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How much work can be extracted from a radiation reservoir?

Q1 Viorel Badescu *

Candida Oancea Institute, Polytechnic University of Bucharest, Spl. Independentei 313, Bucharest 060042, Romania

HIGHLIGHTS

- Radiation reservoirs are more complex than heat reservoirs.
- Reversible and endoreversible work extraction from radiation reservoirs is analyzed.
- The upper bound for reversible work extraction is not Carnot efficiency.
- All upper bound efficiencies depend on the geometric factor of the radiation reservoir.

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ABSTRACT

Radiation reservoirs are more complex than heat reservoirs. They depend on the intensive thermodynamic parameters (such as temperature, pressure, and chemical potential) as well as on other state parameters (such as the geometric factors). The paper refers to work extraction from a high temperature radiation reservoir (the pump), the sink being a heat reservoir, respectively a radiation reservoir. The simplest case of radiation reservoir (i.e. blackbody isotropic radiation) is considered. Reversible and endoreversible conversion is analyzed. The upper bound for reversible work extraction is not Carnot efficiency. All upper bound efficiencies obtained here depend on the pump geometric factor. Q2

1. Introduction

Radiation reservoirs are more complex than heat reservoirs. Indeed, radiation reservoirs are not fully characterized by their temperature. Other thermodynamic parameters (such as pressure and chemical potential [1]), geometric parameters (such as the geometric factor) and/or microscopic parameters (such as the radiation spectra or band-gaps) should be known, depending on case (for examples, see Ref. [2]).

Work extraction from heat reservoirs has been considered from the early stages of thermodynamics. New points of view are seen from time to time (see, e.g. Ref. [3]) but there is general agreement that the upper bound efficiency for reversible work production is given by Carnot formula. Work extraction from radiation reservoirs has been considered less often, mainly in the last decades, in connection with solar energy conversion. There is a well-known debate in the literature whether the upper bound efficiency of solar energy conversion is given by the Carnot (see Ref. [4]) or by the Petela–Landsberg–Press (PLP) formula [5–7]. For a rather recent good review, see Ref. [8].

Recent results show that neither Carnot nor PLP efficiency is the upper bound for reversible work extraction from radiation reservoirs [9]. However, the PLP efficiency is a particular case of the general result (i.e. it applies only for hemispherical radiation sources).

It is known that reversible upper bound efficiencies are too high to be of practical interest. More accurate (i.e., lower) upper bound efficiencies are obtained by relaxing the reversibility assumption. The simplest procedure is to replace it with

* Tel.: +40 21 402 9339; fax: +40 21 318 1019.
E-mail address: badescu@theta.termo.pub.ro.

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the endoreversibility assumption, i.e. irreversibility occurs in the interaction between conversion systems. When work extraction from heat reservoirs is considered, this procedure yields the well-known Chambadal–Novikov–Curzon–Ahlborn efficiency [10]. In case of work extraction from radiation reservoirs, the procedure has been used in Refs. [11,12] and the results obtained there are less known.

The present paper systematically treats the work extraction from a high temperature radiation reservoir, the sink being a heat or a radiation reservoir. Both reversible and endoreversible conversion are considered. The case of endoreversible conversion and sink heat reservoir has been considered in Refs. [1,11–13]. The case of endoreversible conversion and sink radiation reservoir is treated here for the first time. More accurate upper bound efficiencies are obtained in case of endoreversible conversion, for sink reservoirs consisting of heat or radiation. Finally, the accuracy of reversible and endoreversible upper bound efficiencies is emphasized by inter-comparison.

2. Generalities

We consider work extractors operating between a radiation reservoir (the pump) and a heat or radiation reservoir (the sink). The next assumption is that the reservoirs are in thermodynamic equilibrium. The temperatures of the pump and sink are denoted as T_H and T_L, respectively. The work extractor may be a thermal engine, providing mechanical work, or other device providing electrical work (such as a photovoltaic cell; see Refs. [1,14] for early works) or chemical work. Heat fluxes are denoted $\dot{Q}$ and radiation energy density fluxes are denoted φ. Entropy fluxes associated with heat transfer are denoted $\dot{S}$ and radiation entropy density fluxes are denoted ψ. Work rate is denoted $\dot{W}$ while the entropy generation rate during work extraction is denoted $\dot{S}_{gen}(\geq 0)$. Steady state operation is considered here.

The geometric factor of a radiation reservoir is denoted $f(\leq 1)$. The solid angle Ω of a spherical source is given by:

$$\Omega = 2\pi(1 - \cos\delta) \tag{1}$$

where δ is the half-angle of the cone subtending the sphere when viewed from the observer [15,16]. When the sphere's center has the zenith angle θ_0 [15,16]:

$$f = \frac{\Omega}{\pi}\left(1 - \frac{\Omega}{4\pi}\right)\cos\theta_0. \tag{2}$$

The simplest case is considered here, *i.e.* isotropic blackbody radiation reservoirs, which are characterized by two parameters only, *i.e.* their temperature T and geometrical factor f. The energy and entropy density fluxes are, respectively:

$$\varphi = f\sigma T^4, \tag{3a}$$

$$\psi = \frac{4}{3} f\sigma T^3. \tag{3b}$$

Two cases are treated next: (i) the sink is a heat reservoir and (ii) the sink is a *hemispherical* radiation reservoir ($\delta = \pi/2$, $f = 1$).

Work extraction from radiation reservoirs involves radiation absorbers and/or emitters. They may be materials with/without band-gap energy or bodies with selective radiative properties. The simplest case is considered here: the absorber (emitter) is a (non-selective) plane Lambertian blackbody of surface area $A_a(A_e)$ receiving (and emitting) radiation *over the whole hemisphere*. Therefore, their geometric factors are $f_e = f_a = 1$. Local thermal equilibrium is assumed and the temperature of the absorber (emitter) is denoted $T_a(T_e)$.

The following notation is used:

$$a \equiv \frac{T_L}{T_H}, \tag{4a}$$

$$x \equiv \frac{T_a}{T_H}, \tag{4b}$$

$$y \equiv \frac{T_e}{T_H}, \tag{4c}$$

$$r \equiv \frac{A_e}{A_a}. \tag{4d}$$

Lambertian blackbody absorbers imply full thermalization of radiation energy (i.e. the radiation energy is entirely transformed into internal energy of the absorbing body). Therefore, specific work extractors such as thermal engines (for early works see Refs. [11,17]) or thermophotovoltaic devices should be considered.

Two ideal operation regimes are treated next. First, reversible operation is considered. This is associated with vanishing entropy generation rate inside the work extractor and on the borders of the work extractor (these borders are the radiation emitter and the radiation absorber). Second, endoreversible operation is considered. In this case the entropy generation rate inside the work extractor is vanishing but no hypothesis is made about the entropy generation rate at work extractor

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