Energy Conversion and Management 119 (2016) 49–59

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Energy and entropy analysis of closed adiabatic expansion based trilateral cycles

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ARTICLE INFO

Article history:
Received 23 July 2015
Received in revised form 14 March 2016
Accepted 9 April 2016
Available online 16 April 2016

Keywords:
Adiabatic expansion
Carnot factor
Entropy analysis
Second law efficiency
Thermal efficiency
Trilateral cycle

ABSTRACT

A vast amount of heat energy is available at low cost within the range of medium and low temperatures. Existing thermal cycles cannot make efficient use of such available low grade heat because they are mainly based on conventional organic Rankine cycles which are limited by Carnot constraints. However, recent developments related to the performance of thermal cycles composed of closed processes have led to the exceeding of the Carnot factor.

Consequently, once the viability of closed process based thermal cycles that surpass the Carnot factor operating at low and medium temperatures is globally accepted, research work will aim at looking into the consequences that lead from surpassing the Carnot factor while fulfilling the 2nd law, its impact on the 2nd law efficiency definition as well as the impact on the exergy transfer from thermal power sources to any heat consumer, including thermal cycles.

The methodology used to meet the proposed objectives involves the analysis of energy and entropy on trilateral closed process based thermal cycles. Thus, such energy and entropy analysis is carried out upon non-condensing mode trilateral thermal cycles (TCs) characterised by the conversion of low grade heat into mechanical work undergoing closed adiabatic path functions: isochoric heat absorption, adiabatic heat to mechanical work conversion and isobaric heat rejection. Firstly, cycle energy analysis is performed to determine the range of some relevant cycle parameters, such as the operating temperatures and their associated pressures, entropies, internal energies and specific volumes. In this way, the ranges of temperatures within which the Carnot factor is exceeded are determined, where carbon dioxide, nitrogen, helium and hydrogen are considered as real working fluids, followed by an entropic analysis in order to verify 2nd law fulfilment.

The results of the analysis show that within a range of relatively low operating temperatures, high thermal efficiency is achieved, reaching 44.9% for helium when the Carnot factor is 33.3% under a ratio of temperatures of 450/300 K. With respect to entropy analysis, it is verified that the results of the latter demonstrate compliance with the second principle, while violating Carnot constraints, since the Carnot factor is constrained only by the Carnot, Stirling and Ericsson cycles and its associated Carnot engine characteristics. However, the most relevant findings through the performed analysis concern the detection of some inconsistencies regarding the conventional 2nd law efficiency definition and the exergy transfer definition from thermal power sources to thermal cycles.

In summary, a TC undergoing isochoric heat absorption, adiabatic expansion and isobaric heat rejection under closed transformations can yield improved performance over traditional thermal cycles, even exceeding the Carnot factor under relatively low top temperatures, for which Carnot efficiency is lower. Furthermore, the concept of 2nd law efficiency, defined as the ratio of the thermal to the Carnot efficiency, has been reconsidered in agreement with the results achieved. That is, the definition of 2nd law efficiency lacks both theoretical and practical sense. In the same way, as a result of discarding the Carnot factor as limiting the thermal efficiency, the definition of the exergy transfer to a thermal cycle (the maximum available energy) must be defined as the product of the transferred heat from a heat source and the thermal efficiency.

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http://dx.doi.org/10.1016/j.enconman.2016.04.031
0196-8904/

Nomenclature

γ	adiabatic expansion coefficient
η	thermal efficiency (%)
η_S	2nd law efficiency (%)
Cp	specific heat capacity at constant pressure (kJ/kg K)
Cv	specific heat capacity at constant volume (kJ/kg K)
E_q	exergy associated with heat transfer (kJ/kg)
p	pressure (bar)
$q_i = q_{12}$	total specific input heat (kJ/kg)
$q_o = q_{31}$	specific rejected heat (kJ/kg)
R	perfect gases constant (kJ/kg K)
S	specific entropy (kJ/kg K)
ΔS	specific change of entropy (kJ/kg K)
ΔS_{sys}	system change of entropy (kJ/kg K)
S_{final}	final entropy (kJ/kg K)
S_{init}	initial entropy (kJ/kg K)
S_{trans}	transferred specific entropy (kJ/kg K)
S_{gen}	generated specific entropy (kJ/kg K)
T	temperature (K)
T_L	heat sink temperature (K)
T_H	heat source temperature (K)
W	specific work TC (kJ/kg)

Acronyms

C	constant
CF	Carnot factor
ORC	organic Rankine cycle
NORC	non organic Rankine cycle
TC	trilateral thermal cycle
WF	working fluid

1. Introduction

Conventional research on known thermal cycles relies on the fact that Carnot, Stirling and Ericsson thermal efficiency is a limit that cannot be surpassed by any other thermal cycle. However, as result of recent advances on this topic, it is generally accepted that the performance limit is given only by Clausius and Kelvin–Planck statements, summarised as: The performance of any irreversible thermal cycle must be less than 100%. This is a motivation encouraging us to try to enhance the performance of any other thermal cycle that is not limited by any Carnot, Stirling or Ericsson constraint.

It is worth researching this topic in order to advance on the performance of thermal cycles operating at low and medium temperatures, focused on avoiding the depletion of non-renewable energy sources, including fossil fuels and carbon dioxide emissions associated with global warming.

Research methodology was planned based on the research objectives and starting from a logic sequence of causal tasks, summarised as:

- energy and entropy analysis to verify that the fact of surpassing Carnot factor does not mean the violation of the second law,
- the consequence of surpassing the Carnot factor without second law violation on the definition of second law efficiency and
- the consequences of surpassing the Carnot factor without second law violation on the available energy transfer definition (exergy transfer to a thermal cycle).

The research objectives aim to mainly investigate:

- the fulfilment of the second law, even surpassing the Carnot factor, by means of thermodynamic model energy and entropy analysis of a trilateral thermal cycle, considering the effects of top temperatures as well as the effects of the use of different types of working fluids on the performance of the system,
- the consequence of surpassing the Carnot factor on the definition of the second law efficiency and
- the consequences of surpassing the Carnot factor on the available energy transfer definition (exergy transfer to a thermal cycle).

An interesting characteristic of the TC is its capacity to efficiently exploit low grade heat power sources, which may include geothermal heat, ocean thermal heat, residual or waste heat from industrial plants, as well as low temperature heat from direct solar thermal sources. The main reason for reviewing the state of the art technology dealing with low temperature thermal cycles such as the (organic Rankine cycles) ORCs, including conventional TCs, results from the fact that the proposed TC is well suited to operate with low grade heat and hence, offers new characteristics with respect to the existing technology, which is a difference worth highlighting. Therefore, in the low temperature range, Hung et al. [1] and Yamamoto [2] propose bottoming ORCs (organic Rankine cycles) as an interesting alternative for exploiting the low grade or residual heat to power conversion cycles, having shown good thermodynamic performance for bottoming cycles. The interest in organic WFs for residual heat applications with low temperature Rankine cycles is an old technique that has been proposed for different applications such as renewable energy and low temperature heat recovery, according to Angelino and Colonna [3], Saleh et al. [4], Hung [5], Borsukiewicz-Gozdur and Nowak [6] and Mago et al. [7], among others. Recent advances concerning low grade heat sources applied to ORCs include the works of Wang et al. [8] who compared several WFs for low-temperature ORCs, concluding that R123 is the best choice for the temperature range of 100–180 °C and that R141b is the optimal working fluid when the temperature is above 180 °C. In the same way, Jianqin and colleagues [9] proposed an open steam power cycle for internal combustion (ICE) engine exhaust gas energy recovery. The authors concluded that the recovery efficiency of exhaust gas energy is mainly limited by the exhaust gas temperature, and that ICE thermal efficiency can be improved by 6.3% at 6000 r/min. Hua and colleagues [10] presented an ORC system used in ICE exhaust heat recovery, and a techno-economic analysis based on various WFs. They recovered a significant amount of ICE exhaust heat, representing around one-third of the energy generated from the fuel by the ORC system. Results demonstrated that R141b, R123 and R245fa present the highest thermal efficiency, ranging from 16.60% to 13.30%, and net power values from 60 to 49 kJ/kg. Jiangfeng et al. [11] conducted a study on low-temperature ORCs which examined the effects of key thermodynamic design parameters, including the turbine inlet pressure, turbine inlet temperature, pinch temperature difference and approach temperature difference in the HRVG (heat recovery vapour generator) on the net power output and surface areas of both the HRVG and the condenser, using R123, R245fa and isobutene. The results demonstrated that the turbine inlet pressure, turbine inlet temperature, pinch temperature difference and approach temperature difference had significant effects on the net power output and surface areas of both the HRVG and the condenser.