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Thermodynamic relation between irreversibility of heat transfer and cycle performance based on trapezoidal model

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ABSTRACT

Irreversible degree of heat transfer in organic Rankine cycle (ORC) is proposed in this paper. Based on a trapezoidal cycle (TPC) and its theoretical model, the model and mathematic formulas of irreversible degree of heat transfer is built. Thermodynamic relation between irreversible degree and cycle performance (thermal efficiency, net power output and exergy efficiency) is built and studied, which can be applied to the coupling optimization between cycle performance and heat transfer processes. Similar to net power output, there exists a kind of shift-curve of irreversible degree and the corresponding shift-temperature of heating fluid for working fluids, which indicates the shift of irreversible degree from having optimum condition with a minimum to monotonic decrease with heating fluid temperature. The range of irreversible degree and range of cycle performance according to irreversible degree are obtained respectively. Moreover, a model of working fluid with linear saturation line is proposed to study the general thermodynamic principles of TPC (or ORC) theoretically without the restriction of actual working fluids.

1. Introduction

Organic Rankine Cycle (ORC) is a promising process for the conversion of low-grade heat to power. However, the overall efficiency of the ORC system is generally low due to the irreversibility in the system. It is significant and important to specify the process or the components which the irreversible losses are occurred, and investigate the effects of irreversibility on the cycle performance.

In 1975, Curzon and Ahlborn [1] considered the influence of finite-rate heat transfer between the external heat reservoirs and the working fluid of Carnot heat engine (endoreversible heat engine) and obtained the efficiency of Carnot engine at maximum power output, which is the well-known Curzon-Ahlborn efficiency $\eta_{CA} = 1 - (T_L/T_H)^{0.5}$, where T_H and T_L are the temperatures of the hot and cold heat reservoirs. Esposito et al. [2] studied the efficiency η_m at maximum power of engines performing finite-time Carnot cycles between hot and cold reservoir at temperatures T_H and T_L; and found that η_m is bounded from above by $\eta_C/(2 - \eta_C)$ and from below by $\eta_C/2$ in limit of low dissipation. Wang et al. [3] investigated the efficiency at maximum power output (EMP) of an irreversible Carnot engine performing finite-time cycles between two reservoirs at constant temperatures T_H and T_L. Chen et al. [4] pointed out that irreversible process may take part in a finite or in finite interval in time and must find the fundamental optimum relation of the heat engine in order to understand the performance of the heat engine. Chen et al. [5] pointed out that the main cause of irreversible loss of irreversible Carnot heat engine was its internal and external irreversibilities, such as heat resistance, bypass heat-leak, friction, turbulence and other undesirable irreversibility factors. Chen et al. [6] investigated an irreversible model of Meletis-Georgiou cycle, and considered internal irreversibility of the cycle and heat transfer loss. It showed that the compression ratio had its optimal value, which made the work output or thermal efficiency reach to the maximum. Ahmadi et al. [7] studied the external and internal irreversibilities in irreversible Carnot power cycle, and applied the multi objective evolutionary approaches coupled with non-dominated sorting genetic algorithm approach. Gonca et al. [8] conducted ecological performance analyses and optimization of irreversible gas cycle engines based on ecological coefficient of performance criterion which covered internal irreversibility, heat leak and finite-rate of heat transfer. Chen et al. [9] proposed a parameter of irreversibility degree to characterize the irreversible process based on the available energy consumption rate. Chen et al. [10] also used equivalent thermodynamic transformation method to deduce the relationship formulas among the air flow rate of the evaporator, fan power consumption, irreversible loss in heat transfer,

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Nomenclature

c	specific heat ($J\,kg^{-1}\,K^{-1}$)
e	specific exergy ($J\,kg^{-1}$)
E	exergy (W)
Ja	Jacob number
m	mass flow rate ($kg\,s^{-1}$)
q	specific heat ($J\,kg^{-1}$)
Q	heat (W)
s	specific entropy ($J\,kg^{-1}\,K^{-1}$)
T	temperature (K or °C)
r	latent heat ($J\,kg^{-1}$)
w	specific net work output ($J\,kg^{-1}$)
W	net power output (W)

Greek symbols

η	efficiency (%)
ϕ	irreversible degree

Subscripts

C (c)	condensation
cr	critical
E (e)	evaporation
H	heating fluid
ir	irreversibility
L	cooling fluid
l	liquid
Max (m)	maximum
min	minimum
opt	optimal
p	pinch point
r	latent heat
rd	relative deviation
w	working fluid
0	environment state

evaporation temperature, system performance coefficient and system irreversible degree. The minimum system irreversible degree and the optimal thermodynamic parameters for the maximum COP was obtained.

Many studies use the effective energy loss and exergy efficiency as the objective function to analyze the irreversible factors of the ORC system, evaluate the performance of the system, optimize the system parameters and investigate the irreversible loss of the system based on the second law of thermodynamics. Zhu et al. [11] conducted theoretical study on the thermodynamic process of a bottoming Rankine cycle for engine waste heat recovery based on energy balance and exergy balance. Results showed that the working fluid properties, evaporation pressure and superheating temperature were the main factors influencing the system design and performances. Dai et al. [12] examined the effects of thermodynamic parameters on the ORC performance and optimized the thermodynamic parameters of ORC for working fluid with exergy efficiency as an objective function by means of genetic algorithm. Kaska [13] used actual plant data to assess the performance of the cycle and pinpoint sites of primary exergy destruction. Exergy destruction of subcomponents was analyzed quantitatively, and found that the evaporation pressure had significant effect on both energy and exergy efficiencies. Zhang et al. [14] conducted an optimization procedure to optimize five indicators: thermal efficiency, exergy efficiency, recovery efficiency, APR and LEC, and obtained the optimum cycle design and the corresponding operation parameters. Lecompte et al. [15] examined the thermodynamic performance of non-superheated subcritical ORCs with zeotropic mixtures based on second law of thermodynamics. Results showed that the evaporator accounted for the highest exergy loss, and best performance was achieved when the condenser heat profiles were matched. Tony et al. [16] pointed out that the organic flash cycle (OFC) could potentially improve the efficiency with high and intermediate temperature finite thermal sources. The OFC's aim was to improve temperature matching and reduce exergy losses during heat addition. Li [17] investigated the thermal efficiency, exergy destruction rate and mass flow rate under different ORC configurations for various ORC applications based on heat source temperature domain. Results showed that the reheat ORC had a slightly higher exergy destruction rate and the evaporator was the greatest contributor for the exergy destruction rate. Shu et al. [18] used net output power and exergy efficiency as objective functions to optimize operating parameters and analyze component irreversibility based on the engine data and mathematic model. Woudstra et al. [19] established three system designs to evaluate system's combined cycle plants which used different steam bottoming cycles with same gas turbine. Results showed that the application of internal exergy efficiency of a power cycle was useful if the temperature of heat transfer from the cycle will be affected by the cycle performance. Long et al. [20] analyzed the impact of working fluids on internal and external exergy efficiencies based on genetic algorithm by taking exergy efficiency as objective function. The thermophysical properties of working fluid had minor impact on internal exergy efficiency, but played an important role in determining external exergy efficiency. Wang et al. [21] proposed a double organic Rankine cycle for discontinuous waste heat recovery and analyzed the influence of the cycle irreversibility and exergy efficiency at a given pinch point temperature difference. Wang et al. [22] proposed a thermal efficiency model theoretically based on an ideal ORC and evaluated the exergy destruction for various heat source temperatures using exergy analysis. Results showed that the evaporator contributed the major exergy destruction. Mago et al. [23] used exergy topological method to analyze the energy loss of ORC systems, and found that the evaporator accounted for maximum exergy destroyed in ORC and the process responsible for this was the heat transfer across a finite temperature difference. Sun et al. [24] investigated ORC-based cycles combined with absorption refrigeration cycle and ejector refrigeration cycle, and pointed out that exergy efficiency of both systems decreased with the increase of the evaporation temperature of the ORC. Mousapour et al. [25] conducted the first and second law analyses of an irreversible Miller cycle; the relation between specific heat of working fluid and its temperature, the internal irreversibility, friction loss and heat-transfer loss were considered; and thermal efficiency versus compression ratio, and the minimum and maximum temperatures of Miller cycle can be predicted by using artificial neural network (ANN).

The irreversible losses in ORC mainly occurs in heat transfer processes of the evaporator and condenser. It is important to optimize the heat transfer to improve its performance and the temperature match between heat source and work fluids. Pandey et al. [26] investigated the effects of surface geometry, friction factor and exergy loss in a flat plate heat exchanger analytically. Results showed that the heat transfer had larger effect on the exergy loss, exergy loss increased with the mass flow rate, and the pressure drop greatly increased the capital cost. Kostowski et al. [27] proposed an innovative exergy recovery system for natural gas expansion based on integration of internal combustion engine and ORC, and identified the sources of irreversibilities by means of exergy analysis. Yang et al. [28] developed thermodynamic analysis and a finite-temperature-difference heat-transfer method to evaluate the thermal efficiency, total heat-exchanger area, objective parameter, and exergy destruction of the ORC system and proposed optimal