ON HIGH LEVEL EVALUATION AND COMPARISON OF ORC POWER GENERATORS

Henrik Öhman[1]*, Per Lundqvist[2]

[1]KTH, Royal Institute of Technology,
Energy Technology, Stockholm, Sweden
henrik@hohman.se

[2]KTH, Royal Institute of technology,
Energy Technology, Stockholm, Sweden
per.lundqvist@energy.kth.se

* Corresponding Author

ABSTRACT

A review of the thermodynamic performance of ORCs from public, as well as non-public sources has revealed a correlation suitable to be used as a rule of thumb for high-level performance estimation of ORC power generators. Using the correlation, the limited amount of available test data can be generalised leading to a high level evaluation of the commercial benefits of any potential application for ORCs.

Power generators using ORC-technology exist in relatively low numbers. Furthermore, field installations seldom imply comparable boundary conditions. As ORCs generally operate at low temperature differences between source and sink it has been shown that their relative sensitivity to variations in temperatures i.e. the finiteness of source- and sink, is larger than the sensitivity of power generators operating with large temperature differences. Therefore the establishing of practical rule of thumb performance estimation, similar to the figure of merit, Coefficient of Performance, COP, as used in refrigeration and air conditioning industry, has previously not been successful.

In order to arrange field data in a manner suitable for comparison a refinement of suitable figures of merit was required. The suggested, refined terms are presented and explained as well as critically evaluated against the most common efficiency terms traditionally used.

The current lack of a performance rule of thumb leaves room for less serious vendors and laymen to make performance claims unrealistic to practical achievements. Scrutinizing such questionable statements requires detail process simulations and a multitude of technical assumptions. Hence argumentation becomes ineffective. If a suitable rule of thumb can be established argumentation against dubious claims would become significantly more forceful.

This paper suggests a new term to be used as rule of thumb and explains a method on how to use it.

1. INTRODUCTION

In the technical field of ORC power generators, as in most technical fields, the need for universally accepted figures of merit is substantial. Such terms are used daily by engineers and scientists to evaluate choices of many kinds. Design choices, development strategies, economic investments, career decisions are a few examples where figures of merit are used for rule of thumb decision. Only when resources are already allocated to feasibility studies, or similar, will someone spend the time to properly model the details of the conditions and thereby have the position to question any rule of thumb.

Technical fields lacking proper rules of thumb are susceptible to confusion, uncertainty and tend to attract the attention of enthusiasts with more or less respect for physical realities. It is not strange that discussions then have a tendency to become more of debate then scientifically constructive argumentations. This is not only irritating but can also pose a significant entry barrier to the market. If potential investors need the expertise of gurus speaking incomprehensible language the likelihood of powerful market penetration is low. Furthermore enthusiasts claiming unrealistic future performances create excellent reasons to postpone any investment in current applications.

Establishing purely experience based figures of merit for specific technologies tend to require a large enough number of products in commercial use in combination with scientific endorsement of whatever entities used for comparison. Typically the environment of a technology can be limited to a few characteristic parameters, which then could be used for evaluation. Furthermore a clear reference of some representation of an ideal product/cycle has to be available. Compromises between scientific accuracy and practicality of communication are also required to gain acceptance. No figure of merit can be perfect, though over time the inapt terms will naturally disappear. However many still exist despite obvious logical imperfections. Two examples from industrial practice are volumetric screw compressors in the odd case measuring >100% volumetric efficiency and 2-phase compressors showing >100% isentropic efficiency. In the first case dynamic super-filling creates the illusion and in the second case the isentropic reference is badly chosen instead of an isothermal reference. The issue of choosing dubious definitions of figures of merit, as in the examples, cannot be entirely avoided and has to be addressed by educators and senior experts. However, the more implicit error of ill-defined methods is clearly a scientific matter. Communication about ORC technology performance is affected by both types of error.

Technologies for low temperature difference power generators, of which ORC is only one, are mature for market penetration, see example in Öhman (2012). Applications with available low grade heat are available in abundance as of many examples, Biscan and Filipan (2011). Need for heavy investments in new electric power generation is also well determined, see Breeze (2014). A number of industrial suppliers of ORC are offering products for different applications as seen in Öhman and Lundqvist (2013). In science a very high number of articles are published yearly on ORC technology, details of the plurality can be found in Öhman (2014). Environmental benefit of using low grade heat for power generation is furthermore evident to anyone educated in environmental concern. Yet, the number of commercially installed ORCs is not impressive. One way of improving implementation of ORCs in society would be to create universally accepted rules of thumb, guiding anyone involved in determining the quality of ORC-products.

2. FIGURES OF MERIT FOR ORC POWER GENERATORS

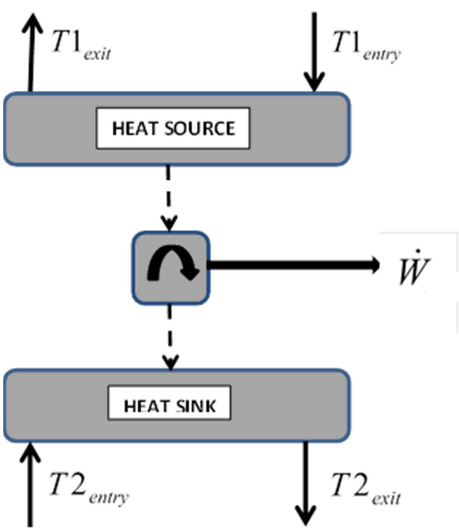

Figure 2. Schematic of a power cycle operating between a finite heat source and a finite heat sink.

Considering a schematic power cycle as of Figure 1, 1st law efficiency, here called thermal efficiency as of Equation (1), is a suitable figure of merit for some technologies, such as high temperature Internal Combustion Engines and Power plants. However, ORCs often operate with low temperature differences between source and sink and is therefore more sensitive to the nature of source and sink than high temperature systems.

$$\eta_{th} = \dot{W} / \dot{Q}_1 \tag{1}$$

where

$$\dot{Q}_1 = \left(T_{1entry} - T_{1exit}\right) / \alpha_1 \tag{2}$$

and if apparent heat capacity if the heat source is constant

$$\alpha_1 = 1 / \left(\dot{m} \cdot Cp\right) \tag{3}$$

Scientific papers of very shifting quality can be found claiming unrealistically high efficiencies of ORCs. A common simplification is to only consider the cycle itself. Temperatures of evaporator and condenser are used to calculate a reference Carnot efficiency, as of Equation (4). Any measure, or simulated, thermal efficiency of the ORC is then compared to the reference and the result is used as characterizing the system, as of Equation (5). Using this type of Carnot efficiency creates an illusion of being physically correct. First law efficiency, internal to the cycle, can sometimes be motivated when combined with some definition of “external” loss, such as Criterion P of Yan (1987) and Yan (1991). Also heat exchanger efficiency, as in Karellas and Schuster (2008) could be interpreted as an “external” loss. However when distinguishing between “internal” and “external” losses one cannot avoid making an assumption about the cycle, thereby biasing any comparison with a different cycle.

$$\eta_C = 1 - \frac{T_2}{T_1} \tag{4}$$

$$FM = \eta_{th} / \eta_C \tag{5}$$

A better, but still misleading, approach is to define a reference Carnot efficiency by using only the entry temperatures of the source and sink. This is a surprisingly common in literature. As no concern is taken to the temperature gradients in source and sink an infinitely small power cycle would appear more attractive than a larger one. Obviously this cannot serve as a universal figure of merit.

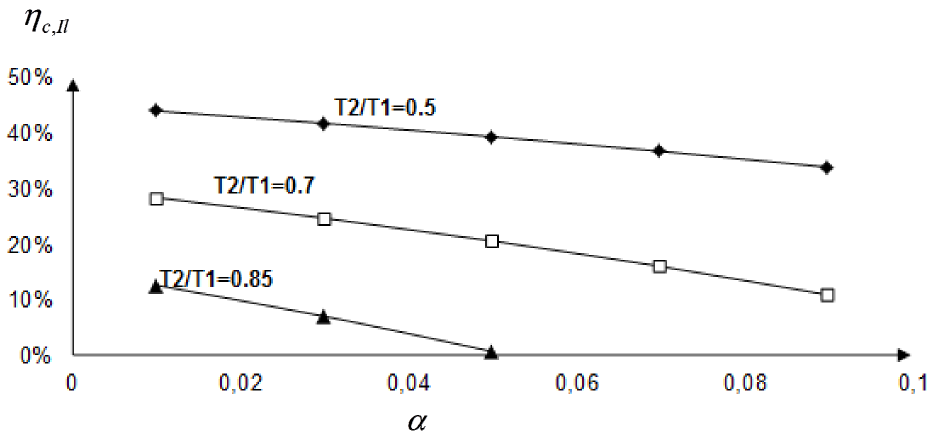

Figure 2. Integrated Local Carnot efficiency vs. inverse apparent heat capacity, α, with source and sink of equal finiteness, α_1 equals α_2. Low temperature ratios show little sensitivity while high temperature ratios show high sensitivity to the finiteness. *From Öhman and Lundqvist (2013)*

Figure 2 shows relative sensitivity to source and sink finiteness as a function of source and sink entry temperature ratio. This is clear evidence of the poor suitability of thermal efficiency as figure of merit for ORCs.

Some authors prefer to use exergy analysis to solve the problem of comparing higher level performance of ORC. In some cases the exergetic efficiency, or 2nd law efficiency, is defined as in Equation (6). It is defined by comparing the work output to the exergy consumption form the source. Not only does Equation (6) leave out any characteristics of the heat sink, but it is also entirely dependent on a randomly chosen reference temperature.

$$\eta_{ex} = \dot{W} \big/ \left[\dot{m}_1 \cdot \left(e_{1,entry} - e_{1,exit} \right) \right] \qquad (6)$$

Some authors use exergy efficiency, as defined in Equation (7), as reference for Equation (5). This approach is physically correct, according to standard textbooks such as Borgnakke and Sonntag (2009), but creates a dilemma explained later.

$$\eta_{ex} = \dot{W} \big/ \left[\dot{m}_1 \cdot \left(e_{1,entry} - e_{1,exit} \right) + \dot{m}_2 \cdot \left(e_{2,entry} - e_{2,exit} \right) \right] \qquad (7)$$

In this case output work is related to the net exergy destruction. This approach serves excellently for further detailed studies on distribution of losses with a focus on cycle improvements. The dilemma created is that if we are to compare high level results between ORCs, operating at different conditions we need to refer to some reversible system, for which we need to define the net reference exergy conditions. Equation (7) only stipulates the exergy changes in the real system, not the exit exergy of the heat sink of the reference reversible system. Furthermore, if Equation (7) is applied to a reversible system it collapses to a simple 1st law relation where output work and heat sink exit temperature are unknown. I.e. an unsatisfactory iterative solutions method is required. Of the common methods used, this is the closest to be suitable as a figure of merit for ORCs. Unfortunately it cannot be used if the apparent heat capacity of any of the source or sink is a function of temperature. This is further discussed in section 4 of this paper.

An approach similar to Equation (5) is using the so-called Curzon-Ahlborn efficiency, as of Equation (8), as reference in Equation (5).

$$\eta_{CA} = \left(1 - \sqrt{T_2/T_1}\right) \qquad (8)$$

η_{CA} was established by Curzon and Ahlborn (1975), though to a large extent preceded by Chambadal (1957) and Novikov (1958). The term is often used as a reference for plant efficiency as it assumes complete equalization of source and sink temperatures exiting the process. Though elegant, this reference will create a favor for very small systems compared to large ones due to 2nd law requirements. If source and sink are assumed similar the smallest power cycle will always operate at a higher average temperature difference. Curzon-Ahlborn efficiency is not suitable as reference for a figure of merit but it comes in very handy defining Utilization, defined in Equation (12), as will be seen later.

To emphasize the dilemma of high level performance comparison of ORCs Figure 3 and Figure 4 show calculated values of the above figures of merit as a function of Utilization for a combination of source and sink characteristics. Figure 3 shows thermal efficiency of a reversible power cycle. Figure 4 shows figures of merit for the same power cycle equipped with one irreversibility, a 10% transmission loss of work. Heat from the loss is assumed to leave the system immediately.

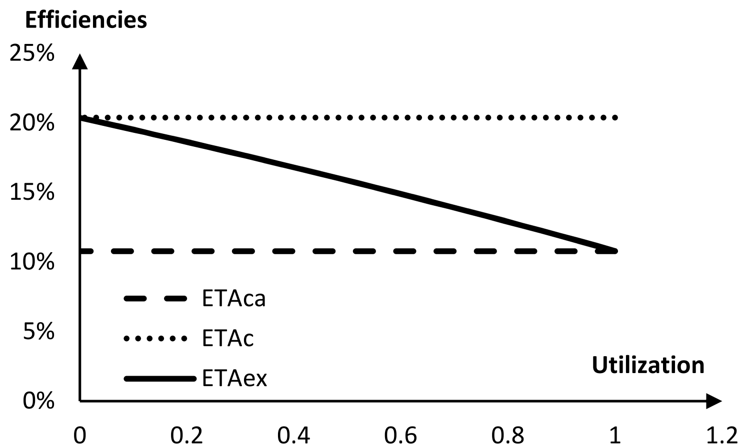

Figure 3. Thermal efficiencies of a reversible power cycle operating at entry temperatures 95/20degC and water flow of 100m3/h in source and sink. ($\eta_{CA}, \eta_C, \eta_{ex}$)

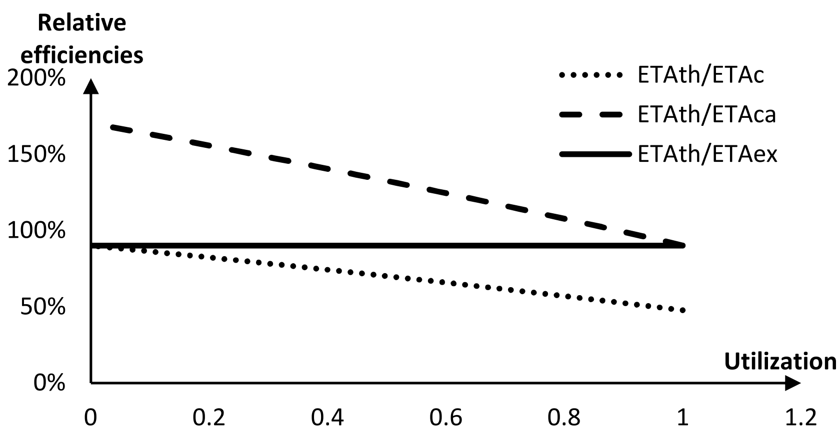

Figure 4. Figures of merit vs. Utilization for the power cycle in Figure 3 but with a 10% external loss of work.

Figures 3 and 4 explain that, of the described figures of merit, only exergy efficiency can be a reasonable reference considering that the thermodynamic *quality* of the power cycle solution is identical in all cases. It is a pity that there is such a difficulty in getting acceptance for the term exergy among practitioners. Entities based on iteration do not make it easier to get acceptance. On top of that variable apparent heat capacities would require each reference to be defined using arbitrary assumptions, being highly unsuitable in a reference for a figure of merit.

3. PROPOSED FIGURE OF MERIT, FRACTION OF CARNOT

From Chapter 2 we can conclude that a suitable figure of merit for ORC should yield results similar to using exergy efficiency as reference but also take variable apparent heat capacity of source and sink into account. Furthermore it should be possible to calculate it without iteration in order to ease the acceptance of the figure of merit among practitioners.
Luckily numerical methods provide a practical solution. Ibrahim and Klein (1996) describe a simple numerical approach, the so called Max Power Cycle. Numerically they defined the reversible work of a Max Power Cycle as Equation (9).

$$\dot{W} = \int_0^{\dot{Q}_1} \left(1 - \frac{T_{2l}}{T_{1l}}\right) \cdot d\dot{Q}_1 \tag{9}$$

Though not apparently solvable analytically this equation is easy to calculate numerically, without requiring iteration. Expressed as a summation we can write Equation (10), as of Öhman and Lundqvist (2012)

$$\eta_{c,Il} = \frac{1}{n} \cdot \sum_{i=1}^{n} \left(1 - \frac{T_{2,l}}{T_{1,l}}\right) \tag{10}$$

where the summation is done in the dimension of heat transfer absorbed by the cycle from the heat source.

The chosen term, Integrated Local Carnot efficiency, represents the thermal efficiency of a reversible power cycle operating between a finite source and a finite sink. I.e. it creates an absolute reference for any figure of merit for power cycles. Note that this entity is physically identical to the exergy efficiency of Equation (7) if the apparent thermal capacities of the two streams are constant.

The proposed figure of merit, *Fraction of Carnot* then becomes defined as in Equation (11).

$$FoC = \eta_{th} / \eta_{c,Il} \tag{11}$$

Fraction of Carnot describes how well the 1st and 2nd law potential of a particular combination of source and sink has been used, at a pre-defined rate of heat transferred from the source. If FoC, defined as of Equation (11), is plotted against Utilization we can draw conclusions from ORCs operating at very different conditions, as shown in Öhman and Lundqvist (2013). Utilization is defined according to Equation (12) and tells us how well the first law potential, of a combination of source and sink, has been used.

$$\psi_U = \dot{Q}_1 / \dot{Q}_{CA} \tag{12}$$

where $\dot{Q}_{CA}$ is the rate of heat transfer from the heat source that would create fully equalized exit temperatures in source and sink using a reversible power cycle. This is calculated based on the Curzon-Ahlborn efficiency as of Equation (8).

$FoC(\psi_U)$ can be used as a universal figure of merit for low temperature difference power cycles, such as ORCs. As such it can be used to create general, high level comparison between different technical solutions. It will then work in a similar manner as Coefficient of Performance, COP, in refrigeration technology.

4. DISCUSSION ON PRACTICAL USE OF FRACTION OF CARNOT

As merely a proposed figure of merit little generalized investigations exist yet. However, Öhman and Lundqvist (2013) shows a correlation extracted from a wide range of applications and technologies, **Figure 5**. As shown in the reference too few data exists currently to make a comprehensive analysis of the statistical significance of the correlation. It should therefore be considered as preliminary.

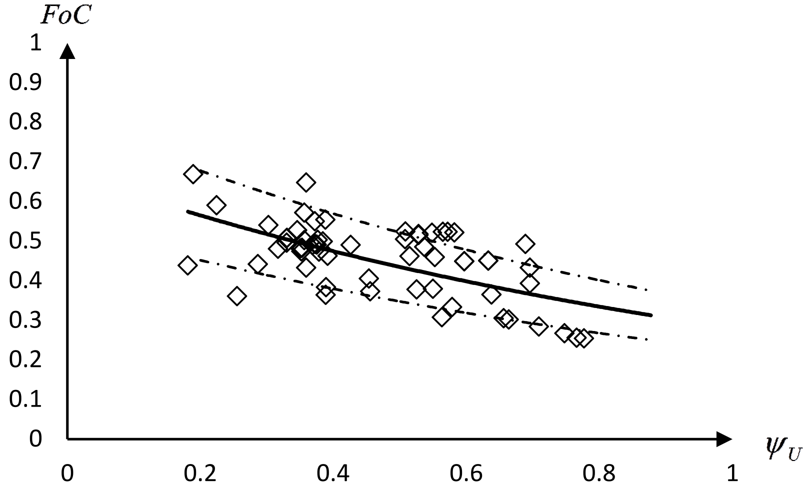

Figure 5. Correlation of Fraction of Carnot vs. Utilization as of Öhman and Lundqvist (2013). *Data covering 0.2kW to 7.5MW electric power, heat sources from 73˚C to 300˚C, different working fluids and different thermodynamic cycles.* Visual error bands of +-20% are indicated as dotted lines.

FoC, correlated with data from real systems, is well suited to make the currently very scattered performance data of few ORCs in different applications into a concentrated substitute for data from large number of, currently non-existing, operating real life units. Equation (13) expresses the correlation between Fraction of Carnot and Utilization.

$$FoC = 0{,}672 \cdot e^{-0{,}874 \cdot \psi_U} \quad (13)$$

As we receive more data from the field the correlation can be refined, however it is already more useful than any other candidate published.

In Öhman and Lundqvist (2014) a simplified method using the correlation for optimization, and sizing, of geothermal applications was shown. Not only was it possible to pre-estimate the expected power output but also the required heat transfer in evaporator and condenser could be pre-estimated. Thereby economic benefit, as well as a rough indicator of equipment size, could be established, allowing proper motivation for further detailed feasibility studies. That is an example on how a figure of merit, such as Fraction of Carnot, can be used. Note that this way an estimation of the optimal rates of heat transfer from the heat source, and to the heat sink, can be made. As a consequence rough estimations on heat exchanger sizes are enabled by assuming basic process temperatures. Considering that heat exchangers are the major cost items in many ORCs an idea of expected product cost is possible to form. A pre-estimation of both investment and benefit can be made since the output power is also indicated by the correlation.

Hereby life is made easier for investors, legislators and practitioners in evaluating and promoting the best solutions. As a consequence market penetration of ORC may have a better chance to become significant. Inverting the argument, the lack of such a figure of merit is likely to harm the market penetration by allowing confusion and lack of confidence.
Of course once there are high numbers of ORC in the field, in each niche of temperature and heat capacity combinations of source and sink, a figure like FoC may become redundant. However, considering the vast number of possible combinations of source and sink characteristics that would require data from millions of ORC field units to become conclusive.

One could argue that Integrated Local Carnot efficiency should be named using exergy efficiency, based on the fact that Carnot efficiency can be derived from the 2nd law. Exergy efficiency could be numerically obtained in a similar manner as Equation (9) and Equation (10) as explained by Borgnakke and Sonntag (2009). This would however become confusing from two reasons; firstly a reversible system should logically always have an exergy efficiency of 1, secondly the risk of mixing up Equation (7) with Equations (9) and (10) would be apparent thereby making the consequential figure of merit ambiguous.

5. CONCLUSIONS

Lack of universally accepted figures of merit is a limiting factor for the implementation of ORC-technology in society in any significant magnitude.
Currently used figures of merit are not suitable due to lack of exact definitions of references and/or terminology alienating practitioners.
The term Fraction of Carnot offers a potential figure of merit useful for all low temperature difference power cycles.
Fraction of Carnot as a function of Utilization provides a general guide to which performance can be expected, from arbitrary ORC market products, as well as an estimation on physical size of the heat exchangers.

NOMENCLATURE

T	temperature	(K)
$\dot{W}$	rate of work	(kW)
$\dot{Q}$	rate of heat transfer	(kW)
α	inverse apparent heat capacity	(K/kW)
η_{th}	thermal (first law) efficiency	(-)
η_C	Carnot efficiency	(-)
η_{ex}	exergy (second law) efficiency	(-)
η_{CA}	Curzon-Ahlborn efficiency	(-)
$\eta_{c,Il}$	integrated local Carnot efficiency	(-)
n	integer	(-)
e	specific exergy	(kW/kg)
FoC	Fraction of Carnot (Figure of merit)	(-)
ψ_U	utilization	(-)
$\dot{Q}_{CA}$	heat transfer from source at $\psi_U = 1$	(kW)

FM	arbitrary figure of merit	(-)
$\dot{m}$	mass flow	(kg/s)
Cp	specific heat	(kJ/(kg,K))

Subscript

1	heat source
2	heat sink
entry	a flow entering the power cycle
exit	a flow leaving the power cycle
l	local

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