Optimization of Transcritical CO₂ Refrigeration Cycle with Parallel Compression Economization

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Abstract

Use of parallel compression economization is one of the promising cycle modifications to improve the COP for transcritical CO₂ refrigeration system. The main aim of the present study is to optimize carbon dioxide refrigeration cycle with the addition of parallel compression economization for air-conditioning applications. The cycle COP improvement over the basic expansion cycle and effect on optimum cycle high side pressure, which is related the system design issues are presented as well. The cooling COP improvement using parallel compression economization can be realized if the ratio of cooling effect improvement and economizing compressor work is more than the COP of basis expansion cycle.

Study shows that there is some optimum economizer pressure where the COP improvement is maximum. Although for simultaneous optimization of gas cooler pressure and economizer pressure, two sets of optimal values can obtained for maximum cooling COP and COP improvement over the basic cycle. For studied gas cooler exit temperatures, the optimum economizer pressures gives narrow values lies between 60 to 63 bar. At the optimum conditions, both the cooling COP and COP improvement compared to basic cycle decreases with increases in gas cooler exit temperature. For the given ranges of operating conditions in this study, the maximum COP improvement over the basis expansion cycle is obtained as 32.8% through the theoretical analyses. The use of parallel compression economization in transcritical CO₂ cycle is profitable for not only COP improvement also for lower optimum high side pressure.

Nomenclature

COP coefficient of performance
COP₀ COP of corresponding basic cycle
h specific enthalpy (kJ/kg)
qₑᵥ specific refrigeration effect (kJ/kg)
wₑ specific compressor work (kJ/kg)
x vapour quality
ΔCOP COP improvement (%)

1. INTRODUCTION

While the synthetic refrigerants exhibit considerably high ODP and GDP, the environment friendly natural refrigerant carbon dioxide has gained interest lately as alternative refrigerants for refrigeration and air-conditioning applications because of their zero ODP and negligible GWP [1]. As the COP of the basic transcritical CO₂ cycle is considerably lower than that of other conventional refrigerant because of very high throttling loss due to high pressure drop compared to other refrigerant based system [2], the cycle modification for COP improvement became an essential part of research. There are several reasons for modifying the basic single-stage transcritical cycle, including improvement of COP, capacity enhancement for a given system and component size, adaptation of the heat rejection temperature profile to given requirements and keeping the pressure ratio and discharge temperature of the compressor within limit. In principle, a large number of modifications are possible, including staging of compression and expansion, splitting of flows, use of internal heat exchange, and work-generating expansion instead of throttling [3]. Recent research progress in different cycle modifications using internal heat exchanger, multistage compression, work recovery expansion machine, vortex tube expansion device, ejector expansion device and thermoelectric device are revised in open literatures [4-5].
The performance of transcritical CO₂ refrigeration cycle can be also improved by several percentages through the successful use of parallel compression economization. In parallel compression refrigerating system, refrigerant vapour is compressed to supercritical discharge pressure in two separate non-mixing streams; one coming from an economiser and the other coming from the main evaporator, so some cylinders of compressor are used to compress vapor from intermediate pressure (in economizer). The parallel compression system will have wide application for automotive air conditioning, window air conditioners and small water chillers, where it is not appropriate to use screw or scroll compressors [6]. Through the theoretical analysis and experimentation for air conditioning application with addition of superheat for the primary compression path, Bell [7] shows that the economized carbon dioxide system outperforms a similar hydrocarbon system in terms of efficiency and capacity under some conditions and most efficient for lower gas cooler exit temperature for fixed discharge pressure. Although detailed optimization studies are scare.

In the present study, optimization studies on transcritical CO₂ refrigeration cycle with the addition of parallel compression economization have been done for air-conditioning applications. The cooling COP improvement over the basic expansion cycle and effect on optimum discharge pressure are presented as well.

\[ h_6 = h_7 \& h_8 = h_9 \]

For unit total mass flow rate, the mass flow rates through the economizing and main compressors are \( x \) and \( 1-x \), respectively, where, vapour quality \( x \) is given by,

\[ x = \frac{h_7 - h_8}{h_3 - h_8} \]

The specific enthalpy of CO₂ at the gas cooler inlet can be found by,

\[ h_3 = x h_4 + (1-x) h_2 \]

Specific refrigerating effect of the evaporator:

\[ q_{ev} = (1-x)(h_1 - h_9) \]

Specific work input to the compressor:

\[ w_c = x(h_1 - h_3) + (1-x)(h_2 - h_1) \]

The cooling COP for parallel compression economization is given by:

\[ COP = \frac{q_{ev}}{w_c} \]
and the cooling COP of corresponding basic cycle is given by,

$$COP_b = \frac{(h_1 - h_6)}{(h_2 - h_1)}$$

(7)

Hence, the COP improvement compared to basic cycle:

$$\Delta COP = 100 \times \frac{(COP - COP_b)}{COP_b}$$

(8)

Now, for no COP improvement, one can write,

$$COP = COP_b = \frac{1 - x}{1 - x} COP = \frac{(1 - x)(h_6 - h_8)}{x(h_4 - h_3)}$$

(9)

Hence, cooling COP improvement can be realized if the ratio of cooling effect improvement and economizer compressor work is more than the COP_b, i.e.

$$\frac{(1 - x)(h_6 - h_8)}{x(h_4 - h_3)} \geq COP_b$$

(10)

Based on the thermodynamic analysis presented above, a simulation code was developed to investigate the effect of different operating parameters, which can evaluate the cooling COP and COP improvement over basic cycle for given evaporator temperature, gas cooler exit temperature, compressor discharge pressure and economizer pressure. The compressor outlet conditions were evaluated using fixed isentropic efficiency. This code was integrated with the thermodynamic property subroutine CO2PROP, developed based on Span and Wagner equations [8], to compute relevant thermodynamic properties of carbon dioxide.

3. RESULTS AND DISCUSSION

The performance of the transcritical carbon dioxide cycle with parallel compression economization, being studied for air-conditioning applications, have been evaluated for various economizer pressure, compressor discharge pressure and gas cooler exit temperature. The following input parameters have been taken for the study: evaporation temperature = 5 °C (typically used for air-conditioning applications), isentropic efficiency = 75% for both main and economizing compressors. For the calculation of optimal values of compressor discharge and economizer pressures, 0.2 bar step was taken in numerical simulation.

Figure 2: COP improvement with economizer pressure at different discharge pressure

Figure 3: Effect of discharge pressure on performance at optimum economizer pressure

The variation of COP improvement over basic cycle with economizer pressure for different discharge pressure at gas cooler exit temperature of 40 °C is shown in Fig. 2. As the vapour quality decreases with increase in economizer pressure, but the refrigeration effect decreases due to increase in liquid enthalpy, and the economizing compressor work decreases due to decrease in quality. Initially, the COP improvement increases due to less predominant effect of refrigeration effect, whereas, after some optimum pressure, the liquid enthalpy increases very fast (near the critical pressure, slope change of saturation line is very fast) and the COP improvement declined. When the economizer inlet touches the saturated liquid line, the cycle becomes basic cycle and cycle becomes unrealistic if touches vapor line. When Eq. (10) is not satisfied, COP improvement is negative. For discharge pressure of 85 bar
(Fig. 2), improvement becomes negative after 66 bar and unrealistic after 69.6 bar.

![Graph showing COP improvement and cooling COP vs. Gas cooler exit temperature]

**Figure 4:** Variation of cooling COP and COP improvement with gas cooler exit temperature for maximum improvement

The variations of cooling COP and COP improvement over the basic valve expansion cycle with compressor discharge pressure for optimum economizer pressure are shown in Fig. 3 at gas cooler exit temperature of 40 °C. Interestingly, the discharge pressure gives two optimal points: one for maximum COP and another for maximum improvement. This can be attributed by the fact that the discharge pressure optimization based on maximum COP is due to the S-shape nature of isotherm line near the critical point and optimization based on maximum improvement is due to the slope changing nature of saturation curve and both optimal points may not be the same. The optimum discharge pressure based on maximum COP gives the higher value than that based on maximum improvement.

![Graph showing variation of discharge and economizer pressures with gas cooler exit temperature]

**Figure 5:** Variation of discharge and economizer pressures with gas cooler exit temperature for maximum improvement

The results show that the variation in the gas cooler exit temperature has a significant effect on system performance and performance improvement. The effect on optimal discharge pressure is also very significant; however effect is moderate for optimal economizer pressure. It can be noted that the variation trends of optimum pressures are reverse. With 10 °C increase in gas cooler exit temperature, the optimum discharge pressure increases by 22 bar, whereas, economizer pressure decreases by only 3 bar. With increase in gas cooler exit temperature, as the optimum discharge pressure increases, the vapour quality increases significantly and hence the improvement of refrigeration effect reduces but the economizer compressor work increases, which lead

![Graph showing variation of cooling COP and COP improvement with gas cooler exit temperature for maximum COP]

**Figure 6:** Variation of cooling COP and COP improvement with gas cooler exit temperature for maximum COP

The variations of cooling COP and COP improvement over basic cycle and corresponding optimum compressor discharge pressure and economizer pressure based on maximum COP improvement with gas cooler exit temperature are shown in Figs. 4 and 5, respectively. With 10 °C increase in gas cooler exit temperature, the optimum discharge pressure increases by 22 bar, whereas, economizer pressure decreases by only 3 bar. With increase in gas cooler exit temperature, as the optimum discharge pressure increases, the vapour quality increases significantly and hence the improvement of refrigeration effect reduces but the economizer compressor work increases, which lead.
to reduction of COP improvement. The results indicate that the design of system for lowest possible gas cooler exit temperature is more effective for not only higher cooling COP and COP improvement but also for lower optimum high side pressure.

The variations of cooling COP and COP improvement over basic cycle and corresponding optimum compressor discharge pressure and economizer pressure based on maximum cooling COP with gas cooler exit temperature are shown in Figs. 6 and 7, respectively. It may be noted that the cooling COP decreases significantly from 2.82 to 1.83 and COP improvement from 19% to 15% with 10 °C increase in gas cooler exit temperature. As the variation in the cooler outlet temperature has a significant impact on the optimal design conditions [1], the optimum discharge pressure increases sharply from 96 to 120 bar with the gas cooler exit temperature. However, the effect of gas cooler exit temperature on optimum economizer is negligible. This can be attributed that although the shape of isotherm changes with change in temperature, the shape of saturation curve is unaltered. Results show that for higher gas cooler exit temperature, the system is not profitable in term of cooling COP and COP improvement as well as cost due to high optimum discharge pressure.

Results clearly show that the use of parallel compression economization is more profitable at lower gas cooler exit temperature due to higher COP improvement. The effect of using parallel compression economization on the variation of optimum discharge pressure with gas cooler exit temperature is shown in Fig. 8. The variation is very similar to the basic valve expansion cycle, however, the optimum values of high side pressure reduces significantly with the use of parallel compression economization as evident from Fig. 8 and the use of parallel compression economization in transcritical CO₂ air-conditioning system is economical in term of lower high side pressure also. The optimum discharge pressure based on the maximum COP improvement is significantly lower than that on maximum cooling COP due to the reason discussed above. It is very interesting to not that for fixed compressor discharge pressure, COP improvement at optimum economizer pressure increases initially then decreases with increases in gas cooler exit temperature and give some optimal value of gas cooler exit temperature. Although for simultaneous optimization of gas cooler pressure and economizer pressure, both the cooling COP and COP improvement compared to basic cycle decreases with increases in gas cooler exit temperature. Present results show that the maximum COP improvement over the basis expansion cycle is obtained as 32.8%.

4. CONCLUSIONS

A detailed optimization studies on transcritical CO₂ refrigeration cycle with the addition of parallel compression economization have been done for air-conditioning applications. The cooling COP improvement over the basic expansion cycle and effect on optimum discharge pressure are presented as well. Study shows that the cooling COP
improvement using parallel compression economization can be realized if the ratio of cooling effect improvement and economizing compressor work is more than the COP of basis expansion cycle. For simultaneous optimization of discharge pressure and economizer pressure, two sets of optimal values can obtained for maximum cooling COP and COP improvement over the basic cycle. Although the optimum discharge pressure varies significantly with gas cooler exit temperature, the optimum economizer pressure gives narrow values lies between 60 to 63 bar. With the increase in gas cooler exit temperature, both the cooling COP and COP improvement at optimum conditions decrease, whereas the optimum discharge pressure increases. The optimum discharge pressure based on the maximum COP improvement is significant lower than that on maximum cooling COP. The design of system for lowest possible gas cooler exit temperature is more effective for not only higher cooling COP and COP improvement also for lower optimum high side pressure. For the studied ranges of operating conditions, the maximum COP improvement over the basis expansion cycle is obtained as 32.8%. The use of parallel compression economization in transcritical CO2 air-conditioning system is profitable for not only COP improvement also for lower optimum high side pressure.

References


Biography

Author received his M. Tech. and Ph.D. degrees in Mechanical Engineering from Indian Institute of Technology Kharagpur in 2001 and 2006, respectively. After, he joined the faculty of Institute of Technology, Banaras Hindu University and working as a Lecturer in Mechanical Engineering Department till date. Author has published 12 research papers in international journal and 12 in national and international conferences in several areas of Heat Transfer and Refrigeration.