Energy 123 (2017) 728–741

Contents lists available at ScienceDirect

Energy

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

Thermo-economic comparison of subcritical organic Rankine cycle based on different heat exchanger configurations

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ARTICLE INFO

Article history:
Received 2 July 2016
Received in revised form
3 January 2017
Accepted 25 January 2017
Available online 30 January 2017

Keywords:
Organic Rankine cycle
Thermo-economic evaluation
Electricity production cost
Plate heat exchanger
Shell-and-tube heat exchanger
Finned-tube heat exchanger

ABSTRACT

The cost of heat exchangers account for a large proportion of total investment in organic Rankine cycle (ORC). In this paper, plate heat exchanger (P), shell-and-tube heat exchanger (S) and finned-tube heat exchanger (F) are used as evaporator and condenser of four subcritical ORC configurations: ORC-PP, ORC-SS, ORC-FP and ORC-FS. The thermo-economic models are built and a thermo-economic evaluation and comparison of four ORC configurations is presented in order to recover the low-temperature waste heat. The optimal evaporating pressure, pinch point temperature difference, net power output and dynamic payback period corresponding to the minimum electricity production cost (EPC) are obtained for different ORC configurations under different heat source temperatures. Results show that the EPCs of ORC-PP and ORC-SS are apparently higher than that of ORC-FP and ORC-FS. Among them, ORC-FS is the most cost-effective configuration. The optimal pinch point temperature difference in evaporator has a decreasing trend with the increase of critical temperature of working fluid for ORC-FS and ORC-FP, while the optimal pinch point temperature difference in condenser keeps nearly constant.

1. Introduction

Along with the rapid development of economy, a large amount of low-temperature waste heat sources is generated by existing industrial process. Meanwhile, environmental pollution and energy shortage have significantly deteriorated. Survey data shows that low/medium grade waste heat accounts for 50% or more proportion of the total heat produced in industrial processes [1]. A lot of approaches have been proposed for the recovery of the waste heat [2] for reducing environmental pollution and energy shortage problems. Among the conversion technologies, organic Rankine cycle (ORC) is the most widely used [3], which can be driven directly by low grade energy such as solar energy [4–7], biomass energy [8–10], geothermal energy [6,11–14], waste heat from gas turbine [15], and exhaust gases from vehicle engines or marine diesel engines [16,17] to electricity.

ORC has the same system components as steam Rankine cycle (a boiler, a condenser, an expansion device and a pump) but uses organic fluid. However, the conversion efficiency is relatively low due to low heat source temperature [18]. In order to maximize the electricity generation efficiency of ORCs, many researches have been carried out. To sum up previous work focused on in the following aspects: selection criteria of optimal organic working fluids (pure or zeotropic working fluids [19]), thermodynamic and physical properties [20], various thermodynamic cycles (basic cycle, trans-/supercritical cycle [14,21–23], regenerative cycle [18,24], reheated cycle, recuperative cycle [24–26] and combined cycle [8,15,27,28]), selection of primary components and geometric dimensions [19,28], and environmental concerns [29]. In addition, commercial applications of ORC have a rapid development in Europe and the US. Among them, Turboden and ORMAT are primarily representative companies for recovering biomass and geothermal energy, respectively [2].

Researchers have increasingly focused on the ORCs' feasibility in terms of views on technical, economic and environmental point in recent years. Li et al. [30] conducted an economical model of the subcritical ORC system for the use of low-temperature flue gas. The electricity production cost was selected as the evaluation criterion. Quoilin et al. [1] investigated the thermodynamic and economic

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http://dx.doi.org/10.1016/j.energy.2017.01.132
0360-5442/

Nomenclature

A	heat transfer surface area (m^2)
Bo	boiling number
C	cost ($)/constant relative to equipment cost correlation
Co	convection number
D	diameter (m)
Fr	Froude number
G	mass velocity (k gm^{-2} s^{-1})
H	fin height (m)
K	constant relative to equipment cost correlation
Nu	Nuselt number
Pr	Prandtl number
Re	Reynolds number
U	overall heat transfer coefficient (Wm^{-2} K^{-1})
V	volume flow rate (m^3/s)
Y	Fin pitch (m)
c_p	specific heat (J kg^{-1} K^{-1})
d_t	fin collar outside diameter (m)
d_b	fin root diameter (m)
g	acceleration due to gravity (m/s^2)
m	mass flow rate (kg/s)
p	pressure (kPa)
pp	payback period (year)
q	average imposed wall heat flux (kW/m^2)
x	dryness fraction

Abbreviations

COM	Cost of Operation and Maintenance
CRF	Capital Recovery Factor
GWP	Global Warming Potential relative to CO$_2$
HX-P	Plate Heat Exchanger
HX-S	Shell-and-tube Heat Exchanger
HX-F	Finned tube Heat Exchanger
ORC-PP	Both evaporator and condenser using plate heat exchanger
ORC-FP	Finned tube bundles as evaporator and plate heat exchanger as condenser
ORC-SS	Both evaporator and condenser using shell-and-tube heat exchanger
ORC-FS	Finned tube bundles as evaporator and shell-and-tube heat exchanger as condenser

Greek letters

Δp	pressure difference (kPa)
ΔT	temperature difference (K)
α	convection heat transfer coefficient (Wm^{-2} K^{-1})
β	Chevron angle/finned ratio
δ	thickness (m)
η	efficiency
ρ	density (kg/m^3)
λ	thermal conductivity (Wm^{-1} K^{-1})
μ	dynamic viscosity (Ns/m^2)

Subscripts/superscripts

LT	lifetime
c	cold/condensation
cond	condenser
crit	critical
e	evaporating
evap	evaporator
eq	equivalent
gen	generator
fg	flue gas
h	heat source/hot/hydraulic
in	inlet/inside
l	liquid
g	gas
max	maximum
min	minimum
out	outlet
pp	pump
sp	single-phase
t	turbine
tot	total
tp	two-phase
wf	working fluid
1–8	state points

optimization of a small scale ORC for recovering waste heat. Plat heat exchanger was used in their model and economic profitability. Lecompte et al. [28] developed a thermo-economic design methodology of ORC based on CHP system, taking into account partial load behavior. A plate heat exchanger and a finned tube heat exchanger with circular fins were selected as evaporator and condenser, respectively.

Zeotropic mixtures are used as working fluids for better temperature profiles match of heat source and heat sink [31]. Wu et al. [32] calculated and compared the performance of ORC using zeotropic mixtures with corresponding pure fluids. The result showed that the economic performance of that system was worse in some extent compared to corresponding pure fluid cycles. However, Kheiri et al. [19] found that the ORC using zeotropic mixture of n-pentane and R245fa could not only weaken flammability of n-pentane well but also made the system reached a good economic profitability.

In addition, thermo-economic assessment for different ORC applications was conducted. Astolfi et al. [11] presented a detailed analysis of binary ORC power plants for recovering low-medium temperature geothermal sources. Walraven et al. [12] performed an economic optimization of air-cooled ORC driven by geothermal heat sources. Yang et al. [13] investigated the economic optimization of an ORC with lower GWP working fluids in geothermal application.

A review of the literature reveals that the thermo-economic comparisons of different ORC systems are of great difference and complicated. Consequently, this paper aims to conducts a comparative analysis of thermo-economic concerning four ORC configurations. In the models, four ORC configurations are: both evaporator and condenser using plate heat exchanger (ORC-PP), a finned tube bundles with circular fins as evaporator and a plate heat exchangers as condenser (ORC-FP), both evaporator and condenser using shell-and-tube heat exchanger (ORC-SS), and a finned tube bundles with circular fins as evaporator and a shell-and-tube heat exchanger as condenser (ORC-FS). The cost of heat exchanger, turbine, electricity generator, working fluid pump and cooling water pump is considered. Then the evaporating pressure, pinch point temperature differences in evaporator and condenser are analyzed and optimized at different heat source temperatures