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# Power Optimization of a Modified Closed Binary Brayton Cycle with Two Isothermal Heating Processes and Coupled to Variable-Temperature Reservoirs

Chenqi Tang<sup>1,2,3</sup>, Lingen Chen<sup>1,2,\*</sup> , Huijun Feng<sup>1,2</sup>, Wenhua Wang<sup>3</sup> and Yanlin Ge<sup>1,2</sup>

<sup>1</sup> Institute of Thermal Science and Power Engineering, Wuhan Institute of Technology, Wuhan 430205, China; tangchenqi7@163.com (C.T.); huijunfeng@139.com (H.F.); geyali9@hotmail.com (Y.G.)

<sup>2</sup> School of Mechanical and Electrical Engineering, Wuhan Institute of Technology, Wuhan 430205, China

<sup>3</sup> College of Power Engineering, Naval University of Engineering, Wuhan 430033, China; wwh\_gt371@163.com

\* Correspondence: lgchenna@yahoo.com or lingenchen@hotmail.com

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**Abstract:** A modified closed binary Brayton cycle model with variable isothermal pressure drop ratios is established by using finite time thermodynamics in this paper. A topping cycle, a bottoming cycle, two isothermal heating processes and variable-temperature reservoirs are included in the new model. The topping cycle is composed of a compressor, a regular combustion chamber, a converging combustion chamber, a turbine and a precooler. The bottoming cycle is composed of a compressor, an ordinary regenerator, an isothermal regenerator, a turbine and a precooler. The heat conductance distributions among the six heat exchangers are optimized with dimensionless power output as optimization objective. The results show that the double maximum dimensionless power output increases first and then tends to be unchanged while the inlet temperature ratios of the regular combustion chamber and the converging combustion chamber increase. There also exist optimal thermal capacitance rate matchings among the working fluid and heat reservoirs, leading to the optimal maximum dimensionless power output.

**Keywords:** finite time thermodynamics; modified binary Brayton cycle power plant; power output; energy saving; heat exchanger optimization

## 1. Introduction

Due to the characteristics of high power density (PD), small vibration, high automation, low operating pressure and easy lubrication, gas turbine plants (Brayton heat engine cycle) are extensively applied in the fields of aviation, energy, transportation, etc. According to the different working fluid (WF) circulation modes, the Brayton cycle is divided into open and closed cycles, and many works concerning the classical thermodynamic analyses and optimizations for various Brayton cycles have been performed [1–3]. The WF of closed Brayton cycle is not directly connected with the atmosphere, and does not participate in the combustion process. Hence, it is applied to convert nuclear energy, geothermal energy, solid fuel and other primary energy into electricity energy.

For the case of simple heating, the temperature of the gas elevates in the direction of a duct when the subsonic compressible gas flows through the smooth heating duct with a fixed cross-sectional area. For the case of simple cross-sectional area change, the temperature drops when the gas flows through the smooth adiabatic duct with a reduced cross-sectional area. Based on these two gas properties, the isothermal processes can be realized when the subsonic compressible gas flows through the smooth heating duct with a reduced cross-sectional area. Vecchiarelli et al. [4] presented a combustion chamber where the WF could be heated isothermally. The introduction of this type of combustion chamber

could effectively improve the thermal efficiency (TEF) of the Brayton cycle, and reduce the emissions of nitrogen oxides and other harmful gases. Göktun and Yavuz [5] applied the isothermal heating combustion chamber to the regenerative Brayton cycle, and discovered the isothermal pressure drop ratio impacted the cycle performance significantly. Based on [5], Erbay et al. [6] compared the optimal performances of an isothermal heating regenerative Brayton cycle under maximum power output (PO) and maximum PD. Jubeh [7] found the exergy efficiency was enhanced by adding the isothermal heating combustion chamber in regenerative Brayton cycle. El-Maksoud [8] combined the isothermal concept and double Brayton cycle to establish a new cycle model. Based on [8], Qi et al. [9] derived the specific work and exergy efficiency, and analyzed the impacts of different parameters on the exergy efficiency. All those works were carried out by using classical thermodynamics.

Finite time thermodynamics (FTT) [10] have been extensively applied in the analyses and optimizations of many thermodynamic systems. The purpose of FTT is to reduce the irreversibilities of processes and cycles and to improve the energy utilization rates [11]. Plenty of FTT studies have been conducted for various heat engine cycles, including the Novikov engine [12], the Stirling engine [13], Rankine cycles [14–21], heated gas expansion process [22], thermoelectric generators [23–26], the fuel cell hybrid cycle [27], the gas–mercury combined cycle [28], the thermocapacitive heat engine [29], the Maisotsenko–Diesel cycle [30], the trigeneration cycle [31], Dual-Miller cycles [32–34], Feynman’s ratchet [35], the Kalina cycle [36] and so on.

For the Brayton cycles, FTT studies have been also conducted for simple cycles [37], regenerative cycles [38–40], multi-intercooling-and-regenerative cycles [41–43], the fuel cell–Brayton combined cycle [44], Maisotsenko–Brayton cycles [45,46], Brayton cycle-based cooling, heat and power combined cycles [47,48] and so on.

For the Brayton cycles with isothermal heating modification, Kaushik et al. [49] optimized the regenerative Brayton cycle with isothermal process whose optimization objective was the PO. Tyagi et al. [50–56] optimized the performances of the isothermal heating modified simple, regenerated and intercooling Brayton cycles with different optimization objectives. Based on [49–56], Wang et al. [57,58] and Tang et al. [59,60] analyzed and optimized the endoreversible simple, irreversible simple and irreversible regenerative Brayton cycles with isothermal processes. Arora et al. [61] optimized the regenerative Brayton cycle with isothermal process by employing the NSGA-II algorithm.

Based on El-Maksoud’s classical thermodynamic model [8], Qi et al. [62] established a closed endoreversible binary Brayton cycle model with two isothermal processes, without internal irreversibility, and coupled to constant-temperature reservoirs (CTRs). They derived the functional expressions of PO, TEF, PD and ecological function, respectively. The impacts of different thermodynamic parameters on the relationships among performance indexes and the pressure ratio of the topping cycle were analyzed, and the heat conductance distributions (HCDs) among heat exchangers were further optimized.

Based on the previously established cycle models in [8,62], a modified closed binary Brayton cycle (MCBBC) with variable isothermal pressure drop ratios and internal and external irreversibilities will be established by using FTT in this paper. The HCDs will be optimized with dimensionless PO. The influences of different thermodynamic parameters on the optimal performance will be analyzed, and the thermal capacitance rate matchings (TCRMs) among the WF and the heat reservoirs will be also discussed.

## 2. Cycle Model

Figure 1a shows the schematic diagram of the MCBBC with two isothermal heating processes [8]. A topping cycle and a bottoming cycle are included in the model. The topping cycle is composed of a compressor (Com1), a regular combustion chamber (RCC), a converging combustion chamber (CCC), a turbine (Tur1) and a precooler (PC1). The bottoming cycle is composed of a compressor (Com2), an ordinary regenerator (OR), an isothermal regenerator (IR), a turbine (Tur2) and a precooler (PC2).

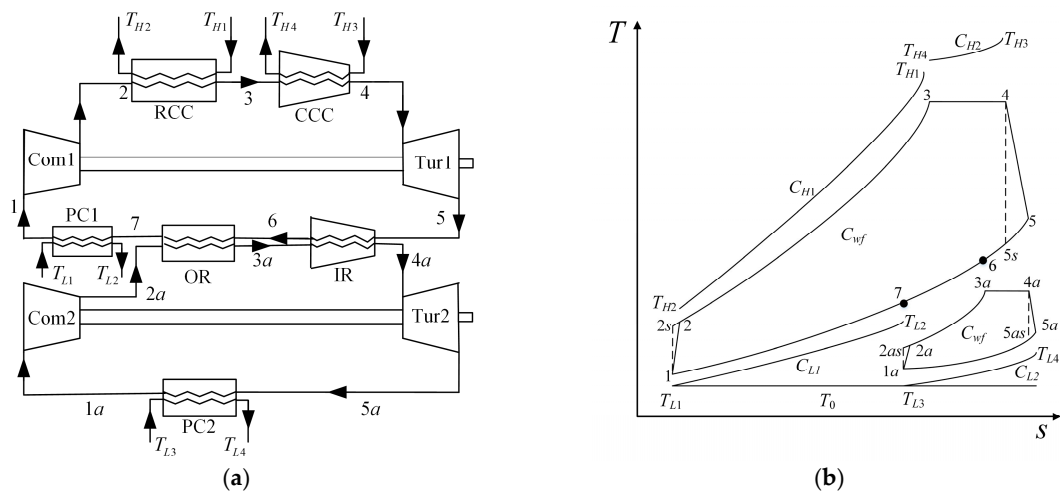


Figure 1. (a) Schematic diagram of the cycle [8]; (b) T-s diagram of the cycle.

Figure 1b illustrates the T-s diagram of the MCBBC. In the figure, processes 1 → 2, 2 → 3, 3 → 4, 4 → 5, 5 → 6, 6 → 7 and 7 → 1 represent the irreversible adiabatic compression, isobaric heating, isothermal heating, irreversible adiabatic expansion and three isobaric exothermic processes of the WF in Com1, RCC, CCC, Tur1, IR, OR and PC1, respectively. Processes 1a → 2a, 2a → 3a, 3a → 4a, 4a → 5a and 5a → 1a represent the irreversible adiabatic compression, isobaric heating, isothermal heating, irreversible adiabatic expansion and isobaric exothermic process of the WF in Com2, OR, IR, Tur2 and PC2, respectively. Processes 1 → 2s, 4 → 5s, 1a → 2as and 4a → 5as are the isentropic processes corresponding to the processes 1 → 2, 4 → 5, 1a → 2a and 4a → 5a respectively.

It is assumed that the WFs of the topping and bottoming cycles are the same, both of which are ideal gases. The specific heat at constant pressure, thermal capacity rate, specific heat ratio, mass flow rate and gas constant of the WF are  $C_p$ ,  $C_{wf}$ ,  $k$ ,  $\dot{m}$  and  $R_g$ , respectively, where  $C_{wf} = C_p \dot{m}$  and  $m = (k - 1)/k$ . The temperatures and pressures at different state points are signed as  $T_i$  and  $P_i$  ( $i = 1, 2, 3, 4, 5, 6, 7, 1a, 2a, 3a, 4a, 5a, 2s, 5s, 2as, 5as$ ), and the ambient temperature is  $T_0$ . The inlet temperatures of the outer fluids in the RCC, CCC, PC1 and PC2 are  $T_{H1}$ ,  $T_{H3}$ ,  $T_{L1}$  and  $T_{L3}$ , and the outlet temperatures of outer fluids in the RCC, CCC, PC and PC2 are  $T_{H2}$ ,  $T_{H4}$ ,  $T_{L2}$  and  $T_{L4}$ , respectively. The thermal capacity rates of outer fluids in the RCC, CCC, PC1 and PC2 are  $C_{H1}$ ,  $C_{H2}$ ,  $C_{L1}$  and  $C_{L2}$ , respectively. The pressure ratios in the Com1 and Com2 are  $\pi_{com1}$  and  $\pi_{com2}$ , and the isothermal pressure drop ratios at the CCC and IR are  $\pi_t$  and  $\pi_{ta}$ , respectively. The heat conductances of the heat exchangers for the RCC, CCC, OR, IR, PC1 and PC2 are  $U_j$  ( $j = H1, H2, R1, R2, L1, L2$ ), and the corresponding effectivenesses are  $E_j$ ; namely:

$$E_{H1} = \frac{1 - \exp[-N_{H1}(1 - C_{H1min}/C_{H1max})]}{1 - (C_{H1min}/C_{H1max}) \exp[-N_{H1}(C_{H1min}/C_{H1max})]} \quad (1)$$

$$E_{H2} = 1 - \exp(-N_{H2}), E_{R1} = N_{R1}/(N_{R1} + 1), E_{R2} = 1 - \exp(-N_{R2}) \quad (2)$$

$$E_{L1} = \frac{1 - \exp[-N_{L1}(1 - C_{L1min}/C_{L1max})]}{1 - (C_{L1min}/C_{L1max}) \exp[-N_{L1}(C_{L1min}/C_{L1max})]} \quad (3)$$

$$E_{L2} = \frac{1 - \exp[-N_{L2}(1 - C_{L2min}/C_{L2max})]}{1 - (C_{L2min}/C_{L2max}) \exp[-N_{L2}(C_{L2min}/C_{L2max})]} \quad (4)$$

where,  $C_{H1max} = \max\{C_{wf}, C_{H1}\}$ ,  $C_{H1min} = \min\{C_{wf}, C_{H1}\}$ ,  $C_{L1max} = \max\{C_{wf}, C_{L1}\}$ ,  $C_{L1min} = \min\{C_{wf}, C_{L1}\}$ ,  $C_{L2max} = \max\{C_{wf}, C_{L2}\}$  and  $C_{L2min} = \min\{C_{wf}, C_{L2}\}$ . The numbers of heat transfer units for the heat exchangers are calculated as:

$$N_{H1} = U_{H1}/C_{H1min}, N_{H2} = U_{H2}/C_{H2} \quad (5)$$

$$N_{R1} = U_{R1}/C_{wf}, N_{R2} = U_{R2}/C_{wf} \quad (6)$$

$$N_{L1} = U_{L1}/C_{L1min}, N_{L2} = U_{L2}/C_{L2min} \quad (7)$$

When  $C_{H1max} = C_{H1min}$ ,  $C_{L1max} = C_{L1min}$  and  $C_{L2max} = C_{L2min}$ , Equations (1), (3) and (4) are simplified into:

$$E_{H1} = N_{H1}/(N_{H1} + 1), E_{L1} = N_{L1}/(N_{L1} + 1), E_{L2} = N_{L2}/(N_{L2} + 1) \quad (8)$$

The efficiencies in the Com1, Com2, Tur1 and Tur2 are  $\eta_{com1}$ ,  $\eta_{com2}$ ,  $\eta_{tur1}$  and  $\eta_{tur2}$ , respectively:

$$\eta_{com1} = (T_{2s} - T_1)/(T_2 - T_1) \quad (9)$$

$$\eta_{com2} = (T_{2as} - T_{1a})/(T_{2a} - T_{1a}) \quad (10)$$

$$\eta_{tur1} = (T_4 - T_5)/(T_4 - T_{5s}) \quad (11)$$

$$\eta_{tur2} = (T_{4a} - T_{5a})/(T_{4a} - T_{5as}) \quad (12)$$

The heat absorbing rates of WF in the RCC, CCC, OR and IR are  $\dot{Q}_{2-3}$ ,  $\dot{Q}_{3-4}$ ,  $\dot{Q}_{2a-3a}$  and  $\dot{Q}_{3a-4a}$ , and the heat releasing rates in the PC1 and PC2 are  $\dot{Q}_{7-1}$  and  $\dot{Q}_{5a-1a}$ . They are calculated as:

$$\dot{Q}_{2-3} = C_{H1}(T_{H1} - T_{H2}) = C_{wf}(T_3 - T_2) = C_{Hmin}E_{H1}(T_{H1} - T_2) \quad (13)$$

$$\dot{Q}_{3-4} = C_{H2}(T_{H3} - T_{H4}) = C_{H2}E_{H2}(T_{H3} - T_3) = \dot{m}(V_4^2 - V_3^2)/2 \quad (14)$$

$$\dot{Q}_{2a-3a} = C_{wf}(T_{3a} - T_{2a}) = C_{wf}(T_6 - T_{H2}) = C_{wf}E_{R1}(T_6 - T_{2a}) \quad (15)$$

$$\dot{Q}_{3a-4a} = C_{wf}(T_5 - T_6) = C_{wf}E_{R2}(T_5 - T_{3a}) = \dot{m}(V_{4a}^2 - V_{3a}^2)/2 \quad (16)$$

$$\dot{Q}_{7-1} = C_{wf}(T_7 - T_1) = C_{L1}(T_{L2} - T_{L1}) = C_{L1min}E_{L1}(T_7 - T_{L1}) \quad (17)$$

$$\dot{Q}_{5a-1a} = C_{wf}(T_{5a} - T_{1a}) = C_{L2}(T_{L4} - T_{L3}) = C_{L2min}E_{L2}(T_{5a} - T_{L3}) \quad (18)$$

The power output and thermal efficiency of the cycle are  $W$  and  $\eta$ , respectively:

$$W = \dot{Q}_{2-3} + \dot{Q}_{3-4} - \dot{Q}_{5a-1a} - \dot{Q}_{7-1} \quad (19)$$

$$\eta = W/(\dot{Q}_{2-3} + \dot{Q}_{3-4}) \quad (20)$$

Processes 3–4 and 3a–4a are the isothermal ones, and the heat absorbing rates of the two processes are:

$$\dot{Q}_{3-4} = \dot{m}(h_4 - h_3) - \dot{m} \int_3^4 v dp = \dot{m}R_g T_3 \ln \pi_t \quad (21)$$

$$\dot{Q}_{3a-4a} = \dot{m}(h_{4a} - h_{3a}) - \dot{m} \int_{3a}^{4a} v dp = \dot{m}R_g T_{3a} \ln \pi_{ta} \quad (22)$$

Processes 1–2s, 1–2as, 4–5s and 4a–5as are the isentropic processes; namely:

$$T_{2s}/T_1 = \pi_{com1}^m = x, T_{2as}/T_{1a} = \pi_{com2}^m = x_a \quad (23)$$

$$T_4/T_5 = \pi_{\text{com1}}^m \pi_t^m = xy, T_{4a}/T_{5a} = \pi_{\text{com2}}^m \pi_{ta}^m = x_a y_a \quad (24)$$

where  $x$ ,  $y$ ,  $x_a$  and  $y_a$  are the parameters of temperature ratios which can be calculated by the pressure ratios.

The upper limits of  $\pi_t$  and  $\pi_{ta}$  are 1, which means that the isothermal heating is not used. When  $\pi_t < 1$  or  $\pi_{ta} < 1$ , the topping or bottoming cycle adopts the isothermal process. The isothermal pressure drop ratios must meet the following constraints:

$$\pi_t \geq \pi_{\text{com1}}^{-1}, \pi_{ta} \geq \pi_{\text{com2}}^{-1} \quad (25)$$

$$\ln \pi_t = \frac{-C_p(k-1)(M_4^2 - M_3^2)}{2R_g} = -0.7(M_4^2 - M_3^2) \quad (26)$$

$$\ln \pi_{ta} = \frac{-C_p(k-1)(M_{4a}^2 - M_{3a}^2)}{2R_g} = -0.7(M_{4a}^2 - M_{3a}^2) \quad (27)$$

where  $M_3$  and  $M_4$  ( $M_{3a}$  and  $M_{4a}$ ) are the Mach numbers at the inlet and outlet of CCC (IR), respectively. If  $M_3 = M_{3a} = 0$  and  $M_4 = M_{4a} = 1$ ,  $(M_4^2 - M_3^2)$  and  $(M_{4a}^2 - M_{3a}^2)$  get their maximum values of 1, and  $\pi_t$  and  $\pi_{ta}$  get their minimum values of 0.4966. For the initial velocity of the WF, the Mach numbers satisfy  $M_3 = M_{3a} = 0.2$  and  $M_4 = M_{4a} = 1$ , and the corresponding minimum values of  $\pi_t$  and  $\pi_{ta}$  are 0.5107. At the same time,  $\bar{W}$  must be greater than or equal to zero; otherwise, the cycle is meaningless.

The major difference between the model in this paper and that in [8] is that all the heat transfer losses in the six heat exchangers are considered in this paper. This is also the major difference between classical thermodynamic model and FTT model. The major differences between the model in this paper and that in [62] are two aspects: One is that the irreversible compression and expansion losses are considered in this paper; this is also the major difference between the endoreversible model and the irreversible one. Another is that the heat reservoirs are assumed to be variable-temperature ones in this paper; this is one of basic characteristics of practical closed engineering cycles.

According to the above model, the dimensionless PO  $\bar{W}$  and TEF  $\eta$  can be given by:

$$\bar{W} = \frac{\{a_1 a_2 + T_{H3} - C_{H1min} E_{H1} (a_1 a_2 + T_{H1}) / C_{wf}\} C_{H2} E_{H2} + C_{H1min} E_{H1} (a_1 a_2 + T_{H1}) + C_{wf} (a_4 - a_5) - C_{wf} [a_1 a_2 \eta_{\text{com1}} / (\eta_{\text{com1}} + x - 1) + a_3]}{C_{wf} T_0} \quad (28)$$

$$\eta = 1 - \frac{C_{wf} [(a_1 a_2 \eta_{\text{com1}}) / (\eta_{\text{com1}} + x - 1) + a_3 - a_4 + a_5]}{C_{H2} E_{H2} \{-C_{H1min} E_{H1} (a_1 a_2 + T_{H1}) / C_{wf} + a_1 a_2 + T_{H3}\} + C_{H1min} E_{H1} (a_1 a_2 + T_{H1})} \quad (29)$$

where  $a_2$ ,  $a_2$ ,  $a_3$ ,  $a_4$  and  $a_5$  are listed in Appendix A.

If Equations (21) and (22) are not considered when solving Equations (28) and (29), the final analytical solutions for  $\bar{W}$  and  $\eta$  of the cycle cannot be obtained. Considering Equations (21) and (22), the values of  $x$  and  $y$  in Equations (28) and (29) are obtained by numerical calculation, and the corresponding values of  $\bar{W}$  and  $\eta$  can be obtained.

If  $C_{H1}$ ,  $C_{H2}$ ,  $C_{L1}$ ,  $C_{L2}$ ,  $E_{H1}$ ,  $E_{H2}$ ,  $E_{R1}$ ,  $E_{R2}$ ,  $E_{L1}$ ,  $E_{L2}$ ,  $\eta_{\text{com1}}$ ,  $\eta_{\text{com2}}$ ,  $\eta_{\text{tur1}}$  and  $\eta_{\text{tur2}}$  take different values, the model can be converted into different special models; Equations (28) and (29) can be reduced to the corresponding dimensionless PO and TEF respectively, which have a certain universality.

When  $\eta_{\text{com1}} = \eta_{\text{com2}} = \eta_{\text{tur1}} = \eta_{\text{tur2}} = 1$ , Equations (28) and (29) can be reduced to the dimensionless PO and TEF of a modified closed endoreversible binary Brayton cycle with two isothermal heating processes and coupled to variable-temperature heat reservoirs (VTHR):

$$\bar{W} = \frac{C_{H2} E_{H2} \{b_1 b_2 + T_{H3} - C_{H1min} E_{H1} (b_1 b_2 + T_{H1}) / C_{wf}\} - C_{wf} [b_1 b_2 / x + b_3] + C_{H1min} E_{H1} (b_1 b_2 + T_{H1}) + C_{wf} (b_4 - b_5)}{C_{wf} T_0} \quad (30)$$

$$\eta = 1 - \frac{C_{wf}[b_1b_2/x + b_3 - b_4 + b_5]}{C_{H2}E_{H2}\{b_1b_2 + T_{H3} - [C_{H1min}E_{H1}(b_1b_2 + T_{H1})]/C_{wf}\} + C_{H1min}E_{H1}(b_1b_2 + T_{H1})} \quad (31)$$

where  $b_1, b_2, b_3, b_4$  and  $b_5$  are listed in Appendix A.

When  $C_{H1} = C_{H2} = C_{L1} = C_{L2} \rightarrow \infty$ , Equations (28) and (29) can be reduced to the dimensionless PO and TEF of a modified closed irreversible binary Brayton cycle with two isothermal heating processes and coupled to CTRs:

$$\bar{W} = \frac{C_{H2}E_{H2}[c_1c_2 + T_{H3} - E_{H1}(c_1c_2 + T_{H1})] - C_{wf}[c_1c_2\eta_{com1}/(\eta_{com1} + x - 1) + c_3] + (c_1c_2 + T_{H1})}{C_{wf}E_{H1} + C_{wf}(c_4 - c_5)} \quad (32)$$

$$\eta = 1 - \frac{C_{wf}[c_1c_2\eta_{com1}/(\eta_{com1} + x - 1) + c_3 - c_4 + c_5]}{C_{H2}E_{H2}[c_1c_2 + T_{H3} - (c_1c_2 + T_{H1})] + C_{wf}E_{H1}(c_1c_2 + T_{H1})} \quad (33)$$

where  $c_1, c_2, c_3, c_4$  and  $c_5$  are listed in Appendix A.

When  $\eta_{com1} = \eta_{com2} = \eta_{tur1} = \eta_{tur2} = 1$  and  $C_{H1} = C_{H2} = C_{L1} = C_{L2} \rightarrow \infty$ , Equations (28) and (29) can be reduced to the dimensionless PO and TEF of a modified closed endoreversible binary Brayton cycle with two isothermal heating processes and coupled to CTRs [62]:

$$\bar{W} = \frac{-C_{wf}[d_1d_2/x + c_3] + C_{H2}E_{H2}[d_1d_2 + T_{H3} - E_{H1}(d_1d_2 + T_{H1})] + C_{wf}E_{H1}(d_1d_2 + T_{H1}) + C_{wf}(d_4 - d_5)}{C_{wf}T_0} \quad (34)$$

$$\eta = 1 - \frac{C_{wf}(d_1d_2/x + d_3 - d_4 + d_5)}{C_{H2}E_{H2}[d_1d_2 + T_{H3} - E_{H1}(d_1d_2 + T_{H1})] + C_{wf}E_{H1}(d_1d_2 + T_{H1})} \quad (35)$$

where  $d_1, d_2, d_3, d_4$  and  $d_5$  are listed in Appendix A.

When  $E_{R1} = E_{R2} = E_{L2} = 0$ , Equations (28) and (29) can be reduced to the dimensionless PO and TEF of a modified closed irreversible Brayton cycle with an isothermal heating process and coupled to VTHR: s:

$$\bar{W} = \frac{C_{wf}xy(C_{H2}E_{H2}T_{H3} + C_{L1min}E_{L1}T_{L1}) + C_{H1min}E_{H1}T_{H1}\{[C_{wf} - C_{H2}E_{H2} + C_{L1min}E_{L1}(\eta_{tur1} - 1)]xy - C_{L1min}E_{L1}\eta_{tur1}\} + e\{-xy[C_{H1min}C_{wf}E_{H1} + C_{H2}E_{H2}(C_{wf} - C_{H1min}E_{H1})] + C_{L1min}E_{L1}(C_{wf} - C_{H1min}E_{H1})[(\eta_{tur1} - 1)xy - \eta_{tur1}]\}}{C_{wf}^2T_0xy} \quad (36)$$

$$\eta = \frac{C_{H1min}C_{L1min}E_{H1}E_{L1}\eta_{tur1}T_{H1} - xy\{C_{H1min}E_{H1}T_{H1}[C_{wf} - C_{H2}E_{H2} + C_{L1min}E_{L1}(\eta_{tur1} - 1)] + C_{wf}(C_{H2}E_{H2}T_{H3} + C_{L1min}E_{L1}T_{L1})\} + e\{xy[C_{H1min}C_{wf}E_{H1} + C_{H2}E_{H2}(C_{wf} - C_{H1min}E_{H1})] - E_{L1}C_{L1min}(C_{wf} - C_{H1min}E_{H1})[(\eta_{tur1} - 1)xy - \eta_{tur1}]\}}{xy\{e_1e_2[C_{H2}C_{wf}E_{H2} + C_{H1min}E_{H1}(C_{wf} - C_{H2}E_{H2})] + C_{H1min}E_{H1}T_{H1}(C_{H2}E_{H2} - C_{wf}) - C_{H2}C_{wf}E_{H2}T_{H3}\}} \quad (37)$$

where  $e$  is listed in Appendix A.

When  $E_{R1} = E_{R2} = E_{L2} = 0$  and  $C_{H1} = C_{H2} = C_{L1} \rightarrow \infty$ , Equations (28) and (29) can be reduced to the dimensionless PO and TEF of a modified closed irreversible Brayton cycle with an isothermal heating process and coupled to CTRs:

$$\bar{W} = \frac{xy(C_{H2}E_{H2}T_{H3} + C_{wf}E_{L1}T_{L1}) + E_{H1}T_{H1}\{[C_{wf} - C_{H2}E_{H2} + C_{wf}E_{L1}(\eta_{tur1} - 1)]xy - C_{wf}E_{L1}\eta_{tur1}\} + b_1b_2\{E_L C_{wf}(1 - E_H)[(\eta_{tur1} - 1)xy - \eta_{tur1}] - [C_{wf}E_H + C_{H2}E_{H2}(1 - E_{H1})]xy\}}{C_{wf}T_0xy} \quad (38)$$

$$\eta = \frac{C_{wf}E_{H1}E_{L1}\eta_{tur1}T_{H1} - xy\{E_{H1}T_{H2}[C_{wf} - C_{H2}E_{H2} + C_{wf}E_{L1}(\eta_{tur1} - 1)] + (C_{H2}E_{H2}T_{H3} + C_{wf}E_{L1}T_{L1})\} + b_1b_2\{[C_{wf}E_{H1} + C_{H2}(1 - E_{H1})E_{H2}]xy - C_{wf}E_{L2}(1 - E_{H1})[xy(\eta_{tur1} - 1) - \eta_{tur1}]\}}{xy\{b_1b_2[C_{H2}E_{H2} + E_{H1}(C_{wf} - C_{H2}E_{H2})] + E_{H1}(C_{H2}E_{H2} - C_{wf})T_{H1} - C_{H2}E_{H2}T_{H3}\}} \quad (39)$$

When  $E_{R1} = E_{R2} = E_{L2} = 0$  and  $\eta_{com1} = \eta_{tur1} = 1$ , Equations (28) and (29) can be reduced to the dimensionless PO and TEF of a modified closed endoreversible Brayton cycle with an isothermal heating process and coupled to VTHERs [59,60]:

$$\bar{W} = \frac{C_{wf}x\{C_{L1min}C_{wf}E_{L1}T_{L1}(y - 1) + C_{H2}E_{H2}[C_{wf}T_{H3}(y - 1) + C_{L1min}E_{L1}T_{H3}T_{L1}xy]\} + C_{H1min}E_{H1}\{C_{L1min}E_{L1}[C_{wf}T_{H1}(x - 1) + C_{wf}T_{L1}x(1 - xy) + C_{H2}E_{H2}x(T_{L1}xy - T_{H3})] + C_{wf}x[C_{wf}T_{H1}(y - 1) + C_{H2}E_{H2}(T_{H3} - T_{H1}y)]\}}{C_{wf}T_0x[C_{wf}^2y - (C_{wf} - C_{H1min}E_{H1})(C_{wf} - C_{L1min}E_{L1})]} \quad (40)$$

$$\eta = \frac{C_{wf}T_0x\{C_{L1min}C_{wf}E_{L1}T_{L1}(y - 1) + C_{H2}E_{H2}[C_{wf}T_{H3}(y - 1) + C_{L1min}E_{L1}(T_{H3} - T_{L1}xy)]\} + C_{H1min}E_{H1}\{C_{L1min}E_{L1}[C_{wf}T_{H1}(x - 1) + C_{wf}T_{L1}x(1 - xy) + C_{H2}E_{H2}x(T_{L1}xy - T_{H3})] + C_{wf}x[C_{wf}T_{H1}(y - 1) + C_{H2}E_{H2}(T_{H3} - T_{H1}y)]\}}{C_{wf}T_0x\{C_{H1min}E_{H1}[C_{wf}^2T_{H1}(y - 1) + C_{H2}C_{wf}E_{H2}(T_{H3} - T_{H1}y) + C_{L1min}C_{wf}E_{L1}(T_{H1} - T_{L1}xy) + C_{H2}C_{L1min}E_{H2}E_{L1}(T_{L1}xy - T_{H3})] + C_{H2}C_{wf}E_{H2}[C_{wf}T_{H3}(y - 1) + C_{L1min}E_{L1}(T_{H3} - T_{L1}xy)]\}} \quad (41)$$

When  $E_{R1} = E_{R2} = E_{L2} = 0$ ,  $C_{H1} = C_{H2} = C_{L1} \rightarrow \infty$  and  $\eta_{com1} = \eta_{tur1} = 1$ , Equations (28) and (29) can be reduced to the dimensionless PO and TEF of a modified closed endoreversible Brayton cycle with an isothermal heating process and coupled to CTRs:

$$\bar{W} = \frac{x\{C_{wf}E_{L1}T_{L1}(y - 1) + C_{H2}E_{H2}[T_{H3}(y - 1) + E_{L1}T_{H3}T_{L1}xy]\} + E_{H1}\{E_{L1}[C_{wf}T_{H1}(x - 1) + C_{wf}T_{L1}x(1 - xy) + C_{H2}E_{H2}x(T_{L1}xy - T_{H3})] + x[C_{wf}T_{H1}(y - 1) + C_{H2}E_{H2}(T_{H3} - T_{H1}y)]\}}{C_{wf}T_0x[y - (1 - E_{H1})(1 - E_{L1})]} \quad (42)$$

$$\eta = \frac{T_0x\{C_{wf}E_{L1}T_{L1}(y - 1) + C_{H2}E_{H2}[T_{H3}(y - 1) + E_{L1}(T_{H3} - T_{L1}xy)]\} + E_{H1}\{E_{L1}[C_{wf}T_{H1}(x - 1) + C_{wf}T_{L1}x(1 - xy) + C_{H2}E_{H2}x(T_{L1}xy - T_{H3})] + x[C_{wf}T_{H1}(y - 1) + C_{H2}E_{H2}(T_{H3} - T_{H1}y)]\}}{C_{wf}T_0x\{E_{H1}[C_{wf}T_{H1}(y - 1) + C_{H2}E_{H2}(T_{H3} - T_{H1}y) + C_{wf}E_{L1}(T_{H1} - T_{L1}xy) + C_{H2}E_{H2}E_{L1}(T_{L1}xy - T_{H3})] + C_{H2}E_{H2}[T_{H3}(y - 1) + E_{L1}(T_{H3} - T_{L1}xy)]\}} \quad (43)$$

When  $E_{H2} = E_{R1} = E_{R2} = E_{L2} = 0$ , Equations (28) and (29) can be reduced to the dimensionless PO and TEF of a closed irreversible simple Brayton cycle coupled to VTHERs [37,63]:

$$\bar{W} = \frac{\{\eta_{com1}C_{wf} - (1 - \eta_{tur1} + \eta_{tur1}/x)[(C_{wf} - C_{L1min}E_{L1})(x - 1 + \eta_{com1}) + \eta_{com1}C_{L1min}E_{L1}]\}C_{H1min}E_{H1}\tau_{H1} - \{(x - 1 + \eta_{com1})[(C_{wf} - C_{H1min}E_{H1})(1 - \eta_{tur1} + \eta_{tur1}/x) + C_{H1min}E_{H1}] - \eta_{com1}C_{wf}\}C_{L1min}E_{L1}}{\eta_{com1}C_{wf}^2 - (x - 1 + \eta_{com1})(C_{wf} - C_{H1min}E_{H1})(C_{wf} - C_{L1min}E_{L1})(1 - \eta_{tur1} + \eta_{tur1}/x)} \quad (44)$$

$$\eta = 1 - \frac{E_{L1}[E_{H1}\eta_{com1}\tau_{H1}(1 - \eta_{tur1} + \eta_{tur1}/x) - \eta_{com1} + (x - 1 + \eta_{com1})(1 - E_{H1})(1 - \eta_{tur1} + \eta_{tur1}/x)]}{E_{H1}\{\tau_{H1}[\eta_{com1} - (x - 1 + \eta_{com1})(1 - E_{L1})(1 - \eta_{tur1} + \eta_{tur1}/x)] - E_{L1}(x - 1 + \eta_{com1})\}} \quad (45)$$

When  $E_{H2} = E_{R1} = E_{R2} = E_{L2} = 0$  and  $C_{H1} = C_{H2} = C_{L1} \rightarrow \infty$ , Equations (28) and (29) can be reduced to the dimensionless PO and TEF of a closed irreversible simple Brayton cycle coupled to CTRs [37,63]:

$$\bar{W} = \frac{\{E_{H1}\tau_{H1}[\eta_{com1} - (1 - \eta_{tur1} + \eta_{tur1}/x)[(x - 1 + \eta_{com1})(1 - E_{L1}) + \eta_{com1}E_{L1}]\} - \{(x - 1 + \eta_{com1})[(1 - \eta_{tur1} + \eta_{tur1}/x)(1 - E_{H1}) + E_{H1}] - \eta_{com1}\}E_{L1}}{\eta_{com1} - (x - 1 + \eta_{com1})(1 - E_{H1})(1 - E_{L1})(1 - \eta_{tur1} + \eta_{tur1}/x)} \quad (46)$$

$$\eta = 1 - \frac{E_{L1}[\eta_{com1}E_{H1}\tau_{H1}(1 - \eta_{tur1} + \eta_{tur1}/x) - \eta_{com1} + (x - 1 + \eta_{com1})(1 - E_{H1})(1 - \eta_{tur1} + \eta_{tur1}/x)]}{E_{H1}\{[\eta_{com1} - (x - 1 + \eta_{com1})(1 - E_{L1})(1 - \eta_{tur1} + \eta_{tur1}/x)]\tau_{H1} - E_{L1}(x - 1 + \eta_{com1})\}} \quad (47)$$

When  $E_{H2} = E_{R1} = E_{R2} = E_{L2} = 0$  and  $\eta_{com1} = \eta_{tur1} = 1$ , Equations (28) and (29) can be reduced to the dimensionless PO and TEF of a closed endoreversible simple Brayton cycle coupled to VTHERs [64]:

$$\bar{W} = \frac{C_{H1min}C_{L1min}E_{H1}E_{L1}(x - 1)(\tau_{H1} - x\tau_{L1})}{C_{L1min}C_{wf}E_{L1} + C_{H1min}E_{H1}(C_{wf} - C_{L1min}E_{L1})} \quad (48)$$

$$\eta = 1 - x^{-1} \quad (49)$$

When  $E_{H2} = E_{R1} = E_{R2} = E_{L2} = 0$ ,  $\eta_{\text{com1}} = \eta_{\text{tur1}} = 1$  and  $C_{H1} = C_{H2} = C_{L1} \rightarrow \infty$ , Equations (28) and (29) can be reduced to the dimensionless PO and TEF of the closed endoreversible simple Brayton cycle coupled to CTRs [65,66]:

$$\bar{W} = \frac{E_{H1}E_{L1}(1 - 1/x)(\tau_{H1} - x\tau_{L1})}{E_{H1} + E_{L1} - E_{H1}E_{L1}} \quad (50)$$

$$\eta = 1 - x^{-1} \quad (51)$$

### 3. Optimal Heat Conductance Distributions

With  $\bar{W}$  as the optimization objective, the heat conductances of six heat exchangers will be optimized by fixing the total heat conductance (THC); namely,  $U_T = \sum U_j$  ( $j = H1, H2, R1, R2, L1, L2$ ). The HCDs in the RCC, CCC, OR, IR, PC1 and PC2 are defined as:

$$u_j = U_j/U_T \quad (52)$$

where  $u_j$  must meet the following constraints:

$$\sum u_j = 1, 0 < u_j < 1 \quad (53)$$

The dimensionless PO of the MCBBC can be maximized by optimizing the HCDs. Finally, the maximum dimensionless PO ( $\bar{W}_{\text{max}}$ ) and the corresponding optimal HCDs ( $(u_{H1})_{\bar{W}_{\text{max}}}$ ,  $(u_{H2})_{\bar{W}_{\text{max}}}$ ,  $(u_{L1})_{\bar{W}_{\text{max}}}$ ,  $(u_{L2})_{\bar{W}_{\text{max}}}$ ,  $(u_{R1})_{\bar{W}_{\text{max}}}$  and  $(u_{R2})_{\bar{W}_{\text{max}}}$ ) can be obtained. Moreover, the optimal isothermal pressure drop ratios ( $(\pi_t)_{\bar{W}_{\text{max}}}$  and  $(\pi_{ta})_{\bar{W}_{\text{max}}}$ ) can be calculated based on the optimal HCDs. The values or ranges of the variables are listed in Table 1. The flow chart of dimensionless PO optimization is displayed in Figure 2. Calculate the negative number of the dimensionless power output, and then the function “fmincon” in MATLAB is used to solve the minimum value. The parameters of “fmincon” are: “TolCon” is  $10^{-6}$ , “TolConSQP” is 300 and “TolFun” is  $10^{-6}$ .

**Table 1.** Values or ranges of the variables.

| Parameters   | Symbol  | Initial Value | Range  | Unit        |
|--|---|---------------|--------|-------------|
| Thermal capacity rate of outer fluid at RCC        | $C_{H1}$                                      | 1.2           | —      | kW/K        |
| Thermal capacity rate of outer fluid<br>kW/Kat CCC | $C_{H2}$                                      | 1             | —      |             |
| Thermal capacity rate of outer fluid<br>kW/Kat PC1 | $C_{L1}$                                      | 1.2           | —      |             |
| Thermal capacity rate of outer fluid at PC2        | $C_{L2}$                                      | 1.2           | —      | kW/K        |
| Thermal capacity rate of WF                        | $C_{wf}$                                      | 1             | —      | kW/K        |
| Specific heats ratio                               | $k$   | 1.4           | —      | —           |
| Gas constant                                       | $R_g$   | 0.287         | —      | kJ/(kg · K) |
| Ambient temperature                                | $T_0$   | 300           | —      | K           |
| THC  | $U_{\text{tot}}$                              | 18            | 8–36   | kW/K        |
| Compressor efficiencies                            | $\eta_{\text{com1}},$<br>$\eta_{\text{com2}}$ | 0.9           | 0.7–1  | —           |
| Turbine efficiencies                               | $\eta_{\text{tur1}}, \eta_{\text{tur2}}$      | 0.9           | 0.7–1  | —           |
| Inlet temperature ratio of outer fluid at RCC      | $\tau_{H1}$                                   | 4             | 3–6.67 | —           |
| Inlet temperature ratio of outer fluid at CCC      | $\tau_{H3}$                                   | 5             | 3–6.67 | —           |
| Inlet temperature ratio of outer fluid at PC1      | $\tau_{L1}$                                   | 1             | —      | —           |
| Inlet temperature ratio of outer fluid at PC2      | $\tau_{L3}$                                   | 1             | —      | —           |
| Pressure ratio at Com1                             | $\pi_{c1}$                                    | —             | 2–20   | —           |
| Pressure ratio at Com2                             | $\pi_{c2}$                                    | —             | 1–6    | —           |

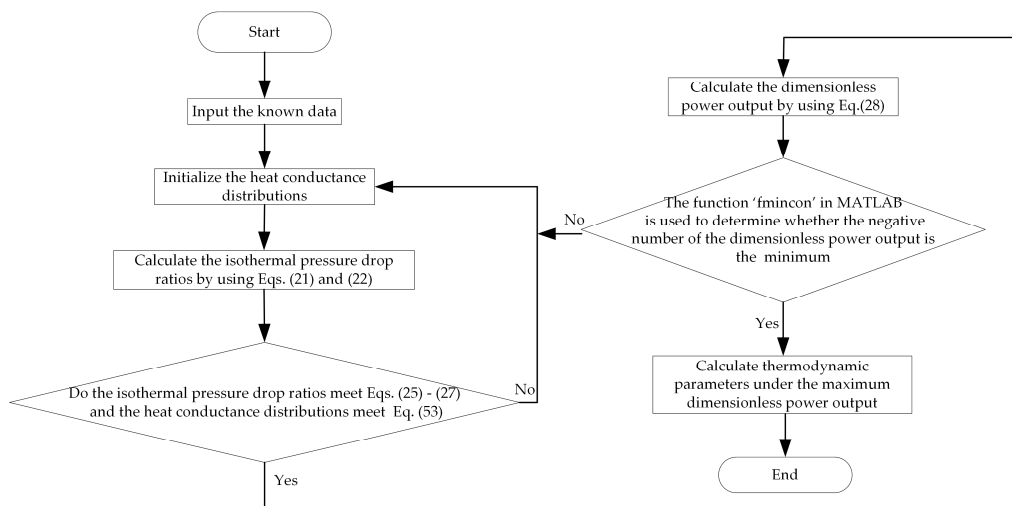


Figure 2. Flow chart of dimensionless power output (PO) optimization.

Figure 3a,b, Figure 4a,b, Figure 5a,b and Figure 6 illustrate the relationships of the maximum dimensionless PO ( $\bar{W}_{max}$ ), the corresponding dimensionless PO ( $\bar{W}_{top}$ ) $\bar{W}_{max}$  of the topping cycle, dimensionless PO ( $\bar{W}_{bot}$ ) $\bar{W}_{max}$  of the bottoming cycle, TEF  $\eta_{\bar{W}_{max}}$ , isothermal pressure drop ratios ( $(\pi_t)_{\bar{W}_{max}}$  and  $(\pi_{ta})_{\bar{W}_{max}}$ ) and HCDs ( $(u_{H1})_{\bar{W}_{max}}$ ,  $(u_{H2})_{\bar{W}_{max}}$ ,  $(u_{L1})_{\bar{W}_{max}}$ ,  $(u_{L2})_{\bar{W}_{max}}$ ,  $(u_{R1})_{\bar{W}_{max}}$ ,  $(u_{R2})_{\bar{W}_{max}}$  and  $(u_{R2})_{\bar{W}_{max}}$ ) versus the pressure ratios ( $\pi_{com1}$  and  $\pi_{com2}$ ) in the Com1 and Com2, respectively.

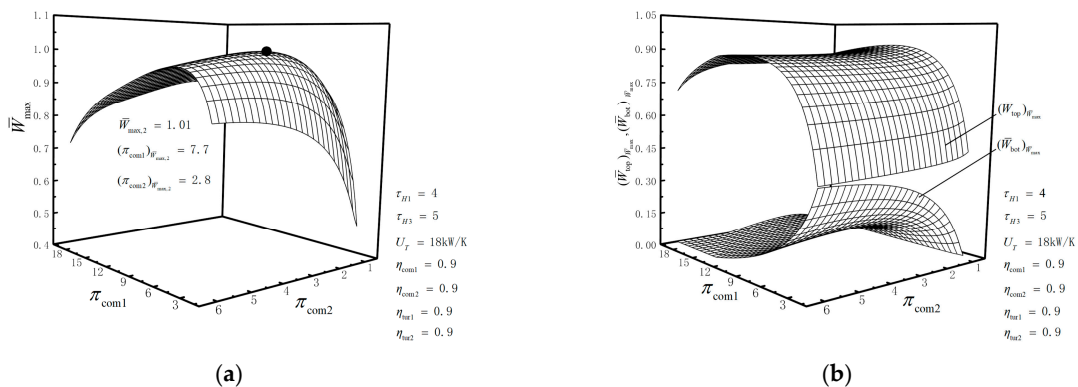


Figure 3. (a) Relationships of  $\bar{W}_{max}$  versus  $\pi_{com1}$  and  $\pi_{com2}$ ; (b) relationships of  $(\bar{W}_{top})_{\bar{W}_{max}}$  and  $(\bar{W}_{bot})_{\bar{W}_{max}}$  versus  $\pi_{com1}$  and  $\pi_{com2}$ .

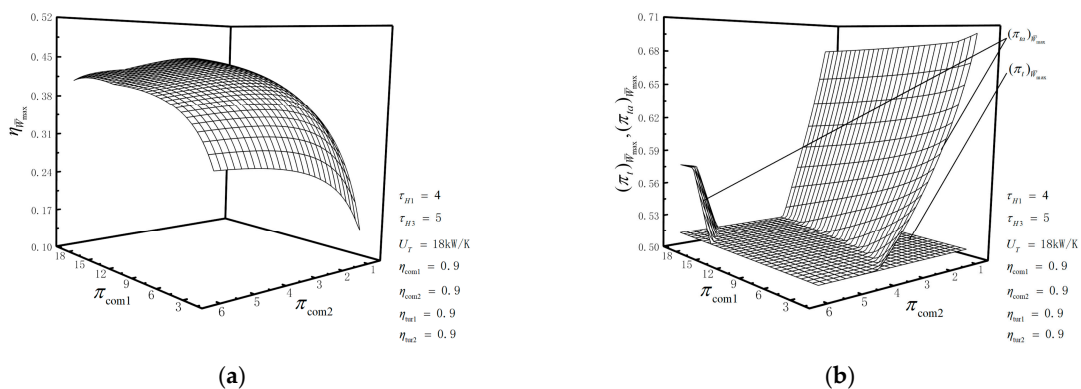
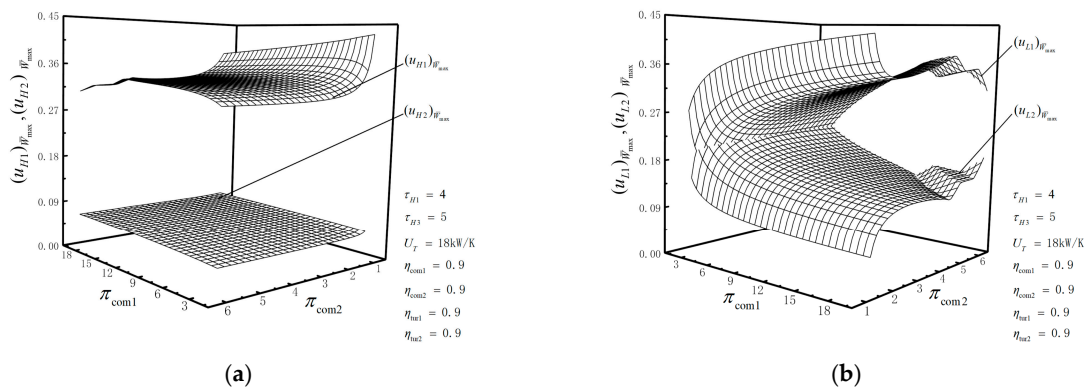
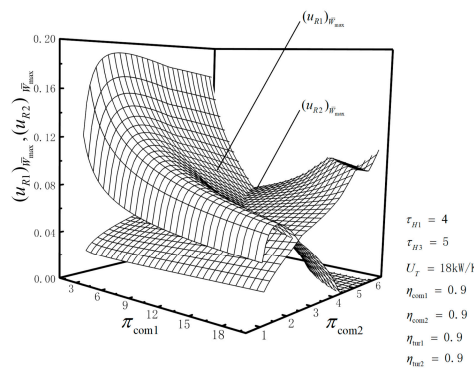


Figure 4. (a) Relationships of  $\eta_{\bar{W}_{max}}$  versus  $\pi_{com1}$  and  $\pi_{com2}$ ; (b) relationships of  $(\pi_t)_{\bar{W}_{max}}$  and  $(\pi_{ta})_{\bar{W}_{max}}$  versus  $\pi_{com1}$  and  $\pi_{com2}$ .



**Figure 5.** (a) Relationships of  $(u_{H1})_{\overline{W}_{\max}}$  and  $(u_{H2})_{\overline{W}_{\max}}$  versus  $\pi_{\text{com1}}$  and  $\pi_{\text{com2}}$ ; (b) relationships of  $(u_{L1})_{\overline{W}_{\max}}$  and  $(u_{L2})_{\overline{W}_{\max}}$  versus  $\pi_{\text{com1}}$  and  $\pi_{\text{com2}}$ .



**Figure 6.** Relationships of  $(u_{R1})_{\overline{W}_{\max}}$  and  $(u_{R2})_{\overline{W}_{\max}}$  versus  $\pi_{\text{com1}}$  and  $\pi_{\text{com2}}$ .

Figure 3a shows that  $\overline{W}_{\max}$  increases first and then decreases as  $\pi_{\text{com1}}$  or  $\pi_{\text{com2}}$  increases. There is a set of optimal pressure ratios ( $(\pi_{\text{com1}})_{\overline{W}_{\max,2}}$  and  $(\pi_{\text{com2}})_{\overline{W}_{\max,2}}$ ), so that  $\overline{W}_{\max}$  achieves the double maximum dimensionless PO  $\overline{W}_{\max,2}$ . This is because when  $\pi_{\text{com1}}$  gradually increases,  $\dot{Q}_{2-3}$ ,  $\dot{Q}_{7-1}$  and  $\dot{Q}_{5a-1a}$  gradually reduce, and  $\dot{Q}_{3-4}$  slightly increases. With the increase in  $\pi_{\text{com2}}$ ,  $\dot{Q}_{2-3}$  decreases,  $\dot{Q}_{3-4}$  decreases slightly,  $\dot{Q}_{7-1}$  decreases first and then increases, and  $\dot{Q}_{5a-1a}$  decreases. Under the given conditions,  $(\pi_{\text{com1}})_{\overline{W}_{\max,2}}$  and  $(\pi_{\text{com2}})_{\overline{W}_{\max,2}}$  are approximately 1.01, 7.7 and 2.8, respectively.

Figure 3b shows that  $(\overline{W}_{\text{top}})_{\overline{W}_{\max}}$  increases first; then decreases as  $\pi_{\text{com1}}$  increases; and remains substantially unchanged with the change of  $\pi_{\text{com2}}$ .  $(\overline{W}_{\text{bot}})_{\overline{W}_{\max}}$  decreases at first and then tends to remain unchanged with the increase in  $\pi_{\text{com1}}$ , the value of which is much smaller than that of  $(\overline{W}_{\text{top}})_{\overline{W}_{\max}}$ . This is because  $T_5$  decreases at first and then tends to be constant as  $\pi_{\text{com1}}$  increases. As  $\pi_{\text{com2}}$  increases,  $(\overline{W}_{\text{bot}})_{\overline{W}_{\max}}$  increases at first and then tends to be constant when  $\pi_{\text{com1}}$  is smaller;  $(\overline{W}_{\text{bot}})_{\overline{W}_{\max}}$  increases at first and then decreases to zero when  $\pi_{\text{com1}}$  is larger. That is,  $\dot{Q}_{2a-3a}$  and  $\dot{Q}_{3a-4a}$  can only be used to maintain the operation of the bottoming cycle. Figure 4a shows that  $\eta_{\overline{W}_{\max}}$  increases at first and then becomes constant with the increase in  $\pi_{\text{com1}}$  or  $\pi_{\text{com2}}$ .

Figure 4b shows that  $(\pi_t)_{\overline{W}_{\max}}$  remains unchanged as  $\pi_{\text{com1}}$  or  $\pi_{\text{com2}}$  increases, and is always located at the lower limit. This indicates that the degree of the isothermal heating in CCC always reaches the maximum. Therefore,  $\dot{Q}_{3-4}$  only slightly changes with the change of  $\pi_{\text{com1}}$  or  $\pi_{\text{com2}}$ . When  $\pi_{\text{com1}}$  or  $\pi_{\text{com2}}$  is smaller,  $(\pi_{ta})_{\overline{W}_{\max}}$  decreases slightly with the increase in  $\pi_{\text{com1}}$  and reaches the lower limit with the increase in  $\pi_{\text{com2}}$ . That indicates that under this condition, the degree of the isothermal heating in IR increases as  $\pi_{\text{com1}}$  or  $\pi_{\text{com2}}$  does; when  $\pi_{\text{com1}}$  and  $\pi_{\text{com2}}$  are larger,  $(\pi_{ta})_{\overline{W}_{\max}}$  increases with the increase in  $\pi_{\text{com1}}$  or  $\pi_{\text{com2}}$ ; when  $(\overline{W}_{\text{bot}})_{\overline{W}_{\max}}$  is zero,  $(\pi_{ta})_{\overline{W}_{\max}}$  remains substantially unchanged as  $\pi_{\text{com1}}$  or  $\pi_{\text{com2}}$  increases.

Figure 5a shows that when  $(u_{R1})_{\bar{W}_{\max}}$  is not zero,  $(u_{H1})_{\bar{W}_{\max}}$  increases slightly at first and then decreases slightly with the increase in  $\pi_{\text{com1}}$ ;  $(u_{H1})_{\bar{W}_{\max}}$  decreases first and then tends to remain unchanged with the increase in  $\pi_{\text{com2}}$ . When  $(u_{R1})_{\bar{W}_{\max}}$  is zero but both of  $(\pi_{ta})_{\bar{W}_{\max}}$  and  $(\bar{W}_{\text{bot}})_{\bar{W}_{\max}}$  are not zero,  $(u_{H1})_{\bar{W}_{\max}}$  decreases as  $\pi_{\text{com1}}$  or  $\pi_{\text{com2}}$  increases; when both of  $(u_{R1})_{\bar{W}_{\max}}$  and  $(\pi_{ta})_{\bar{W}_{\max}}$  are zero but  $(\bar{W}_{\text{bot}})_{\bar{W}_{\max}}$  is not zero, changing  $\pi_{\text{com1}}$  or  $\pi_{\text{com2}}$  does not change  $(u_{H1})_{\bar{W}_{\max}}$ ; when  $(u_{R1})_{\bar{W}_{\max}}$ ,  $(\pi_{ta})_{\bar{W}_{\max}}$  and  $(\bar{W}_{\text{bot}})_{\bar{W}_{\max}}$  are zero,  $(u_{H1})_{\bar{W}_{\max}}$  decreases with the increase in  $\pi_{\text{com1}}$  or  $\pi_{\text{com2}}$ , and is far less than  $(u_{H1})_{\bar{W}_{\max}}$ . With the decrease in  $(u_{H1})_{\bar{W}_{\max}}$ ,  $E_{H1}$  decreases, and then  $\dot{Q}_{2-3}$  decreases.  $(u_{H2})_{\bar{W}_{\max}}$  remains basically unchanged,  $E_{H2}$  is constant and the variation of  $\dot{Q}_{3-4}$  is very small.

Figure 5b shows that when  $(u_{R1})_{\bar{W}_{\max}}$  is not zero,  $(u_{L1})_{\bar{W}_{\max}}$  increases as  $\pi_{\text{com1}}$  increases; it decreases first and then increases slightly as  $\pi_{\text{com2}}$  increases;  $(u_{L2})_{\bar{W}_{\max}}$  decreases first and tends to remain unchanged with the increase in  $\pi_{\text{com1}}$ ; it increases first and then tends to be the same with the increase in  $\pi_{\text{com2}}$ . When  $(u_{R1})_{\bar{W}_{\max}}$  is zero but both of  $(\pi_{ta})_{\bar{W}_{\max}}$  and  $(\bar{W}_{\text{bot}})_{\bar{W}_{\max}}$  are not zero,  $(u_{L1})_{\bar{W}_{\max}}$  decreases sharply with the increase in  $\pi_{\text{com1}}$  or  $\pi_{\text{com2}}$ , while  $(u_{L2})_{\bar{W}_{\max}}$  increases sharply with the increase in  $\pi_{\text{com1}}$  or  $\pi_{\text{com2}}$ . When both of  $(u_{R1})_{\bar{W}_{\max}}$  and  $(\pi_{ta})_{\bar{W}_{\max}}$  are zero but  $(\bar{W}_{\text{bot}})_{\bar{W}_{\max}}$  is not zero,  $(u_{L1})_{\bar{W}_{\max}}$  increases slightly with the increase in  $\pi_{\text{com1}}$  or  $\pi_{\text{com2}}$ , and  $(u_{L2})_{\bar{W}_{\max}}$  remains basically unchanged with the increase in  $\pi_{\text{com1}}$  or  $\pi_{\text{com2}}$ . When  $(u_{R1})_{\bar{W}_{\max}}$ ,  $(\pi_{ta})_{\bar{W}_{\max}}$  and  $(\bar{W}_{\text{bot}})_{\bar{W}_{\max}}$  are zero,  $(u_{L1})_{\bar{W}_{\max}}$  decreases and  $(u_{L2})_{\bar{W}_{\max}}$  increases as  $\pi_{\text{com1}}$  or  $\pi_{\text{com2}}$  increases.

Figure 6 shows that  $(u_{R1})_{\bar{W}_{\max}}$  decreases to zero with the increase in  $\pi_{\text{com1}}$ , and increases at first and then decreases to zero as  $\pi_{\text{com2}}$  increases. When  $(\pi_{ta})_{\bar{W}_{\max}}$  is not zero,  $(u_{R2})_{\bar{W}_{\max}}$  increases with the increase in  $\pi_{\text{com1}}$  or  $\pi_{\text{com2}}$ . When  $(\pi_{ta})_{\bar{W}_{\max}}$  is zero but  $(\bar{W}_{\text{bot}})_{\bar{W}_{\max}}$  is not zero,  $(u_{R2})_{\bar{W}_{\max}}$  decreases with the increase in  $\pi_{\text{com1}}$  or  $\pi_{\text{com2}}$ . When both of  $(\pi_{ta})_{\bar{W}_{\max}}$  and  $(\bar{W}_{\text{bot}})_{\bar{W}_{\max}}$  are zero,  $(u_{R2})_{\bar{W}_{\max}}$  increases with the increase in  $\pi_{\text{com1}}$  or  $\pi_{\text{com2}}$ . Because increasing  $(u_{R2})_{\bar{W}_{\max}}$  leads to the increases in  $E_{R2}$  and  $\dot{Q}_{3a-4a}$  so as to avoid the negative value of  $(\bar{W}_{\text{bot}})_{\bar{W}_{\max}}$ , namely, inverse dimensionless PO of the bottoming cycle.

According to the numerical calculation, the influences of the temperature ratios, compressor efficiencies, turbine efficiencies and THC on optimization results are further analyzed. Figure 7a,b illustrates the relationships of the double maximum dimensionless PO ( $\bar{W}_{\max,2}$ ) and the corresponding TEF ( $\eta_{\bar{W}_{\max,2}}$ ) versus the temperature ratios ( $\tau_{H1}$  and  $\tau_{H3}$ ). As can be seen from figure 7a,b, both  $\bar{W}_{\max,2}$  and  $\eta_{\bar{W}_{\max,2}}$  increase first and then tend to be unchanged with the increase in  $\pi_{\text{com1}}$  or  $\pi_{\text{com2}}$ . There is an optimal temperature ratio  $(\tau_{H3})_{\text{opt}}$  which makes  $\bar{W}_{\max,2}$  reach the optimal. The corresponding fitting expression is  $(\tau_{H3})_{\text{opt}} = 1.1\tau_{H1} + 0.14$ , and the correlation coefficient is  $r = 0.9964$ . As for  $\eta_{\bar{W}_{\max,2}}$ , there also exists  $(\tau_{H3})_{\text{opt}}$  that satisfies the fitting expression:  $(\tau_{H3})_{\text{opt}} = 1.1\tau_{H1} + 0.18$ , and its correlation coefficient is also  $r = 0.9964$ . In the actual design process,  $\tau_{H1}$  and  $\tau_{H3}$  should meet the relationship similar to  $(\tau_{H3})_{\text{opt}} = 1.1\tau_{H1} + 0.14$  or  $(\tau_{H3})_{\text{opt}} = 1.1\tau_{H1} + 0.18$ , in order to obtain as much  $\bar{W}_{\max,2}$  and  $\eta_{\bar{W}_{\max,2}}$  as possible and reduce the requirement for high temperature resistances of materials.

Figure 8a illustrates the relationships of  $\bar{W}_{\max,2}$ ,  $(\bar{W}_{\text{top}})_{\bar{W}_{\max,2}}$ ,  $(\bar{W}_{\text{bot}})_{\bar{W}_{\max,2}}$  and  $\eta_{\bar{W}_{\max,2}}$  versus  $\eta_{\text{com2}}$ . It shows that  $\bar{W}_{\max,2}$ ,  $\eta_{\bar{W}_{\max,2}}$  and  $(\bar{W}_{\text{bot}})_{\bar{W}_{\max,2}}$  increase and  $(\bar{W}_{\text{top}})_{\bar{W}_{\max,2}}$  decreases slightly with the increase in  $\eta_{\text{com2}}$ . With the increase in  $\eta_{\text{com2}}$ ,  $\dot{Q}_{2-3}$  and  $\dot{Q}_{7-1}$  basically increase. With the increase in  $\eta_{\text{com2}}$ ,  $\dot{Q}_{3-4}$  remains substantially unchanged,  $\dot{Q}_{5a-1a}$  decreases and  $\dot{Q}_{3a-4a}$  increases. The amount of change in  $\bar{W}_{\max,2}$  is mainly affected by that in  $\dot{Q}_{5a-1a}$ . It should be noted that when  $\eta_{\text{com2}} \leq 0.75$ ,  $\bar{W}_{\max,2}$ ,  $\eta_{\bar{W}_{\max,2}}$ ,  $(\bar{W}_{\text{top}})_{\bar{W}_{\max,2}}$  and  $(\bar{W}_{\text{bot}})_{\bar{W}_{\max,2}}$  do not exist and are indicated by dashed lines.

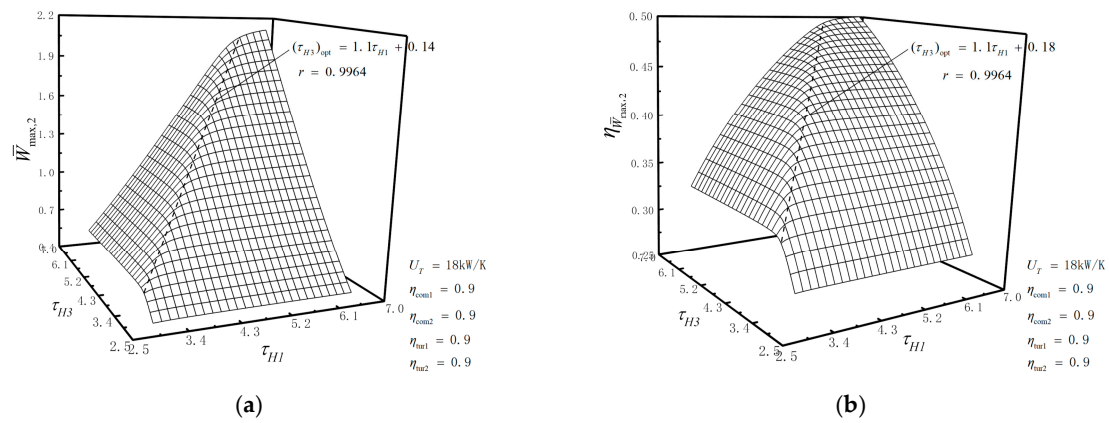


Figure 7. (a) Relationships of  $\bar{W}_{\max,2}$  versus  $\tau_{H1}$  and  $\tau_{H3}$ ; (b) relationships of  $\eta_{\bar{W}_{\max}}$  versus  $\tau_{H1}$  and  $\tau_{H3}$ .

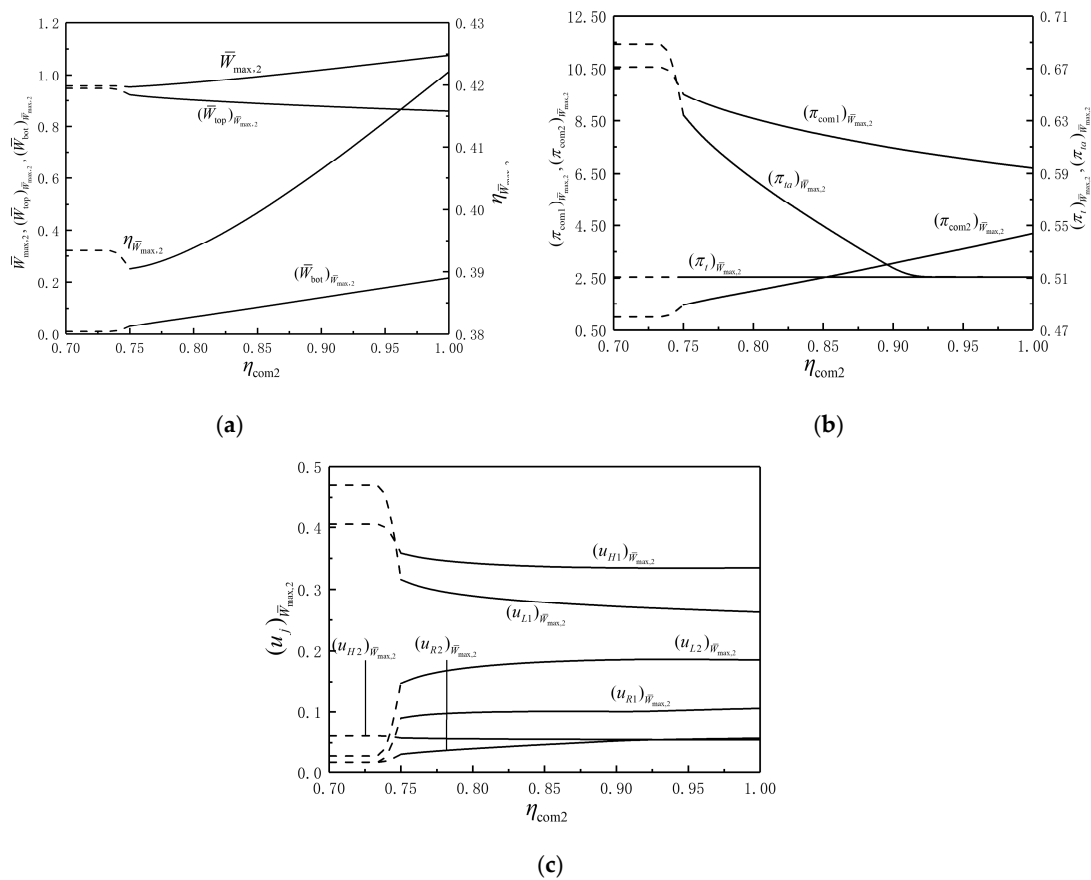


Figure 8. (a) Relationships of  $\bar{W}_{\max,2}$ ,  $\eta_{\bar{W}_{\max,2}}$ ,  $(\bar{W}_{\text{top}})_{\bar{W}_{\max,2}}$  and  $(\bar{W}_{\text{bot}})_{\bar{W}_{\max,2}}$  versus  $\eta_{\text{com}2}$ ; (b) relationships of  $(\pi_{\text{com}1})_{\bar{W}_{\max,2}}$ ,  $(\pi_{\text{com}2})_{\bar{W}_{\max,2}}$ ,  $(\pi_t)_{\bar{W}_{\max,2}}$  and  $(\pi_{ta})_{\bar{W}_{\max,2}}$  versus  $\eta_{\text{com}2}$ ; (c) relationships of  $(u_j)_{\bar{W}_{\max,2}}$  versus  $\eta_{\text{com}2}$ .

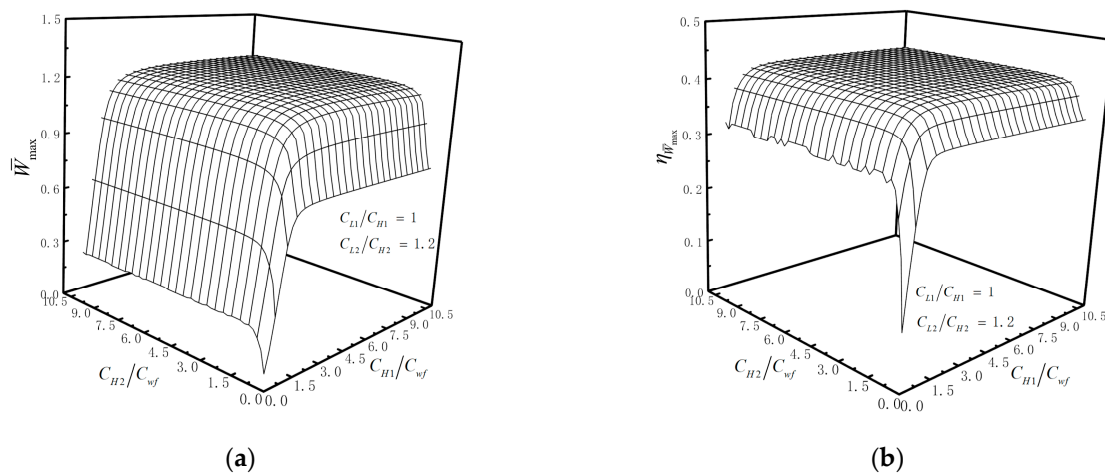
Figure 8b illustrates the relationships of  $(\pi_{\text{com}1})_{\bar{W}_{\max,2}}$ ,  $(\pi_{\text{com}2})_{\bar{W}_{\max,2}}$ ,  $(\pi_t)_{\bar{W}_{\max,2}}$  and  $(\pi_{ta})_{\bar{W}_{\max,2}}$  versus  $\eta_{\text{com}2}$ . It shows that  $(\pi_{\text{com}1})_{\bar{W}_{\max,2}}$  decreases and  $(\pi_{\text{com}2})_{\bar{W}_{\max,2}}$  increases as  $\eta_{\text{com}2}$  increases. The decrease in  $(\pi_{\text{com}1})_{\bar{W}_{\max,2}}$  reduces  $T_2$ , thereby increasing  $\dot{Q}_{2-3}$ . Under the given condition,  $T_{4d}$  is less than  $T_{5a}$  when  $\eta_{\text{com}2}$  is less than or equal to 0.76. As  $\eta_{\text{com}2}$  increases,  $(\pi_t)_{\bar{W}_{\max,2}}$  remains the lower limit, which indicates that the degree of the isothermal heating in CCC always reaches the maximum. As  $\eta_{\text{com}2}$  increases,  $(\pi_{ta})_{\bar{W}_{\max,2}}$  decreases to the lower limit, which indicates that increasing  $\eta_{\text{com}2}$  improves the degree of the isothermal heating in IR.

Figure 8c illustrates the relationship of  $(u_j)_{\bar{W}_{\max,2}}$  versus  $\eta_{\text{com}2}$ . It shows that as  $\eta_{\text{com}2}$  decreases,  $(u_{H1})_{\bar{W}_{\max,2}}$ ,  $(u_{H2})_{\bar{W}_{\max,2}}$  and  $(u_{R1})_{\bar{W}_{\max,2}}$  remains basically unchanged;  $(u_{L1})_{\bar{W}_{\max,2}}$  decreases first and then tends to remain unchanged;  $(u_{L2})_{\bar{W}_{\max,2}}$  increases first and then tends to be unchanged;  $(u_{R2})_{\bar{W}_{\max,2}}$  increases.

Similarly, both of  $\bar{W}_{\max,2}$  and  $\eta_{\bar{W}_{\max,2}}$  increase as  $\eta_{\text{com}1}$ ,  $\eta_{\text{tur}1}$  and  $\eta_{\text{tur}2}$  increase. The effects of  $\eta_{\text{com}1}$  and  $\eta_{\text{tur}1}$  on  $\bar{W}_{\max,2}$  and  $\eta_{\bar{W}_{\max,2}}$  are greater than those of  $\eta_{\text{com}2}$  and  $\eta_{\text{tur}2}$ .  $(\bar{W}_{\text{top}})_{\bar{W}_{\max,2}}$  increases with the increases in  $\eta_{\text{com}1}$  and  $\eta_{\text{tur}1}$ , while  $(\bar{W}_{\text{top}})_{\bar{W}_{\max,2}}$  decreases with the increases in  $\eta_{\text{com}2}$  and  $\eta_{\text{tur}2}$ .  $(\bar{W}_{\text{bot}})_{\bar{W}_{\max,2}}$  decreases with the increases in  $\eta_{\text{com}1}$  and  $\eta_{\text{tur}1}$ , while  $(\bar{W}_{\text{top}})_{\bar{W}_{\max,2}}$  increases with the increases in  $\eta_{\text{com}2}$  and  $\eta_{\text{tur}2}$ . It should be noted that when  $\eta_{\text{tur}2} \leq 0.74$ ,  $\bar{W}_{\max,2}$ ,  $\eta_{\bar{W}_{\max,2}}$ ,  $(\bar{W}_{\text{top}})_{\bar{W}_{\max,2}}$  and  $(\bar{W}_{\text{bot}})_{\bar{W}_{\max,2}}$  also do not exist. When  $\eta_{\text{tur}2} > 0.74$ , the change of  $\eta_{\text{tur}2}$  has little effects on  $\bar{W}_{\max,2}$  and  $\eta_{\bar{W}_{\max,2}}$ . Within the given range, the changes in  $\bar{W}_{\max,2}$  and  $\eta_{\bar{W}_{\max,2}}$  do not exceed 7% and 4%, respectively. In practical design of improving cycle performance, it is suggested to give priority to appropriately increasing  $\eta_{\text{com}2}$  and  $\eta_{\text{tur}2}$ . Then one can choose to increase  $\eta_{\text{com}1}$  and  $\eta_{\text{tur}1}$ , successively. Apart from this,  $\bar{W}_{\max,2}$  and  $\eta_{\bar{W}_{\max,2}}$  increase as  $U_T$  increases.

#### 4. Optimal Thermal Capacitance Rate Matchings

The  $\bar{W}$  of the cycle also affected by the TCRMs. By taking  $\bar{W}$  as the optimization objective, TCRMs are optimized. Figure 9a,b illustrates the relationships of  $\bar{W}_{\max}$  and  $\eta_{\bar{W}_{\max}}$  versus  $C_{H1}/C_{wf}$  and  $C_{H2}/C_{wf}$  when  $C_{L1}/C_{H1} = 1$  and  $C_{L2}/C_{H2} = 1.2$ . The figures show that both of  $\bar{W}_{\max}$  and  $\eta_{\bar{W}_{\max}}$  increase, and then tend to remain constant with the increase in  $C_{H1}/C_{wf}$  or  $C_{H2}/C_{wf}$ . These indicate that there is a set of the optimal  $C_{H1}/C_{wf}$  and  $C_{H2}/C_{wf}$ , so that  $\bar{W}_{\max}$  gets the optimal value. Similarly, there is a set of the optimal  $C_{H1}/C_{wf}$  and  $C_{H2}/C_{wf}$ , so that  $\eta_{\bar{W}_{\max}}$  gets the optimal value.



**Figure 9.** (a) Relationships of  $\bar{W}_{\max}$  versus  $C_{H1}/C_{wf}$  and  $C_{H2}/C_{wf}$ ; (b) relationships of  $\eta_{\bar{W}_{\max}}$  versus  $C_{H1}/C_{wf}$  and  $C_{H2}/C_{wf}$ .

Figure 10 illustrates that the effects of  $C_{L1}/C_{H1}$  on the characteristics of  $\bar{W}_{\max} - C_{H1}/C_{wf}$  and  $\eta_{\bar{W}_{\max}} - C_{H1}/C_{wf}$  when  $C_{H2} = 1$  and  $C_{L2}/C_{H2} = 1.2$ . It shows that when  $\bar{W}_{\max}$  and  $\eta_{\bar{W}_{\max}}$  reach the optimal values,  $C_{L1}/C_{H1}$  mainly reduces the corresponding  $C_{H1}/C_{wf}$ , and has little effect on the optimal values of  $\bar{W}_{\max}$  and  $\eta_{\bar{W}_{\max}}$ . Similarly,  $C_{L1}/C_{H1}$  mainly reduces the corresponding  $C_{H1}/C_{wf}$  when  $\bar{W}_{\max}$  and  $\eta_{\bar{W}_{\max}}$  reach the optimal values, and has little effects on the optimal values of  $\bar{W}_{\max}$  and  $\eta_{\bar{W}_{\max}}$ .

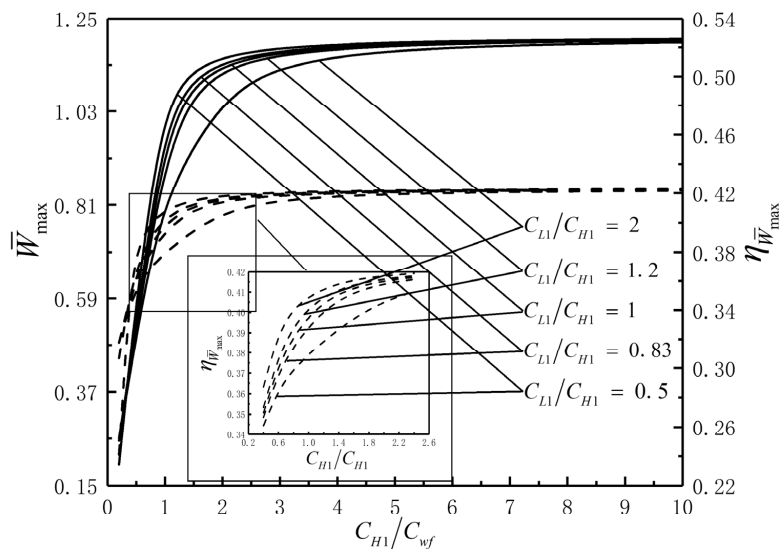


Figure 10. Effects of  $C_{L1}/C_{H1}$  on the characteristics of  $\bar{W}_{\max} - C_{H1}/C_{wf}$  and  $\eta_{\bar{W}_{\max}} - C_{H1}/C_{wf}$ .

## 5. Conclusions

Based on the previous established models in [8,62], a modified closed binary Brayton cycle model coupled to VTHR with two isothermal heating processes and variable isothermal pressure drop ratios is established by using FTT in this paper. The HCDs of the six heat exchangers are optimized, and the effects of  $\tau_{H1}$ ,  $\tau_{H3}$ ,  $U_T$ ,  $\eta_{\text{com}1}$ ,  $\eta_{\text{com}2}$ ,  $\eta_{\text{tur}1}$ ,  $\eta_{\text{tur}2}$ ,  $C_{H1}/C_{wf}$  and  $C_{H2}/C_{wf}$  on the optimal performances are analyzed by taking  $\bar{W}$  as the optimization objective. The results show that there is a set of  $\pi_{\text{com}1}$  and  $\pi_{\text{com}2}$  which makes  $\bar{W}_{\max}$  reach  $\bar{W}_{\max,2} = 1.01$ .  $\tau_{H1}$  and  $\tau_{H3}$  have certain linear relationship ( $(\tau_{H3})_{\text{opt}} = 1.1\tau_{H1} + 0.14$ , and the correlation coefficient is  $r = 0.9964$ ), which makes  $\bar{W}_{\max,2}$  optimal.  $\bar{W}_{\max,2}$  increases with the increases in  $U_T$ ,  $\eta_{\text{com}1}$ ,  $\eta_{\text{com}2}$ ,  $\eta_{\text{tur}1}$  and  $\eta_{\text{tur}2}$ . It should be noted that when  $\eta_{\text{com}2} \leq 0.75$  or  $\eta_{\text{tur}2} \leq 0.74$ ,  $\bar{W}_{\max,2}$  does not exist.  $\bar{W}_{\max,2}$  increases first and then remain unchanged with the increases in  $C_{H1}/C_{wf}$  and  $C_{H2}/C_{wf}$ . This cycle can effectively improve energy efficiency and reduce emissions of nitrogen oxide and other harmful gases. Additionally, the optimal results can guide the practical designs for the gas turbine plants.

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## Nomenclature

|  |  |
|--|--|
| $a, b, c, d, e, m, x, y$                   | Intermediate variables                               |
| $C$  | Thermal capacity rate (kW/K)                         |
| $C_p$                                      | Specific heat at constant pressure (kJ/(kg·K))       |
| $E$  | Effectiveness of heat exchanger                      |
| $k$  | Specific heat ratio                                  |
| $M$  | Mach number  |
| $N$  | Number of heat transfer units                        |
| $\dot{Q}$                                  | Heat absorbing rate or heat releasing rate           |
| $R_g$                                      | Gas constant (kJ/(kg·K))                             |
| $T$  | Temperature (K)                                      |
| $U$  | Heat conductance (kW/K)                              |
| $u$  | Heat conductance distribution                        |
| $W$  | Power output(kW)                                     |
| $\bar{W}$                                  | Dimensionless power output                           |
| <b>Greek symbol</b>                        |  |
| $\eta$                                     | Efficiency   |
| $\pi$                                      | Pressure ratio                                       |
| $\tau$                                     | Temperature ratio                                    |
| <b>Subscripts</b>                          |  |
| bot  | Bottoming cycle                                      |
| com  | Compressor   |
| $H$  | Hot-side heat exchanger                              |
| $L$  | Cold-side heat exchanger                             |
| $R$  | Regenerator  |
| $s$  | Isentropic   |
| $t/ta$                                     | Converging combustion chamber/isothermal regenerator |
| tot  | Total  |
| tur  | Turbine  |
| top  | Topping cycle  |
| $wf$                                       | Working fluid  |
| 1,2,3,4,5,6,7,1a,2a,3a,4a,5a,2s,5s,2as,5as | State points   |

## Abbreviations

|       |                                      |
|-------|--------------------------------------|
| CCC   | Converging combustion chamber        |
| CTR   | Constant-temperature reservoir       |
| FTT   | Finite-time thermodynamics           |
| HCD   | Heat conductance distribution        |
| IR    | Isothermal regenerator               |
| MCBBC | Modified closed binary Brayton cycle |
| PO    | Power output                         |
| PD    | Power density                        |
| OR    | Ordinary regenerator                 |
| RCC   | Regular combustion chamber           |
| TCRM  | Thermal capacitance rate matching    |
| TEF   | Thermal efficiency                   |
| THC   | Total heat conductance               |
| Tur   | Turbine                              |
| VTHR  | Variable-temperature heat reservoir  |
| WF    | Working fluid                        |

Appendix A

$$\begin{aligned}
 a_1 = & \left\{ C_{L2min} E_{L2} [(\eta_{tur2} - 1) x_a y_a - \eta_{tur2}] \left\{ -C_{wf} (2E_{R1} - 1) (E_{R2} - 1) (\eta_{com1} + x - 1) [(\eta_{tur1} - 1) xy - \eta_{tur1}] (C_{H1min} E_{H1} + C_{L1min} E_{L1}) + C_{H1min} C_{L1min} E_{H1} E_{L1} (2E_{R1} - 1) (E_{R2} - 1) (\eta_{com1} + x - 1) [(\eta_{tur1} - 1) xy - \eta_{tur1}] + C_{wf}^2 \{ (2E_{R1} - 1) (E_{R2} - 1) (\eta_{com1} + x - 1) \eta_{tur1} (xy - 1) + xy [E_{R1} (\eta_{com1} + 2x - 2 - 2E_{R2} (\eta_{com1} + x - 1))] + E_{R2} (\eta_{com1} + x - 1) - x + 1 \} \right\} / \{ (\eta_{com1} + x - 1) C_{wf} xy [E_{R1} (2E_{R2} - 1) - E_{R2}] (C_{wf} - C_{L1min} E_{L1}) \} + \{ -C_{H1min} E_{H1} (E_{R2} - 1) [(\eta_{tur1} - 1) xy - \eta_{tur1}] \{ x_a y_a [-E_{R1} (\eta_{com2} + 2x_a - 2) + x_a - 1] + (2E_{R1} - 1) \eta_{tur2} (\eta_{com2} + x_a - 1) (x_a y_a - 1) \} / (xy) + C_{wf}^2 \eta_{com1} \{ x_a y_a [(\eta_{com2} + x_a - 1 - E_{R2} \eta_{com2}) E_{R1} - x_a + 1] - \eta_{tur2} (E_{R1} - 1) (\eta_{com2} + x_a - 1) (x_a y_a - 1) \} / [(\eta_{com1} + x - 1) (C_{wf} - C_{L1min} E_{L1})] + C_{wf} (E_{R2} - 1) [(\eta_{tur1} - 1) xy - \eta_{tur1}] \{ (2E_{R1} - 1) \eta_{tur2} (\eta_{com2} + x_a - 1) (x_a y_a - 1) + x_a y_a [x_a - 1 - E_{R1} (\eta_{com2} + 2x_a - 2)] \} / (xy) \} / [(-2E_{R1} E_{R2} + E_{R1} + E_{R2}) (\eta_{com2} + x_a - 1)] \} / (x_a y_a) \right\} \\
 a_2 = & \{ \{ x_a y_a \{ C_{L1min} E_{L1} \{ C_{L2min} E_{L2} (\eta_{com2} + x_a - 1) [E_{R1} T_{L3} (2E_{R2} - 1) + (E_{R1} - 1) (\eta_{tur2} - 1) T_{L1} - E_{R2} T_{L3}] - C_{wf} T_{L1} [E_{R1} \eta_{com2} (E_{R2} + \eta_{tur2} - 1) + E_{R1} (\eta_{tur2} - 1) (x_a - 1) - \eta_{tur2} (\eta_{com2} + x_a) + \eta_{tur2} + x_a - 1] - [E_{R1} (2E_{R2} - 1) - E_{R2}] C_{L2min} C_{wf} E_{L2} T_{L3} (x_a + \eta_{com2} - 1) \} + C_{L1min} E_{L1} \eta_{tur2} T_{L1} (E_{R1} - 1) (\eta_{com2} + x_a - 1) (C_{wf} - C_{L2min} E_{L2}) \} / \{ (\eta_{com2} + x_a - 1) x_a y_a (C_{wf} - C_{L1min} E_{L1}) [E_{R1} (2E_{R2} - 1) - E_{R2}] - C_{H1min} E_{H1} (E_{R2} - 1) T_{H1} [(\eta_{tur1} - 1) xy - \eta_{tur1}] \{ (2E_{R1} - 1) C_{L2min} E_{L2} (\eta_{com2} + x_a - 1) (\eta_{tur2} + x_a y_a - x_a y_a \eta_{tur2}) + C_{wf} x_a y_a [E_{R1} \eta_{com2} (2\eta_{tur2} - 1) + 2E_{R1} (\eta_{tur2} - 1) (x_a - 1) - (\eta_{com2} + x_a) \eta_{tur2} + \eta_{tur2} + x_a - 1] - C_{wf} \eta_{tur2} (2E_{R1} - 1) (x_a + \eta_{com2} - 1) \} \} / \{ C_{wf} xy x_a y_a [E_{R1} (2E_{R2} - 1) - E_{R2}] (\eta_{com2} + x_a - 1) \} \} \\
 a_3 = & \{ a_1 E_{R1} [E_{R1} (2E_{R2} - 1) - E_{R2}] \{ C_{H1min} E_{H1} (E_{R2} - 1) [(\eta_{tur1} - 1) xy - \eta_{tur1}] \{ C_{L1min} C_{L2min} E_{L1} E_{L2} (\eta_{com1} + x - 1) \{ x_a y_a [E_{R1} (\eta_{tur2} - 1) T_{L1} - E_{R1} T_{L3} + T_{L3}] - E_{R1} \eta_{tur2} T_{L1} \} + C_{L1min} C_{wf} E_{L1} E_{R1} T_{L1} (\eta_{com1} + x - 1) (\eta_{tur2} + x_a y_a - x_a \eta_{tur2} y_a) + C_{L2min} C_{wf} E_{L2} \{ E_{R1} \eta_{com1} \eta_{tur2} T_{H1} + x_a y_a [E_{R1} \eta_{com1} (T_{H1} + T_{L3} - \eta_{tur2} T_{H1}) + E_{R1} T_{L3} (x - 1) - T_{L3} (\eta_{com1} + x) + T_{L3}] \} / C_{wf} + C_{wf}^2 E_{R1} \eta_{com1} T_{H1} [(\eta_{tur2} - 1) x_a y_a - \eta_{tur2}] \} + C_{L1min} E_{L1} (\eta_{com1} + x - 1) [(\eta_{tur1} - 1) xy - \eta_{tur1}] (E_{R2} - 1) \{ (C_{wf} - C_{L2min} E_{L2}) E_{R1} T_{L1} (\eta_{tur2} - 1) + C_{L2min} E_{L2} (E_{R1} - 1) T_{L3} \} x_a y_a + E_{R1} \eta_{tur2} T_{L1} (C_{L2min} E_{L2} - C_{wf}) \} - C_{L2min} C_{wf} E_{L2} T_{L3} x_a y_a \{ (E_{R1} - 1) (E_{R2} - 1) \eta_{tur1} (\eta_{com1} + x - 1) (xy - 1) + xy [E_{R1} (E_{R2} + \eta_{com1} + x - 1 - 2E_{R2} \eta_{com1} - E_{R2} x) + E_{R2} (\eta_{com1} + x - 1) - x + 1] \} / [xx_a y_a (\eta_{com1} + x - 1)] - a_1 a_2 E_{R2} (E_{R1} - 1) (E_{R1} + E_{R2} - 2E_{R1} E_{R2}) \{ C_{H1min} E_{H1} E_{R1} (C_{wf} - C_{L1min} E_{L1}) (E_{R2} - 1) [(\eta_{tur1} - 1) xy - \eta_{tur1}] / (C_{wf} E_{R2} xy) + E_{R1} \eta_{tur1} (E_{R2} - 1) (C_{wf} - C_{L1min} E_{L1}) / (E_{R2} xy) - E_{R1} (E_{R2} - 1) (\eta_{tur1} - 1) (C_{wf} - C_{L1min} E_{L1}) / E_{R2} + C_{wf} \eta_{com1} (E_{R1} - 1) / (\eta_{com1} + x - 1) \} + E_{R2} (E_{R1} - 1) (-2E_{R1} E_{R2} + E_{R1} + E_{R2}) \{ -C_{H1min} E_{H1} E_{R1} (E_{R2} - 1) T_{H1} (C_{wf} - C_{L1min} E_{L1}) [(\eta_{tur1} - 1) xy - \eta_{tur1}] / (C_{wf} E_{R2} xy) - C_{L1min} E_{L1} (E_{R1} - 1) T_{L1} \} / \{ (C_{wf} - C_{L1min} E_{L1}) (E_{R1} + E_{R2} - 2E_{R1} E_{R2})^2 \} \\
 a_4 = & \{ \eta_{com2} \{ \{ a_1 a_2 (E_{R1} - 1) \{ C_{H1min} E_{H1} (E_{R1} - 1) (E_{R2} - 1) [(\eta_{tur1} - 1) xy - \eta_{tur1}] \} / (C_{wf} xy) + [(E_{R1} E_{R2} - 1) C_{wf} \eta_{com1}] / [(x + \eta_{com1} - 1) (C_{wf} - C_{L1min} E_{L1})] - [(E_{R1} - 1) (E_{R2} - 1) (xy - 1) \eta_{tur1}] / (xy) + E_{R1} E_{R2} - E_{R1} - E_{R2} + 1 \} \} / (E_{R1} + E_{R2} - 2E_{R1} E_{R2}) \{ E_{R1} \{ C_{H1min} E_{H1} E_{R1} T_{H1} (E_{R2} - 1) [(\eta_{tur1} - 1) xy - \eta_{tur1}] \} / (C_{wf} xy) + [C_{L1min} E_{L1} E_{R2} T_{L1} (E_{R1} - 1)] / (C_{wf} - C_{L1min} E_{L1}) \} \} / (E_{R1} + E_{R2} - 2E_{R1} E_{R2}) - \{ \{ C_{H1min} E_{H1} E_{R1} (E_{R2} - 1) T_{H1} (C_{wf} - C_{L1min} E_{L1}) [(\eta_{tur1} - 1) xy - \eta_{tur1}] \} / (C_{wf} E_{R2} xy) + E_{L1} T_{L1} C_{L1min} (E_{R1} - 1) \} / \{ (E_{R1} + E_{R2} - 2E_{R1} E_{R2}) (C_{wf} - C_{L1min} E_{L1}) \} + \{ C_{H1min} E_{H1} (E_{R2} - 1) T_{H1} [(\eta_{tur1} - 1) xy - \eta_{tur1}] \} / (C_{wf} E_{R2} xy) \} / \{ (E_{R1} - 1) (\eta_{com2} + x_a - 1) \} \\
 a_5 = & [1 / (C_{wf} E_{R2} x_a y_a)] [(\eta_{tur2} - 1) x_a y_a - \eta_{tur2}] \{ -\{ a_1 a_2 E_{R2} \{ C_{H1min} E_{H1} (2E_{R1} - 1) (E_{R2} - 1) [(\eta_{tur1} - 1) xy - \eta_{tur1}] + [xy \eta_{com1} (E_{R1} - 1) C_{wf}^2] / [(\eta_{com1} + x - 1) (C_{wf} - C_{L1min} E_{L1})] - C_{wf} (2E_{R1} - 1) (E_{R2} - 1) [(\eta_{tur1} - 1) xy - \eta_{tur1}] \} \} / (E_{R1} + E_{R2} - 2E_{R1} E_{R2}) \} + \{ C_{H1min} E_{H1} E_{R1} T_{H1} (E_{R2} - 1) (C_{wf} - C_{L1min} E_{L1}) [(\eta_{tur1} - 1) xy - \eta_{tur1}] + (E_{R1} - 1) C_{L1min} C_{wf} E_{L1} E_{R2} T_{L1} xy \} / \{ E_{R1} (2E_{R2} - 1) - E_{R2} \} (C_{wf} - C_{L1min} E_{L1}) \} + C_{H1min} E_{H1} (E_{R2} - 1) T_{H1} [(\eta_{tur1} - 1) xy - \eta_{tur1}] \\
 b_1 = & \left\{ -C_{L2min} E_{L2} \left\{ C_{wf} x (2E_{R1} - 1) (E_{R2} - 1) (C_{H1min} E_{H1} + C_{L1min} E_{L1}) - C_{H1min} C_{L1min} E_{H1} E_{L1} x (2E_{R1} - 1) (E_{R2} - 1) + C_{wf}^2 \{ x (2E_{R1} - 1) (E_{R2} - 1) (xy - 1) + xy [E_{R1} (2x - 1 - 2E_{R2} x) + E_{R2} x - x + 1] \} \right\} / \{ [E_{R1} (2E_{R2} - 1) - E_{R2}] C_{wf} x^2 y (C_{wf} - C_{L1min} E_{L1}) \} \right\} + \left\{ C_{H1min} E_{H1} (E_{R2} - 1) \{ [x_a - 1 + x_a (2E_{R1} - 1) (x_a y_a - 1) - E_{R1} (2x_a - 1)] x_a y_a \} / (xy) + C_{wf}^2 \{ x_a y_a [(x_a - E_{R2}) E_{R1} - x_a + 1] - x_a (E_{R1} - 1) (x_a y_a - 1) \} / [x (C_{wf} - C_{L1min} E_{L1})] - C_{wf} (E_{R2} - 1) \{ x_a (2E_{R1} - 1) (x_a y_a - 1) + x_a y_a [x_a - 1 - E_{R1} (2x_a - 1)] \} / (xy) \} / [x_a (E_{R1} + E_{R2} - 2E_{R1} E_{R2})] \} / (x_a y_a) \right\} \\
 b_2 = & \{ \{ x_a y_a \{ C_{L1min} E_{L1} \{ C_{L2min} E_{L2} x_a [E_{R1} T_{L3} (2E_{R2} - 1) - E_{R2} T_{L3}] - C_{wf} T_{L1} [E_{R1} E_{R2} - (1 + x_a) + x_a] \} - C_{L2min} C_{wf} E_{L2} T_{L3} x_a [E_{R1} (2E_{R2} - 1) - E_{R2}] \} + C_{L1min} E_{L1} T_{L1} x_a (E_{R1} - 1) (C_{wf} - C_{L2min} E_{L2}) \} / \{ x_a^2 y_a (C_{wf} - C_{L1min} E_{L1}) [E_{R1} (2E_{R2} - 1) - E_{R2}] \} + C_{H1min} E_{H1} T_{H1} (E_{R2} - 1) \{ (2E_{R1} - 1) C_{L2min} E_{L2} x_a + C_{wf} x_a y_a [E_{R1} - (1 + x_a) + x_a] - (2E_{R1} - 1) C_{wf} x_a \} \} / \{ C_{wf} xy x_a^2 y_a [E_{R1} (2E_{R2} - 1) - E_{R2}] \} \\
 b_3 = & \{ b_1 E_{R1} [E_{R1} (2E_{R2} - 1) - E_{R2}] \{ -C_{H1min} E_{H1} (E_{R2} - 1) \{ C_{L1min} C_{L2min} E_{L1} E_{L2} x [x_a y_a (T_{L3} - E_{R1} T_{L3}) - E_{R1} T_{L1}] + C_{wf} E_{L1} C_{L1min} E_{R1} T_{L1} x + C_{L2min} C_{wf} E_{L2} \{ E_{R1} T_{H1} + x_a y_a [x E_{R1} T_{L3} - T_{L3} (1 + x) + T_{L3}] \} / C_{wf} - C_{wf}^2 E_{R1} T_{H1} \} - x C_{L1min} E_{L1} (E_{R2} - 1) [x_a E_{L2} C_{L2min} T_{L3} y_a (E_{R1} - 1) + E_{R1} T_{L1} (C_{L2min} E_{L2} - C_{wf})] - C_{L2min} C_{wf} E_{L2} T_{L3} x_a y_a \{ x (E_{R1} - 1) (E_{R2} - 1) (xy - 1) + xy [E_{R1} (E_{R2} + x - 2E_{R2} - E_{R2} x) + E_{R2} x - x + 1] \} \} / (x^2 x_a y_a y_a) - b_1 b_2 E_{R2} (E_{R1} - 1) (E_{R1} + E_{R2} - 2E_{R1} E_{R2}) \{ -C_{H1min} E_{H1} E_{R1} (C_{wf} - E_{L1} C_{L1min}) (E_{R2} - 1) / (C_{wf} E_{R2} xy) + E_{R1} (C_{wf} - C_{L1min} E_{L1}) (E_{R2} - 1) / (E_{R2} xy) + C_{wf} (E_{R1} - 1) / x \} + E_{R2} (E_{R1} - 1) (E_{R1} + E_{R2} - 2E_{R1} E_{R2}) \{ C_{H1min} E_{H1} E_{R1} T_{H1} (C_{wf} - C_{L1min} E_{L1}) (E_{R2} - 1) / (C_{wf} E_{R2} xy) - C_{L1min} E_{L1} (E_{R1} - 1) T_{L1} \} \} / \{ (C_{wf} - C_{L1min} E_{L1}) (E_{R1} + E_{R2} - 2E_{R1} E_{R2})^2 \} \\
 \end{aligned}$$

$$\begin{aligned}
b_4 &= \{ \{ b_1 b_2 (E_{R1} - 1) [ -C_{H1min} E_{H1} (E_{R1} - 1) (E_{R2} - 1) / (C_{wf} x y) + \{ (E_{R1} E_{R2} - 1) C_{wf} \} / \{ x (C_{wf} - C_{L1min} E_{L1}) \} - \{ (E_{R1} - 1) (E_{R2} - 1) (x y - 1) \} / (x y) + E_{R1} E_{R2} - E_{R1} - E_{R2} + 1 \} / (E_{R2} + E_{R1} - 2 E_{R1} E_{R2}) + \{ E_{R1} [ \{ -C_{H1min} E_{H1} E_{R1} (E_{R2} - 1) T_{H1} \} / (C_{wf} x y) + \{ C_{L1min} E_{L1} E_{R2} T_{L1} (E_{R1} - 1) \} / (C_{wf} - C_{L1min} E_{L1}) / (E_{R1} + E_{R2} - 2 E_{R1} E_{R2}) - \{ -E_{H1} C_{H1min} E_{R1} T_{H1} (E_{R2} - 1) (C_{wf} - C_{L1min} E_{L1}) \} / (C_{wf} E_{R2} x y) + C_{L1min} E_{L1} T_{L1} (E_{R1} - 1) \} / \{ (C_{wf} - C_{L1min} E_{L1}) (E_{R1} + E_{R2} - 2 E_{R1} E_{R2}) + \{ -C_{H1min} E_{H1} (E_{R2} - 1) T_{H1} \} / (C_{wf} E_{R2} x y) \} ] / \{ x_a (E_{R1} - 1) \} \\
b_5 &= [ -1 / (C_{wf} E_{R2} x_a y y_a) ] \{ - \{ b_1 b_2 E_{R2} \{ -C_{H1min} E_{H1} (2 E_{R1} - 1) (E_{R2} - 1) + [ C_{wf}^2 x y (E_{R1} - 1) ] / [ - (C_{wf} - C_{L1min} E_{L1}) ] + C_{wf} (2 E_{R1} - 1) (E_{R2} - 1) \} / ( -2 E_{R1} E_{R2} + E_{R1} + E_{R2} ) \} + \{ -C_{H1min} E_{H1} E_{R1} T_{H1} (E_{R2} - 1) (C_{wf} - C_{L1min} E_{L1}) + C_{L1min} C_{wf} E_{L1} E_{R2} T_{L1} x y (E_{R1} - 1) \} / \{ E_{R1} (2 E_{R2} - 1) - E_{R2} \} (C_{wf} - C_{L1min} E_{L1}) \} - C_{H1min} E_{H1} T_{H1} (E_{R2} - 1) \\
c_1 &= \{ C_{wf} E_{L2} [ (\eta_{tur2} - 1) x_a y_a - \eta_{tur2} ] \{ -C_{wf} (2 E_{R1} - 1) (E_{R2} - 1) (\eta_{com1} + x - 1) [ (\eta_{tur1} - 1) x y - \eta_{tur1} ] (C_{wf} E_{H1} + C_{wf} E_{L1}) + E_{H1} C_{wf}^2 E_{L1} (2 E_{R1} - 1) (E_{R2} - 1) (\eta_{com1} + x - 1) [ (\eta_{tur1} - 1) x y - \eta_{tur1} ] + C_{wf}^2 \{ \eta_{tur1} (2 E_{R1} - 1) (E_{R2} - 1) (\eta_{com1} + x - 1) (x y - 1) + x y \{ E_{R1} [ \eta_{com1} + 2 x - 2 - 2 E_{R2} (\eta_{com1} + x - 1) ] + E_{R2} (\eta_{com1} + x - 1) - x + 1 \} \} / \{ (\eta_{com1} + x - 1) [ E_{R1} (2 E_{R2} - 1) - E_{R2} ] C_{wf}^2 x y (1 - E_{L1}) \} + \{ -C_{wf} E_{H1} (E_{R2} - 1) [ (\eta_{tur1} - 1) x y - \eta_{tur1} ] \{ x_a y_a [ x_a - 1 - E_{R1} (\eta_{com2} + 2 x_a - 2) ] + \eta_{tur2} (2 E_{R1} - 1) (\eta_{com2} + x_a - 1) (x_a y_a - 1) \} / (x y) + C_{wf}^2 \eta_{com1} \{ x_a y_a [ (\eta_{com2} + x_a - 1 - E_{R2} \eta_{com2}) E_{R1} - x_a + 1 ] - \eta_{tur2} (E_{R1} - 1) (\eta_{com2} + x_a - 1) (x_a y_a - 1) \} / [ C_{wf} (\eta_{com1} + x - 1) (1 - E_{L1}) ] + C_{wf} (E_{R2} - 1) [ (\eta_{tur1} - 1) x y - \eta_{tur1} ] \{ (2 E_{R1} - 1) (\eta_{com2} + x_a - 1) (x_a y_a - 1) \eta_{tur2} + x_a y_a [ x_a - 1 - E_{R1} (\eta_{com2} + 2 x_a - 2) ] \} / (x y) \} / \{ (E_{R1} + E_{R2} - 2 E_{R1} E_{R2}) (\eta_{com2} + x_a - 1) \} \} / (x_a y_a) \\
c_2 &= \{ \{ x_a y_a [ C_{wf} E_{L1} \{ C_{wf} E_{L2} (\eta_{com2} + x_a - 1) [ E_{R1} T_{L3} (2 E_{R2} - 1) + (E_{R1} - 1) (\eta_{tur2} - 1) T_{L1} - E_{R2} T_{L3} ] - C_{wf} T_{L1} \{ (E_{R2} + \eta_{tur2} - 1) E_{R1} \eta_{com2} + E_{R1} (\eta_{tur2} - 1) (x_a - 1) - \eta_{tur2} (\eta_{com2} + x_a) + \eta_{tur2} + x_a - 1 \} - C_{wf}^2 E_{L2} T_{L3} [ E_{R1} (2 E_{R2} - 1) - E_{R2} ] (\eta_{com2} + x_a - 1) \} + C_{wf}^2 E_{L1} \eta_{tur2} T_{L1} (E_{R1} - 1) (\eta_{com2} + x_a - 1) (1 - E_{L2}) \} / \{ (\eta_{com2} + x_a - 1) x_a y_a C_{wf} (1 - E_{L1}) [ E_{R1} (2 E_{R2} - 1) - E_{R2} ] \} - C_{wf} E_{H1} (E_{R2} - 1) T_{H1} [ (\eta_{tur1} - 1) x y - \eta_{tur1} ] \{ C_{wf} E_{L2} (2 E_{R1} - 1) (\eta_{com2} + x_a - 1) (\eta_{tur2} + x_a y_a - x_a \eta_{tur2} y_a) + C_{wf} x_a y_a [ E_{R1} \eta_{com2} (2 \eta_{tur2} - 1) + 2 E_{R1} (\eta_{tur2} - 1) (x_a - 1) - (\eta_{com2} + x_a) \eta_{tur2} + \eta_{tur2} + x_a - 1 ] - C_{wf} \eta_{tur2} (2 E_{R1} - 1) (\eta_{com2} + x_a - 1) \} / \{ (\eta_{com2} + x_a - 1) C_{wf} x y x_a y_a [ E_{R1} (2 E_{R2} - 1) - E_{R2} ] \} \\
c_3 &= \{ c_1 E_{R1} [ E_{R1} (2 E_{R2} - 1) - E_{R2} ] \{ C_{wf} E_{H1} (E_{R2} - 1) [ (\eta_{tur1} - 1) x y - \eta_{tur1} ] \{ C_{wf}^2 E_{L1} E_{L2} (\eta_{com1} + x - 1) \{ E_{R1} \eta_{tur2} T_{L1} - x_a y_a [ E_{R1} T_{L1} (\eta_{tur2} - 1) - E_{R1} T_{L3} + T_{L3} ] \} + C_{wf}^2 E_{L1} E_{R1} T_{L1} (\eta_{com1} + x - 1) (\eta_{tur2} + x_a y_a - x_a \eta_{tur2} y_a) + C_{wf} E_{L2} \{ E_{R1} \eta_{com1} \eta_{tur2} T_{H1} + x_a y_a [ T_{L3} + E_{R1} \eta_{com1} (T_{H1} + T_{L3} - \eta_{tur2} T_{H1}) + E_{R1} T_{L3} (x - 1) - T_{L3} (\eta_{com1} + x) \} \} + C_{wf}^2 E_{R1} \eta_{com1} T_{H1} [ (\eta_{tur2} - 1) x_a y_a - \eta_{tur2} ] \} + C_{wf} (\eta_{com1} + x - 1) E_{L1} [ (\eta_{tur1} - 1) x y - \eta_{tur1} ] (E_{R2} - 1) \{ x_a y_a [ C_{wf} E_{R1} T_{L1} (1 - E_{L2}) (\eta_{tur2} - 1) + C_{wf} E_{L2} (E_{R1} - 1) T_{L3} ] + E_{R1} \eta_{tur2} T_{L1} (C_{wf} E_{L2} - C_{wf}) \} - C_{wf}^2 E_{L2} T_{L3} x_a y_a \{ (\eta_{tur1} E_{R1} - 1) (E_{R2} - 1) (\eta_{com1} + x - 1) (x y - 1) + x y \{ E_{R1} (E_{R2} + \eta_{com1} + x - 1 - 2 \eta_{com1} E_{R2} - E_{R2} x) + E_{R2} (\eta_{com1} + x - 1) - x + 1 \} \} / [ x x_a y y_a (\eta_{com1} + x - 1) ] - c_1 c_2 E_{R2} (E_{R1} - 1) (E_{R1} + E_{R2} - 2 E_{R1} E_{R2}) \{ C_{wf}^2 (1 - E_{L1}) (E_{R2} - 1) E_{H1} E_{R1} [ (\eta_{tur1} - 1) x y - \eta_{tur1} ] / (C_{wf} E_{R2} x y) + E_{R1} C_{wf} (E_{R2} - 1) (1 - E_{L1}) \eta_{tur1} / (E_{R2} x y) - C_{wf} (\eta_{tur1} - 1) (1 - E_{L1}) (E_{R2} - 1) E_{R1} / E_{R2} + C_{wf} \eta_{com1} (E_{R1} - 1) / (\eta_{com1} + x - 1) \} + E_{R2} (E_{R1} - 1) (E_{R1} + E_{R2} - 2 E_{R1} E_{R2}) \{ -C_{wf}^2 E_{H1} E_{R1} T_{H1} (E_{R2} - 1) (1 - E_{L1}) [ (\eta_{tur1} - 1) x y - \eta_{tur1} ] / (C_{wf} E_{R2} x y) - C_{wf} E_{L1} T_{L1} (E_{R1} - 1) \} / [ C_{wf} (1 - E_{L1}) (E_{R1} + E_{R2} - 2 E_{R1} E_{R2})^2 ] \\
c_4 &= \{ \eta_{com2} \{ \{ c_1 c_2 (E_{R1} - 1) \{ E_{H1} (E_{R1} - 1) (E_{R2} - 1) [ (\eta_{tur1} - 1) x y - \eta_{tur1} ] / (x y) + \eta_{com1} (E_{R1} E_{R2} - 1) / [ (\eta_{com1} + x - 1) (1 - E_{L1}) ] - \eta_{tur1} (E_{R1} - 1) (E_{R2} - 1) (x y - 1) / (x y) + E_{R1} E_{R2} - E_{R1} - E_{R2} + 1 \} / (E_{R1} + E_{R2} - 2 E_{R1} E_{R2}) + \{ E_{R1} \{ (E_{R2} - 1) E_{H1} E_{R1} T_{H1} [ (\eta_{tur1} - 1) x y - \eta_{tur1} ] / (x y) + \{ E_{L1} E_{R2} T_{L1} (E_{R1} - 1) \} / (1 - E_{L1}) \} / (E_{R1} + E_{R2} - 2 E_{R1} E_{R2}) - \{ \{ C_{wf} (E_{R2} - 1) (1 - E_{L1}) C_{wf} E_{H1} E_{R1} T_{H1} [ (\eta_{tur1} - 1) x y - \eta_{tur1} ] / (C_{wf} E_{R2} x y) + C_{wf} E_{L1} T_{L1} (E_{R1} - 1) \} / [ C_{wf} (E_{R1} + E_{R2} - 2 E_{R1} E_{R2}) (1 - E_{L1}) ] + \{ C_{wf} E_{H1} (E_{R2} - 1) T_{H1} [ (\eta_{tur1} - 1) x y - \eta_{tur1} ] / (C_{wf} E_{R2} x y) \} / [ (E_{R1} - 1) (\eta_{com2} + x_a - 1) \} \\
c_5 &= [ 1 / (C_{wf} E_{R2} x_a y y_a) ] [ (\eta_{tur2} - 1) x_a y_a - \eta_{tur2} ] \{ - \{ \{ c_1 c_2 E_{R2} \{ C_{wf} E_{H1} (2 E_{R1} - 1) (E_{R2} - 1) [ (\eta_{tur1} - 1) x y - \eta_{tur1} ] + C_{wf} x y \eta_{com1} (E_{R1} - 1) / [ (\eta_{com1} + x - 1) (1 - E_{L1}) ] - C_{wf} (2 E_{R1} - 1) (E_{R2} - 1) [ (\eta_{tur1} - 1) x y - \eta_{tur1} ] \} / (E_{R1} + E_{R2} - 2 E_{R1} E_{R2}) \} + \{ C_{wf} E_{H1} E_{R1} T_{H1} (E_{R2} - 1) (1 - E_{L1}) [ (\eta_{tur1} - 1) x y - \eta_{tur1} ] + C_{wf} E_{L1} E_{R2} T_{L1} x y (E_{R1} - 1) \} / \{ E_{R1} (2 E_{R2} - 1) - E_{R2} \} (1 - E_{L1}) \} + C_{wf} E_{H1} T_{H1} (E_{R2} - 1) [ (\eta_{tur1} - 1) x y - \eta_{tur1} ] \} \\
d_1 &= \{ -C_{wf} E_{L2} \{ C_{wf}^2 x (2 E_{R1} - 1) (E_{R2} - 1) (E_{H1} + E_{L1}) - C_{wf}^2 E_{H1} E_{L1} x (2 E_{R1} - 1) (E_{R2} - 1) + C_{wf}^2 \{ x (2 E_{R1} - 1) (E_{R2} - 1) (x y - 1) + x y \{ E_{R1} [ 2 x - 1 - 2 E_{R2} x ] + E_{R2} x - x + 1 \} \} / \{ C_{wf}^2 x^2 y (1 - E_{L1}) [ E_{R1} (2 E_{R2} - 1) - E_{R2} ] \} + \{ C_{wf} E_{H1} (E_{R2} - 1) \{ x_a y_a [ -E_{R1} (2 x_a - 1) + x_a - 1 + x_a (2 E_{R1} - 1) (x_a y_a - 1) ] \} / (x y) + C_{wf} \{ x_a y_a [ (x_a - E_{R2}) E_{R1} - x_a + 1 ] - x_a (E_{R1} - 1) (x_a y_a - 1) \} / [ x (1 - E_{L1}) ] - C_{wf} (E_{R2} - 1) \{ x_a (2 E_{R1} - 1) (x_a y_a - 1) + x_a y_a [ x_a - 1 - E_{R1} (2 x_a - 1) ] \} / (x y) \} / \{ x_a (E_{R1} + E_{R2} - 2 E_{R1} E_{R2}) \} \} / (x_a y_a) \\
d_2 &= \{ \{ x_a y_a \{ C_{wf}^2 E_{L1} \{ E_{L2} x_a [ E_{R1} T_{L3} (2 E_{R2} - 1) - E_{R2} T_{L3} ] - T_{L1} (E_{R1} E_{R2} - 1) \} - C_{wf}^2 E_{L2} T_{L3} x_a [ E_{R1} (2 E_{R2} - 1) - E_{R2} ] \} + C_{wf}^2 E_{L1} T_{L1} x_a (E_{R1} - 1) (1 - E_{L2}) / \{ C_{wf} x_a^2 y_a (1 - E_{L1}) [ E_{R1} (2 E_{R2} - 1) - E_{R2} ] \} + C_{wf}^2 E_{H1} T_{H1} (E_{R2} - 1) \{ (2 E_{R1} - 1) E_{L2} x_a + x_a y_a (E_{R1} - 1) - x_a (2 E_{R1} - 1) \} \} / \{ C_{wf} x y x_a^2 y_a [ E_{R1} (2 E_{R2} - 1) - E_{R2} ] \} \\
d_3 &= \{ d_1 E_{R1} [ E_{R1} (2 E_{R2} - 1) - E_{R2} ] \{ -C_{wf} E_{H1} (E_{R2} - 1) \{ C_{wf}^2 E_{L1} E_{L2} x \{ x_a y_a T_{L3} (1 - E_{R1}) - E_{R1} T_{L1} \} + x C_{wf}^2 E_{L1} E_{R1} T_{L1} + C_{wf} E_{L2} \{ E_{R1} T_{H1} + x_a y_a [ E_{R1} T_{L3} + E_{R1} T_{L3} (x - 1) - T_{L3} x ] \} - C_{wf}^2 E_{R1} T_{H1} \} - \{ E_{L2} T_{L3} x_a y_a (E_{R1} - 1) + (E_{L2} - 1) E_{R1} T_{L1} \} C_{wf}^2 x E_{L1} (E_{R2} - 1) - C_{wf}^2 E_{L2} T_{L3} x_a y_a \{ x y \{ E_{R1} (E_{R2} + x - 2 E_{R2} - E_{R2} x) + E_{R2} x - x + 1 \} + x (E_{R1} - 1) (E_{R2} - 1) (x y - 1) \} / (x^2 x_a y y_a) - d_1 d_2 E_{R2} (E_{R1} - 1) (E_{R1} + E_{R2} - 2 E_{R1} E_{R2}) \{ -C_{wf}^2 (1 - E_{L1}) (E_{R2} - 1) E_{H1} E_{R1} / (C_{wf} E_{R2} x y) + C_{wf} E_{R1} (1 - E_{L1}) (E_{R2} - 1) / (E_{R2} x y) + C_{wf} (E_{R1} - 1) / x \} + (E_{R1} + E_{R2} - 2 E_{R1} E_{R2}) E_{R2} (E_{R1} - 1) \{ C_{wf}^2 E_{H1} E_{R1} T_{H1} (1 - E_{L1}) (E_{R2} - 1) / (C_{wf} E_{R2} x y) - C_{wf} E_{L1} (E_{R1} - 1) T_{L1} / [ (C_{wf} - C_{wf} E_{L1}) (E_{R1} + E_{R2} - 2 E_{R1} E_{R2})^2 ] \} \\
\end{aligned}$$

$$\begin{aligned}
d_4 &= \{ \{ d_1 d_2 (E_{R1} - 1) \{ -E_{H1} (E_{R1} - 1) (E_{R2} - 1) / (xy) + (E_{R1} E_{R2} - 1) / [x(1 - E_{L1})] - (E_{R1} - 1) (E_{R2} - 1) (xy - 1) / (xy) + \\
&E_{R1} E_{R2} - E_{R1} - E_{R2} + 1 \} / (E_{R2} + E_{R1} - 2E_{R1} E_{R2}) + \{ E_{R1} \{ -E_{H1} E_{R1} (E_{R2} - 1) T_{H1} / (xy) + E_{L1} E_{R2} T_{L1} (E_{R1} - 1) / (1 - E_{L1}) \\
&\} \} / (-2E_{R1} E_{R2} + E_{R1} + E_{R2}) - \{ -E_{H1} E_{R1} T_{H1} (E_{R2} - 1) (1 - E_{L1}) / (E_{R2} xy) + E_{L1} T_{L1} (E_{R1} - 1) \} / [(1 - E_{L1}) (E_{R1} + E_{R2} - 2 \\
&E_{R1} E_{R2}) - E_{H1} T_{H1} (E_{R2} - 1) / (E_{R2} xy)] \} / [x_a (E_{R1} - 1)] \\
d_5 &= [-1 / (C_{wf} E_{R2} x x_a y y_a)] \{ - \{ \{ d_1 d_2 E_{R2} \{ -C_{wf} E_{H1} (2E_{R1} - 1) (E_{R2} - 1) - C_{wf} xy (E_{R1} - 1) / (1 - E_{L1}) + C_{wf} (2E_{R1} - 1) ( \\
&E_{R2} - 1) \} / (E_{R1} + E_{R2} - 2E_{R1} E_{R2}) \} + \{ C_{wf}^2 E_{L1} E_{R2} T_{L1} xy (E_{R1} - 1) - C_{wf}^2 E_{H1} E_{R1} (E_{R2} - 1) (1 - E_{L1}) T_{H1} \} / \{ C_{wf} (1 - E_{L1}) [ \\
&E_{R1} (2E_{R2} - 1) - E_{R2} \} - C_{wf} E_{H1} T_{H1} (E_{R2} - 1) \} \\
e &= \{ -(\eta_{com1} + x - 1) \{ C_{H1min} E_{H1} (C_{wf} - C_{L1min} E_{L1}) T_{H1} [(\eta_{tur1} - 1) xy - \eta_{tur1}] - C_{L1min} C_{wf} E_{L1} T_{L1} xy \} \} / \{ C_{H1min} C_{L1min} E_{H1} E_{L1} \\
&(\eta_{com1} + x - 1) [(\eta_{tur1} - 1) xy - \eta_{tur1}] + C_{wf}^2 [(1 - x) xy + \eta_{tur1} (\eta_{com1} + x - 1) (xy - 1)] - C_{wf} (C_{H1min} E_{H1} + E_{L1} C_{L1min}) (\eta_{com1} + \\
&x - 1) [(\eta_{tur1} - 1) xy - \eta_{tur1}] \}
\end{aligned}$$

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