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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.

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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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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].

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

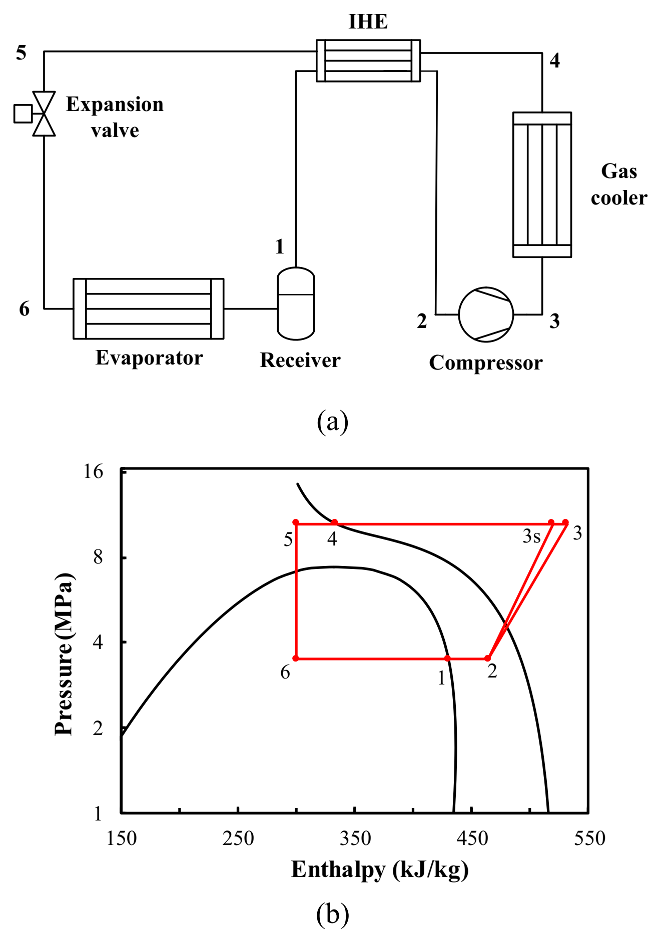

Fig. 1. Schematic (a) and *p-h* diagram (b) of the CO_2 transcritical cycle.

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

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

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