Applied Thermal Engineering 127 (2017) 378–389

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Parametric study of a novel organic Rankine cycle combined with a cascade refrigeration cycle (ORC-CRS) using natural refrigerants

R. Lizarte [a,*], M.E. Palacios-Lorenzo [b], J.D. Marcos [c]

[a] *Universidad Carlos III de Madrid, Avda. de la Universidad 30, 28911 Leganés, Madrid, Spain*
[b] *Escuela Técnica Superior de Ingeniería y Diseño Industrial, U.P.M., Ronda de Valencia 3, 28012 Madrid, Spain*
[c] *Escuela Técnica Superior Ingeniería Industrial, U.N.E.D., Juan del Rosal 12, 28040 Madrid, Spain*

HIGHLIGHTS

- A novel organic Rankine cycle combined with a cascade refrigeration cycle is shown.
- Natural refrigerants (toluene, NH_3, CO_2) used as working fluids.
- Regression models of COP and η_{ex} enable a better design of this ORC-CRS system.
- Suited to be driven with low- or medium-temperature renewable sources.
- Encouraging results for its application where electricity supply is unreliable.

ARTICLE INFO

Article history:
Received 10 March 2017
Revised 17 July 2017
Accepted 11 August 2017
Available online 12 August 2017

Keywords:
Organic Rankine cycle
Cascade
Refrigeration
Natural refrigerants
Simulation

ABSTRACT

This paper presents a novel design of a stand-alone refrigeration system consisting of a combined organic Rankine cycle and a cascade refrigeration system (ORC-CRS) for low-evaporation-temperature applications (from −55 °C to −30 °C). Natural refrigerants were used as working fluids: toluene for the organic Rankine cycle and NH_3/CO_2 for the cascade refrigeration system. A parametric study and a regression analysis have been performed to characterize the system and to estimate the overall system coefficient of performance (COP_{oval}) and exergetic efficiency (η_{ex_oval}). The highest values of COP_{oval} and η_{ex_oval} calculated were 0.79 and 31.6%, corresponding to ORC evaporation temperatures of 315 °C and 255 °C, respectively. Renewable thermal energy sources from 100 to 350 °C can be used to drive the facility, thus reducing dependence on fossil fuel and CO_2 emissions. This stand-alone facility seems to be a feasible option to exploit low- and medium-grade thermal energy (geothermal, solar, waste heat) in places where the electricity supply is unreliable.

1. Introduction

There is increasing general concern about global warming related to CO_2 emissions due to fossil-fuel combustion to produce electricity. In addition, the oil and gas reserves are predicted to become depleted and coal is projected to be the only cost-effective fossil fuel remaining after about 2042 [1]. Moreover, it is estimated that more than 2.5 billion people in the world live with unreliable electric power supply or none at all [2]. Accordingly, the use of low-grade thermal energy (geothermal, solar, waste heat) to produce electricity can help reduce conventional energy consumption and dependence, and relieve environmental pollution. In this sense, organic Rankine cycle technology has proven to be economical and reliable for using thermal sources as low as 80 °C [3]. On the other hand, Columb [4] pointed out that refrigeration consumes about 15% of all electricity produced worldwide, which is generated mostly using fossil fuels (coal, oil, and gas), and highlighted that reducing the energy consumption of refrigeration equipment will become a key environmental priority throughout the sector. Among all the possible solutions [5], one application that is gaining attention involves the use of organic Rankine cycles and vapour-compression cycles (ORC-VCC) [6–9]. In the organic Rankine-cycle-powered vapour-compression cycle, the ORC is used to convert heat energy into mechanical shaft power, which in turn is used to drive the compressor of a single-stage refrigeration system (VCC) instead of an electrically powered motor. The ORC makes use of organic compounds as a working fluid and, since the normal boiling point of these compounds is lower than that of water, low temperature sources (such as solar,

* Corresponding author.
E-mail address: rlizarte@ing.uc3m.es (R. Lizarte).

http://dx.doi.org/10.1016/j.applthermaleng.2017.08.063
1359-4311/

Nomenclature

COP	coefficient of performance
dt	temperature difference in the cascade heat exchanger (°C)
h	specific enthalpy (kJ/kg)
NBP	normal boiling point (°C)
GWP	global warming potential
$\dot{m}$	mass flow rate (kg/s)
P	pressure (bar)
$\dot{Q}$	heat transfer rate (kW)
Rc	compressor pressure ratio
$\dot{S}_g$	entropy generation (kW/K)
s	specific entropy (kJ/kg K)
t	temperature (°C)
W	mechanical power (kW)

Greek symbols

η	efficiency

Subscripts

comp	compressor
cond	condensation
CHX	cascade heat exchanger
CRS	cascade refrigeration system
evap	evaporation
ex	exergy
exp	expansion
H	high temperature reservoir
IHX	internal heat exchanger
L	low temperature reservoir
ORC	organic Rankine cycle
oval	overall
p	pump
s	isentropic
sub	subcooled
sup	superheated

geothermal, waste heat) can be used to drive the compressor of a VCC. Thus, this is a promising technology to mitigate both the dependence on fossil fuels as well as CO_2 emissions, and it could be applied in places where the electricity supply is unreliable (e.g. islands, deserts). In a computational analysis carried out by Molés et al. [10], a combined organic Rankine cycle and vapour-compression cycle (ORC-VCC) achieved overall thermal COP ranging from 0.3 to 1.1, for evaporating temperatures ranging from −13 °C to 7 °C. Nasir and Kim [11] reported the thermal performance of seven working fluids, in an ORC-VCC for domestic air conditioning. They found overall COP and exergetic efficiency values ranging from 0.172 to 0.217 and from 24.99% to 26.76%, respectively. Aphornratana and Sriveerakul [12] performed a theoretical analysis of an ORC-VCC coupled with a device called an expander-compressor unit. With R134a, for an evaporator temperature of −10 °C, and a condenser temperature of 35 °C, the overall COP was 0.125. Li et al. [13] evaluated an ORC-powered VCC using low-grade thermal energy with hydrocarbon refrigerants for condenser temperatures of 30–50 °C, boiler-exit temperature ranging from 60 °C to 90 °C and evaporation temperature from −15 °C to 15 °C. Butane gave the best results with an overall COP of 0.47 for an evaporation temperature of 5 °C. For evaporation temperatures of −15 °C, the overall COP was 0.22. Bu et al. [14] developed a thermodynamic model of an ORC/VCC ice maker driven by solar energy for generating temperatures of 60–160 °C, condensation temperatures from 35 °C to 45 °C and evaporation temperature of −5 °C. Aneke et al. [15] compared a waste-heat-driven ORC-powered VCC with a waste-heat-driven NH_3-H_2O absorption refrigeration system. They had better results with the ORC driven VCR system with a COP of 0.57 for an evaporator temperature of −20 °C.

However, for very low-temperature applications (e.g. storage of frozen food, tissues, rapid freezing, etc.) where the required evaporating temperature of the refrigeration system is also very low, ranging from −30 °C to −55 °C, it is not cost effective to use a single-stage refrigeration system, since the high temperature difference between the heat source and the heat sink results in a high pressure ratio, low volumetric efficiency, and a low coefficient of performance of the system. For this reason, cascade refrigeration systems are usually adopted to meet those requirements [16–18]. The electricity grid is the source for these conventional mechanical compression systems.

The present study proposes a novel stand-alone refrigeration system using an organic Rankine cycle (ORC) combined with a cascade refrigeration system (CRS) for applications that need very low evaporating temperatures and low-to medium-grade thermal energy as the heating source. The overall system coefficient of performance (COP_{oval}) and exergetic efficiency (η_{ex_oval}) were estimated by means of a parametric study for different operating conditions and a regression analysis. The regression models obtained can be useful to establish the operating conditions of the system. This facility is presented as an option for places having an unreliable electric power service or lacking electric power.

2. Working fluids

The selected working fluid for the organic Rankine cycle is toluene. Toluene is one of the fluids currently used in commercial ORC power plants [19]. Although HFC-134a (GWP = 1300) and HFC-245fa (GWP = 950) are also used [19,20], according to the Directive 517/2014 [21], domestic refrigerators and freezers that contain HFCs with GWP > 150 have been prohibited since 2015, and refrigerators and freezers for commercial use (hermetically sealed equipment) that contain HFCs with GWP > 2500 will be prohibited by 2020, and those containing HFCs with GWP > 150 will be prohibited by 2022. For this reason, in this study low-GWP fluids are used as working fluids. Toluene has a GWP = 3.3 for a 100-year timescale [22]. Toluene is a natural refrigerant that showed good performance in previous ORC studies [23,24]. Pezzuolo et al. [25] proposed toluene as the most promising among the fluids studied both thermodynamically and economically. Since toluene is a dry fluid, the expanded stream at the turbine outlet is always superheated vapour. In this way, the superheated apparatus is no longer needed [19]. The selected working fluids for the cascade refrigeration system are CO_2 for the low-temperature circuit and NH_3 for the high-temperature circuit. Using different refrigerants for each cycle makes it possible to select those which are best suited for that particular temperature range. The evaporating pressure of ammonia is below atmospheric pressure when the evaporating temperature is below −35 °C, thus causing air to leak into the refrigeration system and leading to short-term inefficiency and long-term unreliability of the system. A gas with a positive evaporating pressure should be chosen for evaporation below −35 °C. The use of a cascade system using CO_2 in the low temperature stage and NH_3 in the high temperature stage turned out to be an excellent alternative for cooling applications at very low temperatures [26–30]. Ammonia is the natural substance most