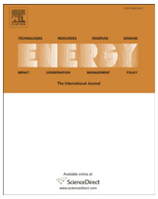
Energy 65 (2014) 91–100

Contents lists available at ScienceDirect

Energy

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



Thermodynamic analysis of an organic Rankine cycle for waste heat recovery from gas turbines

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A R T I C L E I N F O

Article history:
Received 11 April 2013
Received in revised form
18 October 2013
Accepted 29 November 2013
Available online 6 January 2014

Keywords:
Organic Rankine cycle
Gas turbine
Combined cycle
Waste heat recovery

A B S T R A C T

The use of an organic Rankine cycle is a promising choice for the recovery of waste heat at low/medium temperatures. In fact, the low temperature heat discharged in several industrial applications cannot be recovered with a traditional bottomer steam cycle but, using an organic Rankine cycle, this waste heat can be converted into electrical energy. The choice of the fluid is fundamental for a good cycle performance because the optimal thermophysical properties depend on the source temperature. This study illustrates the results of the simulations of an organic Rankine cycle combined with a gas turbine in order to convert the gas turbine waste heat into electrical power. A diathermic oil circuits interposed between these two plants for safety reasons. This paper presents a comparison between four different working fluids in order to identify the best choice. The selected fluids are: toluene, benzene, cyclopentane and cyclohexane. The design is performed by means of a sensitivity analysis of the main process parameters and the organic Rankine cycle is optimized by varying the main pressure of the fluid at different temperatures of the oil circuit; moreover, the possible use of a superheater is investigated for each fluid in order to increase electrical power.

1. Introduction

In the last decades, the global demand for energy has grown steadily and consequently the consumption of fossil fuels has increased. This, in turn, has led to several environmental problems such as air pollution, global warming and the depletion of the ozone layer. Furthermore, according to several studies [1,2], industrial applications waste more than 50% of the total heat generated at a low/medium temperature. In recent years the number of installations of small/medium-sized power plants has increased due to the outsourcing of generation systems. Aeroderivative gas turbines present a high thermodynamic efficiency and a low/medium temperature waste heat and the conversion of low grade waste heat into electrical energy results in a reduction of fossil fuels consumption. The traditional steam bottoming cycles do not perform satisfactorily when waste heat at low/medium temperature is used due to its low thermal efficiency and large volume flows. Other power plant configurations were studied, i.e. Carcasci et al. [3,4] have studied the CRGT (Chemical Recuperated Gas Turbine) cycle. The ORC (organic Rankine cycle) power plant has proved to be an attractive solution, indeed it is one of the most promising technologies for converting low/medium grade heat into electrical power. Thermodynamic analysis and working fluid selection have become the main topics in recent years. Waste heat recovery ORCs have been studied in a number of previous works: Badr et al. [5], Gu et al. [6], Dai et al. [7] used simple thermodynamic models comparing different working fluids. These studies illustrate the reliance of efficiency on the evaporating pressure and some present a parametric optimization and performance analysis of waste heat recovery from low grade sources [7–10]. Advanced cycle configurations have been studied as well: Gnutek et al. [11] proposed an ORC cycle with multiple pressure levels and sliding vane expansion machines in order to maximize the efficiency of the heat source. Chen et al. [12] studied a transcritical CO_2 power cycle. The different use of several ORC bottoming cycles has been analyzed: solar applications [13–15], geothermal heat sources [16,17], high temperature fuel cells [18] and heat recovery from gas turbines. Chacartegui et al. [19,20] showed a parametric optimization of a combined cycle with a gas turbine topping cycle and an ORC low temperature bottoming cycle in order to achieve better integration between these two technologies and they presented a part-load analysis.

Organic fluids are classified into three different categories depending on the slope of their saturation vapor curves in the *T*-*s* diagram: fluids with a negative slope are called “wet fluids”, fluids

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0360-5442/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.energy.2013.11.080

Nomenclature

c	specific heat [kJ/kg K]
L	specific work [kJ/kg]
m	mass flow rate [kg/s]
Mm	molar mass
P	pressure [bar]
Q	heat [kW]
s	entropy [kJ/kg K]
T	temperature [°C]
W	power [kW]
W_{sp}	specific Power [kJ/kg]

Greek symbols

η	efficiency
ρ	density [kg/m^3]

Subscripts

air	air in ambient condition
amb	ambient
app	approach
con	condenser
cr	fluid critical condition
ec	economizer
el	electric
ex	expander
exh	exhaust from gas turbine
fl	organic fluid
gb	gearbox
GT	gas turbine
in	inlet
is	isentropic
lim	limit
max	maximum
oil	oil
opt	optimized
pp	pinch point
pump	pump
rec	reuperator
sat	saturation
s,max	saturation curve with maximum entropy
st	stack
sub	subcooling

Acronyms

CON	condenser
CRGT	chemical recuperated gas turbine
ECO	economizer
EV	evaporator
EX	expander
GT	gas turbine
HRB	hot gas–oil heat recovery boiler
HRSG	oil-fluid heat recovery steam generator
ORC	organic Rankine cycle
REC	recuperator/regenerator
SH	superheater

with a positive slope are called "dry fluids" and fluids whose slope of the saturated vapor curve tends to be infinitive are called "isentropic fluids". Lai et al. [21] and Sahleh et al. [22] presented a detailed review of working fluids for a low and high temperature organic Rankine cycle and cyclopentane seems to be the best answer for a high temperature organic Rankine cycle. Vankeirsbilck et al. [23] showed a high efficiency regenerative cycle based on toluene. According to Chacartegui et al. [19], toluene and cyclohexane present high global efficiency in a gas turbine combined cycle and a low purchase cost of the fluid. Chacartegui et al. [19] analyzed toluene and cyclohexane and concluded these working fluids are a good solution to replace steam in small sized combined cycles. They highlight how an increase in combined cycle efficiency with respect to the steam cycle would compensate for the fluid acquisition. Other works presented some applications based on the use of toluene [24–26]. Victor et al. [27] studied organic Rankine cycles and Kalina cycles for the heat sources at temperatures between 100 °C and 250 °C.

In particular, Carcasci et Ferraro [28] showed that a gas turbine cycle combined with an organic Rankine cycle based on toluene offers the best conditions in a regenerative non-superheated layout and also that a higher value of the maximum oil temperature allows to recover more heat and to produce more power, although this may lead to the formation of acid condensate due to the very low stack temperature. Bianchi et al. [28] described benzene as one of the working fluids with the highest bottoming cycle power and total heat recovery efficiency. Tchanche et al. [29] studied low-temperature solar organic Rankine cycle systems. He et al. [30] studied a subcritical organic Rankine cycle using 22 working fluids for a 150 °C temperature heat source.

In the present paper, four different working fluids have been used to simulate an organic Rankine cycle: toluene, benzene, cyclopentane and cyclohexane. A thermodynamic cycle with a regenerator has been selected and the use of a superheater has been evaluated for each working fluid.

Generally, working fluids used for an organic Rankine cycle are highly flammable, therefore a diathermic oil circuit between the heat source and the ORC is needed to prevent explosions. Common commercial diathermic oils can reach up to 400 °C [32]; thus, in order to determine the influence of the heat transfer recovery on the cycle power output, the cycle is simulated at three different maximum temperatures of the diathermic oil: $T_{\mathrm{oil,max}} = T_B = 360\,^\circ\mathrm{C}$, 380 °C and 400 °C.

Finally, a cycle optimization is presented by varying the expander inlet pressure. The gas turbine considered is the GE10-1 from General Electric – Nuovo Pignone which is a heavy duty single shaft turbine used for oil and gas or power generation applications [33]. The main GE10-1 specifications are shown in Table 1.

2. Working fluids

Four different dry working fluids have been tested: toluene, benzene, cyclopentane and cyclohexane. NIST (National Institute of Standards and Technology) software has been used to simulate the behavior of these working fluids. The thermodynamic properties of the selected fluids are obtained at the critical point values in terms of both pressure and temperature, which are shown in Table 2. The last column illustrates the pressure where the vapor saturation entropy has reached the maximum value. In a plant layout without

Table 1
GE10-1 main specification [33].

W_{GT}	η_{GT}	m_{GT}	T_{GT}
11,250 kW	31.4%	47.5 kg/s	482 °C