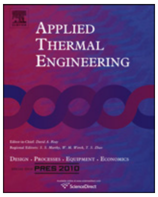
Applied Thermal Engineering 41 (2012) 18–29

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

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



A review – Status of CO_2 as a low temperature refrigerant: Fundamentals and R&D opportunities

Pradeep Bansal*,[1]

Department of Mechanical Engineering, The University of Auckland, Private Bag, 92019 Auckland, New Zealand

ARTICLE INFO

Article history:
Received 19 May 2011
Accepted 5 December 2011
Available online 15 December 2011

Keywords:
Refrigeration
CO_2
Flow boiling
Transcritical
Booster
Secondary loop
Supermarket

ABSTRACT

Carbon dioxide (CO_2) has emerged as one of the most promising and preferred refrigerants for low temperature refrigeration systems in the food and refrigeration industry and/or recreational activities. In recent times, the widespread use of CO_2 refrigerant, particularly in supermarkets, has proved commercially attractive worldwide. Some of the designs that are most commonly used in industry include cascade, transcritical and transcritical booster, while many other interesting designs and variations are also being consistently used for specific situations. This paper presents the holistic view of the fundamentals and application of CO_2 refrigerant in low temperature refrigeration systems, along with some discussion on its benign properties, thermodynamic analysis, the challenges, the need for fundamental research and design of novel systems for its continuing dominance in the refrigeration industry.

1. Introduction

Refrigeration plays a pivotal role in today's society in preserving food and providing thermal comfort in the built environment. According to the International Institute of Refrigeration [22], refrigeration consumes about 15% of all electricity consumed worldwide. Improved energy efficiency in these operations is critical to companies for reasons of reduced cost and lesser impact on the environment. Carbon dioxide (CO_2) has emerged as one of the most promising environmentally friendly and energy efficient refrigerants to provide low temperatures in the refrigeration industry due to its favourable thermodynamic and transport properties [2,4–7,14–17,36–38,41]. CO_2 is an odourless, colourless, non-flammable and eco-friendly refrigerant that is available as a byproduct from many processes and plants (e.g. power plants, ammonia and beer production units etc.) and hence does not contribute to the global warming.

Lately CO_2 is becoming a mainstream refrigerant to achieve low temperatures in the food and refrigeration industry, where a number of novel designs are being used in the industry including cascade, transcritical, transcritical booster, secondary loop and the variations thereof Refs. [7,15,16] and [12–14,17,23,29,35,37,38]. Such systems are typically used in the temperature range from (−) 25 °C to (−)50 °C for applications in food, pharmaceutical, recreational (i.e. ice skating), chemical and other industries, blast freezing, cold storages, liquefaction of gases such as natural gas, supermarket refrigeration systems etc. At such low temperatures single stage compression systems with reciprocating compressors are generally not feasible due to high pressure ratios that lead to high discharge temperatures and low volumetric efficiencies and hence low COPs. To increase volumetric efficiency and refrigerating effect and to reduce the power consumption, cascade systems involving multistaging with intercooling and/or sub-cooling are often employed in industry. CO_2 has already been investigated quite extensively as a transcritical refrigerant for air-conditioning and water heating applications [28] over the past two decades. Recently its use in low temperature applications has also received favourable response from the industry. This paper, therefore, discusses the architecture of some of these novel designs mainly involving cascade, transcritical and transcritical booster systems. This appears to be a dynamic field of research that is resulting in continuous evolution of numerous interesting ideas and processes.

Although cascade systems are becoming more common in the refrigeration industry, particularly in warmer climates, they generally use traditional fin and tube heat exchangers. The refrigeration research at the University of Auckland [3,8,9,21,42,45,46] suggests that there is very little information available in the open

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* Tel.: +64 9 923 8203.
E-mail address: p.bansal@auckland.ac.nz.

[1] Current address: Building Equipment Program, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN37831-6070, USA. Tel.: +1 865 576 7376.

1359-4311/$ – see front matter
doi:10.1016/j.applthermaleng.2011.12.006

literature on the fundamental boiling and condensation heat transfer characteristics of CO_2 at low temperatures below (−)30 °C and (−)15 °C respectively. The appropriate optimal design of new heat exchangers (e.g. mini, compact and brazed plate) may be impeded due to this information missing from the open literature. Accurate measurements of the boiling/condensation heat transfer coefficients and a better understanding of the heat transfer mechanisms are essential for developing compact heat exchangers and novel system designs over a wide range of operating conditions.

To be thermodynamically sound, heat exchangers [31] must exhibit high effectiveness and low pressure drops in both the heat exchanging fluid streams. However, industry is now challenged to produce modern systems with zero leak and minimum refrigerant charge, leading to more compact and efficient heat exchangers. Therefore, fundamental research needs to be carried out to design more efficient (but with less refrigerant charge) and compact systems (including mini, compact and brazed plate heat exchangers) for improved energy efficiency and reduced pressure drops. This paper discusses some of these matters along with the need for developing more efficient compressors and associated componentry (e.g. expansion valves and control strategies) and proposes guidelines for the continuing dominance of CO_2 in the refrigeration industry in future years.

2. Thermo−physical properties of CO_2 at low temperatures

CO_2 possesses excellent thermo−physical properties at low temperatures that are quite different from other refrigerants. At a given saturation temperature and pressure, the surface tension, the liquid viscosity and ratio of liquid to vapour density (ρ_l/ρ_v) of CO_2 are the smallest (see Figs. 1 and 2 respectively) among other refrigerants, such as R717, R22, R410A and R134a. For example, at 0 °C, the surface tension (see Fig. 1) of CO_2 is only 17%, 39.3%, 38.6% and 46.3% to that of the refrigerant R717, R134a, R22 and R410A, respectively, while at (−)40 °C, it increases to 34.1%, 69.1% 67.4% and 74.8%, respectively. Lower surface tension facilitates the bubble formation, thus resulting in higher nucleate boiling at low vapour quality. The ratio of liquid to vapour density for CO_2 at (−)40 °C is only 3.9%, 8.4%, 14.8% and 22.7% to that of the refrigerant R717, R134a, R22 and R410A, respectively. The lower density ratio of liquid to vapour results in a smaller change in velocity and lower two-phase Reynolds number for a fixed mass flow rate during the boiling process. This feature can improve the two-phase distribution of CO_2 inside the direct expansion type evaporators. Simultaneously the lower liquid viscosity of CO_2 leads to smaller pressure losses than other refrigerants.

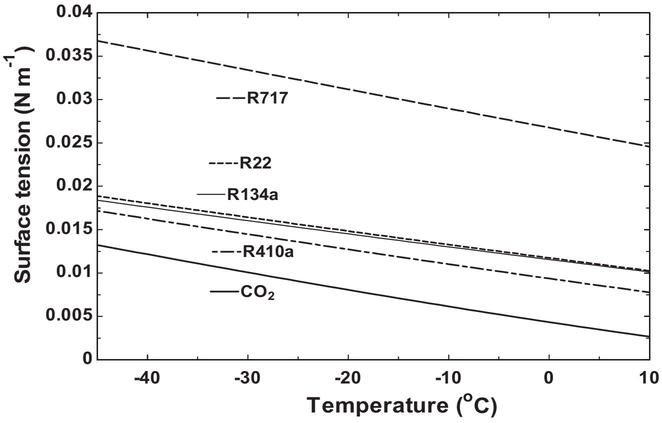

Fig. 1. Surface tension of CO_2 and other refrigerants at saturation temperatures.

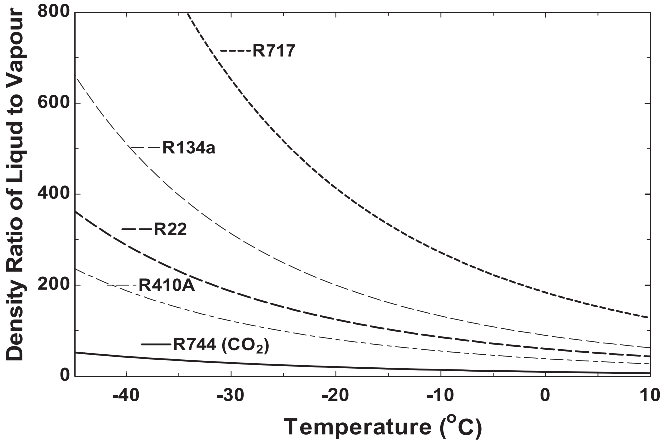

Fig. 2. Comparison of density ratio of liquid to vapour of CO_2 at saturation temperatures.

As can be seen from Fig. 3, the vapour pressure curve of CO_2 is much steeper than the other refrigerants [1], which makes it a favourable refrigerant especially at low temperatures with a small temperature difference per unit pressure difference. This feature results in higher flow velocities and hence a good two-phase distribution inside a heat exchanger. On the other hand, the other refrigerants operate at sub-atmospheric pressures at low temperatures, and hence suffer from low velocities to keep a check on the pressure drop so that the log-mean temperature difference (LMTD) does not drop steeply. These lower velocities often lead to phase separation and oil management problems in the system. Therefore, the higher liquid and vapour thermal conductivities, with lower liquid viscosity and surface tension make CO_2 an ideal refrigerant for two-phase boiling and condensation applications.

For an efficient refrigeration system, both the Volumetric Refrigeration Capacity (VRC), given by Equation (1), and the Coefficient of Performance (COP) given by Equation (2), should be as high as possible. The high COP minimizes the running cost, while the high VRC minimizes the investment cost. It may be noted from Fig. 4 that CO_2 has the highest volumetric refrigeration capacity amongst all other refrigerants at low temperatures, due to its relatively lower specific volume, resulting in smaller size compressors for the same operating conditions-

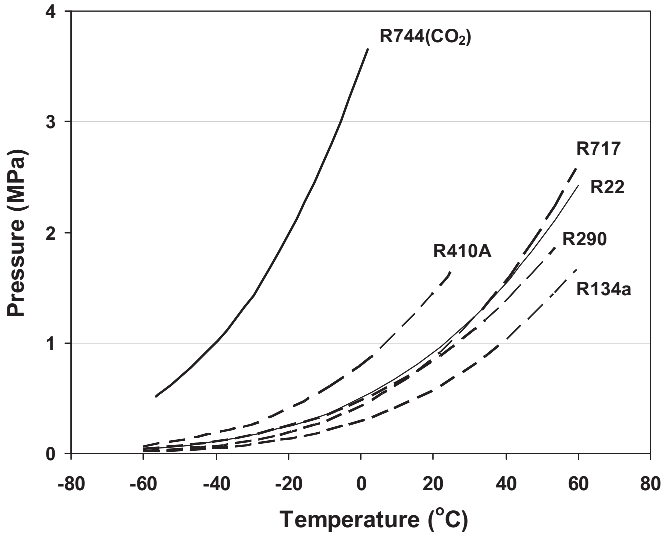

Fig. 3. Refrigerant vapour pressure curves at different saturation temperatures.