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EXPERIMENTAL DESIGN AND REGRESSION ANALYSIS FOR PERFORMANCE OF A CHILLER SYSTEM

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Abstract: In this paper, we perform experimental design and regression analysis for performance of a chiller system. First, we complete design of experiment (DOE) on response so that determine the main and the interaction effects of the pre-defined factors. Second, we omit the insignificant factors from the analysis and, develop regression functions by considering the significant factors (inputs). Four factors are considered in DOE, these are: the water temperature, water flow rate, electronic expansion valve (EEV) opening percentage and compressor speed. Eight responses (outputs) are considered in DOE. They are the coefficient of performance (COP), capacity of evaporator, capacity of condenser, power consumption of the compressor, temperature of condensing, temperature of evaporation, superheating, and sub-cooling. The DOE results are analyzed, and regression functions are developed by MINITAB - a statistical software - at a 95% confidence level.
Keywords: Water chiller, Experimentation, Variable speed, Performance.

BİR SU SOĞUTMA GRUBUNUN PERFORMANSI İÇİN DENEYSEL TASARIM VE REGRESYON ANALİZİ

Özet: Bu çalısmada, bir su soğutma grubunda deneysel tasarım ve regresyon analizi yapılmıştır. Öncelikle, performans değerleri üzerinde deneysel tasarım (DT) uygulanmış, böylece önceden belirlenen faktörlerin ana ve etkileşimli etkileri tespit edilmiştir. İkinci olarak, analizden önemsiz faktörler çıkarılmış ve önemli faktörler gözetilerek regresyon fonksiyonları bulunmuştur. DT'de, dört faktör gözetilmiştir, bunlar: suyun sıcaklığı, su debisi, elektronik genleşme valfi (EGV) açıklık oranı ve kompresor hızı. DT'de sekiz performans değeri göz önünde bulundurulmuştur. Bunlar, soğutma performans katsayısı (COP), evaporatör kapasitesi, kondenser kapasitesi, kompresör gücü, yoğuşma sıcaklığı, buharlaşma sıcaklığı, aşırı ısıtma ve aşırı soğutma. DT ve regresyon fonksiyon analizleri MINITAB – istatistiksel bir yazılım – ile % 95 güven aralığında elde edilmiştir.
Anahtar kelimeler: Su soğutma grubu, Deneysel tasarım, Değişken hız, Performans.

NOMENCLATURE

adj	Adjusted
Cs	Compressor speed [Hz]
Fw	Flow rate [kg s^{-1}]
I	Insignificant
k	Number of factors
P_1	Coefficient of performance
P_2	Evaporator capacity [kW]
P_3	Condenser capacity [kW]
P_4	Compressor power consumption [kW]
P_5	Condensing temperature [^{o}C]
P_6	Evaporation temperature [^{o}C]
P_7	Superheating [^{o}C]
P_8	Sub-cooling[^{o}C]
Po	electronic expansion valve opening percentage [%]
R^2	Coefficient of determination
S	Significant
s	Speed
Tw	Water temperature [^{o}C]
w	Water

INTRODUCTION

Refrigeration is defined as a process of heat removal. It is also referred as vapor-compression of a refrigeration cycle. A refrigeration system has four main components which are the compressor, condenser, evaporator, and expansion device. In this system, a serial of process takes place which is called refrigeration cycle. In a refrigeration cycle, the substance refrigerant absorbs the heat from the refrigerated space in the evaporator and rejects it to the cooling agent in the condenser (Cengel et al., 2006; Dossat et al., 2001). Here, if the heat is removed via a liquid it is called chiller. The main components of a general refrigeration system are shown in Fig.1.

The power consumption of a variable speed refrigeration system is due to the individual components, compressors, inverters, fans, electronic expansion valves etc.

It is crucial to design a chiller system with optimum operation conditions which provide high working performance with low energy consumption. In this study our aim is to explore the optimum points of pre-defined input factors to achieve a chiller system with optimum performance.

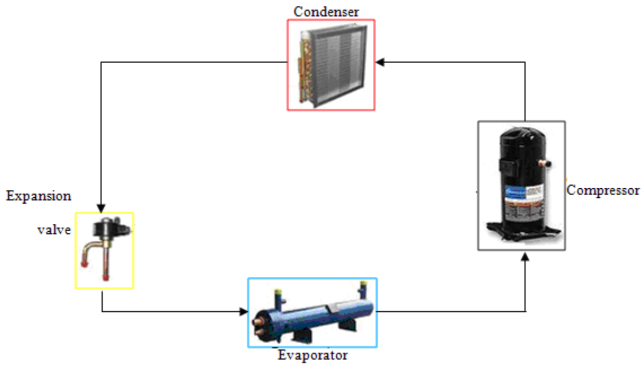

Figure 1. The main components of a refrigeration system.

Literature Review

There are various studies in the literature that investigate to maintain lower energy consumption in refrigeration systems. Larsen and Thybo (2004) study energy saving of a refrigeration system by setting the optimum points of the working condition. Their results show that a substantial amount of energy can be saved by using a suboptimal control strategy. Also, according to them, by finding an optimal condenser pressure, without changing the cycling capacity, it is possible to decrease the energy consumption, especially in the cold season where the ambient temperature is low. Björk and Palm (2006) have reported experimental results of an on/off cycling domestic refrigerator at varied expansion device capacity, quantity of charge and ambient temperature in their study. An analysis is conducted by Shao et al. (2004) for modeling the variable speed compressor to have scattered the real operation performance of inverter compressor. The map-based method is utilized to fit the performance curves of the inverter compressor. A second-order function for condensation and evaporation temperature is obtained at basic frequency and map condition. They also discuss the relationship between COP and the compressor frequency. It is also mentioned that there is an optimal frequency to optimize the COP. Aprea et al. (2009) conduct an experimental study to identify the optimum compressor speed for energy, exergy and economy aspects on reciprocating and scroll type compressor. Ekren et al. (2009) develop an algorithm to decrease the energy consumption of a chiller system. This study also shows the effects of different control methods on variable speed scroll compressor (VSSC) and EEV in a chiller system.

It is crucial to determine the statistically significant factors that could affect the critical performance measures of a chiller system. Different from the existing studies in this paper first, we complete DOE to determine the main and the interaction effects of the pre-defined four factors on the performance of a chiller system. Second, we omit the insignificant factors from the analysis based on the performance measure and, develop the regression functions by considering those significant factors. In another word, the objective of this study is to determine the statistically significant factors on various performance measures of a chiller system and to identify how these factors affect the performance measures, and find out the optimum values of the significant factors on each performance measure.

Experimental Setup

In this section, because we study a water chiller system first, we explain the experimental setup of this system. The experimental chiller system has a vapor compression refrigeration cycle working with the refrigerant R134a. It consists of a scroll compressor, a shell–tube liquid type evaporator, an air-cooled condenser inside the thermally insulated air-channel. Besides, an electrical heater, a fan and a nozzle are mounted in the insulated air channel. In the system, the air flow rate and the temperature can be changed by a fan and an electrical heater, respectively. Refrigerant flow is adjusted by an EEV. While experimenting, to be able to obtain a constant cooling load in the evaporator, electrical heaters are used in the water tank. The temperature through the cooling cycle is measured at different points by a "*T*" type thermocouples, and the pressures are measured by rotiometric type pressure transducers. We measure the power consumption by a wattmeter. A control and a data acquisition unit are installed to send a control signal to the VSSC and EEV. The experimental setup allows us to vary the compressor electric motor frequency and its speed by an inverter linked to the three-phase electric motor of the compressor. Fig. 2 shows the experimental plant.

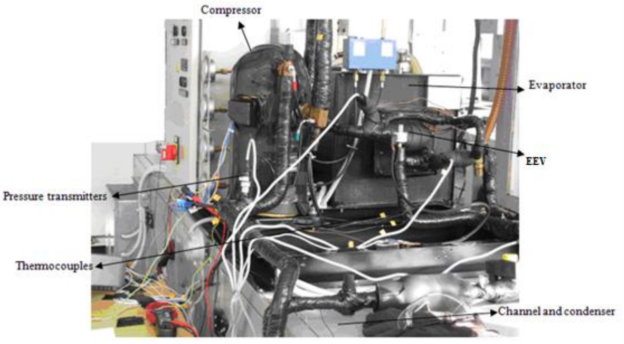

Figure 2. Experimental setup.

The specifications of the equipment are given in Table 1.

Table 1. Specifications of the experimental setup.

Compressor	Type : Copeland ZR34K3-PFJ, vertical scroll (R134a refrigerant) Capacity: 2.8 Hp, 380 V, 50 Hz
Condenser	Type : Air cooled
Evaporator	Type : Shell-tube liquid
Expansion valve	Type : Electronic Port size : 1.8 mm Operating range : 0–480 pulse Rated voltage : DC 12 V Control method : Stepper motor controlled
Pressure Transducer	Type : Carel SPKT, Rotiometric Range : low pressure (between -1 and 9 bar), high pressure (between 0 and 45 bar) absolute Error : ±%1.2
Thermocouple	Type : "T" Range : -200 and 350 ^{o}C Error : ±%1.5
Wattmeter	Type : Bs157 Range : 220/600 V , 50/60 Hz Error : ±%1.5
Data Acquisition and Control System	Agilent-34970 data logger and 34907 control card Stepper motor control circuit and personnel computer parallel port
Inverter	Type : Pulse Width Modulation (PWM) Capacity : 2.2 kW Frequency Range : 0-100 Hz

Design of Experiments

DOE is a design tool that makes changes to the independent (input) variables to determine their effect on the dependent (output) variables. It not only identifies the significant factors (independent variables) that affect the response (dependent variable), but also how these factors affect the response. Thus, the objective of our study is not only to investigate how the performance measures of a chiller system are affected by the pre-defined factors but also to ascertain how the measures can be improved by adjusting these factors. The performance measures considered in DOE are COP (P_1), capacity of evaporator (P_2), capacity of condenser (P_3), power consumption of the compressor (P_4), temperature of condensing (P_5), temperature of evaporation (P_6), superheating (P_7) and sub-cooling (P_8). The performance measures are chosen by considering all possible outputs of the system.

The factors that are likely to have an effect on the performance measures are: the water temperature (T_W) and flow rate (F_W), EEV opening percentage (P_O) and, the compressor speed (C_S). In this section first, we mount the experimental setup. Second, we conduct a DOE based on these pre-defined factors and their levels (see Table 2). Third, we analyze the results using analysis of variance (ANOVA) to determine the main and interaction effects of the factors. Last, we omit the insignificant factors from the DOE, re-conduct the experiments, and re-analyze the results.

Table 2. Levels of Factors.

	Factors	Codes		Levels
1	T_W	1	(Low level)	12^{0}C
		2	(High Level)	16^{0}C
2	F_W	1	(Low level)	0.15 kg s^{-1}
		2	(High Level)	0.5 kg s^{-1}
3	P_O	1	(Low level)	15%
		2	(High Level)	35%
4	C_S	1	(Low level)	40 Hz
		2	(High Level)	50 Hz

As seen in Table 2, all factors have two levels. Thus, we conduct a 2^k DOE (Montgomery, 1996). k denotes the number of factors which is four, here. We conduct 16 experiments (2^4) as in Tables 3a-3b. Low and high levels of each factor in Table 2 are chosen by considering the possible minimum and maximum values that those factors can get.

DOE Results

Table 3a. DOE table for all factor combinations and average responses for P_1 – P_4.

Exp	T_W	F_W	Po	C_S	P_1	P_2	P_3	P_4
1	1	1	1	1	2.04	2.5	5.71	1.23
2	2	1	1	1	2.30	2.87	5.96	1.25
3	1	2	1	1	2.66	3.61	6.46	1.36
4	2	2	1	1	2.96	4.08	6.55	1.38
5	1	1	2	1	2.08	2.55	5.68	1.23
6	2	1	2	1	2.27	2.82	5.91	1.24
7	1	2	2	1	2.79	3.73	6.33	1.34
8	2	2	2	1	2.86	3.98	6.56	1.39
9	1	1	1	2	1.67	2.78	6.31	1.66
10	2	1	1	2	1.88	3.36	6.91	1.79
11	1	2	1	2	2.24	4.34	7.66	1.93
12	2	2	1	2	2.28	4.52	7.88	1.98
13	1	1	2	2	1.80	2.91	6.22	1.62
14	2	1	2	2	1.87	3.34	6.83	1.78
15	1	2	2	2	2.26	4.33	7.65	1.92
16	2	2	2	2	2.29	4.52	7.87	1.98

It is important to find out the significant factors that could affect the performance of the chiller system. Hence, a carefully designed factorial experiment is undertaken to determine the relative importance of the factors and their interaction. The DOE table is shown in Tables 3a-3b. In this table, experiments are designed by considering all possible combinations of level of each factor (2^k). In this table "1" and "2" show the coded values for low and the high levels of the related factors, respectively (see also Table 2). We complete five replications for each experiment. Tables 3a-3b also show the average values of these five replications for each response. It should be noted that in Minitab, we replace all the replications' results so that we use 80 (16*5) values to obtain the knowledge of significant main and interaction effects of factors, initially.

Table 3b. DOE table for all factor combinations and average responses for $P_5 - P_8$.

Exp	T_W	F_W	Po	C_S	P_5	P_6	P_7	P_8
1	1	1	1	1	49.95	-7.96	5.42	15.06
2	2	1	1	1	50.53	-5.68	8.45	14.54
3	1	2	1	1	52.68	-2.21	6.85	14.56
4	2	2	1	1	53.19	0.51	9.59	12.63
5	1	1	2	1	49.71	-8.03	4.59	14.75
6	2	1	2	1	50.34	-5.61	4.97	14.44
7	1	2	2	1	52.18	-2.31	5.63	14.01
8	2	2	2	1	53.37	0.55	6.10	12.98
9	1	1	1	2	52.11	-9.90	7.64	15.67
10	2	1	1	2	54.09	-6.65	9.80	15.51
11	1	2	1	2	56.27	-2.62	9.76	14.54
12	2	2	1	2	56.80	0.06	11.12	12.97
13	1	1	2	2	51.31	-10.55	5.19	15.96
14	2	1	2	2	53.87	-6.62	5.77	15.24
15	1	2	2	2	56.14	-2.53	6.74	14.31
16	2	2	2	2	56.69	-0.05	6.24	13.37

ANOVA Results

We analyze the results using ANOVA in MINITAB statistical software at the 95% confidence level. ANOVA is a general technique that can be used to test the hypothesis that the means of two or more groups are equal. ANOVA assumes that the sampled populations are normally distributed. To be able to interpret the ANOVA results, there are other assumptions that must be met. This is also referred as model adequacy check. The model adequacy requires that residuals must be normally and independently distributed, have a mean of zero and, have constant variance. If one of these assumptions is not met, a suitable transformation such as, inverse, logarithm, natural logarithm, square root, inverse, inverse square root, etc. should be applied on the response to achieve the model adequacy.

In the current model, because the ANOVA assumptions are not met for the P_3, P_4 and P_7 we apply inverse square root transformation on these responses. After the transformation the model adequacy assumptions are met for these responses. Table 4 presents the ANOVA output of MINITAB for the P_1 as an example.

Table 4. ANOVA results for P_1.

Source	Deg of fre.	Seq. Sums of Squa	Adj. Sum of Squa	Adj. Mean Square	*F*-test *(F)*	Prob. *(P)*
Tw	**1**	**0.173**	**0.173**	**0.173**	**14.390**	**0.002**
Fw	**1**	**2.446**	**2.446**	**2.446**	**203.530**	**0.000**
Po	**1**	0.004	0.004	0.00	0.330	0.572
Cs	**1**	**1.673**	**1.673**	**1.673**	**139.180**	**0.000**
Tw*Po	**1**	0.011	0.011	0.010	0.880	0.362
Tw*Fw	**1**	0.025	0.025	0.025	2.080	0.168
Tw*Cs	**1**	0.026	0.026	0.026	2.190	0.159
Fw*Po	**1**	0.001	0.001	0.001	0.070	0.799
Fw*Cs	**1**	**0.066**	**0.066**	**0.066**	**5.500**	**0.032**
Po*Cs	**1**	0.001	0.001	0.001	0.100	0.751
Tw*Fw*Po	**1**	0.000	0.000	0.000	0.010	0.917
Tw*Fw*Cs	**1**	0.003	0.003	0.003	0.240	0.627
Tw*Po*Cs	**1**	0.003	0.003	0.003	0.260	0.616
Fw*Po*Cs	1	0.002	0.002	0.002	0.150	0.703
Tw*Fw*Po*Cs	1	0.010	0.010	0.010	0.810	0.382

In ANOVA the *F*-test is used to compare variances. The bigger the *F*, the more likely it is that the factor is significant. In ANOVA table probability (labeled *P*) indicates whether or not the factor affects the performance measure. The factor having small *P* value (e.g, $P<0.05$) means that this factor has significant effect on this response. We show the rows of all significant factors ($P<0.05$) in bold in Table 4. According to that the *Po* does not have a significant effect on the P_1 ($P>0.05$). However, there is a significant two-way interaction effect of *Fw* and *Cs* on this response. Because there is a two-way interaction effect of these factors, this also means that *Fw* and *Cs* have significant main effects on P_1. In addition, *Tw* also has significant main effect on P_1. Because *Po* is not significant on the response, we omit this factor from the design table and re-analyze the results in Minitab. This time, because there are three factors, we consider eight (2^3) experiments in Minitab. It should be noted that in the second analyze, we only consider the statistically significant factors on the response (i.e., *Tw*, *Fw* and *Cs*). If still there is an insignificant factor on the response in the second analyze, we omit that (those) factor(s) and re-analyze the results.

We apply the same procedure on each response. According to the initial DOE analysis, only the *Po* factor is statistically insignificant for all the responses except the P_7. So, we apply second analysis for all the performance measures except the P_7. It should be noted that P_3, and P_4 are the transformed (inverse square root) responses. Therefore, we also apply the second analysis on the transformed performance measures of P_3 and P_4.

We summarize the ANOVA results based on the response types in the following section, in Table 5.

ANOVA Interpretations

Table 5. Factor effects for each response.

Effects	P_1	P_2	1/*sq.* (P_3)	1/*sq.* (P_4)	P_5	P_6	1/*sq.* (P_7)	P_8
Four-way								
*Tw*Fw*Po*Cs*	I	I	I	I	I	I	I	I
Three-way								
*Tw*Fw*Po*	I	I	I	I	I	I	I	I
*Tw*Fw*Cs*	I	I	I	I	I	I	I	I
*Fw*Po*Cs*	I	I	I	I	I	I	I	I
*Tw*Po*Cs*	I	I	I	I	I	I	I	I
Two-way								
*Tw*Fw*	I	I	I	I	I	I	I	I
*Tw*Po*	I	I	I	I	I	I	I	I
*Tw*Cs*	I	I	I	I	I	I	I	S
*Fw*Po*	I	I	I	I	I	I	I	I
*Fw*Cs*	I	I	I	I	I	S	I	S
*Po*Cs*	I	I	I	I	I	I	I	I
Main								
Tw	S	S	S	S	S	S	S	S
Fw	S	S	S	S	S	S	S	S
Po	I	I	I	I	I	I	S	I
Cs	S	S	S	S	S	S	S	S

Table 5 illustrates the significant and insignificant factor effects on each response obtained by ANOVA. In Table 5, "I" denotes the "insignificant" and "S" denotes the "significant". According to the ANOVA results, there are only the main significant effects of factors on response, P_1. The main effect of a factor is the average change in the output due to the factor shifting from its low level to high level, while holding all other factors constant. For instance, the most significant factors that affect P_1 in order are, the *Fw*, *Cs* and *Tw* (see, the *F* values in Table 4). From Table 5, we understand that only *Tw*, *Fw* and *Cs* are significant on P_1, P_2, 1/*sqrt* (P_3), 1/*sqrt* (P_4) and P_5 and, there is no significant interaction effect of factors on these responses. On P_6, there is significant *Fw* and *Cs* two-way interaction effect. When two factors interact, the effect on the response variable of one explanatory variable depends on the specific value or level of the other explanatory variable. Because the lower order factor effects depend upon the presence of higher order factor effects and because there is significant two-way interaction effect of *Fw* and *Cs* on P_6, then there are also significant main effects of *Fw* and *Cs* on P_6. Besides, *Tw* is also significant on P_6. All factors have significant main effects on response 1/*sqrt.* (P_7). On P_8, two-way interaction effects of *Tw*Cs* and *Fw*Cs* are significant so, are main effects of *Tw*, *Cs* and *Fw*.

After determining the significant effects on each response, we develop regression functions of each response by considering those significant factors (inputs). The procedure is explained in the following section.

Regression Analysis

Because the system under study is quite complex, it makes it difficult for an experimenter to identify how input parameters affect an output in the system. Regression analysis enables us to understand and evaluate the performance of the system in terms of the input variables (i.e., *Tw*, *Fw*, P_O, *Cs*).

Regression analysis is a statistical tool for investigation of relationships between output and input variables. Usually, one seeks to ascertain the causal effect of one variable on another e.g., the effect of a price increase on demand, or the effect of changes in the money supply on the inflation rate, etc. To explore such issues, the investigator assembles data on the underlying variables of interest and employs regression to estimate the quantitative effect of the causal variables on the variable that they influence.

Because we have eight outputs (responses) from the system (see Table 5), we develop eight regression functions. In the regression functions, the input variables are the significant factor effects which are determined in the "Anova Interpretations" section. It should be noted that the regression functions for P_3, P_4 and P_7 are developed for their inverse square root transformations.

Regression Functions

In a regression function, the coefficient of determination - R^2- provides a measure of how well outputs are likely to be predicted by the regression model. The bigger the value, the better fit the model. However, only considering R^2 is not adequate to evaluate a regression function because the R^2 value always increases with the addition of a new input variable to the function, even if it is not significant. Therefore, usually adjusted R^2- R^2_{adj} – value is used for evaluating a regression function. If the R^2_{adj} value is significantly lower than R^2, it normally means that one or more explanatory variables are missing. So, for a good fit it is preferred for R^2_{adj} to be big and close enough to the R^2. We also check whether or not the regression model adequacy is met. The model adequacy is the same as in ANOVA. As a result the regression functions for P_1, P_2, 1/*sqrt* (P_3), 1/*sqrt* (P_4), P_5, P_6, 1/*sqrt* (P_7) and P_8 are obtained as in (1)-(8), respectively.

$P_1 = 3.13 + 0.0507\ Tw + 1.61\ Fw - 0.047\ Cs$ (1)

$R_1^2 = 94.3\%\ R_{1adj}^2 = 92.9\%$

$P_2 = -\ 1.25 + 0.101\ Tw + 3.60\ Fw + 0.0483\ Cs$ (2)

$R_2^2 = 95.9\%\ R_{2adj}^2 = 94.9\%$

$1/sqrt(P_3) = 0.574 - 0.00214\ Tw - 0.0749\ Fw - 0.00290\ Cs$ (3)

$R_3^2 = 94.7\%\ R_{3adj}^2 = 93.4\%$

$1/sqrt(P_4) = 1.52 - 0.00320\ Tw - 0.130\ Fw - 0.0139\ Cs$ (4)

$R_4^2 = 99\%\ R_{4adj}^2 = 98.8\%$

$P_5 = 32.7 + 0.225\ Tw + 8.75\ Fw + 0.323\ Cs$ (5)

$R_5^2 = 92.4\%\ R_{5adj}^2 = 90.5\%$

$P_6 = -\ 9.75 + 0.731\ Tw - 0.245\ Cs + 0.420\ Fw*Cs$ (6)

$R_6^2 = 98.7\%\ R_{6adj}^2 = 98.3\%$

$1/sqrt(P_7) = 0.570 - 0.00709\ Tw - 0.0985\ Fw + 0.00377\ Po - 0.00323\ Cs$ (7)

$R_7^2 = 83.5\%\ R_{7adj}^2 = 80.4\%$

$P_8 = 10.5 - 0.686\ Tw*Fw - 0.185\ Fw*Cs + 0.117\ Cs + 13.7\ Fw$ (8)

$R_8^2 = 92.3\%\ R_{8adj}^2 = 91.2\%$

Interpretations of the Results

All the functions in (1) - (8) have large enough R^2 and R_{adj}^2 values and all the regression assumptions are met so that we accept those functions as good fit. The positive or negative signs before the input variables show how those inputs affect the output. For example, in (1) while *Tw* and *Fw* have positive effects on the P_1, *Cs* has negative effect. Hence, increasing *Tw* and *Fw* increases P_1 and, increasing *Cs* decreases P_1. For P_2, this time *Tw*, *Fw* and *Cs* have positive effects, etc.

We develop the regression functions based on the original values of the input factors. So, to try different values the real values of the input variables can be replaced. It should be noted that the inputs factors can get the values only between their low and high levels. For instance, we can put the values for *Tw* between 12^0C - 16^0C, for *Fw* between 0.15 kg s^{-1} - 0.5 kg s^{-1}, etc. in the regression functions (see also Table 2). It should also be noted that the Eqs. (3), (4), and (7) give the inverse square root outputs of P_3, P_4 and P_7. Therefore, we need to calculate the original values of these responses. For example, for the values of $Tw = 15^0$C, $Fw = 0.4$kg s^{-1} and $Cs = 45$ Hz. by (3), P_3 is obtained as 6.873 kW.

Optimization of the functions

After developing the regression functions, we optimize the performance measures using these regression functions. Here, we would like to maximize the P_1, P_6 and P_8 and minimize the P_4 and P_7. We choose the performance measures that are to be optimized based on the most commonly used performance measures in comparison systems in the literature. We optimize the functions using the LINGO software. We also consider the constraints as the factors must be between at their low and high levels in LINGO. Some functions are not so complex so that we can also find out the optimum values easily by considering the positive and negative effect of the factors on the responses. For example, P_1 can be maximized by the large values of *Tw* and *Fw* and the small value of *Cs*. So, when $Tw = 16^0$C, $Fw = 0.5$kg s^{-1} and $Cs = 40$Hz., P_1 becomes maximum where its value is 2.866 at maximum. The LINGO codes of optimization of P_1 are given below as an example:

```
Max = 13.13 + 0.0507* Tw + 1.61* Fw – 0.047* Cs;

Tw<=16;
Tw>=12;
Fw<=0.5;
Fw>=0.15;
Cs<=50;
Cs>=40;
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The optimum values of all the performance measures and input variables (factors) obtained by LINGO are summarized in Table 6.

From Table 6, we understand that the optimum values of the performance measures are obtained at low or high (boundary) levels of the input variables. For example, P_4 is minimized at low levels of *Tw*, *Fw* and *Cs*. This means that decreasing water temperature, compressor speed and flow rate also decreases compressor power consumption. Evaporation temperature is maximized when water temperature and flow rate increase and compressor speed decreases. Superheating is minimized by the low levels of water temperature, flow rate and compressor speed, and high level of electronic expansion valve opening percentage. And, sub-cooling is maximized at low levels of water temperature and flow rate, and at high level of compressor speed.

Table 6. Optimum values of the performance measures and input variables.

Perf. measures	Optim. type	Optimum Values Output	*Tw* (^{0}C)	*Fw* (kg s^{-1})	*Po* (%)	*Cs* (Hz)
P_1	Maxim.	2.866	16	0.500	-	40
P_4	Minim.	1.218 kW	12	0.150	-	40
P_6	Maxim.	0.546 ^{0}C	16	0.500	-	40
P_7	Minim.	4.472 ^{0}C	12	0.150	35	40
P_8	Maxim.	15.782 ^{0}C	12	0.150	-	50

CONCLUSION

In this study, we analyze the performance of a chiller system by DOE and regression analysis. First, we define four factors that could affect the eight performance measures of the system. Second, we identify the statistically significant factors that affect those performance measures using ANOVA at 95% confidence level by MINITAB. Third, we ignore the insignificant factors and re-analyze the results. Fourth, we develop the regression function of each response by considering the significant factors as inputs. Last, we optimize the pre-defined performance measures by the LINGO software. The results show that the electronic expansion valve opening percentage is only significant on superheating. Compressor power consumption, superheating and sub-cooling are optimized by the low levels of water temperature and flow rate and, low, low and high value of compressor speed, respectively. Superheating is also optimized by the high level of electronic expansion valve opening percentage. Coefficient of performance and evaporation temperature are optimized by high levels of water temperature and flow rate and low level of compressor speed.

By obtaining the regression functions - Eqs. (1) – (8) - we achieve various advantages. First, we understand which inputs are significant on the particular performance measure as well as in which direction - positively or negatively- they affect that response. Second, we can obtain the values of the performance measures at any levels of the inputs when they are between their low and the high levels. Third, by defining the regression functions we could find out the optimum points of the factors that optimize the performance measures. Consequently, we come up with that the optimum points are obtained at the low or high levels of the factors for each response as shown in Table 6.

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