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Theoretical analysis of a vapour compression refrigeration system with R502, R404A and R507A

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ABSTRACT

This paper presents a detailed exergy analysis of an actual vapour compression refrigeration (VCR) cycle. A computational model has been developed for computing coefficient of performance (COP), exergy destruction, exergetic efficiency and efficiency defects for R502, R404A and R507A. The present investigation has been done for evaporator and condenser temperatures in the range of −50 °C to 0 °C and 40 °C to 55 °C, respectively. The results indicate that R507A is a better substitute to R502 than R404A. The efficiency defect in condenser is highest, and lowest in liquid vapour heat exchanger for the refrigerants considered.

Analyse théorique d'un système frigorifique à compression de vapeur au R502, R404A et R507A

Mots clés : Système frigorifique ; Système à compression ; Modélisation ; COP ; Exergie ; Efficacité ; R502 ; R404A ; R507A

1. Introduction

R502 was favourably used as a suitable working substance, in recent past, for low temperature applications in vapour compression refrigeration plants (Aprea and Mastrullo, 1996). It is an azeotropic mixture of R22 and R115 and both these refrigerants are harmful to ozone layer. The ozone depletion potential for R22 and R115 is 0.055 and 0.4, respectively (Calm and Hourahan, 2001). The provisions of Montreal protocol have prohibited the use of R115 and it was proposed to be phased

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Nomenclature

COP	coefficient of performance (non-dimensional)
$\dot{E}D$	exergy destruction rate (kW)
$\dot{E}F$	exergy rate of fuel (kW)
$\dot{E}L$	exergy loss rate (kW)
$\dot{E}P$	exergy rate of product (kW)
$\dot{E}_X$	exergy rate of fluid (kW)
h	specific enthalpy (kJ kg^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
P	pressure (kPa)
$\dot{Q}$	rate of heat transfer (kW)
s	specific entropy (kJ kg^{-1} K^{-1})
T	temperature (K)
$\dot{W}$	work rate (kW)

Greek symbols

η	efficiency (non-dimensional)
δ	efficiency defect (non-dimensional)
δP	pressure drop (kPa)
ε	effectiveness
$\Delta T_{sb,lvhe}$	degree of subcooling of liquid refrigerant in lvhe (K)
$\Delta T_{sh,lvhe}$	degree of superheating of vapour refrigerant in lvhe (K)

Subscripts

c	condenser
comp	compressor
e	evaporator
ex	exergetic
i	ith component
lvhe, l	liquid vapour heat exchanger
r	refrigerant, space to be cooled
rr	reversible refrigerator
t	refrigerant throttle valve
vcr	vapour compression refrigeration system
0	dead state

out by the year 1996 in developed countries, and before 2010 in developing countries. The deadline for the phase out of R22 is year 2020 in developed countries and year 2030 in the developing countries, respectively.

Various researchers (Aprea and Mastrullo, 1996; Döring et al., 1997; Camporese et al., 1997; Günther and Steimle, 1997; Göktun, 1998; Sami and Desjardins, 2000a,b) have suggested different HCFC, HFC and HC blends as potential substitutes for R502 and compared the performance of these substitutes either theoretically or experimentally. In some of these studies, measurements of thermodynamic and thermo-physical properties were carried out. In one of the recent study, Xuan and Chen (2005) experimentally tested HFC-161 mixture (HFC-161, HFC-125 and HFC-143a (10/45/45 wt.%)) as an alternative refrigerant to R502. Their results substantiated that this new refrigerant can achieve a high level of COP than R404A and R507 and can be considered as a promising retrofit refrigerant to R502. Arcaklıoğlu et al. (2005) numerically calculated rational efficiency of cooling system based on the second law of thermodynamics for HFC and HC based azeotropic and zeotropic mixture refrigerants. In another study (Stegou-Sagia and Paignigiannis, 2005), exergy efficiency of a number of refrigerants including R404A and R507 was calculated. Arcaklıoğlu et al. (2006) developed an algorithm to search for refrigerant mixtures of equal volumetric cooling capacity when compared to CFC based refrigerants in vapour compression refrigeration systems. Their results showed that R32/R125/R134a (43/5/52 wt.%) mixture can be used as appropriate replacement for R502. R507 is also recognized as R507A in order to allow for the possibility of different future azeotrope configurations of R507 (ecr-ref, 2007).

First, literature survey emphasizes that most promising alternate refrigerants for R502 are R507A and R404A. Table 1 shows physical and environmental characteristics of these refrigerants (Xuan and Chen, 2005). Second, it is observed that in most of the studies referred above, the performance analysis of refrigeration systems is investigated using an energy approach based on the first law of thermodynamics, i.e. by means of the coefficient of performance (COP). Unfortunately this approach is of limited use in view of the fact that it fails to make out the real energetic losses in a refrigeration system. Thus in contrast to energetic approach exergy analysis, based on both first and second laws of thermodynamics, allows an explicit presentation and an improved comprehension of thermodynamic processes by quantifying the effect of irreversibility occurring in the system along with its location. Exergy analysis utilizes exergetic efficiency criterion, taking into account all the losses appearing in the refrigeration system, for measuring the efficiency. Keeping in view the facts stated above, it is intended to communicate the results of theoretical performance analysis of the R502 and its alternate refrigerants (R404A and R507A) based on energy and exergy concepts. The various parameters computed are COP, exergy destruction, exergetic efficiency and efficiency defects in the system. Effects of degree of subcooling, pressure drops in evaporator and condenser, and dead state temperature are also computed and discussed.

Table 1 – Physical and environmental characteristics of R502, R404A and R507A (Xuan and Chen, 2005)

	R502	R404A	R507A
Molecular weight (g/mol)	111.63	97.60	98.86
Critical temperature (°C)	80.7	72.1	70.9
Critical pressure (MPa)	4.02	3.74	3.79
Bubble point[a] (°C)	−45.4	−46.5	−46.7
Dew point[a] (°C)	−45.4	−46	−46.7
Temperature glide (°C)	0	0.5	0
ODP	0.221	0	0
GWP	4500	3800	3900
Safety group	A1	A1	A1

a Bubble point and dew point are saturation temperatures under standard atmosphere pressure, 101.325 kPa.