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The reversed chemical engine cycle with application to desalination processes

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HIGHLIGHTS

- A new thermodynamic cycle, termed the reversed chemical engine, is proposed.
- It is analogous to the reversed Carnot cycle.
- A new work term based on difference of hydraulic and osmotic pressure is defined.
- Performance ratio at reversible limit and for minimum power requirement is found.
- Hybrids of RO with FO and PRO are applications of this cycle.

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ABSTRACT

In this paper, a novel thermodynamic cycle is proposed, termed the reversed chemical engine cycle. In the cycle, a net input of work is used to transfer mass from a low chemical potential reservoir to a high chemical potential reservoir. The cycle has two mass exchangers, a pump and a turbine. The only irreversibility considered in the model is finite-rate mass transfer. Similar to the reversed Carnot cycle, expressions for the performance ratio (analogous to the coefficient of performance) are obtained under the condition of minimized power requirement for the endoreversible and, in turn, the reversible case. The reversed mass engine cycle is shown to be a special case of the reversed chemical engine. An equipartitioned hybrid forward osmosis reverse osmosis (FO–RO) system is considered as an example of the cycle.

1. Introduction

Reversible cycles provide an upper bound on performance parameters, e.g., thermal efficiency in Carnot heat engines and coefficient of performance (COP) in reverse Carnot cycles. In the latter, the cycle receives heat from the low-temperature reservoir and rejects heat to the high-temperature reservoir, which requires a net input of power. This power input is equal to the difference in the heat transfers, as required by the first law of thermodynamics. Two heat exchangers are used to transfer heat between the thermal reservoirs and the working fluid over an infinitesimal temperature difference. The typical example of such a cycle includes two other components; a compressor and a turbine. In the reversible case, the overall cycle includes two isothermal and two isentropic processes [1,2].

When finite thermal resistances are included for the heat exchangers, efficiencies are reduced relative to the reversible case. In this so-called endoreversible case, the thermal efficiency and COP are determined under the conditions of maximum and minimum power, respectively, with the heat transfer process driven by a finite temperature difference. Real power plants or refrigeration/heat pump systems can have thermal efficiency and COP that are, respectively, greater or lesser than the endoreversible value [3–5].

Analogy is a powerful tool that can be used to solve problems and derive new ways of understanding. An important example is the use of electric circuit theory in solving heat transfer problems [6,7]. The maximum power relations for chemical engines have also been derived using analogies to heat engines. Applications range from chemical reactions and mass exchangers to solid-state converters [8–11]. Even an analogy to thermal engine-driven heat pumps has been derived [12]. Design requirements for restrained chemical engines was provided by Miller et al. [13] using a fuel cell with a motor attachment as an example.

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Nomenclature

G	Gibbs free energy of transferred species (J)
h	conductance for mass flow (mol^2/J s)
I	irreversibility (J)
K	permeability coefficient (kg/s kPa)
m	mass flux of transferred species (kg)
N	mole flux of transferred species (mol)
P	hydraulic pressure (kPa)
PR	performance ratio
Q	heat transfer (J)
S	salinity (g/kg)
S_{gen}	total entropy generation (J/K)
s	specific entropy (J/kg K)
T	temperature (K)
t	residence time (s)
W	internally reversible work (J)
$\tilde{W}$	hydro-osmotic work (J)
$\dot{W}$	power input (W)
w	solute concentration (kg/kg)

Greek symbols

Δ	difference
μ	chemical potential of transferred species (J/mol)
π	osmotic pressure (kPa)
ρ	density (kg/m^3)

Superscripts

$()^*$	at condition of minimum power for endoreversible case
$()'$	value of property in the engine fluid

Subscripts

CE	chemical engine
H	high side
i	ith component
L	low side
ME	mass engine
net	net
rev	reversible case
w	pure water

Abbreviations

COP	coefficient of performance
FO	forward osmosis
PRO	pressure retarded osmosis
RO	reverse osmosis

Further information on current technologies for power generation using salinity gradients may be taken from Jia et al. [14] and Sharma et al. [15]. Recently, analogous to the Carnot heat engine, a reversible mass engine cycle was proposed by Sharqawy [16]. In this cycle, instead of heat exchangers, mass exchangers using semi-permeable membranes were used that allowed water to pass through but not other substances; other components included a pump and turbine. The same amount of mass was added to and rejected by the cycle. An expression for the reversible limit was established in which, instead of a temperature ratio, the process was characterized by pressure and concentration ratios. The cycle includes two isobaric and two constant concentration processes. An osmotic power plant using pressure-retarded osmosis, a type of salinity gradient engine, was envisaged as an application of the cycle.

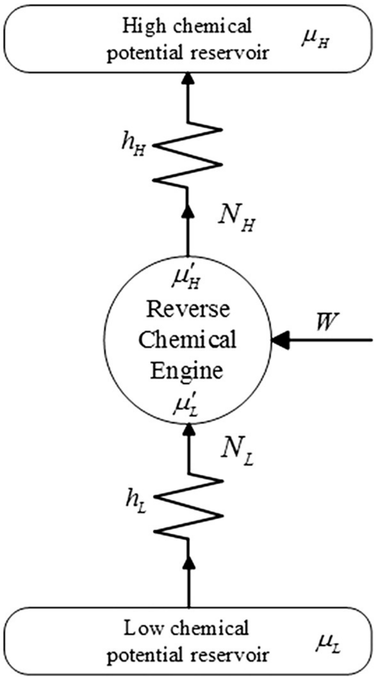

Fig. 1. Endoreversible reverse chemical engine.

The reverse Carnot cycle is the reversible cycle for refrigeration and heat pump systems (described above); and, therefore, by analogy the reversible mass engine cycle proposed by Sharqawy [16] can also be reversed. Thus, by extension, so can the isothermal chemical engine cycle. Generally speaking, such a cycle would receive some mass from a low-potential reservoir and reject the same mass to a high-potential reservoir, which would require a net power input (see Fig. 1). An example would be a desalination process, which transfers water from a saline mixture (low chemical potential) to a pure water reservoir (high chemical potential). The net power input would be equal to the difference in the energy transfers associated with the masses or the difference between the pump and turbine work. For the endoreversible chemical engine, two chemical exchangers of finite resistance would be used to transfer mass between the fixed chemical potential reservoirs. In the case of a desalination process, the driving potential (the partial molar Gibbs energy of water) is represented in terms of differentials in the hydraulic and osmotic pressures [17,18]. The other two components of the cycle are a pump and a turbine.

It should be noted that to reduce the energy consumption of desalination systems, hybrids of known desalination processes are being considered that work in a cycle [19]. Therefore, there is a need to evaluate the efficiency of these hybrids on a thermodynamic basis. Reversible and endoreversible forms of these hybrid cycles can help to achieve this by establishing limiting values, which is not yet addressed in the literature.

The objective of the current work is to introduce the concept of the reversed chemical engine cycle and its components. The cycle will be driven by chemical potential differences and analyzed in analogy with classical heat engines. Additionally, we aim to derive the relevant thermodynamic relations and performance metrics, the most important of which are the reversible limit of performance and the limit under the condition of the minimum power requirement for the endoreversible (internally reversible) case.

2. Reverse chemical engine: endoreversible and reversible case

An isothermal (endoreversible) reverse chemical engine is shown in Figs. 1 and 2. Taking the resistance to mass transfer (such as a