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Energy and exergy analysis and optimization of Kalina cycle coupled with a coal fired steam power plant

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HIGHLIGHTS

- ► KCS11 can be efficiently coupled with steam power plant for exhaust heat recovery.
- ► In the Kalina bottoming cycle, maximum exergy destruction is found in evaporator.
- ► There is an optimum ammonia fraction at each pressure that gives best performance.
- ► At a moderate pressure of around 4000 kPa, optimum ammonia mass fraction is 0.8.
- ► A flue gas desulphurization unit and Teflon coating required in coal fired plants.

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ABSTRACT

This paper provides a computer simulation of a Kalina cycle coupled with a coal fired steam power plant with the aim of examining the possibility of exploiting low-temperature heat of exhaust gases for conversion into electricity. The numerical model described here has also been used to find the optimum operating conditions for the Kalina cycle. The effect of key parameters namely ammonia mass fraction in the mixture and ammonia turbine inlet pressure on the cycle performance has been investigated. Results indicate that for a given turbine inlet pressure, there is an optimum value of ammonia fraction that yields the maximum cycle efficiency. Increasing the turbine inlet pressure increases the maximum cycle efficiency further corresponding to a much richer ammonia–water mixture. With a moderate pressure of 4000 kPa at ammonia turbine inlet and an ammonia fraction of 0.8, when the exhaust gas temperature is reduced from existing 407.3 K to 363.15 K, the bottoming cycle efficiency reaches a maximum value of 12.95% and a net bottoming cycle output of 605.48 kW is obtained thereby increasing the overall energy efficiency of the plant by 0.277% and the overall exergy efficiency by 0.255%. In the Kalina cycle, maximum exergy destruction was found in the evaporator.

1. Introduction

Power generation industry plays a key role in the economic growth of a country. Therefore, the demand of energy is increasing day by day. Rapid utilization of fossil fuel resources to meet the increasing energy demand is not only causing these resources to diminish faster but also causing the environmental degradation. In view of this, the utilization of low-grade heat for conversion into electricity from sources such as geothermal and the utilization of waste heat from industrial processes, heat from the gasification and combustion of municipal waste, exhaust heat from gas and diesel engines, cement kiln waste heat etc. to improve the efficiency of power generation, have been receiving increasing attention and considerable efforts have also been undertaken in this direction. With the advancement of technology, there is greater interest in designing an efficient, reliable, and cost-effective energy conversion system that will provide a means of utilization of low temperature heat sources which might not otherwise be utilized. Cycles using a binary mixture of ammonia and water as working fluid have interesting characteristics and a high potential for generating electricity from a low-temperature heat source [1]. There are some cycles such as the one developed by Goswami and Xu [2], and Xu and Goswami [3] which not only produce power but also a certain amount of cooling using low temperature heat sources. As far as only the power generation is concerned, the Kalina cycle [4,5] is the best known cycle that uses ammonia–water mixture as working fluid and is capable of generating electricity from a low-temperature heat source very efficiently.

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Nomenclature

a_1, a_2, a_3, a_4	coefficients of Ziegler and Trepp's empirical relations
a_i	constants of Patek and Klomfar correlations
A_1, A_2, A_3, A_4	dimensionless coefficients of Ziegler and Trepp's empirical relations
b_1, b_2, b_3	coefficients of Ziegler and Trepp's empirical relations
B_1, B_2, B_3	dimensionless coefficients of Ziegler and Trepp's empirical relations
c_1, c_2, c_3, c_4	coefficients of Ziegler and Trepp's empirical relations
C_1, C_2, C_3, C_4	dimensionless coefficients of Ziegler and Trepp's empirical relations
$\bar{C}_p$	isobaric molar specific heat (kJ/kmol K)
cw_1, cw_2, cw_3, cw_4	nodal points in the cooling water line of condenser
d_1, d_2, d_3	coefficients of Ziegler and Trepp's empirical relations
D_1, D_2, D_3	dimensionless coefficients of Ziegler and Trepp's empirical relations
ESP	electrostatic precipitator
$\dot{E}_{combustion}$	rate of heat generated during combustion or chemical potential energy (heating value) associated to the fuel (kW)
$E_1, E_2, E_3 \ldots E_{16}$	dimensionless coefficients of Ibrahim and Klein's empirical relations
F_1, F_2, F_3	dimensionless coefficients of Ibrahim and Klein's empirical relations
FC	fuel consumption (kg/year)
$g_1, g_2 \ldots g_7$	nodal points in gas passage
$\bar{g}$	Gibbs free energy (kJ/kmol)
$\bar{g}^e$	Gibbs excess energy (kJ/kmol)
h	specific enthalpy (kJ/kg)
h_0	specific enthalpy at environmental state (kJ/kg)
$\bar{h}$	molar specific enthalpy (kJ/kmol)
$\bar{h}_0$	molar specific enthalpy at environmental state (kJ/kmol)
$\bar{h}^e$	excess molar specific enthalpy (kJ/kmol)
$\dot{H}$	enthalpy (kJ/s)
ID	induced draft
$\dot{I}$	exergy destruction rate (kW)
KCS	Kalina cycle system
$LMTD_c$	log mean temperature difference for the condenser
$LMTD_e$	log mean temperature difference for the evaporator
$\dot{m}$	mass flow rate (kg/s)
m_i	constants of Patek and Klomfar correlations
M	molecular mass
n_i	constants of Patek and Klomfar correlations
p	pressure (kPa)
p_0	actual environmental pressure (kPa)
p_B	constant (=10 bar)
$\dot{Q}$	heat transfer rate (kW)
R	universal gas constant (=8.31451 kJ/kmol K)
s	specific entropy (kJ/kg K)
s_0	specific entropy at environmental state (kJ/kg K)
$\bar{s}$	molar specific entropy (kJ/kmol K)
$\bar{s}_0$	molar specific entropy at environmental state (kJ/kmol K)
$\bar{s}^e$	excess molar specific entropy (kJ/kmol K)
T	absolute temperature (K)
T_0	environmental temperature (K)
T_B	constant (=100 K)
$\bar{v}$	molar Specific volume (m^3/kmol)
$\dot{W}$	work done rate (kW)
$\dot{W}_{net}$	net power output (kW)
x	ammonia mole fraction
x_v	vapour phase mole fraction of ammonia
$\dot{X}$	exergy flow rate (kW)
$\dot{X}_f$	fuel exergy (kW)
$\dot{X}_{heat}$	net exergy transfer by heat (kW)
y	ammonia mass fraction
1.2.3.4 etc.	nodal points

Greek letters

ψ	specific exergy (kJ/kg)
ψ_{Ph}	specific physical exergy (kJ/kg)
ψ_{Ch}	specific chemical exergy (kJ/kg)
ψ^0_{Ch}	standard specific chemical exergy (kJ/kg)
$\bar{\psi}^0_{Ch}$	standard molar specific chemical exergy (kJ/kmol)
η_{Th}	thermal efficiency (%)
η_{ex}	exergy efficiency (%)

Subscripts

A	ammonia
cw_1, cw_2, cw_3, cw_4	for nodal points in the cooling water line of condenser
$g_1, g_2 \ldots g_7$	for nodal points in gas passage
KC	Kalina cycle
mix	mixture
p	pump
r	for reduced properties
RC	Ranhine cycle
t	turbine
w	water
0	for environmental state

Superscripts

g	for gas
l	for liquid
o	for ideal gas

The Kalina cycle is principally a "modified" Rankine cycle [6]. The difference between the two is that the Rankine cycle uses water as working substance whereas Kalina cycle uses binary mixture of ammonia and water. This cycle was developed by Alexander I. Kalina. It was basically designed to replace the commonly used Rankine Cycle as a bottoming cycle for a combined-cycle energy system as well as for generating electricity using low-temperature heat sources. Most of the studies on this cycle have been made by Kalina himself. A number of other investigators have also thermodynamically analysed this cycle [7–12]. Due to its advantages, it has been commercialized at a few places in the world [13–15].

Kalina cycle can be used in a variety of applications ranging from bottoming cycles for gas turbines to providing power from lower temperature waste heat sources [16–23]. The unique feature of all Kalina cycle systems is the use of heat exchanger network theory to recapture as much heat as possible from the turbine exhaust in order to preheat the working fluid prior to its entry into the boiler. A proper optimization of the cycle from thermodynamics point of view, taking into account the influence of various operating parameters on cycle efficiency and generated power, is necessary.

Different versions of Kalina cycle system have been designed that are specifically applicable for different types of heat sources.