Applied Thermal Engineering 128 (2018) 173–178

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Constrained optimal high pressure equation of CO_2 transcritical cycle

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HIGHLIGHTS

- Constrained optimization of high pressure of CO_2 transcritical cycle was proposed.
- Two approaches to constrained optimal high pressure equation were developed.
- High pressure was significantly reduced with no more than 5% COP loss.

ARTICLE INFO

Article history:
Received 8 October 2016
Revised 20 August 2017
Accepted 6 September 2017
Available online 6 September 2017

Keywords:
CO_2
Transcritical cycle
High pressure
Constrained optimization

ABSTRACT

CO_2 transcritical cycle has been widely applied in commercial refrigeration and heat pump water heating systems. Its cycle COP (coefficient of performance) heavily depends on the high pressure optimization and control. In theory, the optimal high pressure increases quickly with the increasing gas cooler outlet temperature or ambient temperature. However, due to reliability and cost concerns, there is an upper limit of the high pressure in compressor design and system operation. In this work, we proposed a constrained optimization method for getting constrained optimal high pressure equation of CO_2 transcritical cycle. With the new method, the high pressure and its upper bound were simultaneously optimized at a given level of COP loss. Two specific approaches were developed to get the constrained optimal high pressure equation. Up to 1 MPa high pressure reduction was achieved with about maximum 5% and average 1% COP losses.

1. Introduction

To efficiently use the natural and safe refrigerant carbon dioxide (CO_2), Lorentzen and Pettersen [1,2] proposed a CO_2 transcritical cycle. Since then CO_2 transcritical cycle has been in-depth investigated and successfully applied, particularly in commercial refrigeration and heat pump water heating systems [3–7].

Different from the common subcritical vapor compression cycles, CO_2 transcritical cycle performance heavily depends on the optimal control of high pressure. Therefore, many researches have been done at this point. Kauf [8] first developed a single-variable linear control function of optimal high pressure based on real compressor performance. Later Liao, Zhao and Jakobsen [9] proposed some optimal high pressure correlations of single-stage CO_2 transcritical cycle. Three variables including the gas cooler outlet temperature, the evaporating temperature and the isentropic efficiency of compressor were involved in the correlations. The gas cooler outlet temperature had the most significant impact on the optimal high pressure. Similar approach was adopted by many researchers in development of optimal high pressure equations for different CO_2 transcritical cycles [10–27]. A brief review of the optimal high pressure equations was given by Yang, Li, Cai, Shao and Zhang [28]. However, this approach for high pressure optimal control was found not very robust in application [29,30]. To mitigate the robustness risk, Yang, Li, Cai, Shao and Zhang [28] suggested to minimize the COP loss instead of minimize the deviations of optimal high pressures. Shao and Zhang [31] defined different control parameters as alternatives of high pressure. Cecchinato, Corradi and Minetto [30] suggested to develop more efficient and robust real-time algorithm for determining the optimal high pressure. Since then, real-time control methods have been further investigated and demonstrated excellent control performance [32–35].

From the existing investigations we can reach the following conclusions. Firstly, gas cooler outlet temperature is the main influence factor of the optimal high pressure. In the temperature range of interest, the optimal high pressure increases near-linearly with the increasing gas cooler outlet temperature. Secondly, due to reliability and cost concerns, there is an upper limit of the high pressure in compressor design and system operation. [36]. In the existing optimal high pressure equations, however,

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http://dx.doi.org/10.1016/j.applthermaleng.2017.09.023
1359-4311/

Nomenclature

a_1,a_2,b_1,b_2	empirical coefficients in high pressure equations
AD	average relative deviation
COP	coefficient of performance
ΔCOP	COP loss
f	functional equation of transcritical CO_2 cycle
h	enthalpy (kJ kg^{-1})
MaxD	maximum relative deviation
N	number of data
p	pressure (MPa)
SD	standard deviation
T	temperature (°C)

Greeks

ε	effectiveness

Subscripts

c	gas cooler outlet
cut-off	cut-off point
e	evaporator outlet
IHE	internal heat exchanger
max	maximum
opt	optimal
s	isentropic

no consideration has yet been made at this point. Once the optimal high pressure control is overridden by the high pressure limit in operation, the system performance will no longer be guaranteed.

In this work, we proposed a constrained optimization method for getting constrained optimal high pressure equation of CO_2 transcritical cycle. The high pressure and its upper bound were simultaneously optimized at a given level of COP loss. Two constrained optimal high pressure equations were therefore developed. The constrained optimal high pressure equation would help the real CO_2 transcritical system perform better subject to its pressure limit.'

2. Unconstrained optimal high pressure equation

To set a baseline for comparison, unconstrained optimal high pressure equation is developed first. As shown in Fig. 1, a typical CO_2 transcritical cycle with an internal heat exchanger (IHE) is studied in this work. A receiver is positioned at the downstream of evaporator for saturated vapor leaving the evaporator. In other words, there is no superheat at the exit of evaporator. The IHE is designed to lower the refrigerant temperature before expansion valve and to guarantee no liquid carry-over to the compressor.

The basic equations for cycle analysis are as follows.

$$\mathrm{COP} = \frac{h_1 - h_5}{h_3 - h_2} = \eta_s \frac{h_1 - h_5}{h_{3s} - h_2} \tag{1}$$

To achieve the maximum cycle COP (hereinafter called the optimal COP) at certain high pressure (hereinafter called the optimal high pressure), we have

$$\left[\frac{\partial \mathrm{COP}}{\partial p_c}\right]_{pc=popt} = 0 \tag{2}$$

The isentropic efficiency of compressor can be calculated by [9]

$$\eta_s = 1 - K\frac{p_c}{p_e} \tag{3}$$

The COP loss minimization method [28] is applied to get unconstrained optimal high pressure equation of the cycle. The calculation conditions are listed in Table 1. Within the parameter range, we used the above basic equations to generate hundreds of data points for getting the optimal high pressure equation.

As many researchers recommended, the unconstrained optimal high pressure can be simply expressed as a linear function of the gas cooler outlet temperature. Therefore, the COP loss minimization problem is defined as below [28].

$$\mathrm{minimize} \sum_{k=1}^{N} (\mathrm{COP}_k - \mathrm{COP}_{\max,k})^2 \tag{4}$$

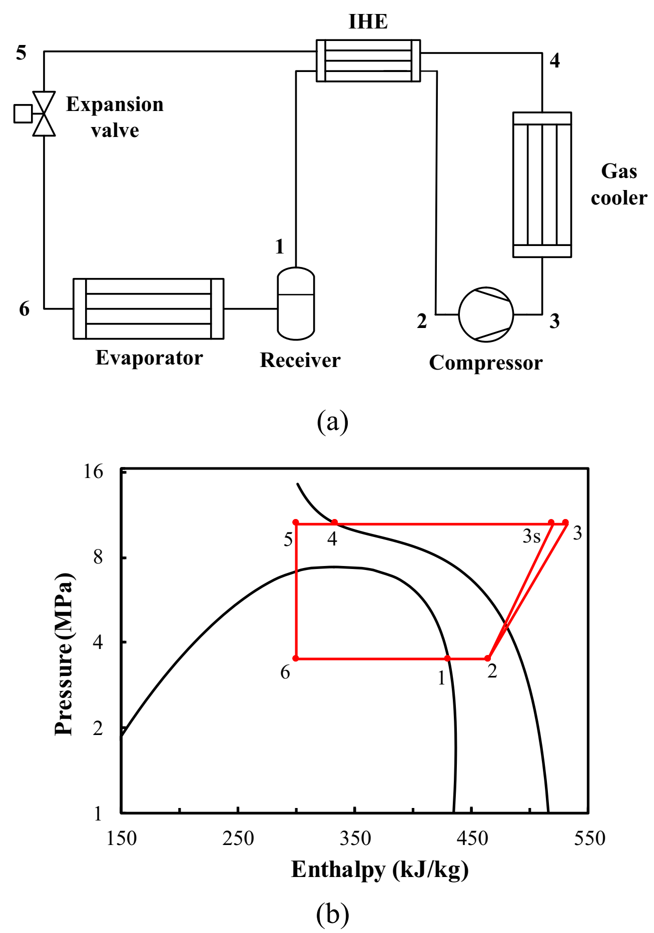

Fig. 1. Schematic (a) and *p-h* diagram (b) of the CO_2 transcritical cycle.

Table 1
Calculation conditions of unconstrained high pressure optimization.

Parameter	Range
Evaporating temperature (°C)	−10 to 20
Gas cooler outlet temperature (°C)	30–60
Coefficient K in Eq. (3)	0.06–0.14 [9]
IHE effectiveness	0–0.9
Refrigerant properties	REFPROP 9.0 [37]

subject to

$$\mathrm{COP}_k = f(T_{c,k}, T_{e,k}, p_{c,k}), \quad k = 1, 2, \ldots, N \tag{5}$$

$$\mathrm{COP}_{\max,k} = f(T_{c,k}, T_{e,k}, p_{opt,k}), \quad k = 1, 2, \ldots, N \tag{6}$$

$$p_{c,k} = a_1 T_{c,k} + a_2, \quad k = 1, 2, \ldots, N \tag{7}$$

where, N is the number of data points. Coefficients a_1 and a_2 can be determined by minimizing the objective function (4).

Eventually, we have the following unconstrained optimal high pressure equation.

$$p_{opt} = 0.272T_c - 0.948 \tag{8}$$

Meanwhile, the impact of ignoring other parameters in Table 1 on the optimal cycle performance should be evaluated as well. Fig. 2 through Fig. 4 are plotted to compare Eq. (8) based optimal high pressure and cycle COP with the original data.

Fig. 2(a) shows that in a wider temperature range the actual optimal high pressure is not precisely a linear function of the gas cooler outlet temperature. Since the major COP loss happens at lower gas cooler outlet temperatures [28], the COP loss minimization method leads to larger deviation of optimal high pressure at higher gas cooler outlet temperatures. However, as shown in Fig.2(b), the optimal COP loss is quite small in the whole range of gas cooler outlet temperature. In addition, deviations of optimal high pressure and COP from the evaporating temperature are marginal.

Fig. 3(a) shows that higher compressor isentropic efficiency leads to smaller deviation of Eq. (8). Nevertheless, as shown in Fig. 3(b), its impact on the optimal COP loss is negligible.

Fig.4(a) shows that lower IHE effectiveness leads to smaller deviation of Eq. (8), which indicates the linearity of optimal high pressure equation will get worse if an IHE is used in the cycle. However, as shown in Fig. 4(b), the existence of IHE has little impact on the optimal COP as well as the COP loss. This is in consistent with Liao, Zhao and Jakobsen [9].

3. Constrained optimal high pressure equation

To get the constrained optimal high pressure equation, we had better understand the cycle performance from lower pressure to higher pressure in the supercritical region. As shown in Fig. 5, there are three COP curves at three different gas cooler outlet temperatures. The calculation conditions used in Fig. 5 include T_e = 10 °C, K = 0.121, and ε = 0.8. When the gas cooler outlet temperature gets lower and closer to the critical temperature (31.1 °C), the peak on COP curve becomes more prominent. Consequently, the maximum COP is more sensitive to the deviation of optimal high pressure. On the other end, when the gas cooler outlet temperature goes higher, the COP curves flatten out and the maximum COP becomes less sensitive to the deviation of optimal high pressure.

Therefore, we can select optimal cut-off pressure or corresponding cut-off temperature (gas cooler outlet temperature) to manage the COP loss at an acceptable level (e.g. maximum 5% COP loss). In

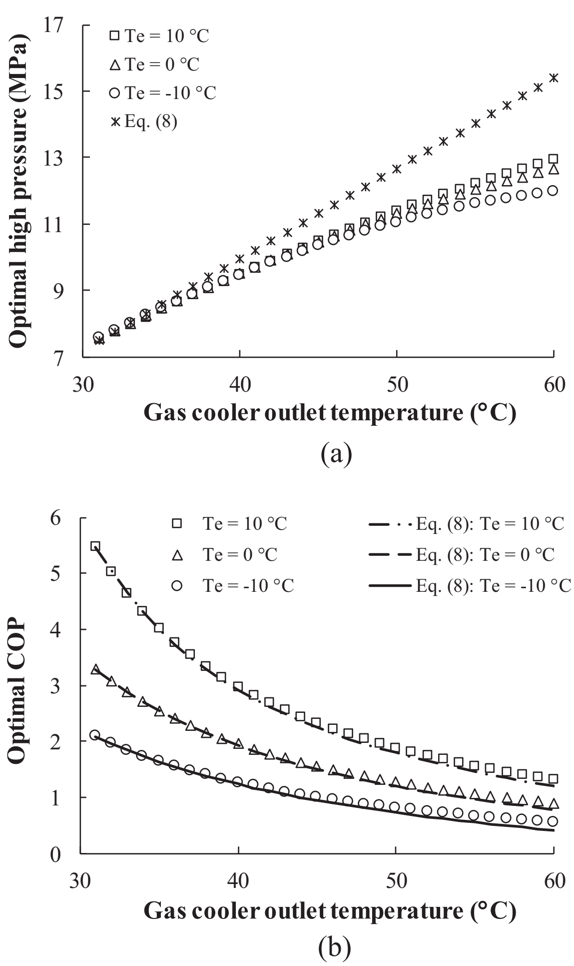

Fig. 2. Optimal cycle performance at different evaporating temperatures.

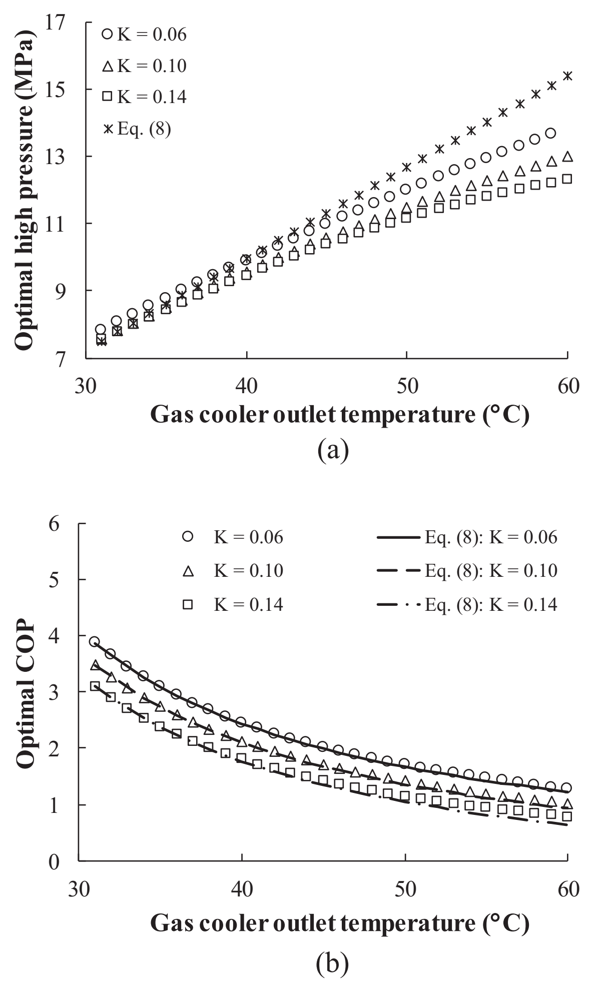

Fig. 3. Optimal cycle performance at different compressor isentropic efficiencies.

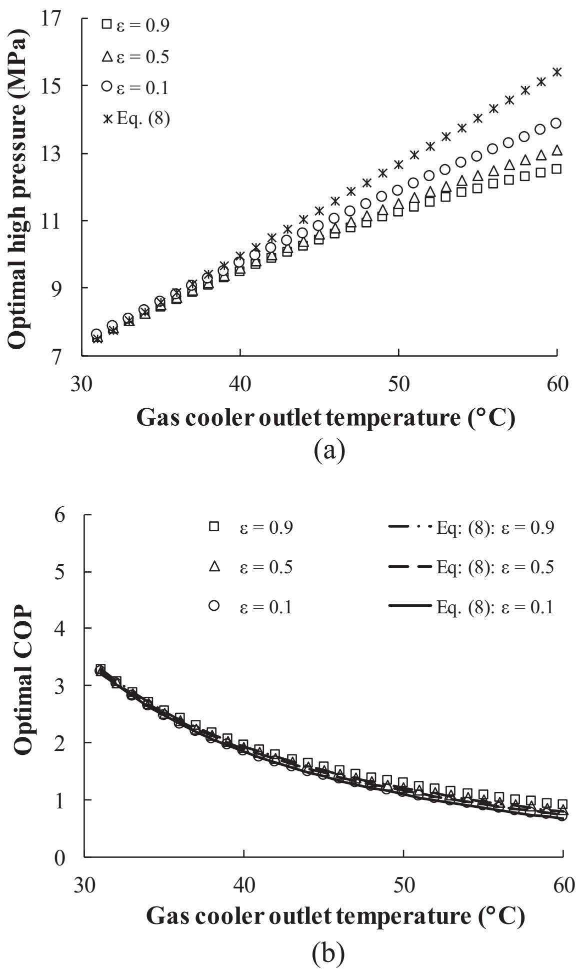

Fig. 4. Optimal cycle performance at different IHE effectiveness.

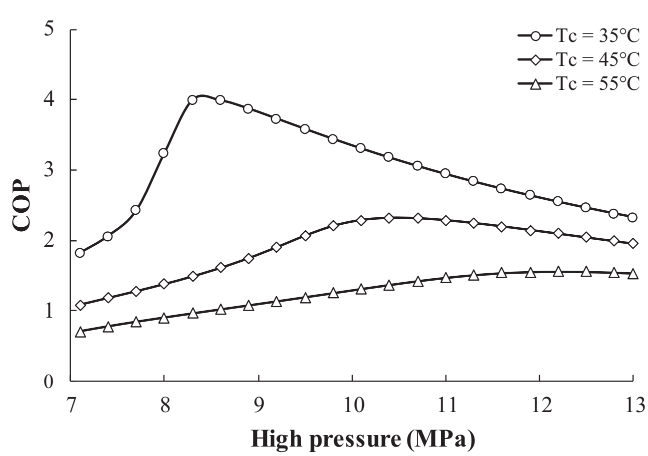

Fig. 5. COP variation with high pressure and gas cooler outlet temperature.

detail, two approaches are developed to get constrained optimal high pressure equation.

3.1. Unconstrained optimal high pressure equation with cut-off point

An easy approach coming to mind is to combine the unconstrained optimal high pressure Eq. (8) with certain cut-off pressure.

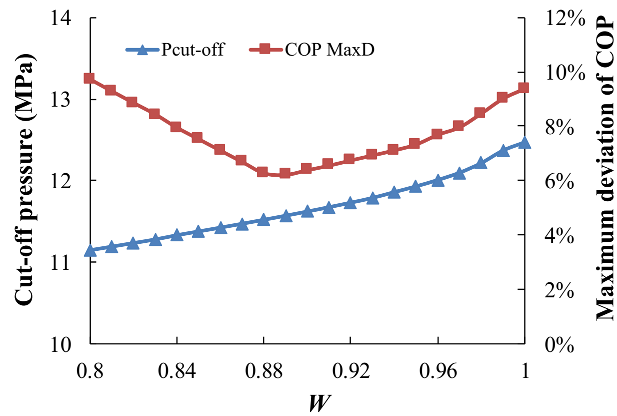

Fig. 6. Impact of W in Eq. (9).

To get the cut-off pressure, we define the following optimization function.

$$\text{minimize } F = W \cdot \max\left(\frac{\Delta \mathrm{COP}_k}{\mathrm{COP}_{\mathrm{opt},k}}\right)^2 + (1-W)\frac{p_{\text{cut-off}}}{p_{\mathrm{opt,max}}} \tag{9}$$

Subject to

$$\Delta \mathrm{COP}_k = COP_{\mathrm{opt},k} - \mathrm{COP}_k, \quad k = 1, 2, \ldots, N \tag{10}$$

$$\mathrm{COP}_{\mathrm{opt},k} = f(T_{\mathrm{c,max}}, T_{\mathrm{e},k}, p_{\mathrm{opt},k}), \quad k = 1, 2, \ldots, N \tag{11}$$

$$\mathrm{COP}_k = f(T_{\mathrm{c,\,max}}, T_{\mathrm{e},k}, p_{\text{cut-off}}), \quad k = 1, 2, \ldots, N \tag{12}$$

$$p_{\mathrm{opt,max}} = \max(p_{\mathrm{opt},k}), \quad k = 1, 2, \ldots, N \tag{13}$$

where W is the weight and will be discussed later. $T_{\mathrm{c,max}}$ is the maximum value over a range of gas cooler outlet temperature, e.g. in the range of 30 °C ~ 60 °C, 30 °C is the minimum gas cooler outlet temperature in all cases of this study while 60 °C is the $T_{\mathrm{c,max}}$ in this case.

In Eq. (9), when the cut-off pressure increases and approaches the real optimal high pressure, the first term on right-hand side of Eq. (9) will decrease but the second term will increase. Therefore, the weight W balances two opposites to get best results. To determine W in Eq. (9), impact of W on $p_{\text{cut-off}}$ and COP MaxD was plotted in Fig. 6 ($T_{\mathrm{c,max}}$ = 60 °C). It indicates that the cut-off pressure increases monotonically with W, while COP MaxD can be minimized at certain value, e.g. W = 0.89 in this case.

At each maximum gas cooler outlet temperature $T_{\mathrm{c,max}}$, we can determine one cut-off pressure. All the cut-off pressures and the corresponding optimal high pressure curve (Eq. (8)) are plotted in Fig. 7. Apparently, the cut-off pressure is much lower than the optimal high pressure. More pressure reduction can be achieved at higher $T_{\mathrm{c,max}}$. Furthermore, the cut-off pressure increases with $T_{\mathrm{c,max}}$ and can be nearly expressed as a linear function of $T_{\mathrm{c,max}}$. Namely,

$$p_{\text{cut-off}} = 0.122 T_{\mathrm{c,max}} + 4.33 \tag{14}$$

Eq. (14) can work together with the unconstrained optimal high pressure Eq. (8) to control the high pressure of CO2 transcritical cycle. In Table 2, results of three typical cut-off points are given, in which $T_{\text{c,cut-off}}$, COP AD, COP MaxD and COP SD are defined as follows. In terms of average deviations, maximum deviations and standard deviations of COP, the overall accuracy of this approach is acceptable.

$$\mathrm{COP\ AD} = \frac{1}{N}\sum \frac{\mathrm{COP}_{\mathrm{opt},k} - \mathrm{COP}_k}{\mathrm{COP}_{\mathrm{opt},k}}, \quad k = 1, 2, \ldots, N \tag{15}$$

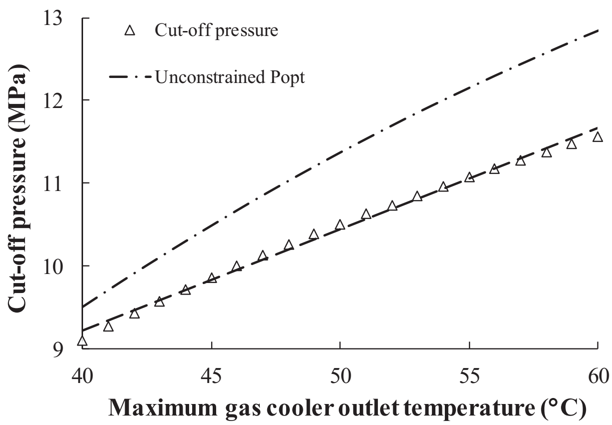

Fig. 7. Cut-off points of unconstrained optimal high pressure equation.

Table 2
Typical cut-off points from Eq. (14).

$T_{c,max}$ (°C)	$p_{cut\text{-}off}$ (MPa)	$T_{c,cut\text{-}off}$ (°C)	COP AD (%)	COP MaxD (%)	COP SD (%)
40	9.22	37.4	0.4	2.1	0.5
50	10.45	41.9	2.1	5.4	1.9
60	11.67	46.3	2.7	5.5	2.0

$$\text{COP MaxD} = \max\left(\frac{\text{COP}_{\text{opt},k} - \text{COP}_k}{\text{COP}_{\text{opt},k}}\right), \quad k = 1, 2, \ldots, N \tag{16}$$

$$\text{COP SD} = \sqrt{\frac{1}{N}\sum_{k=1}^{N}(\text{COP}_{\text{opt},k} - \text{COP}_k - \text{COP AD})^2}, \quad k = 1, 2, \ldots, N \tag{17}$$

3.2. Constrained optimal high pressure equation

To get better accuracy, we propose a more generic approach for simultaneous optimization of high pressure and cut-off pressure.

$$\text{minimize } G = W\sum_{k=1}^{N}\left(\frac{\Delta\text{COP}_k}{\text{COP}_{\text{opt},k}}\right)^2 + (1-W)\frac{p_{\text{cut-off}}}{p_{\text{opt,max}}} \tag{18}$$

Subject to

$$\Delta\text{COP}_k = COP_{\text{opt},k} - \text{COP}_k, \quad k = 1, 2, \ldots, N \tag{19}$$

$$\text{COP}_{\text{opt},k} = f(T_{c,k}, T_{e,k}, p_{\text{opt},k}), \quad k = 1, 2, \ldots, N \tag{20}$$

$$\text{COP}_k = f(T_{c,k}, T_{e,k}, p_{c,k}), \quad k = 1, 2, \ldots, N \tag{21}$$

$$p_{\text{opt,max}} = \max(p_{\text{opt},k}), \quad k = 1, 2, \ldots, N \tag{22}$$

$$p_c = \min\{b_1 T_c + b_2, p_{\text{cut-off}}\} \tag{23}$$

where, the weight W is determined by the same method as shown in Fig. 6.

In comparison with the former approach (Eqs. (9) – (13)), the new one (Eqs. (18)--(23)) has two main differences. Firstly, COP deviations of all data points are taken into account, as seen in Eq. (18). Secondly, coefficients b_1 and b_2 of the unconstrained high pressure equation are re-optimized, as seen in Eq. (23)

Eventually, the optimization results in the following constrained optimal high pressure equation.

Table 3
Typical cut-off points from Eq. (24).

$T_{c,max}$ (°C)	$p_{cut\text{-}off}$ (MPa)	$T_{c,cut\text{-}off}$ (°C)	COP AD (%)	COP MaxD (%)	COP SD (%)
40	9.22	38.2	0.3	1.5	0.4
50	10.45	43.5	0.7	5.4	1.2
60	11.67	48.7	0.8	5.1	1.0

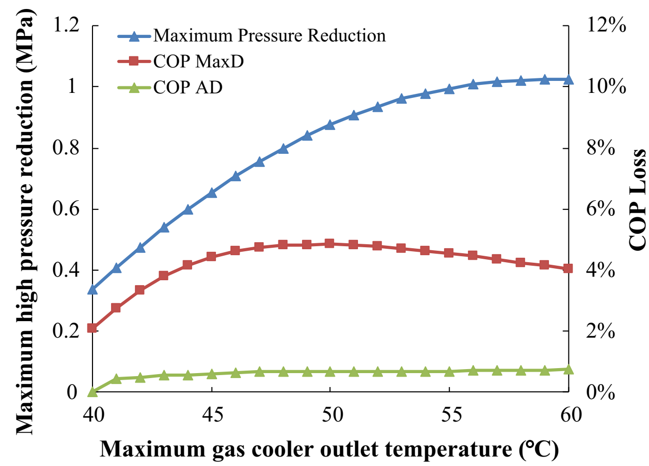

Fig. 8. Maximum high pressure reduction and COP MaxD at different $T_{c,max}$.

$$p_c = \min\{0.240T_c, 0.132T_{c,max} + 3.89\} \tag{24}$$

where 40 °C ≤ $T_{c,\ max}$ ≤ 60 °C, 30 °C ≤ T_c ≤ $T_{c,\ max}$.

Results of the new approach are listed in Table 3. As expected, the AD and SD of COP losses are lower than that of the former approach (as seen in Table 2). In addition, at the same cut-off pressure, higher cut-off temperature is obtained.

According to Eq. (24), we plotted the maximum high pressure reduction and COP loss at different $T_{c,max}$. As shown in Fig. 8, Eq. (24) can help reduce the high pressure up to 1 MPa with about maximum 5% and average 1% COP losses in the given temperature range.

4. Conclusions

CO_2 transcritical cycle COP heavily depends on the supercritical high pressure optimization and control. From reliability and cost perspective, we developed a constrained optimization method for getting constrained optimal high pressure equation of CO_2 transcritical cycle. Two approaches were considered. Unconstrained optimal high pressure equation with cut-off point was simple, but the constrained optimal high pressure equation from simultaneous optimization of the high pressure and the cut-off pressure showed better accuracy and higher cut-off temperature at the same cut-off pressure. The work would help the CO_2 transcritical system perform better subject to its actual pressure limit.

Acknowledgments

This work is supported by the Fundamental Research Funds for the Central Universities.

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