Energy 64 (2014) 942–952

Contents lists available at ScienceDirect

Energy

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

Thermodynamic analysis of carbon dioxide blends with low GWP (global warming potential) working fluids-based transcritical Rankine cycles for low-grade heat energy recovery

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ARTICLE INFO

Article history:
Received 25 June 2013
Received in revised form
1 November 2013
Accepted 6 November 2013
Available online 6 December 2013

Keywords:
Zeotropic mixture
Carbon dioxide
Transcritical Rankine cycle
Low GWP
Low-grade heat
Energy efficiency

ABSTRACT

Carbon dioxide is a promising natural working fluid that can be used in transcritical Rankine cycles due to environmental and safety concerns. However, the high operation pressure has to be reduced and the relatively low efficiency of the system has to be increased. Traditional working fluids have been widely investigated to reclaim low-grade heat energy, and most of them have high GWPs (global warming potentials) or are flammable or even toxic. Consequently, to mitigate the above disadvantages, we studied zeotropic mixtures of carbon dioxide blends with 7 low GWP working fluids for use in a TRC (transcritical Rankine cycle) for low-grade heat conversion. The results revealed that these zeotropic mixtures can help improve the thermal efficiency of the TRC and decrease the operation pressure compared to that of pure CO_2. Owing to the perfect thermal match in the heat transfer process, higher exergy efficiencies were achieved for the entire system when zeotropic mixtures were used than pure CO_2. Maximum exergy efficiencies exist for the TRC at the corresponding optimal pressures for each mixture. Finally, the mixture CO_2/R161 is recommended for small capacity instruments for its high efficiency, in spite of its high flammability; the mixtures CO_2/R1234yf and CO_2/R1234ze can be used in TRCs with larger capacities due to their lower flammability.

1. Introduction

In recent years, the growing consumption of fossil fuels has caused several serious environmental issues such as climate change, acid rain, and air pollution. In addition, the energy shortage problem is growing more serious with the increasing demand for energy in the world. In this situation, the development and utilization of renewable energy sources are effective ways to solve energy and environmental problems. Renewable energy resources like solar energy and geothermal energy, as well as industrial waste heat, can partially alleviate the requirement for fossil fuels. Low- and medium- temperature heat sources with temperatures typically ranging from 100 to 200 °C are the most commonly available resources at present [1]. The temperature of the fluid in a solar collector can reach up to about 180 °C on summer days and 140 °C on winter days [2]. Furthermore, the temperature range of industrial waste heat is typically between ambient temperature and 250 °C [3]. However, these low- and moderate-temperature heat sources can hardly be used to generate electricity through the conventional power generation method.

To efficiently utilize these energy sources, many thermodynamic cycles such as the ORC (organic Rankine cycle), TRC (transcritical Rankine cycle), and Kalina cycle have been proposed to convert low-temperature thermal energy into power [4]. The ORC has been extensively investigated and is considered to be an excellent cycle for converting low-grade heat energy to electrical power. The Kalina cycle is more complex and needs more maintenance in its practical operation, though the efficiency of the Kalina cycle is 3% higher in comparison with those of the other two cycles [5]. Nevertheless, for pure working fluids, during the isothermal evaporation process, the constant evaporation temperature is mismatched with the temperature change of the heat source in the heat exchangers, and this causes a large number of irreversibilities. Partially, a traditional ORC is not suitable for sensible heat sources [6]. Compared with a conventional ORC, the working fluid in a TRC can be heated directly from liquid to the supercritical state, which results in a better thermal match in the gas heater/evaporator and reduces the exergy destruction in the heating process [7].

TRCs have been investigated widely as an effective method to recover the low-grade heat energy. Zhang et al. [2,8–14]

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http://dx.doi.org/10.1016/j.energy.2013.11.019

Nomenclature

c_p	specific heat capacity (kJ/kg °C)
E	exergy (kW)
h	specific enthalpy (kJ/kg)
I	irreversibility (kW)
m	mass flow rate (kg/s)
s	specific entropy (kJ/kg °C)
T	temperature (°C)
p	pressure (MPa)
Q	heat exchange capacity (kW)
W	work output (kW)
X_{CO_2}	mass fraction of CO_2 (−)

Subscripts

0	dead state
1, 2, 2′, 3, 4, 4′, 5, 6	state point
b	boiling
c	critical
cal	calculated
in	inlet
net	net
out	outlet
pinch	pinch point
sat	saturated state
spe	specified
total	total

Greek symbols

η_I	thermal efficiency (−)
η_{II}	exergy efficiency (−)

Acronyms

C	condenser
CW	cooling water
DME	dimethyl ether
GH	gas heater
GWP	global warming potential
HC	hydrocarbon
HFC	hydrofluorocarbon
HS	heat source
IHX	internal heat exchanger
LEL	lower explosive limit
LOC	limiting oxygen concentration
ODP	ozone depletion potential
OEL	occupational exposure limit
ORC	organic Rankine cycle
P	pump
R	regenerator
T	turbine
TRC	transcritical Rankine cycle

experimentally and theoretically studied the performance of a solar Rankine system using CO_2 as a working fluid. Experimental results showed that the power generation efficiency ranged from 8.78 to 9.45% [12] and that the COPs (coefficients of performance) of the cycle were 0.548 and 0.406 on typical summer and winter days in Japan, respectively [2]. Chen et al. [15–17] compared a carbon dioxide-based transcritical power cycle with a traditional ORC using R123 as a working fluid to recover the energy from industrial waste heat. The results indicated that a CO_2 transcritical power cycle showed a higher power output than that of the ORC, considering the thermal match of the heat transfer in the evaporator. Cayer et al. [18,19] introduced an IHX (internal heat exchanger) to a CO_2 transcritical power cycle system and found that the maximum energy efficiency increased and that the corresponding optimum pressure decreased by using the pinch analysis methodology. Vélez et al. [6,20] carried out an exhaustive simulation of a carbon dioxide-based transcritical power cycle. The results revealed that there exists a maximum value for the cycle energy efficiency as well as the net specific work at various turbine inlet temperatures and that a TRC was a reliable way to convert low-grade heat energy. Guo et al. [21] compared the performances of CO_2 and 12 pure conventional working fluids used in a transcritical Rankine power cycle. They concluded that temperature glide of fluids that were well-matched in the evaporator can improve the power output. Chen et al. [22] also compared CO_2 with R32 as working fluids in a TRC. They concluded that the thermal efficiency of an R32-based cycle was 12.6%–18.7% higher than that of CO_2 at much lower pressures. Gu et al. [23] studied transcritical cycles with propane, R125, and R134a as working fluids by using geothermal sources (>190 °C) as heat sources, and propane and R134a were recommended for use in this cycle due to their high efficiencies. Saleh et al. [24] carried out a theoretical study on a TRC operating between 30 and 100 °C using R143a, R290 and R41 as working fluids, and the thermal efficiency, expansion ratio, and volume flow rate at the inlet of the turbine were discussed. Karellas et al. [7] investigated the performance of transcritical and subcritical Rankine cycles by using the working fluids R227ea and R134a at turbine inlet temperatures ranging from 105 to 135 °C. Schuster et al. [25] studied the performance of 12 pure working fluids, including water, R236fa, R245fa, and isobutene, used in transcritical and subcritical Rankine cycles with a heat source at 210 °C. Performance characteristics such as the work output, thermal efficiency, and heat transfer capacity were discussed.

From the above mentioned researches, CO_2 is considered to be a promising fluid for TRCs. It is an environmentally-friendly natural working fluid with zero ODP (ozone depletion potential) and a negligible GWP (global warming potential), and it is non-flammable and non-toxic [18]. In addition, it has favorable thermodynamics and transport properties. A disadvantage of CO_2 is its critical point, which is as low as 31.1 °C and its potential effect on the condensation process due to the temperature limitations of available cooling sources [4]. Another disadvantage of CO_2 is its high critical pressure, which is as high as 7.38 MPa. The normal operating pressure of a CO_2 system is usually above 10 MPa, which leads to safety concerns in a real operation. Besides CO_2, some working fluids like HFCs (hydrofluorocarbons) and HC (hydrocarbons) have been selected and also used with TRCs [7,23–25]. These fluids have relatively high critical temperatures and low pressures and are well suited for TRCs in comparison with CO_2. However, some of these conventional working fluids are either flammable or toxic and some of them have excessively high GWP values. These disadvantages impede the actual application of these working fluids in TRCs.

To solve the problem of high operational pressure in a CO_2 transcritical refrigeration cycle, CO_2 is blended with other pure working fluids such as R290 [26,27], R600, R600a [28], and DME (dimethyl ether) [29,30] and the operation pressure of the system is reduced efficiently. Furthermore, some researches [31–33] have shown that the addition of carbon dioxide or nitrogen added to a combustible gas can effectively reduce the combustion possibility