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Sensitivity analysis of steam power plant-binary cycle

H. Rosyid [a,*], R. Koestoer [a], N. Putra [a], Nasruddin [a], A.A. Mohamad [b], Yanuar [a]

[a] Department of Mechanical Engineering, University of Indonesia, UI Campus Depok 16424, Indonesia
[b] Department of Mechanical and Manufacturing Engineering, Schulich School of Engineering, The University of Calgary, Calgary, AB, T2N 1N4, Canada

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ABSTRACT

This paper analyses a steam power – two-stage binary cycle plant (SPP–2BCP), in which low temperature waste heat from a conventional steam power plant can be efficiently utilized to generate electricity by installing a bottoming binary cycle. The result from a previous calculation on the installation of binary cycle technology on a Steam Power Plant (SPP) with n-Pentane working fluid indicates an increase in plant efficiency of about 9%. The purpose of this study is to analyze the sensitivity of performance of the binary cycle system against variations in the SPP operational load and the condenser's cooling water temperature. The calculation is conducted on SPP load variations of 25%, 50%, 75% and 100%, inlet turbine pressure variations of 5 bar–30 bar, and inlet turbine temperature variations of 125 °C up to 235 °C. Each of these is also analyzed with ambient cooling water temperatures of 30 °C–37 °C. The results of the analysis indicate that the performance of this binary cycle SPP degrades slightly with SPP load, turbine inlet temperature, and turbine inlet pressure variations and with cooling water variations.

1. Introduction

Currently, the steam power plant capacity in Indonesia is greater than 15 GW. There are plans to increase the capacity of power generation to 30 GW by 2010. Unfortunately, the conventional SPPs built in Indonesia have low efficiency. This is because huge amounts of heat are wasted out of the cycle and emitted to the cooling water system which discharges it as hot water through the condenser. This thermal waste is a potential energy that can be utilized to generate electricity by installing a bottoming binary cycle, which is called a Steam Power Plant–Binary Cycle Plant (SPP-BCP). Combined cycle (SPP-BCP) is employed where a steam power plant (SPP) is available and additional electricity is required. The SPP-BCP operates with two working fluids, such as water- n-Pentane, water-ammonia, water-HCFC123 and water- PF5050 [1,2]. These systems utilize the waste heat produced during SPP electricity generation and allow more efficient energy cascading, which increases the plant efficiency and power output.

Binary cycle technology was introduced in the last two decades in geothermal fields. Low enthalpy Binary cycles, have been used in closed geothermal energy cycles, which are based on the Rankine cycle (ORC). Geothermal binary plants are relatively poor converters of heat into work. The first law thermal efficiencies are typically in the range of 8–12% and exergetic efficiencies of 40% or greater have been achieved in certain plants where the geo fluids have specific exergies of 200 kJ/kg or lower [3–10]. Another cycle using an ammonia/water mixture called Kalina cycle shows a 30–60% higher thermal efficiency [11,12].

Despite the large number of published articles on the ORC and Kalina cycle, most are limited to geothermal heat source applications and none of them present a detailed analysis of the utilization of low heat waste from an SPP to electricity as presented in this paper. Also included here is a new concept to transform the low exergy waste heat, originally discarded by the SPP condenser into cooling water, to a higher exergy by passing this low exergy steam flow into turbine extraction steam, then utilizing the extraction steam as a heat source of the binary cycle in SPP-BCP. The previous studies showed that the plant efficiency of conventional steam power plants can be increased from current levels, that vary from 30% to 35% to over 37% in the SPP-BCP [13,14].

Included in this paper is a detailed analysis for the energetic and exergetic evaluation of the steam power plant two-stage binary cycle (SPP-2BCP), whereas only a single-stage binary cycle without any exergy cascading is discussed in some previous publications. An evaluation of the performance and sensitivity of the SPP-2BCP system against variations in the SPP operational load and the condenser's cooling water temperature, as well as turbine inlet temperature, turbine inlet pressure, and partial loading on the system, is also presented. A detailed thermodynamic analysis for the plant components of a binary cycle plant is developed and discussed. The steam cycle is not described in this analysis because it has already been discussed in previous research [13–16]. The

* Corresponding author.
E-mail address: harun.rosyid@ui.ac.id (H. Rosyid).

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Nomenclature

$\dot{E}_x$	Exergy rate (kW)
$\dot{E}_{xdest}$	Rate of exergy destruction (kW)
$\dot{E}_{xheat}$	Rate of exergy transfer by heat (kW)
h	Enthalpy (kJ/kg)
$\dot{m}$	Mass flow rate (kg/s)
$\dot{Q}$	Rate of heat transfer (kW)
s	Entropy (kJ/kg K)
T	Temperature (K)
T_0	Environment temperature (K)
w	Specific work (kJ/kg)
$\dot{W}$	Power (kW)
w_{rev}	Specific reversible work (kJ/kg)

Greek Symbols

η	Energy efficiency
η_{turb}	Turbine isentropic efficiency
η_{pump}	Pump isentropic efficiency
ε	Exergy efficiency
ψ	Specific flow exergy (kJ/kg)

Abbreviations

BLR	Boiler
CD	Condenser
EV	Evaporator
DEA	Deaerator
CWP	Circulating water pump
CS	Cooling system
FWP	Feed water pump
PH	Preheater
P	Pump
T	Turbine
CD	Condenser

Subscripts

BF	Brute
FUNC	Functional
des	Destroyed
exc	Exchanger
gen	Generated
a	Actual
n-C5	n-Pentane
t	Total
w	Water
s	Isentropic
0	Dead state
1,2,	State points
i	In
e	Exit

energy and exergy analysis was produced by using some parameters from the operation of a typical 100 MW SPP in Indonesia, specifically the existing Gresik SPP 2 × 100 MW located in East Java. The site layout of this SPP is shown in Fig. 1

2. System descriptions and the energy & exergy analysis

The steam power plant two-stage binary cycle plant (SPP–2BCP) operates with two working fluids, water for the SPP and n-Pentane for the two-stage binary cycle. The objective of the operation process of the binary cycle is to transfer part of the steam exergy flow, originally discarded by the SPP condenser into cooling water which has low exergy values, into turbine extraction steam in order to increase its exergy. Then the turbine extraction steam is channeled into a binary cycle n-Pentane evaporator (hot side) with n-Pentane working fluid (cool side). N-Pentane vapor, with higher pressure from an n-Pentane evaporator, is put into an n-Pentane nozzle of the turbine, which produces kinetic energy that is converted into electricity.

In a two-stage binary cycle as shown in Fig. 2, the binary cycle of stage-1 (medium pressure) consists of an n-Pentane evaporator −1, an n-Pentane turbine, a generator, an n-Pentane condenser, an n-Pentane pump and a cooling water pump. The main components of the binary cycle of stage-2 (low Pressure) are an n-Pentane evaporator, an n-Pentane turbine, a generator, an n-Pentane condenser, an n-Pentane pump and a cooling water pump. The n-Pentane vapor of higher pressure from the n-Pentane evaporator of stage-1 is injected into the n-Pentane nozzle of the turbine of stage-1 while the n-Pentane vapor of lower pressure is injected into the low-pressure n-Pentane turbine.

Some assumptions used in this study are:

- The SPP-2BCP system operates under steady state conditions.
- Changes in potential and kinetic energy are neglected.
- Temperatures and pressures of environmental conditions (dead state) are taken from actual ambient conditions. The dead state condition is assumed to be $P_0 = 1$ atm and $T_0 = 25\,°C$.
- Kinetic exergy, potential exergy, and chemical exergy are neglected.
- The heat and friction losses are also neglected.
- The pumps and turbine isentropic efficiencies are 80%.
- The n-Pentane at condenser exit is a saturated liquid.

2.1. The energy and exergy balances

The energy and exergy balances for a flow process in a system during a specified time-interval:

$$\text{Energy input} - \text{energy out} = \text{Energy accumulation} \quad (1)$$

$$\text{Exergy input} - \text{Exergy output} - \text{Exergy Consumption} = \text{Exergy accumulation} \quad (2)$$

The above equations describe an important difference between energy and exergy. Energy is a conservative quantity, while exergy decreases because of irreversibility associated with the system. Exergy defines the quality of energy and in any actual process it will not be conserved but will be destroyed. The balance of mass and the energy and exergy conservation equations for a steady state system can be written as follows:

$$\sum \dot{m}_i = \sum \dot{m}_e \quad (3)$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \quad (4)$$

$$\dot{E}x_{heat} + \dot{W} = \sum \dot{m}_e \psi_e - \sum \dot{m}_i \psi_i + \dot{E}x_{dest} \quad (5)$$

where $\dot{Q}$ and $\dot{W}$ are heat and work inputs, $\dot{m}$ is the mass of flow of fluid, h is enthalpy, ψ is specific flow exergy which is defined as Specific flow exergy $(\dot{E}_x/\dot{m})$, subscript i and e are incoming and outgoing positions, respectively, $\dot{E}x_{dest}$ is the amount of exergy destroyed. $\dot{E}x_{heat}$ is the net exergy transferred from heat at a temperature of T, which is expressed as