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A correlation-free on-line optimal control method of heat rejection pressures in CO_2 transcritical systems

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ABSTRACT

This paper proposes a novel correlation-free on-line optimal control method for CO_2 transcritical refrigeration systems. It uses the on-line correction formula to track the optimal pressure set point. As a critical advantage against the existing empirical correlations of the heat rejection pressure, it is independent of the cycle, the system specifications, and the operating conditions. Dynamic numerical simulation demonstrates how to apply the new method to a basic CO_2 transcritical refrigeration system. The results show that the proposed method can well track the optimal pressures and is robust to resist the sampling noise.

Méthode sans corrélation de régulation optimale en ligne des pressions de refoulement dans les systèmes au CO_2 transcritiques

Mots clés : cycle ; dioxyde de carbone ; transcritique ; pressure élevée ; optimisation ; régulation ; mise en service ; modéle

1. Introduction

Applications of CO_2 in vapor compression systems were revisited since 1990s to deal with global warming and ozone depletion. The critical achievements and issues of CO_2 refrigeration technologies were addressed by different researchers (Lorentzen, 1994, 1995; Cavallini and Neksa, 2001; Kim et al., 2004; Groll and Kim, 2007). In these reports, it was emphasized that the optimization of the heat rejection pressure is important for energy efficiencies of CO_2 transcritical systems.

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Nomenclature

C, K	coefficients in linear compressor efficiency equation
COP	coefficient of performance
f	compressor frequency (Hz)
h	specific enthalpy (kJ kg^{-1})
P_{fans}	total fan power (W)
p	pressure (kPa)
q	heat flow per unit mass flow (kJ kg^{-1})
T	temperature (°C)
w	electrical work per unit mass flow (kJ kg^{-1})
$V_{d,comp}$	compressor volumetric flow rate (m^3 s^{-1})

Greek symbols

θ	a parameter related to the derivative of COP
ϵ	heat exchanger effectiveness
ρ	density (kg m^{-3})
η	compressor efficiency

Subscripts

1	suction port
2	discharge port
3	gas cooler exit
amb	ambient
i	indoor
is	isentropic
evap	evaporator
gc	gas cooler
max	maximum
o	outdoor
opt	optimal
vol	volumetric

The widely applied control method of the optimal heat rejection pressures relies on the empirical optimal pressure correlations generated offline. There are three typical approaches to develop the optimal pressure correlations: the experiments, the physics-based plant modeling and the thermodynamic cycle simulation. The experimental approach is the most straightforward one. But considering the wide operating conditions, the experiment-based optimization is expensive and time-consuming. Meanwhile, the experiment results are not applicable if the main component specifications or the cycle are changed. Therefore, it's rarely used by researchers. The physics-based plant modeling is also seldom used because it requires much more modeling efforts than the thermodynamic cycle simulation. Regarding the heat rejection pressure optimization based on thermodynamic cycle simulation, the most representative work can be found from Kauf (1998), Liao et al. (2000), Sarkar et al. (2004), Sawalha (2008), Chen and Gu (2005), Agrawal et al. (2007) and Cecchinato et al. (2009).

There are two critical challenges in developing the optimal pressure correlations. First of all, the correlations rely on the cycle and the component specifications. Once the component or the cycle is changed, the optimization procedure should be repeated. The second challenge is the complex non-linear thermal fluid behaviors in wide operating conditions. Simple mathematical models are not able to capture the complex thermal fluid systems' behaviors. Therefore, experimental investigations have been conducted by some researchers for directly getting the data for correlations. But experimental approach is too expensive and time-consuming to be widely applied. In summary, the strict optimal heat rejection pressure correlation should consider the component specifications, the cycle layout and the operating conditions. Therefore, it is unrealistic to expect a generic and accurate empirical optimal pressure correlation.

Some recent experimental reports have revealed that the published correlations based on the cycle simulation had significant deviations against the experimentally optimized pressures. Cabello et al. (2008) compared the correlations developed by Liao et al. (2000), Sarkar et al. (2004), Chen and Gu (2005) and Kauf (1998) with their experimental data. The maximum deviations of the four correlations are 4.6%, 1.5%, 15.7% and 7.5%, respectively. Aprea and Maiorino (2009) found that the actual optimal pressures in their experiments had 1.7–4.4% errors compared to Liao's correlation (2000). Considering those experimental data were limited to the testing conditions, the accuracy of correlations could be even worse if more data in wider operating conditions are available. Cecchinato et al. (2010) evaluated the theoretical optimal pressure correlations against the results derived from physics-based detailed models. Significant deviations of the theoretical correlations were found as well.

To reduce the efforts and risks to generate empirical correlations, a correlation-free on-line optimal heat rejection pressure control concept is introduced in this paper. It takes some real-time parameters as inputs of the correction formula to estimate the optimal pressure set point. It is generic and independent of the cycle, the component specifications, and the operating conditions. Feasibility study of the new method is conducted by the dynamic modeling approach.

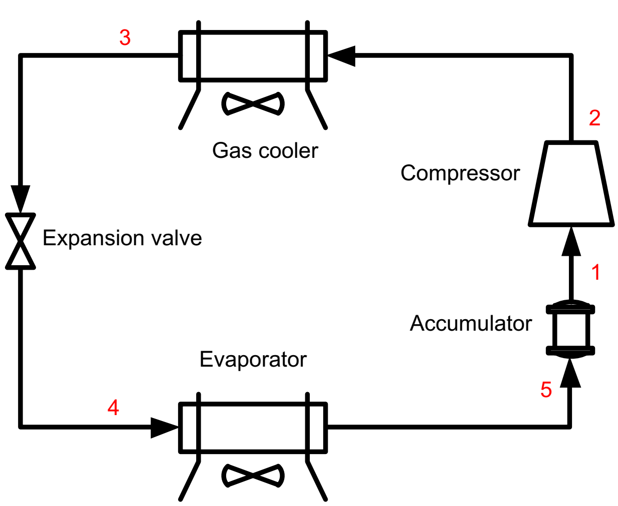

Fig. 1 – A typical single-stage CO_2 transcritical refrigeration system.