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Multi-criteria exergy based optimization of an Organic Rankine Cycle for waste heat recovery in the cement industry

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ABSTRACT

In this study, an Organic Rankine Cycle (ORC) with three different working fluids (cyclohexane, benzene and toluene) is proposed for a cogeneration system used in cement industry. A parametric study is conducted to evaluate the effects of some key parameters on the system performance. The exergy, exergoeconomic and exergoenvironmental analyses of the ORC cycle with considered working fluids are carried out. The multi-objective optimization is performed to achieve the system optimal operating conditions. The optimization considers the exergy efficiency, the cost and the environmental impact per exergy unit of the net produced power as the objective functions.

1. Introduction

The cement plant is identified as one of the energy-intensive industrial sectors with high waste heat recovery potential. It has been estimated that about 40% of total energy consumption in cement production process is transferred to the environment as waste heat [1]. This make the cement sector is one of the major industrial emitters of greenhouse gases [2].

Organic Rankine Cycle (ORC) has been demonstrated to be a promising technology for conversion low-grade heat into power [3]. It is a relatively simple power cycle with high flexibility, in terms of efficient utilization of various heat sources [4]. Therefore, there are a number of publications that report improving in the energy and exergy efficiencies of cement plants thought application of ORC for waste heat recovery (WHR) [1,5].

Recently, the economic criteria are considered for the design and optimization of ORC. For example, an exergoeconomic approach [6] has been successfully used for the analysis and optimization of ORC [7–10]. Exergy analysis has also been combined with environmental assessment in order to improve the ecological performance of energy systems [11]. The so-called exergoenvironmental analysis [12] has already been successfully applied for the evaluation of an integrated ORC for trigeneration. Here, the authors have considered environmental aspects by adding the costs caused by pollutants to the economic costs, however the life cycle of system components was not considered in this work.

Most of the aforementioned studies focus on improving the exergetic and/or exergoeconomic performances of ORC system. As well, there are few studies have been conducted to investigate the environmental performance of this system. It is therefore important to consider energetic, economic and environmental criteria simultaneously in order to exploit full advantages of this system. The objective of the present study is to apply the multi-objective optimization for an ORC for waste heat recovery in the cement plant. Exergy, exergoeconomic and exergoenvironmental performance are considered and three working fluids are selected to achieve the multicriteria optimal design of this system.

2. Waste heat recovery system

The flow diagram of ORC implemented to the exhaust heat recovery in the cement plant is shown in Fig. 1. The temperature of the exhaust gas from the rotary kiln, after preheating and precalcinating the raw material is assumed to be equal to 350 °C [13]. This high temperature waste heat can be utilized via bottoming an ORC, consisting of heat recovery vapor generator (HRVG), turbine, condenser and pump. For safety reasons, an intermediate thermal oil circuit is used in order to transfer the heat from the heat sources to the working fluid within the intermediate heat

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Nomenclature

A	heat transfer area (m^2)
$\dot{B}$	environmental impact rate (Pts/h)
b	environmental impact per unit of exergy (Pts/GJ)
$\dot{C}$	cost rate ($/h)
c	cost per exergy unit ($/GJ)
$\dot{E}$	exergy rate (kW)
h	specific enthalpy (kJ/kg)
M	weight of equipment (kg)
$\dot{m}$	mass flow rate (kg/s)
p	pressure (bar)
T	temperature (°C)
$\dot{W}$	power (kW)
$\dot{Y}$	component-related environmental impact rate associated with LCA (Pts/h)
$\dot{Z}$	capital investment cost rate ($/h)

Abbreviations

HRVG	heat recovery vapor generator
IHE	intermediate heat exchanger
LCA	life cycle assessment
MOPSO	Multi Objective Particle Swarm Optimizer
ORC	Organic Rankine Cycle
WHR	waste heat recovery

Subscripts

0	ambient
$1,2,\ldots,i$	system state points
con	condenser
D	destruction
desup	desuperheater
eva	evaporator
F	fuel
HTF	heat transfer fluid
in	inlet
k	*k*th component
L	loss
out	outlet
P	product
p	pump
pre	preheater
recp	recuperator
sys	system
tur	turbine

Greek letters

η	isentropic efficiency of turbine and pump (%)
ε	exergy efficiency (%)
τ	annual plant operation (h)
ρ	density (kg/m^3)
δ	thickness of a tube (m)
ω	life cycle inventory associated with the production of stainless steel (mPts/kg)

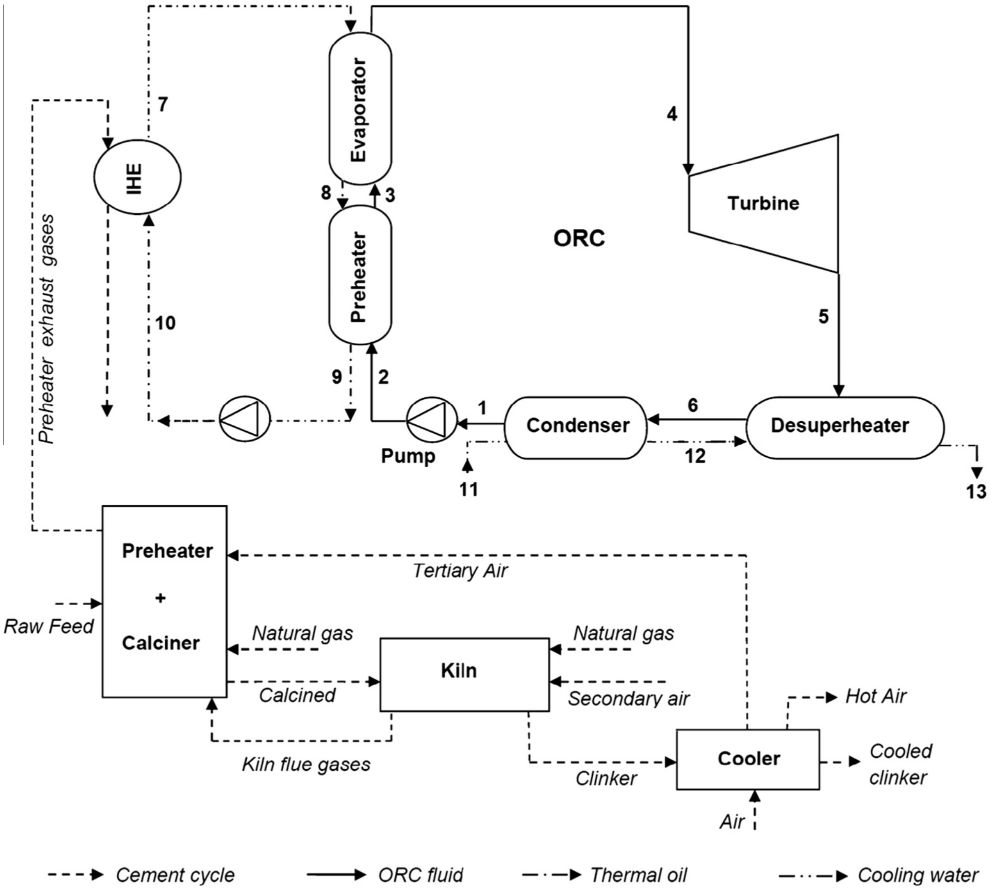

Fig. 1. Flow diagram of an ORC for waste heat recovery in a cement plant.