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Thermoeconomic operation optimization of a coal-fired power plant

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ABSTRACT

Thermoeconomic models, which combine the concept of cost in the field of economics and the concept of exergy in the field of thermodynamics, provide a possibility of optimizing complex energy-generating systems to achieve a best balance between thermodynamic efficiency and economic cost (including investment cost and operation cost). For the first time, operation optimization on a 300 MW coal-fired power plant located in Yiyang (Hunan Province, China) is accomplished based on the structure theory of thermoeconomic. Two optimization strategies, global optimization and local optimization, are successively realized on the power plant. Both strategies aim to minimize the total annual cost of the plant, and a 2.5% reduction in the total annual cost and a 3.5% reduction in the total investment cost are achieved. In addition, the costs of products of almost all units after optimization processes decrease obviously. It is worth noting that local optimization proposed in this paper attains almost the same performance as global optimization but with faster speed. Furthermore, sensitivities of optimal operation parameters with respect to external environmental parameters and the sensitivity of the objective function (the total annual cost) with respect to decision variables (e.g., the equipment efficiency) are presented.

1. Introduction

An optimization work could be briefly defined as the process of finding the values of variables that minimize (or maximize) objective functions. For different optimization objects, an optimization work of an energy-generating system can be considered at three levels: synthesis optimization, design optimization as well as operation optimization [1]. In this paper, the optimization is at the operation level. In this sense, the synthesis and design of a system are known and fixed.

The conventional thermodynamic optimization process of an energy-generating system usually focuses on the energy saving or exergy saving. This kind of optimization has many drawbacks: (1) an increase of the efficiency or a decrease of the irreversibility of the system will lead to a decrease of fuel consumption. However, this is generally achieved with a corresponding increase of the investment cost. Thus it is difficult to reach a balance between thermodynamics and economics; (2) such optimization is usually based on the first and second laws of thermodynamics [2] (i.e., the conversation law of energy and the irreversibility of exergy). As known, the same amount of energy in different thermal devices may have quite different amounts of exergy and therefore quite different economic values. Thermodynamic optimization is thus unable to differentiate the complex relationship among energy, exergy and cost. A combination of economic analysis and thermodynamic optimization is one of the ways to overcome these difficulties inherent in conventional methods.

Thermoeconomics achieves the goal by combining the concepts of cost [3–5] (an economic property) and exergy (an energetic property), both having the characteristics of scarcity and dissipation. El-Sayed and Evans [6,7] introduced thermoeconomic optimization in 1970 for the first time. Several kinds of thermoeconomic optimization methods were then developed by different researchers. A famous project about thermoeconomic optimization is the CGAM project (1993) [8], which was led by C. Frangopoulos (Thermoeconomic Functional Analysis) [9], G. Tsatsaronis (Exergy - costing) [10], A. Valero (exergetic cost theory) [11] and M. Von Spakovsky (Engineering Functional Analysis) [12]. These four research groups used their own methodologies to solve a predefined problem, for example, optimizing a gas turbine cogeneration cycle (CGAM system) consisting of an air compressor, a regenerative air pre-heater, a combustion chamber, a gas turbine and a heat-recovery steam generator (HRSG). The final goal of the CGAM project was the unification of the different methodologies. The structural theory of thermoeconomics [13,14], developed from the exergetic cost theory, finally unified previous research works. It

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Nomenclature

Abbreviations

B-SH	Boiler and Super-heater
BFPT	Feed Water Pump Turbine
CND	Condenser
CP	Condenser Water Pump
CWP	Circle Water Pump
DTR	Deaerator
FWH	Feed Water Heater
FWP	Feed Water Pump
GEN	Generator
GO	Global Optimization
HP, IP, LP	High Pressure, Intermediate Pressure and Low Pressure Turbine
HRSG	Heat Recovery Steam Generator
LO	Local Optimization
QP	Quadratic Programming
RH	Re-Heater
SQP	Sequential Quadratic Programming
TTD	Terminal Temperature Difference

Scalars

c_p, c_F	Unit thermoeconomic cost of the product, fuel ($/kJ)
f	Annual capital recovery factor
F, FB, P	Fuel and Product exergy of a unit (kW)
h	Enthalpy (kJ/kg)
H	Operation hours per year (h)
k, kB, kW	Unit exergy consumption, technical production coefficient
kS	Unit negentropy consumption
kZ	Unit amortization cost
m	Number of decision variables
n	Number of units
r	Junction or exergy ratio
s	Entropy (kJ/kg K)
T	Temperature (°C)
W	Mechanical or electrical power (kW)
x	Decision variable
y	Dependent variable
Z, Z_L	Investment cost ($), Amortization cost ($/s)

Matrices and vectors

$\langle \mathbf{KP} \rangle$	Matrix ($n \times n$) of unit exergy consumption
$\mathbf{P}$, $\mathbf{P}_s$	Product vectors ($n\times1$), final product vector ($n\times1$)

Greek letters

ε	Change rate, ratio
ω	Final products of the system
η	Efficiency
Δ	Increment
Γ	Objective function
ξ	Amortization factor (1/s)
ϕ	Maintenance factor

Subscripts

0	Ambient conditions
net	Net output
e	Number of inlet flows of the system

Superscripts

0	Initial status
*	Optimal status

provided a standard and common mathematical formulation for thermoeconomics. In this paper, the structural theory of thermoeconomics is adopted for optimization.

In addition to the systems considered in the CGAM project (especially the HRSG [15–21]), many other systems, such as heat exchangers [22–25], refrigerator systems [26–30], nuclear power generation systems [31–33], fuel cell–gas turbine power plants [34], gas turbine-based dual-purpose power and desalination plants [35], heat-pump cycle [26,36], and absorption chiller systems [37] were optimized by using different thermoeconomic optimization methodologies. Most of the optimization works mentioned above belong to design optimization.

There is few reference on the detailed (high disaggregation level) thermoeconomic optimization of an actual coal-fired power plant. To the best of our knowledge, there is only one similar work on a dual-purpose power and desalination plant by Uche [38], where global optimization of the system is performed based on separated local optimizations of different plant units, such as boiler, turbine as well as multi-stage flash. As known, in China over 70% of the total energy is supplied by coal-fired power plants. As a result, coal-fired power plants have become main emission sources of pollutants such as SO_x, NO_x, particulate matter and CO_2. Thus thermoeconomic optimization on coal-fired power plants is necessary and important in the advent of increasing requests on cost saving, efficiency improving and meeting the requirement of pollutant emission control. In this paper, thermoeconomic optimization work is performed on an actual 300 WM pulverized coal-fired power plant located in Hunan province, China.

The optimization strategies employed in the literature are usually local optimization (LO) or global optimization (GO). In the GO process, a global objective function and all constraints are considered together. It is very precise (as a benchmark) but complicated (time-consuming). In the LO process, units are optimized one at a time, though this does not imply that a unit is only influenced or restricted by its own decision variables. Several decision variables may influence a single unit, and at the same time, a single decision variable may influence several units [15]. That is because the whole system is complicated and units may be related to each other. Consequently, LO is fast but may not be very accurate if the objective function selected for each unit is not appropriate. Some system decomposition methods, such as thermoeconomic isolation principle [39], were presented to appropriately decompose the whole system into several blocks hoping to have little interactions among the blocks (or units). However, it is difficult for a complex energy system to meet the isolation conditions. Furthermore, optimization of one unit may affect the states of other units (even an optimal state). In this situation, the global objective function may fluctuate with the optimization process, and convergence may be slow. Therefore, in order to validate some thermoeconomic optimization methods on a complex energy system and search for a method with a high accuracy and calculation speed, in this paper, GO and LO were performed on the power plant as described in Section 3, based on the thermoeconomic modeling of a coal-fired power plant presented in Section 2. Sensitivity analysis of the optimization results is presented in Section 4. This paper is the last in a series of three on the investigation of the coal-fired power plant from the thermoeconomic point of view. The first paper [40] provided a detailed exergy cost analysis for cost formation as well as the effects of different operating conditions and parameters on the performance of individual units. The second paper [41] established a progressive separation procedure for diagnosis based on structural theory and symbolic thermoeconomics.

2. Thermoeconomic modeling of a coal-fired power plant

2.1. Thermodynamic modeling

We developed a simulator for thermodynamic modeling of a 300 MW pulverized coal-fired power plant [40] whose schematic is presented in Fig. 1. The water/steam cycle is mainly considered in the simulation. In the simulator, a set of nonlinear algebraic equations for mass and energy flows of water/steam and other stream in different devices is solved by using the Powell hybrid method [42]. The Powell hybrid method is a global method that provides better convergence of the system of equations than solving them sequentially. It calculates the Jacobian by a forward difference formula and utilizes a relaxation technique to update values in a new iteration. The maximum relative error for each variable between two consecutive iterations is set to be lower than the specified tolerance 10^{-5}. The thermodynamic simulator can reproduce cycle behaviors for different operating conditions with relative errors less than 2% [40]. It is capable of offering reference conditions needed for thermoeconomic optimization.

2.2. Thermoeconomic modeling

A simple thermodynamic model is not sufficient for the complete analysis of the behaviors of the plant. As shown in the Fig. 1, there are 20 physical devices and 47 mass (energy) flows. Each device has its own productive purpose, such as steam for the boiler and power for the generator. The productive purpose of a process device measured in terms of exergy is named as "product"; and the consumed exergy flow to create the product is "fuel" [43]. Thus, a set of higher-level relationships derived from the productive purpose of each device could be defined. When using the Fuel-Product concept to describe the system, the physical flows of each device in the model can be classified into product or fuel based on the functionality of each device. Thus the model can be converted into the productive structure (also called Fuel/Product diagram), which is a graphical representation of resource distribution throughout the plant. The productive structure diagram for the power plant is presented in Fig. 2. HP (High Pressure) and IP (Intermediate Pressure) all have two stages, and LP (Low Pressure) has five stages.

The productive structure is composed of physical "plant units" (combined or disaggregated from devices in the physical model of the plant) represented by squares as well as two types of fictitious units represented by rhombuses (junctions, J) and circles (bifurcations, B). The lines with solid arrows are exergy resources (fuels and products). The F inlet arrows going into squares are the fuels of the corresponding units and P outlet arrows represent the products. The N arrows represent the negentropy [40,44], product of the condenser, consumed in each unit. From a thermodynamic point of view, the condenser is a dissipative unit. Its function allows the working fluid to reach the physical conditions to perform a complete thermodynamic cycle.

The thermoeconomic model is formed by a set of "characteristic equations" [44,45], which relate each inlet flow to outlet flows and internal parameters that depend only on the behaviors of relevant subsystems. The characteristic equations of the plant ($F_i = g_i(x_i, P_i)$) were presented in [40] and can be rewritten in the matrix form as [46]:

$$\mathbf{P} = \mathbf{P}_S + \langle \mathbf{KP} \rangle \mathbf{P}, \tag{1}$$

or in the scalar format as:

$$P_i = \omega_i + \sum_{j=1}^{n} k_{ij} P_j, \tag{2}$$

where $\mathbf{P}$ is an $n \times 1$ vector whose elements contain the product of each unit (P_i); $\mathbf{P}_S$ an $n \times 1$ vector whose elements contain the final production of the system (ω_i); $<\mathbf{KP}>$ an $n \times n$ matrix (also called unit exergy consumption matrix) whose elements contain the unit exergy consumption (k_{ij}) where k_{ij} represents the portion of the ith unit production needed to get a unit of the jth unit production. The matrix $<\mathbf{KP}>$ quantifies the productive interactions among units and plays a key role in the thermoeconomic analysis and diagnosis [41,46]. In detail, k_{ij} has three forms—kB, kS and kW, which are the specific expression of k_{ij} relates to exergy, negentropy and work, respectively. After solving the characteristic equations, the amount of exergy consumptions for each unit can be obtained. More details about the Fuel-Product definition of each device and the thermoeconomic model of the plant under consideration can be found in [40].

The purpose of the thermoeconomic modeling is to establish the following thermoeconomic cost functions:

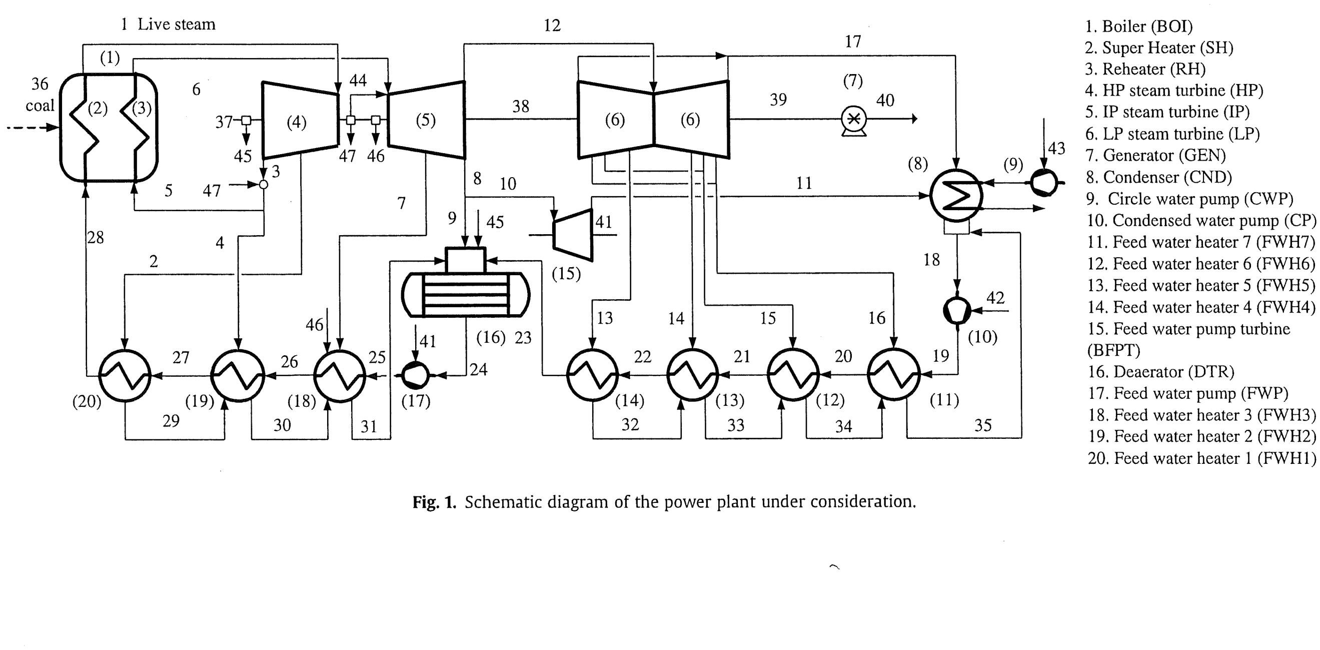

Fig. 1. Schematic diagram of the power plant under consideration.

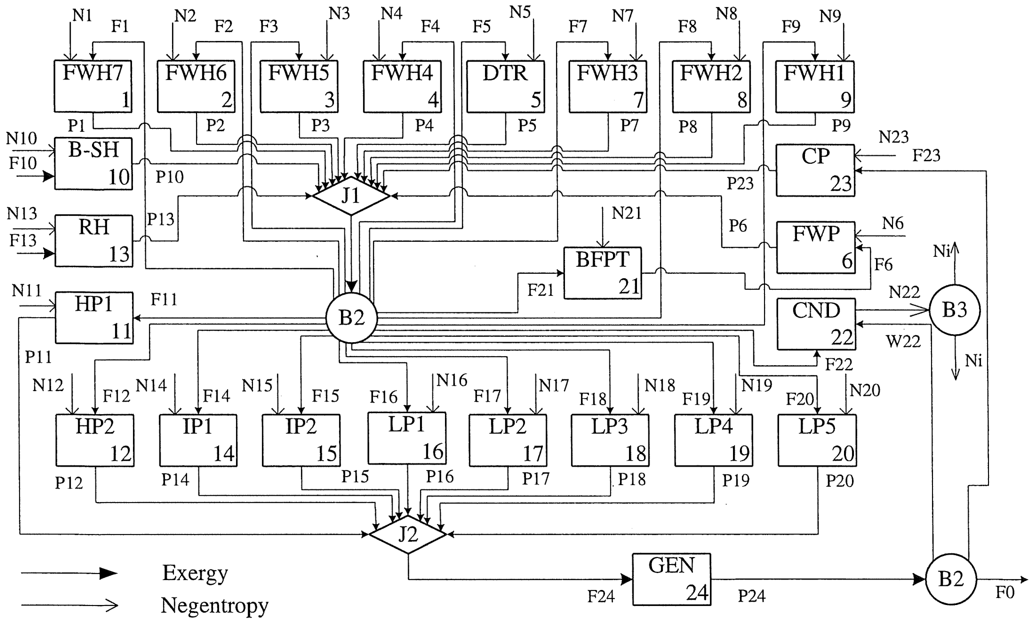

Fig. 2. Productive structure of the analyzed plant.

$$c_{pi} = \sum_{j=1}^{n} c_{F_j}\frac{F_j}{P_i} + \frac{Z_{Li}}{P_i} = \sum_{j=1}^{n} c_{F_j}k_{ji} + kZ_i, \tag{3}$$

in which, c_{pi} and c_{Fi} are the unit thermoeconomic cost of the product and the fuel of the ith unit, respectively. They mean the cost, in monetary units, of each unit of exergy expended in producing the product/fuel flow ($/kJ); and $kZ_i = Z_{Li}/P_i$ means the amortization cost (Z_L) per each unit of product. As shown above, the thermoeconomic cost of a flow includes two contributions: energy factor (exergy consumption to produce this flow) and economic factor (capital, maintenance, etc.). It is necessary and important to calculate Z_L to obtain the unit thermoeconomic cost described in Equation (3). The thermoeconomic cost functions [38] of major units in the Fig. 2 are listed in the Table 1.

Based on the investment cost Z_i (shown in Table 2) [38,47], the general equation for the amortization cost Z_{Li} ($/s) associated with capital investment and the maintenance costs for the ith device is [8,48]:

$$Z_{Li} = \frac{\phi f}{3600H} Z_i = \xi Z_i, \tag{4}$$

in which ϕ is the maintenance factor ($\phi = 1.06$ in this paper) ; f the annual capital recovery factor (f = 18.2% in this paper); H the number of hours of plant operation per year (H = 8000 h in this paper); and ξ the amortization factor (1/s). In Table 1, the junction/exergy ratio r_i is the ratio of the product of the ith unit to the product of its corresponding junction (J1, J2).

After obtaining k_{ij} and kZ_i, c_{pi} can be calculated by Equation (3) and is the base of system optimization.

3. Thermoeconomic optimization

Based on the model established above, thermoeconomic optimization can be performed on the 300 MW pulverized coal-fired power plant. In this section, two kinds of optimization methodology are presented: GO and LO.

The scopes of optimization are the same: the boiler (BOI), the turbines (HP, IP, LP and BFPT), the pumps (FWP (Feed Water Pump) and CP (Condenser Water Pump)) and the feed water heaters (FWH). The operation of GEN (Generator) is independent of the steam/water cycle; and the operation of CND (Condenser) is decided by the physical parameters of the exhaust steam from LP5, therefore these two units are not considered in the optimization. The decision variables ($\boldsymbol{x}$) are chosen from the characteristic variables of the 21 units optimized, such as efficiency (η), terminal temperature difference (T_{TTD}) and temperature (T). Therefore $\boldsymbol{x}$ can be described as:

$$\boldsymbol{x} = (\eta_{BOI}, \eta_{HP1}, \eta_{HP2}, \eta_{IP1}, \eta_{IP2}, \eta_{LP1}, \eta_{LP2}, \eta_{LP3}, \eta_{LP4}, \eta_{LP5}, \eta_{FWP}, \eta_{BFPT}, \eta_{CP}\ T_{TTDFWH1-FWH7}, T_{SH}), \tag{5}$$

where η_{BOI} is the thermodynamic efficiency of the boiler; the other efficiencies are the isentropic efficiencies of their corresponding units. The isentropic efficiency can be calculated as:

$$\eta = (h_{in} - h_{out})/(h_{in} - h'_{out}), \tag{6}$$

in which h_{in}, h_{out} and h'_{out} are the inlet enthalpy, the factual outlet enthalpy and the outlet enthalpy under the isentropic state of one stage in the turbines, respectively. Finally, T_{SH} is the temperature of the live steam (viz. superheated steam) and the reheat steam. In

Table 1
Thermoeconomic cost equations of the major units in the system.

Device	Number	Thermoeconomic cost equations
B-SH	10	$c_{P,10} = kB_{10}c_F + kS_{10}c_{FS,10} + kZ_{10}$
RH	13	$c_{P,13} = kB_{13}c_F + kS_{13}c_{FS,13} + kZ_{13}$
FWH	1–4,7–9	$c_{P,i} = kB_ic_{FB,i} + kS_ic_{FS,i} + kZ_i$
Turbine	11,12,14–20	$c_{P,i} = kB_ic_{FB,i} + kS_ic_{FS,i} + kZ_i$
Pump	6,23	$c_{P,i} = kB_ic_{FB,i} + kS_ic_{FS,i} + kZ_i$
CND	22	$c_{P,22} = kB_{22}c_{FB,22} + kW_{22}c_{FW,22} + kZ_{22}$
GEN	24	$c_{P,24} = kB_{24}c_{P,26} + kZ_{24}$
J1	25	$c_{P,25} = \sum r_i\, c_{P,i}$
J2	26	$c_{P,26} = \sum r_i\, c_{P,i}$

Table 2
Investment cost equations of the major devices in the system.

Device	Investment cost equations	Remark
B-SH	$Z_{BOI} = 20.1552224 \times \exp(0.0014110546 \times P_1) \times \exp(0.7718795 \times \ln(M_1)) \times F_{AR} \times F_{AN} \times F_{AT}$	P_1, M_1 and T_1 are the pressure (MPa), the mass flow rate (kg/s) and the temperature (°C) of the super-heater steam, respectively;
RH	$F_{AR} = 1.0 + ((1-\Delta P_r)/(1-\Delta P))^8$ $F_{AN} = 1.0 + ((1-\eta_{1r})/(1-\eta_1))^7$ $F_{AT} = 1.0 + 5 \times \exp((T_1 - 1100)/18.75)$ $Z_{B-SH} = (1-f_{RH})Z_{BOI}$, $Z_{RH} = f_{RH}Z_{BOI}$	ΔP is the relative pressure variation of water flowing through the boiler (Mpa); η_1 the thermodynamic efficiency of the boiler; f_{RH} the ratio of investment cost of the re-heater to the investment cost of the whole boiler. $\Delta P_r = 0.16, \eta_{1r} = 0.95, f_{RH} = 0.12$
FWH	$Z_i^H = 1000 \times 0.02 \times 3.3 \times Q\left(\frac{1}{T_{TTD,i}+a}\right)^{0.1} \times (10\Delta P_t)^{-0.08}(10\Delta P_s)^{-0.04}$	Q is the amount of heat transfer in the FWH (kW); T_{TTD} the difference between the saturated temperature of the steam extracted from the turbine and the temperature of the outlet feed water in FWH (°C); ΔP_t and ΔP_s are the pressure drop of the feed water and the extraction steam in the FWH, respectively (Mpa). $a = 6$ for FWH1–2, and $a = 4$ for others
Turbine	$Z_i^T = 3000 \times \left[1 + 5 \times \exp\left(\frac{T_1 - 866}{10.42}\right)\right] \times \left[1 + \left(\frac{1-\eta_{Tr}}{1-\eta_{T,i}}\right)^3\right] W_T^{0.7}$	η_T is the isentropic efficiency of the turbine section; W is the output power (kW). $\eta_{Tr} = 0.95$ for HP, and $\eta_{Tr} = 0.85$ for others
Pump	$Z_i^P = 378 \times \left[1 + \left(\frac{1-0.808}{1-\eta_{P,i}}\right)^3\right] B^{0.71}$	η_P is the isentropic efficiency of the pump; B the exergy of the product of the pump (kW).
CND	$Z_{CND} = (1/T_0 e) \times \left\{ \begin{array}{l} 217 \times \left[0.247 + (1/3.24V_w^{0.8})\right] \\ \times \ln(1/(1-e)) + 138 \end{array} \right\} \times (1/(1-\eta_C)) \times S$ $e = \frac{T_{wo} - T_{wi}}{T_{in} - T_{wo}}$; $\eta_C = T_0 \times \frac{s_{in} - s_{out}}{h_{in} - h_{out}}$	T_0 is the ambient temperature; V_w the flow rate of cooling water in CND (m/s); T_{wo}, T_{wi} and T_{in} are the temperature of the outlet cooling water, inlet cooling water and inlet steam in CND, respectively (°C); e the thermal effectiveness; η_C the efficiency of the CND.
GEN	$Z_{GEN} = 60 \times W_G^{0.95}$	

this paper, the temperatures of the two kinds of steam are assumed to be the same.

The value ranges of the decision variables are set to be: the efficiency (η) is between 0.8 and 0.95; the terminal temperature difference (T_{TTD}) is between −2.8 °C and 2.8 °C; and the temperature of the live steam (T_{SH}) is 535–545 °C. The ambient temperature (T_0) is set to be 20 °C and the unit price of fuel (c_F) is 2×10^{-6} (\$/kJ).

3.1. Global optimization

Global optimization of this system can be expressed as: under a certain economic status (such as a fixed annual capital recovery factor, maintenance factor, etc.) and with an invariable total product output (the net load of the system), searching the minimal value of the sum of the annual cost of the fuel and the total amortization cost, viz. the total annual cost, by adjusting the values of the decision variables $\boldsymbol{x}$. The objective function of the GO can be described as:

$$\min_x \Gamma = \Gamma_F + \Gamma_Z = \sum_{i=1}^{e} cFF_i + \xi \sum_{r=1}^{n} Z_r, \tag{7}$$

subject to the constraints $\left\{ \begin{array}{l} p_j(x,y) = 0, \ j = 1, ..., J \\ q_k(x,y) \le 0, \ k = 1, ..., K \end{array} \right.$'

Table 3
The optimization result of the decision variables.

Decision variable	x^0	x^{*G}	x^{*L1}	x^{*L2}	$\varepsilon^{L1\text{-}G}$ (%)	$\varepsilon^{L2\text{-}G}$ (%)
η_{BOI}	0.91802	0.92136	0.92117	0.92136	−0.02	0
η_{HP1}	0.82624	0.86122	0.84933	0.86122	−1.38	0
η_{HP2}	0.90949	0.91320	0.90452	0.91320	−0.95	0
η_{IP1}	0.90779	0.90841	0.90452	0.90841	−0.43	0
η_{IP2}	0.93463	0.91040	0.90595	0.91040	−0.49	0
η_{LP1}	0.89003	0.92269	0.90559	0.92269	−1.85	0
η_{LP2}	0.91176	0.85356	0.91394	0.85352	7.07	0
η_{LP3}	0.93839	0.92608	0.92382	0.92608	−0.24	0
η_{LP4}	0.90426	0.91777	0.91496	0.91777	−0.31	0
η_{LP5}	0.78556	0.82261	0.82319	0.82261	0.07	0
η_{FWP}	0.78963	0.85669	0.84801	0.85669	−1.01	0
η_{BFPT}	0.79889	0.81061	0.80210	0.81060	−1.05	0
η_{CP}	0.80000	0.83330	0.82939	0.83330	−0.47	0
$T_{TTDFWH1}$	−1.70000	2.8	1.30522	2.8	−53.38	0
$T_{TTDFWH2}$	0.00000	2.44774	0.75193	2.44943	−69.28	0.07
$T_{TTDFWH3}$	0.00000	−2.8	0.87919	−2.8	−131.4	0
$T_{TTDFWH4}$	2.80000	−0.88876	0.66622	−0.90786	−174.97	2.15
$T_{TTDFWH5}$	2.80000	−1.69336	0.48686	−1.68088	−128.75	−0.74
$T_{TTDFWH6}$	2.80000	−1.47274	−0.19684	−1.49539	−86.63	1.54
$T_{TTDFWH7}$	2.80000	−0.58316	−1.37445	−0.52352	135.69	−10.23
T_{SH}	537.00000	545	545	545	0	0
Total annual cost (\$/s)	2.4776404	2.4161197	2.4289045	2.4161198	0.53	0
Total investment cost (10^8\$)	1.530263	1.48057	1.487197	1.48056	0.45	0

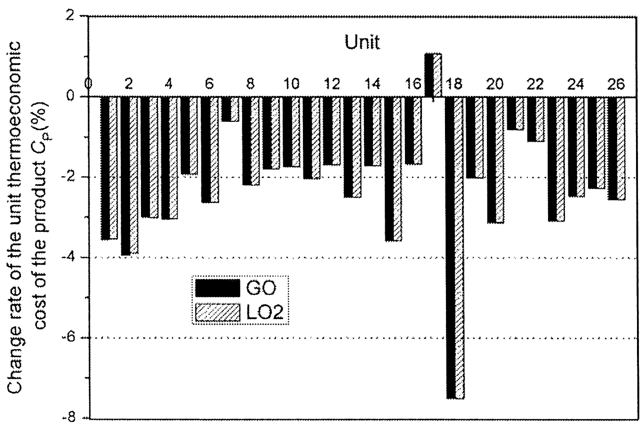

Fig. 3. The unit thermoeconomic cost of the product (c_P) in each unit after the GO and the LO2.

where $\boldsymbol{x}$=(x_1, x_2, ..., x_m); $\boldsymbol{y}$ is the symbol of dependent variables including temperature, pressure, flux as well as specific enthalpy of each flow; p_j are equality constraint functions derived by physical modeling (mass/energy balance functions, characteristic functions of the devices, etc.); q_k are inequality constraint functions corresponding to design and operation limits, state regulations, safety requirements, etc.

In the objective function, the external fuel consumption and the investment cost can be obtained by the following functions:

$$\begin{cases} F_i = F_i(x, y), & i = 1, ..., e \\ Z_r = Z_r(x, y), & r = 1, ..., n' \end{cases} \tag{8}$$

where $F_i(\boldsymbol{x}, \boldsymbol{y})$ is the function of the external fuel consumption. The system (see Fig. 2) consumes two kinds of external fuel (F_{10} and F_{13}). And $Z_r(\boldsymbol{x}, \boldsymbol{y})$ is the function of the investment cost of each device (see Table 2).

The optimization result of the GO is considered as benchmark (with the highest precision) in this paper.

Table 4
The optimization result of the unit thermoeconomic cost c_P (10^6\$/kJ).

Number	Unit	c_P^0	c_P^{*G}	c_P^{*LO1}	ε^G (%)	ε^{L1} (%)
1	FWH7	14.3633	13.8526	13.85982	−3.5556	−3.5053
2	FWH6	10.3778	9.9686	9.90096	−3.943	−4.5948
3	FWH5	9.1871	8.9111	8.92466	−3.0042	−2.8566
4	FWH4	8.8539	8.5838	8.67512	−3.0506	−2.0192
5	DTR	8.9590	8.7870	8.83794	−1.9199	−1.3513
6	FWP	11.9325	11.6181	11.61436	−2.6348	−2.6662
7	FWH3	7.9018	7.8536	7.81492	−0.61	−1.0995
8	FWH2	7.3909	7.2285	7.29096	−2.1973	−1.3522
9	FWH1	7.2274	7.0977	7.11653	−1.7946	−1.534
10	B-SH	5.8357	5.7345	5.75466	−1.7342	−1.3887
11	HP1	7.7771	7.6185	7.63903	−2.0393	−1.7753
12	HP2	7.7502	7.6197	7.63290	−1.6838	−1.5135
13	RH	5.4160	5.2804	5.32019	−2.5037	−1.769
14	IP1	7.6525	7.5211	7.55885	−1.7171	−1.2238
15	IP2	7.6994	7.4236	7.44878	−3.5821	−3.2551
16	LP1	7.8837	7.7520	7.73530	−1.6705	−1.8824
17	LP2	7.7401	7.8229	7.61241	1.0698	−1.6497
18	LP3	7.8839	7.2919	7.66815	−7.509	−2.7366
19	LP4	8.0264	7.8641	7.89000	−2.0221	−1.6994
20	LP5	9.2943	9.0032	9.03114	−3.132	−2.8314
21	BFPT	9.8553	9.7760	9.78570	−0.8046	−0.7062
22	CND	0.5452	0.5392	0.54009	−1.1005	−0.9373
23	CP	11.2646	10.9161	10.96258	−3.0938	−2.6811
24	GEN	8.2588	8.0537	8.09635	−2.4834	−1.967
25	J1	6.2429	6.1011	6.13108	−2.2714	−1.7912
26	J2	7.9053	7.7038	7.74569	−2.5489	−2.019

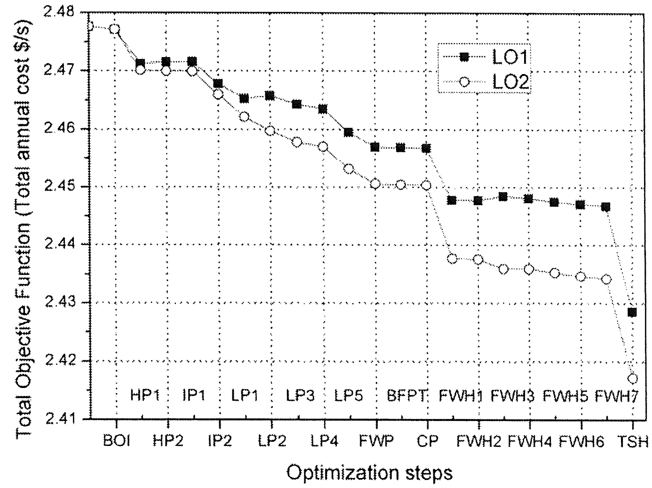

Fig. 4. The change processes of the global objective function in the first iteration of the LO1 and LO2.

3.2. Local optimization

For local optimization, units are optimized one by one. During conventional local optimization, the objective function and constraints of one unit optimization are usually only related to the variables and parameters in that unit. Taking HP1 (#11) for example, the objective function in conventional LO is:

$$\begin{aligned} \min_{\eta_{HP1}} \Gamma_{HP1} &= c_{P,11} P_{11} = \left(\sum_{i=0}^{n} k_{i11} c_{P,i} + kZ_{11} \right) \\ P_{11} &= (kB_{11} c_{FB,11} + kS_{11} c_{FS,11} + kZ_{11}) P_{11}. \end{aligned} \tag{9}$$

Because thermal units generally are related to each other and the local optimal operation of each unit may be quite different from the global optimal operation, therefore the result of this LO will be imprecise, as shown in Table 3 (remarked by L1). We further carried out a local optimization that set the objective function of each unit as the total annual cost of the plant, which is same as the objective function of the GO (viz. Equation (7)). It is

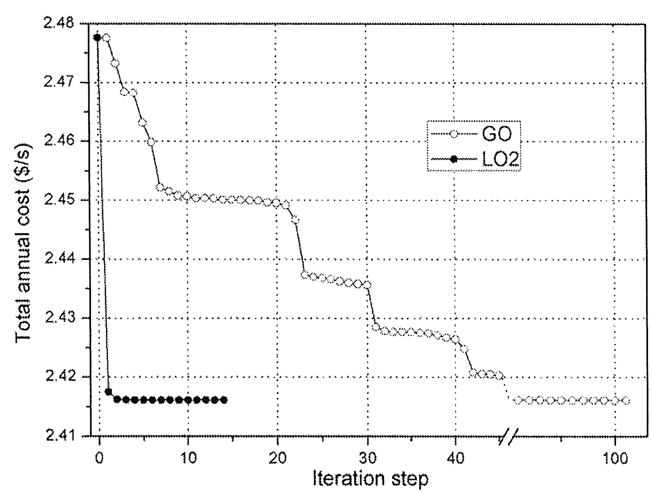

Fig. 5. Comparison of the iteration characteristics of the GO and the LO2.

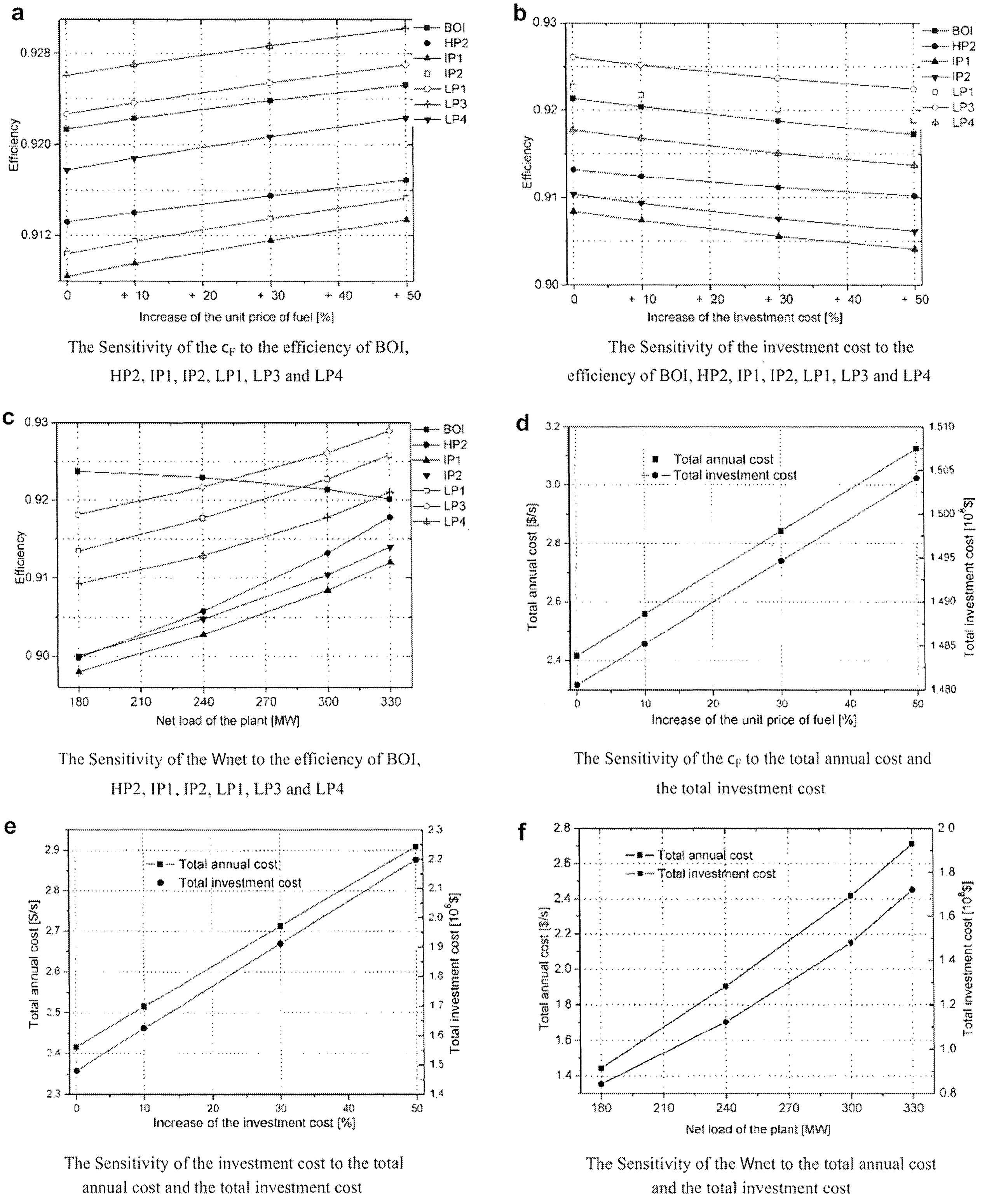

Fig. 6. Sensitivity analysis of the external environment parameters on the decision variables, the total annual cost and the total investment cost.

also optimized one unit at a time and the constraint functions are only related to the decision variables of the unit being optimized. The optimization results of this LO (remarked by L2) are shown in Table 3 and Fig. 3.

3.3. Optimization arithmetic and convergence criterion

For each optimization in this paper, the objective function is nonlinear and the decision variables are continuous, so the

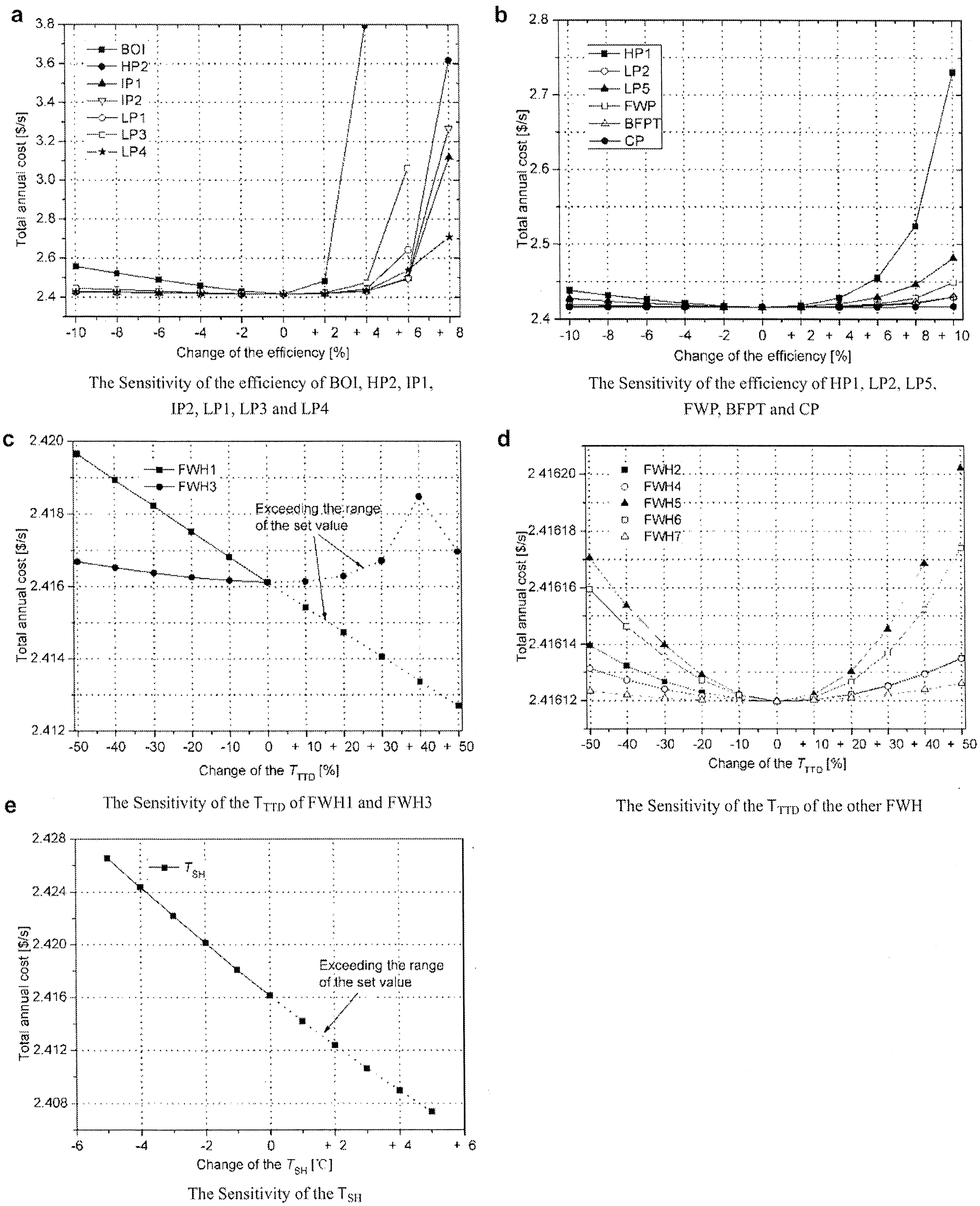

Fig. 7. Sensitivity analysis of the decision variables on the total annual cost (objective function).

Sequential Quadratic Programming (SQP) mathematical arithmetic [1,49–51] was chosen to solve the optimization models.

The standard SQP [1,49] tries to convert a general nonlinear programming problem into several consecutive Quadratic Programming (QP) problems. In detail, a nonlinear programming problem can be converted to be a Lagrange function by adding the constraints (equality and inequality) with their corresponding Lagrange multipliers to the original objective function. Then, the Lagrange function can be converted to a QP problem by employing the Taylor Series Expansion. Then an iteration process is conducted and in each iteration an appropriate QP problem is an approximation to the original nonlinear programming problem. Since the new objective function is of second degree (quadratic) and the constraints are linear, the necessary conditions lead to a system of linear equations, which is solved easily. The sequential application of this technique will not stop unit the optimum point is reached. Many researchers [50,51] have improved the standard SQP for a better convergence speed, also for the optimization problem has greater dimensions and more constraints. This improved SQP method is adopted in this paper.

The design values of the decision variables are chosen as the initial values for each optimization. The convergence criterion is that the relative variation rates of the decision variables $\boldsymbol{x}$ between two consecutive iterations are all less than 10^{-5}.

3.4. Optimization results

The results of the global optimization and the two local optimizations are shown in Table 3, Table 4 and Fig. 3. Table 3 shows the optimization result of the decision variables: $\boldsymbol{x}^0$, $\boldsymbol{x}^{*G}$ and $\boldsymbol{x}^{*L}$ means the initial values of the decision variables, the optimal solution of the GO and the LO, respectively; $\boldsymbol{\varepsilon}^{L\text{-}G}$ means the relative error of the optimal solution of the LO to that of the GO. The results show that not only the total annual cost but also the total investment cost of the system decrease observably after the optimization, which indicates that the thermoeconomic optimization methods performed in this paper are valid. The results of $\boldsymbol{\varepsilon}^{L1\text{-}G}$ and $\boldsymbol{\varepsilon}^{L2\text{-}G}$ reveal that the LO1 is not very precise; however, the LO2 and the GO could have the similar optimization accuracy because of the modification of the objective function in the LO2.

Table 4 and Fig. 3 show the optimization result of the unit thermoeconomic cost of the product ($\boldsymbol{c}_\mathrm{P}$) of each unit in each optimization. The superscript "0", "G" and "L" also means "initial," "Global," and "Local," respectively. But in the Table 4, $\boldsymbol{\varepsilon}^G$ and $\boldsymbol{\varepsilon}^L$ means the relative variation of the $\boldsymbol{c}_\mathrm{P}^G$ and $\boldsymbol{c}_\mathrm{P}^L$ to the $\boldsymbol{c}_\mathrm{P}^0$, respectively. The results show that the c_P of all units, except for LP2 in the GO and LO2, decrease due to optimization, which means that nearly all of the costs of the products of each unit decrease. Take the GEN as the example, the cost of its product (electricity) decreases about 2.5% after the optimization. In Fig. 3, each c_P changes in a same trend after the two kinds of optimization; moreover, the $\boldsymbol{c}_\mathrm{P}$ results of the LO2 is very close to that of the GO.

In order to find out the reasons of the differences of the results between the LO1 and the LO2, the change process of the global objective function in the first iteration (21 steps because there are 21 decision variables) of the LO1 and LO2 is shown in the Fig. 4. The result shows that although the global objective function decreases during the LO1, it fluctuates with the individual unit optimized. While in the LO2, the global objective function decreases quickly and without fluctuation. That is because the global objective function is not the optimization object in the LO1 and each unit is not isolated from others. Therefore the global objective function in the LO1 can obviously not reach the minimum.

In addition, Fig. 5 shows the overall convergence process of the GO and LO2. In order to be the optimal state, the GO needs a large iteration steps (more than 100) which is about 7 times to that of the LO2. Moreover, it spends many steps (about 45) for the objective function to be the stable state in the GO. However, the stable state comes rapidly in the LO2.

4. Sensitivity analysis

Sensitivity analysis is utilized to assess how robust a small perturbation of a parameter or variable in the system affects the performance of the system. Here two kinds of sensitivity analysis have been performed: (1) the sensitivity of the decision variables, the total annual cost (objective function, Γ) and the total investment cost (Z) with respect to the change of the external environment parameters; (2) the sensitivity of the objective function with respect to the change of the decision variables.

4.1. The sensitivity of the external environment parameters

An optimization process is usually performed under pre-established conditions of the external environment. However, the environment parameters are usually fluctuant and uncertain. So the sensitivities of the decision variables and the objective function with respect to the change of unit price of fuel (c_F), investment cost of the device as well as the net load of the plant (W_net) were analyzed in this paper and some salient (or representative) results were selected to be represented in Fig. 6 (a–f). The results show that decision variables are most correlated with W_net. Furthermore, c_F and the investment cost influence decision variables in opposite directions. It is because higher efficiencies of these units (especially for the BOI) can reduce the consumption of the fuel while lower efficiencies of these units can reduce the base investment costs. In addition, the sensitivity characteristics of the total annual cost (objective function, Γ) and the total investment cost (Z) with respect to the three external environment parameters are similar except that Z is nearly not correlated with c_F.

4.2. The sensitivity of the decision variables

Fig. 7 (a–e) shows the results of the sensitivity analysis of the total annual cost (objective function) with respect to the decision variables. This work was based on the optimization result of the global optimization and it could validate the optimal solutions. As shown in Fig. 7, the objective function (total annual cost, Γ) has a minimal value with the optimal solutions obtained in this paper. In addition, Γ is most correlated with the efficiency of the boiler and is strongly correlated with the other efficiencies as well as T_SH. The effect of T_TTD on Γ is very low.

5. Conclusions

In this paper, a thermodynamic model of a 300 MW coal-fired power plant was established. Based on the results of thermodynamic simulation, a thermoeconomic cost model was obtained based on the structure theory of thermoeconomics and then global optimization and local optimization were performed on the plant. The SQP mathematical arithmetic was chosen to solve the optimization models. The results of the optimizations show that the total annual cost and the total investment cost of the system decreases by nearly 2.5% and 3.5%, respectively. In addition, the unit thermoeconomic cost of the product ($\boldsymbol{c}_\mathrm{P}$) of each unit, except for LP2, decreases after the optimization.

As for two optimization strategies, the global optimization can sever as a benchmark solution however performs comparatively low computational efficiency. The local optimization demonstrates a fast convergence speed; however its precision depends on the selected objective function for each separable unit. With respect to the coal-fired power plant, it is found that the local optimization is able to work with high precision and speed at the same time if the total annual cost is set as the objective function of each thermal unit, which corresponds to the local optimization 2 proposed in this paper. The local optimization is expected to be used real-time and dynamic optimization simulation.

A sensitivity analysis to the performance of the system was also undertaken. The results of the sensitivity analysis show that the three environment parameters (unit price of fuel (c_F), investment cost of the device and the net load of the plant (W_{net})) all have a remarkable influence on the decision variables but the W_{net} is the most. Also, the effects of the three parameters on the total annual cost (Γ) and the total investment cost (Z) are also significant except for c_F on Z. In addition, the results of the sensitivity analysis of the objective function (Γ) with respect to the decision variables show that Γ has a minimal value with each optimal decision variable obtained, which indicates that the optimization process could achieve the optimal solution of the optimization model established in this paper. Moreover, Γ is most correlated with the efficiency of the boiler and is strongly correlated with the other efficiencies as well as T_{SH}. The influence of T_{TTD} on Γ is inconspicuous.

This work shows that the thermoeconomic optimization technique for a coal-fired power plant is essential for both plant management and plant system design to achieve improved or optimal system performance with reduced investment or operation costs.

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