

THE WAY TO OPTIMIZE THE IRREVERSIBLE CYCLES*

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Rezumat. Optimizarea ciclurilor se poate face prin intermediul criteriilor aferente principiului unu, respectiv randamentul termic pentru ciclurile motoare sau coeficientul de performanță pentru ciclurile inverse și principiului doi ale termodinamicii, respectiv randamentului exergetic sau metoda minimizării generării de entropie prin ireversibilitate. Uneori optimizarea recurge la aplicarea modelului de maximizare a puterii dezvoltat de Novikov–Curzon–Ahlborn. Lucrarea analizează puterea ciclurilor reale prin intermediul unui nou criteriu ce combină cele două principii, denumit în această lucrare coeficientul de performanță energetică ireversibilă. Acest criteriu nou este de fapt o variantă a criteriului de optimizare globală aferent principiului unu al termodinamicii în care sunt incluse explicit atât ireversibilitatea externă cât și ireversibilitatea internă, prin intermediul generării ireversibile de entropie. Ireversibilitatea internă afectează negativ variațiile de entropie ale agentului de lucru în relațiile termice cu sursele de căldură externe, respectiv căldură consumată pe ciclu este diminuată iar căldură cedată crește. Ireversibilitatea externă a fost definită prin intermediul eficienței termice ireversibile a schimbătoarelor de căldură, definită la rândul ei ca un raport între fluxul termic ireversibil, și cel reversibil corespunzător ciclului CARNOT. Astfel, coeficientul de performanță energetică ireversibilă permite optimizarea globală a unui ciclu, ce include și sursele termice externe, prin intermediul a două numere, al ireversibilității externe și interne.

Cuvine-cheie: cicluri ireversibile de bază, ireversibilitate internă și externă, coeficientul de performanță energetică ireversibilă, eficiența termică ireversibilă a unui schimbător de căldură

Abstract: The optimization of cycles considers the criteria: first and second law efficiencies, entropy generation minimization and sometimes the Novikov–Curzon–Ahlborn maximum power issue. The paper analyzes the power of real cycles by combining the first and second law criteria in a all-purpose relation for the irreversible first law efficiency. The idea is to emphasize concisely both the internal and external irreversibility within the first law efficiency. Actually, the internal irreversibility has a harmful end result on the entropy variations of the working fluid during the thermal relations with external heat sinks. The external irreversibility might be defined by an irreversible or second law heat transfer “effectiveness/efficacy/ratio”, which is rating the real heat exchange to the ideal heat exchange achieved by the ideal cycle (e.g. CARNOT). The irreversible first law efficiency include in this way all irreversibility in a general relation useful in optimizing the design of basic irreversible cycles, by the intermediary of two numbers, of internal and external irreversibility.

Keywords: basic irreversible cycles / internal and external irreversibility / irreversible first law efficiency / “second law heat transfer efficacy/ratio”.

1. INTRODUCTION

The thermodynamic analysis and optimization is based on ideal cycles. Any ideal cycle is characterized by no entropy generation, $\dot{S}_{gen} = 0$. This very concise restrictive condition can originate a lot of ideal cycles. In classical Thermodynamics, the ideal cycles work in contact with two external heat sources at infinitesimal temperature differences, see Figure 1 – engine cycles.

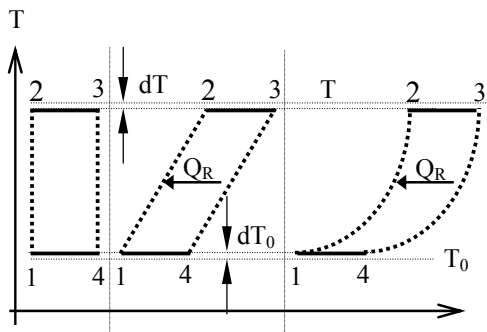


Fig. 1. The possible ideal engine cycle in temperature – entropy diagram.

In the case of cycles with internal heat exchange, the two non-adiabatic processes, must exchange each other (internal regeneration of the heat) the heat Q_R fulfilling the following requirements:

$$s_2 - s_1 = s_3 - s_4 = c \cdot \ln(T/T_0) \quad (1)$$

where c is the heat capacity, at constant volume, constant pressure or for polytropic.

It is very easy to demonstrate for all above considered ideal cycle, that the first law and second law efficiencies are respectively identical.

First law efficiency

$$\eta_I = \frac{\text{output power}}{\text{input heat rate}} = \frac{\dot{W}}{\dot{Q}} = 1 - \frac{|\dot{Q}_0|}{\dot{Q}} = 1 - \frac{T_0 + dT_0}{T - dT} = 1 - \frac{T_0}{T} < 1 \quad (2)$$

Second law efficiency

$$\eta_{II} = \frac{\dot{W}}{\dot{W}_{rev}} = 1 - \frac{\dot{W}_{lost}}{\dot{W}_{rev}} = 1 - \frac{T_0 \cdot \dot{S}_{gen}}{\dot{W}_{rev}} = 1 \quad (3)$$

It is noted that the both efficiencies for all entirely reversible cases are maximum possible ones. Any irreversible engine cycle has both efficiencies smaller. Development of the second law analysis and optimization methods leans upon the complete ideal cycles, having the

* COFRET'08, Juin 11-13, 2008, Nantes – France.

$$= 1 - \frac{\dot{m} \cdot T_{mq}^{4r-5t} \cdot |\Delta S_{4-5}|}{\dot{m} \cdot T_{mq}^{2r-3t} \cdot \Delta S_{2-3}} = 1 - \frac{T_{mq}^{4r-5t}}{T_{mq}^{2r-3t}} N_{irr,int} \quad (6)$$

where T_{mq} is the mean thermodynamic temperature during the heating or cooling processes.

The external irreversibility might be predicted by defining the irreversible/second law heat transfer “effectiveness/efficacy/ratio”:

$$\varepsilon_{II} = \frac{\dot{Q}_{2-3}}{\dot{Q}_{max}^{2-3}} = \frac{\dot{m} \cdot T_{mq}^{2r-3t} \cdot \Delta S_{2-3}}{\dot{m} \cdot T \cdot \Delta S_{2-3}} = \frac{T_{mq}^{2r-3t}}{T} < 1,$$

$$\text{and } \varepsilon_{0,II} = \frac{\dot{Q}_{4-5}}{\dot{Q}_{min}^{4-5}} = \frac{\dot{m} \cdot T_{mq}^{4r-5t} \cdot \Delta S_{4-5}}{\dot{m} \cdot T_0 \cdot \Delta S_{4-5}} = \frac{T_{mq}^{4r-5t}}{T_0} > 1 \quad (7)$$

where T and T_0 are the mean thermodynamic temperatures of the external heat sinks.

$\dot{Q}_{max}^{2-3} = \dot{m} \cdot T \cdot \Delta S_{2-3}$ is the maximum reversible heat rate that can be received from the hot source and so $\varepsilon_{II} < 1$ reflects the irreversibility caused by the real heat transfer at finite temperature difference ΔT , i.e. $\dot{Q} < \dot{Q}_{max}$.

$\dot{Q}_{min}^{4-5} = \dot{m} \cdot T_0 \cdot \Delta S_{4-5}$ is the minimum reversible heat rate that it is rejected to the cold sink and so $\varepsilon_{0,II} > 1$ assesses the irreversibility caused by the real heat transfer at finite temperature difference ΔT_0 , respectively $\dot{Q}_0 > \dot{Q}_{min}$.

Finally, it is yielding the first law efficiency including also the external irreversibility:

$$\eta_I = 1 - \frac{T_0}{T} \frac{\varepsilon_{0,II}}{\varepsilon_{II}} N_{irr,int} = 1 - \frac{1}{\tau} N_{irr,ext} N_{irr,int} \quad (8)$$

where $N_{irr,ext} = \frac{\varepsilon_{0,II}}{\varepsilon_{II}} > 1$ is number of external irreversibility, and $N_{irr,int} = 1 + \frac{(\sum \Delta S_{irr})_{int}}{\Delta S_{2-3}} > 1$ is number of

internal irreversibility. For any ideal cycle, both numbers of irreversibility are equal to one, and the first law efficiency becomes equal to that of Carnot cycle.

A way to define the irreversible/second law heat transfer “effectiveness/efficacy/ratio” at the hot and the cold sources is included in Dumitrascu (2006, 2007), for the operational cycles using heat exchangers for the external heat transfer relationships. In the case of cycles without heat exchangers (e.g. gas turbine engines), wherein the heating is done by internal combustion and the cooling of the flue gases is made in the atmosphere, the “hot” sink might have the temperature T equalizing the maximum temperature on the cycle $T_{3t} = T_{3r}$, and the “cold” sink the temperature T_0 equal to the minimum temperature on the cycle $T_{5t} = T_1$.

2.2 The Basic Irreversible Reverse Cycles – Refrigeration

Figure 4 present a basic irreversible reverse cycle, consisting of the following compulsory processes: 1 – 2r irreversible adiabatic compression, 2r – 3r irreversible cooling (constant volume, constant pressure or polytropic), 3r – 4r irreversible adiabatic process (expansion

or throttling), 4r – 1 irreversible heating (constant volume, constant pressure or polytropic). The internal irreversibility also “amends” the entropy variations of the working fluid during the heat exchanges with external heat sinks. Hence, the entropy variations are:

$$\Delta S_{4-1} = s_{1t} - s_{4r}$$

is the entropy variation along the heating process, coupled to external heat transfer,

$$|\Delta S_{2-3}| = s_{2r} - s_{3t} =$$

$$= \Delta S_{4-1} + \Delta S_{irr}^{1-2} + \Delta S_{irr}^{2-3} + \Delta S_{irr}^{3-4} + \Delta S_{irr}^{4-1} =$$

$$= \Delta S_{4-1} \cdot \left(1 + \frac{\sum \Delta S_{irr}}{\Delta S_{4-1}} \right) = \Delta S_{4-1} \cdot N_{irr,int}$$

is the entropy variation along the cooling process, matching the external heat transfer, and

$$N_{irr,int} = \left(1 + \frac{(\sum \Delta S_{irr})_{int}}{\Delta S_{4-1}} \right)$$

is the number of internal irreversibility.

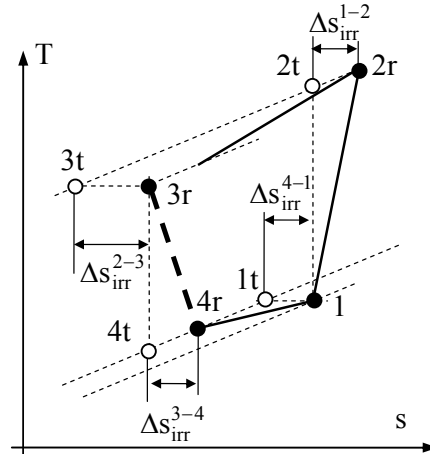


Fig. 4. Scheme of an irreversible reverse cycle, temperature – entropy diagram.

The irreversible entropy internally generated is stored in the entropy variation during the cooling process, and accordingly we can identify it in the first law efficiency (COP):

$$\text{COP} = \frac{\dot{Q}_{4-1}}{|\dot{W}|} = \frac{\dot{Q}_{4-1}}{|\dot{Q}_{2-3}| - \dot{Q}_{4-1}} =$$

$$= \frac{\dot{m} \cdot T_{mq}^{4r-1t} \cdot \Delta S_{4-1}}{\dot{m} \cdot T_{mq}^{2r-3t} \cdot |\Delta S_{2-3}| - \dot{m} \cdot T_{mq}^{4r-1t} \cdot \Delta S_{4-1}} = \quad (9)$$

$$= \frac{1}{\frac{T_{mq}^{2r-3t}}{T_{mq}^{4r-1t}} N_{irr,int} - 1}$$

where T_{mq} is the mean thermodynamic temperature during the heating and cooling processes.

The external irreversibility might be gained in a similar way, by defining the irreversible/second law heat transfer “effectiveness/efficacy/ratio”

$$\varepsilon_{H,II} = \frac{\dot{Q}_{2-3}}{\dot{Q}_{\min}^{2-3}} = \frac{\dot{m} \cdot T_{mq}^{2r-3t} \cdot \Delta S_{2-3}}{\dot{m} \cdot T_H \cdot \Delta S_{2-3}} = \frac{T_{mq}^{2r-3t}}{T_H} > 1,$$

$$\text{and } \varepsilon_{C,II} = \frac{\dot{Q}_{4-1}}{\dot{Q}_{\max}^{4-1}} = \frac{\dot{m} \cdot T_{mq}^{4r-1t} \cdot \Delta S_{4-1}}{\dot{m} \cdot T_C \cdot \Delta S_{4-1}} = \frac{T_{mq}^{4r-1t}}{T_C} < 1 \quad (10)$$

where T_H and T_C are the mean thermodynamic temperatures of the hot and cold external heat sinks.

$\dot{Q}_{\min}^{4-1} = \dot{m} \cdot T_C \cdot \Delta S_{4-1}$ is the maximum reversible heat rate received from the cold source and so $\varepsilon_{C,II} < 1$ considers the irreversibility caused by the real heat transfer at finite temperature difference ΔT , i.e. $\dot{Q}_C < \dot{Q}_{\max}$.

$\dot{Q}_{\min}^{2-3} = \dot{m} \cdot T_H \cdot \Delta S_{2-3}$ is the minimum reversible heat rate that rejected out to the hot sink and $\varepsilon_{H,II} > 1$ reflects the irreversibility caused by the real heat transfer at finite temperature difference ΔT_0 , respectively $|\dot{Q}_H| > |\dot{Q}_{\min}|$.

Therefore, it is yielding the first law efficiency, COP, including also the external irreversibility:

$$\text{COP} = \frac{1}{\frac{T_H}{T_C} \frac{\varepsilon_{H,II}}{\varepsilon_{C,II}} N_{\text{irr,int}} - 1} = \frac{1}{\tau \cdot N_{\text{irr,ext}} \cdot N_{\text{irr,int}} - 1} \quad (11)$$

where: $N_{\text{ext,irr}} = \frac{\varepsilon_{H,II}}{\varepsilon_{C,II}} > 1$ is number of external irre-

versibility, and $N_{\text{int,irr}} = 1 + \frac{(\sum \Delta S_{\text{irr}})_{\text{int}}}{\Delta S_{4-1}} > 1$ is number of internal irreversibility.

3. SOME CONCLUSIONS

✓ The irreversible first law efficiency has a general relation for all basic irreversible cycles, that can be used in a preliminary design of optimum power, maximum in the case of engines and minimum for reverse cycles.

✓ The new-defined irreversible/second law heat transfer “effectiveness/efficacy/ratio” reflects the external irreversibility caused by the real heat transfer at finite temperature difference, i.e. $(\dot{Q} = \varepsilon_{II} \cdot \dot{Q}_{\max})_{\text{heating}}$, $(\varepsilon_{II})_{\text{heating}} < 1$, during the heating process, and $(\dot{Q} = \varepsilon_{II} \cdot \dot{Q}_{\min})_{\text{cooling}}$, $(\varepsilon_{II})_{\text{cooling}} > 1$, during the cooling process.

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