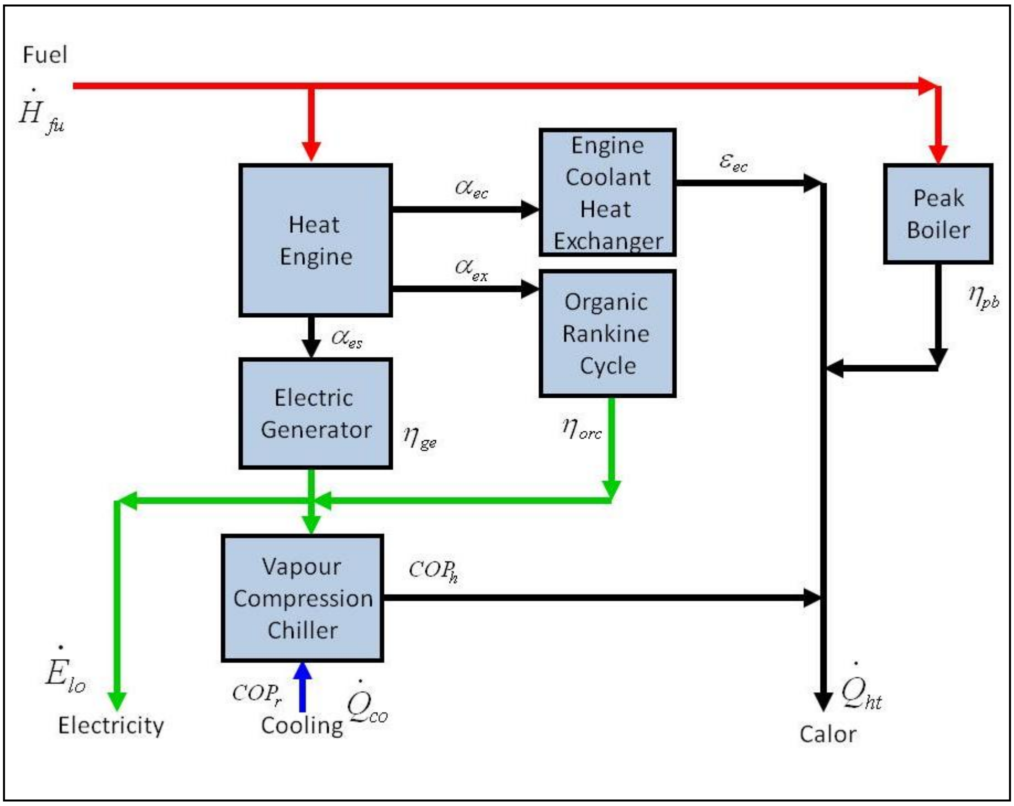

Figure 27. Energy flow diagram of a trigeneration system using an ORC and vapor compression chiller.

In order to evaluate the performance of a trigeneration system, analogous to a heat engine's thermal efficiency or a refrigeration cycle's coefficient of performance, a parameter that relates the energy products with energy consumption is presented by Parise et al. [64] The energy conversion ratio of the trigeneration system,ECR_{tg}, is defined as the total of the energy products (refrigeration, electricity and heat) divided by the fuel energy consumption (from the engine and peak boiler):

$$ECR_{tg} = \frac{\Sigma(energy\ products)}{energy\ consumption} = \frac{Q_{co}+E_{lo}+Q_{ht}}{H_{fu}} \tag{4.1}$$

In order to compare the magnitudes of the electricity, heating and cooling power load demands, three non-dimensional ratios are also defined:

$$R_{HC} = \frac{Q_{ht}}{Q_{co}} \tag{4.2}$$

$$R_{EC} = \frac{\dot{E}_{lo}}{\dot{Q}_{co}} \tag{4.3}$$

$$R_{HE} = \frac{\dot{Q}_{ht}}{\dot{E}_{lo}} \tag{4.4}$$

where, R_{HC} is the heating-to-cooling load ratio, R_{EC} the electricity-to-cooling load ratio and R_{HE} the heating-to-electricity load ratio.

4.3.
Thermodynamic Study of the trigeneration system

The assumptions made about the energy demands to model the system are as follows:

i. The vapor compression chiller is sized to supply all the cooling load, $\dot{Q}_{co}$.

ii. The heat engine/electric generator compound and the ORC provide sufficient power to meet the electricity demand, $\dot{E}_{lo}$, and to drive the vapour compression chiller.

iii. The temperature at which the waste heat is recovered is sufficiently high to power the ORC and to supply the heat load demand.

The total fuel consumption distributed in the system is:

$$\dot{H}_{fu} = \dot{H}_{fe} + \dot{H}_{fb} \tag{4.5}$$

where $\dot{H}_{fe}$ is the heat engine fuel consumption and $\dot{H}_{fb}$ is the peak boiler fuel consumption.

Replacing Eqs. (4.2),(4.3) and (4.5) in (4.1), one has:

$$ECR_{tg} = \frac{1 + R_{EC} + R_{HC}}{(\dot{H}_{fe} + \dot{H}_{fb})/\dot{Q}_{co}} \tag{4.6}$$

The peak boiler serves as a backup in the system, in order to supply the necessary heat load, when the heat recovered from the engine coolant system and chiller condenser is not sufficient.

The heat provided by the peak boiler is defined as:

$$\dot{Q}_{pb} = \dot{Q}_{ht} - \dot{Q}_{rc} \tag{4.7}$$

where $\dot{Q}_{ht}$ is the total heat load and $\dot{Q}_{rc}$ the total heat recovered from the engine coolant system and chiller condenser.

The peak boiler efficiency, η_{pb}, which relates the heat supplied to the fuel consumption is defined:

$$\dot{H}_{fb} = \frac{\dot{Q}_{pb}}{\eta_{pb}} \tag{4.8}$$

Substituting Eqs. (4.7) and (4.8) into (4.6), one has:

$$ECR_{tg} = \frac{1+R_{EC}+R_{HC}}{\left(\frac{\dot{H}_{fe}}{\dot{Q}_{co}}\right)+\left(\frac{\dot{Q}_{ht}/\eta_{pb}}{\dot{Q}_{co}}\right)-\left(\frac{\dot{Q}_{rc}/\eta_{pb}}{\dot{Q}_{co}}\right)} \tag{4.9}$$

The total heat recovered from the engine coolant system and chiller condenser to supply the heat load demand is:

$$\dot{Q}_{rc} = \dot{Q}_{ec} + \dot{Q}_{cd} \tag{4.10}$$

All the waste heat that is recovered in the trigeneration system depends on two factors:

(i) The energy balance of the heat engine, which is described by the fractions of energy rate equivalent of fuel consumption that go into exhaust gases, α_{ex}, engine coolant, α_{ec}, and shaft power, α_{es} .

(ii) The heat recovery efficiencies of the engine coolant heat exchanger and the ORC system, ε_{ec} and η_{orc}.

These energy flows are best described by the following equations:

$$\alpha_{es} = \frac{\dot{W}_{es}}{\dot{H}_{fe}} \tag{4.11}$$

$$\alpha_{ec}\varepsilon_{ec} = \frac{\dot{Q}_{ec}}{\dot{H}_{fe}} \tag{4.12}$$

$$\alpha_{ex} = \frac{\dot{W}_{orc}}{\dot{H}_{fe}} \tag{4.13}$$

where $\dot{W}_{es}$ is the heat engine shaft power output and $\dot{W}_{orc}$ the ORC's power output.

The total electricity power load is the sum of the outputs generated by the heat engine and ORC minus the necessary input to the chiller compressor. Thus:

$$\dot{E}_{lo} = \dot{E}_{he} + \dot{E}_{orc} - \dot{W}_{cp} \qquad (4.14)$$

Replacing Eqs. (4.11) and (4.13) in (4.14) and taking into account the efficiencies of the electric generator and ORC, η_{ge} and η_{orc} the energy balance of the electric power output gives:

$$\dot{E}_{lo} = \alpha_{es}\eta_{ge}\dot{H}_{fe} + \alpha_{ex}\eta_{orc}\dot{H}_{fe} - \dot{W}_{cp} \qquad (4.15)$$

Powered by a fraction of the generated electric power, the vapor compression chiller produces refrigeration power and heating power, recovered from the waste heat of the condenser. The refrigerating and heating coefficients of performance of the chiller are:

$$COP_r = \frac{\dot{Q}_{co}}{\dot{W}_{cp}} \qquad (4.16)$$

$$COP_h = \frac{\dot{Q}_{cd}}{\dot{W}_{cp}} \qquad (4.17)$$

From Eq. (4.15), the power consumption of the compressor can be substituted in Eqs.(4.16) and (4.17) to obtain the cooling capacity and condenser heating capacity of the chiller, which gives:

$$\dot{Q}_{co} = COP_r\left(\alpha_{es}\eta_{ge}\dot{H}_{fe} + \alpha_{ex}\eta_{orc}\dot{H}_{fe} - \dot{E}_{lo}\right) \qquad (4.18)$$

$$\dot{Q}_{cd} = COP_h\left(\alpha_{es}\eta_{ge}\dot{H}_{fe} + \alpha_{ex}\eta_{orc}\dot{H}_{fe} - \dot{E}_{lo}\right) \qquad (4.19)$$

Substituting Eqs. (4.12) and (4.19) in (4.10), one obtains:

$$\dot{Q}_{rc} = \dot{H}_{fe}\left(COP_h\alpha_{es}\eta_{ge} + COP_h\alpha_{ex}\eta_{orc} + \alpha_{ec}\varepsilon_{ec}\right) - COP_h\dot{E}_{lo} \qquad (4.20)$$

Using Eq. (4.18), $\dot{H}_{fe}$ can be written as:

$$\dot{H}_{fe} = \frac{(\dot{Q}_{co}/COP_r) + \dot{E}_{lo}}{(\alpha_{es}\eta_{ge} + \alpha_{ex}\eta_{orc})} \qquad (4.21)$$

In order to simplify the equations, the following algebraic auxiliary parameters are defined:

$$\Gamma_{es} = \alpha_{es}\eta_{ge} \qquad (4.22)$$

$$\Gamma_{orc} = \alpha_{ex}\eta_{orc} \tag{4.23}$$

$$\Gamma_{ec} = \alpha_{ec}\varepsilon_{ec} \tag{4.24}$$

where Γ_{es} is the overall fuel to electricity conversion ratio of the heat engine/electric generator compound, Γ_{orc} the overall fuel to electricity conversion ratio of the ORC, and Γ_{ec} the total heat recovery to fuel ratio of the engine coolant system.

Substituting Eqs. (4.20) and (4.21) in (4.9) and using the newly defined parameters a final expression for the energy conversion ratio can be defined by the characteristic parameters, of the system components (energy ratios, efficiencies and coefficients of performance) and in terms of the heating to cooling and electricity to cooling load ratios, as follows:

$$ECR_{tg} = \frac{(1+R_{EC}+R_{HC})(\eta_{pb})(\Gamma_{es}+\Gamma_{orc})}{\frac{1}{COP_r}[\eta_{pb}-(COP_h\Gamma_{es}+COP_h\Gamma_{orc}+\Gamma_{ec})]+R_{EC}(\eta_{pb}-\Gamma_{ec})+R_{HC}(\Gamma_{es}+\Gamma_{orc})} \tag{4.25}$$

4.3.1.
Heat load less than the heat recovered

When the demanded heat load is less than the total recoverable heat, only the required amount of waste heat will be recovered and the rest will be rejected. The limit situation is attained when the total heat recovered is equal to the heat load. In this condition, the heating to cooling load ratio, R_{HC} is obtained by substituting the value of $\dot{Q}_{rc}$ from Eq. (4.20) in $\dot{Q}_{ht}$ from (4.2), thus:

$$R^{*}_{HC} = \frac{\left[\left(\frac{1}{COP_r}+R_{EC}\right)\right](COP_h\Gamma_{es}+COP_h\Gamma_{orc}+\Gamma_{ec})}{\Gamma_{es}+\Gamma_{orc}} - COP_h R_{EC} \tag{4.26}$$

This limit has implications for the energy conversion ratio of the system as well; since the peak boiler will not operate when $\dot{Q}_{rc}$ supplies the entire heat load $\dot{Q}_{ht}$. As a result of this, the boiler's fuel consumption will be, of course, zero. Now, by inserting Eq.(4.21) in (4.6):

$$ECR_{tg} = \frac{(1+R_{HC}+R_{EC})(\Gamma_{es}+\Gamma_{orc})}{(1/COP_r)+R_{EC}} \tag{4.27}$$

4.3.2. Conventional system with no heat recovery

The energy conversion ratio of a conventional trigeneration system without any heat recovery, ECR_{cv}, can be calculated using Eq.(4.25) considering $COP_h = 0$, $\varepsilon_{ec} = 0$ and $\eta_{orc} = 0$, that is:

$$ECR_{cv} = \frac{(1+R_{EC}+R_{HC})(\eta_{pb})(\Gamma_{es})}{\frac{\eta_{pb}}{COP_r}+R_{EC}(\eta_{pb})+R_{HC}(\Gamma_{es})} \tag{4.28}$$

A non-dimensional parameter, Φ_{ECR}, is defined to compare the energy conversion ratio of the trigeneration system with waste heat recovery with a conventional system without any heat recovery, that produces electricity with a motor generator, refrigeration with the electrically driven chiller and heat through the boiler.

$$\Phi_{ECR} = \frac{ECR_{tg}}{ECR_{cv}} \tag{4.29}$$

4.4. Trigeneration system results

Energy conversion ratios for both the conventional and trigeneration systems, considering same load ratios, were estimated from Eqs. (4.25),(4.27) and (4.28), with the following input data α_{ec}=0.3; α_{ex}=0.3; ε_{ec}=0.75; η_{ge}=0.9; η_{pb}=0.9; η_{orc}=0.2; COP_r=3 and COP_h=4. The efficiency considered for the ORC was based on the results obtained from the thermodynamic model solution. The heating to cooling load ratio, R_{HC} , was made to vary from zero (no heat demand) to 10. The electric power to cooling load ratio, R_{EC} , varied from 0.5 to 4.0.

Figure 28 shows the calculated values of ECR for the trigeneration system as a function of the heating and cooling to electricity load ratios. The full utilization of the waste heat by the ORC is attained when the waste heat equals the electric power demand. Beyond this point the conventional heat engine will provide the electric power demands, thus affecting the overall conversion ratio.

Figure 29 shows a comparison of the energy conversion ratio between the trigeneration and conventional systems, the latter with no heat recovery.

It can be seen that the trigeneration system provides a significant gain in energy conversion ratio, with loads close to the amount of waste heat recovered.

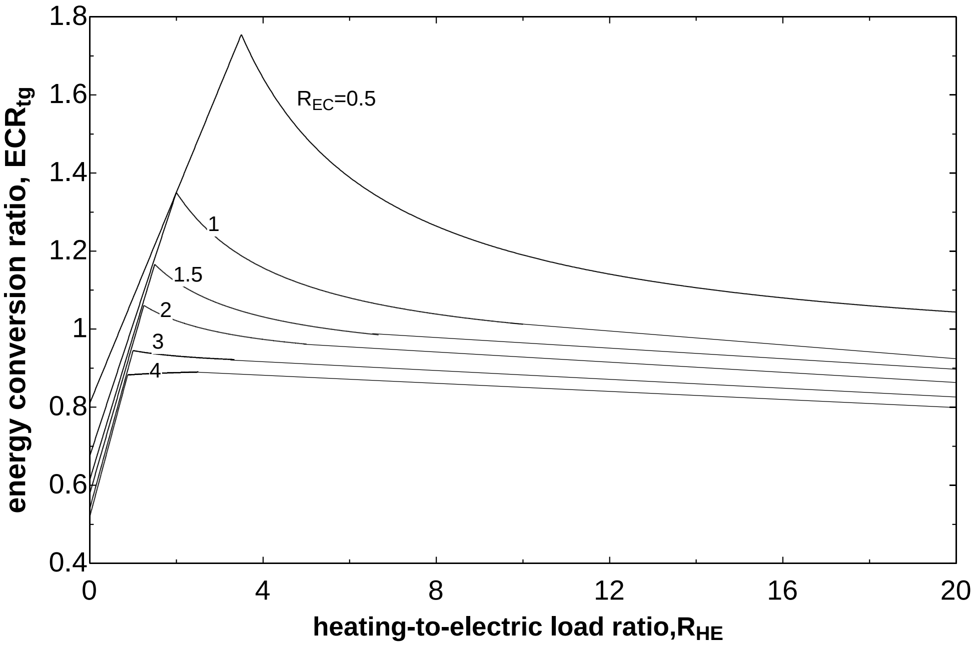

Figure 28. Variation of the energy conversion ratio with heating and cooling to electric power load ratios for a trigeneration system (α_{ec}=0.3; α_{ex}=0.3; ε_{ec}=0.75; η_{ge}=0.9; η_{pb}=0.9; η_{orc}=0.2; COP_r=3; COP_h=4**).**

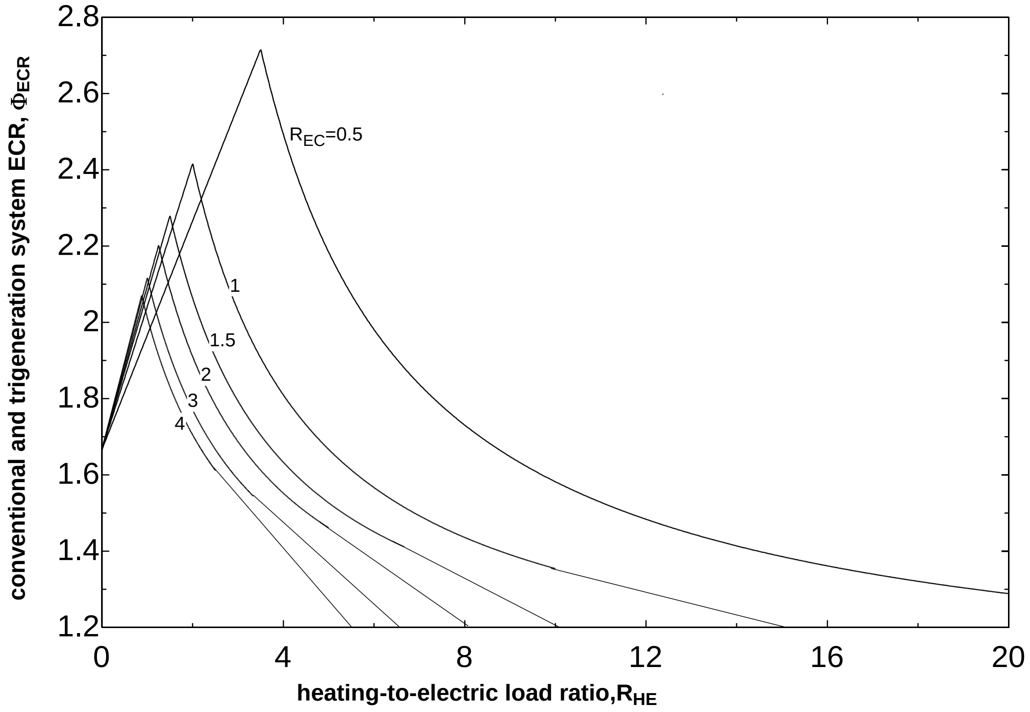

Figure 29. Trigeneration and conventional system ECR ratio as a function of heating and cooling to electric power load ratios(α_{ec}=0.3; α_{ex}=0.3; ε_{ec}=0.75; η_{ge}=0.9; η_{pb}=0.9; η_{orc}=0.2; COP_r=3; COP_h=4) .