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**Article**

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## Research paper

## Exergoeconomic performance optimization for a regenerative closed-cycle gas turbine combined heat and power plant

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## ABSTRACT

A combined heat and power plant with regenerative closed-cycle gas turbine is considered. The heat transfer losses, irreversible adiabatic losses and irreversible pressure drop losses are considered in the plant. The expressions of dimensionless profit rate and exergy efficiency are gained. The optimal heat conductance distributions and compressor pressure ratio are derived based on maximum dimensionless profit rate and maximum exergy efficiency objectives, respectively. The results show that the heat conductance distributions and compressor pressure ratio have their optimal values which results in maximum dimensionless profit rate. The curve of maximum dimensionless profit rate and the corresponding exergy efficiency is loop-shaped one. With the increases in heat reservoir temperature ratio  $\tau_1$ , price ratios  $a$  and  $b$  as well as total heat exchanger inventory  $U_T$ , the maximum dimensionless profit rate increases. With the decrease in  $a$  and increases in  $\tau_1$ ,  $b$  and  $U_T$ , the corresponding exergy efficiency increases. The heat reservoir temperature ratio  $\tau_2$  has its optimal value which leads to double maximum dimensionless profit rate. Moreover, the maximum exergy efficiency performance of the plant is also analyzed. Because the exergoeconomic performance of irreversible regenerative closed-cycle gas turbine cogeneration plant has not been investigated by the researchers before, the exergoeconomic performance optimization is conducted in this paper, and the results obtained can offer new design guidelines for this kind of cogeneration plants.

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## 1. Introduction

Combined heat and power plant (CHPP) has a higher energy utilization rate compared with the pure power plant (Wang et al., 2017; Han et al., 2017; Mehrpooya et al., 2019; Urbanucci et al., 2019). Many scholars have conducted parameters optimizations to improve CHPP performances (Caliano et al., 2017; Wang et al., 2018; Abbasi et al., 2018; Wang et al., 2019; Sheykhi et al., 2019; Wu et al., 2019) by using classical thermodynamics.

Finite-time thermodynamics (FTT) (Andresen et al., 1984; Bejan, 1996; Chen et al., 1999; Chen and Xia, 2018; Abam et al., 2018; Lucia and Grisolia, 2019; Chen and Xia, 2019; Chen and Li, 2020) has exhibited its advantages in performance optimizations of various thermodynamic processes and cycles. Among them, FTT optimizations for CHPPs are one of the hot issues. Bojic

(1997) considered the heat transfer losses (HTLs) of a CHPP with Carnot cycle, and optimized its thermoeconomic performance by changing the heat conduction distributions. Kaushik et al. (2005) and Atmaca et al. (2009) discussed the exergetic performances of a Carnot CHPP, and found that the irreversibility parameters had evident effects on its performances. Atmaca et al. (2016) further studied the CHPP applications for the housing complex, and obtained a short payback period of the CHPP. Besides Carnot CHPPs, Ust et al. (2007) discussed the exergy performance coefficient of a CHPP with Dual cycle, and pointed out that this coefficient showed a good compromise between exergy output rate (EOR) and entropy generation rate (EGR). Yilmaz et al. (2008) optimized the EOR of a CHPP with simple Brayton cycle, and pointed out that a lower temperature of the thermal consumer (TTC) led to a higher EOR. Hao and Zhang (2013) analyzed the useful-energy rate (UER) and efficiency of a CHPP with open Brayton cycle, and found that the optimal results derived by maximizations of UER and efficiency were different when the ratio of power to heat was larger. Dubey et al. (2016) calculated the UER of a CHPP with reheat Joule–Brayton cycle, and found that the performance of

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**Nomenclature**

$a$	Price ratio
$b$	Price ratio
$C$	Thermal capacity rate, kW/K
$D$	Pressure recovery coefficient
$E_H$	Net exergy output rate (EOR), kW
$E_P$	EOR of power, kW
$E_K$	Thermal EOR, kW
$P$	Power output, kW
$p$	Pressure, Pa
$Q$	Heat transfer rate, kW
$T$	Temperature, K
$U$	Heat conductance, kW/K
$u$	Heat conductance distribution

**Greek symbols**

$\gamma$	Effectiveness of the heat exchanger
$\eta$	Exergy efficiency
$\lambda$	Process efficiency
$\Pi$	Profit rate, \$
$\pi$	Pressure ratio
$\sigma$	Entropy generation rate, kW/K
$\varphi$	Price, \$/kW
$\tau$	Temperature ratio for heat reservoir
$\omega$	Temperature ratio for process 1–2 s

**Subscripts**

$\bar{\Pi}$	Maximum dimensionless profit rate
$H$	Hot-side
$K$	Thermal consumer-side
$L$	Cold-side
max	Maximum
opt	Optimal
$R$	Regenerator
$T$	Total
$\eta$	Maximum exergy efficiency
$0$	Ambient
1, 2, 2s, 3, 4, 5, 5s, 6, 7	State points

**Superscript**

–	Dimensionless
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(Salamon and Nitzan, 1981; Chen et al., 1997, 2004; Ding et al., 2011; Kan et al., 2010; Feng et al., 2010; Ge et al., 2019; Wu et al., 2000; Chen et al., 1996; Tao et al., 2009; Yang et al., 2011; Chen et al., 2014; Yang et al., 2014b; Chen et al., 2011; Feng et al., 2011). The dimensionless profit rate (DPR) was maximized in the FTEA, and the corresponding exergy efficiency (EE) was named as finite time exergoeconomic performance bound (FTEPB). The FTEA is widely used in the cycle performance evaluations, such as Carnot heat engine cycles (Chen et al., 1997, 2004), universal two-heat-reservoir heat engine cycle (Ding et al., 2011), universal two-heat-reservoir refrigerator cycle (Kan et al., 2010), universal two-heat-reservoir heat pump cycle (Feng et al., 2010), complex Brayton cycle (Ge et al., 2019), quantum Stirling heat engine cycle (Wu et al., 2000), absorption cycles (Chen et al., 1996), CHPPs with simple and complex Brayton cycles (Tao et al., 2009; Yang et al., 2011; Chen et al., 2014; Yang et al., 2014b), and trigeneration plants with simple Brayton cycle (Chen et al., 2011; Feng et al., 2011), etc. FTEA was conducted in the researches mentioned above from the viewpoint of long-run economic optimization, and new performance bounds were provided different from those derived by traditional analyses.

In this paper, the FTEA will be introduced into the performance optimizations of a CHPP with regenerative closed-cycle gas turbine (RCCGT). Three kinds of losses will be considered in the CHPP. The expressions of DPR and EE of CHPP will be derived. The heat conductance distributions (HCDs) and compressor pressure ratio (CPR) will be optimized based on maximum DPR and maximum EE objectives, respectively. Characteristics of optimal results of CHPP versus heat reservoir temperature ratios, price ratios and total heat exchanger inventory (THEI) will be analyzed. The result differences between this paper and previous researches will be compared. Two innovations of this paper are introducing the FTT theory and FTEA method into the performance optimization of the irreversible RCCGT, and new guidelines for the CHPP designers will be offered.

**2. Cycle model**

Figs. 1 and 2 show the flow diagram as well as the relationship of temperature and specific entropy of a CHPP with RCCGT, respectively. The heat reservoir temperatures of the heat exchangers (HEs) at hot-, cold- and consumer-sides (HEHCCSs) are  $T_H$ ,  $T_L$  and  $T_K$ , respectively, and the working fluid (WF) runs between the heat reservoirs. The compression and expansion processes 1–2 and 4–5 in the compressor and turbine are non-isentropic ones. The CPR of the compressor is  $\pi = p_2/p_1$ . The isobaric processes 3–4 and 7–1 are heat absorbing and releasing processes, and processes 2–3 and 5–6 are those in the regenerator. The processes 1–2–3–4–5–6–7–1 form the whole cycle of CHPP, and processes 1–2s–3–4–5s–6–7–1 are the corresponding endoreversible cycle. The differences between the endoreversible and irreversible RCCGTs are reflected in the two adiabatic processes. For the former cycle, processes 1–2 s and 4–5 s are isentropic processes, which are the deal processes. For the latter cycle, the irreversible factors in the compressor and turbine are considered, and the more practical non-isentropic processes 1–2 and 4–5 are adopted instead of processes 1–2 s and 4–5 s.

The two pressure recovery coefficients are given as:

$$D_1 = p_4/p_2, D_2 = p_1/p_5. \quad (1)$$

The heat transfer rate (HTR,  $Q_H$ ) of hot-side HE is:

$$Q_H = C_{wf}(T_4 - T_3) = C_{wf}\gamma_H(T_H - T_3), \quad (2)$$

where  $C_{wf}$  is the rate of thermal capacity, and the effectiveness  $\gamma_H$  is calculated by:

$$\gamma_H = 1 - e^{-(U_H/C_{wf})}, \quad (3)$$

the CHPP could be evidently improved by adopting reheater. Yang et al. (2014a, 2016) conducted the exergy optimizations of the CHPPs with intercooled regenerated Brayton cycles, and obtained the optimal consumer-side temperatures leading to optimal exergy performances. Moreover, the trigeneration systems (Chen et al., 2013; Mohammadi et al., 2017; Mirzaee et al., 2019) were also investigated by some scholars based on FTT.

Besides the optimization objectives mentioned above, exergoeconomic (or thermoeconomic) optimizations (Tsatsaronts, 1993; El-Sayed, 2003) have also been attracted by some scholars. Salamon and Nitzan (1981) introduced the exergoeconomic concept (Tsatsaronts, 1993; El-Sayed, 2003) into the performance analyses of endoreversible models, formed a new analysis method – finite time exergoeconomic analysis (FTEA)

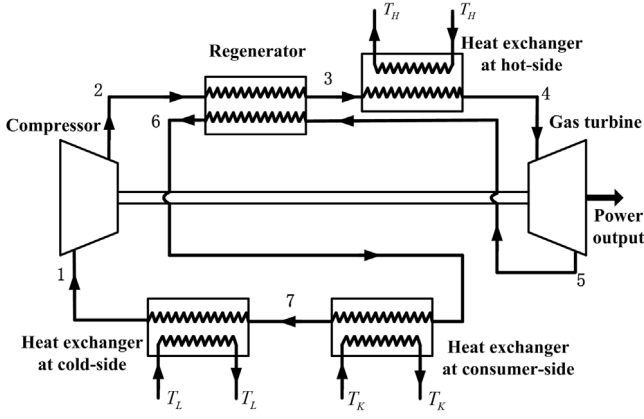


Fig. 1. Flow diagram of CHP plant composed of a regenerative closed-cycle gas turbine.

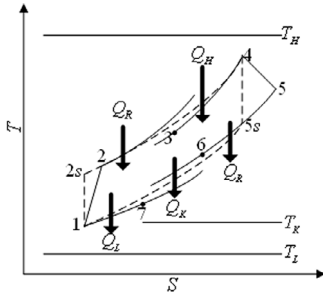


Fig. 2. T-s diagram of CHP plant composed of a regenerative closed-cycle gas turbine.

where  $U_H$  is the heat conductance. The HTRs ( $Q_L$ ,  $Q_K$  and  $Q_R$ ) of the cold- and consumer-side HEs and regenerator can be derived similar with Eqs. (2) and (3) (Tao et al., 2009), and the corresponding meanings of the symbols are similar with those of the hot-side HE.

### 3. Performance relations

The temperature ratio for process 1–2 s can be expressed as:

$$\omega = T_{2s}/T_1 = \pi^m, \tag{4}$$

where  $m$  is a constant, and  $\pi$  is the CPR. For endoreversible cycle in Fig. 2, one has:

$$T_1 T_4 = T_{2s} T_{5s}. \tag{5}$$

Combining Eqs. (1), (4) and (5) yields:

$$T_4/T_{5s} = (p_4/p_5)^m / (D_1 D_2)^m = \omega. \tag{6}$$

The power output (PO) of the CHPP, i.e. the EOR derived from PO, is:

$$E_p = P = Q_H - Q_L - Q_K. \tag{7}$$

According to the definition of exergy and exergy balance equation, the net thermal exergy rate (NTER), thermal EOR and EGR of CHPP can be expressed as:

$$E_H = c_H Q_H - c_L Q_L = E_p + E_K + T_0 \sigma, \tag{8}$$

$$E_K = Q_K \left[ 1 - \frac{T_0 \cdot \ln(T_6/T_7)}{T_6 - T_7} \right], \tag{9}$$

$$\sigma = \frac{Q_L}{T_L} - \frac{Q_H}{T_H} + \frac{Q_K \cdot \ln(T_6/T_7)}{T_6 - T_7}, \tag{10}$$

where  $T_0$  is the ambient temperature, and  $c_i = 1 - T_0/T_i$  ( $i = H, L$ ). The profit rate of CHPP is:

$$\Pi = \varphi_p E_p + \varphi_K E_K - \varphi_H E_H, \tag{11}$$

where  $\varphi_H$ ,  $\varphi_K$  and  $\varphi_p$  are the prices of the NTER, thermal EOR and PO, respectively.

Combining Eqs. (1)–(9), the DPR can be expressed as:

$$\begin{aligned} & a \{ \{ \lambda_1 [ 1 - p [ \gamma_R + (1 - \gamma_R) (\gamma_K + \gamma_L - \gamma_L \gamma_K) ] \} - q (1 - \gamma_L) \\ & \times (1 - \gamma_K) [ \gamma_R + p (1 - 2\gamma_R) ] \} \gamma_H \tau_1 + \{ \lambda_1 [ 1 - \gamma_R p (1 - \gamma_H) ] \\ & - q [ \gamma_H + \gamma_R - \gamma_H \gamma_R + p (1 - \gamma_H) (1 - 2\gamma_R) ] \} (1 - \gamma_L) \\ & \times \gamma_K \tau_2 + \gamma_L \tau_3 \} + b \gamma_K (1 - \tau_2^{-1}) \{ \lambda_1 (1 - \gamma_R) p \gamma_H \tau_1 - \lambda_1 p [ 1 \\ & - \gamma_R (1 - \gamma_H) ] \tau_2 + q [ \gamma_R + p (1 - \gamma_H) (1 - 2\gamma_R) ] (1 - \gamma_L) \tau_2 \\ & + \gamma_L \tau_3 \} - \gamma_H (1 - \tau_1^{-1}) \{ \{ \lambda_1 [ 1 - \gamma_R p ] - q (1 - \gamma_L) (1 - \gamma_K) \\ & \times [ \gamma_R + (1 - 2\gamma_R) p ] \} \tau_1 - (1 - \gamma_R) q [ (1 - \gamma_L) \gamma_K \tau_2 + \gamma_L \tau_3 ] \\ & + \gamma_L (1 - \tau_3^{-1}) \{ (1 - \gamma_K) (1 - \gamma_R) p \lambda_1 \gamma_H \tau_1 + \lambda_1 [ 1 - \gamma_R p (1 - \gamma_H) ] \\ & \times (\gamma_K \tau_2 - \tau_3) + (1 - \gamma_K) q [ \gamma_R + p (1 - \gamma_H) (1 - 2\gamma_R) ] \tau_3 \} \\ \overline{\Pi} = & \frac{\lambda_1 [ 1 - \gamma_R p (1 - \gamma_H) ] - q (1 - \gamma_L) (1 - \gamma_K) [ \gamma_R + p (1 - \gamma_H) (1 - 2\gamma_R) ]}{\lambda_1 [ 1 - \gamma_R p (1 - \gamma_H) ] - q (1 - \gamma_L) (1 - \gamma_K) [ \gamma_R + p (1 - \gamma_H) (1 - 2\gamma_R) ]}, \end{aligned} \tag{12}$$

where  $p = 1 - \lambda_2 + \lambda_2 \omega^{-1} (D_1 D_2)^{-m}$ ,  $q = \omega - 1 + \lambda_1$ ,  $\lambda_1$  and  $\lambda_2$  are the efficiencies of processes 1–2 and 4–5, the price ratios are defined as:  $a = \varphi_p / \varphi_H$  and  $b = \varphi_K / \varphi_H$ , and the heat reservoir temperature ratios are defined as:  $\tau_1 = T_H/T_0$ ,  $\tau_2 = T_K/T_0$  and  $\tau_3 = T_L/T_0$ , respectively.

Combining Eqs. (1)–(9), the EE of the CHPP can be expressed as:

$$\begin{aligned} & \{ \lambda_1 [ 1 - p [ \gamma_R + (1 - \gamma_R) (\gamma_K + \gamma_L - \gamma_L \gamma_K) ] \} - q (1 - \gamma_L) \\ & \times (1 - \gamma_K) [ \gamma_R + p (1 - 2\gamma_R) ] \} \gamma_H \tau_1 + \{ \lambda_1 [ 1 - \gamma_R p (1 - \gamma_H) ] \\ & - q [ \gamma_H + \gamma_R - \gamma_H \gamma_R + p (1 - \gamma_H) (1 - 2\gamma_R) ] \} (1 - \gamma_L) \gamma_K \tau_2 \\ & + \gamma_L \tau_3 + \gamma_K (1 - \tau_2^{-1}) \{ \lambda_1 (1 - \gamma_R) p \gamma_H \tau_1 - \lambda_1 \tau_2 [ 1 - \gamma_R p (1 \\ & - \gamma_H) ] + q [ \gamma_R + p (1 - \gamma_H) (1 - 2\gamma_R) ] (1 - \gamma_L) \tau_2 + \gamma_L \tau_3 \} \\ \eta = \frac{E_p + E_K}{E_H} = & \frac{\gamma_H (1 - \tau_1^{-1}) \{ \{ \lambda_1 [ 1 - \gamma_R p ] - (1 - \gamma_L) (1 - \gamma_K) q [ \gamma_R \\ & + p (1 - 2\gamma_R) ] \} \tau_1 - (1 - \gamma_R) q [ (1 - \gamma_L) \gamma_K \tau_2 + \gamma_L \tau_3 ] \\ & - \gamma_L (1 - \tau_3^{-1}) \{ (1 - \gamma_K) (1 - \gamma_R) p \lambda_1 \gamma_H \tau_1 + \lambda_1 [ 1 - \gamma_R \\ & \times p (1 - \gamma_H) ] (\gamma_K \tau_2 - \tau_3) + (1 - \gamma_K) q [ \gamma_R + p (1 - \gamma_H) \\ & \times (1 - 2\gamma_R) ] \tau_3 \}}{\gamma_H (1 - \tau_1^{-1}) \{ \{ \lambda_1 [ 1 - \gamma_R p ] - (1 - \gamma_L) (1 - \gamma_K) q [ \gamma_R \\ & + p (1 - 2\gamma_R) ] \} \tau_1 - (1 - \gamma_R) q [ (1 - \gamma_L) \gamma_K \tau_2 + \gamma_L \tau_3 ] \\ & - \gamma_L (1 - \tau_3^{-1}) \{ (1 - \gamma_K) (1 - \gamma_R) p \lambda_1 \gamma_H \tau_1 + \lambda_1 [ 1 - \gamma_R \\ & \times p (1 - \gamma_H) ] (\gamma_K \tau_2 - \tau_3) + (1 - \gamma_K) q [ \gamma_R + p (1 - \gamma_H) \\ & \times (1 - 2\gamma_R) ] \tau_3 \}}. \end{aligned} \tag{13}$$

### 4. Discussions

When  $\varphi_p \geq \varphi_H$  and  $\varphi_K \geq \varphi_H$ , the CHPP may be profitable. The DPR and EE in Eqs. (12) and (13) are generalized expressions, and many results obtained in previous work are special cases of these equations.

(1) When  $\gamma_R = 0$ ,  $\lambda_1 = \lambda_2 = 1$  and  $D_1 = D_2 = 1$ , Eqs. (12) and (13) become the DPR and EE of CHPP with endoreversible simple Brayton cycle (SBC). However, the EEs are also different when the calculation methods of thermal EORs are different in this paper and available reference.

(2) When  $\gamma_R = 0$  and  $D_1 = D_2 = 1$ , Eqs. (12) and (13) become the DPR and EE of CHPP with irreversible SBC.

(3) When  $\lambda_1 = \lambda_2 = 1$  and  $D_1 = D_2 = 1$ , Eqs. (12) and (13) become the DPR and EE of CHPP with endoreversible regenerative gas turbine (Tao et al., 2009).

(4) When  $\varphi_p = \varphi_K = \varphi_H$ , Eq. (11) becomes:

$$\Pi = \varphi_p (E_p + E_K - E_H) = -\varphi_p T_0 \sigma. \tag{14}$$

The maximum DPR objective is simplified into minimum EGR objective.

(5) When  $\varphi_p / \varphi_H \rightarrow \infty$  and  $\varphi_p = \varphi_K$ , Eq. (11) is simplified into:

$$\Pi = \varphi_p (E_p + E_K). \tag{15}$$

The maximum DPR objective is simplified into maximum exergy production objective.

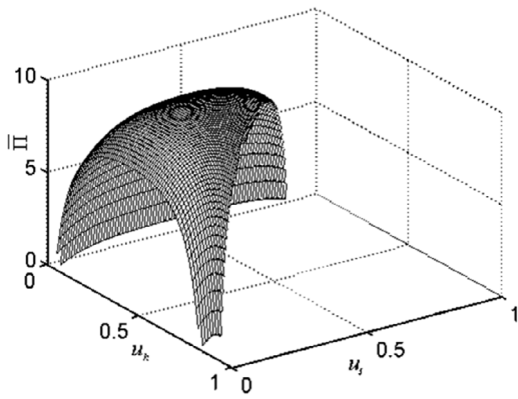


Fig. 3. Three-dimensional characteristic of  $\bar{\Pi}$  versus  $u_h$  and  $u_l$ .

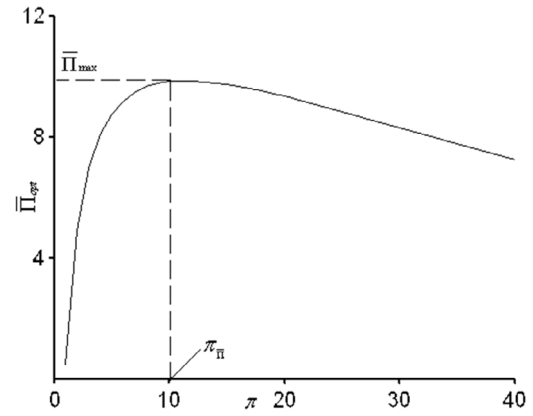


Fig. 4. Characteristic of  $\bar{\Pi}_{opt}$  versus  $\pi$ .

### 5. Performance optimizations

According to Eq. (12), the DPR  $\bar{\Pi}$  is a function of  $a, b, D_1, D_2, \lambda_1, \lambda_2, \tau_1, \tau_2, \tau_3, \pi, U_H, U_L, U_K$  and  $U_R$ . Similar with the constraints for regenerative Brayton cycles in Refs. Tao et al. (2009), Yang et al. (2011), Chen et al. (2014) and Yang et al. (2014b), the constraint of THEI ( $U_T$ ) is considered in the performance optimization of the CHPP with RCCGT.

When  $U_T$  is unchanged, the definitions of the four HCDs are expressed as:

$$(u_h, u_l, u_k, u_r) = (U_H, U_L, U_K, U_R)/U_T, \tag{16}$$

where the sum of the four HCDs is 1. Numerical calculation shows that the DPR reach its maximum when  $u_r = 0$ , which illustrates that the regeneration leads to a decrement of DPR.

Actually, the regeneration is useful for energy saving of CHPP. To avoid the contradiction in the optimization, the HCD of regeneration is fixed. For the fixed  $U_T, u_r, u_h, u_l, u_k$  and  $\pi$  will be varied to research for the maximum value of DPR. In the optimizations,  $a = 10, b = 6$  (Tao et al., 2009; Yang et al., 2011; Chen et al., 2014; Yang et al., 2014b; Chen et al., 2011; Feng et al., 2011),  $C_{wf} = 1.0$  kW/K,  $U_T = 10$  kW/K,  $k = 1.4, \lambda_1 = \lambda_2 = 0.85, D_1 = D_2 = 0.95, \tau_1 = 5, \tau_2 = 1.4$  and  $\tau_3 = 1$  are set. The relationship of  $\bar{\Pi}, u_h$  and  $u_l$  is shown in Fig. 3. When the other parameters are fixed, the DPR can be maximized by varying  $u_h$  and  $u_l$  simultaneously. When the HCD  $u_h$  is further varied, the optimal DPR ( $\bar{\Pi}_{opt}$ ) can be obtained. The characteristic of  $\bar{\Pi}_{opt}$  versus the CPR  $\pi$  is shown in Fig. 4.  $\pi$  has its optimal value ( $\pi_{\bar{\Pi}}$ ) which leads to maximum DPR ( $\bar{\Pi}_{max}$ ) of CHPP, and the corresponding HCDs at  $\bar{\Pi}_{max}$  condition are signed as  $(u_h)_{\bar{\Pi}}, (u_l)_{\bar{\Pi}}$  and  $(u_k)_{\bar{\Pi}}$ , respectively.

#### 5.1. Optimal heat conductance distributions and compressor pressure ratio

The characteristics of  $(u_h)_{\bar{\Pi}}, (u_l)_{\bar{\Pi}}, (u_k)_{\bar{\Pi}}$  and  $\pi_{\bar{\Pi}}$  versus  $\tau_1, a$  and  $U_T$  are shown in Figs. 5–7, respectively. Similar characteristics for  $\tau_2$  and  $b$  are also analyzed by numerical calculations. They illustrate that  $(u_l)_{\bar{\Pi}}$  increases when  $\tau_2, a$  and  $U_T$  increase, and the tendency is reversed when  $\tau_1$  and  $b$  increase;  $(u_k)_{\bar{\Pi}}$  increases when  $\tau_1$  and  $b$  increase, and the tendency is reversed when  $\tau_2$  and  $a$  increase;  $\pi_{\bar{\Pi}}$  increases when  $\tau_1, a$  and  $U_T$  increase, and the tendency is reversed when  $b$  increases;  $(u_h)_{\bar{\Pi}}$  does not evidently change when the discussed parameters vary. One can see that most of the design parameters have significant impacts on the optimal values of design variables, which illustrates the importance of parameter analyses in this section.

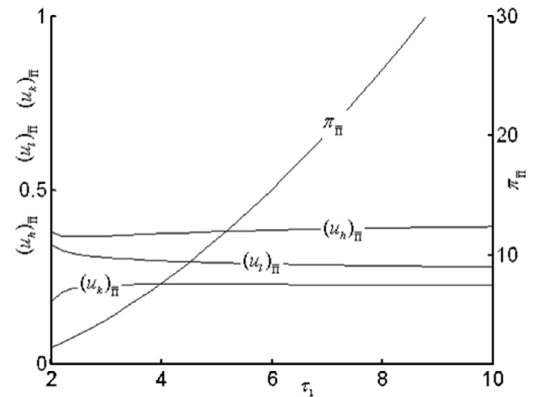


Fig. 5. Characteristics of  $(u_h)_{\bar{\Pi}}, (u_l)_{\bar{\Pi}}, (u_k)_{\bar{\Pi}}$  and  $\pi_{\bar{\Pi}}$  versus  $\tau_1$ .

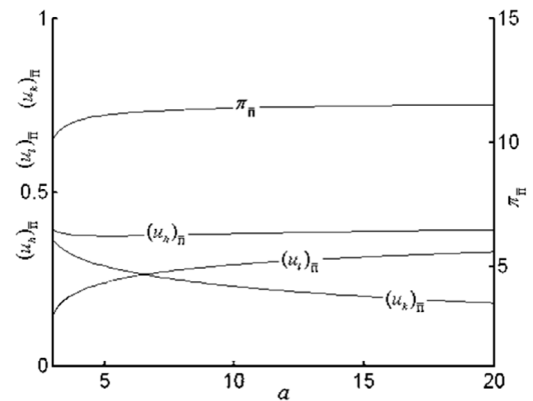


Fig. 6. Characteristics of  $(u_h)_{\bar{\Pi}}, (u_l)_{\bar{\Pi}}, (u_k)_{\bar{\Pi}}$  and  $\pi_{\bar{\Pi}}$  versus  $a$ .

#### 5.2. Dimensionless profit rate versus exergy efficiency characteristic

The characteristic of optimal DPR ( $\bar{\Pi}_{opt}$ ) versus the corresponding EE ( $\eta_{\Pi opt}$ ) with different  $u_r$  is shown in Fig. 8. It shows that  $\bar{\Pi}_{opt} - \eta_{\Pi opt}$  characteristic is leaf-shaped one. The maximum DPR ( $\bar{\Pi}_{max}$ ) and the FTEPB ( $\eta_{\bar{\Pi}}$ ) can be derived at the highest point of the leaf-shaped curve. Furthermore, the maximum EE ( $\eta_{max}$ ) and the corresponding DPR ( $\bar{\Pi}_{\eta}$ ) can be also obtained. When  $u_r \approx 0.1$ , the optimization results derived by DPR and EE maximizations are equal to each other.

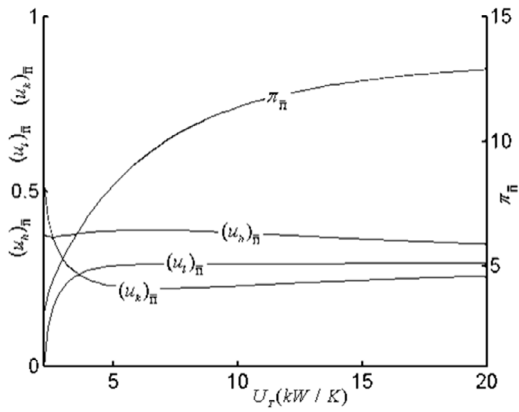


Fig. 7. Characteristics of  $(u_h)_n$ ,  $(u_l)_n$ ,  $(u_k)_n$  and  $\pi_n$  versus  $U_T$ .

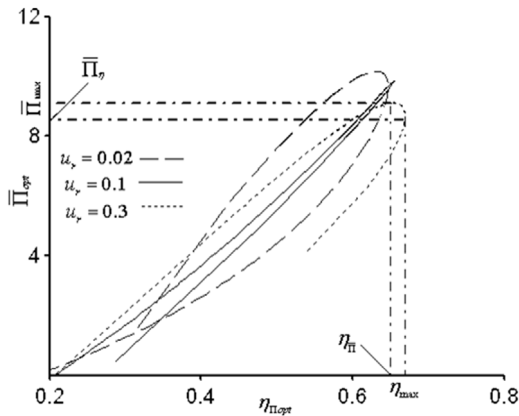


Fig. 8. Influence of  $u_r$  on characteristic of  $\bar{\pi}_{opt}$  versus  $\eta_{opt}$ .

### 5.3. Maximum dimensionless profit rate and finite time exergoeconomic performance bound

The characteristics of maximum DPR ( $\bar{\pi}_{max}$ ) versus  $\tau_1$ ,  $U_T$  and  $\tau_2$  are shown in Figs. 9–11, respectively. Similar characteristics for  $a$  and  $b$  are also analyzed by numerical calculations. One can see that,  $\bar{\pi}_{max}$  increases when  $\tau_1$ ,  $a$ ,  $b$  and  $U_T$  increase; the FTEPB ( $\eta_{\bar{\pi}}$ ) increases when  $\tau_1$ ,  $b$  and  $U_T$  increase, and the tendency is reversed when  $a$  increases;  $\tau_2$  has an optimal value which leads to double maximum value of the DPR. The optimal TTC exists, which is different from the results obtained in Refs. Ust et al. (2007), Yilmaz et al. (2008), Hao and Zhang (2013) and Dubey et al. (2016). One can see that the design parameters have significant impacts on the performances of CHPP, which provides some opportunities to improve their performances.

### 5.4. Maximum exergy efficiency and the corresponding dimensionless profit rate

The variations of  $\eta_{max}$  and  $\bar{\pi}_\eta$  with  $U_T$  are shown in Fig. 12. From the figure,  $\eta_{max}$  and  $\bar{\pi}_\eta$  increase when  $U_T$  increases. Similar analyses show that  $\eta_{max}$  and  $\bar{\pi}_\eta$  increase when  $\tau_1$  and  $\tau_2$  increase. However, the CHPP becomes a pure heat supply plant when  $\tau_2 > 1.44$ , and the maximum  $\eta_{max}$  is vanished. Therefore, an appropriate  $\tau_2$  should be chosen in the designs of CHPP.

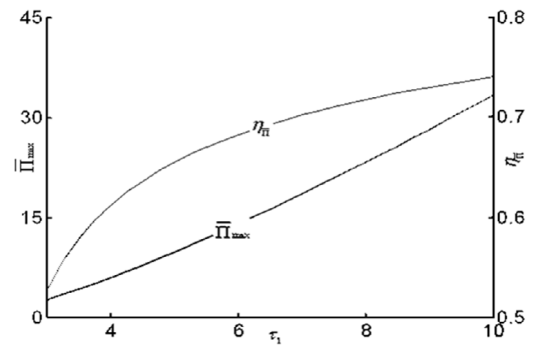


Fig. 9. Variations of  $\bar{\pi}_{max}$  and  $\eta_{\bar{\pi}}$  with  $\tau_1$ .

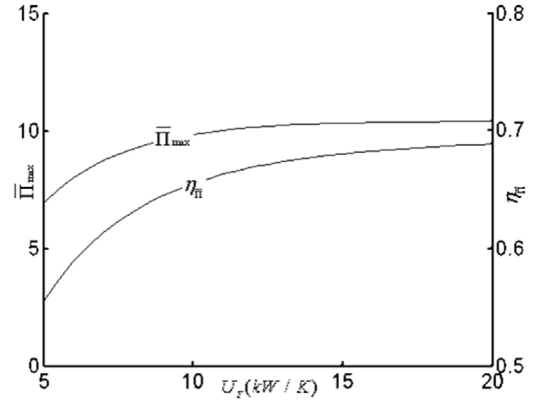


Fig. 10. Variations of  $\bar{\pi}_{max}$  and  $\eta_{\bar{\pi}}$  with  $U_T$ .

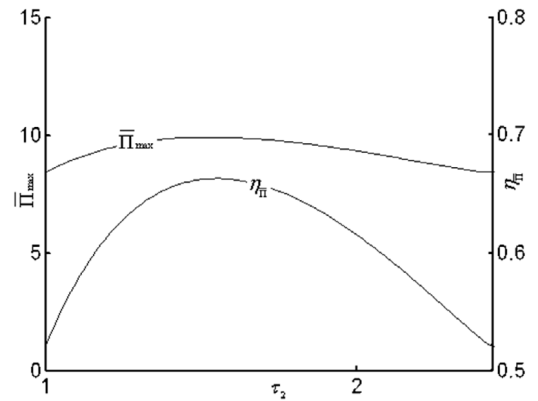


Fig. 11. Variations of  $\bar{\pi}_{max}$  and  $\eta_{\bar{\pi}}$  with  $\tau_2$ .

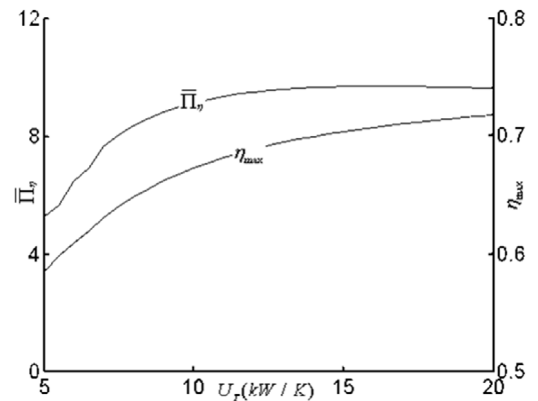


Fig. 12. Variations of  $\eta_{max}$  and  $\bar{\pi}_\eta$  with  $U_T$ .

## 6. Conclusions

A CHPP with RCCGT is investigated based on FTT theory. The HTLs, IALs and irreversible PDLs are considered. The expressions of DPR and EE of CHPP are derived. The HCDs and CPR are optimized, and the DPR and EE of CHPP are maximized. The results show that:

(1) The HCDs and CPR have their optimal values which lead to maximum value of DPR. The characteristic of maximum DPR and corresponding EE is leaf-shaped curve, and the FTEPB at the maximum DPR point is obtained. When  $u_r \approx 0.1$ , the optimization results derived by DPR and EE maximizations are equal to each other.

(2) The maximum DPR increases when  $\tau_1$ ,  $a$ ,  $b$  and  $U_T$  increase. The corresponding EE increases with the decrease in  $a$  and increases in  $\tau_1$ ,  $b$  and  $U_T$ . The optimal TTC exists in this paper, which is different from the previous results. One can see that most of the design parameters have significant impacts on the optimal design variables derived by exergoeconomic performance optimizations, which illustrates the importance of parameter analyses.

(3) Moreover,  $\eta_{\max}$  and  $\overline{T}_\eta$  increase with the increases in  $\tau_1$ ,  $\tau_2$  and  $U_T$ . However, the CHPP becomes a pure heat supply plant when  $\tau_2 > 1.44$ , and the maximum  $\eta_{\max}$  is vanished. Therefore, an appropriate  $\tau_2$  should be chosen to avoid pure heat supply of CHPP.

Because the exergoeconomic performance of irreversible RCCGT has not been investigated by the researchers before, the exergoeconomic performance optimization is conducted in this paper. Many new optimal results are obtained, which can offer new guidelines for CHPP designers.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## References

Abam, F.I., Ekwe, E.B., Effiom, S.O., Ndukwu, M.C., 2018. A comparative performance analysis and thermo-sustainability indicators of modified low-heat organic Rankine cycles (ORCs): An exergy-based procedure. *Energy Rep.* 4, 110–118.

Abbasi, M., Chahartaghi, M., Hashemian, S.M., 2018. Energy, exergy, and economic evaluations of a CCHP system by using the internal combustion engines and gas turbine as prime movers. *Energy Convers. Manage.* 173, 359–374.

Andresen, B., Berry, R.S., Ondrechen, M.J., Salamon, P., 1984. Thermodynamics for processes in finite time. *Acc. Chem. Res.* 17 (8), 266–271.

Atmaca, M., Gumus, M., Inan, A.T., Yilmaz, T., 2009. Optimization of irreversible cogeneration systems under alternative performance criteria. *Int. J. Thermophys.* 30 (5), 1724.

Atmaca, M., Yilmaz, E., Kurtulus, A.B., 2016. Application of cogeneration on a housing complex. *J. Clean Energy Technol.* 4 (2), 129–135.

Bejan, A., 1996. *Entropy Generation Minimization*. CRC Press, Boca Raton FL.

Bojic, M., 1997. Cogeneration of power and heat by using endoreversible Carnot engine. *Energy Convers. Manage.* 38 (18), 1877–1880.

Caliano, M., Bianco, N., Graditi, G., Mongibello, L., 2017. Design optimization and sensitivity analysis of a biomass-fired combined cooling, heating and power system with thermal energy storage systems. *Energy Convers. Manage.* 149, 631–645.

Chen, L.G., Feng, H.J., Sun, F.R., 2011. Exergoeconomic performance optimization for a combined cooling, heating and power generation plant with an endoreversible closed Brayton cycle. *Math. Comput. Modelling* 54 (11–12), 2785–2801.

Chen, L.G., Feng, H.J., Sun, F.R., 2013. Exergy optimization for irreversible closed Brayton cycle combined cooling, heating and power generation plant. *J. Energy Inst.* 86 (2), 97–106.

Chen, L.G., Li, J., 2020. *Thermodynamic Optimization Theory for Two-Heat-Reservoir Cycles*. Science Press, Beijing.

Chen, L.G., Sun, F.R., Wu, C., 1997. Exergoeconomic performance bound and optimization criteria for heat engines. *Int. J. Ambient Energy* 18 (4), 216–218.

Chen, L.G., Sun, F.R., Wu, C., 2004. Maximum profit performance for generalized irreversible Carnot engines. *Appl. Energy* 79 (1), 15–25.

Chen, L.G., Wu, C., Sun, F.R., 1996. Maximum profit performance of an absorption refrigerator. *Int. J. Energy Environ. Econ.* 4 (1), 1–7.

Chen, L.G., Wu, C., Sun, F.R., 1999. Finite time thermodynamic optimization or entropy generation minimization of energy systems. *J. Non-Equilib. Thermodyn.* 24 (4), 327–359.

Chen, L.G., Xia, S.J., 2018. *Generalized Thermodynamic Dynamic-Optimization for Irreversible Cycles – Thermodynamic and Chemical Theoretical Cycles*. Science Press, Beijing, (in Chinese).

Chen, L.G., Xia, S.J., 2019. Progresses in generalized thermodynamic dynamic-optimization of irreversible processes. *Sci. Sin.: Technol.* 49 (9), 981–1022.

Chen, L.G., Yang, B., Ge, Y.L., Sun, F.R., 2014. Finite time exergoeconomic performance of a real, intercooled, regenerated gas turbine cogeneration plant. Part 1: Model description and parametric analyses. *Int. J. Low-Carbon Technol.* 9 (1), 29–37.

Ding, Z.M., Chen, L.G., Sun, F.R., 2011. Finite time exergoeconomic performance for six endoreversible heat engine cycles: Unified description. *Appl. Math. Model.* 35 (2), 728–736.

Dubey, M., Chandra, H., Kumar, A., 2016. Thermal modelling and optimisation of total useful energy rate of Joule-Brayton reheat cogeneration cycle. *Int. J. Sustain. Energy* 35 (2), 103–114.

El-Sayed, M., 2003. *The Thermoeconomics of Energy Conversion*. Elsevier, London.

Feng, H.J., Chen, L.G., Sun, F.R., 2010. Finite time exergoeconomic performance optimization for a universal steady flow endoreversible heat pump model. *Int. J. Low-Carbon Technol.* 5 (2), 105–110.

Feng, H.J., Chen, L.G., Sun, F.R., 2011. Exergoeconomic optimal performance of an irreversible closed Brayton cycle combined cooling, heating and power plant. *Appl. Math. Model.* 35 (9), 4661–4673.

Ge, Y.L., Wang, W.H., Chen, L.G., Meng, F.K., 2019. Exergoeconomic performance analyses and optimization of an irreversible closed intercooled regenerated gas turbine cycle. *Int. J. Ambient Energy* in press.

Han, B.C., Cheng, W.L., Li, Y.Y., Nian, Y.L., 2017. Thermodynamic analysis of heat driven Combined Cooling Heating and Power system (CCHP) with energy storage for long distance transmission. *Energy Convers. Manage.* 154, 102–117.

Hao, X.L., Zhang, G.Q., 2013. Maximum useful energy rate and efficiency of a recuperative Brayton cogeneration plant. *J. Cent. South Univ.* 20 (1), 156–163.

Kan, X.X., Chen, L.G., Sun, F.R., Wu, F., 2010. Exergoeconomic performance optimization for a steady-flow endoreversible refrigerator cycle model including five typical cycles. *Int. J. Low-Carbon Technol.* 5 (2), 74–80.

Kaushik, S.C., Chandra, H., Khaliq, A., 2005. Thermal exergy optimisation for an irreversible cogeneration power plant. *Int. J. Exergy* 2 (3), 260–273.

Lucia, U., Grisolia, G., 2019. Exergy inefficiency: An indicator for sustainable development analysis. *Energy Rep.* 5, 62–69.

Mehrpooya, M., Sadeghzadeh, M., Rahimi, A., Pouriman, M., 2019. Technical performance analysis of a combined cooling heating and power (CCHP) system based on solid oxide fuel cell (SOFC) technology – A building application. *Energy Convers. Manage.* 198, 111767.

Mirzaee, M., Zare, R., Maddah, H., Sadeghzadeh, M., Ahmadi, M.H., Acikcalp, E., Chen, L.G., 2019. Thermodynamic analysis of different scenarios in a CCHP system with micro turbine - absorption chiller, and heat exchanger. *Energy Convers. Manage.* 198, 111919.

Mohammadi, A., Kasaeian, A., Pourfayaz, F., Ahmadi, M.H., 2017. Thermodynamic analysis of a combined gas turbine, ORC cycle and absorption refrigeration for a CCHP system. *Appl. Therm. Eng.* 111, 397–406.

Salamon, P., Nitzan, A., 1981. Finite time optimizations of a Newton's law Carnot cycle. *J. Chem. Phys.* 74 (6), 3546–3560.

Sheykhi, M., Chahartaghi, M., Balakheili, M.M., Hashemian, S.M., Miri, S.M., Rafiee, N., 2019. Performance investigation of a combined heat and power system with internal and external combustion engines. *Energy Convers. Manage.* 185, 291–303.

Tao, G.S., Chen, L.G., Sun, F.R., 2009. Exergoeconomic performance optimization for an endoreversible regenerative gas turbine closed-cycle cogeneration plant. *Riv. Mex. Fis.* 55 (3), 192–200.

Tsatsaronis, G., 1993. Thermoeconomic analysis and optimization of energy systems. *Prog. Energy Combust. Sci.* 19 (3), 227–257.

- Urbanucci, L., Bruno, J.C., Testi, D., 2019. Thermodynamic and economic analysis of the integration of high-temperature heat pumps in trigeneration systems. *Appl. Energy* 238, 516–533.
- Ust, Y., Sahin, B., Kodal, A., 2007. Optimization of a Dual cycle cogeneration system based on a new exergetic performance criterion. *Appl. Energy* 84 (11), 1079–1091.
- Wang, Z., Han, W., Zhang, N., Liu, M., Jin, H., 2017. Proposal and assessment of a new CCHP system integrating gas turbine and heat-driven cooling/power cogeneration. *Energy Convers. Manage.* 144, 1–9.
- Wang, J., Lu, Z., Li, M., Lior, N., Li, W., 2019. Energy, exergy, exergoeconomic and environmental (4E) analysis of a distributed generation solar-assisted CCHP (combined cooling, heating and power) gas turbine system. *Energy* 175, 1246–1258.
- Wang, X., Yang, C., Huang, M., Ma, X., 2018. Multi-objective optimization of a gas turbine-based CCHP combined with solar and compressed air energy storage system. *Energy Convers. Manage.* 164, 93–101.
- Wu, F., Chen, L.G., Sun, F.R., Wu, C., 2000. Finite-time exergoeconomic performance bound for a quantum Stirling engine. *Internat. J. Engrg. Sci.* 38 (2), 239–247.
- Wu, D., Han, Z., Liu, Z., Zhang, H., 2019. Study on configuration optimization and economic feasibility analysis for combined cooling, heating and power system. *Energy Convers. Manage.* 190, 91–104.
- Yang, B., Chen, L.G., Ge, Y.L., Sun, F.R., 2014a. Exergy performance analyses of an irreversible two-stage intercooled regenerative reheated closed Brayton CHP plant. *Int. J. Exergy* 14 (4), 459–483.
- Yang, B., Chen, L.G., Ge, Y.L., Sun, F.R., 2014b. Finite time exergoeconomic performance of a real, intercooled, regenerated gas turbine cogeneration plant. Part 2: Heat conductance distribution and pressure ratio optimization. *Int. J. Low-Carbon Technol.* 9 (4), 262–267.
- Yang, B., Chen, L.G., Sun, F.R., 2011. Finite time exergoeconomic performance of an irreversible intercooled regenerative Brayton cogeneration plant. *J. Energy Inst.* 84 (1), 5–12.
- Yang, B., Chen, L.G., Sun, F.R., 2016. Exergy performance optimization of an endoreversible variable-temperature heat reservoirs intercooled regenerated Brayton cogeneration plant. *J. Energy Inst.* 89 (1), 1–11.
- Yilmaz, T., Bayraktar, S., Tasci, F., 2008. Efficiency optimisation of gas turbine based cogeneration cycle. *J. Energy Inst.* 81 (2), 110–113.