Applied Thermal Engineering 70 (2014) 33–41

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

A thermodynamic analysis of waste heat recovery from reciprocating engine power plants by means of Organic Rankine Cycles

Antti Uusitalo*, Juha Honkatukia, Teemu Turunen-Saaresti, Jaakko Larjola

Lappeenranta University of Technology, Institute of Energy Technology, Laboratory of Fluid Dynamics, P.O. Box 20, 53851 Lappeenranta, Finland

HIGHLIGHTS

- Waste heat recovery potential of reciprocating engines was studied.
- Thermodynamic optimization for ORCs was carried out with different fluids.
- The utilization of exhaust gas and charge air heat is presented and discussed.
- Simplified economic feasibility study was included in the analysis.
- Power increase of 11.4% was obtained from exhaust gas and 2.4% from charge air.

ARTICLE INFO

Article history:
Received 3 September 2013
Accepted 28 April 2014
Available online 9 May 2014

Keywords:
Thermodynamic optimization
Waste heat utilization
Organic working fluid
Combined cycle

ABSTRACT

Organic Rankine Cycle (ORC) is a Rankine cycle using organic fluid as the working fluid instead of water and steam. The ORC process is a feasible choice in waste heat recovery applications producing electricity from relatively low-temperature waste heat sources or in applications having a rather low power output. Utilizing waste heat from a large high-efficiency reciprocating engine power plant with ORC processes is studied by means of computations. In addition to exhaust gas heat recovery, this study represents and discusses an idea of directly replacing the charge air cooler (CAC) of a large turbocharged engine with an ORC evaporator to utilize the charge air heat in additional power production. A thermodynamic analysis for ORCs was carried out with working fluids toluene, *n*-pentane, R245fa and cyclohexane. The effect of different ORC process parameters on the process performance are presented and analyzed in order to investigate the heat recovery potential from the exhaust gas and charge air. A simplified feasibility consideration is included by comparing the ratio of the theoretical heat transfer areas needed and the obtained power output from ORC processes. The greatest potential is related to the exhaust gas heat recovery, but in addition also the lower temperature waste heat streams could be utilized to boost the electrical power of the engine power plant. A case study for a large-scale gas-fired engine was carried out showing that the maximum power increase of 11.4% was obtained from the exhaust gas and 2.4% from the charge air heat.

1. Introduction

The environmental impacts of energy production and high fuel prices highlight the demand for developing more efficient and environmentally friendly energy systems. In reciprocating engine power plants, a large proportion of fuel power is not converted into electrical power but is removed from the engine in the form of waste heat. The efficiency of the engine system could be improved by converting these waste heat streams into additional electricity. The conventional steam cycle has been widely used to utilize high-temperature exhaust gas waste heat in different heat recovery and combined cycle applications. However, a steam Rankine cycle does not allow efficient recovery of low-temperature waste heat at temperature levels below ~370 °C [1]. One of the most promising technologies in low-temperature heat utilization is related to Organic Rankine Cycles (ORC). ORC is a Rankine cycle which uses organic fluid as the working fluid instead of water and steam. The main components of a simple ORC are the turbine, evaporator, generator, condenser, and pump. ORC processes are suitable in producing electricity from relatively low-temperature waste heat

* Corresponding author. Tel.: +358 40 583 7741.
E-mail addresses: antti.uusitalo@lut.fi (A. Uusitalo), juha.honkatukia@lut.fi (J. Honkatukia), teemu.turunen-saaresti@lut.fi (T. Turunen-Saaresti), jaakko.larjola@lut.fi (J. Larjola).

http://dx.doi.org/10.1016/j.applthermaleng.2014.04.073
1359-4311/

Nomenclature

Latin alphabet

A	heat transfer area, m^2
P	power output, kW
p	pressure, bar
q_m	mass flow rate, kg/s
T	temperature, °C, K
U	overall heat transfer coefficient, W/m^2 K

Greek alphabet

ε	recuperator effectiveness
η	efficiency
ϕ	heat rate, kW

Subscripts

c	condensing
co	condenser
cr	critical
e	electrical
ev	evaporator, evaporation
fp	feed pump
gm	generator and mechanical
in	inlet
l	liquid
LMTD	Log Mean Temperature Difference
max	maximum
mis	miscellaneous
net	net
out	outlet
pp	pinch-point
re	recuperator
sh	superheating
t	turbine
theo	theoretical
tot	total
v	vapor

Abbreviations

CA	Charge Air
CAC	Charge Air Cooler
EG	Exhaust Gas
ORC	Organic Rankine Cycle

sources and in applications having a rather small power output [1,2,3]. Typical existing ORC applications are geothermal energy, biomass applications, solar energy and the recovery of waste heat [4,5].

The ORC working fluids can be generally divided into three main categories: 1) dry, 2) isentropic, and 3) wet [1,6]. For most of the organic fluids, the expansion process in the turbine occurs in the dry region, and therefore, there is no risk of liquid drops damaging the turbine [6]. Saleh et al. [7] carried out a study using 31 different working fluids for low-temperature ORC processes. They concluded that the superheating of the working fluid does not improve the thermal efficiency of the ORC cycle with fluids having overhanging saturated vapor line in the temperature versus entropy *T,s*-diagram. Thus, the need for superheating should be evaluated based on the working fluid properties and the evaporator type used in the process. In most of the cases, a single-stage turbine can be used because of the low enthalpy drop over the turbine with organic fluids [2]. When using dry fluids, the working fluid temperature after the turbine is relatively high and the working fluid exits the turbine at superheated state. Therefore, a recuperator can be used for preheating the liquid working fluid entering the evaporator with low-pressure vapor exiting the turbine, in order to increase the obtained efficiency of the ORC process [3]. An example of a typical ORC process with the recuperator is presented in Fig. 1 and the principle of a subcritical, superheated and recuperated ORC process is presented on *T,s*-diagram in Fig. 2. According to Figs. 1 and 2, the ORC process can be divided into the following stages: expansion in the turbine (1–2), desuperheating in the recuperator and in the condenser (2–4), condensing in the condenser (4–5), pressure rise in the feed pump (5–6), preheating in the recuperator and in the evaporator (6–8), evaporation (8,9) and superheating (9–1) in the evaporator.

The selection of the working fluid and the selection of the ORC working parameters, as well as the cycle configuration, can be considered as the most important steps in designing ORC systems. Quoilin et al. [8] studied the optimization of a small-scale ORC for waste heat recovery applications, taking into account both the thermodynamic and economic aspects. They concluded that the thermodynamic optimization can be used for evaluating the suitable fluid candidates, but does not necessarily result in the selection of a fluid, that would be the optimal from the economic point of view. Branchini et al. [9] considered six ORC performance

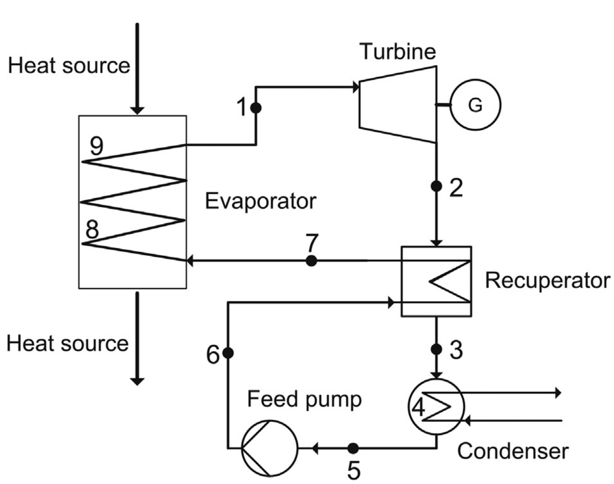

Fig. 1. Example of a typical ORC process with a recuperator.

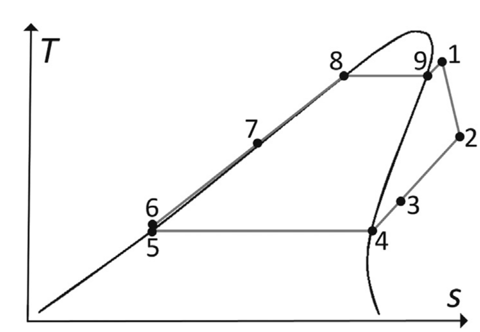

Fig. 2. The principle of a superheated ORC process on *T,s*-diagram.