



Thermodynamic performance simulation and design optimisation of trilateral-cycle engines for waste heat recovery-to-power generation



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HIGHLIGHTS

- Steady-state models of trilateral cycle (TLC) power plants are established and implemented.
- Thermodynamic performance simulation and design optimisation of the TLCs are conducted.
- Four configurations of the TLCs are analysed and compared their performance metrics.
- Results show that thermal integration of the simple TLC enhanced energy conversion efficiency.
- Comparative study shows that the recuperated TLC achieved the best performance metrics.

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ABSTRACT

The trilateral cycle (TLC) is one of the most promising alternatives among the heat recovery-to-power technologies, due to its compact system configuration and high performance at relatively low compression work and low-to-moderate expander inlet temperature. These feats make the TLC beneficial for off-grid applications particularly in remote or offshore applications where power-to-weight ratio of the power plant is of significance. This study presents the thermodynamic performance simulation and design optimisation of the TLCs using unconventional working fluid for heat recovery-to-power generation from low-grade waste heat, which is considered for process development and integration of the TLC. Four system configurations, comprising the simple TLC, recuperated TLC, reheat TLC and regenerative TLC are analysed and compared their performance metrics. Based on the theory of steady-state steady-flow thermodynamics, the simulation models of the TLC power plants, corresponding to their thermodynamic processes are established and implemented using engineering equation solver. The results show that the thermal efficiencies of the simple TLC, recuperated TLC, reheat TLC and regenerative TLC employing *n*-pentane are 11.85–21.97%, 12.32–23.91%, 11.86–22.07% and 12.01–22.9% respectively at subcritical operating conditions with low-grade heat in the temperature limit of 393–473 K. These suggest that the thermal integration of the optimised design of the simple TLC enhanced heat exchange efficiencies as well as the performance metrics. A comparative study among these cycles shows that the proposed recuperated TLC achieved the best performance metrics.

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1. Introduction

There has been renewed significance for innovative heat recovery-to-power technologies for sustainable power generation from renewable energies and waste heat. This is due to the growing concern over the Earth's limited fossil fuel reserves [1], rising cost of energy prices in the global market [2], high demand for electricity by an increasing world population, energy shortage,

effects of greenhouse gas emissions [3,4] and thermal pollution [5]. The fundamentals of heat recovery-to-power have been a long-standing challenge that Carnot, Clausius and Rankine had figured out in the 19th century [6]. Conventionally, mechanical power is recovered from external heat sources, such as combustion products, using Rankine-cycle engine that uses steam as the working fluid [7]. It has gained prominence because of its very attractive features like good thermal integration with the topping cycle, high reliability and extensive industry experience [8].

However, because the heat discharged can be in the range of 70–370 °C [9], value not compatible with the conventional Rankine-cycle engine or due to the low conversion efficiency

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Nomenclature

1, 2, 3, 4 states of working fluid
a, b, c, d points of heat sources and sinks
h specific enthalpy (J kg^{-1})
m mass flow rate (kg s^{-1})

Greek letters

η efficiency (%)

Subscripts

o ambient state
exp expander
con condenser
hx heat exchanger
is isentropic

Superscripts

in in/inlet
 $\dot{Q}$ heat transfer rate (J kg^{-1})
s specific entropy ($\text{J kg}^{-1} \text{K}^{-1}$)
T temperature (K)
 $\dot{W}$ specific work (J kg^{-1})
p pump
recup recuperator
th thermal
wf working fluid
out out/outlet

[10,11]; low-grade (low-to-medium temperature) heat sources of renewable energies as well as the waste heat of combustion processes are typically under-exploited. One consequence of these, at present, is the intensified study of heat recovery-to-power cycles using unconventional working fluid for heat recovery-to-power generation [12,13] from low-grade heat sources. As a result, a number of innovative vapour power cycles have been proposed for improved efficiency, reduced emissions and to gain on a smaller scale, comparable advantages of efficiency [14]. Among these cycles, the organic Rankine cycles (ORCs) have been broadly studied and employed to generate or co-generate power from low-to-moderate temperature heat sources due to their efficiency, simplicity in the cycle configuration [10,11,15–18], ease of maintenance, improved part-load performance [19–21] and ability to be adapted to different heat source temperature profile [22]. But a crucial limitation of the ORCs is the isothermal boiling particularly with the pure fluids, which causes poor thermal match during the heat transfer from the heat source to the working fluid due to pinch-point, causing huge exergy destruction [11].

The trilateral cycles (TLCs) have been proposed to improve the performance of heat recovery-to-power generation from low-to-medium temperature non-isothermal heat sources, i.e. of variable temperatures for mini-grid and off-grid applications, especially in remote or offshore applications where power-to-weight ratio of the power plant is of significance. Basically, the TLC has the same components as the Rankine-cycle engines but unlike the Rankine cycle, it does not evaporate the working fluid during the heating phase; instead expands it, from the saturated liquid condition, as a two-phase mixture. Due to the bypass of the isothermal boiling phase, there is a better thermal match during the heat transfer from the heat source to the working fluid [12,23], which minimizes exergy destruction. Moreover, there is a growing interest in the cycle because it thermally matches the exergy of the temperature profiles of non-isothermal heat sources and functions at moderate pressures such that its application is viable economically for shaft work or power generation [12]. While the ORCs are used in existing power plants, the TLC, despite the fact that it has been proposed some decades ago, its potentials is yet to be appreciated because it is still at the research stage for technical development.

The TLC engines, utilising unconventional working fluids and low-grade heat sources, are usually, of the classical (simple) type. The expansion machine, which depends on the working fluid used, rotational speed and mechanical or electrical power output, might either be a turbine or a positive displacement machine [24]. Usually, turbines (either of the impulse or reaction type that could be a single- or multi-stage configuration) are utilised for applications with high speeds and power outputs. Positive displacement

expanders, instead, are generally used for low rotational speeds and power outputs [24]. The choice of suitable working fluid for a given application, feasible operating conditions and system configurations are the utmost essential factors that influence the performance of heat recovery-to-power cycles [11,25]. Like the conventional Rankine cycles, the efficiency of TLC is constrained by the exergy destruction; i.e. its thermodynamic irreversibilities, as a result of entropy change within the system and environment during heat exchange processes [26]. These irreversibilities and efficiency of the system depend on the working fluid and operating conditions; therefore the highest system efficiency can be attained when a suitable working fluid is selected and operated at optimal conditions [26]. The applicability range of the working fluid must be within its thermo-physical properties and the chemical stability in a desirable range of temperature [20]. The cycle high temperature upper limit depends on the fluid thermal stability and its lower limit on the techno-economic factors [27] such as the size of the heat exchangers required for the heat addition to and rejection from the working fluid.

There are limited numbers of published works in the literature on the TLC technology for waste heat recovery-to-power generation, which can typically be categorised into the following: development of simple TLC [1,28,29], two-phase expanders modelling and design [30–32], working fluids selection [6,33,34], modelling and process simulation of the TLC [12,35,36] and applications of the TLC [37–39]. A review of the relevant studies in the literature highlighted the need for research and development of the TLC technology for waste heat recovery-to-power generation using unconventional working fluid. It underscored that, in recent years, though significant development has been achieved, largely in the areas of applications of TLC, its working fluid selection and two-phase expanders modelling and design approaches. Yet, there is still a knowledge gap in the design and optimisation of the TLC. Thus, this paper presents the thermodynamic performance simulation and design optimisation of the TLC for its thermodynamic process development and thermal integration. The integration of a recuperator, reheat and regenerator in the system to improve its heat exchange performance and energy conversion efficiency are analysed, simulated and compared their performance metrics, to evaluate the merits of future thermal integration technologies of the simple TLC.

2. Methodology

Design criteria for the trilateral cycle (TLC) power plants are established subject to engineering design constraints and their system configurations for waste heat recovery-to-power generation

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