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Investigating Into the Optimum Performance and Reliability Assessment of a Vapor Compression Refrigeration System Using Statistical Approach

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***Abstract*:-Response Surface Method of Design of Experiments was done using design-expert® 10 software to establish the design matrix and to analyze the experimental data. The relationships between independent variables (inlet air temperature in condenser, the air mass flow in the condenser, inlet air temperature in evaporator and air mass flow in the evaporator) and the response (Coefficient Of Performance) were established. The central composite design (CCD) was selected for design and optimization of the process. The developed mathematical model was tested for adequacy using analysis of variance (ANOVA) and other adequacy measures. Analysis of variance revealed that these regressions are statistically significant and model fitted the experimental data well, with a coefficient of determination R^2 of 0.9133 and an Adj-R^2 of 0.8944 at a confidence level of 95% compounded with a very low standard deviation (0.075) and a high adequate precision(20.111). Based on response surface and desirability functions, the optimum conditions for the system were inlet air temperature in condenser 30^0C , the air mass flow in the condenser 30g/s , inlet air temperature in evaporator 22.5^0C and air mass flow in the evaporator 30g/s. The close relationship between the predicted COP values and the actual values further proves the worthiness of the empirical equation. It was observed that inlet air temperature in the evaporator had the highest influence on the COP. Through response surface diagrams, the interactive influence of the variables were also observed. The results of a confirmation experiment (Aveg COP =1.125) is found to be in good agreement with the value predicted by the model (COP =1.170)**

I. INTRODUCTION

Due to environmental and energy concerns, the refrigerator industry is facing the challenge of developing more efficient and environmental friendly refrigerators. New policies have taken effect which is facing the refrigerator industry to develop refrigerators that will reduce energy consumption in order to reduce energy bills and to reduce refrigerant emissions in order to reduce the global warming effects of the refrigerators.

In situations where appropriate characterization process and product is lacking , a considerable amount of assumptions and guesswork about which independent variable(control factor) have significant effect on the dependent variable (response) of interest will usually occur. Changing one independent variable and keeping the others constant is a frequently used practice, even when it is strongly discouraged .The one-independent variable at a time method offers advantages only in exceptional conditions[1] .However ,this approach suffers from a number of problems(that is, it is usually not possible to hold all other variables constant),there is no way to account for the effect of joint variation of independent variables ,such as interaction ,there is no way to account for experimental errors ,including measurement variation. So it is recommended to use an approach supported by statistical and mathematical techniques that has provided in a way that leaves no doubt evidence of its usefulness .The statistically design of experiment usually involves varying two or more variables simultaneously and obtaining multiple measurements under the same experimental conditions.

Design of Experiment and data analysis is an effective and commonly used approach in scientific investigations and technological applications in a wide variety of science fields, including in mechanical, chemical, and biotechnological engineering. Applications in product design and development comprise a Multidisciplinary design optimization approach for high , bike-frames[2], A statistical and experimental investigation on product design for Copolymer based multichannel polyester draw textured yarns . The main goal of this work is to reach to the scientific and optimal solution in a shortest time on value added product design in textile industry and enlighten to future developments with this approach via implementing Response Surface Methodology[3].

This work seek to investigate and the effects of various parameters to the improvement of the system efficiency in terms of the coefficient of performance (COP). Variables which affect the performance of the system.

These experiments were done with a statistical approach so as to improve repeatability and reliability of the results. More information on important parameters which influences COP and their interactive effects are shed in this study.

II. MATERIALS AND METHODS

2.1 Experimental System

The experimental system for this thesis is the Air conditioning and Refrigeration laboratory (TPS 3953) of Delta State Polytechnic Ogwashi-uku, Nigeria. The system is a multipurpose module with all features of a complete refrigeration system. It is designed with a hermetic type compressor of 0.17hp using R134a refrigerant. There are temperature sensors to measure the temperatures at various point on the system. Pressure gauge are provided for the suction and discharge pressures.

The TPS-3953 panel includes 2 evaporators in two separate cooling rooms. The two evaporators are operated in parallel mode of connection . In parallel connection V6 and V8 are open and V7 is closed. In this way the refrigerant goes in parallel to both evaporators. Each of the evaporators is controlled by its own TEV valve. The capillary mode is disabled in parallel connection. In parallel mode, each evaporator is controlled by its own thermostat. Each thermostat controls only the valve to the relevant evaporator and does not turns OFF the compressor. In this way, if one evaporator stops cooling, the other one continues. If the valves of both evaporators are closed, the suction pressure will go down and then the compressor stops working. Each evaporator is not depending on the other evaporator. The compressor will stop working when both evaporators' valves are closed and the low pressure is below the SP-PD point.

The system is shown in figure 2.2.

(2.2) Test Facility

Figure 2.1: Test Rig of the Refrigeration system (TPS 3953)

(2.3) Design Of Experiment Using RSM

Response Surface method is an empirical optimization technique for evaluating the relationship between experimental outputs (or responses) and factors

Response surface method was applied to study the effects of inlet air temperature in condenser (*Tcond*), the air mass flow in the condenser ($\dot{m}cond$), inlet air temperature in evaporator (*Tevap*) and air mass flow in the evaporator ($\dot{m}evap$) on the dependent variable (Coefficient of Performance). The experiments were established based on a face-centered central composite design. This experimental design consists of Four (4) factors ,three (3) level full factorial design (3^4 = 81 experiments), using the run size economy it is not economical to use a 3^4 design with 81 runs except the experiment is not costly . Defining a 3^{4-1} experiment, it employs a one- third fraction of the 3^4 design. This is denoted as a 3^{4-1}. Also in this experimental design, three coded levels for each variable were selected: -1, 0 and +1 corresponded to the low level, mid-level and high level of each independent variable, respectively. The independent variables and representative coded and un-coded levels are given in Table 2.1

Table2.1 The Independent Variables and representative coded and uncoded Values

Independent Variables	Units	Coded Values		
		-1	0	1
Tcond	^{0}C	25	30	35
Tevap	^{0}C	10	17	24
m. cond	g/s	10	20	30
m. evap	g/s	10	20	30

(2.3) Development of Generalized Mathematical and Statistical Model for the (Problem Formulation)

The field of Response Surface Methodology includes empirical statistical modeling to develop an appropriate approximation relationship between the response y and the independent variables

$\xi 1, \xi 2, . . . \xi k$

In general the relationship is

$$y=f(\xi 1,\xi 2,.\xi k)+\mathcal{E} \quad (1)$$

Where the form of the true response function f is unknown and Ɛ is a term that represents other sources of variability not accounted for in f . Ɛ is a statistical error, Then,

$$E(Y)= \eta =E[f(\xi 1, \xi 2 . . . \xi k)] + E(\mathcal{E}) = f(\xi 1, \xi 2, . . . \xi k) \quad (2)$$

The variables $\xi 1, \xi 2, \ldots \ldots \xi k$ in equation (2) are called natural variables . In much RSM work it is convenient to transform the natural variables to coded variables, x_1, x_2, x_k . in terms of the coded variables, the response function (in equation 2 will be written as)

$$\eta = f\ (x_1, x_2, .x_k) \qquad (3)$$

Case of two independent variables , the first – order model in terms of the coded variable is

$$\eta = \beta 0 + \beta 1x1 + \beta 2x2 \qquad (4)$$

$$\eta = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 \qquad (5)$$

This is the first –order model with interaction . Adding the interaction term introduces curvature into the response function . For the case of two variables, the second – order model is

$$\eta = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 \qquad (6)$$

This model is useful as an approximation to the true response surface in a relatively small region

In general, the second-order model is

$$Y = f(x) = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \sum_{j=i+1}^{k} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 \qquad (7)$$

where Y is the predicted response (Coefficient Of Performance) used as a dependent variable; k the number of independent variables (factors), xi (i = 1, 2) the input predictors or controlling variables (factors); β0 the constant coefficient, and βi, βij and βii the coefficients of linear, interaction and quadratic term, respectively. The general motivation for a polynomial approximation for the true response function f is based on the Taylor series expansion. The following second order polynomial was used to fit the experimental data to have

y = b0 + b1x1+b2x2 + b3x3 + b4x4 + b5x12+b6x22 + b7x32+b8x42+b9x1x2+b10x1x3+b11x1x4+b12x2x3+b13x2x4+b14x3x4 (8)

The coefficient parameters were estimated using a multiple linear regression analysis employing the software Design-Expert (version 10). Design-Expert was also used to find the 3-D surface and 2-D contour plots of the response models.

III. RESULTS AND DISCUSSION

(3.1) Model Accuracy Checking

Here the accuracy of the model is analyzed. It is important to examine the fitted model if the model provides an adequate approximation of the true response surface. The model is checked by using Regression analysis , Analysis of variance and Normality.

Design Expert version (10) is used to conduct the regression analysis and variance of analysis of the coefficient of performance.

Table 3.2 shows the experimental design matrix and response of the experiments .The results were reliably consistent. The COP ranged from 0.4619 to 1.3412.

It is believed that even better COPs could be achieved when variable values are beyond the limits of this study. Still, the average COP value was 0.87 which means that at all conditions, the system will be working better than when conventional methods (e.g single evaporators) are applied.

(3.2) Model Determination

Table3.3 shows the statistical summary for each model that was output by Design Expert V 10. A quadratic model was suggested, even though it has lower R2 (0.9364) and adjusted-R2 (Adj-R2) (0.8727) values than a cubic model. This is due to the fact that the cubic model is aliased, which means that the effects of each variable that cause different signals become indistinguishable. For a linear relationship, the R2 and Adj-R2 values are 0.8301 and 0.8017, respectively. It is clear that the linear relationship is not adequate for the experimental data. The quadratic model was therefore selected to fit the experimental data.

Table 3.2 Experimental data obtained for the response variable

RUN	Factor1 A:Tcond ^{0}C	Factor 2 B:Tevap ^{0}C	Factor 3 C:$\dot{m}_{cond}$ g/s	Factor 4 D: $\dot{m}_{evap}$ g/s	Response COP
1	30	17	20	20	0.9731
2	35	10	10	10	0.7184
3	35	10	10	10	0.5471
4	25	25	30	30	1.2135
5	35	25	30	30	1.1053
6	25	10	30	30	0.6162
7	25	25	10	10	1.3412
8	35	25	30	30	1.2135
9	30	17	20	20	0.9312
10	35	10	30	30	0.4815
11	25	10	30	30	0.5618
12	25	10	10	10	0.6778
13	25	10	10	10	0.5482
14	30	17	20	20	0.9187
15	35	25	10	10	1.127
16	25	25	10	10	0.9038
17	35	10	30	30	0.6464
18	25	25	30	10	0.9541
19	30	17	20	20	0.9137

20	35	25	10	30	1.1082
21	30	17	10	20	0.8633
22	30	25	20	20	0.8894
23	30	10	20	20	0.4619
24	30	17	20	20	0.9003
25	30	17	20	10	0.8663
26	30	17	20	20	0.9192
27	30	17	20	30	0.9003
28	35	17	20	20	0.9289
29	30	17	30	20	1.0105
30	25	17	20	20	0.9388

Table 3.3: Model Summary Statistics

Source	**Std. Dev**	**R^2**	**Adjusted R^2**	**Predicted R^2**	**PRESS**	Characteristic
Linear	0.10	0.8301	0.8017	0.7335	0.40	
2FI	0.11	0.8462	0.7608	0.4495	0.82	
Quadratic	0.082	0.9364	0.8727	0.5252	0.71	Suggested
Cubic	0.029	0.9966	0.9841	0.4452	0.83	Aliased

(3.3) Mathematical Model Development and Analysis of Variance (ANOVA)

(3.3.1) Mathematical Model Development

Experiments were performed using the Central composite experimental design. The experimental coefficient of Performance is shown along with the experimental conditions in Table 3.2.

Based on the model analysis in the first part, a quadratic model was chosen to fit the data. The relationship between the Coefficient of performance and the four chosen control factors is shown in Equation(9):

$$COP = + 0.92 + 0.26B - 1.78E\text{-}003C + 0.068D - 0.17B^2 + 0.083C^2 \quad (9)$$

The coefficient of determination (R^2) is defined as the ratio of the explained variation to the total variation, and is a measure of the degree of fit **[5].** R^2 value is very high for the model , therefore the variability of the response could accurately be explained by the mathematical model of equation 9. On the other hand, the value of R^2 for the model is 0.9133 which implies that 91.33% of the total variation in the COP responses is attributed to the experimental variables studied as stipulated by the model. This is further stressed by the low value of the standard deviation (0.075), the high value of Adequate Precision (20.111) –"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 20.111 indicates an adequate signal. This model can be used to navigate the design space. **[4]** suggested that a good model fit should yield an R^2 of at least 0.8. This means that the response model evaluated in this study can explain the process very well, with an R^2 of 0.9133 and an Adj-R^2 of 0.8944 at a confidence level of 95%, with the closeness between the Adjusted R-squared (0.8944) and the Predicted R-squared (0.8392) which are in reasonable agreement i.e. the difference is less than 0.2. In addition, the model is very significant, as is evident from its F-value (F model = 48.43) and very low probability value ($p< 0.0001$)-value lower than 0.05 indicates that the model is statistically significant, whereas a value higher than 0.1000 indicates that the model is not significant **[6]** .

In this work, a generalized mathematical model was developed to estimate the COP of the system for optimization purpose. According to the obtained results the developed models are statistically accurate and can be used for further analysis. The final models in terms of coded and actual factors are shown below Equations.(10) and (11).

Final Equation in Terms of Coded Factors

$$COP = 0.92 + 0.26B - 1.78E\text{-}003C + 0.068D - 0.17B^2 + 0.083C^2 \quad (10)$$

Final Equation in Terms of Actual Factors:

$$COP = -0.52565 + 0.15592Tevap - 0.033493m.cond + 6.84222E\text{-}003m.evap - 3.48198E\text{-}003Tevap^2 + 8.32842E\text{-}004m.cond^2 \quad (11)$$

(3.3.2) Analysis of Variance (ANOVA)

Table 3.4 shows the ANOVA results for the acquired model.

Based on the ANOVA table, there are three tests required to evaluate the model, these are, significance of factor test, R-squared test and lack of fit test. The significance test was indicated by the Fisher variance ratio (the F-test value) and its associated probability (Prob>F). The model equation was evaluated by F-test ANOVA which revealed that these regressions are statistically significant at 95% confidence level (table 3.4). As a general rule, the greater the F-value is from unity, the more certain it is that the empirical model describes the variation in the data about its mean and the estimated significant terms of the variables are real. The values of prob>F which are 0.05 or less indicate significance. Quadratic model was suggested to be the best because its prob>F is less than 0.05 (<0.0001).

By using multiple regression analysis, the response (COP) obtained in table 3.2 was correlated with the four variables studied using the polynomial equation (10) after excluding the insignificant terms identified.

The coefficients of the variables in equation (11) represent the magnitude of the effect the variable has on COP which is dictated by its F value and prob > F. The effect of the variable on COP becomes high if its coefficient is high. The opposite happens if the coefficient is low. In this study, statistically significant linear , quadratic terms and interaction term, and one can see that *B* (*Tevap*) is the most important one to maximize COP, and has the highest coefficient (0.26). In practice, the greater the inlet air temperature in evaporator *Tevap* value is, the higher cycle efficiency (COP value) will be, though the quadratic effect of *Tevap* (-0.17) has a negative influence on COP value since its coefficient is lower than zero. However, their interactive effects are still highly significant and important.

These experimental results are in accordance with the theoretical knowledge, since it is known that evaporator temperature has significant impact on COP [7]. On the other hand, air flow rates effect is very small both linearly and in quadratic form, thus it is not a parameter of much concern.

The Model F-value of 48.43 in table 3.4 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case B, D, B^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve model.

Table 3.4: The Second-Order Model for the COP (Sequential Model Sum of Squares)

Source	Sum of Squares	Df	Mean Square	F Value	P value Prob F>	Characteristics
Model	1.36	5	0.27	48.43	< 0.0001	significant
B-Tevap	*1.27*	*1*	*1.27*	*226.66*	*< 0.0001*	
C-m. cond	*5.760E-005*	*1*	*5.760E-005*	*0.010*	*0.9202*	
D-m. evap	*0.084*	*1*	*0.084*	*15.00*	*0.0008*	
B^2	*0.12*	*1*	*0.12*	*21.41*	*0.0001*	
C^2	*0.022*	*1*	*0.022*	*3.91*	*0.0601*	
Residual	0.13	23	5.619E-003			
Lack of Fit	*0.13*	*19*	*6.677E-003*	*11.31*	*0.0150*	*significant*
Pure Error	*2.361E-003*	*4*	*5.903E-004*			
Cor Total	1.49	28				

Table 3.5: Post-ANOVA (ANOVA for Response Surface Reduced Quadratic Model)

Std. Dev.	0.075	R^2	0.9133
Mean	0.87	Adj R^2	0.8944
C.V. %	8.59	Pred R^2	0.8392
PRESS	0.24	Adeq Precision	20.111

(3.4) Diagnostics Model Accuracy

Before accepting any model, the satisfactoriness of the adopted model must be checked by an appropriate statistical analysis. In other words , to obtain an adequate model, an accuracy check is necessary. The model accuracy was checked by comparing the predicted and experimental Coefficient Of Performance.

Fig 3.1 shows the linear relationship between the predicted and experimental COP. In addition, a normal plot of residuals between the normal probability (%) and the residuals was also obtained. In this way, the residuals can be checked to determine how well the model satisfies the assumptions of ANOVA, and the internally studentized residuals can be used to measure the standard deviations separating the experimental and predicted values **[8].** Fig. 13 shows the relationship between the normal probability (%) and the internally studentized residuals. The straight line means that no response transformation was required and that there was no apparent problem with normality. The only sign of any problems in this data may be the point at the far right.

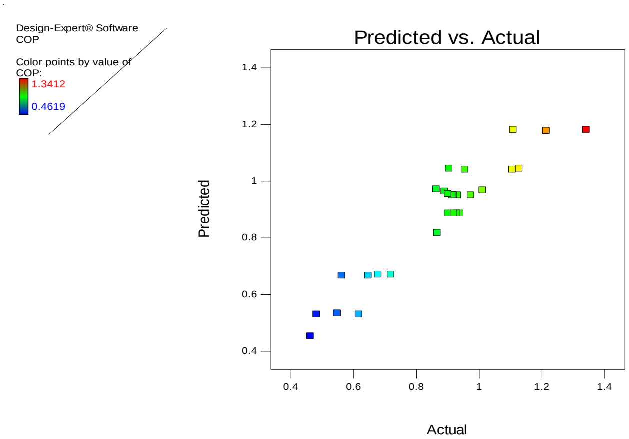


Fig 3.1: Comparison of Predicted And Experimental COP

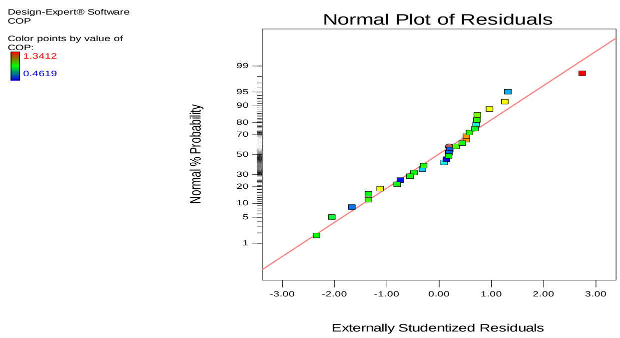


Fig 3.2: Relationship between normal probability (%) and externally studentized residual

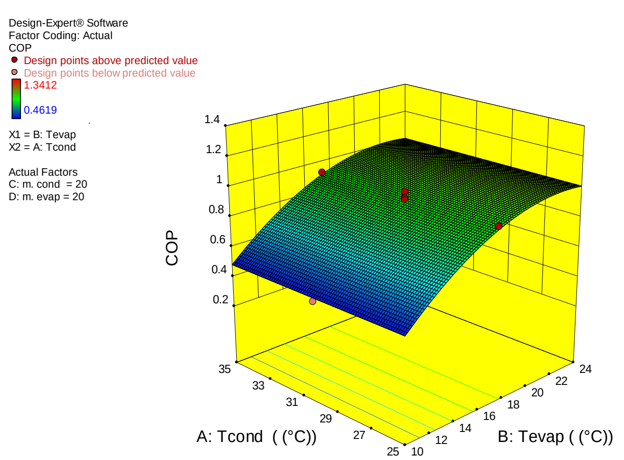
(3.5) Response Analysis

The relationships between the COP and the four factors are shown in 3-D response graph. Each plot shows the effects of two variables within their studied ranges, with the other variable fixed to the zero level . The response surface better visualizes the tendency of each factor to influence the COP.

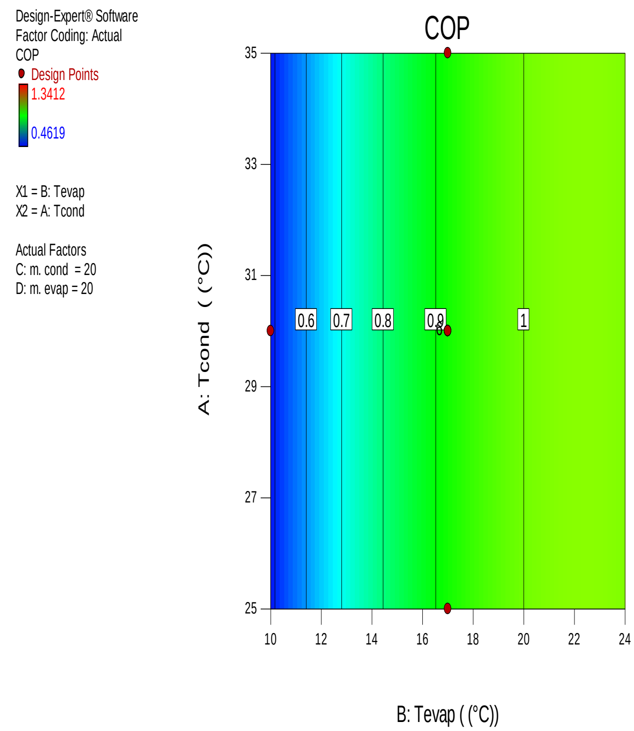
Figures 3.3 ,3.4 are (a) 3D plots of the interaction between the variables and their effect to COP and (b) contour plots of the predicted COP . These response surfaces facilitate a straight-forward examination of the effects the variables exert on the COP of the system.

Figure 3.3 (a) shows the response graph for two varying parameters inlet air temperature of condenser and inlet air temperature of evaporator by keeping the two other parameters at constant middle level which indicates that the increase of inlet air temperature of the evaporator increases the COP.

Figure 3.4 (a) shows the surface plot for two varying parameters inlet air temperature of condenser and mass flow of evaporator . The results show that the increases of the inlet air temperature of the condenser reduces the COP.

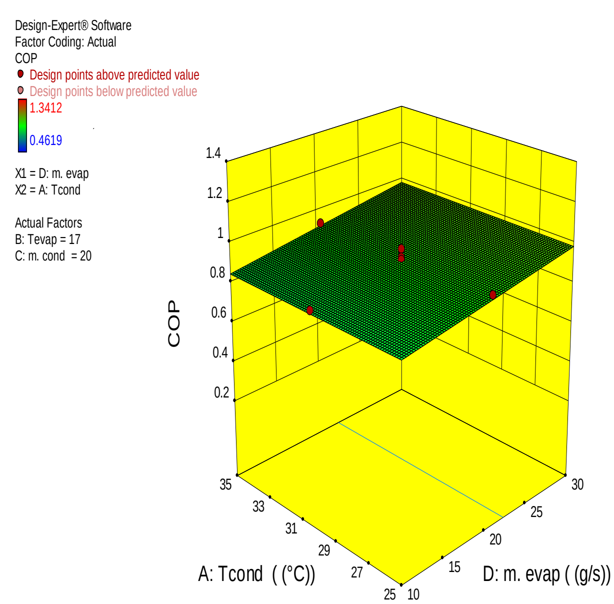


(a)

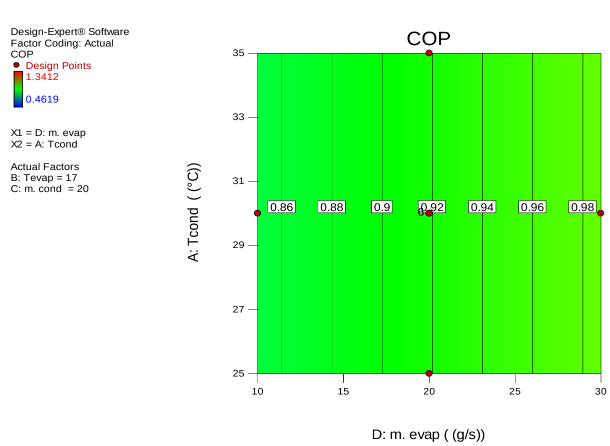


(b)

Fig 3.3: Interactive effect of inlet air temperature of condenser and inlet air temperature of evaporator on the COP



(a)



(b)

Fig 3.4: Interactive Effect Of Inlet Air Temperature Of Condenser and Mass Flow Of Evaporator On The COP

(3.6) Optimization Condition and Formulation

To achieve the highest COP value and respective optimal coded values, Design-Expert software's numerical optimization was used. The numerical optimization finds a point that maximizes the desirability function. Table 3.6 presents the specific optimum conditions for the define COP of the system. In fact this work goal is at optimum conditions to obtain maximum COP , The achieved COP value, slightly higher than 1 (COP = 1.170) is not surprising, taking into account the installation used here[9]. The performance of current refrigeration systems is, in fact, higher since they integrate components of higher quality (with better technical characteristics). The achieved COP value is low from a theoretical point of view. However, this does not mean that experimental methodology and study results are of no interest or unhelpful. One can't ignore that small instructional units are not designed or developed with efficiency purposes but rather for teaching and learning aid. They are a valuable teaching aid for students, for craft and technician training at Polytechnics and Universities, and are used to help them in visualizing and understanding the events within the various components.

The suitable optimum formulation (inlet air temperature in condenser 30^0C, the air mass flow in the condenser 30g/s, inlet air temperature in evaporator 22.5^0C and air mass flow in the evaporator 30g/s).

Table 3.6 : Optimization criteria used in this study

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Tcond	is equal to 30	25	30	1	1	3
B:Tevap	is target = 22.5	10	24	1	1	3
C:m. cond	maximize	10	30	1	1	3
D:m. evap	maximize	10	30	1	1	3
COP	maximize	0.4619	1.3412	1	1	3

Table 3.7: Confirmatory experiment at optimum condition

Tcond (°C)	*ṁcond* (g/s)	*Tevap* (°C)	*ṁevap* (g/s)	COP
30	30	22.5	30	1.11
30	30	22.5	30	1.14

(3.7) Optimized Condition Validation Of The Developed Model (Confirmatory Test)

To validate the COP value obtained from the optimization process (COP = 1.17), two confirmatory experiments with variable settings at optimal values were run. Experimental runs and results are displayed in Table 3.7, and one can see that COP values are in agreement with those achieved from the optimization of model fitted to COP, i.e the COP obtained from additional experiments are very close to those estimated using the model, implying that the RSM approach was appropriate and effective tool for optimizing individual factors in a new process. Thus, one can argue that experimental methodology illustrated here was helpful to better understand the influence of selected control factors on refrigeration cycle performance.

IV. CONCLUSION

In the present study, an attempt is made to investigate into the optimum performance and reliability assessment of a vapor compression refrigeration system. Statistically designed experiments are performed using design-expert® 10 software based on four factors, three levels and central composite face -centered design (CCFD) with full factorial and results are analyzed with the objective of maximizing the efficiency of a vapor compression refrigeration cycle using the installation and also analyzed according to the principle of Response Surface Methodology (RSM). Analysis of variance method is use to identify significant variables both linearly, in quadratic form and in interaction. A second-order model was fitted to Coefficient of Performance and considerable benefits result from it. In addition it expresses the functional relationship between design variables and the response, the model provides an estimate of the response at any point within the experimental region, which is useful for refrigeration cycle design and operation improvement purposes.

The model fitted the experimental data well, with a coefficient of determination R^2 of 0.9133 and an Adj-R^2 of 0.8944 at a confidence level of 95% which shows a very high correlation between the observed and predicted values. Furthermore, the *p*-value of this model was less than 0.0001, which indicates that the model is very significant.

All variables were significant but inlet air temperature in evaporator had the highest effect on COP. Evidently, results show that, with the exception of the inlet air temperature in condenser, which must be set at low level, the remaining variables must be set at high level or close of it to maximize the cycle performance. Confirmatory experiments corroborated these results.

The results of a confirmation experiment were found to be in good agreement with the values predicted by the model. This demonstrates that to obtain a maximum amount of information in a short period of time, with the least number of experiments, RSM and CCD can be successfully applied for modeling and optimizing the cycle process.

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