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Waste Heat Recovery and Conversion into Electricity: Current Solutions and Assessment

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Abstract

The main energy consumption sectors are the residential, industry and transport. In all of them, a part of the energy consumption is not used and generally rejected as heat in the environment. This is named the waste heat. Firstly, the main way is to optimize the process to reduce the fuel consumption. Then, if there is a residual waste heat, a valorization way is to convert this heat into electricity. Some technologies are developed. The main technology is the Organic Rankine Cycle engine. Then, a new concept, named Turbosol, is based on the quasi-isothermal expansion of a water and oil mixture in a nozzle. Some piston engines are also developed, based on Stirling, Ericsson and Joule cycles. All these technologies are named externally heated engines. Some other research studies concern the thermo-electric effect and the thermo-magnetic effect. In this article, a non-exhaustive list, with description and comments on these technologies is proposed. The aim is to assess the potential of them and identify the current limits. To compare the different technologies in first law efficiency terms is not sufficient. Some new criterions are proposed. The first consideration is to assess the heat rate consumption referred to the heat rate available. To assess the quality of waste heat to power conversion, it is pertinent to evaluate the power output divided by the available heat rate. Then, because of the second law, it is pertinent to evaluate the exergy recovery ratio. These new waste heat criterions are compared to the classical first law efficiency in different cases. Then, the main current issue is to produce enough electrical power output to ensure the profitability. Some thermo-economic considerations are proposed, including the impact of a waste heat taxation.

Keywords: *Thermodynamics; energy; exergy; sustainability.*

1. Introduction

The main energy consumption sectors are the residential, industry and transport [1]. In all of them, a part of the energy consumption is not used and generally rejected as heat in the environment. This is named the waste heat. Firstly, the main way is to optimize the process to reduce the fuel consumption. Then, if there is a residual waste heat, a valorization way is to convert this heat into electricity.

The classical thermal power plants are based on the Rankine/Hirn cycle with water as working fluid. The heat source can be coal, gas or nuclear reaction. In case of nuclear power plant, the maximal water temperature is generally close to 300°C and the maximal pressure is close to 150 bar. The lower range of power is 1000 MW and the efficiency is close to 30%. For the other heat sources, the working fluid temperature is higher, generally from 500°C to 600°C. The maximal pressure is close to 220 bar for subcritical cycles, and higher 300 bars for ultra-critical cycles. The lower range of power is 10 MW and the efficiency is from 38% to 40% [2]. In case of waste heat, the heat source temperature is less than 500°C and the range of power is from 1W to 20 MW [3]. In this range of power, the steam turbine is not adapted and not profitable.

Some other technologies are developed. Firstly, the Organic Rankine Cycle technology. It is based on the classical steam engine cycle. Then, a new concept, named Turbosol, is based on the quasi-isothermal expansion of a water and oil mixture in a nozzle. Some piston engines are also developed, based on Stirling, Ericsson and Joule cycles. All these technologies are named externally heated engines. Some other research studies concern the thermo-electric effect and the thermo-magnetic effect. The article aims to do a state of the art in order to assess the potential of them and identify the current limits. Some review articles are available in the literature, specifically a review on technologies for utilization of industrial excess heat, published in 2014 [4], but many new articles have been published since then. A recent article propose to "A review of thermodynamic cycles used in low temperature recovery systems over the last two years" [5] but it is focus on the ORC technology.

The assessment of the waste heat recovery system is an issue. Generally, only the first law efficiency is considered, but it is not sufficient. Some articles propose to assess, at different criterions, the waste heat to power [6, 7]. In the section 3, it is proposed to define some criterions to assess the waste heat recovery. These criterions are applied to evaluate the performances of an endo-reversible Carnot engine optimized to produce the maximum of power.

Then, the main current issue is the economic cost of technologies. The economic constraint is to produce enough electrical power output to ensure the profitability. The thermo-economic optimization of the waste heat to power is

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a current research area [8-10]. In the last section, some thermo-economic considerations are proposed as perspectives, including the impact of waste heat taxation.

2. Technologies of Waste Heat to Power

2.1 Organic Rankine Cycle Engine (ORC)

The Organic Rankine Cycle engine is the most developed current solution. A lot of demo/prototype phase and commercial engines are installed around the world. A review of the ORC market in the world is done in [3]. The key data concerning the waste heat recovery are summarized here. For this application, there are 1073 ORC plants, which corresponds to 376 MW of cumulated installed systems [3]. In Figure 1, the different manufacturers are represented, with Ormat as leader. Moreover, 65% of the total installed capacity correspond to heat recovery from Diesel or gas engines and turbines [3]. The main limit of the ORC commercialization is the long-term paybacks.

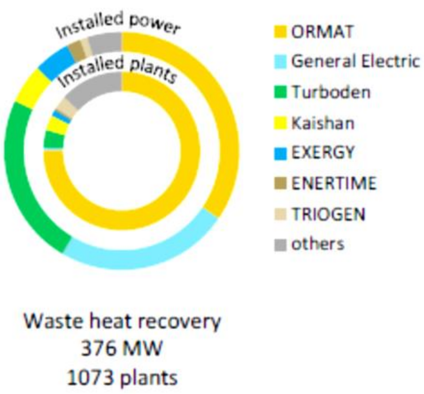


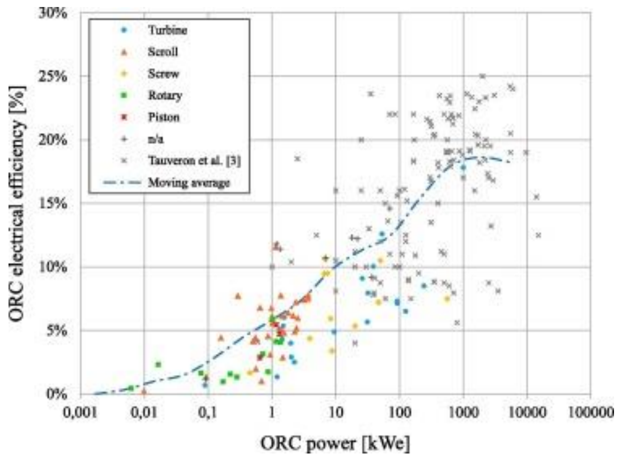
Figure 1. ORC Market share per manufacturer [3].

In terms of Research and Development, the main current issues are the architecture choice [11], the working fluid selection [12], the expander design and the management of operating conditions. The literature is very large. A recent article proposed a generic "solution strategy to simultaneously find the optimal ORC architecture and its operating conditions (including the working fluid selection) for heat recovery in the context of waste heat recovery in industrial processes" [13].

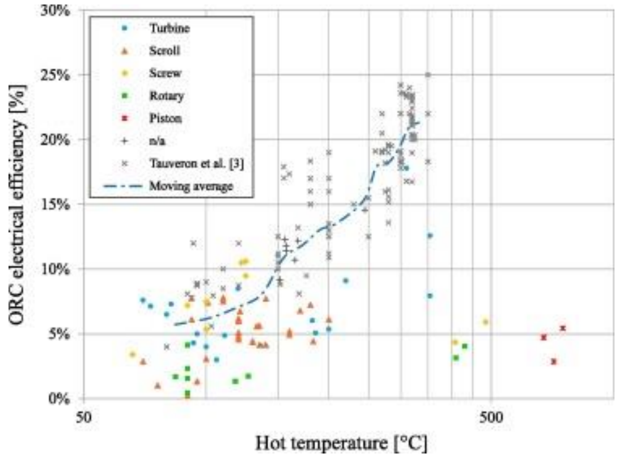
A comparison of different ORC installations based on experimental database is proposed in [14]. The efficiency variation with the ORC power and the hot temperature are given in Figure 2a and Figure 2b respectively. The ORC efficiency increases with the power and the hot temperature rise.

2.2 Turbosol®

Turbosol® is a converter of thermal energy into electrical energy [15]. The patent is exploited by Hevatech, a French company. Turbosol® is an engine with a cycle close to the ideal Carnot engine cycle. The quasi-isothermal expansion of the working fluid is made possible by the specific behavior of a mixture of a gas, here water vapor, and a liquid, here an oil, during the expansion. The expansion is done in a nozzle, and the high velocity mixture drives a hydraulic turbine. A prototype is developed in the Hevatech premises. The main research and development issue is the diphasic nozzle characterization [16]. The main Turbosol® advantage is the operation at low pressure, low speed and a short time payback. That permits to make profitable the waste heat to power generation using water as working fluid.



a)



b)

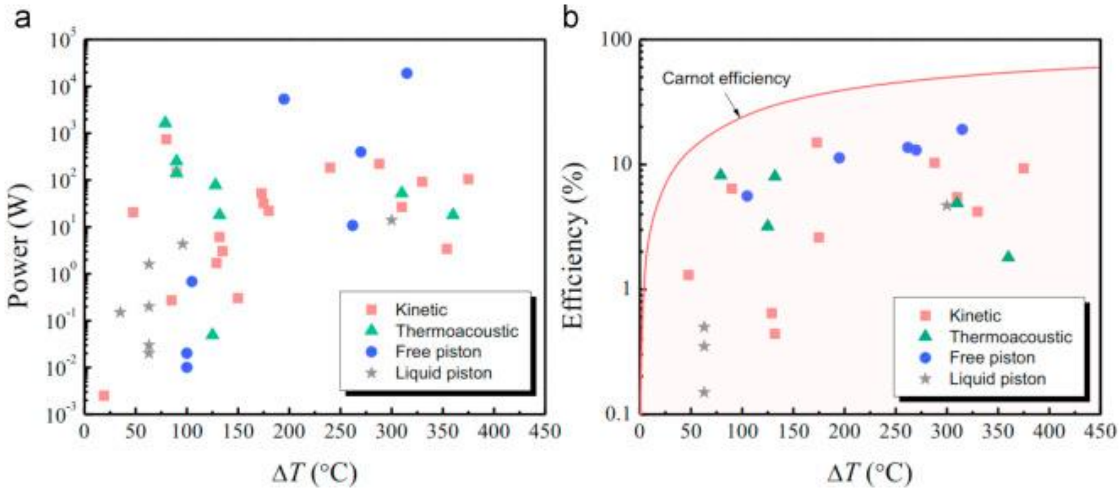
Figure 2. ORC electrical efficiency variation with (a) ORC power and (b) hot temperature [14].

The current range of power is from 20 to 100 kWe, will soon be to 500 kWe at medium and high temperature.

This mixture expansion is also considered in ORC engines [17]. An analysis of the ORC with liquid-flooded expansion is proposed in [18]. The authors shows that the cycle performances are better than the classical ORC engine. The authors also precise that "high built-in volume ratio expanders such as screw-type are desirable to benefit from the presence of large amounts of lubricant oil in the working chamber". But, an experimental study with a scroll expander shows that the efficiency of ORC turbines decrease with the liquid mass fraction [19]. To be close to the isothermal expansion, the liquid mass fraction must be high, so the two effects are contrary. This downside is not present is in case of hydraulic turbine, so neither in Turbosol® case.

2.3 Hot Air Engines

During the theoretical Stirling cycle the working fluid is successively heated with constant volume, expanded with constant temperature, cooled with constant volume and compressed with constant temperature. During the constant volume cooling, the heat is stored in a regenerator. The stored heat is given back to the working fluid during the constant volume heating. The Stirling cycle efficiency, for complete thermal regeneration, is equivalent to the Carnot cycle efficiency.



a) b)

Figure 3. Available experimental results of (a) power and (b) thermal efficiency of the developed Stirling cycle engines [20].

This high theoretical efficiency is the main interest of the Stirling cycle. Stirling cycle engines can be classified in four categories: kinetic, thermo-acoustic, free-piston and liquid piston types. A review of Stirling cycle engines for recovering low and moderate temperature is done by Kai Wand et all. in [20]. In this review article, experimental results are reported in Figure 3. It is shown that the kinetic Stirling cycle engine is a good candidate for the waste heat recovery at low and medium temperature. The experimental results for low temperature differential correspond to a gamma configuration and the working fluid is generally air at ambient pressure.

For the author [20], the research development must focus on the reduction of fabrication cost of low pressure and large scale kinetic Stirling engines to value low grade heat. The second conclusion of the author is the development of the kinetic Stirling engine for waste heat temperature in the range of 250 to 450°C. The compromise between moderate efficiency and costs could make them profitable. The development of thermos-acoustic Stirling engine for the waste heat recovery just starts. Because of its simple structure, high reliability and low cost, this configuration is a good candidate for low temperature waste heat, typically under 100 °C, with very large scalable powers. For the author, the free piston Stirling engine is, at the moment, too expensive and too difficult to produce. Concerning the liquid piston engine, its power range is limited to several watts, and its efficiency is very low [20].

One of the main difficulties of the Stirling engine is the necessity of a compromise between a large area and a small volume of the heat exchanger [21, 22]. Indeed, in a Stirling engine, the heat exchangers volume are considered as dead. In the Ericsson engine, the heating and cooling transformations take place on classical exchangers. So "the compression and expansion enclosures are isolated from heat exchangers when working" [23]. During the Ericsson cycle, the theoretical transformations are 2 isothermal processes and 2 isobaric ones. But, in reversible case, heat transfers take place at constant pressure and compression and expansion at constant entropy. That corresponds to the Joule cycle.

The advantage of the Joule-cycle Ericsson engine, is the corresponding breaking down of the cycle transformations into components. But, valves separate the different components and increase the engine complexity [23]. The current Joule-cycle Ericsson engine issue is the development of steady state [24] and dynamic models [22], with optimization [25] and the prototype achievement [23]. The current application is the micro-CHP systems. The waste heat recovery application is not clearly active.

2.4 Thermo-Electric Effect

The system conversion of heat rate to electrical power is named thermoelectric generator (TEG). Thermo-electric materials produce electric field under temperature gradient by Seebeck effect. A thermoelectric material must have a low thermal conductivity, a high electrical conductivity, a large Seebeck coefficient and an acceptable cost. The main difficulty is to obtain all these properties for a same material [26]. Some recent articles studied the feasibility of the thermoelectric power generation by recovering waste heat [27-29]. In these article, thermoelectric generator operating range size is from We to kWe and the performances are low. A review of the thermoelectric generator applications is done in [30]. The author concludes that, until now, "the development of TEGs has been limited to Space" and "have proven their extreme reliability". The waste heat recovery differs strongly to these applications, because "the heat sources do not vary significantly and the materials are therefore not subject to high thermal tress" [30]. That is why, the extensions to the waste heat recovery is not direct and need research and development.

2.5 Thermo-Magnetic Effect

The Thermo-Magnetic Energy Generation (TMEG) is based on the effect of heat on magnetic properties of ferromagnetic materials near the Curie temperature. A review on design and performance of thermomagnetic devices is done in [31]. "Rapid change in magnetization around a specific temperature can be used to design a device that converts thermal energy into electrical energy, either directly or indirectly via mechanical energy" [31]. The author presents two methodologies for converting thermal energy into electrical energy. The first method relies on direct energy conversion by using active thermomagnetic devices. The corresponding technology is named magnetic generator [32]. The second method is based upon indirect energy conversion via mechanical energy by using passive thermomagnetic devices [33]. The corresponding technology is named thermomagnetic motor or Curie motor. The author shows that the magnetic generators have better efficiency than the passive thermomagnetic devices. In [34], some limitations are proposed to study the feasibility of the magneto-caloric energy conversion. The main author conclusion is that the development of the TMEG depends on the discovery of magneto-caloric materials with Curie temperature higher than 100°C [35]. The other issue is to develop some prototypes [36].

3 Assessment of Technologies

3.1 Model of an Endo-reversible Carnot Engine

To convert waste heat into electricity, an endo-reversible Carnot engine is modelled. This permits to define an upper bound. The system in the environment is represented in Figure 4. The heating and cooling fluids are generally rejected into the environment after flowing through the system. This case is considered here.

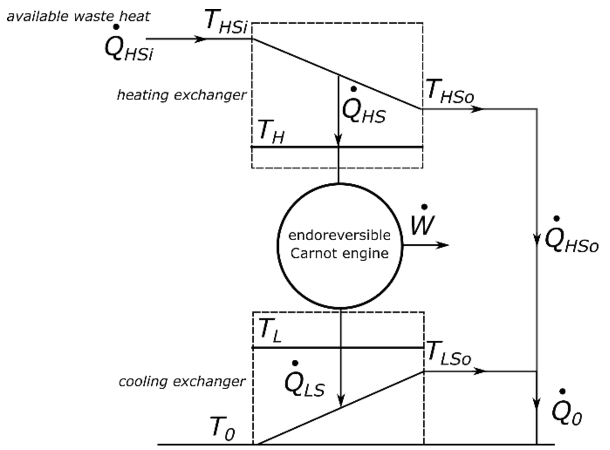


Figure 4: Schema of the Carnot engine in the environment.

The available heat rate of the system in the environment at T_0 can be written as:

$$\dot{Q}_{HSi} = \dot{m}_{HS} cp_{HS} (T_{HSi} - T_0) \tag{1}$$

The output heat rate of the system in the environment can be written as follows:

$$\dot{Q}_0 = \dot{Q}_{HSo} + \dot{Q}_{LS} = \dot{m}_{HS} cp_{HS} (T_0 - T_{HSo}) + \dot{m}_{LS} cp_{LS} (T_0 - T_{LSo}) \tag{2}$$

The input heat rate of the converter is:

$$\dot{Q}_{HS} = \dot{Q}_{HSi} + \dot{Q}_{HSo} = \dot{m}_{HS} cp_{HS} (T_{HSi} - T_{HSo}) = \dot{m}_{HS} cp_{HS} \varepsilon_H (T_{HSi} - T_H) \tag{3}$$

where ε_H is the effectiveness of the hot side exchanger.
The exchanger effectiveness is assumed to be independent of the optimization variables. It is also assumed that the external fluids (heating and cooling fluids) are limiting the heat transfer.
The output heat rate of the cooling exchanger is:

$$\dot{Q}_{LS} = \dot{m}_{LS} cp_{LS} (T_0 - T_{LSo}) = \dot{m}_{LS} cp_{LS} \varepsilon_L (T_0 - T_L) \tag{4}$$

The calorific heat rates are defined as follows $\dot{C}_{LS} = \dot{m}_{LS} cp_{LS}$ and $\dot{C}_{HS} = \dot{m}_{HS} cp_{HS}$, supposing cp_{HS} and cp_{LS} constant specific heat, whatever the temperature is.

There are optimal values of T_H^*, T_L^*, ε_H^* and ε_L^* which maximize the net power output [37]. The optimal temperatures and effectiveness are:

$$\begin{cases} T_H^* = \sqrt{T_{HSi}} \dfrac{\sqrt{\dot{C}_{HS} T_{HSi}} + \sqrt{\dot{C}_{LS} T_0}}{\sqrt{\dot{C}_{HS}} + \sqrt{\dot{C}_{LS}}} \\ T_L^* = \sqrt{T_0} \dfrac{\sqrt{\dot{C}_{HS} T_{HSi}} + \sqrt{\dot{C}_{LS} T_0}}{\sqrt{\dot{C}_{HS}} + \sqrt{\dot{C}_{LS}}} \\ \varepsilon_H^* = \varepsilon_T \dfrac{\sqrt{\dot{C}_{LS}}}{\sqrt{\dot{C}_{HS}} + \sqrt{\dot{C}_{LS}}} \\ \varepsilon_L^* = \varepsilon_T \dfrac{\sqrt{\dot{C}_{HS}}}{\sqrt{\dot{C}_{HS}} + \sqrt{\dot{C}_{LS}}} \end{cases} \tag{5}$$

where ε_T is a total effectiveness that is available to allocate between the hot and the cold sides according to the finite physical dimension constraint $\varepsilon_H + \varepsilon_L + \varepsilon_T = 0$ is satisfied. The maximal corresponding power output is:

$$-\dot{W}^* = \varepsilon_T \frac{\left(\sqrt{T_{HSi}} - \sqrt{T_0}\right)^2}{\left(\frac{1}{\dot{C}_{LS}} + \frac{1}{\dot{C}_{HS}}\right)} \tag{6}$$

This result is an upper bound of the maximum power output. In the general case, the optimal allocation of a total calorific rate $\dot{C}_T$ between the heating and cooling fluids leads to the equipartition $\left(\dot{C}_{HS} = \dot{C}_{LS} = \dot{C}_T/2\right)$. In our case, the heating fluid calorific rate is imposed, so choose a total calorific rate is equivalent to impose the cooling fluid mass flow rate.

3.2 Criteria

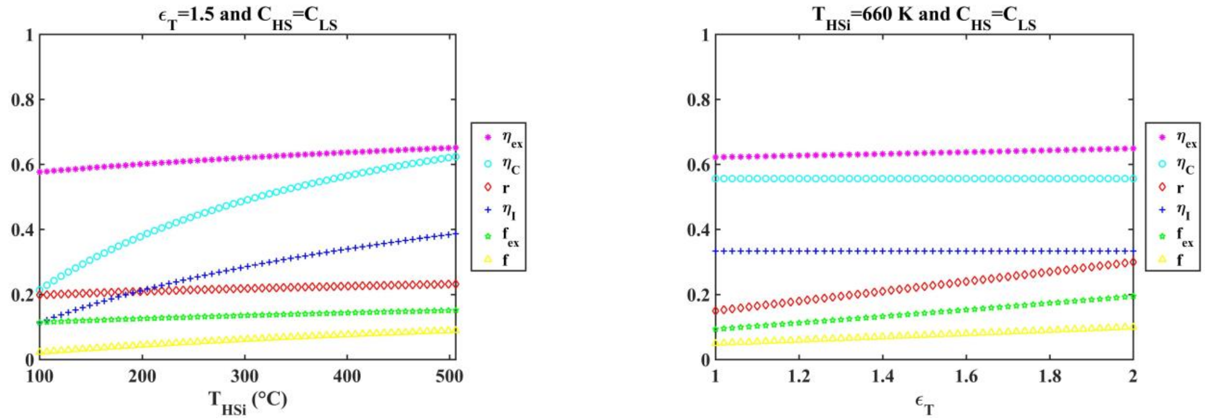
Some classical and new criterions are defined and expressed for endo-reversible Carnot engine at maximum power output in Table 1. The first law efficiency takes notice of useful effects regarding the costs to produce these useful effects. It is a classical criterion, largely used. In case of endo-reversible Carnot engine at maximum power output, the first law efficiency corresponds to the nice radical.
The second criterion is the heat recovery ratio. This ratio quantifies the valued heat regarding the available heat. In the developed model, the heat recovery ratio depends on the total exchanger's effectiveness, the heating and cooling fluids' calorific heat rates, the waste heat temperature and the ambient temperature. Then, the waste heat to power ratio quantifies the produced power regarding the available heat. The exergy efficiency is also defined, and it takes notice of the heat to power conversion's quality. Then, the exergy recovery ratio is proposed, if quantifying the produced exergy regarding the available exergy.

3.3 Sensitivity Analysis to the Waste Heat Temperature

Equipartition of calorific heat rates is assumed, so $\dot{C}_{HS} = \dot{C}_{LS}$. The criterion variations with the waste heat temperature T_{HSi} are given in Figure 5a. The first law efficiency η_I and the Carnot efficiency η_C increase strongly with the temperature. However, the exergy efficiency η_{ex}, the heat recovery ratio r and the exergy recovery ratio f_{ex} are not significantly sensitive to the waste heat's temperature. The waste heat to power ratio f increases slightly with the waste heat temperature. The waste heat recovery criterions (r, f and f_{ex}), are generally lower than the classical criterions (η_C, η_I and η_{ex}).

Table 1. Definition and expression of different criteria.

		Definition	Expression for thermo-mechanical converter	Expression for endoreversible Carnot engine at maximum power output
First law efficiency	η_I	$\frac{useful\ effects}{energy\ costs}$	$\frac{-\dot{W}}{\dot{Q}_{HS}}$	$\eta_I = 1 - \sqrt{\frac{T_0}{T_{HSi}}}$
Heat recovery ratio	r	$\frac{valued\ heat}{available\ heat\ rate}$	$\frac{\dot{Q}_{HS}}{\dot{Q}_{HSi}}$	$\varepsilon_T \frac{\dot{C}_{LS}}{\left(\sqrt{\dot{C}_{HS}} + \sqrt{\dot{C}_{LS}}\right)^2} \sqrt{\frac{T_{HSi}}{T_{HSi} + T_0}}$
Waste heat to power ratio	f	$\frac{mechanical\ power}{available\ heat\ rate}$	$\frac{-\dot{W}}{\dot{Q}_{HSi}}$	$r\eta_I$
Exergy efficiency	η_{ex}	$\frac{useful\ exergy}{exergy\ cost}$	$\frac{-\dot{W}}{\dot{Q}_{HS}\left(1-\frac{T_0}{\tilde{T}_{HS}}\right)}$ with $\tilde{T}_{HS} = \frac{(T_{HSo}-T_{HSi})}{\ln(T_{HSo}/T_{HSi})}$	$\frac{f\eta_C}{r\eta_C + \frac{T_0}{T_{HSi}}\ln(1-r\eta_C)}$ with $\eta_C = 1 - \frac{T_0}{T_{HSi}}$
Exergy recovery ratio	f_{ex}	$\frac{useful\ exergy}{available\ exergy}$	$\frac{-\dot{W}}{\dot{Q}_{HSi}\left(1 - \frac{T_0}{\tilde{T}_{HS}}\right)}$	$r\eta_{Ex}$



a) b)

Figure 5. (a) Variation of criteria with waste heat's temperature; (b) Variation of criteria with total exchanger's effectiveness.

The criterion variation with the total exchanger's efficiency ε_T is given in Figure 5b. The heat recovery ratio r, the exergy recovery ratio f_{ex} and the waste heat to power ratio f increase slightly with the total exchanger's efficiency. However, the exergy efficiency η_{ex}, the first law efficiency η_I and the Carnot efficiency η_C are not significantly sensitive to the waste heat's temperature

Conclusions and Perspectives

In case of waste heat, the heat source temperature is less than 500°C and the range of power is from 1W to 20 MW. In this range of power, the steam turbine is not adapted and not profitable. So different technologies are developed to convert waste heat into electricity. The must developed technology is the Organic Rankine Cycle engine. The use of Organic Fluid permits to value waste heat with low temperature. The Organic Rankine Cycle engine is a commercialized technology. The main difficulty is to make them profitable in the waste heat range of power. Indeed, the main limit of the ORC commercialization is the long-term paybacks. Then, a new concept, named Turbosol®, is a good candidate. The main Turbosol® advantage is the operation at low pressure, low speed and short time payback. The prototype development is leading to the installation of a demonstrator. The other candidates are the hot air engine. The most advanced is the Stirling engine. The kinetic type is bright for medium temperature. A lot of prototypes are developed. Thermoelectric generator has been developed to Space applications. Contrary to space application, in case of waste heat, the materials are subject to high thermal stress. That is why, the extensions to the waste heat recovery is not direct. A lot of studies are in progress. Concerning the magneto-caloric effect, the main issue is the discovery of low cost magneto-caloric materials with Curie temperature higher than 100°C.

As perspective, a simplified model is proposed for economic considerations. Waste to power conversion represents a cost. The investment cost is presumed linearly increasing with the produced power $\dot{W}$. The proportionality coefficient is v_{invest}. The operating cost is presumed increased linearly with the total produced energy during rhe time of life Δt_l. The proportionality coefficient is v_{op}. So the converter cost can be expressed as follows:

$$C_{conv} = v_{invest}|\dot{W}| + v_{op}|\dot{W}|\Delta t_l > 0 \quad (7)$$

The power production permits to do a benefit:

$$B_{conv} = v_{power}|\dot{W}|\Delta t_l > 0 \quad (8)$$

The waste heat could be taxed to promote the waste heat valorization. An exergetic point of view is proposed to determinate the instantaneous waste heat cost as follows:

$$C_{waste} = v_{waste}\left(1-\frac{T_0}{T_{waste}}\right)\left|\dot{Q}_{waste}\right| > 0 \qquad (9)$$

where v_{waste} is a coefficient to determinate. T_{waste} is the waste heat temperature and $\dot{Q}_{waste}$ the waste heat rate quantity. Without waste heat recovery, $T_{waste} = T_{HSi}$ and $\dot{Q}_{waste} = \dot{Q}_{HSi}$.

The waste heat to power conversion cost during all the system life is:

$$C_{val} = \left|\dot{W}\right|\left[v_{invest} + \Delta t_{life}\left(v_{op} - v_{power}\right)\right] + \\ +v_{waste}\Delta t_{life}\left[\left(1-\frac{T_0}{T_{HSo}}\right)\left|\dot{Q}_{HSo}\right| + \left(1-\frac{T_0}{T_{LSo}}\right)\left|\dot{Q}_{LS}\right|\right] \qquad (10)$$

The payback time must satisfy the following relation:

$$C_{val}\left(\Delta t_{life} = \Delta t_r\right) = v_{waste}\left(1-\frac{T_0}{T_{HSi}}\right)\dot{Q}_{HSi}\Delta t_r \qquad (11)$$

After some calculations, the payback time is:

$$\Delta t_r = \frac{v_{invest}}{v_{op}-v_{power}+v_{waste}Z} \qquad (12)$$

with

$$Z = \left[\left(1-\frac{T_0}{T_{HSo}}\right)\left(\frac{1}{f}-\frac{1}{\eta}\right) + \left(1-\frac{T_0}{T_{LSo}}\right)\left(\frac{1}{\eta}-1\right) - \frac{1}{f}\left(1-\frac{T_0}{T_{HSi}}\right)\right] \qquad (13)$$

The limit case without waste heat taxation corresponds to $v_{waste} = 0$.
The output temperatures can be expressed as follows:

$$\begin{cases} T_{HSo} = T_{HSi} - r(T_{HSi} - T_0) \\ T_{LSo} = T_0 + (r-f)\frac{\dot{C}_{HS}}{\dot{C}_{LS}}(T_{HSi} - T_0) \end{cases} \qquad (14)$$

To spur valorizing the waste heat, imposing a waste heat taxation is a way. With the proposed taxation law, the payback time of a waste heat to power system depends on the system first law efficiency, the system heat recovery ratio, the system waste heat to power ratio, the heat source temperature and mass flow rate, the ambient temperature and the cooling flow rate. The present work will be extend to the comparison of the different technologies in term of payback time. Two cases must be compared: with or without waste heat taxation. The present work is focus on simple waste heat to power systems, but, cascade systems, district heating and polygeneration must be also considered.

Acknowledgments

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