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System performance optimization of ORC-based geo-plant with R245fa under different geothermal water inlet temperatures

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ABSTRACT

Organic Rankine cycle (ORC) is effective for heat-work conversion. However, the system performance should be improved due to the high irreversible loss. The pinch point temperature difference (PPTD) is a very important parameter for the ORC-based plant and is often fixed to be a constant value, especially for low- and medium-grade heat sources. In this paper, the influence of the PPTD on the system performance was analyzed base on the laws of thermodynamics. The net power output, the product of the total thermal conductance, the size parameter (SP), and the volumetric flow ratio (VFR), were calculated. The results show that the net power output and the total thermal conductance are opposite with the PPTD. The optimal PPTD is closely correlated with the heat source inlet temperature (HSIT), and there is a quadratic function between them, with the optimal PPTD from 2 to 21 °C for the HSIT ranging from 80 to 180 °C, which can be popularized in engineering applications.

1. Introduction

Energy shortage, global warming and ozone layer depletion are main issues that the human beings are facing (Falkner, 2014; Bilgen, 2014). Moreover, the continued growth of the energy demand results in the rapid depletion of the fossil fuels. So far as China is concerned, the coal-dominated energy structure has aroused serious environmental pollution, such as the water pollution (Bao et al., 2012; Zhang et al., 2015; Miao et al., 2015), the air pollution (Hu et al., 2015; Tanaka, 2015; Chang et al., 2014), the solid waste pollution (Yang et al., 2015a; Wang et al., 2015a; Yang et al., 2015b), the indoor air pollution (Pei et al., 2015; Deng et al., 2015; Sun et al., 2015). The serious energy situation calls for the efficient energy utilization to improve the energy structure. The renewable energies and kinds of the waste heat have attracted broad attention. For these low-to-medium grade heat sources, the organic Rankine cycle (ORC) technology is effective due to its simple cycle configuration, high reliability and flexibility, and convenient maintenance (Bianchi and De Pascale, 2011), and it has been successfully applied to geothermal power generation (Cheng et al., 2013; Ayub et al., 2015; Astolfi et al., 2014; Li et al., 2012a), solar thermal power generation (Khan and Arsalan, 2016; Casati et al., 2013; Li et al., 2013; Quoilin et al., 2011; Manolakos et al., 2009), ocean thermal energy conversion (Aydin et al., 2014; Kim et al., 2016; Jung et al., 2016), and waste heat recovery (Pu et al., 2016; Ge et al., 2015; Yang et al., 2015c; Shu et al., 2013a; Shu et al., 2013b; Shu et al., 2014).The thermal efficiency of the ORC system is relatively low mainly due to the poor temperature matching between the working fluid and the heat source/sink. The performance improvement is the main research hotspot for the ORC system. Many researchers have been focusing on the parametric optimization (Li et al., 2013; Quoilin et al., 2011; Ge et al., 2015; Shu et al., 2014; DiPippo, 2004; Roy and Misra, 2012; Xi et al., 2013a; Yamamoto et al., 2001; Madhawa Hettiarachchi et al., 2007; Roy et al., 2010), working fluid selection (Shu et al., 2013a; Shu et al., 2014; Saleh et al., 2007; Liu et al., 2004), cycle configuration improvement (Shu et al., 2013a; Shu et al., 2013b; Shu et al., 2014; Roy and Misra, 2012; Xi et al., 2013a; Kanoglu, 2002a; Xi et al., 2013b; Liu et al., 2012; Zhang et al., 2013; Yang et al., 2014; Li et al., 2014a; Li et al., 2015a; Li et al., 2015b), and economic evaluation (Jung et al., 2016; Yang et al., 2015c; Kosmadakis et al., 2009). However, the pinch point temperature difference (PPTD) is often assumed to be a constant value based on engineering experiences, which may lead to a relatively sub-optimal system performance. The typical PPTDs used in the literatures have been listed in Table 1.

Few literatures can be found focusing on the optimization of the PPTD. Wu et al. (Wu et al., 2014) optimized the PPTD of evaporator for waste heat recovery by exergo-economic principle using the

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Nomenclature

Greek symbols
η Efficiency (%)
ρ Density (kg/m^3)

Subscripts
c Condenser
cri Critical
cw Cooling water
e Evaporator
ex Exergetic
g Generator
gw Heat source
opt Optimal
p Pump
pp Pinch point
s Isentropic
t Turbine
th Thermal
wf Working fluid
0 Environment
1, 2,3, 4, 5,6 State points

Acronyms
ALT Atmosphere life time (yr)
GWP Global warming potential
ODP Ozone deletion potential
ORC Organic rankine cycle
VFR Volumetric flow ratio
SP Size parameters

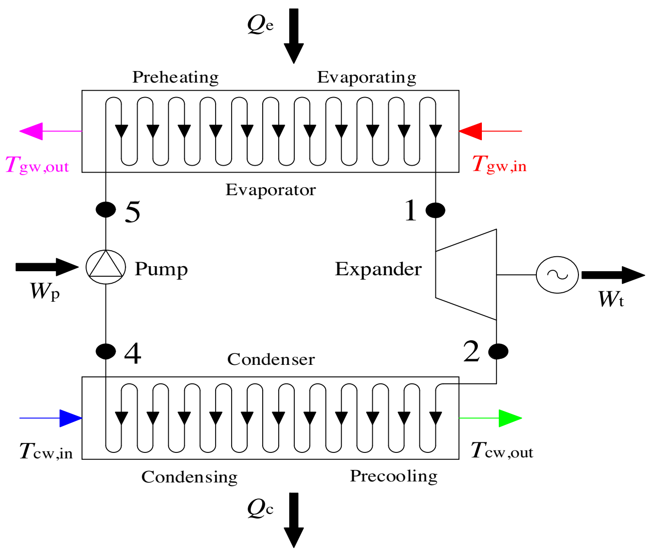

Fig. 1. Schematic diagram of an ORC system.

annual net profit per transferred heat load as objective function, and they found that the optimal PPTD from the perspective of exergy recovery is larger than that from the view of exergy destruction. Li et al. (Li et al., 2012b) presented the analysis on the influence of the PPTD and the evaporation temperature on the performance of ORC system in recovering the low temperature waste heat of the flue gas, and the results showed that the total heat transfer area decreases first and then increases with the increase of the PPTD of the evaporator at a given total temperature difference, while the corresponding cost-effective performance (ratio of the net power output to total heat transfer area) displays almost the opposite variation tendency. The PPTD of the evaporator for the optimization cost-effective performance is approximately the same for different organic working fluids. Li et al. (Shu et al., 2014) presents a brief analysis to optimize the PPTD to be 5 °C when the heat source is 105 °C.

Apparently, from the perspective of the comprehensive optimization of the system performance, the PPTD should be also optimized. The PPTD is an essential parameter to an ORC plant, and it plays a much crucial role for the plants driven by the low-to-medium grade heat sources. On the one hand, a high PPTD will lead to decrease the thermal conductance in the evaporator and condenser, which is at the cost of increasing the irreversibility between the heat source/sink and the working fluid. On the other hand, a low PPTD will decrease the irreversibility between the heat source/sink and the working fluid, which is at the cost of increasing the thermal conductance in the evaporator and the condenser. From this sense, the system profit represented by the power output is inversely proportional to the PPTD. On the contrary, the system cost represented by the total thermal conductance (the production of the thermal conductance both in the evaporator and condenser) is proportional to the PPTD. Therefore, there exists an optimal PPTD corresponding to the optimal system performance.

In this paper, the PPTD ranges from 1 to 15 °C with R245fa as the working fluid. The system performances including the mass flow rate of the working fluid, the net power output, the irreversible loss, the thermal conductance, the VFR, the SP are optimized and evaluated. Moreover, the PPTD is also optimized for the heat source ranging from 80 to 150 °C.

Table 1
Values of the pinch point temperature difference obtained from literatures.

PPTD(°C)	Process	Sources	PPTD(°C)	Process	Sources
10	Evaporation, Condensation	Yari (2010)	5, 8	Evaporation	Xiao et al. (2015)
10	Evaporation, Condensation	Wang et al. (2009)	≥5	Evaporation, Condensation	Xue et al. (2015)
7.4, 2.7	Evaporation	Kanoglu (2002b)	≥5	Evaporation, Condensation	Wang et al. (2015b)
5	Evaporation, Condensation	Heberle and Brüggemann (2010)	≥5	Evaporation, Condensation	Chaitanya Prasad et al. (2015)
11	Evaporation	Sun and Li (2011)	10	Evaporation	Sarkar and Bhattacharyya (2015)
6	Evaporation	Deethayat et al. (2015)	5	Condensation	Sarkar and Bhattacharyya (2015)
3	Condensation	Deethayat et al. (2015)	10	Evaporation	Liu et al., (2015)
5	Evaporation, Condensation	Habka and Ajib (2015)	10	Evaporation, Condensation	Peter and R.Aabe (2015)
3–10	Evaporation, Condensation	Feng et al. (2015a)	10	Evaporation, Condensation	Di Maria and Micale, (2015)
5–25	Evaporation	(Khaljani et al., 2015)	10	Evaporation, Condensation	Zhu et al. (2015)
3	Evaporation	Maalouf et al. (2016)	10	Evaporation	Yu et al., (2015)
10	Evaporation	Feng et al. (2015b)	8	Evaporation	Amicabile et al. (2015)
5	Condensation	Feng et al. (2015b)	10	Evaporation, Condensation	Kim and Perez-Blanco (2015)