

Predictive Modeling for Parametric Analysis of an Air Conditioning System in a 400-seat Auditorium in Warri

Abstract- Considering the fact that Nigeria is located in sub-tropical region which is characterized by excessive high temperature and highly humid made it necessary to develop an air-conditioning system which can reduce the hot and ambient temperature within a confined space for human comfort. The research is basically a design of an air-conditioning system for comfort of occupants in a 400-Seater auditorium. The three independent variables considered for this design are the number of occupants, air exchange rate and the outdoor temperature. The auditorium was properly measured and the heat generated by the bulbs, appliances and occupants were adequately considered to get the total cooling load. The calculated cooling load was determined and a regression analysis was carried out to obtain a regression or predictive model which was used to determine the predicted cooling load. Optimization analysis was also done to determine the optimal condition for maximum cooling load. The plant capacity that will provide thermal comfort for the 400 occupants was calculated to be 25TR.

Keywords: *Air-conditioning system; parametric analysis; predictive model; optimization; temperature; heat.*

1.0 Introduction

Air conditioning can be explained as any process that alters the properties of air (primarily humidity and temperature) to favorable conditions, typically with the aim of distributing the conditioned air to a space that is occupied in order to improve comfort. Air conditioning is any type of technology used for cooling, cleaning, humidification, heating, ventilation, dehumidification or movement of air that modifies temperature of air (Marderos & Mohammad, 2011; Bansal et. al., 1996; Franck et. al., 2015).

In general, air conditioner is a device that lowers the air temperature. The cooling is mostly done using a simple refrigeration cycle, but sometimes the evaporation is used, commonly for the comfort of cooling in buildings and motor vehicles (Jadhav & Lele, 2015; Wufeng et. al., 2015; Pankaj et al, 2015). In its simplest form, a complete system of heating, ventilation /air conditioning is referred to as heating, ventilation and air conditioning (Shahi *et. al*, 2016; Onoroh et al, 2013; Duarte et al, 2017). Air conditioning can be provided also by the simple process called free cooling which uses pumps to circulate a coolant from a cold source, which in turn acts as a heat sink for the energy that is removed from the cooled space (Edward et. al, 2011; Diaz et al, 2020; Mohamed & Alnahhal, 2019).

Generally, air conditioner can be classified into window unit air-conditioners, central unit air-conditioner, and split unit air-conditioner (Yujin et al, 2017; Khurmi & Gupta, 2008; Prathibha et. al., 2017). The various components of a window unit air conditioner, e.g. condenser, expansion valve, compressor, evaporator and cooling coil are designed in single system unit. This type of air conditioning unit is usually placed on open wall whereby interior air is cool as fan blow it over the evaporator. On the outside of the air conditioning unit, the heat extracted from the inside is discharged to the outside environment as the second fan outside blows outdoor air over the air condition system condenser. For large buildings with several rooms, each room can be made to have a cooling unit allowing cooling of each room separately.

The central unit conditioner is for cooling big building houses, offices, entire hotels, cinema hall, and factory etc. The central unit air conditioner is made of huge compressor that has the

capacity to produce tons of air conditioning. Split unit air conditioning system comprises of two parts the outdoor unit and indoor unit. The outdoor unit fitted outside the room is housing components like the compressor, condenser, and the expansion valve. The indoor unit comprises the evaporator, and cooling fan. Considering that Nigeria is located in subtropical region characterized by excessive temperature and highly humid, it became necessary to design an air conditioning system which can help reduce the hot ambient temperature within a confined space for human comfort. In this research work, the parametric analysis of an air conditioning system for a 400 seat capacity auditorium in Warri was carried out.

2.0 Methodology

2.1 Problem Description/Assumptions

The air conditioned auditorium is to be maintained at comfort condition of 22 °C DBT and 65 – 55% R.H. The number of occupants and the ambient condition varies in the following order:

- Number of occupants; 0 – 400 persons
- Outdoor Temperature: (29 – 41 °C) DBT and (25 - 32°C) WBT
- Air exchange rate: 0.46 – 0.54 [ACH]

The ventilation requirement inside the auditorium is such that 55% of the return air is recirculated and mixed with 45% of the make-up air after the cooling coil. The condition of air leaving the cooling coil is to be maintained at 14 °C. Seating capacity of the auditorium is 400 persons.

Sensible heat given per person and the latent heat gain per person are assumed to be 320 kJ/hr and 100 kJ/hr respectively. The inside condition varies in accordance with the degree of activity of the occupants and intended use of the auditorium.

The following response functions can be considered: total cooling load (Watt); cooling coil capacity (TR); and amount of water removed by dehumidification (kg/s).

The system is represented in block diagram as Figure 1. The block diagram description of the problem is given in Figure 1(a) followed by an equivalent representation on the psychrometric chart in Figure 1(b).

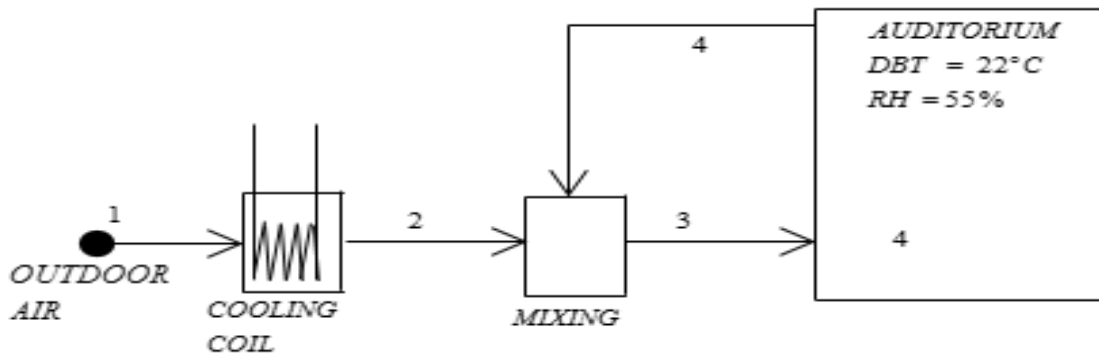


Figure 1(a): Block diagram representation of the auditorium air-conditioning problem.

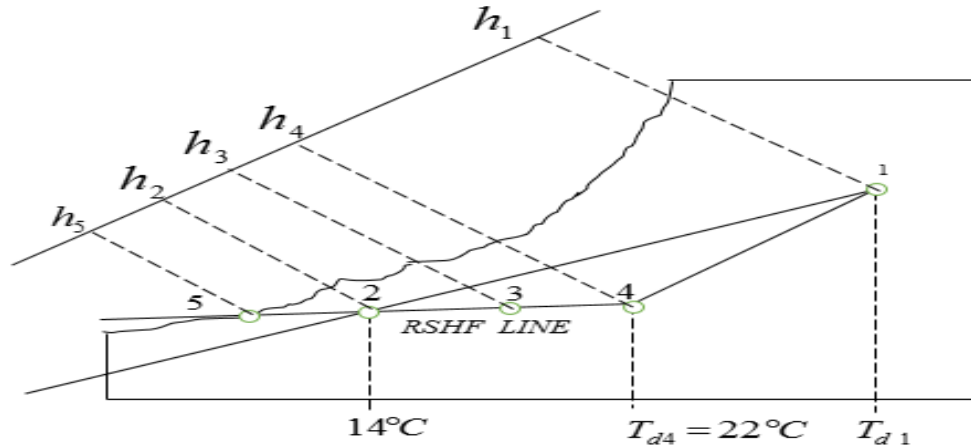


Figure 1(b): Representation of the auditorium air-conditioning problem on psychrometric chart

Given that 55% of air from the auditorium is recirculated and mixed with 45% of make-up air after the cooling coil, the mixing condition of air is shown by point 3 such that;

$$\frac{\text{Length } 2 - 3}{\text{Length } 2 - 4} = \frac{55}{100} = 0.55$$

$$\text{Therefore, Length } 2 - 3 = 0.55 \times (\text{Length } 2 - 4) \quad (1)$$

Point 3 equally describes the condition of air entering the auditorium.

From material and energy balance analysis the total cooling load is given by;

$$\text{Total cooling load} = \dot{m}_a (h_4 - h_3) \quad (2)$$

Where \dot{m}_a is mass flow rate of supply air.

Since make-up air is 45% of supply air, the mass flow rate of make-up air is given as; $0.45 \times \dot{m}_a$.

Outdoor design condition was considered as the observed range of outdoor dry bulb temperature in Petroleum Training Institute environment during 2020 summer season, given as 29 – 41 °C by the metrological report.

Infiltration into the auditorium is given as;

$$Q_s = 1.2Q\Delta T \quad (3)$$

Where Q is volumetric flow rate (m^3/s), Q_s is sensible heat (W), ΔT is the temperature difference between the outdoor and inside temperature ($T_o - T_i$)°C.

$$\text{Size of the auditorium} = (L \times B \times H) m^3 \quad (4)$$

2.2 Design of experiment and response prediction via polynomial response surface (PRS) method

The important system variables that affect the total cooling load of an air-condition system include; number/activities of the occupants (X_1), outdoor temperature (X_2) and air exchange rate (X_3). In a typical design it is necessary to optimize these variables to ensure that optimum plant capacity is achieved. This requires development of a suitable functional approximation model from which the overall behavior of the system could be studied. In this regard the polynomial response surface (PRS) method is proposed for statistical analysis of the system. The PRS is widely applied in reaction engineering, process design and general design situation to monitor quality of engineering products using mathematical principle. The PRS does not rely on high volume of data to yield accurate result. However, certain minimum number of data points is required. Thus, the implementation of PRS procedure utilized a design of experiment (DOE)

developed for a range of the input variables called the central composite design (CCD). The design optimization study is intended to reveal the optimal plant capacity required to achieve the desired comfort of the occupants of the auditorium. The three key input variables were considered at the levels described in Table 1. The CCD template is presented in Table 2. Both the experimental design and the statistical analysis were implemented on model-based calibration (MBC3.3) toolbox found in MATLAB (R2007b). The modeling utilized a quadratic model of the generalized form presented in equation 1.

$$f(X_j X_j) = \beta_0 + \sum_{j=1}^k \beta_j X_j + \sum_{j=1}^k \beta_{jj} X_j X_j + \sum_{i < j=2} \sum \beta_{ij} X_i X_j + \varepsilon \quad (5)$$

Where, $f(X_j X_j)$ is the objective function, β_0 is the model intercept, k is the number of design variables. X_j , $X_j X_j$ and $X_i X_j$ represent the first-order term(s), the second-order term(s), the interaction term(s) of the model, respectively. β_j , β_{jj} and β_{ij} are the respective coefficients of the model terms. ε is the random error of prediction.

Table 1: Design points indicating the levels at which the independent variables were observed

Design variables ($X_i, i = 1, 2, 3$)	Levels of independent variables				
	$-\alpha$	-1	0	1	α
Number of occupants, X_1	0	81	200	319	400
Outdoor temperature, X_2 ($^{\circ}\text{C}$)	29	31.4	35	38.6	41
Air exchange rate, X_3 (ACH)	0.46	0.48	0.5	0.52	0.54

Table 2: The CCD template in coded notation

S/N	X_1	X_2 $^{\circ}\text{C}$	X_3	$Y(W)$
1	0	0	0	Y_1
2	0	0	0	Y_2
3	0	0	0	Y_3
4	0	0	0	.
5	-1	-1	-1	.
6	1	-1	-1	.
7	-1	1	-1	.
8	1	1	-1	.
9	-1	-1	1	.
10	1	-1	1	.
11	-1	1	1	.
12	1	1	1	.
13	$-\alpha$	0	0	.
14	α	0	0	.
15	0	$-\alpha$	0	.
16	0	α	0	.
17	0	0	$-\alpha$.
18	0	0	α	Y_N

2.3 Design optimization via genetic algorithm

The genetic algorithm (GA) is an evolutionary method for solving both constrained and unconstrained optimization problems that is based on the principle of natural selection. The algorithm starts with an initial population representing nominal individual solution. The genetic algorithm repeatedly modifies the population. At each step, the GA selects individuals at random from the current population to be parents and uses them to produce offspring for the next generation following three major genetic operators including; Selection, Crossover and Mutation.

Selection rules select the individuals, called parents that contribute to the population at the next generation based on the resulting fitness value. Crossover rules combine two parents to form children for the next generation. Mutation rules apply random changes to individual parents to form children. Over successive generations, the population "evolves" toward an optimal solution. GA can be applied to solve a variety of optimization problems that are not well suited for standard optimization algorithms, including problems in which the objective function is discontinuous, non-differentiable, stochastic, or highly nonlinear. The implementation and result using the genetic algorithm will be presented and discussed in chapter four.

3.0 Results and Discussion

3.1 Experimental design and statistical modelling

The study basically involves calculation of the total cooling load (TCL) of the auditorium at operating condition as presented in Table 3. To this end, the contributions to the total sensible heat (TSH)/the total latent heat (TLH) resulting from human activities, the available facilities and infiltrations, calculated at various operating conditions prescribed by the experimental design were added up to obtain the calculated TCL, $Y(W)$.

The information obtained for the observed eighteen data points were clearly not sufficient to describe completely the behavior of the system, thus further statistical analysis via mathematical model was conducted. The quadratic model presented in equation 5 was fitted to the input – output data set. Following the least squares approximation method, the unknown constant and coefficient terms of the fitting function were determined to obtain the actual predictive model for the total cooling load presented as equation 6. The total cooling load was also evaluated via the predictive model at the DOE test conditions and the results (Predicted Y) were juxtaposed with the calculated TCL (Y) in Table 3.

$$Y(X_1^2, X_2^2, X_3^2) = 32485.2373 + 116.66X_1 - 22914.58X_3 + 1041.67X_2X_3 + 0.0000118X_1^2 \quad (6)$$

Table 3: Calculated and predicted cooling load at some selected design points using the CCD

S/N	X_1	$X_2 \text{ }^\circ\text{C}$	X_3	$Y(W)$	Predicted_Y(W)
1	200	35	0.5	62590	62590.21
2	200	35	0.5	62590	62590.21
3	200	35	0.5	62590	62590.21
4	200	35	0.5	62590	62590.21
5	81	31.4	0.48	46636	46636.03
6	319	31.4	0.48	74403	74402.97
7	81	38.6	0.48	50236	50236.03
8	319	38.6	0.48	78003	78002.97
9	81	31.4	0.52	47028	47027.78
10	319	31.4	0.52	74795	74794.72

11	81	38.6	0.52	50928	50927.78
12	319	38.6	0.52	78695	78694.72
13	0	35	0.5	39257	39257.11
14	400	35	0.5	85924	85924.25
15	200	29	0.5	59465	59465.21
16	200	41	0.5	65715	65715.21
17	200	35	0.46	62049	62048.46
18	200	35	0.54	63132	63131.96

Table 4: Model summary of statistics

Observations	18
Parameters	5
Box-Cox	1
RMSE	0.261
R^2	1
R^2 Adjusted	1
$PRESSR^2$	1

The performance of the resulting model was first evaluated using the resulting summary of statistics (SOS) for the model presented in Table 4. The SOS reflects high prediction accuracy of the model. The R^2 , the *adjusted* R^2 and the *PRESS* R^2 all stand at maximum value of 1. These are indications that 100% of the overall system behavior can be predicted via the predictive model within the range of input variables. The result of maximum R^2 value of 1 is valid in this case since the original response data were obtained by calculation using existing theoretical relationships and not from experimentation. Thus, random error usually associated with experimental irregularities was totally avoided. The RMSE value is sufficiently close to zero. This also suggests that the prediction error was adequately minimized. Moreover, there is no indication of over-fitting of the model. The high prediction accuracy of the quadratic model is further illustrated by the agreement witnessed between the predicted response and the calculated response over the entire design space as recorded in both Table 3 and Figure 2.

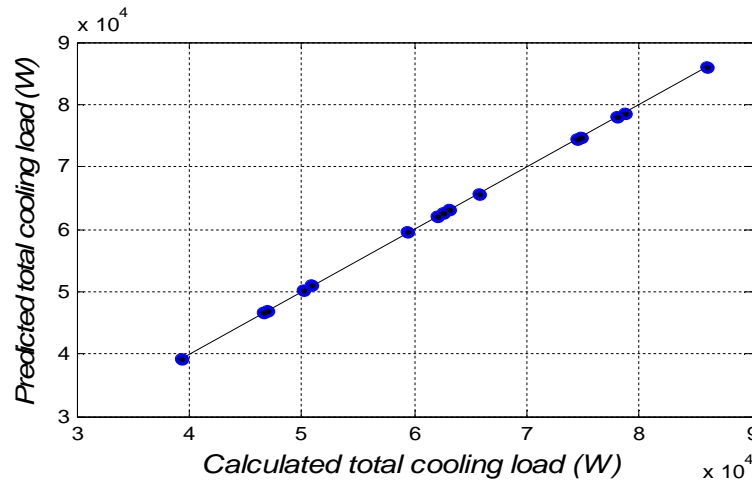


Figure 2: Comparison of the calculated and predicted response

3.2 Interaction effects of the design variables

Looking at the results holistically an overall linear interaction were observed. For various significant interactions presented, two factors were varied simultaneously while the third factor is kept at its mean value. The combined effects of the number of occupants and outdoor temperature on the predicted total cooling load are presented in Figure 3. From the results, the number of occupants appears to be the most influential factor for the studied range of parameters. The TCL was found to increase progressively along a straight line while both the number of occupants and the outdoor temperature were increased at mean air exchange rate. This observation agrees with the intuition that higher cooling efforts (or greater plant capacity) will be required to maintain cooling comfort for increased number of occupants or increased outdoor temperature.

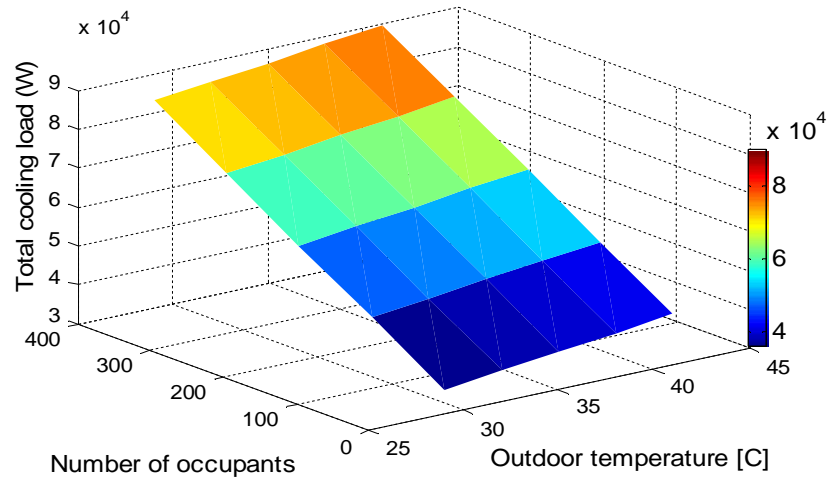


Figure 3: Combined effects of the number of occupants and the outdoor temperature on the predicted total cooling load

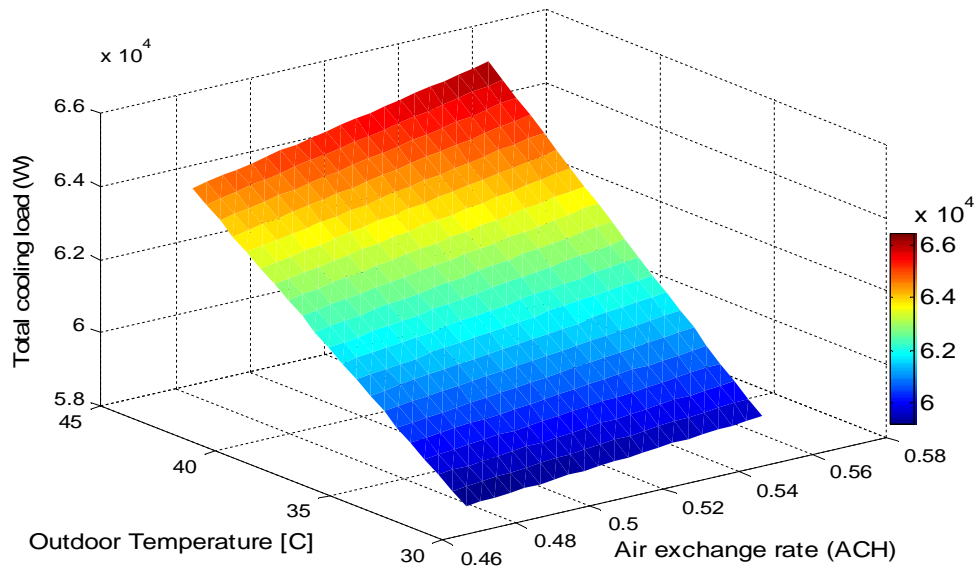


Figure 4: Combined effect of the outdoor temperature and the air exchange rate on the predicted total cooling load

Similar results were recorded with respect to the interactive effects of the outdoor temperature and the natural air exchange rate as shown in figure 4. However, the outdoor temperature condition show relatively greater effect on TCL compared to air exchange rate. The overall result suggests that maximum TCL could be obtained towards the positive axial points of the three design variables.

3.3 Prediction of optimal cooling load via Genetic Algorithm (GA)

In order to specify the appropriate plant capacity that would guarantee occupants' comfort in the auditorium over a wide range of ambient condition and human activities, the optimal cooling load must be evaluated. Thus, maximization of the total cooling load, Y was considered a major design objective. The response Y was identified as a function of three independent variables including; the number of occupants X_1 , the outdoor temperature X_2 and the air exchange rate X_3 which are considered the design variables. The optimization study was implemented in global optimization toolbox found in MATLAB. The steps involved include; selection of optimization algorithm, calling of the fitting function via the function handle, setting of the number of variables, specification of the boundary points and the algorithm specific parameters.

The *GA specific optimal parameters* utilized in the study are: crossover fraction '0.9'; crossover function scattered; mutation function 'adaptive'; population size '100'; engeneration '100'.

The predicted optimal solution is presented in Table 5.

Table 5: Predicted optimum condition for maximum cooling load

X_1	X_2 °C	X_3 (ACH)	Y (W)
390	38.2	0.52	86851.5

From the predicted optimal cooling load, $Y_{optimal}$, the optimal plant capacity in tons of refrigeration is given by;

$$\frac{Y_{optimal}}{3500} = \frac{86851.5}{3500} = 24.81TR \quad (7)$$

Considering reasonable design tolerance, the installed capacity of the air conditioning plant should be 25TR.

4.0 Conclusion

The design of an air-conditioning unit for a 400 seat capacity auditorium was successfully carried out. A plant of 25TR capacity was recommended for the auditorium to guarantee occupants comfort over a wide range of operating conditions. Although the number of occupants appears to be the most important variable, the two other identified system variables including; outdoor temperature and natural air exchange rate equally have considerable effects on the total cooling load of the auditorium. A mathematical model for predicting the total cooling load for the proposed auditorium air conditioning project at typical design condition was developed and the optimal plant capacity for the proposed auditorium air conditioning project was determined.

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