

The effect of recuperator on the efficiency of ORC and TFC with very dry working fluid

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Abstract. Organic Rankine Cycles (ORC) and Trilateral Flash Cycles (TFC) are very similar power cycles; ideally, they have a reversible adiabatic (isentropic) compression, an isobaric heating, an isentropic expansion and an isobaric cooling. The main difference is that for ORC, the heating includes the full evaporation of the working fluid (prior expansion); therefore, the expansion starts in a saturated or dry vapour state, while for TFC, the heating terminates upon reaching the saturated liquid states. Therefore, for TFC, expansion liquid/vapour state (in bubbly liquid or in vapour dispersed with droplets), requiring a special two-phase expander. Being ORC a more “complete” cycle, one would expect that its thermodynamic efficiency is always higher than for a TFC, between the same temperatures and using the same working fluids. Surprisingly, it was shown that for very dry working fluids, the efficiency of TFC can exceed the efficiency of basic (i.e. recuperator- and superheater-free) ORC, choosing sufficiently high (but still subcritical) maximal cycle temperature. Therefore in these cases, TFC (having a simpler heat exchange unit for heating) can be a better choice than ORC. The presence of a recuperator can influence the situation; by recovering the proper percentage of the remaining heat (after the expansion), the efficiency of ORC can reach and even pass the efficiency of TFC.

1 Introduction

The utilization of low-temperature heat sources for energy conversion required novel technologies; one of the novelty is the use of alternative working fluids (like organic materials or carbon dioxide) for Rankine cycles [1]. Using these methods, one can produce electricity from heat sources unavailable for this purpose before, like low-temperature geothermal heat, unfocused solar heat or low-temperature industrial waste heat. Most of these heat sources are existing ones; without proper utilization, they would only dissipate their heat into the environment; sometimes, this is “only” the waste of sources, but in several cases, it can have a direct negative environmental impact. Therefore the application of ORC- (or some similar technology-) based power plants can be used to reach the goals for a greener World.

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The idealized basic form of the Organic Rankine cycle (just like the Steam Rankine cycle) has four steps, two isobaric heat exchange and two adiabatic (isentropic) expansion/compression. This can be seen in Figure 1/a, using a so-called wet or ACZ-type working fluid, like water, carbon dioxide, propane, etc. [2]. The type of the working fluid (namely the shape of the T-s diagram has very strong effect on the process [3,4,5]. For wet working fluids, in the first step, the working fluid is in a saturated, cold liquid state (point 1), where the temperature is usually equal to the environmental one; it is compressed then to a compressed liquid state with a little bit higher temperature (point 2). In an ideal cycle, the compression would be isentropic; in a real system, there is a small entropy production, and the entropy of point 2 would be higher than the entropy of point 1; but these non-idealities (together with the non-idealities of the other steps) are neglected in this study. The next step is isobaric heating; for basic ORC, it has two sub-steps. First, the liquid heating (from point 2 to point 3*), then the evaporation (from 3* to 3) happen. Technically, this can be done by two different heat exchanger (a liquid heater and an evaporator) or is one having two parts. In point 3*, the working fluid is in a high-temperature saturated *liquid* state, while in point 3, it is in a high-temperature saturated *vapour* state. In a basic ORC, heating terminates here (i.e. no superheating to reach dry vapour state). The expansion also starts from point 3* (a high-temperature saturated vapour state) and terminates at point 4 (a low-temperature, two-phase state; in this case, it is wet vapour, i.e. vapour with liquid droplets). Then a second heat exchanger (a condenser) would fully condenses this vapour till the initial state (point 1, saturated cold liquid) state is reached.

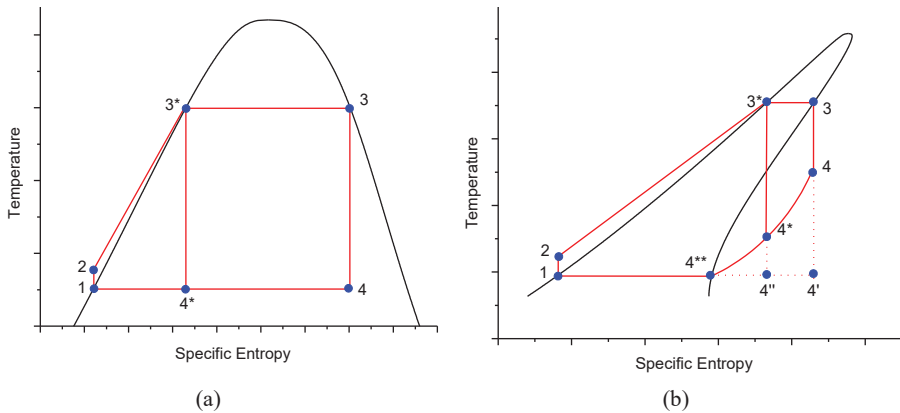


Fig. 1. Comparison of the recuperator- and superheater-free ORC and TFC cycles (see text).

In Figure 1/a, an alternative technology can also be seen; the so-called (organic) Trilateral Flash Cycle (TFC) [6]. In TFC, heating terminates at point 3* (hot saturated liquid state); expansion starts there and terminates in the two-phase region, at point 4*, which is – at least in this case, concerning the position of the point – is a very wet vapour state with a lot of bubbles. Similarly to ORC, a condenser condenses the vapour from this state to the initial cold saturated liquid state (point 1).

ORC is usually considered superior to TFC for several reasons:

- efficiency is higher (see later);
- due to the evaporation (between points 3* to 3), the heat input is higher and therefore, power output is also higher (even with equal efficiency);
- for the realization of a TFC cycle, a very special expander is needed because of the very high fraction of droplets (especially in the early stage of the expansion); this can be, for example, a volumetric expander [7,8].

Concerning the efficiency, one can realize very easily, that by using wet (ACZ-type) working fluid, the efficiency of ORC is higher than the efficiency of TFC. From Figure 1/a, it can be seen that the ORC (i.e. the whole $1 \rightarrow 2 \rightarrow 3^* \rightarrow 3 \rightarrow 4 \rightarrow 4^* \rightarrow 1$ cycle) is virtually the combination of a TFC ($1 \rightarrow 2 \rightarrow 3^* \rightarrow 4^* \rightarrow 1$) and a strange pseudo-Carnot cycle, running entirely in the two-phase region ($4^* \rightarrow 3^* \rightarrow 3 \rightarrow 4 \rightarrow 4^*$). Although one cannot simply sum the efficiencies of the TFC and the pseudo-Carnot cycle, still - being the efficiency of Carnot-cycles is the highest possible one among all others, between the same maximal and minimal cycle temperatures – it is plausible to assume that the addition of this highly efficient pseudo-Carnot cycle to the TFC to complete it to ORC would increase the efficiency. It was shown previously that in this case, using the same temperature ranges, the efficiency (using wet working fluid) of ORC is always above the TFC, except at the critical point (the top of the T - s dome), where points 3 and 3^* would merge, making the TFC and ORC identical. This has a surprising consequence, namely that the efficiency of ORC (with a fixed minimal cycle temperature) has to reach a maximum at high temperatures (usually a very few Kelvin below the critical point) then it will decrease and smoothly reach the continuously increasing efficiency of TFC at the critical point [9,10]. An example for a typical wet working fluid (CO_2) can be seen on Figure 2/a; the efficiencies of ORC (magenta) and TFC (blue) cycles are with minimal cycle temperature fixed at 217 K and maximal one varied between 217 K and the critical temperature. A well-recognizable maximum for ORC efficiency of around 300 K (used as maximal cycle temperature) can be seen; it means that increasing the maximal cycle temperature above this value is counterproductive. For TFC, the efficiency smoothly increases along with the whole temperature range [9].

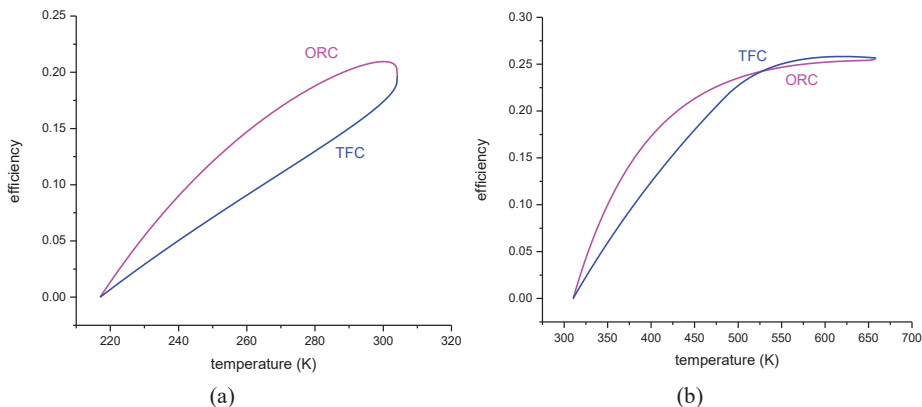


Fig. 2. The thermodynamic efficiencies of the ORC and TFC cycles using wet (a: CO_2) and very dry (b: dodecane) working fluid, using the basic layout, without superheating and heat recuperation. Minimal cycle temperatures are fixed (a: 217 K; b: 310 K), while the maximal cycle temperatures gradually increased up to the critical temperature of the given fluid.

In the case of dry working fluids without a recuperator, one can lose some (even significant) part of the heat without converting it to work. The total lost part (as can be seen in Figures 1a and 1b) are almost triangular ones, $4-4'-4^{**}$ for ORC and $4^*-4''-4^{**}$ for TFC. This loss will cause some loss of efficiency. As it can be seen in Figure 1b, sometimes the loss for ORC can be significantly bigger than for TFC, causing higher efficiency loss. For moderately dry working fluids [9], it can cause a smaller and smaller efficiency surplus for ORC. In extremely dry fluids (like dodecane, a class ANZCM –fluid [2] the loss for ORC can be so high that choosing high maximal cycle temperature (while keeping the low one in the original value) can shift ORC efficiency below TFC one, as can be seen in Figure 2b for

dodecane with minimal cycle temperature at 310 K and maximal one above this value, up to the critical point. In this case, the maximum for ORC efficiency disappears, while the efficiency curve for TFC can show a small, insignificant maximum [9].

Although the minimal temperatures chosen for this demonstration for carbon dioxide (as 217 K) and dodecane (as 310 K) are quite low, they are not unrealistic. 217 K can be easily reached in cryogenic cycles (for example using liquid methane, LNG as heat sink), see for example in Ref. [11], while 310 K (almost 33 Celsius) can be obtained by a good air cooling. It is important to remark, that in both cases, the shape of the curves would be the same by choosing higher minimal temperature, only the loops would be smaller and therefore the effect would be less remarkable.

2 The effect of heat recovery

As it was already mentioned, some part of the input heat can be lost when dry working fluids are used. Some part of the lost heat can be recovered by using a recuperative or regenerative method. By using this part for liquid pre-heating, the efficiencies can be increased. Theoretically, this part is the part of the former triangular regions located at temperatures above the temperature of point 2; technically, one should consider the loss of an extra “few K-wide” region to provide proper heat flow in the recuperator or regenerator.

In Figure 3, one can see the cycle for dodecane (like in Figure 2b), without recovering any heat ($rec=0$); recovering half of the theoretically recoverable one ($rec=0.5$) and recovering all of the theoretically possible one ($rec=1$). One should remember that even for $rec=1$; the part below the temperature of point 2 is still lost. In Figure 3, the recuperated and un-recuperated cases are shown at two different temperatures. In Figure 3/a, the case with minimal temperature fixed at 310 K can be seen (like for Figure 2/b), while in Figure 3/b, the curves represent the case with minimal temperature fixed at 272 K. Technically, this second temperature is less relevant (although it can be reached even in mild cryogenic cases), this case demonstrates that both effects (the crossing of the two efficiency lines with low recuperation ratio and the disappearance of the crossing point at higher recuperation ratio) exist on various temperatures, i.e. it is a general phenomenon.

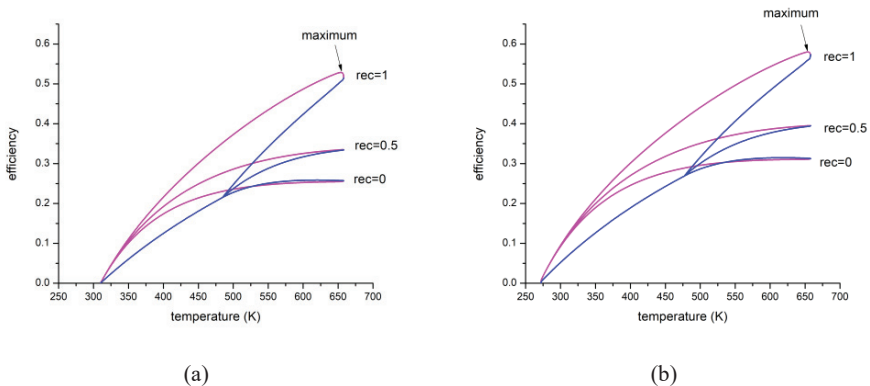


Fig. 3. The effect of lost heat recovery and the use of it for liquid pre-heating in ORC and TFC with extremely dry working fluid (dodecane), on two different minimal temperatures.

Heat recovery is clearly advantageous for ORC as well as TCT efficiencies. One can see that by recovering a proper amount of heat, ORC will be more efficient than TFC, although one

have to consider the cost of appropriate heat regenerators versus the positive effect of efficiency increase (compared to recovery-free ORC). It might happen that the extra earning caused by the efficiency increase (connected with power output increase) is negligible; in this case the use of recuperator-free system can be advantageous, and among them, TFC-type system can surpass ORC-type one in efficiency (as well as in power output)

3 Discussion

The advantages and disadvantages for ORC-and TFC based systems with and without recuperator are summarized here:

Advantages using simple TFC over simple ORC with very dry working fluid

- Simple initial heating unit (only liquid heater); i.e. lower installation and maintenance cost
- Higher efficiency, due to the lower heat lost after expansion

Disadvantages using simple TFC over simple ORC with very dry working fluid

- The need for a special (wetness resistant) expander; i.e. higher installation and maintenance costs.

Advantages using recuperated ORC over simple TFC with very dry working fluid

- Possibility to reach efficiency above the efficiency of simple TFC

Disadvantages using recuperated ORC over simple TFC with very dry working fluid

- Need of complex initial heating unit (liquid heater plus evaporator); i.e. higher installation and maintenance costs.
- Need of recuperative heat exchanger to recover part of the leftover heat after expansion; i.e. higher installation and maintenance costs.

Advantages using recuperated ORC over recuperated TFC with very dry working fluid

- Possibility to reach efficiency above the efficiency of recuperated TFC (the potential increase is bigger for ORC than for TFC)

Disadvantages using recuperated ORC over recuperated TFC with very dry working fluid

- Need of complex initial heating unit (liquid heater plus evaporator); i.e. higher installation and maintenance costs.
- Although both systems need a recuperative heat exchanger to recover part of the leftover heat after expansion, this heat exchanger has to be bigger for ORC, i.e. higher installation and maintenance costs (although the difference here will be only minor one).

4 Conclusions

The choice of working fluid is a multi-dimensional optimization process involving various (chemical, environmental, economical, etc.) criteria. Under some circumstances – for example, due to some compatibility problem - the number of potential working fluids can be pretty low; therefore, the utilization of a given heat source has to be solved with a given working fluid. In that case, one has to tune other parameters, like the type of cycle (ORC or TFC) or the system layout (with or without recuperator). Using our results, one might choose the proper (most effective) system to turn heat to work (and power), when the use of extremely dry working fluid (like dodecane) would be advantageous for some other reason (like temperature levels, etc.).

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