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Original article

Novel and concise approach to thermodynamic and techno-economic optimization – A regenerative plant study

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ABSTRACT

The applicability of a concise optimization methodology in thermodynamic and techno-economic optimization of a power generating plant is examined. The case study regenerative plant is optionally coupled to an auxiliary heat supply source (for instance, CSP panels): the influence of the fundamental variables on thermal efficiency, cost profile and power generation is investigated. Notably, the classical thermal efficiency index which shows inconsistency in differentiating between optimal and suboptimal power generation operations is compared with the power-energy quantity ratio (PQR), an index of optimal operation, which gives an indication of the value of the objective variable for which optimal operation is possible. From the result, the thermal efficiency index is inadequate to differentiate between optimal and sub-optimal thermal operations in the plant, while the PQR congruently indicates the point of optimal power production.

Introduction

The aim of this study is to present a method of thermodynamic and techno-economic optimization of power generating plants in a form that consolidates and simplifies the analysis of data on heat-work interaction of the plant components. The case study plant is a regenerative rankine plant. A good number of studies incorporate diverse techniques of optimization however they do not give a holistic profile of the operational dynamics of a power plant embodying simplified models, which are desirable in practical operating environments.

A number of studies on optimization of power plants have been undertaken. Valdés et al. [1] conducted a study on thermoeconomic optimization of combined cycle gas turbine power plants using genetic algorithms. Two different objective functions were suggested: one minimizes the cost of production per unit of output and the other maximizes the annual cash flow. Data from both functions were compared in order to find the better optimization strategy. Desidieri and Bidini [2] investigated a number of possible optimization criteria for geothermal power plants. The obtained results showed that there is a prospect for optimization of the performance, by modifying the main parameters, such as turbine inlet pressure, and type of fluid. Badr et al. [3] simulated the performance of Rankine-cycle power-plants, which used steam as the working fluid, and developed a BASIC program to facilitate the prediction for optimal design of Rankine-plants in varying operating conditions. Kapooria [4] conducted a study into rankine cycle plant, and observed that the efficiency can be improved by using intermediate reheat cycle. Ho et al. [5] compared the Organic Flash Cycle (OFC) to other advanced vapor cycles for intermediate and high temperature waste heat reclamation and solar thermal energy applications, and found that aromatic hydrocarbons are better suited as working fluids in Organic Rankine Cycles (ORC) and OFC due to their higher power output, and require less complex turbine designs. Chen et al. [6] reviewed the Rankine and supercritical Rankine cycles for the conversion of low-grade heat into electrical power, and concluded that the thermodynamic and physical properties, stability, environmental impacts, safety, compatibility, availability and cost are important considerations for selecting a working fluid. Geete and Khandwawala [7] obtained correction curves for power output on account of conflicts between actual and predicted output value for a 120 MW thermal power plant. Also, Jamal [8] conducted a comparative study into working fluids of Organic Rankine Cycles – ORC. It was determined that the temperature profile in the evaporator and condenser is of key importance to the exergy losses, and best energy utilization.

There are also a variety of studies on optimization techniques into various thermal plant processes. Wang et al. [9] undertook a study on thermodynamic analysis and optimization of an ORC using low grade heat source, and obtained a ratio of net power output to

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Nomenclature

Q	heat (kJ/kg)
h	enthalpy (kJ/kg)
P_t	turbine (Generated) power (W)
W	work (kJ/kg)
E	power (W)
s	entropy (kJ/kg)
P	pressure (Pa)
T	temperature (W)
υ	specific volume (m^3/kg)
W	work (kJ/kg)
E	power (W)
s	entropy (kJ/kg)
S_{gen}	entropy generation (kJ/kgK)
m	mass fraction
$\dot{m}$	mass flow rate (kg/s)
ΔE_{system}	energy difference (kJ/kg)
Δke_s	potential energy difference (kJ/kg)

Subscripts

boil.	boiler
cond.	condenser
dest	destroyed
p	pump
t	turbine
out	outlet
source	pump
sink	pump
e	temperature (W)
in	in
i	intermediate
reg.	regenerator
sup .	superheater

Symbols

0	destroyed
η	efficiency
b, in	system boundary, in
b, out	system boundary, out

total heat transfer area as the performance evaluation criterion. Roy and Misra [10] conducted a parametric optimization and performance analysis of a regenerative Organic Rankine Cycle using R-123 for waste heat recovery, and developed a computer program to parametrically optimize and compare the system performance. Other relevant studies include this given in Refs. [11–20].

The above studies incorporate diverse techniques of optimization however they do not give a holistic an approach of profiling the operational dynamics of a power plant, which is desirable in practical operating environments. The object of the study is to present a method of thermodynamic and techno-economic optimization of the power generating plant; evaluating the influence of the fundamental variables on thermodynamic performance; more so, the required thermodynamic measures necessary to improve optimal operating condition.

Cycle description

In Fig. 1, the regenerative rankine plant is shown. Fig. 2 shows schematically the components of the plant, considering the stand-alone operation in which there is no axillary heat input – an operational mode in which the energy input to the boiler is supplied by means of a gas heating or concentrated solar power (CSP) technology – this will facilitate the determination of the influence of the thermodynamic variables on performance. Fig. 3 shows the temperature-entropy (T-s) diagram of the regenerative rankine cycle. The main components of the plant consist of a boiler/vaporizer, the superheater, turbine, condenser, regenerator and a pump.

Thermodynamic analysis

Analyzing the rankine plant as a steady state flow process [21], the changes in kinetic and potential energy are negligible in the working fluid (steam) relative to the work and heat transfers quantities. The steady-state flow mass and energy equations per unit mass of steam can be written as

$$\overset{o}{Q} - \overset{o}{W} = \sum_{out}(\overset{o}{m}h) - \sum_{in}(\overset{o}{m}h) \quad (1)$$

The general exergy balance for a steady flow system is given by [21]

$$\overset{o}{Q} - \overset{o}{W} = T^o\left(\sum_{out}\dot{m}s + \frac{\dot{Q}_{out}}{T_{b,out}} - \sum_{out}\dot{m}s + \frac{\dot{Q}_{in}}{T_{b,in}}\right) \quad (2)$$

on per unit mass basis for single inlet, exit, steady flow process [14]

$$\chi_{dest} = T^o S_{gen} = T^o\left(S_e - S_i + \frac{\dot{q}_{out}}{T_{b,out}} - \sum_{out}\dot{m}s + \frac{\dot{q}_{in}}{T_{b,in}}\right) \quad (3)$$

where S_{gen} is the generated entropy, $T_{b,in}$ and $T_{b,out}$ are the temperatures of the system boundaries in which heat is transferred. The exergy destruction for a cycle with high- and low-temperature reservoirs on per unit mass basis is expressed as [21]

$$\chi_{dest} = T^o S_{gen} = T^o\left(\sum_{out}\frac{\dot{q}_{out}}{T_{b,out}} - \sum_{out}\frac{\dot{q}_{in}}{T_{b,in}}\right) \quad (4)$$

Considering source and sink temperatures in the cycle, the equation reduces to [21]

$$\chi_{dest} = T^o S_{gen} = T^o\left(\frac{\dot{q}_{out}}{T_L} - \frac{\dot{q}_{in}}{T_H}\right) \quad (4)$$

where T_L and T_H are the source and sink temperatures, respectively. For a fluid stream ψ, the exergy at any state of the fluid can be determined from [21]

$$\psi = (h - h_o) - T^o(h - h_o) + \frac{v^2}{2} + gz \quad (5)$$

where is h the enthalpy, v is the velocity and T is the temperature, "0" denotes the state boundaries. The thermal efficiency gives an indication of the energy conversion potentials, from heat to mechanical work; the rankine efficiency is given by

$$\eta_{th} = \frac{W_{net}}{\sum Q_{in}} = \frac{Q_{in} - Q_{out}}{\sum Q_{in}} \quad (6)$$

Importantly, the above equations are applied to the thermal nodes in the cycle (Fig. 3) which reference the thermodynamic state functions as such conservation laws are maintained. Assuming adiabatic conditions for the turbine, consequently

$$E_{in} - E_{out} \rightarrow \sum_{in}\dot{m}h = \sum_{out}\dot{m}h \quad (7)$$