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Applicability of entropy, entransy and exergy analyses to the optimization of the Organic Rankine Cycle

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ABSTRACT

Based on the theories of entropy, entransy and exergy, the concepts of entropy generation rate, revised entropy generation number, exergy destruction rate, entransy loss rate, entransy dissipation rate and entransy efficiency are applied to the optimization of the Organic Rankine Cycle. Cycles operating on R123 and N-pentane have been compared in three common cases which are variable evaporation temperature, hot stream temperature and hot stream mass flow rate. The optimization goal is to produce maximum output power. Some numerical analyses and simulations are presented, and the results show that when both the hot and cold stream conditions are fixed, all the entropy principle, the exergy theory, the entransy loss rate and the entransy efficiency are applicable to the optimization of the ORC, while entransy dissipation is not. This conclusion is available no matter what kind of working fluid is used, nevertheless, the system performances and parameters may be much different. The results also indicate that when the hot stream condition (temperature or mass flow rate) varies, the entransy loss rate is the only parameter which always corresponds to the maximum power output.

1. Introduction

Global energy demands escalating at a dramatic speed are contradict with global warming attributed to a large extent, to significant rise in the use of fossil fuels for electricity generation. However, it must be conceded that economic development and energy consumption are closely associated. Up to now over a half of the low or moderate temperature heat sources ($\sim$773.15 K), e.g. as solar energy, biomass energy, geothermal energy and waste heat are directly rejected to the environment. How to recovery these parts of low-grade heat attracts large attention for the purpose of energy conservation and thermal pollution reduction. Although heat recovery has huge potential and is around the corner, but the progresses of the technologies still require more research and development.

Recovery system based on the ORC (Organic Rankine Cycle) [1–38] with heat input and power output reversing low-grade heat into high-grade electricity with its simplicity and commonly available components has been widely discussed in recent decades. Analyses [33–38] of the ORC are mainly around the first and second law efficiency by thermodynamics. In this paper, we distinctively consider the applications of some theories, such as entropy generation, exgergy destruction concepts and entransy theory.

Entropy generation minimization is always related to the optimal output and minimized irreversibility since it stands for the ability loss of doing work. However, in recent years there are some different voices, the applicability of this theory is challenged. It was found not lead to the maximum system performance all the time unless the refrigeration capacity is prescribed [39,40].

The entransy theory [41–51] was proposed by Guo et al. [41] and developed for optimization design of thermal system and heat transfer. It is a quantity corresponds to the electrical potential energy in a capacitor, and now it is defined to describe the “potential energy of heat” in heat exchangers or heat-work conversion systems. It was also investigated to analyses of heat-work conversion processes by Cheng [42–46] as the “ability to release heat of the system”. The results show that the increase in output power is corresponding to the increasing entransy loss. Yang et al. [47] applied the entransy theory and finite-time thermodynamics theory to research a two-heat-reservoir heat engine model with heat leakage, finite heat capacity high-temperature source and infinite heat capacity low-temperature heat sink. Their results are classified into three different cases. Wang et al. [48] extended the entransy theory to the steam power cycle and proved that it can serve as an approach of optimization. Zhou et al. [49] analyzed

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Nomenclature

C	heat capacity flow rate, kW/K
c	specific heat capacity, kJ/(kg K)
$\dot{E}_d$	exergy destruction rate, kW
e	specific exergy, kJ/kg
G^*	entransy efficiency
$\dot{G}_{dis}$	entransy dissipation rate, kW K
$\dot{G}_f$	heat entransy flow rate, kW K
$\dot{G}_{loss}$	heat entransy loss rate, kW K
M	molar mass, g/mol
$\dot{m}$	mass flow rate, kg/s
N_{RS}	revised entropy generation number
h	specific enthalpy, kJ/kg
P	Pressure, kPa
$\dot{Q}$	heat exchange rate, kJ/s
$\dot{S}_f$	entropy flow rate, kW/K
$\dot{S}_g$	entropy generation rate, kW/K
$\Delta\dot{S}$	entropy change rate, kW/K
s	specific entropy, kJ/(kg K)
T	temperature, K
$\dot{W}$	power output, kW

Subscripts

0	environment
1–16	state points of the cycle
bp	boiling point
c	cold stream
cond	condensation
cr	critical
evap	evaporation
exp	expansion
fp	fusing point
H	high temperature side
h	hot stream
in	flow into the system
L	low temperature side
out	flow out of the system
pp	pinch point
pump	working fluid pump
r	working fluid
sub	subcooling
sup	superheating
total	the total system

and optimized Stirling cycle by taking the maximum output work as an objective, and discussed suitability of entransy loss, entransy dissipation, entropy generation, number of entropy generation, and improved number of entropy generation in optimization of system parameters, and the results showed that the consistency of entransy loss was better than others when it was applied to optimize the output power of Stirling cycle. However, the organic Rankine cycle is far different from the steam power cycle with working fluids, heat stream temperature range and circulation way. For steam Rankine cycle, the suitable working fluid is only water (wet fluid), thus not many conditions need to be considered. However, for ORC, dry fluids or adiabatic fluids are used to generate. Beyond that, ORC is an approach to recovery the waste heat from the exhaust gas from steam Rankine cycle, therefore the gas inlet temperature of ORC is always lower that of steam Rankine cycle. Besides, steam Rankine cycle usually adopts steam turbine as power machine, however, ORC utilizes screw or scroll expander to replace the turbine. That means the efficiencies and efficiency correction factors of the power machines are different. Since there are many differences, whether the entransy theory can be applied to any fluid and temperature range of ORC is need to be verified. The applicability of the entransy theory to ORC still needs further discussions for lack of reports.

Mago et al. [8] applied exergy destruction to ORC operating on R113, the result demonstrates that for the ORC the evaporator is the component with the highest exergy loss contribution (77%) followed by the expander with 21.4%. Moreover, he summarized that the total system exergy loss decreases with the evaporator pressure increase in the analyzed case.

In this paper, R123 and N-pentane are chosen as working fluids and compared by different indicators. The concepts of entransy loss and dissipation are applied to the analyses of the ORC. The relationship of the concepts of entropy generation, entransy loss, entransy dissipation, exergy destruction and the output power for ORC are derived and demonstrated under both fixed and variable hot stream conditions. Different evaporation temperatures, hot stream inlet temperatures and mass flow rates are simulated so as to find the variation tendency of the concepts mentioned above. The article firstly analyzed the Organic Rankine Cycle and introduced the difference with steam Rankine cycle in Section 2. And then it expressed the formulas and the derivation processes of the evaluation indicators in Section 3. After that, in Section 4, the global model including hot and cold stream conditions, brief assumptions, and working fluids properties is given. Finally, 3 typical cases have been taken into consideration to give a crosswise comparison in Section 5. Results prove that the entransy loss rate can be a method to optimize the output power of ORC in all the three cases, which gives us a train of thoughts that when designing the system operating condition, finding the maximum entransy loss rate is same to getting the maximum output power. However, other concepts which are widely used not are not suitable for all three cases.

2. Analyses of Organic Rankine Cycle

Fig. 1 shows that the elementary configuration of ORC system contains an evaporator, an expander, a condenser, a working fluid pump and a cooling cycle. The evaporator and the condenser are both expressed as three-step models by Quoilin et al. [15] and Wei et al. [9]. The thermodynamic processes on the *T–S* diagram for the ideal ORC system corresponding to the numbers in Fig. 1 are illustrated in Fig. 2 where the tawny curve connecting points 4, 7, 8 and 3 is the saturation curve. The whole system is under equilibrium state and stable, without leakages, mechanical and heat losses. In the following, the quantities T_i, P_i, h_i, and s_i denote the temperature, the pressure, the specific enthalpy and the specific entropy at state point *i* and the quantities $\dot{W}_{i,j}$ and $\dot{Q}_{i,j}$ denote the specific work and heat in the process from state point *i* to state point *j*.

At state point 1, the working fluid with pressure P_1, temperature $T_1 = T_{evap} + T_{sup}$ is superheated vapor, then it enters the expander where it undergoes an expansion till it arrives at point 2 with pressure P_2, temperature T_2, $s_1 = s_2$. During the expansion, work $\dot{W}_{1,2} = \dot{m}_r(h_1 - h_2)$ is delivered from the expander. At state point 2 the working fluid enters the condenser in which it returns isobarically to subcooled state point 5 by releasing the specific heat $\dot{Q}_{2,5}$ to the cold stream. At state point 5 whose temperature and pressure are the lowest ones in the ORC, the working fluid is subcooled liquid at $T_5 = T_{cond} - T_{sub}$ and the corresponding vapor