Energy Conversion and Management 51 (2010) 2516–2522

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Study on expansion power recovery in CO_2 trans-critical cycle

Tian Hua *, Ma Yitai, Li Minxia, Wang Wei

Thermal Energy Research Institute, Tianjin University, 92 Weijin Rd., Nankai District, Tianjin 300072, China

ARTICLE INFO

Article history:
Received 14 January 2009
Received in revised form 27 August 2009
Accepted 11 May 2010
Available online 11 June 2010

Keywords:
CO_2
Trans-critical cycle
Energy recovery
Rolling piston expander
Recovery ratio
Efficiency

ABSTRACT

Due to the ozone depletion potential and global warming potential of CFCs and HCFCs, CO_2 is considered as most potential alternative refrigerant. However, there are serious throttle losses and low system efficiency to CO_2 trans-critical cycle because of its low critical temperature and high operating pressure. The aim of this paper is to design an expander to recover expansion power in CO_2 trans-critical cycle. The theoretical analysis and calculation show that 14–23% of input power of compressor can be recovered. A prototype of rolling piston expander is designed and manufactured and its test facility is established. The test facility consists of CO_2 trans-critical cycle, the expander, the chilling water system and the cooling water system. The experimental results show that the recovery ratio and expander efficiency are affected by rotational speed, inlet temperature and mass flow of expander. The highest recovery ratio can reach to 0.145, which means 14.5% of input power of compressor can be recovered. The expander efficiency can reach to 45%.

1. Introduction

The F Gas Regulation (EC842-2006 and EC40-2006) [1–3] is to limit and reduce emissions of fluorocarbons (HFCs) from refrigeration and heat pump plants. In recent years, new alternative refrigerants have been concerned due to the ozone depletion potential and global warming potential of CFCs and HCFCs. The natural working fluids became popular candidates to replace traditional refrigerants, especially in Europe and Japan. CO_2 is considered as most potential substitute for its non-flammable, non-toxic, environmental friendliness and good thermodynamic properties, especially when trans-critical cycle has been presented [4]. However, CO_2 has low critical temperature and its operating pressure is higher than traditional refrigerants. These properties bring on serious throttle losses and low system efficiency. Theoretical researches and analysis show that plenty expansion power could be recovered and the COP could be equal to or even higher than that of the common refrigerant cycles by using an expander instead of the expansion valve in CO_2 trans-critical cycle [5–7]. Therefore, this study presents the research of expander to recover expansion power in CO_2 trans-critical cycle.

* Corresponding author. Tel.: +86 022 27890061; fax: +86 022 27404741.
E-mail address: 2000_tianhua@163.com (H. Tian).

0196-8904/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enconman.2010.05.016

2. Theoretical analysis

2.1. Cycle analysis

Fig. 1 shows the pressure-enthalpy diagram of CO_2 trans-critical cycle. The whole process is described as follows.

Vapor will flow into compressor through a gas–liquid separator. The vapor will be compressed to be high pressure and high temperature gas in compressor. 1–2 Means isentropic compression process, which is ideal and unattainable. If considering efficiency of compressor, the real compression process will be 1–2′.

High pressure and high temperature gas exhausts from the compressor and then flows into the gas cooler to reject heat. 2–3 or 2′–3 mean rejecting heat in gas cooler. It is isobaric process, which proceed in super-critical region basically for its low critical temperature.

After rejecting heat in the gas cooler, the fluid with high pressure enters into the expander or flows through the expansion valve to decrease the pressure and temperature. In traditional CO_2 system, expansion valve is always used for throttling, which is considered to be isenthalpic process, shown as 3–4′; 3–4″ means isentropic expansion process, which is ideal and unattainable. 3–4 Means process of using an expander instead of the expansion valve. If the expander efficiency is high enough, the point 4 will be closer to point 4″.

After expanding in expander or throttling in the expansion valve, the fluid becomes two-phase flow with low temperature and pressure. Two-phase fluid flows into the evaporator to absorb

Nomenclature

W_r	recovered power (kW)	B_v	the thickness of vane (m)
Q_k	cooling capacity (kW)	h_v	the length of vane in the cylinder (m)
W_{in}	input power of compressor (kW)	a	radius ratio, r/R
COP	refrigeration efficiency	D	inner diameter of cylinder (m)
κ	recovery ratio	ψ	relative eccentricity
h	enthalpy (kJ/kg)	λ	relative height of cylinder
v_d	specific volume on exhaust condition (m^3/kg)	θ	rotational angle (°)
v_s	specific volume on suction condition (m^3/kg)	θ_e	starting-expansion angle of expander (°)
m_c	mass flow of compressor (kg/s)	θ_d	exhaust angle of expander (°)
V	whole volume of cylinder (m^3)	θ_s	exhaust angle of expander (°)
V_s	suction chamber volume (m^3)	ε	expansion ratio
V_d	discharge volume (m^3)	ς_A	total uncertainty associated with the dependent variable A
n	rotational speed of expander (rpm)	x_i	independent variable which affects the dependent variable A
R	inner radius of cylinder (m)	ς_z	uncertainty of the variable x_i
r	outer radius of rolling piston (m)		
H	height of cylinder (m)		

heat and becomes vapor. Then the vapor returns to the compressor. A cycle is completed. 4–1 Means isobaric evaporating process.

The recovered power of CO_2 trans-critical cycle can be defined as shown in

$$W_r = h_3 - h_4 \tag{1}$$

The cooling capacity [8,9] of CO_2 trans-critical cycle can be calculated as

$$Q_k = h_1 - h_4 \tag{2}$$

The input power [8,9] of compressor is as follow:

$$W_{in} = h_2 - h_1 \tag{3}$$

The coefficient [8,9] of performance is obtained by

$$\mathrm{COP} = \frac{Q_k}{W_{in}} = \frac{h_1 - h_4}{h_2 - h_1} \tag{4a}$$

$$\mathrm{COP}_h = \frac{Q_o}{W_{in}} = \frac{h_2 - h_3}{h_2 - h_1} \tag{4b}$$

In order to analyzing the magnitude of recovered power by expander, recovery ratio is defined as follow

$$\kappa = \frac{W_r}{W_{in}} = \frac{h_3 - h_4}{h_2 - h_1} \tag{5}$$

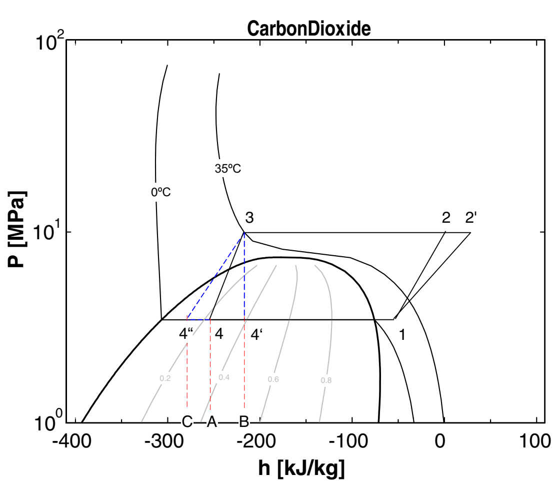

Fig. 1. Pressure-enthalpy diagram of CO_2 trans-critical cycle.

Expansion ratio is defined as

$$\varepsilon = v_d / v_s \tag{6}$$

Table 1 shows the work condition, on which the CO_2 trans-critical cycle with or without expander are calculated.

2.2. Calculation results

Fig. 2 shows the variation of COP with evaporating temperature. It has an increase tendency as evaporating temperature is increasing. The COP of CO_2 trans-critical cycle with expander is about 6–10% higher than that of CO_2 trans-critical cycle without expander averagely on default work condition. Fig. 3 shows the variation of recovery ratio (κ) with efficiency of expander on CO_2 trans-critical cycle with expander. When the efficiency of expander is 70%, the recovery ratio is 0.16, which means the recovered power is 16% of input power of compressor. It also has an increase tendency as efficiency of expander is increasing. When the efficiency of expander is 100%, which means isentropic expansion process, recovery ratio (κ) can be 23%. Similarly, the COP has an increase tendency.

As outlet temperature of gas cooler is increasing, recovery ratio (κ) has an increase tendency but COP has a decrease tendency, as shown in Fig. 4. When outlet temperature of gas cooler is 50 °C, the recovery ratio (κ) can reach to 32.1%. Therefore, it is significant to recover expansion power in CO_2 trans-critical cycle by using expander.

CO_2 trans-critical cycle has a small expansion ratio (ε), it is about 3. The reason is that super-critical CO_2, which has the similar specific volume with liquid, will flows into expander.

3. Prototype of expander

A rolling piston expander is chosen to design and manufacture. Fig. 5 shows the sketch map of rolling piston type expander. There are three processes during two rotations of the piston: inspiration, expansion and discharge. During the inspiration process, the suction valve opens and CO_2 at the super-critical pressure flows into the cylinder and drives the piston to rotate. When the piston rotates to a certain angle, the suction valve closes and the expansion process begins. Expansion presented by the CO_2 will keep the piston rotating. As the piston rotates to the discharge port, the two-phase fluid is discharged. A suction control valve is used for the expander to control the mass flow rate of CO_2. In order to recover the energy, a generator is combined with the expander.