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ANALYSIS OF HEAT PUMPS WITH ZEOTROPIC REFRIGERANT MIXTURES BY TAGUCHI METHOD

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Abstract: The goal of this work is to determine the optimum set of parameters by using the Taguchi method in vapour compression heat pump systems. The experimental apparatus consist of an air-to-liquid vapor compression heat pump, a water cooled condenser, a forced air evaporator, an electrical air and water heaters, and various measuring elements and other auxiliary equipments. Refrigerants R22, R407C, and five of their binary mixtures which contain about 0%, 25%, 50%, 75%, and 100% mass fractions of R407C were tested. 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. The most effective parameters are found to be the condenser water mass flow rate for the coefficient of performance and to be condenser water inlet temperature for the exergetic efficiency.
Keywords: Heat pump, R22, R407C Zeotropic mixture, Taguchi method, Optimum working conditions

ZEOTROPİK GAZ KARIŞIMLARI KULLANAN ISI POMPALARININ TAGUCHI METODU İLE ANALİZİ

Özet: Bu çalışmanın amacı Taguchi metodu kullanarak buhar sıkıştırmalı ısı pompası sistemlerinin optimum çalışma parametrelerini belirlemektir. Deney sistemi; su soğutmalı kondenser, zorlanmış hava soğutmalı evoparator, hava ve su ısıtıcıları, çeşitli ölçüm cihazları ve yardımcı ekipmanları içeren ısı pompası sisteminden oluşmaktadır. Soğutucu akışkan olarak R22, R407C ve bunların kütlesel olarak beş faklı (0%, 25%, 50%, 75%, 100% R407C) karışımı kullanılmıştır. Etkin ve optimum çalışma parametrelerini hesaplamak için Genichi Taguchi tarafından önerilen deneysel yöntem kullanılmıştır. Performans katsayısı için en etkin parametre kondenser su debisi, ekserji verimi için en etkin parametre kondenser suyu giriş sıcaklığı olarak bulunmuştur.
Anahtar Kelimeler: Isı pompası, R22, R407c, Zeotropik gaz karışımı, Taguchi metot, Optimum çalışma şartları

Nomenclature

COP	Coefficient of performance
c_p	Specific heat rate at constant pressure (kJ/kgK)
Cosφ	Power factor
e	Random error
F	Value of F table
h	Specific Enthalpy (kJ/kg)
I	Current (A)
m	Degree of freedom
$\dot{m}$	Mass flow rate (kg/s)
N	Number of total experiments
n	Number of repetitions done for an experimental conditions
$\dot{Q}$	Heat load (kW)
T	Temperature (K)
T_O	Reference temperature (K)
U	Voltage (V)
$\dot{W}$	Power supplied (kW)
X	Fixed effect of the parameter level combination used in the experiment
Y	Performance value of the experiment
Z	Performance statistics
Greek letters	
α	Error level
η_{ex}	Exergetic efficiency
φ	Phase angle
μ	Overall mean performance
Subscripts	
a	Air
C	Condenser
E	Evaporator
in	Inlet
L	*Larger*
out	Outlet
r	Refrigerant
S	*Smaller*
w	Water

INTRODUCTION

Taguchi method, consisting of a plan of experiments with the objective of acquiring data in a controlled way, executing these experiments and analyzing data, is used 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. In addition to keeping the experimental cost at the minimum level, one of the advantages of the Taguchi method over the conventional experimental design methods 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 (Taguchi, 1987; Kackar, 1985; Phadke 1986)

Taguchi method has been applied for various engineering systems, but the application of the Taguchi method for the energy based system has been scarce (Nakayama, 2003; Lu et al., 2003; Bilen et al., 2001). A methodology to work on geometrically complex heat transfer systems was investigated by Nakayama (2003) 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. (2003). Bilen et. al. (2001) applied Taguchi method to heat transfer from a surface equipped with rectangular blocks. They showed that the Taguchi method can successfully be applied to heat transfer studies. Yun and Lee (2000) analyzed the effect of various design parameters on the heat transfer and pressure drop characteristics of the heat exchanger with a slit by 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. (1999) determined optimum working conditions in heat-pumps using nonazeotropic refrigerant mixtures. The selected parameters were mixture concentrations, evaporator air source temperature, flow rate of condenser cooling water and air flow rate in the cooling tower. Refrigerants R11, R12, R22 and six of their binary mixtures which contain about 25%, 50% and 75% mass fractions of R22 were tested. This study was the first application of Taguchi method to heat pumps. Although this study has contributed some important knowledge on the heat pump studies, there are two important reasons that encouraged making this investigation:

- As noted above, there is a little study on the application of Taguchi method to heat pumps. The main goal of this study is to provide a new approach to heat pump researches by using the Taguchi method.
- It is well known that chlorine atoms liberated from chloro-fluorocarbons (CFCs) such as R11 and R12 act as catalysts in ozone depleting reaction and contribute to the greenhouse effect. Reduction of CFCs emissions into the ambient in the refrigeration based industry can be achieved by various measures. These measures can be classified as short term and long term measures, as presented in Table 1 (Mattarolo, 1990). As R-22 is gradually phased out, non ozone depleting alternative refrigerants are being introduced.

Table 1 Measures to achieve reduction of CFCs emissions into the ambient in the refrigeration based industry (Mattarolo, 1990)

Measures	
Short Term Measures	**Long Term Measures**
1- A more accurate design of the plants	1- The substitution of the actual refrigerants with non-polluting ones that could meet the requirements of absence of toxicity, flammability and all exigencies from the thermodynamic and thermophysical points of view,
2-Better maintenance operations	2- The use of alternative refrigeration systems as compared to the vapor compression ones, such as air refrigerating machines, steam jet refrigerating machines and absorption refrigerating machines using different circuit types etc.
3- Recycling the refrigerants whenever possible	

Various substitutes to R-22 have been proposed (Karagoz et al., 2004; Aprea and Greco, 2002; Zhao, 2004; Henderson et al.,2001): R134a, R404A, R407C, R410A, R410B, R508, etc. Among these alternatives, three directions seem to be gaining the most favorable support, depending on application and system design (Cavallini, 1996): the use of a look-alike zeotropic mixture such as 407C, the use of higher pressure, nearly azeotropic

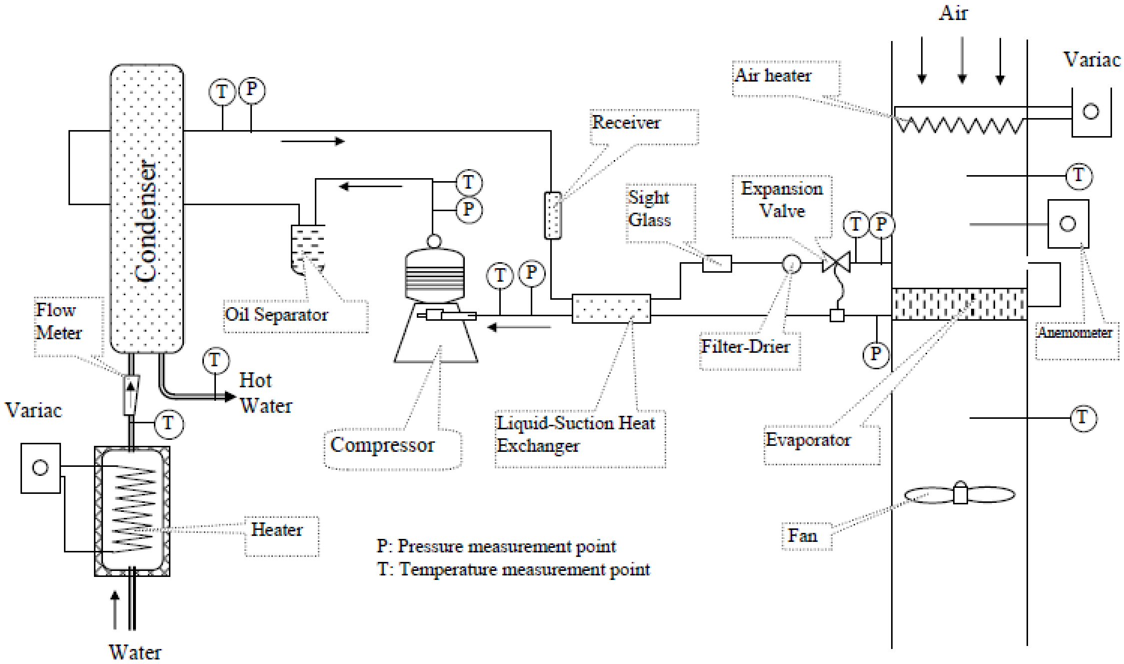

Figure 1 Schematic view of the experimental setup

,mixtures R410A or R410B and the use of the lower pressure refrigerant R134a. In the light of this knowledge, the second purpose of this study was to investigate the possibilities of using R407C as a working fluid to replace R22 for vapor compression heat pumps, and to evaluate performance.

On the other hand, various parameters influence performance of vapor compression heat pumps. Among them are the evaporator air inlet temperature, evaporator source mass flow rate, condenser water inlet temperature, condenser mass flow rate, type of refrigerant etc. Applying the Taguchi method, the effects of gas mixture rate, evaporator air inlet temperature, evaporator air mass flow rate, condenser water inlet temperature and condenser water mass flow rate on the coefficient of performance and exergetic efficiency of vapor compression heat pump systems were investigated. The most effective parameters on the performance were also determined.

EXPERIMENTAL SET-UP AND PROCEDURE

Experimental Set-up

A schematic diagram of the experimental apparatus is shown in Figure 1. The experimental apparatus consists of three loops: the refrigerant loop, the condensing water loop, and the evaporating air loop. The main components of the system are briefly described below. The refrigerant loop consists of a compressor, a shell-and-tube condenser, a plate-fin evaporator, and a thermostatic expansion valve. The compressor was of a reciprocating type compressor. The rotating speed of the compressor can be changed with a variable diameter belt pulley of the electrical motor. The condenser is a horizontal shell-and-tube heat exchanger. A receiver tank provides a storage media for the condensed liquid so that a constant supply of liquid is available to the evaporator as needed. The subcooler was made of concentric copper tube for counterflow heat exchanger. Before entering to the expansion valve, the working fluid passes through a sight glass, a solenoid valve, and a filter-drier. As an expansion device, a thermostatic type expansion valve is used to regulate mass flow rate of the working fluid and to set pressure difference. The condensing water loop is used for cooling the working fluid in the plant. It consists of a condenser, a water heater and measuring devices. The water heater controlled by a variac is used to heat the condenser water and to ensure the water to enter the condenser at a desired temperature. The temperature of the condenser cooling water was measured at the inlet and outlet of the condenser. The flow rate of the condenser cooling water was measured using a flow meter.The evaporating air loop consists of the evaporator, an electric air heater, and a fan. The electric air heater controlled by a variac was used to ensure the air to enter into the evaporator at a desired temperature. Air temperatures were measured at the inlet and outlet of the evaporator. The local air velocities were measured across the channel cross section using an electronic thermal anemometer. The flow rate of air was determined by averaging the local measurements of air velocity across the channel cross section. Temperature and pressure of the working fluid were measured at several locations of interest, as shown in Fig.1. K-type chrome-nickel thermocouples were used to measure the temperatures of the working fluid, and the thermocouples were calibrated with a digital temperature controller. The working fluid temperatures were measured at the inlets and outlets of the evaporator, condenser and compressor. Six Bourdon type manometers were installed at the inlets and outlets of the condenser, compressor and evaporator to measure the pressures. Compressor input current was measured using an ammeter. The overall composition of the refrigerant mixtures was determined by measuring the charging quantity of individual refrigerant using a precision digital balance. First, the system was charged with R22. Temperature and pressure values in the key-points of the plant, as shown in Fig. 1, were continuously monitored in order to check the achievement of steady-state conditions. Usually, the required start-up time was about one hour. After each experimental run, the raw data which consists of temperatures, pressures, water flow rate, compressor input current were recorded. On completion of the measurements to obtain the baseline performance results, the compressor and the system were drained and evacuated. The system was recharged with the refrigerant to be tested. This procedure was repeated for R407C and each mixture under investigation. The tested mixtures were mixtures of R22/407C (mass fractions of R407C was 0, 25, 50, 75, 100%).

Experimental Parameters and Plan

Experimental parameters and their levels studied are given in Table 2. The orthogonal array (OA) experimental design method was chosen to determine the experimental plan, five parameters with five levels (values) each, $L_{25}(5^6)$ (Table 3). In addition, the responses, which are the coefficient of performance and exergetic efficiency**,** are also given in Table 3 for 2 repeats. The parameters, namely gas mixture ratio, evaporator air inlet temperature, evaporator air mass flow rate, condenser water inlet temperature and condenser water mass flow rate are inserted in columns A, B, C, D, E. Column F that is empty is used for calculation of error. To observe the effect of noise source on the heat pump system, each experiment was repeated two times under the same conditions at the different times, for which the order of the experiments was selected randomly. At the end of the study, it is aimed to obtain maximum COP and maximum exergetic efficiency of the system. The performance statistics was chosen as the optimization criteria. It was used for "the larger the better" and "the smaller the better" situations evaluated by using the following equations (Kackar, 1985):

$$Z_L = -10\mathrm{Log}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y_i^2}\right) \tag{1}$$

$$Z_S = -10\mathrm{Log}\left(\frac{1}{n}\sum_{i=1}^{n}Y_i^2\right) \tag{2}$$

where Z_L and Z_S are the performance statistics, n the number of repetitions done for an experimental combinations, and Y_i the performance value of the *i*th experiment. In the Taguchi method the experiments corresponding to optimum working conditions might not have been done during the whole period of the experimental stage. In such cases, the performance value corresponding to optimum working conditions can be predicted by utilizing the balanced characteristic of OA. For this aim the additive model may be used (Phadke et al.,1983):

$$Y_i = \mu + X_i + e_i \tag{3}$$

where μ is the overall mean performance value, X_i the fixed effect of the parameter level combination used in the *i*th experiment, and e_i the random error in the *i*th experiment. The optimum performance was calculated using Eq. 3. Because Eq. 3 is a point estimation calculated by using experimental data to determine whether the results of the confirmations experiments are meaningful or not, the confidence interval must be evaluated. The confidence interval at a chosen error level may be calculated by (Ross, 1987)

$$Y_i \pm \sqrt{F_{\alpha;1,DF_{MSe}} * MSe * \left(\frac{1+m}{N}+\frac{1}{n_r}\right)} \tag{4}$$

where F is the value of F table, α the error level, DF_{MSe} the degree of freedom of mean square error, m the degree of freedom used in the prediction of Y_i, N the number of total experiments, and n_r the number of repetitions in the confirmation experiments. The order of the experiments was obtained by inserting parameters into the columns of OA, L_{25} (5^6), chosen as the experimental plan given in Table 3, but the order of experiments was made randomly in order to avoid noise sources which had not been considered initially and which could take place during an experiment and affect the results in a negative way.

The interactive effects of the parameters were not taken into account in the theoretical analysis because some preliminary tests showed that they could be neglected. The validity of this assumption was checked by confirming experiments conducted at the optimum conditions.

Table 2 The parameters and their levels studied in the experiments

Parameters		Levels				
		1	2	3	4	5
A	Gas mixture ratio, R22/R407C (%)	0	25	50	75	100
B	Evaporator air inlet temperature (°C)	24	27	30	33	36
C	Evaporator air mass flow rate (kg/s)	0.447	0.536	0.625	0.804	0.983
D	Condenser water inlet temperature (°C)	14	18	22	26	30
E	Condenser water mass flow rate (kg/s)	0.038	0.051	0.063	0.076	0.088

Table 3 Chosen L_{25} (5^6) experimental plan

	Parameters and their levels						COP		Exergy efficiency (%)	
Experiment No	A	B	C	D	E	F (empty)	1	2	1	2
1	1	1	1	1	1	1	1.95	1.95	8.22	8.92
2	1	2	2	2	2	2	2.60	2.42	14.73	11.92
3	1	3	3	3	3	3	2.73	2.85	16.22	16.44
4	1	4	4	4	4	4	3.05	2.95	19.97	19.00
5	1	5	5	5	5	5	3.33	3.24	24.60	23.47
6	2	1	2	3	4	5	2.73	2.70	12.49	11.64
7	2	2	3	4	5	1	2.73	2.67	14.02	13.67
8	2	3	4	5	1	2	1.86	1.38	11.22	10.30
9	2	4	5	1	2	3	2.73	2.83	11.44	11.72
10	2	5	1	2	3	4	2.70	2.69	11.57	11.16
11	3	1	3	5	2	4	1.80	1.75	13.37	12.80
12	3	2	4	1	3	5	1.95	1.83	2.55	1.62
13	3	3	5	2	4	1	3.43	3.66	13.83	17.01
14	3	4	1	3	5	2	3.68	3.86	18.30	20.38
15	3	5	2	4	1	3	1.28	1.17	7.48	6.60
16	4	1	4	2	5	3	3.57	3.83	13.97	15.33
17	4	2	5	3	1	4	1.66	1.50	10.24	8.36
18	4	3	1	4	2	5	1.89	1.89	11.88	11.98
19	4	4	2	5	3	1	2.33	2.15	16.80	15.45
20	4	5	3	1	4	2	1.79	1.59	0.53	0.37
21	5	1	5	4	3	2	2.07	2.31	12.26	14.34
22	5	2	1	5	4	3	2.63	2.51	18.71	16.84
23	5	3	2	1	5	4	2.61	2.41	3.24	2.01
24	5	4	3	2	1	5	1.28	1.54	4.48	6.56
25	5	5	4	3	2	1	1.50	1.50	6.37	6.25

Data reduction

The coefficient of performance for a heat pump cycle indicates the overall power consumption for a desired output and was evaluated using the following equation:

$$\text{COP}=\frac{\dot{Q}_c}{\dot{W}_C} \qquad (5)$$

where $\dot{Q}_C$ and $\dot{W}_C$ are the heat delivered by the condenser and compressor power, respectively. It is assumed that the condenser and evaporator were well insulated. Thus the heat delivered by the condenser was calculated by

$$\dot{Q}_C = \dot{m}_r (h_2 - h_3) = \dot{m}_w c_{p,w} \left(T_{w,out} - T_{w,in}\right) \qquad (6)$$

The heat absorbed by the evaporator was calculated by

$$\dot{Q}_E = \dot{m}_r (h_4 - h_1) = \dot{m}_a c_{p,a} \left(T_{a,out} - T_{a,in}\right) \qquad (7)$$

The power input to the compressor was calculated by

$$\dot{W}_C = \dot{m}_r (h_2 - h_1) = \sqrt{3}.\text{Cos}\varphi.\text{U.I} \qquad (8)$$

where U, I and Cosφ are voltage (V), current (A) and power factor, respectively. The power factor was taken as 0.8 in the calculation. Exergy is defined as the maximum amount of work, which can be produced by a system, or a flow of matter or energy as it comes to equilibrium with a reference environment (Comakli et al., 2004) The exergy efficiency can be expressed as the ratio of the useful exergy output and exergy input in heat pump. Thus the exergetic efficiency of the system was calculated using the following equation (Kaygusuz, 1993; Ayhan et al.,1992)

$$\eta_{ex} = \frac{\dot{Q}_C - T_0 \dot{m}_w c_{p,w} \ln\left(T_{w,out} / T_{w,in}\right)}{\dot{Q}_E + \dot{W}_C - T_0 \dot{m}_{air} c_{p,air} \ln\left(T_{air,in} / T_{air,out}\right)} \quad (9)$$

Experimental Uncertainties

Uncertainty analysis is needed to prove the accuracy of the experiments. In the present study, by using the estimation method of Holman (2001), maximum uncertainties of the COP and exergy efficiency are found to be 3.45% for COP, and 3.45 % for Exergy efficiency.

RESULT AND DISCUSSION

The collected data were analyzed by using ANOVA-TM computer software package for evaluation of the effect of each parameter on the optimization criteria. The results obtained are given in Figures 2 and 3. The orders of graphs in these figures are according to the degree of the influence of parameters on the performance statistics. The most effective parameter on the performance statistics is shown on the left of the Figs. 2 and 3, the less effective parameter on the right. At the first sight, it is difficult and complicated to deduct experimental conditions from the graphs given in these figures. By taking Figure 2, this shows the variation of the performance statistics with the parameters on COP. Also, by trying to determine experimental conditions for the first point. The condenser water inlet temperature for this point is 14°C that is level 1 for which column D is 1, as presented in Table 2. The performance statistics value of the first data point is, thus, the average of those obtained from experimental number of 1, 9, 12, 20 and 23 (see Table 3). The experimental conditions for the second point are the conditions of the experiments for which column D is 2 (i.e., experiments nos. 2, 10, 13, 16 and 24), and so on. The numerical value of the maximum point in each graph shows the best value of that particular parameter. These maximum parameters indicate the optimum condition in the range of the experimental conditions. These optimum parameters are also given in Table 4. An evaluation of Figure 2 reveals that the effective parameters on the COP are ordered as follows: condenser water mass flow rate, gas mixture ratio, evaporator air mass flow rate, evaporator air inlet temperature, and condenser water inlet temperature, respectively. Figure 2 reveals that the condenser water mass flow rate has the most influence on the COP. Performance statistics increases by increasing condenser water mass flow rate. Performance statistics decreases by increasing gas ratio of R407C in the gas mixture. The evaporator air mass flow rate, evaporator air inlet temperature and condenser water inlet temperature are less effective on the performance statistics than the condenser water mass flow rate and gas mixture ratio. The experiment corresponding to the optimum conditions for COP is found to be the experiment of A1B4C5D2E5. Namely, to maximize COP, the optimum combination of parameters is: the gas mixture ratio of 100/0 R22/R407C, the evaporator air inlet temperature of 33oC, the evaporator air mass flow rate of 0.983 kg/s, the condenser water inlet temperature of 18oC, and the condenser water mass flow rate of 0.088 kg/s. If the experimental plan given in Table 3 is examined carefully together with Table 2, it can be seen that the experiment corresponding to the optimum conditions (i.e. for COP, A1B4C5D2E5) was not performed during the experimental plan. This is the superior of the Taguchi technique that the optimum experimental conditions can be determined without conducting this experiment. The effective parameters on the exergetic efficiency are ordered as follows, as presented in Figure 3: condenser water inlet temperature, evaporator air mass flow rate, gas mixture ratio, evaporator air inlet temperature, and condenser water mass flow rate, respectively. Figure 3 reveals that the condenser water inlet temperature has the most influence on the exergetic efficiency. The performance statistics increases by increasing the condenser water inlet temperature. It is also found that the performance statistics decreases towards a minimum value, 0.625 kg/s, then increases as the evaporator air mass flow rate increases. The performance statistics decreases by increasing gas ratio of R407C in the gas mixture. The evaporator air inlet temperature and condenser water mass flow rate have lower effect on the performance statistics in comparison to other three parameters, namely the condenser water inlet temperature, the evaporator air mass flow rate and the gas mixture ratio. If the experimental plan given in Table 3 is examined carefully together with Table 2, it is seen that the experiment corresponding to optimum conditions for the exergetic efficiency is the experiment of A1B4C5D5E5. Namely, to maximize exergetic efficiency, the optimum combination of the parameters is: the gas mixture ratio of 100/0 R22/R407C, the evaporator air inlet temperature of 33oC, the evaporator air mass flow rate of 0.983 kg/s, the condenser water inlet temperature of 30oC, and the condenser water mass flow rate of 0.088 kg/s.

The optimum working conditions determined from Figure 2 and 3 are given in Table 4. First of all, each goal was optimized, separately. The optimization of COP is presented in the line of COP, the optimization of exergetic efficiency in the line of Exergetic Efficiency in Table 4. Then, two goals, the COP and the exergetic efficiency, were optimized together, considering the exergetic efficiency is the primary goal. This result of the optimization was presented in the line of General in Table 4. The COP predicted by Eq. 3 is presented in Table 4 in the column of entitled Prediction.

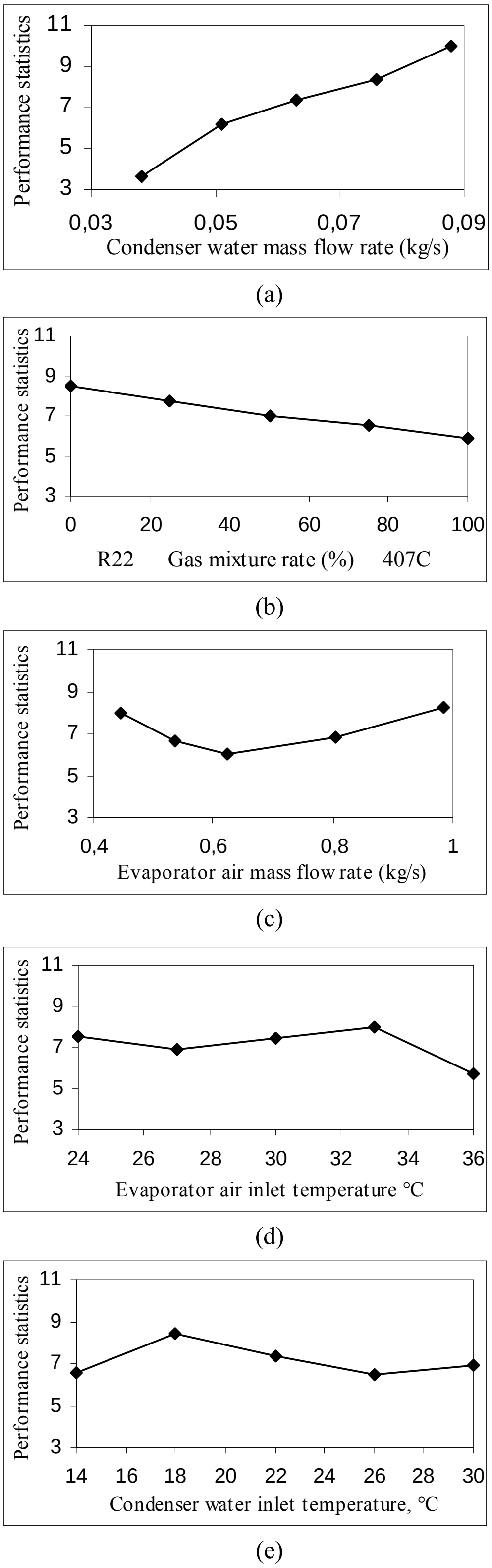

Figure 2 The effect of each parameter on coefficient of performance (COP)

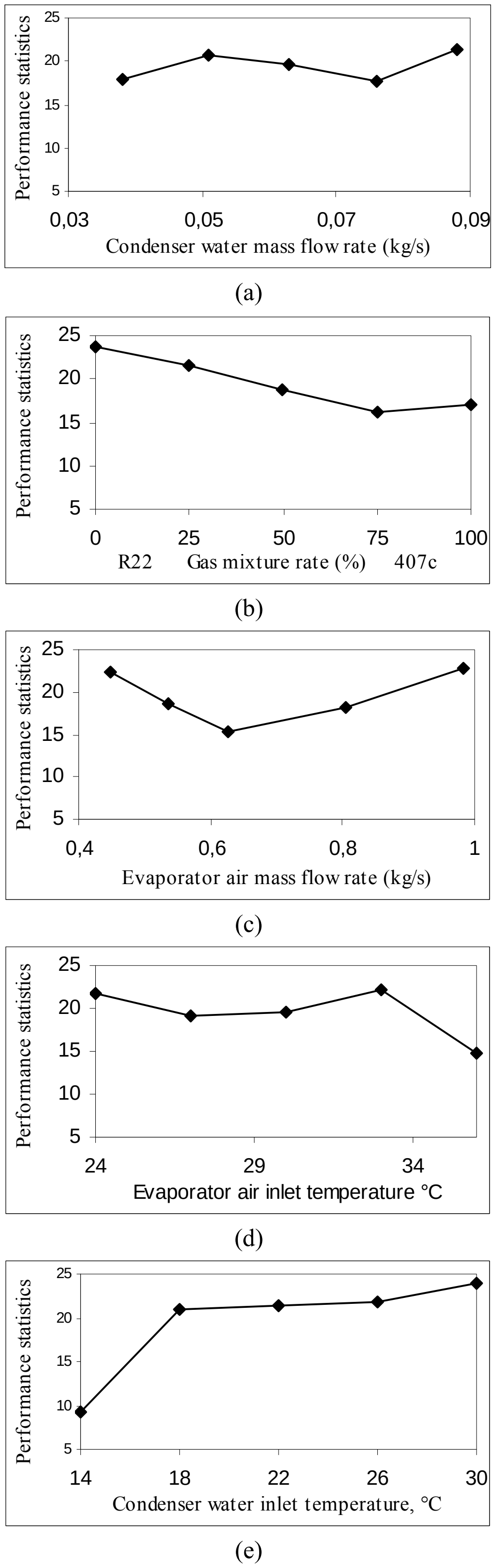

Figure 3 The effect of each parameter on exergetic efficiency

Table 4 Optimum working conditions and performance values obtained this condition for heat pump system

		Parameters					COP			
		A	B	C	D	E				
		Gas mixture ratio	Evaporator air inlet temperature °C	Evaporator air mass flow rate (kg/s)	Condenser water inlet temperature , °C	Condenser water mass flow rate (kg/s)	Prediction	Confidence interval	Real	Predicti
COP	Optimum level	1[2]	4[4]	5[3]	2[5]	5[1]	4.46	3.66 - 5.26	3.71	25.03
	Optimum value	0	33	0.983	18	0.088				
Exergy efficiency (%)	Optimum level	1[3]	4[4]	5[2]	5[1]	5[5]	3.98	3.18 - 4.78	3.22	29.33
	Optimum value	0	33	0.983	30	0.088				
General	Optimum level	1	4	5	5	5	3.98	3.18 - 4.78	3.22	29.33
	Optimum value	0	33	0.983	30	0.088				

[1] *1st degree effective parameter*
[2] *2nd degree effective parameter*
[3] *3rd degree effective parameter*
[4] *4th degree effective parameter*
[5] *5th degree effective parameter*

The confidence interval column in the table, calculated by Eq. 4, presents a 95% confidence level. In order to test predicted results, confirmation experiments were carried out twice at the optimum conditions and the average of the results are presented in the column of *Real*. For instance, the real COP of 3.71 is the arithmetic average of two confirmation experiments, 3.70 and 3.72. It can also be said that the results are within the calculated confidence intervals (3.66-5.26) with ±5% error.

The predicted exergetic efficiency, the confidence interval and the real exergetic efficiency are also given in Table 4. These results show that the interactive effects of the parameters are, indeed, negligible and also prove that the Taguchi method can successfully be applied heat pump systems**,** with a very limited number of experiments and shorter time to obtain the optimum values of parameters.

The above results and discussion show that optimum working conditions of heat pumps can be determined by using the Taguchi method. In this investigation, which is one of the first investigations using the Taguchi method in heat pumps, five parameters were selected. More general and extensive results could be obtained when one of the following items is considered: (i) The level of parameters can be increased; (ii) Different parameters of working conditions can be included.

It is useful to note that the results of this study are in agreement with those obtained with similar investigations by other authors and our earlier study (Comakli et al., 2009) in which the most effective parameter on the COP was similarly found to be the condenser water mass flow rate although a different gas mixture (R22/404A) was used. However, the condenser mass flow rate in the study performed by Yılmaz (2003) was not consider as an effective parameter, it is explained that the mixture ratio affects significantly the COP and second law efficiency of heat pumps. A literature review shows that (Greco et al.,1997; Aprea and Greco, 2003):

- Both the thermodynamics and general performance of R407C are comparable with those of R22.
- The COP of R407C is lower than that of R22.
- The use of R407C in existing plants would only require discharge of mineral oil and refilling with compatible polyoester oil.

CONCLUSIONS

This paper presents the results of an investigation carried out to determine experimentally the effects of gas mixture ratio, evaporator air inlet temperature, evaporator air mass flow rate, condenser water inlet temperature and condenser water mass flow rate on the coefficient of performance and exergetic efficiency of vapor compression heat pump systems. Refrigerants R22, R407C, and five of their binary mixtures which contain about 0%, 25%, 50%, 75% and 100% mass fractions of R407C were tested. The effects of the chosen parameters on the system and optimum working conditions were determined by Taguchi method. The following conclusions can be derived from the above results and discussion:

- R22/R407C mixtures can be used in replacement for R22 or R407C in vapour compression heat pump systems.
- The most effective parameter on the COP is found to be the condenser water mass flow rate. The effective parameters on the COP are ordered as follows: condenser water mass flow rate, gas mixture ratio, evaporator air mass flow rate, evaporator air inlet temperature, and condenser water inlet temperature, respectively
- The most influential parameter on the exergetic efficiency is the condenser water inlet temperature. The effective parameters on the exergetic efficiency are ordered as: condenser water inlet temperature, evaporator air mass flow rate, gas mixture ratio, evaporator air inlet temperature, and condenser water mass flow rate, respectively.
- The experiments corresponding to optimum conditions for the coefficient of performance and the exergetic efficiency are the experiment of $A_1B_4C_5D_2E_5$ and $A_1B_4C_5D_5E_5$, respectively. When all the goals were take into account together, the trade-off among goals was considered, the optimum results were obtained for exergetic efficiency at $A_1B_4C_5D_5E_5$ conditions.

It may be stated that since the optimum conditions determined by the Taguchi method in a laboratory environment are also reproducible in real production environments, the findings of the present laboratory scale study may be very useful for heat pump applications in industrial scale.

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