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Optimization of a CO_2–C_3H_8 cascade system for refrigeration and heating

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Abstract

Conventional working fluids (refrigerants) are being phased out worldwide to combat with the twin menace of ozone layer depletion and global warming and natural refrigerants are fast gaining favour lately. Single stage and multi stage refrigeration systems fail to widen the gap between heat source and heat sink temperatures required in many industrial applications requiring simultaneous heating and cooling and cascaded systems appear to be the best alternative. Modest research has been done in cascaded systems based on natural refrigerants thereby offering good potential for research. In this paper, a cascaded system for simultaneous heating and cooling (refrigeration and heat pump system) with a carbon dioxide based HT cycle and propane based LT cycle for simultaneous refrigeration and heating applications has been analyzed. To facilitate prediction of optimum performance parameters, performance trends with variation in the design parameters and operating variables have been presented in this article. Relevant expressions have been developed to serve as guidelines to the user for selecting appropriate design parameters like intermediate temperature so that the system yields optimum performance. Independently developed property codes have been employed for both carbon dioxide and propane for higher accuracy.

Keywords: Heat pumps; Refrigeration; Heating; Cascade system; Carbon dioxide; Transcritical cycle; Propane; Optimization

Système au CO_2–C_3H_8 en cascade utilisé en application frigorifique et pour le chauffage: optimisation

Mots clés : Thermofrigopompe ; Réfrigération ; Chauffage ; Système en cascade ; Dioxyde de carbone ; Cycle transcritique ; Propane ; Optimisation

1. Introduction

A cascade system for simultaneous heating and cooling provides the best way to obtain large temperature lift between heat source and heat sink. Many industrial applications such as liquefaction of petroleum vapours requires low temperature cooling as well as high temperature heating that cannot be attained by single stage and multi

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Nomenclature

H	specific enthalpy (kJ kg^{-1})
$\dot{Q}$	heat transfer rate (kW)
$\dot{m}_c$	mass flow rate of CO_2 (kg s^{-1})
COP	coefficient of performance
$\dot{W}_{HT}$	HT compressor power (kW)
$\dot{m}_p$	mass flow rate of propane (kg s^{-1})
T	temperature (K)
$\dot{W}_{LT}$	LT compressor power (kW)
$\in$	effectiveness of internal heat exchanger
η_{II}	exergetic efficiency
η_c	isentropic efficiency

Subscripts

1–6	points of refrigerant (HT side)
$1'$–$6'$	points of refrigerant (LT side)
c	Carbon dioxide
ci	HT heat exchanger inlet
co	HT heat exchanger outlet
H	heating
L	cooling
LTcooling	low temperature cooling cycle
HTheating	high temperature heating cycle
max	maximum
opt	optimum
p	propane
sys	system

stage systems. The cascaded systems are typically employed for the temperature zone of 203–373 K [1]. An intelligent selection of refrigerants in both cycles of the cascade system can provide us with all the requirements of industrial applications. For cascade systems, lower temperature limit of the HT side is termed intermediate or coupling temperature (IT). Coefficient of performance of a cascade system depends on IT and hence they require to be optimized.

Lately, the use of natural refrigerants has been emphasized through a series of conferences exclusively catering to the natural refrigerant based systems; this is named after the pioneer Gustav Lorentzen [4–6]. Although the NH_3–CO_2 cascade system employing CO_2 in the LT side and NH_3 in the HT side have been promoted lately [2–4] for very low temperature applications, but this type of system is not suitable for high temperature heating applications. So, Sarkar et al. [5] have proposed NH_3–CO_2 cascade system with CO_2 in the HT side for simultaneous cooling and heating applications. However, a carbon dioxide-propane cascade system with CO_2 in the HT side and C_3H_8 in the LT side can offer a much larger temperature lift. Carbon dioxide and propane both have zero ozone depletion potential and negligible global warming potential. Propane has excellent thermodynamic properties, quite similar to those of ammonia. The molar mass of 44 is ideal for turbo compressors and is only about one third of its halocarbon competitors [6]. Propane is cheaply and universally available. The major advantage of selecting propane as the refrigerant over ammonia is that propane is non-toxic. However its flammability is a serious concern and hence safe design and operating practice is of paramount importance. However this disadvantage can be eluded by using it as a refrigerant for the LT cycle. It is important to note that propane can be used for very low temperature refrigeration applications (between -30 and -60 °C) compared to ammonia due to its lower NBP. There has been a strong surge in installing CO_2 based systems and a large number of research studies have been reported to highlight its extremely favourable thermodynamic and environmental properties [7].

In 2000, a new refrigeration technology to build cascade systems with carbon dioxide and propane as refrigerants was implemented in a small supermarket in Denmark [8]. Comparative study with conventional system showed decrease in energy consumption by approximately 5% compared to an average, conventional and comparable supermarket. However, not only in refrigeration, the carbon dioxide-propane heat pump refrigeration systems have great potential in simultaneous refrigeration and heating applications as well. Hence the present study was undertaken to fill the information void. In this analysis, a single stage cascaded refrigeration heat pump system with carbon dioxide (HT) and propane (LT) for simultaneous refrigeration and heating applications has been studied. Further, this cascaded system has also been numerically optimized to obtain the maximum coefficient of performance of this system.

2. Thermodynamic property calculation

To facilitate the analysis, an exclusive computer code was developed for the thermophysical properties of propane and carbon dioxide. The code for propane was developed based on Younglove and Ely [9] and that of carbon dioxide using Span and Wagner [10] correlations. Many accurate iterative procedures and close initial assumptions were used. Rigorous checking of the developed code with respect to thermodynamic tables of propane [9] and carbon dioxide [10] reflect errors to be confined to a maximum of 0.04%, which was quite satisfactory. It will be quite relevant to mention that the developed code to evaluate properties is highly accurate compared to some commercially available softwares. Comparison between them reveal that the errors tend to soar up to 25% in some regions from commercial