Energy Conversion and Management 160 (2018) 31–47

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Optimizations of the organic Rankine cycle-based domestic CHP using biomass fuel

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A R T I C L E I N F O

Keywords:
Combined heat and power (CHP)
Organic Rankine cycle
Biomass
Optimization
Working fluids

A B S T R A C T

The purpose of this study is to determine the optimal operating conditions and performance for the design of ORC based biomass compact CHP for 2 kW of electric, 25 kW of thermal power productions and 60 °C warm water supply. Eight organic working fluids were selected based on thermo-physical properties and related environmental regulations: cyclopentane, isopentane, n-pentane, diethyl ether, HFO-1233zd, HFC-245fa, HFE-7000 and HFE-7100. The selected organic fluids were classified into three groups considering latent heat and boiling point. The group A fluids contained cyclopentane, isopentane, n-pentane and diethyl ether. The group B fluids contained HFO-1233zd and HFC-245fa. The group C fluids contained HFE-7000 and HFE-7100. A micro CHP system composed of a biomass boiler (200 °C heat source), an ORC power cycle and a cooling water line (20 °C cooling water supply) was modeled in four variants depending on whether post-heater and IHE were applied or not. The subcritical ORC cycle and saturated vapor state at the inlet of the expander were considered for the analysis. As a result of thermodynamic analyses and optimizations, the group A fluids have the best CHP performance because of the greatest latent heat amount. The systems using the group A fluids have the lowest mass flow rates from 0.053 kg/s to 0.081 kg/s, the lowest required heat supplies from 31.64 kW to 34.61 kW, the highest ORC efficiencies from 5.95% to 7.29% and the CHP efficiencies from 71.83% to 72.32%. The group B fluids have the mass flow rates from 0.157 to 0.215 kg/s, the highest required heat supplies from 36.98 kW to 46.41 kW, the lowest system efficiencies from 4.59% to 6.05% and the highest CHP efficiencies from 72.05% to 73.41%. The group C fluids have the highest mass flow rates from 0.213 kg/s to 0.230 kg/s, the required heat supplies from 32.30 kW to 40.54 kW, the system efficiencies from 5.07% to 6.36% and the lowest CHP efficiencies from 71.31% to 72.33%. In addition, ORC systems using the group A or group C fluids can operate at low pressure and can meet system requirements with low cooling water mass flow rate because of the high boiling points. For the group A fluids, both post-heater and IHE are very effective for the system, and the system using the group B fluids can highly improve the system through the application of the post-heater. For the group C fluids, application of the IHE significantly improves system performance.

1. Introduction

Worldwide energy demands are increasing continuously with the shortage of fossil fuel resources and the risk of climate change due to global warming. According to the 6 °C scenario (6DS) in the IEA report [1], the worldwide energy demands and average temperature will increase by 70% and 6 °C until 2050. To prepare for this situation, the report proposed a plan to reduce 25% of the energy demands and 50% of the greenhouse-gas emissions over the next 40 years by an increase in renewable energy utilization, smart grid application and system efficiency improvement. In particular, using distributed power generation (DPG) instead of centralized power generation (CPG) is useful for energy savings because it can reduce deficiencies such as excessive energy production and electric power transmission losses in CPG [2].

CHP is a technology that greatly increase energy utilization from a single heat resource by enabling simultaneous supply of electric power and hot water for district heating. Especially, the technical advantage is more remarkable because the waste or renewable heat source can be utilized. This technology has already been demonstrated through commercial operations over long periods. Water is a common working fluid for the CHP system, and it is necessary to supply a large-scale high temperature heat source to maintain superheated steam conditions at the turbine inlet because of its high specific heat and wet fluid feature [3]. Thus, most CHP systems are operated by CPG since the component

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https://doi.org/10.1016/j.enconman.2018.01.025
Received 6 November 2017; Received in revised form 12 January 2018; Accepted 13 January 2018

Nomenclature

Symbols

c_p	isobaric specific heat, [kJ/kg-K]
h	specific enthalpy, [kJ/kg]
k	thermal conductivity coefficient, [kW/m^2-K]
$\dot{m}$	mass flow rate, [kg/s]
MW	molar Mass, [g/mol]
P	pressure, [kPa]
Q	heat transfer rate, [kW]
T	temperature, [K]
s	specific entropy, [kJ/kg-K]
$\dot{V}$	volumetric flow rate, [m^3/s]
W	power output, [kW]

Greek symbols

η	efficiency
μ	viscosity
ρ	density, [kg/m^3]

Subscripts

CBP	condenser Boiling Point
COND	condenser
G	generator
EXP	expander
EVAP	evaporator
IS	isentropic
LL	lower limit
lv	liquid to vapor vaporization
M	motor
P	pump
TH	thermal
UL	upper limit
W	water

Acronyms

CCHP	Combined Cooling Heating and Power
CHP	Combined Heat and Power
CPG	Centralized Power Generation
DPG	Distributed Power Generation
EES	Engineering Equation Solver
ER	Volumetric Expansion Ratio
FR	Feed Rate of Fuel
GHS	Globally Harmonized System
GWP	Global Warming Potential
HHV	High Heating Value
HTF	Heat Transfer Fluid
IEA	International Energy Agency
IHE	Internal Heat Exchanger
NBP	Normal Boiling Point
ODP	Ozone Depletion Potential
ORC	Organic Rankine Cycle
VCC	Vapor Compression Cycle

and system sizes are large, and large-scale electric and thermal power are provided to neighboring areas. However, if ORC is applied to CHP, which uses organic working fluids, small-scale electric and thermal power can be generated with low-grade heat sources. These systems have the advantage of enabling the use of low-temperature waste heat sources and making the system compact. ORC-based compact or micro CHPs are ideal for DPG network that is applicable to meet the demands of remote areas and customers use. This corresponds with the energy perspective that energy generation will rely on distributed systems to prepare for increasing the energy demands and the climate crisis [4]. Thus, compact CHPs are a promising technology that meets future expectations, so systematic studies are necessary regarding compact CHPs.

Biomass, which is classified as renewable energy, is the fourth largest energy resource in the world and accounts for 14% of major resources. It has an advantage of providing a stable energy supply, unlike wind power and solar heat [5]. In addition, it is better than geothermal and solar heat because a high temperature heat source can be available by the direct combustion of gasified or solid biomass. The power generation efficiency generally increases, and heating supply quality following generation is better with a higher temperature heat source [6]. Currently, household heat pumps utilizing less than 50 kW biomass boilers, which burn wood-pellets and supply heat and warm water, have been commercialized. Thus, generating small-scale electric power and supplying heating and warm water are possible if the biomass boiler is coupled with an ORC.

Many studies on micro CHPs using renewable energy source have been conducted [7], but there are not many studies on ORC-based micro CHPs using a biomass heat source. Liu et al. [8] carried out a study on the thermodynamic analysis of a 2 kWe biomass fired ORC-based micro CHP. The following 3 types of cycle conditions were considered: saturated vapor at the turbine inlet and no subcooled condition at the pump inlet, superheated vapor and no subcooled condition, and saturated vapor and a subcooled condition. Parametric studies were conducted per variations of maximum and minimum cycle pressures, which concluded that n-pentane has the highest ORC efficiency in saturated vapor with no subcooled condition, and heat recuperation is necessary to increase ORC efficiency. Jradi et al. [9] performed a study on ORC-based micro CHPs utilizing dual heat sources, biomass and solar heats. They considered HFE-7100 as a working fluid and predicted the system performance by thermodynamic analysis. The analysis result showed that the higher portion of solar heat results in lower system performance due to low efficiency of the solar collector. Thus, a 12 kW biomass heat source was used in the micro CHP, and 500 W of electric power and 9.58 kW of thermal power were generated using a 0.047 kg/s mass flow rate of HFE-7100. Additionally, the maximum efficiency of the scroll expander was 74.23%, the ORC efficiency was 5.64%, and the total CHP efficiency was 83.08%. Qiu et al. [10] tested the ORC-based micro CHP utilizing a 50-kW biomass boiler with about 80% boiler efficiency. The IHE was applied for ORC, and HFE-7000 was used as a working fluid. The test results showed that the electric power was 860.7 W with a thermal power of 47.26 kW, so the electricity generation efficiency and the CHP efficiency were calculated as 1.41% and 78.69%, respectively. Algieri et al. [6] conducted thermodynamic and economic analyses of a 2-kWe ORC-based micro CHP utilizing a biomass heat source. They considered cyclohexane, decane and toluene as the working fluids and conducted parametric studies per variation of evaporation temperature on 4 cases including simple CHP with saturated vapor condition, simple CHP of the superheated vapor condition, CHP with IHE of saturated vapor condition and CHP with IHE of superheated vapor condition. They concluded that the evaporation temperature has a large effect on ORC electric power and efficiency, and IHE is more useful in a superheated vapor condition than in a saturated vapor condition. Karellas et al. [11] carried out the thermodynamic and economic analyses for micro CCHP system using biomass fuel and solar power. They considered HFC-245fa as a working fluid and investigated effects of evaporation and condensation temperature variation, superheating and system configuration. The study showed that the system