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SOME INVESTIGATIONS TO EVALUATE OPTIMUM VENTILATION STRATEGY FOR UFAD VENTILATED ROOM

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ABSTRACT

Major objective of any room ventilation system is to provide fresh, clean and contaminant-free air to occupants. Out of various contaminants present indoors, particle contaminants have more impact on human health in terms of different respiratory diseases. Also, because of the concerns about impact of Indoor Air Quality (IAQ) impact on occupants' health and productivity, newer ventilation strategies are emerging for indoor spaces. In this paper, it is attempted to develop an appropriate/optimum ventilation strategy, from contaminant particle removal from the breathing zone point of view. This will help the HVAC designers and operators to improve the Indoor Air Quality(IAQ) by reducing the contaminant particle concentrations in various zones of a room. Taguchi's method based on Design of Experiments(DOE) is used along-with actual experimentation in a UFAD ventilated "Experimental Test Room"(ETR). Number of experiments conducted is based on Taguchi method using L9 Orthogonal Array with three level and three factors. The main effect plots for the means, for the Contaminant Particle Removal Effectiveness, were obtained using Minitab 14 Software. For this study, to evaluate the significance of the parameters in effecting the desired quality characteristic of our interest (i.e. Contaminant Particle Removal Effectiveness), Analysis of variance (ANOVA) was performed keeping the objective "larger is better". The input parameters considered are Air Changes per Hour, Particle source location and Particle size. The results will help in deciding the most influential parameter for highest Contaminant Particle Removal Effectiveness in breathing zone which, in turn, will help the HVAC system designers and operators in maintaining these parameters and providing clean and healthy indoor air for the occupants.

KEYWORDS: Indoor environment, UFAD. Ventilation System, Taguchi method, Contaminant particles, Contaminant Removal Effectiveness.

INTRODUCTION

Ventilation is most important for maintaining acceptable indoor environment in buildings and human occupied places. Ventilation could control the air velocity, air temperature, relative humidity, and species concentrations in the air of the enclosed spaces. There are many standards to formulate the requirements of indoor environment, and ventilation design should be optimal for creating and maintaining an environment to satisfy the requirements. Traditionally, researchers and engineers applied a method of trials and errors in designing ventilation system, which means predicting and evaluating the ventilation performance with different design variables to find a scenario that has the best agreement with the design objective. Researchers and engineers normally predicted or evaluated the ventilation performance typically by empirical models, experimental measurements, and CFD simulations.

With the development of advanced computers, the Computational Fluid Dynamics (CFD) simulations have become most popular for predicting ventilation performance. The CFD simulation could provide the field distributions of air velocity, air temperature, species, etc. With a validated turbulence model and associated mixture models for contaminant particle phases, the CFD simulations have become more informative than the analytical and empirical models and much faster than the experimental measurements.

However, since this method of trials requires experimentations and CFD simulations for many scenarios, it would need longer times to obtain an optimal design for a ventilated space. Most importantly, because of the complexity of fluid flow, it is less probable that the repeated trials in an interactive analysis and design procedure can lead to a truly optimal design. The optimization approach, on the other hand, provides scope of using some statistical tools to decide the influential parameters related to system design and help in reducing number of experiments required to arrive at the most feasible solution. Thus, in the present study Taguchi's DOE approach is used for finding out appropriate ventilation strategy in a UFAD ventilated room environment.

LITERATURE REVIEW

L. Lu et al (1) conducted elaborate studies concerning optimization of HVAC Systems in built environment They tried various ventilation configurations using CFD based simulation approach and concluded that ventilation parameters can be optimized, to some extent, by using optimization methods.

S.W. Wang and X.Q. Jin (2) focused on operational aspects of HVAC systems and developed a model based optimal control system using genetic algorithm. Their studies suggest that by using appropriate control strategies related to air flow rate, temperature and humidity control it is possible to increase ventilation efficiency in room environment.

J.A. Wright et al (3) used multi-criterion genetic algorithm for optimization of building thermal design. They considered energy costs, operational costs, thermal comfort and ventilation efficiency in their optimization studies.

M. Wetter and J. Wright (4) evaluated the feasibility of application of genetic algorithm optimization methods for issues related to indoor ventilation studies. They concluded that these methods provide useful insights into air flow distribution and contaminant transport.

P. Wargocki et al (5) carried out studies on the effects of outdoor air supply rate in an office on Perceived Air Quality, Sick Building Syndrome (SBS) Symptoms and Productivity. As per this study, the indoor air quality and productivity are affected by changes in supply air flow rate.

H. Brohus et al (6) studied the effect of renovating an office building on occupants' Comfort and Health. They conducted research using CFD modeling approach where model room was modified considering various room layouts and furniture's. Their simulation based findings suggest that the thermal comfort and contaminant dispersions are affected because of these obstacles.

From the reviewed literature, it is observed that the research on evaluation of contaminant removal effectiveness in breathing zone in a UFAD ventilation system, by using Taguchi method, is not yet fully explored. Even-though there are efforts taken by researchers for determining optimal ventilation strategy using other optimization methods, there is ample scope for carrying out research on determination of appropriate ventilation strategy using Taguchi method.

There are number of parameters governing the indoor air quality. It is important to find out the influential parameters from the view-point of contaminant particle removal effectiveness. Different ventilation methods have variable impacts on indoor air quality. Further, air changes per hour, particle source locations and particle sizes also have influence on quality of indoor air.

It is important to evaluate most influential parameter with the objective of improving contaminant particle removal effectiveness through combination of statistical methods and experimental methods.

The major objective of this research is to study the effects of various input parameters i.e., ACH, Particle source location and Particle size on the Contaminant Particle Removal Effectiveness in a UFAD ventilated room.

METHODOLOGY

In the present study experiments were carried out in an "Experimental Test Room" which was well-equipped with appropriate instruments. Air velocity and temperatures were measured by using pre-calibrated hot wire anemometer and particle concentrations were measured by using pre-calibrated Particle counter. The contaminant particle removal effectiveness in breathing zone was computed from the measured data at various measurement points. Taguchi's approach was used to decide number of experiments, problem formulation, identification of performance characteristics, control factors, selection of factors and levels, selection of Orthogonal Array, preparation and conduct of experiments, collection of data, statistical analysis of data, interpretation of experimental results and finally arriving at influential parameters and optimal solution. The details of present studies related to room ventilation studies are summarized below.

Input Parameters and their Levels for the study of various types of ventilation are shown below in Table 1. The Orthogonal Array details are given in Table 2.

Table 1 Ventilation Input parameters

Input Parameter	Symbol	Unit	Levels		
			Level 1	Level 2	Level 3
ACH	ACH	$^{-1}$hr	3.6	6.0	8.4
Particle size	PS	µm	0.5	2.5	10
Particle source location	SL	m	0.5	2.4	3.5

Table 2 Taguchi Orthogonal Array Design for ventilation study.

Experiment	ACH	Particle size	Particle source location
1	3.6	0.5	0.5
2	3.6	2.5	2.4
3	3.6	10.0	3.5
4	6.0	0.5	2.4
5	6.0	2.5	3.5
6	6.0	10.0	0.5
7	8.4	0.5	3.5
8	8.4	2.5	0.5
9	8.4	10.0	2.4

The schematic diagram of experimental set-up is as shown in figure 1.

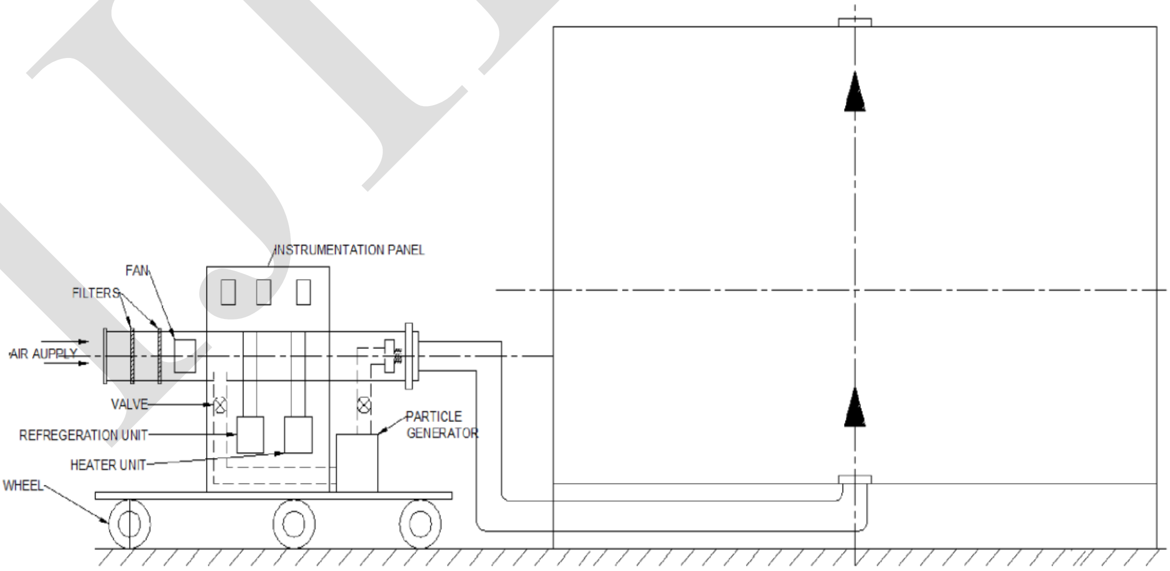

Figure 1: Experimental set-up for UFAD Ventilation Studies

Air is supplied to the Ventilation Test Room through appropriate ducting. In the present case Under-Floor Air Distribution (UFAD) ventilation strategy is adopted. The measured contaminant particles are supplied in the test room through particle generator. By using a traversing unit particle concentrations at various locations in the room are carried out.

Three different supply air velocities, particle source locations and particle sizes are used. Nine test runs are carried out. Particle Removal Efficiency is computed for each test run.The results of these trials are tabulated in Table 3.

Table 3 Details of test runs

Test Runs	Parameters			
	ACH	Particle size	Particle source location	Contaminant Removal Effectiveness (ε_{BZ})
1	3.6	0.5	0.5	1.118
2	3.6	2.5	2.4	1.154
3	3.6	10.0	3.5	1.168
4	6.0	0.5	2.4	1.138
5	6.0	2.5	3.5	1.149
6	6.0	10.0	0.5	1.137
7	8.4	0.5	3.5	1.142
8	8.4	2.5	0.5	1.146
9	8.4	10.0	2.4	1.142

RESULTS AND DISCUSSIONS

These experiments were conducted according to Taguchi Design method by using proper instrumentation in and Experimental Test Room. Experiments were varied to complete 9 altered trials with parameters like ACH, Particle Source Location, Particle Size, which are varied to measure Contaminant Particle Removal Effectiveness in breathing zone for UFAD ventilation configuration.

The objective of this research was to study the effect of various input parameters like Air changes per hour, Particle Source Location, Particle Size on the Contaminant Particle Removal Effectiveness in breathing zone. Various results and their interpretations are provided in following sections..

4.1 INFLUENCES ON PARTICLE REMOVAL EFFICIENCY

A) TAGUCHI ANALYSIS

The S/N ratios for Contaminant Removal Effectiveness are calculated as per the equation (1). Taguchi method is used to analysis the result of response of parameter for “Larger is better” criteria.

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where S/N ratios calculated from observed values, y_i represents the experimentally observed value of the i^{th} experiment and n=1 is the repeated number of each experiment in L-9 Orthogonal Array is conducted. (Refer Table 4)

Table: 4: L-9 Orthogonal Array

ACH	Particle size	Particle source location	Contaminant Removal Effectiveness (εBZ)	SNRA1	MEAN1
3.6	0.5	0.5	1.118	0.96884	1.118
3.6	2.5	2.4	1.154	1.24412	1.154
3.6	**10.0**	**3.5**	**1.168**	**1.34886**	**1.168**
6.0	0.5	2.4	1.138	1.12285	1.138
6.0	2.5	3.5	1.149	1.20640	1.149
6.0	10.0	0.5	1.137	1.11521	1.137
8.4	0.5	3.5	1.142	1.15332	1.142
8.4	2.5	0.5	1.146	1.18369	1.146
8.4	10.0	2.4	1.142	1.15332	1.142

Chart shows the optimum solution of the given set of parameters is given by the value having SN ratio is largest i.e **1.34886**.

B) MINITAB RESULTS AND GRAPHS

From Fig 2 and 3, it can be observed that the parameters like Air Changes per Hour, Particle Source Location, Particle Size affect the Contaminant Removal Effectiveness in breathing zone in a UFAD ventilated room environment.

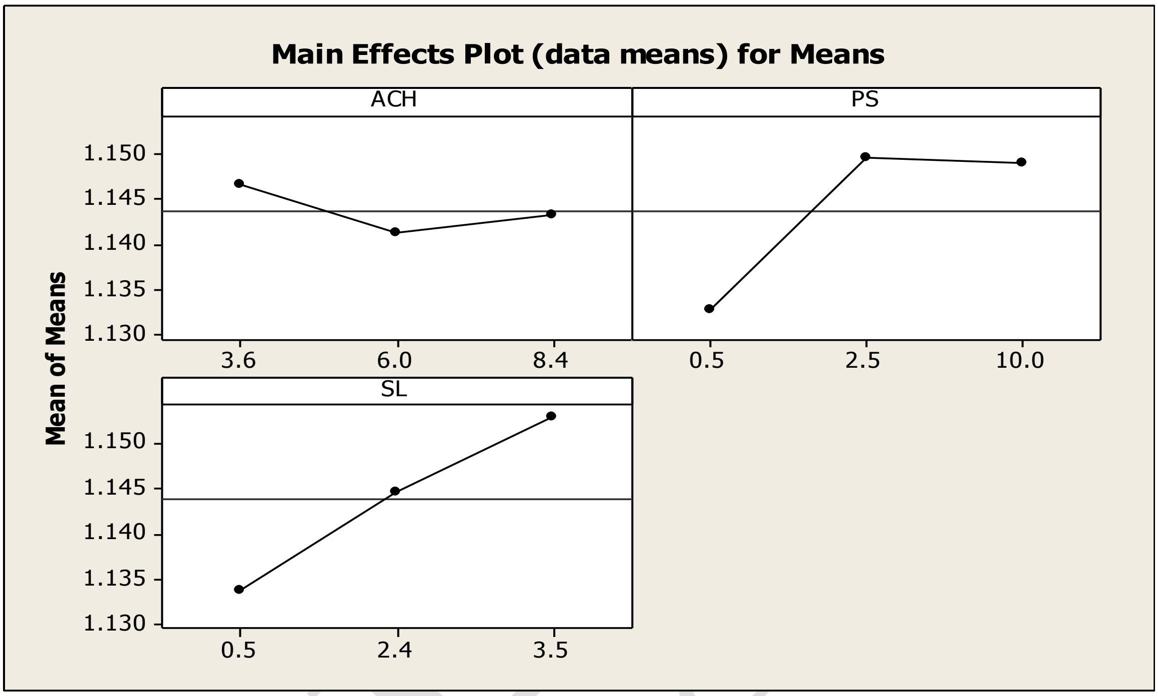

Fig 2: Main Effects Plot of Means for Contaminant Removal Effectiveness

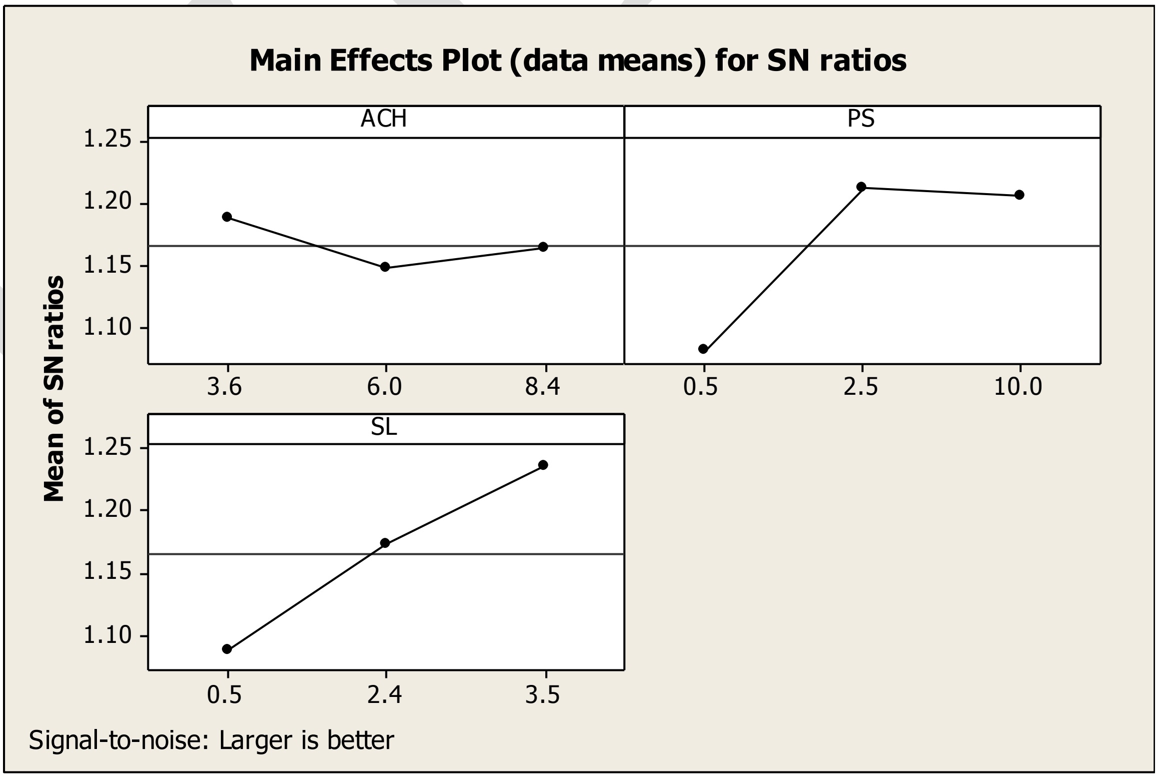

Fig 3: Main Effects Plot of S/N Ratios for Contaminant Removal Effectiveness

From Table 5 it is concluded that Particle Source Location is more influencing parameter on Particle Removal Efficiency than Air velocity and Particle Size.

Table 5: Response table for Signal to Noise Ratios (Larger is better)

Level	ACH	Particle size	Particle source location
1	1.187	1.082	1.089
2	1.148	1.211	1.173
3	1.163	1.206	1.236
Delta	0.039	0.130	0.147
Rank	3	2	1

C) REGRESSION ANALYSIS: EBZ VERSUS ACH, PARTICLE SIZE, SOURCE LOCATION-

The regression equation (2) is as given below-

$$\varepsilon_{BZ} = 1.13 - 0.00069\ ACH + 0.00122\ PS + 0.00637\ SL \qquad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Table 6 Predictor table

Predictor	Coef	SE Coef	T	P
Constant	1.12905	0.01468	76.92	0.000
ACH	-0.000694	0.001970	-0.35	0.739
Particle Size	0.0012237	0.0009438	1.30	0.251
Source Location	0.006372	0.003115	2.05	0.096

ANALYSIS OF VARIANCE

Table 7 Table for Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	0.006035	0.002012	1.73	0.277
Residual Error	5	0.005827	0.001165		
Total	8	0.011862			

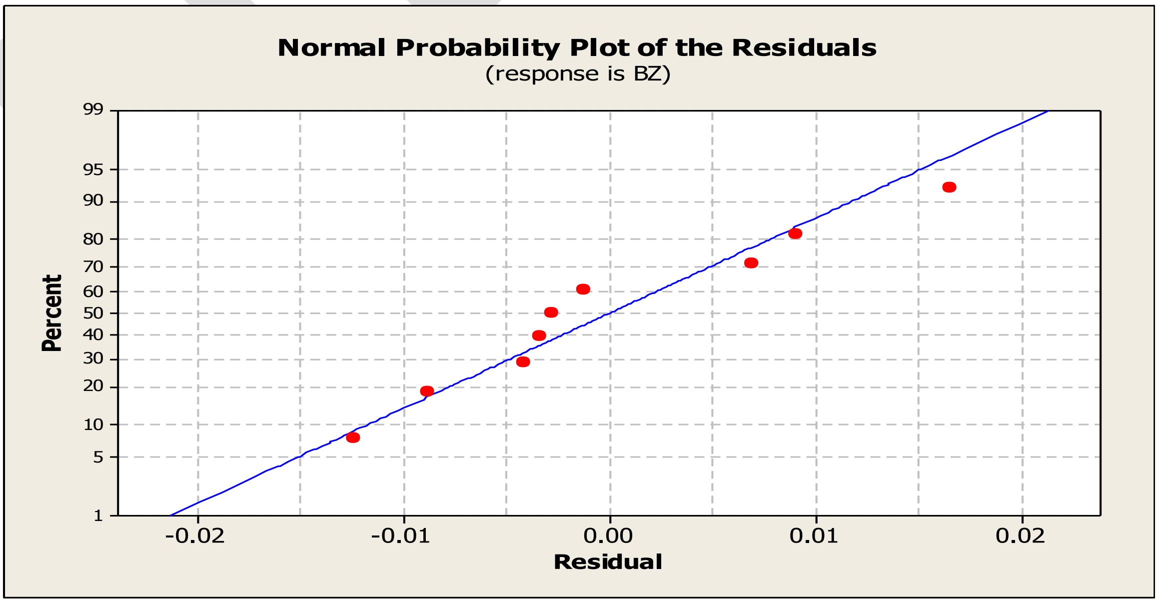

Figure 4 : Normplot of Residuals for BZ

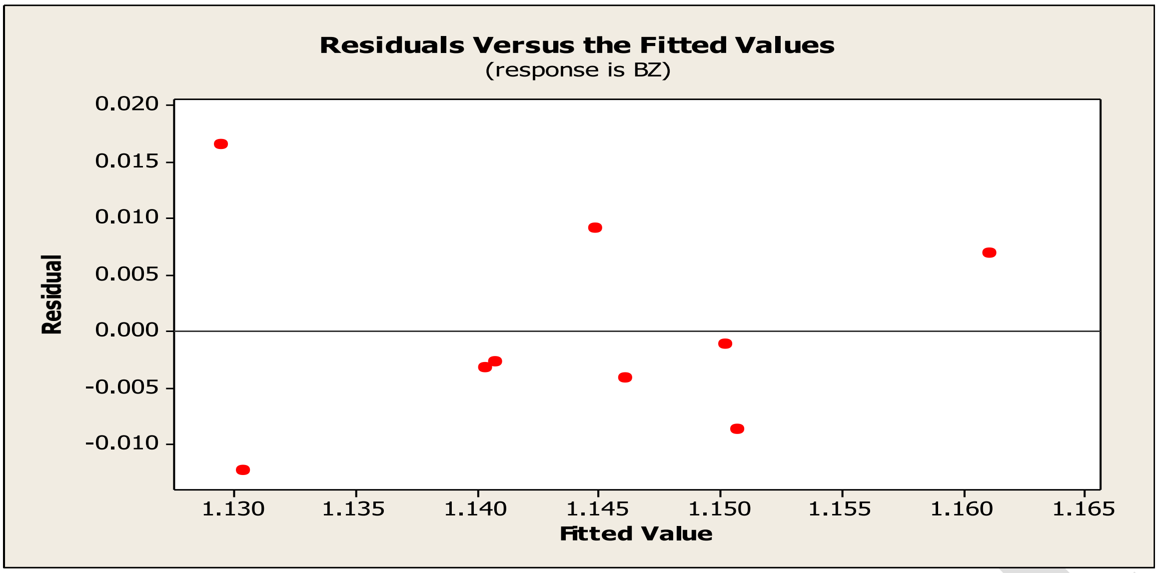

Figure 5: Residuals vs Fits for BZ

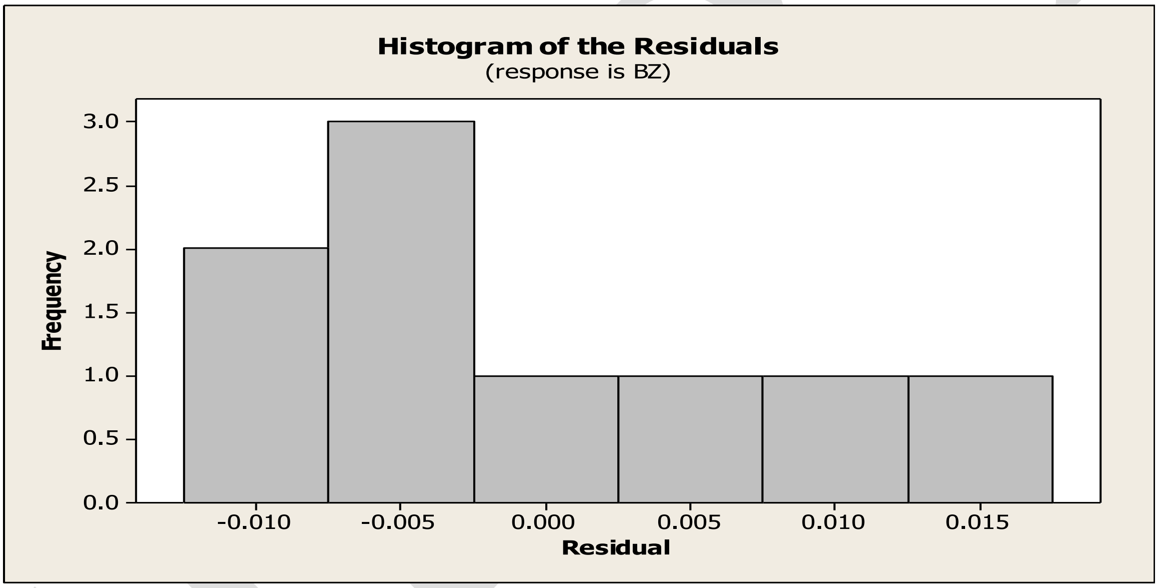

Figure 6: Residual Histogram for BZ

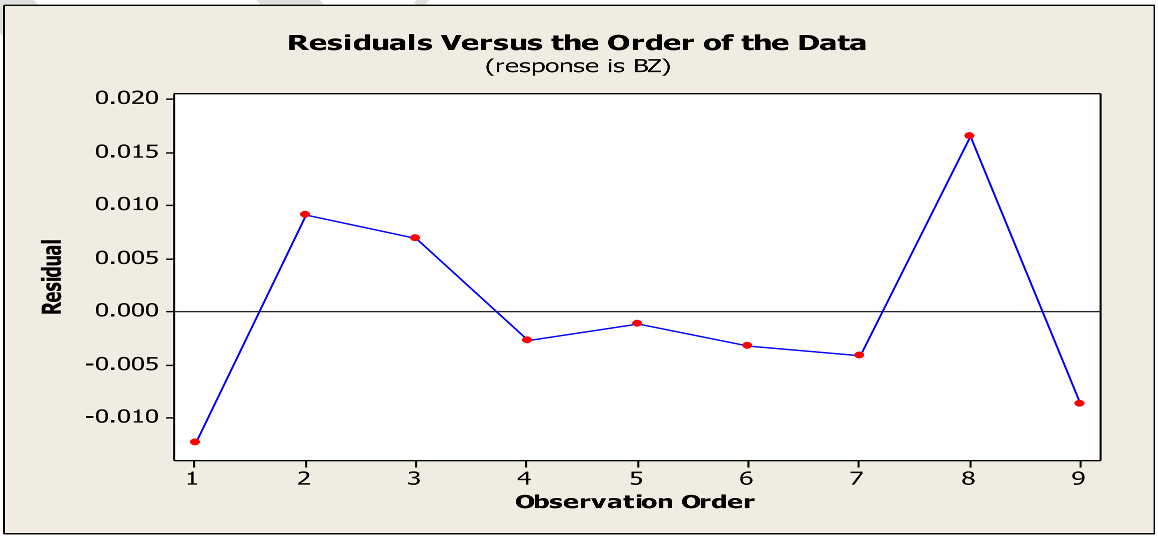

Figure 7: Residuals vs Order for BZ

C) ANALYSIS OF VARIANCE FOR S/N RATIO OF PARTICLE SOURCE LOCATION

Analysis of variance for Efficiency is given in Table: 8. These values are obtained from MINITAB 14 software.

Table: 8 Analysis of Variance for S/ N ratios

SL	Contaminant Particle Removal Effectiveness(εBZ)	RESI1	FITS1
0.5	1.118	-0.0156667	1.13367
2.4	1.154	0.0093333	1.14467
3.5	1.168	0.0150000	1.15300
2.4	1.138	-0.0066667	1.14467
3.5	1.149	-0.0040000	1.15300
0.5	1.137	0.0033333	1.13367
3.5	1.142	-0.0110000	1.15300
0.5	1.146	0.0123333	1.13367
2.4	1.142	-0.0026667	1.14467

Table: 9 One way ANOVA for Contaminant removal effectiveness v/s Particle source location

Source	DF	SS	MS	F	P
Particle source location	2	0.000564	0.000282	1.86	0.235
Residual Error	6	0.000909	0.000152		
Total	8	0.001474			

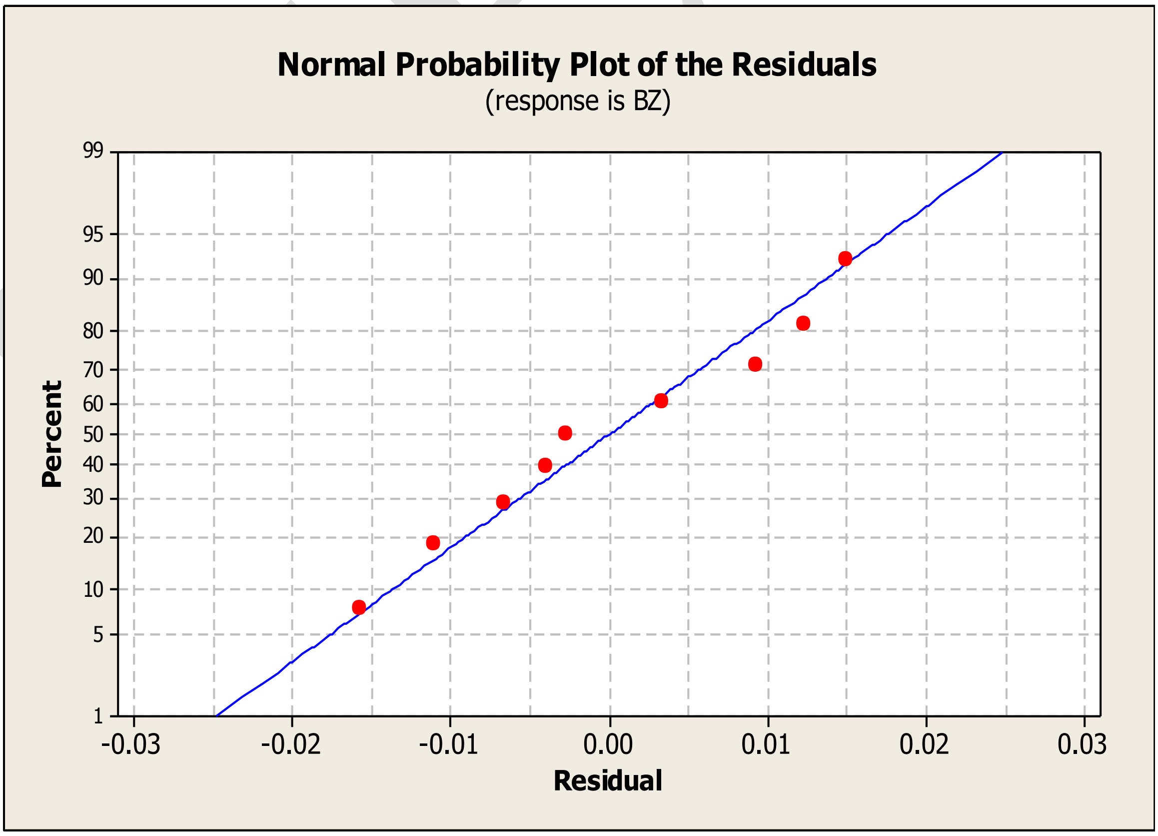

Figure 8: Normplot of Residuals for Breathing Zone

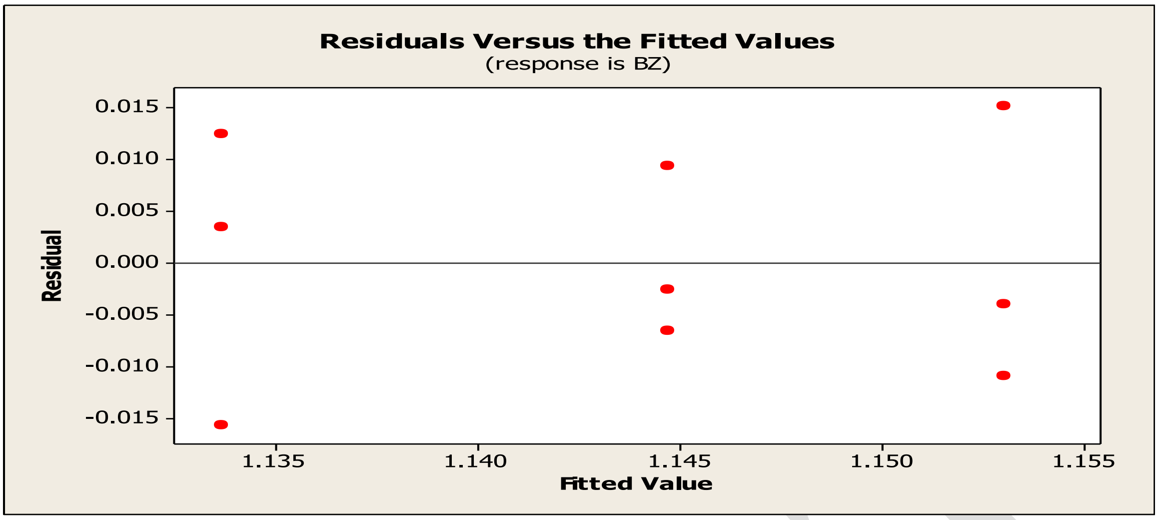

Figure 9: Residuals vs Fits for Breathing Zone

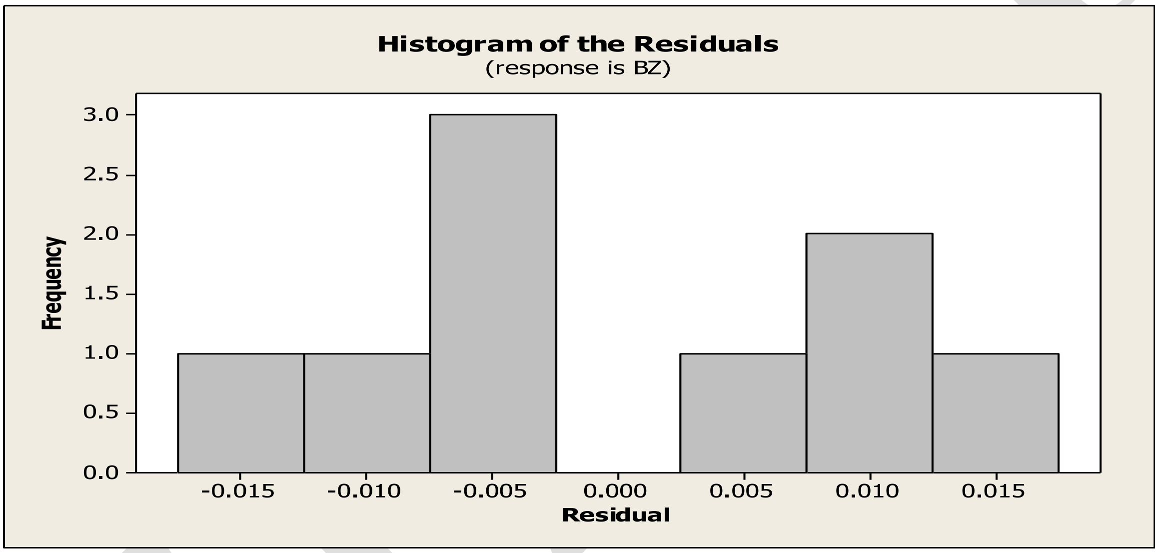

Figure 10: Residual Histogram for Breathing Zone

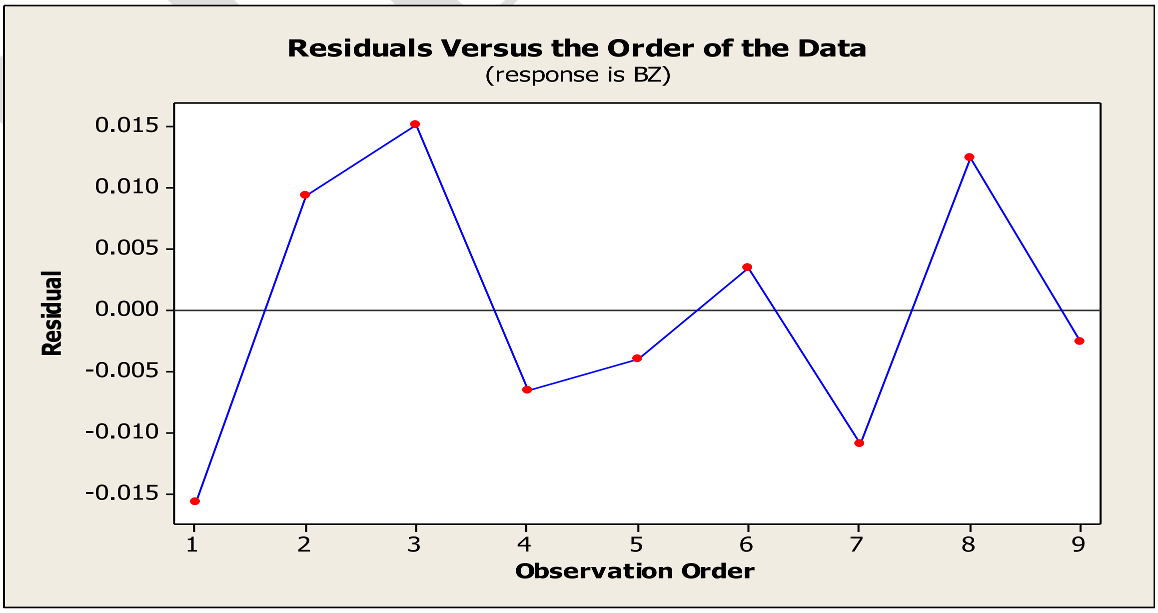

Figure 11: Residuals vs Order for Breathing Zone

CONCLUSIONS

From results provided in figures 2 to 11 and tables 5 to 9, following conclusions can be drawn.

1. Air Changes per Hour, Contaminant particle source location and particle size are found to be the influential parameters for Contaminant Particle Removal Effectiveness in breathing zone in UFAD ventilated room.
2. Maximum Contaminant Particle Removal Effectiveness in breathing zone is obtained at ACH of 3.6. This suggests that if particle source location and particle size are not controllable, in mixing ventilation system, it is recommended to use ACH of 3.6 for better contaminant particle removal.
3. Maximum Contaminant Particle Removal Effectiveness in the breathing zone is obtained at source location of 3.5 m distance from opposite wall of the Experimental Test Room. This leads to the conclusion that if ACH and particle size are not controllable, better contaminant particle removal is obtained for source location of 3.5m.
4. Maximum Contaminant Particle Removal Effectiveness in the breathing zone is obtained when the contaminant particle size is 10μm. This provides us the guideline that if ACH and particle source location are not controllable, good contaminant removal can be obtained for particle size of 10 μm.

Thus, for determination of optimal ventilation strategy from the point of view of contaminant particle removal, these studies provide useful guidelines for HVAC system engineers and operators. This, in turn, will help in providing cleaner and healthier indoor environment.

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