Applied Energy 86 (2009) 2451–2458

Contents lists available at ScienceDirect

Applied Energy

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

Determination of optimum working conditions R22 and R404A refrigerant mixtures in heat-pumps using Taguchi method

K. Comakli *, F. Simsek, O. Comakli, B. Sahin

Ataturk University, Mechanical Engineering Department, 25240 Erzurum, Turkey

ARTICLE INFO

Article history:
Received 3 August 2008
Received in revised form 25 February 2009
Accepted 1 March 2009
Available online 1 April 2009

Keywords:
Heat-pump
Gas mixture
R404A
R22
Taguchi method

ABSTRACT

In this study, refrigerants R22 and R404A five of their binary mixtures which contain about 0%, 25%, 50%, 75% and 100% mass fractions of R404A were tested. It is investigated experimentally the effects of gas mixture rate, evaporator air inlet temperature (from 24 to 32 °C), evaporator air mass flow rate (from 0.58 to 0.74 kg/s), condenser air inlet temperature (from 22 to 34 °C) and condenser air mass flow rate (from 0.57 to 0.73 kg/s) on the coefficient of performance (COP) and exergetic efficiency values of vapor compression heat-pump systems. To determine the effect of the chosen parameters on the system and optimum working conditions, an experimental design method suggested by Genichi Taguchi was used. In this study, it was observed that the most effective parameters are found to be the condenser air inlet temperature for COP and exergetic efficiency.

1. Introduction

In recent years, ozone layer depletion, global warming and energy efficiency have become one of the most important global issues and scientist are proposed to resolve this issue. The refrigeration industry has gone through substantial changes due to the continuing debate on environmental issues such as depletion of the ozone layer, global warming. There is an urgent need to replace traditional refrigerants (CFCs and HCFCs) as the import of CFCs was banned in 1996 and HCFC imports will be progressively restricted, with complete phase-out early next century [1].

R22 has been used extensively as the refrigerant for residential heat-pump and air-conditioning systems for more than four decades due to its excellent safety, energy efficiency and operating characteristics. It is a partly halogenated refrigerant (HCFC) with a lifetime of approximately 20 years and ozone depletion potential (ODP) of 0.055 (Table 1). The Copenhagen Revision stated that substances of the HCFC type (controlled substances) ought to be frozen in 1996 with progressive reductions from 2004 to 2020 (99.5% cuts) and complete elimination by 2030. As R22 is gradually phased-out, non-ozone-depleting alternative refrigerants are being introduced. It has been proposed various substitutes to R22: R134a, R404A, R407C, R410A, R410B, R508, etc. (see Table 1). Among these alternatives, three directions seem to be gaining most favorable support depending on application and system design: the use of a look-alike zeotropic mixture such as 407C; the use of higher pressure, nearly azeotropic mixtures R410A or R410B; and the use of the lower pressure refrigerant R134a [2].

Nowadays, it is well known that chlorine atoms liberated from chloro-fluorocarbons (CFCs) act as catalysts in ozone-depleting reaction and contribute to the greenhouse effect. Therefore, many actions have been performed to reduce the production and consumption of CFCs by different countries and international organizations. In 1987 the Montreal Protocol, an international environmental agreement, established requirements for the worldwide phase-out of ozone-depleting CFCs. The Montreal Protocol and further amendments to it led to the phase-out of CFCs in all developed countries in 1996, whereas the developing countries benefited from a more relaxed phase-out schedule [3–6].

The use of refrigerant mixtures in vapor compression heat-pumps and other vapor compression cycles has been known for many years. There are two types of refrigerant mixtures: azeotropic and zeotropic mixtures. To improve performance, zeotropic refrigerant mixture is selected as a working fluid in the heat-pump. When using zeotropic refrigerant mixture, the temperature of the refrigerant in the evaporator and condenser does not constantly result from the difference in the boiling point of each refrigerant component. This phenomenon can be explained by the Lorenz cycle [7].

Many works have reported an increase in heat-pump performance when using zeotropic refrigerant mixture [8–22]. For example, Nuntaphan et al. [8] reported that the performance of the combined solar-water-heater and heat-pump was investigated using a simulation program. In this analysis, a model for a heat-pump using the refrigerant mixture R22/R124/R152a was selected.

* Corresponding author. Tel.: +90 442 231 48 49; fax: +90 442 236 09 57.
E-mail addresses: kcomakli@atauni.edu.tr, kcomakli@hotmail.com (K. Comakli).

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doi:10.1016/j.apenergy.2009.03.003

Table 1
Characteristic feature of R22 and possible substitutes to R22 [8].

Refrigerant	R22	R-134a	R404A	R410A	R407C	R508A	R508B
Composition (wt%)	–	–	R125/143a/134a (44/52/4)	R32/125 (50/50)	R32/125/134a (23/25/52)	R23/116 (39/61)	R23/116 (46/54)
Molar mass (kg/kmol)	86.48	102.03	97.6	72.59	86.2	100	95.39
Boiling point at 1 atm (°C)	−40.80	−26.1	−46.5	−51.81	−43.7	−87.4	−87.4
Critical temperature (°C)	96	101.06	72.1	70.17	86.05	11	14
Critical pressure (bar)	49.9	40.64	37.32	47.70	46.34	37	39.3
Ozone depletion potential	0.055	0	0	0	0	0	0
Global warming potential	1700	1300	3700	1900	1600	12,000	12,000

From the simulation program, the results show that the highest performance occurred at a mass fraction of R22 = 20%, R124 = 57% and R152a = 23%, a compressor speed of 20 rps, and mass flow rate of refrigerant at 0.01 kg/s. The coefficient of performance (COP) of this system is between 2.5 and 5.0. Ge and Cropper [9] developed a detailed simulation model for air-cooled finned-tube condensers using the distributed method. The results showed that useful energy savings are expected when this new control strategy is employed. The model does, however, predict that somewhat lower heat-load performances are expected when R404A is used to replace R22 in the condenser.

Park et al. [10] investigated thermodynamic performance of R433A and HCFC22 is measured in a heat-pump bench tester under air-conditioning and heat-pumping conditions. Test results showed that the coefficient of performance of R433A is 4.9–7.6% higher than that of HCFC22 while the capacity of R433A is 1.0–5.5% lower than that of HCFC22 for both conditions.

Park et al. [11] studied performances of two pure hydrocarbons and seven mixtures composed of propylene, propane, HFC152a, and dimethylether were measured to substitute for HCFC22 in residential air-conditioners and heat-pumps. They showed that the coefficient of performance of these mixtures is up to 5.7% higher than that of HCFC22. Nanxi et al. [12] developed a new triple mixture named HTR01 for a moderately high temperature water-source heat-pump. Tests with 2.92 and 300 kW heat-pump systems showed that when the difference between the water temperatures of the condenser outlet and the evaporator inlet was less than 30 °C, the COP_h was always larger than 3. He et al. [13] indicated that the COP of a heat-pump using a R22/R142b refrigerant mixture was higher than those of R22 and R142b by approximately 3.5%. Kiatsiriroat and Na Thalang [14] claim that optimum mass fraction of R22 in the refrigerant blend R22/R124/R152a is approximately 20–40% for an air-conditioning system.

R404A, a zeotropic blend of R125/143a/134a (44/52/4 wt.%, respectively) is the only known substitute that might be regarded as a drop-in. Its compatibility with plant materials is good, except for the lubricating oils. Indeed, with R404A polyester oils must be adopted. Although replacement of R12 by R134a for refrigeration has been widely accepted and this is in commercial use, R134a R404A and R407C are not yet available for residential applications in the US, but are commonly found in residential air-conditioning systems and heat-pumps in Europe [23,24].

R22 is the most widely used refrigerant in air-conditioning applications in Turkey. The main purpose of this study was to investigate to the possibilities of using R404A as a working fluid to replace R22 for vapor compression heat-pumps. Considering that existing heat-pump units using R22 can continue to be serviced with R22 until 2020, this study also included the use of various mass mixtures of R22/R404A in the heat-pump. It is proposed that the new substitute refrigerants be used with making some changes to system components. Therefore, this study includes the preliminary results obtained with making no changes to system components. Our investigation continues in the redesigned heat-pump, which will include the comparison of new result with those of this investigation. The effect of mixture ratio gas mixture ratio, evaporator air inlet temperature, evaporator air mass flow rate, condenser air inlet temperature and condenser air mass flow rat on the COP and exergetic efficiency have not been investigated in detail, because it requires a vast number of experiments, which enormously increases the experimental cost and period. However, quantitative estimations of the various parameters affecting the performance of the heat-pump, and the main factors for optimum design can be determined by an optimization criterion. Therefore, the purpose of this study is to perform an optimization of design working conditions. The optimum working conditions of the parameters which affect the COP and exergetic efficiency of heat-pumps using R22/R404A refrigerant mixtures are investigated experimentally using the Taguchi method.

Taguchi method consists of a plan of experiments with the objective of acquiring data in a controlled way, executing these experiments and analyzing data, in order to obtain information about the behavior of a given process. In other words, Taguchi method is an optimal parameter design of experimental tool, which first chooses several important parameters from a governing equation or relative characteristics of engineering, such as weight, length, or configuration and inputs them into one appropriate plan table designed by Taguchi with plural levels for each parameter. By comparing the calculated results for each parameter for each level from a response table, a set of optimal parameters with corresponding weight can be found. One of the advantages of the Taguchi method over the conventional experiment design methods, in addition to keeping the experimental cost at the minimum level, is that it minimizes the variability around the target when bringing the performance value to the target value. Another advantage is that optimum working conditions determined from the laboratory work can also be reproduced in the real production environment [25–39].

Taguchi method has been applied for various engineering systems, but the application of the Taguchi method for the energy based system has been scarce [32–39]. A methodology to work on geometrically complex heat transfer systems was investigated by Nakayama [32] using the Taguchi method and through a genetic algorithm-type reasoning. The methodology was demonstrated on the cases of heat conduction through composite slabs. Optimum design of natural-circulation solar-water-heater by the Taguchi method was presented by Lu et al. [33]. Bilen et al. [34], Sahin [35], Sahin and Demir [36,37] applied Taguchi method to enhancement heat transfer. They showed that the Taguchi method can successfully be applied to heat transfer studies. Yun and Lee [38] analyzed the effect of various design parameters on the heat transfer and pressure drop characteristics of the heat exchanger with a slit using the Taguchi method. The optimum design value of each parameter was presented and the reproducibility of the results was discussed. To the authors' knowledge there has been little work on the application of the Taguchi method on heat-pumps. Comakli et al. [39] determined optimum working conditions in heat-pumps using nonazeotropic refrigerant mixtures.