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An experimental evaluation of the transcritical CO_2 refrigerator performances using an internal heat exchanger

Ciro Aprea[*], *Angelo Maiorino*

Department of Mechanical Engineering, University of Salerno, Via Ponte Don Melillo 1, 84084 Fisciano, Salerno, Italy

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A B S T R A C T

The classical substances as hydrochlorofluorocarbons (HCFCs) used as working fluids in the vapour compression plants have to be replaced by new substances because of their ozone depletion potential and their greenhouse effect. Carbon dioxide (CO_2) is non-toxic, non-flammable, has zero ozone depletion potential and negligible global warming potential as refrigerant. Referring to a transcritical CO_2 cycle working as a classical "split-system" to cool air in residential applications, the aim of this paper is the evaluation of the energy performances using an internal heat exchanger. The experimental plant employs a semi-hermetic compressor, plate-finned tube type heat exchangers, a back pressure valve electronically controlled and an expansion valve. Besides it is possible to control the flash gas produced in the liquid receiver thanks to another semi-hermetic compressor linked to an inverter. An increase of the coefficient of performance has been found using the internal heat exchanger. The comparison of the coefficients of performance of two cycles, working with and without the internal heat exchanger, is discussed.

Evaluation expérimentale des systèmes frigorifiques au CO_2 transcritique utilisant un échangeur de chaleur interne

Mots clés : Système frigorifique ; Système à compression ; Dioxyde de carbone ; Cycle transcritique ; Expérimentation ; Amélioration ; Performance ; Échangeur de chaleur ; Liquide-vapeur

1. Introduction

The use of natural refrigerant after CFC has been attracting many research institutions and related industries. Among common substances that can be used as refrigerant, such as air, carbon dioxide, and water, carbon dioxide has unique characteristics and almost fulfils all required properties to be used as refrigerant. Carbon dioxide has zero ODP, negligible GWP, excellent heat transfer coefficients (Yoon et al., 2004), compatibility with material of refrigeration system and very

[*] *Corresponding author*. Tel.: +39 089964315; fax: +39 089964037.
E-mail address: aprea@unisa.it (C. Aprea).
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Nomenclature

Symbols

c	specific heat (kJ/kg K)
COP	coefficient of performance (–)
h	enthalpy (kJ/kg)
IHX	internal heat exchanger
$\dot{m}$	mass flow rate (kg/s)
T	temperature (°C)
$\dot{W}$	electrical power supplied to the compressor (W)

Subscripts

cp	compressor
ea	external air
ev	evaporator
in	inlet
out	outlet
p	constant pressure
va	valve

low cost. At high temperature, the carbon dioxide refrigeration cycle is operating in transcritical mode and at high working pressure because of the specific thermodynamic properties of carbon dioxide (relatively low critical temperature and relatively high critical pressure). This leads to the need of completely new design of system components (Hesse and Kruse, 1993; Huai et al., 2004). The energetic performance concerning the transcritical carbon dioxide cycle is smaller than the energetic performance obtainable using the classical refrigerant in sub-critical cycles (Beaver et al., 1999). For this reason it is necessary to experiment methodologies able to improve these performances; to this aim an internal heat exchanger can be used. In this heat exchanger the carbon dioxide at the outlet of the gas-cooler exchanges heat with the carbon dioxide flowing out of the evaporator before entering into the compressor.

The internal heat exchanger (IHX) is often employed in refrigerating systems. Generally the cooling of the refrigerant flowing out of the gas-cooler prevents flash gas at the expansion valve and the superheating of the suction gas avoids that liquid refrigerant from the evaporator entering into the compressor. On the other hand, the thermodynamic efficiency could be improved employing an internal heat exchanger, especially in applications which require low suction temperature (ASHRAE, 1994). One can note that employing the internal heat exchanger increases the specific refrigerating effect, on the other hand, the specific volume of the refrigerant vapour at the beginning of the compression rises and, as a consequence, the specific compression work increases too. The system coefficient of performance, that is the ratio of the refrigerating effect to the compression work, could be higher or lower than one of a cycle without internal heat exchanger. In the following a simple criterion for evaluating the suitability of using an internal heat exchanger will be applied to carbon dioxide (Aprea et al., 1999). The evaluation criterion can be settled as follows:

$$c_p T_{\mathrm{in,cp}} > (h_{\mathrm{in,cp}} - h_{\mathrm{out,va}}) \quad (1)$$

When this inequality is verified, the adoption of an internal heat exchanger turns out to be advantageous. Furthermore, it is important to fix the suction temperature value under which this occurs. To this aim, the following inequality should also be true when the temperature at the compressor inlet is evaluated using the internal heat exchanger:

$$\frac{\partial(\Delta \mathrm{COP})}{\partial T_{\mathrm{in,cp}}} > 0 \quad (2)$$

One can find out that this is always true when Eq. (1) is verified. On other terms, if the internal heat exchanger allows an increasing COP, this effect will be amplified when the temperature of the working fluid at the outlet of this heat exchanger, that is the suction temperature, increases. Of course, the actual limit would be fixed by the well-known discharge temperature limits. Using a software (Labview) the criterion has been verified in all tests performed on the transcritical plant; these results are in according to the literature reporting the improvement of the energetic performances adopting the internal heat exchanger for the carbon dioxide (Robinson and Groll, 1998).

2. Experimental equipment

Fig. 1 shows a sketch of the experimental plant. Basically there are two single-stage semi-hermetic reciprocating compressors, an oil separator, an air gas-cooler, a liquid receiver, an air evaporator, an electronic expansion valve, and an electronic back pressure valve. To study the influence of the ''flash vapour'' a by-pass with an auxiliary compressor has been mounted (Elbel and Hrnjak, 2004).

The refrigerant state at the outlet of the expansion device is in a two-phase condition, provided that the fluid crosses the saturated liquid line during the isenthalpic expansion process. For this reason some fraction of the refrigerant flow enters the evaporator in vapour state not having a cooling effect. Using the flash gas by-pass the performances of transcritical carbon dioxide cycle increase improving the low pressure side of the system because the evaporator is fed with liquid only (Beaver et al., 1999; Hanson and Van Essen, 2001). The main compressor is a semi-hermetic compressor and its working pressure range is from 15 bar to 120 bar. As the intermediate pressure is about 65 bar, the working pressure range of the auxiliary compressor is from 55 bar to 120 bar. At evaporating temperature of 5 °C and temperature of 30 °C at the gas-cooler exit when the pressure is 80 bar, the refrigerating power is about 3000 W. An internal heat exchanger between the refrigerant at the compressor suction and the refrigerant at the exit of the gas-cooler has been set up. The lamination process has been obtained thanks to the back pressure valve and to the electronic expansion valve. To fix the air temperature on the gas-cooler and to simulate the external conditions, the air flows under the influence of a blower in an thermally insulated channel where are located some electrical resistances that can be modulated. In Fig. 2 a photo of the plant is shown. In Table 1 the heat exchangers' specifications are reported. In order to investigate on improvement of COP including the IHX, the tests were carried out using a basic plant configuration: main compressor, oil separator, gas-cooler,