INTERNATIONAL JOURNAL OF REFRIGERATION 32 (2009) 1683–1693

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

A novel CO_2 refrigeration system achieved by CO_2 solid–gas two-phase fluid and its basic study on system performance

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ARTICLE INFO

Article history:
Received 20 August 2008
Received in revised form
12 April 2009
Accepted 2 May 2009
Published online 19 May 2009

Keywords:
Refrigeration system
Compression system
Cascade system
Carbon dioxide
Transcritical cycle
Triple point
Design
Experiment
Pressure
Temperature

ABSTRACT

In this report, a new CO_2 refrigeration system is introduced, which can achieve a refrigeration capability below the CO_2 triple point of −56.6 °C. The proposed CO_2 refrigeration system consists of two thermodynamic cycles arranged in cascade, where one is a CO_2 trans-critical cycle and another is a trans-triple-point cycle. An experimental set-up is constructed and tested in order to obtain a basic knowledge about this CO_2 system. Based on the measured data, it is concluded that the built CO_2 refrigeration system can operate continuously and stably, although dry ice particles exist in the closed CO_2 loops. An average COP (a ratio of cooling energy to the compressor power consumption) is measured at 2.45 in the present experiment range for the low-pressure system of the experimental set-up. In addition, the influence of the condensation temperature on the refrigeration cycle is investigated and more studies are needed for the future optimization work.

Nouveau système frigorifique au CO_2 réalisé à l'aide d'un fluide diphasique au CO_2 solide/gaz et étude de la performance de ce système

Mots clés : Système frigorifique ; Système à compression ; Système en cascade ; Dioxyde de carbone ; Cycle transcritique ; Point triple ; Conception ; Expérimentation ; Pression ; Température

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0140-7007/$ – see front matter
doi:10.1016/j.ijrefrig.2009.05.003

Nomenclature

COP_{LPC} coefficient of performance, which is a ratio of cooling capacity in LPC to compressor work in LPC, Eq. (2)
COP_{SL} coefficient of performance, which is a ratio of cooling capacity in LPC to all the compressor works in the whole cascade system, Eq. (3)
W_h compressor work in the high-pressure cycle
W_ℓ compressor work in the low-pressure cycle
Δh_{lcool} cooling capacity in the low-pressure cycle
Δh_{lc1}, Δh_{lc2} heat exchanging quantities in the condenser of hot water, and the condenser of cool water, in the low-pressure cycle, respectively
Δh_{lc1}, Δh_{lc2} heat exchanging quantities in the gas cooler of hot water, and the gas cooler of cool water, in the high-pressure system, respectively.

1. Introduction

With CFC and HCFC problem becoming pressing issues in the late 1980s, the interest in CO_2 used as refrigerant/working fluid increased considerably throughout the nineties (Lorentzen, 1993, 1994; Kim et al., 2004; Zhang et al., 2005; Rieberer, 2005; Yamaguchi et al., 2008). From the viewpoint of protecting the ozone layer and preventing global warming, there is now strong demand for technology based on ecologically safe 'natural' working fluids like carbon dioxide. CO_2 is a non-flammable natural fluid with no Ozone Depletion Potential (ODP) and a negligible Global Warming Potential (GWP). Because of the advantages, CO_2 fluid has received much attention in recent years in CO_2 trans-critical compression thermodynamics cycle of air conditioners, heat pump and turbine reactors. Among these CO_2 trans-critical compression thermodynamics cycles, CO_2 heat pump is a representative and promising one. For the recent ten years, many researchers have carried out the detailed studies on the CO_2 heat pump (Cho et al., 2009; Kim et al., 2009; Cheng et al., 2008; Afroz et al., 2008; Hafner, 2000; Sarkar et al., 2006; Stene, 2005; Chen and Gu, 2005; White et al., 2002; Hafner et al., 1998; Neksa et al., 1998; Cecchinato et al., 2005; Girotto et al., 2004; Neksa, 2002; Bredesen et al., 1997a,b). For example, a recent developments and state of the art for trans-critical CO_2 cycle technology in various refrigeration, air-conditioning and heat pump applications was presented in the paper (Kim et al., 2004). The article provides a critical review of literature, and discusses important trends and characteristics in the development of CO_2 technology in refrigeration, air-conditioning and heat pump applications. Advanced cycle design options are also introduced suggesting possible performance improvements of the basic cycle. Various field-test systems using carbon dioxide as the only refrigerant have been installed and measured. The seasonal COP is calculated and a comparison is made with a conventional using R404A (Girotto et al., 2004). An overview of some activities in the CO_2 heat pump field was presented and the important characteristics of the trans-critical CO_2 process applied to heat pumps are discussed in the paper (Neksa, 2002). The performance and operating characteristics of a two-stage CO_2 cycle with gas injection were experimentally investigated to improve the cooling performance and reliability of a trans-critical CO_2 cycle. It was found that the cooling COP of the two-stage gas injection cycle was maximally enhanced by 16.5% over that of the two-stage non-injection cycle in the experiments (Cho et al., 2009). In addition, heat transfer performances and pressure drop of condensation process of mixtures of CO_2 and DME inside a horizontal smooth tube have been experimentally measured in order to study the way to enhance the CO_2 heat pump performance (Afroz et al., 2008).

Among these refrigeration processes achieved by CO_2 heat pumps, the refrigeration temperature range is about from $-30.0 \sim 0.0\,^{\circ}C$. As far as the authors are aware, the refrigeration below $-30.0\,^{\circ}C$ by CO_2 heat pump is few in the existing studies. For example, a refrigeration system was designed and installed using CO_2 as a volatile secondary refrigerant in cascade with an ammonia plant. The system included a screw compressor, plate condenser, surge drum and hermetic pump to deliver carbon dioxide to a single air cooler installed in a low-temperature cold chamber. The plant was designed to extract 100 kW (28.5 ton) at an air temperature of $-48\,^{\circ}C$. Because of the temperature limit, the present CO_2 heat pump seldom is used in the refrigeration of below $-30.0\,^{\circ}C$, such as biological engineering and fishing industries. In this report, a new CO_2 refrigeration system is proposed, which can achieve a low temperature below CO_2 triple-point temperature — $-56.6\,^{\circ}C$. The proposed refrigeration system is based on a refrigeration method, which can be achieved by liquid CO_2 expanding into solid–gas two-phase fluid. Fig. 1 shows a schematic of the CO_2 refrigeration principle. The process of a–b represents the liquid CO_2 expansion into the two-phase flow, the dry ice region, shown in Fig. 1, which goes down through the CO_2 triple point in CO_2 P–h diagram. By the CO_2 expansion process, the CO_2 solid–gas two-phase fluid is obtained, which is below $-56.6\,^{\circ}C$. The b–c process in Fig. 1 shows CO_2 solid particles obtained from the expansion process sublimate and absorb a great deal of heat quantity, which can achieve a refrigeration environment below $-56.6\,^{\circ}C$ (Yamaguchi et al., 2008). The interest of the previous study (Yamaguchi et al., 2008) is the feasibility of expanding liquid CO_2 into CO_2 solid–gas flow in a horizontal circular tube by expansion valve and in a closed loop. Especially, focus is put on the feasibility of expanding process of liquid CO_2 into solid–gas flow, such as dry ice particle size, distribution and temperature etc. Based on the refrigeration method shown in Fig. 1, a new CO_2 refrigeration system is proposed in this