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Thermodynamic performance optimization of a combined power/cooling cycle

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ABSTRACT

A combined thermal power and cooling cycle has already been proposed in which thermal energy is used to produce work and to generate a sub-ambient temperature stream that is suitable for cooling applications. The cycle uses ammonia–water mixture as working fluid and is a combination of a Rankine cycle and absorption cycle. The very high ammonia vapor concentration, exiting turbine under certain operating conditions, can provide power output as well as refrigeration. In this paper, the goal is to employ multi-objective algorithms for Pareto approach optimization of thermodynamic performance of the cycle. It has been carried out by varying the selected design variables, namely, turbine inlet pressure (P_h), superheater temperature ($T_{superheat}$) and condenser temperature ($T_{condensor}$). The important conflicting thermodynamic objective functions that have been considered in this study are turbine work (w_T), cooling capacity (q_{cool}) and thermal efficiency (η_{th}) of the cycle. It is shown that some interesting and important relationships among optimal objective functions and decision variables involved in the combined cycle can be discovered consequently. Such important relationships as useful optimal design principles would have not been obtained without the use of a multi-objective optimization approach.

1. Introduction

The world demand for energy is expected to increase continuously. Moreover, pollution caused by the exhaust emissions has become of primary significance. Therefore, applying more efficient energy conversion processes are necessary to minimize the negative environmental impact of utilizing energy resources. Thermodynamic power cycles are the basis for the operation of heat engines, which supply most of the world's electric power. There are several possible thermal power cycles which can be classified based on their working fluid, such as vapor power cycles and gas power cycles. In a vapor power cycle, the gas that spins the turbine is obtained from vaporizing a liquid. In a gas power cycle, such as a Brayton cycle, the working fluid is in a gaseous state throughout the cycle.

A development in the search for higher overall energy conversion efficiency of conventional power cycles has been the introduction of combined-cycle plants. Another recent improvement in thermal power cycles is based on using mixed working fluids. Kalina is recognized for introducing the use of ammonia–water mixture as the working fluids in the bottoming cycle of a combined power plant [1,2]. Since that time, many efforts have been made to use the ammonia–water mixtures in power cycle applications [3–5].

A topic of recent interest is the idea of combined power and cooling cycles that use an ammonia–water working fluid. The cycle was originally proposed by Goswami and coworkers [6] and is intended primarily for power production while producing a cooling output simultaneously. The cycle is a combination of the Rankine cycle and an absorption refrigeration cycle. A binary mixture of ammonia and water is partially boiled to produce vapor rich ammonia. This vapor is further enriched in a rectifier/condenser and after superheating expanded through a turbine. The vapor leaving the turbine in this cycle is cold enough to extract refrigeration output [7]. The use of volatile component such as ammonia allows vapor to be formed at high enough pressure that is useful for power generation. Moreover, it is suitable for the use of low temperature finite heat sources such as heat from solar collectors and geothermal heat.

Optimization in engineering design has always been of great importance and interest particularly in solving complex real-world design problems. Basically, the optimization process is defined as finding a set of values for a vector of design variables so that it leads to an optimum value of an objective or cost function. In such single-objective optimization problems, there may or may not exist some constraint functions on the design variables and they are respectively referred to as constrained or unconstrained optimization problems. There are many calculus-based methods including gradient approaches to search for mostly local optimum solutions and these are well documented in [8]. However, some basic difficulties in the gradient methods such as their strong dependence

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Nomenclature

x	ammonia mass fraction, –
q_{cool}	cooling capacity, kg/kJ
h	enthalpy, kg/kJ
s	entropy, kJ/kg K
G	Gibbs free energy, kg/kJ
P	pressure, bar
υ	specific volume, m^3/kg
T	temperature, K
η_{th}	thermal efficiency, –
w_T	Turbine work output, kg/kJ

Superscripts and subscripts

a	ammonia
b	bubble point
c	critical
CW	critical water
d	dew point
E	excess energy
g	gas state
L	liquid state
m	mixture property
mix	mixture state
0	ideal gas state
r	reduced property
B	reference value for reduced property
w	water state

Dimensionless group

$h_r = h/RT_B$ reduced enthalpy
$S_r = S/R$ reduced entropy
$G_r = G/RT_B$ reduced gas free energy
$P_r = P/P_B$ reduced pressure
$T_r = T/T_B$ reduced temperature
$\upsilon_r = \upsilon/RT_B$ reduced specific volume

on the initial guess can cause them to find a local optimum rather than a global one. This has led to other heuristic optimization methods, particularly genetic algorithms (GAs) being used extensively during the last decade. Such nature-inspired evolutionary algorithms differ from other traditional calculus-based techniques. The main difference is that GAs work with a population of candidate solutions, not a single point in search space. This helps significantly to avoid being trapped in local optima as long as the diversity of the population is well preserved. In multi-objective optimization problems, there are several objective of cost functions (a vector of objectives) to be optimized (minimized or maximized) simultaneously. These objectives often conflict with each other so that as one objective function improves, another deteriorates. Therefore, there is no single optimal solution that is best with respect to all the objective functions. Instead, there is a set of optimal solutions, well-known as Pareto optimal solutions [9,10], which distinguishes significantly the inherent natures between single-objective and multi-objective optimization problems. The concept of a Pareto front in the space of objective functions in multi-objective optimization problems (MOPs) stand for a set of solutions that are non-dominated to each other but are superior to the rest of solutions in the search space. Evidently, changing the vector of design variables in such Pareto optimal solutions consisting of these non-dominated solutions would not lead to the improvement of all objectives simultaneously. Consequently, such change leads to a deterioration of at least one objective to an inferior one. Thus, each solution of the Pareto set includes at least one objective inferior to that of another solution in that Pareto set, although both are superior to others in the rest of search space. The inherent parallelism in evolutionary algorithms makes them suitably eligible for solving MOPs.

In thermal systems, like many other real-world engineering design problems, there are many complex optimization design problems [11] which can also be multi-objective in nature. The objectives in thermal systems are usually conflicting and non-commensurable and thus Pareto solutions provide more insights into the competing objectives [12,13]. Most of the studies on different configuration of thermal power and cooling systems, referred in this section, have been focussed on analytical performance of the cycles. Recently, Sadrameli and Goswami published the results of their work on optimum operating conditions of the combined cycle. In their work the cooling production was used as the only objective function for the optimization purposes [14]. The present study is centered on multi-objective optimization as this may provide a complement in this field.

In this paper a combined cooling and power cycle, proposed by Goswami and coworkers [6], is considered for optimization purposes. In this investigation, a method that combines the Gibbs free energy method for mixture properties and bubble and dew point temperature equations for phase equilibrium is used to evaluate thermodynamics properties of binary working fluid (ammonia–water) at different pressures, temperatures and ammonia mass fractions [15]. The main goal of this work is then to perform multi-objective thermodynamic optimization of the proposed cycle. In this way, three optimal set of design variables in the cycle, namely, turbine inlet pressure, superheater temperature and condenser temperature are found using a Pareto approach to multi-objective optimization. Turbine work, cooling capacity and thermal efficiency of the system are first thermodynamically modeled to determined objective functions. Finally, Pareto-based optimization approach is employed to find the best possible combination of cycle outputs known as Pareto fronts.

2. Thermodynamic properties of ammonia–water mixture

In this section, a method which combines the Gibbs free energy method for the mixture properties and bubble and dew point temperature equations for phase equilibrium is used to find the thermodynamic properties of the ammonia–water mixture. The method was first introduced by Xu and Goswami [15]. They showed an excellent agreement with the experimental data. A brief description of the applied method is given in the following.

2.1. Gibbs free energy equation for a pure component

The Gibbs free energy of a pure component is given by

$$G = h_0 - T_{S_0} + \int_{T_0}^{T} C_p\, dT + \int_{p_0}^{p} \upsilon\, dP - T\int_{T_0}^{T}\left(\frac{C_p}{T}\right)dT \quad (1)$$

where h_0, S_0, T_0 and P_0 are the specific enthalpy, specific entropy, temperature and pressure at the reference state respectively. Using the empirical relations for υ and C_p [16] in Eq. (1) and integration leads to the following equations.