Energy Conversion and Management 174 (2018) 793–801

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Techno-economic evaluation of waste heat recovery by organic Rankine cycle using pure light hydrocarbons and their mixtures as working fluid in a crude oil refinery

Z. Varga*, T. Csaba

MOL Department of Hydrocarbon and Coal Processing, University of Pannonia, Veszprém, Hungary

ARTICLE INFO

Keywords:
Waste heat recovery
Organic Rankine cycle
Techno-economic evaluation
Light hydrocarbons
Carbon dioxide emission reduction

ABSTRACT

This paper summarizes the results of a study aimed at using isobutane, butane, isopentane and pentane as working fluid of an organic Rankine cycle utilizing heat of an air cooler. Ranking of different working fluids based on the maximum achievable power output, cycle efficiency, heat recovery, required heat exchanger area, attainable CO_2 emission reduction, and payback period was performed. By applying pure components, the extractable turbine power varied in the range of 452–678 kW and the CO_2 emission reduction potential was in the range of 723–1085 t/y in which isobutane provided the best results. Economic calculation involving both the capital and operating expenditures was conducted, which showed that the estimated payback periods were between 3.4 and 4.6 years with the best result of butane. The results of calculations that were obtained by using working fluids composed from pairs of light hydrocarbons showed that the extractable turbine power was higher for mixtures of butanes than those for butanes/pentanes and pentane mixtures. Based on the payback period, the hydrocarbon mixtures were composed from isobutane/butane in 25:75 and 50:50, and butane/pentane in 75:25 mass ratios that can be applied as favourable working fluids.

1. Introduction

One of the most important challenges for mankind is the reduction in the emission of gases causing the greenhouse gas (GHG) effect, e.g. carbon dioxide (CO_2), methane (CH_4), dinitrogen oxide (N_2O) and hydrofluorocarbons. The increasing world population and industrialisation as well as the demand for growing standard of living resulted in a considerable increase in CO_2 emissions in the last decades, which is well supported by data of the International Energy Agency (IEA) published yearly, e.g. from 13.9 billion tonnes of CO_2 emissions in 1971 to 32.3 billion tonnes of CO_2 emissions in 2015 [1].

One of the biggest CO_2 emitters is the hydrocarbon processing industry (HPI). The production of high quality fuels (gasoline, jet kerosene and diesel fuel) having less sulphur and aromatic but higher hydrogen content requires higher energy consumption and more hydrogen generation resulting in higher CO_2 emissions. Fig. 1 shows the GHG emissions of the refining sector of the European Union (EU) and the United States of America (USA) as well as their contribution to the global GHG emissions based on data provided by EPA [2], FuelsEurope [3] and IEA [1]. This displays that the GHG emissions varied in a narrow range both in EU and USA, and there is no clear evidence for setting the GHG emissions to a decreasing path. This suggests that further energy efficiency improving measures should be taken in the future to obtain positive changes.

Additionally, the HPI has to face up to decreasing fuel consumption arising by using more efficient internal combustion engines and from using more hybrid and pure electric vehicles, especially in Europe. Crude oil refineries can improve their competitiveness by improving energy efficiency, which contributes to a decrease in the operating expenditures, and eventually it reduces significantly the emission of flue gases, e.g. CO_2, nitrogen oxides (NO_x) etc.

Some examples of energy efficiency improving measures that are commonly used in the HPI are the following: energy integration of heat exchanger networks [4], optimization of distillation columns [5], use of divided wall distillation towers [6], improvement in utility networks (steam, cooling water) [7,8] and vapour recompression assisted reboiling [9] etc.

However, the utilization of the heat content of process streams that have temperature below or equal to 140 °C is only slightly solved, while almost all process units contain air and/or water coolers as condenser and/or product cooler to condense or cool down process streams. The low temperature process streams are generally used for preheating

---

* Corresponding author.
E-mail address: vargaz@almos.uni-pannon.hu (Z. Varga).

https://doi.org/10.1016/j.enconman.2018.08.031

Nomenclature

Variables

A	heat exchanger area
C_{bHX}	basic cost for heat exchangers depending on the heat exchanger area
C_{bpump}	basic cost for pumps depending on the volumetric flowrate and head
H	enthalpy
$\dot{m}$	mass flowrate
Q	duty
s	specific entropy
T	temperature
T_{P1}	process stream inlet temperature
T_{P2}	process stream outlet temperature
T_{w4}	condenser outlet temperature
U	overall heat transfer coefficient
W	power
η	efficiency

Chemical symbols

$n\text{-}C_4$	normal butane
$n\text{-}C_5$	normal pentane
CH_4	methane
CO_2	carbon dioxide
$i\text{-}C_4$	isobutane
$i\text{-}C_5$	isopentane
N_2O	dinitrogen oxide
NO_x	nitrogen oxides

Subscripts/superscripts

C	cooler
cond	condenser
evap	evaporator
exp	expander
H	heater
pump	circulation pump
T	total or turbine
WF	working fluid

Abbreviations and acronyms

API	American Petroleum Institute
CAPEX	capital expenditures
CHP	combined heat and power plants
EPA	Environmental Protection Agency
GHG	greenhouse gas
GWP	global warming potential
HPI	hydrocarbon processing industry
IEA	International Energy Agency
MINLP	Mixed Integer Nonlinear Programing
NBP	normal boiling point
ODP	ozone depleting potential
OPEX	operation expenditures
ORC	organic Rankine cycle

process streams or boiler feed water.

Several techniques were developed to utilize the heat content of low temperature waste heat sources. Such techniques include a thermo electric generator [10], heat pump [11], Stirling engine [12] and thermodynamic cycles, such as Kalina cycle using ammonia-water solution as working fluid [13]. Chan and his co-authors [14] investigated the utilization of low grade heat by using different techniques, such as chemical heat pump, thermodynamic cycles, including organic Rankine cycle (ORC) and thermal energy storage technologies. The application of ORC is the most common and used reportedly in the following processes: geothermal [15] and solar heat [16] utilization, waste heat recovery in combined heat and power plants (CHP) [17] as well as in small scale bioenergy power plants [18]. Furthermore, ORC can be a promising waste heat recovery technology in the energy intensive industries, e.g. steel processing [19], glass production [20], cement industry [21] and HPI [22].

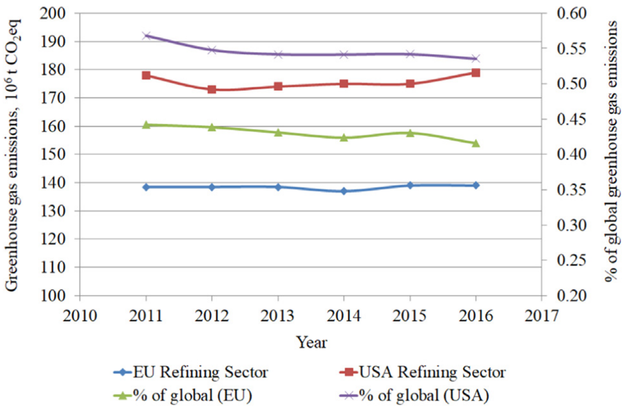

Fig. 1. Change in and contribution of the EU and USA refining sectors to the global GHG emissions.

The proper technical and economical selection of the working fluid of ORC highly depends on the properties of the available waste heat source, e.g. temperature, pressure, problems arising from cross contamination etc. Additionally, the following environmentally damaging properties of the candidate working fluids should also be considered: ozone depleting potential, global warming potential and atmospheric lifetime [23]. In terms of long term operation, the knowledge on thermal and chemical stabilities of the working fluids is inevitable. Dai and co-authors [24] investigated the thermal stability of alkanes and cycloalkanes in supercritical ORC. The results showed that cycloalkanes are not good choices based on thermal stability and long carbon chain hydrocarbons (longer than C_6) are not suitable for supercritical ORCs due to the thermal stability limitation. An apparent chemical kinetics model was developed by using pentane working fluid in a transcritical ORC [25], which gives significant guidance for the working fluid selection and ORC system design.

A number of papers were published dealing with the selection of working fluid for ORC. Siddiqi and Atakan [26] investigated alkanes and aromatics as working fluids at three temperature levels. It was stated that the chain length of the optimum alkane increases with the temperature of the heat source that is available, additionally the advantageous process conditions were also selected by using *T-H* Diagrams. Song and Gu [27] studied the waste heat recovery of a diesel engine by applying cyclohexane, benzene and toluene as working fluid. The authors found that the cyclohexane was the most suitable working fluid. Additionally mixtures of the former with hydrofluorocarbons (R414b and R11) as flame retardant were also investigated. The accomplished exergetic analysis showed that when using a mixture as working fluid, the exergy destruction rates of the evaporator and condenser decrease significantly, which decreases the irreversible loss for the whole ORC system and resulted in an increase in the net power output of the system. Yu and co-workers [28] developed a new method to determine the optimum working fluid and operating conditions simultaneously by using a pinch based method. A newly introduced