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Optimization of Combined Conductive and Convective Heat Transfer Model of a Cold Storage using Taguchi S/N Ratio Analysis

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Abstract

In this project work design of experiments have been used to optimize various control factors of a cold storage so as the heat gain in the cold room or in the other words the heat flow from the outside ambience to the inside of the cold room will be mínimum and heat transfer due to convection and condensation process in the evaporator space of the cold room will be máximum. Taguchi orthogonal array have been used as a design of experiments.Three control factors with three levels of each have been chosen for analysis. The control factors for heat gain in the cold room due to conduction process are insulation thickness of sidewalls (TW), area of the sidewalls (AW), and insulation thickness of the roof (TR) and the control factors for heat transfer in the evaporator space of the cold room due to convection and condensation process are velocity of air (V), temperature difference (dT), relative humidity (RH).Due to conduction process different amount of heat gains in the cold room for different set of test runs have been taken as the output parameter and due to convection and condensation process different amount of heat transfer in the evaporator space of the cold room for different set of test runs have been taken as the output parameter. The objective of this work is to find out the optimum setting of the control factors or design parameters so as the heat gain in the cold room will be mínimum and heat transfer in the evaporator space of the cold room will be máximum. The Taguchi S/N ratio analysis have been used as an optimization technique. Due to conduction process smaller the better type S/N ratio have used for calculating the optimum level of control parameters, because it is a minimization problem and due to convection and condensation process larger the better type

S/N ratio have used for calculating the optimum level of control parameters, because it is a maximization problem.

Key words

Design of Experiment (D.O.E.), S/N ratio.

1. Introduction

A major use of refrigeration is in the preservation, storage and distribution of perishable foods. Cold storage plays an important role in the preservation of perishables especially fruits and vegetables. It helps in scientific preservation of perishables, stabilizes prices by regulating marketing period and supplies. It also helps the primary producer from distress sale and encourages farmers to produce more. In view of the fall in prices of fruits and vegetables immediately after harvest and to avoid spoilage of fruits and vegetables worth crores of rupees, it has become necessary to create cold storage facility in the producing as well as consuming centres to take care of the existing and projected production of fruits and vegetables. A cold storage is a building or a group of buildings with thermal insulation and a refrigerating system in which perishable food products can be stored for various lengths of times in set conditions of temperature and humidity. Such storage under controlled conditions slows the deterioration and spoilage that would naturally occur in an uncontrolled natural environment. Thus, cold storage warehouses play an important role in the storage of food products in the food delivery chain throughout the year under conditions specially suited to prevent their degradation. This function makes seasonal products available all year round. So it is very important to make cold storage energy efficient or in the other words reduce its energy consumption. The energy consumption of the cold storage can be reduced, by minimizing the heat flow from high temperature ambience to low temperature cold room and by maximizing the heat transfer in the evaporator space of the cold room. By setting optimum values of different control parameters the heat gain in the cold room can be reduced and the heat transfer in the evaporator space of the cold room can be increased.M.S. Soeylemez et al (1997)[1] has suggested A thermo economic optimization analysis is presented yielding a simple algebraic formula for estimating optimum insulation thickness for refrigeration applications. The effects of design parameters on the optimum insulation thickness are investigated for three test cities using an interactive computer code written in Fortran 77. The equivalent full load hour’s method is used to estimate the energy requirements. N.Yusoff et al (2010)[2] has suggested that study presents a procedure for selecting optimization variables in a Refrigerated Gas Plant(RGP) using Taguchi method with L27(93) orthogonal arrays. Patel Amit M., Patel R. I., (2012)[3] has also studied effect of various control parameters on cold storage energy consumption with the help of L9(33) orthogonal array. Dr.M.Chourasia (2009) [4] deals with different aspects cold storage design to improve its performance. He studied air flow pattern inside the cold room.Some researchers [5] also proposed some mathematical model of heat gain in the cold room. By studying those models one can get the idea about optimum values of the various control factors. D.O.E [5] techniques enable designers to determine simultaneously the individual and interactive effects of many control factors that could affect the output parameter.Simply put, DOE 3helps to pin point the sensitive parts and sensitive areas in designs that cause problems in Yield. It helps turn any design into robust one.A D.O.E technique not only savethe time but also saves the money for conducting the experiments.There are several D.O.E methods available like factorial design, response surface methodology (RSM), Taguchi methodology Taguchi method [6] is based on performing evaluation or experiments to test the sensitivity of a set of response variables to a set of control parameters (or independent variables) by considering experiments in “orthogonal array” with an aim to attain the optimum setting of the control parameters. It was developed Dr. Taguchi of Nippon Telephones and Telegraph Company, Japan. Orthogonal arrays provide a best set of well balanced (minimum) experiments. As the name suggest, the columns of this array are mutually orthogonal. Here, orthogonality[7] is interpreted in the combination based sense i.e. for any pair of columns;all combinations of factor levels would occur and appear in the design matrix an equal number of times. This is called the balancing property and it implies orthogonality.The advantage of Taguchi methodology over other design of experiments is that it requires less number of test runs than the other methods. Thus saves the time and resource for data handling. This method uses a special set of arrays called orthogonal array. While there are many standard orthogonal arrays available, each of arrays is meant for a specific number of independent control variables and levels. Due to conduction process Taguchi S/N ratio employed as an optimization tool to determine the best combination of control parameters such as insulation thickness of side walls(TW), area of the side walls(AW),insulation thickness of the roof(TR) to attain minimum heat gain(Q) in the cold room and due to convection and condensation process Taguchi S/N ratio employed as an optimization tool to determine the best combination of control parameters such as air velocity(V), temperature difference(dT),relative humidity(RH) to attain the maximum heat transfer in the evaporator space of the cold room.

2. Mathematical model development

In this study due to conduction process three control parameters insulation thickness of the side walls(TW), area of the side walls(AW), insulation thickness of the roof(TR) taken as control parameters and heat flow(Q) from outside to inside of the cold room taken as output variable and due to convection and condensation process three control parameters air velocity(V), temperature difference(dT), relative humidity(RH) taken as control parameters and heat transfer(Q) in the evaporator space of the cold room taken as output variable.

For conduction process TABLE 1 shows the control parameters and their levels-

TABLE 1 control parameters and their levels

Notation	**Factors**	**Unit**	**levels**		
			1	**2**	**3**
TW	Insulation thickness of the side wall	m	0.100	0.150	0.200
AW	Area of the side wall	m^2	78	104	130
TR	Insulation thickness of the roof	m	0.080	0.100	0.150

The following equation is used for calculating the values Q:

Q=(K*A*TD)/x[10] (1)

Where,

K= thermal conductivity of insulating material =.023 W/mK

A= area, TD= temperature difference

.X= insulation thickness.

Table 2 shows the L9 OA combinations among various control factors.

Test Runs	Control factors		
	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Here 1, 2, 3 indicates the levels of each control factor. Using the level values of control factors from Table 2 and the observation table become:

Table 3 Observation table

TEST RUNS	TW	AW	TR	Q
1	0.100	78	0.080	13155.89
2	0.100	104	0.100	13941.45
3	0.100	130	0.150	14727.02
4	0.150	78	0.100	21196.35
5	0.150	104	0.150	22391.78
6	0.150	130	0.080	20057.63
7	0.200	78	0.150	29428.03
8	0.200	104	0.080	26357.82
9	0.200	130	0.100	27930.21

To find out best set of combinations of control variables to attain the minimum heat gain (Q) in the cold room, Taguchi S/N ratio has been used. ‘Smaller- the -better’ type S/N ratio has been chosen for the analysis. MINITAB 15 software has been used for data analysis.

For convection and condensation process Table 4 shows the control parameters and their levels

Table 4 control parameters and their levels

Notation	**Factors**	**Unit**	**levels**		
			1	**2**	**3**
V	Air Velocity	m/s	0.74	1.25	1.76
Dt	Temperature Difference	centrigade	2	4	6
RH	Relative Humidity		0.85	0.90	0.95

Basic equation for heat transfer

$Q_T = Q_{conv} + Q_{condensation}$. Q_{conv}=AhcdT & $Q_{condensation}$=Ahm(RH)hfg.

Here Qconv=heat transfer due to convection & Qcondensation=heat transfer due to condensation & QT=Total heat transfer or absorb heat into refrigerant.

And $h_c/h_m=c_p(Le)^{2/3}$ & $h_cL/K=Nu=0.026(Re)^{0.8}(Pr)^{0.3}$

The final heat transfer equation due to velocity of air (V), temp. difference(dT) & relative humidity RH) is $QT=7.905V^{0.8}(dT + 2490\ RH)$.......(1). [4]

Here A=surface area of tubes in evaporator space 1872 m2.hc=convective heat transfer co-efficient. hm=convective mass transfer co-efficient.hfg=latent heat of condensation of moisture 2490 KJ/Kg-K.Cp=specific heat of air 1.005 KJ/Kg-K. Le=Lewis number for air it is one

Table 5 shows the L9 OA combinations among various control factors.

Test Runs	Control factors		
	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1

7	3	1	3
8	3	2	1
9	3	3	2

Here 1, 2, 3 indicates the levels of each control factor. Using the level values of control factors from Table 2 and the observation table become:

Table 6 Observation table

TEST RUNS	V	dT	RH	Q
1	0.74	2	0.85	13155.89
2	0.74	4	0.90	13941.45
3	0.74	6	0.95	14727.02
4	1.25	2	0.90	21196.35
5	1.25	4	0.95	22391.78
6	1.25	6	0.85	20057.63
7	1.76	2	0.95	29428.03
8	1.76	4	0.85	26357.82
9	1.76	6	0.90	27930.21

To find out best set of combinations of control variables to attain the maximum heat transfer (Q) in the evaporator space of the cold room, Taguchi S/N ratio has been used. ‘Larger- the -better’ type S/N ratio has been chosen for the analysis. MINITAB 15 software has been used for data analysis.

2.1 S/N ratio (Signal-to-noise ratio)

The signal to noise ratios (S/N), which are log functions of desired output, serve as the objective functions for optimization, help in data analysis and the prediction of the optimum results. There are 3 types of S/N ratios are available-namely smaller-the –better, larger – the –better & nominal-is–the best.

In this problem we both use smaller-the-better and larger-the-better types S/N ratio.

In case of conduction process we use smaller-the-better type S/N ratio to minimise the heat flow from outside of wall to inside and in case of convection process we use larger-the-better type S/N Ratio to maximise the heat transfer in the evaporator space of the cold room.

2.1.1 For conduction process

Smaller-the-better

This is expressed as – (S/N)= -10log10 (mean of sum of squares of measured data)
This is usually the chosen S/N ratio for all the undesirable characteristics like “defects” for which the ideal value is zero. When an ideal value is finite and its maximum or minimum value is defined (like the maximum purity is 100% or the maximum temperature is 92 K or the minimum time for making a telephone connection is 1 sec) then the difference between the measured data and the ideal value is expected to be as small as possible. Thus, the generic form of S/N ratio becomes-(S/N)=—10Log10 {mean of sum of squares of (measured-ideal) data}

2.1.2 For convection and condensation process

Larger-the-better

For calculating S/N ratio for larger the better for maximum heat transfer, the equation is
$SNi = -10 \log[\sum(1/(Qi)2/n]$
Where n= number of trials in a row
Qi= calculated value in the test run or row.
Trial number = i
SNi = S/N ratio for respective result

For conduction process

Table 7 shows S/N ratios for each test run.

Table 7 (S/N) ratio table smaller-the-better type

TEST RUNS	TW	AW	TR	Q	S/N RATIO
1	0.100	78	0.080	706.56	-57.1105
2	0.100	104	0.100	794.88	-58.1289
3	0.100	130	0.150	864.80	-58.4879
4	0.150	78	0.100	507.84	-53.8641
5	0.150	104	0.150	529.92	-54.6117
6	0.150	130	0.080	754.40	-57.6749
7	0.200	78	0.150	362.48	-51.3086
8	0.200	104	0.080	563.04	-54.7604
9	0.200	130	0.100	579.60	-55.3901

For convection and condensation process

Table 8 shows S/N ratios for each test run.

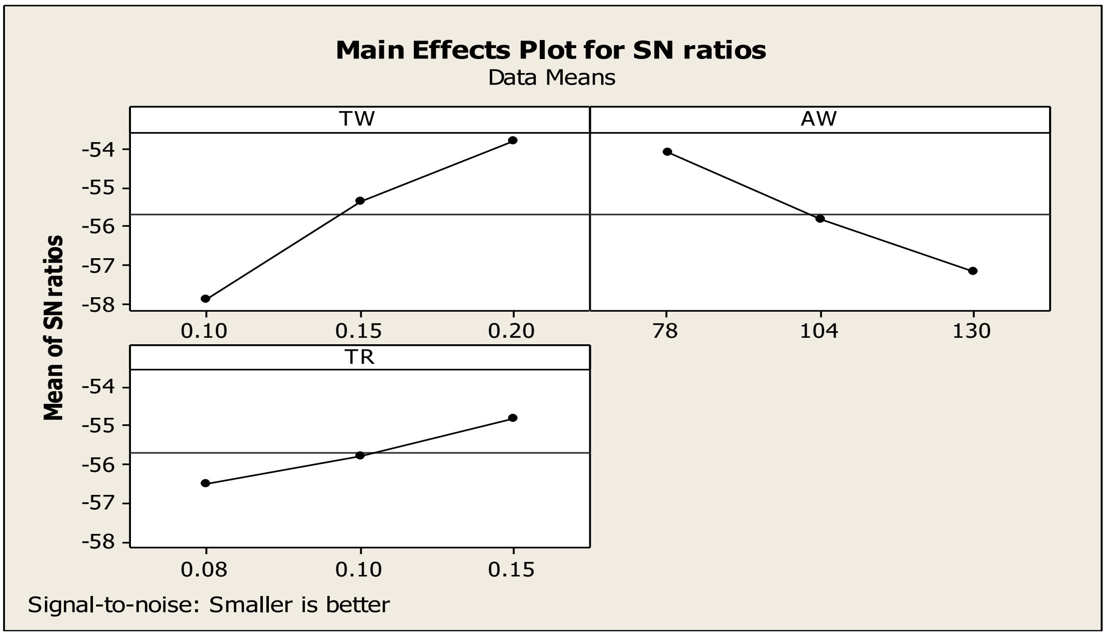
Table 8 (S/N) ratio table larger-the-better type

TEST RUNS	V	dT	RH	Q	S/N RATIO
1	0.74	2	0.85	13155.89	82.3824
2	0.74	4	0.90	13941.45	82.8862
3	0.74	6	0.95	14727.02	83.3623
4	1.25	2	0.90	21196.35	86.5252
5	1.25	4	0.95	22391.78	87.0018
6	1.25	6	0.85	20057.63	86.0456
7	1.76	2	0.95	29428.03	89.3752
8	1.76	4	0.85	26357.82	88.4182
9	1.76	6	0.90	27930.21	88.9215

3. Results and Discussions

3.1 For conduction process

Fig. 1. Shows the main effect plot for S/N ratio for heat gain in the cold room (Q) for conduction process



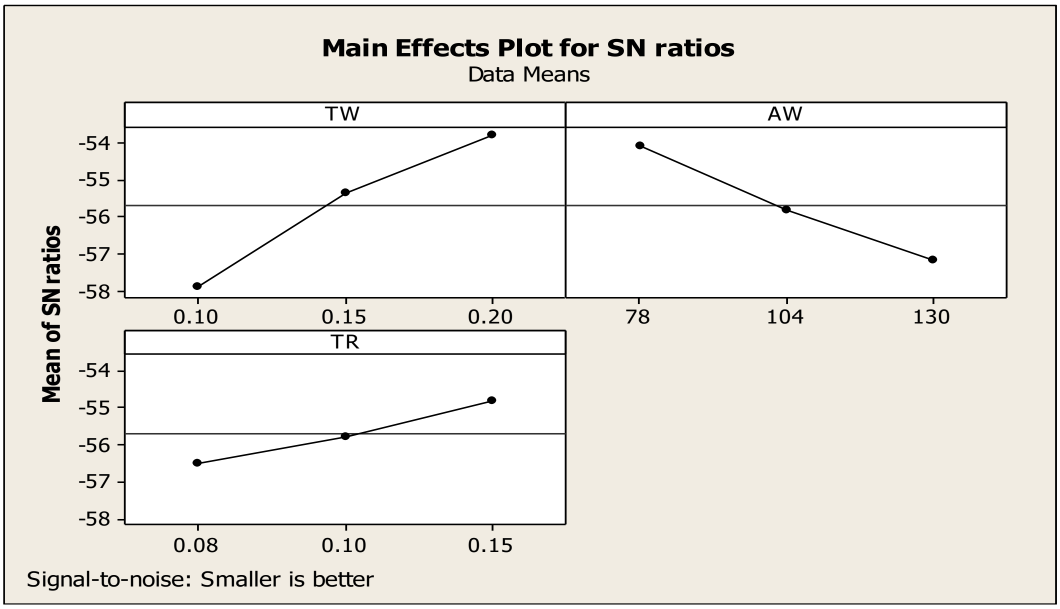


Fig. 1. Variation of mean of S/N ratio with TW, AW, TR for heat gain in the cold room (Q) for conduction process

Fig. 2. Shows the main effects plot for Means for heat gain in the cold room (Q) for conduction process

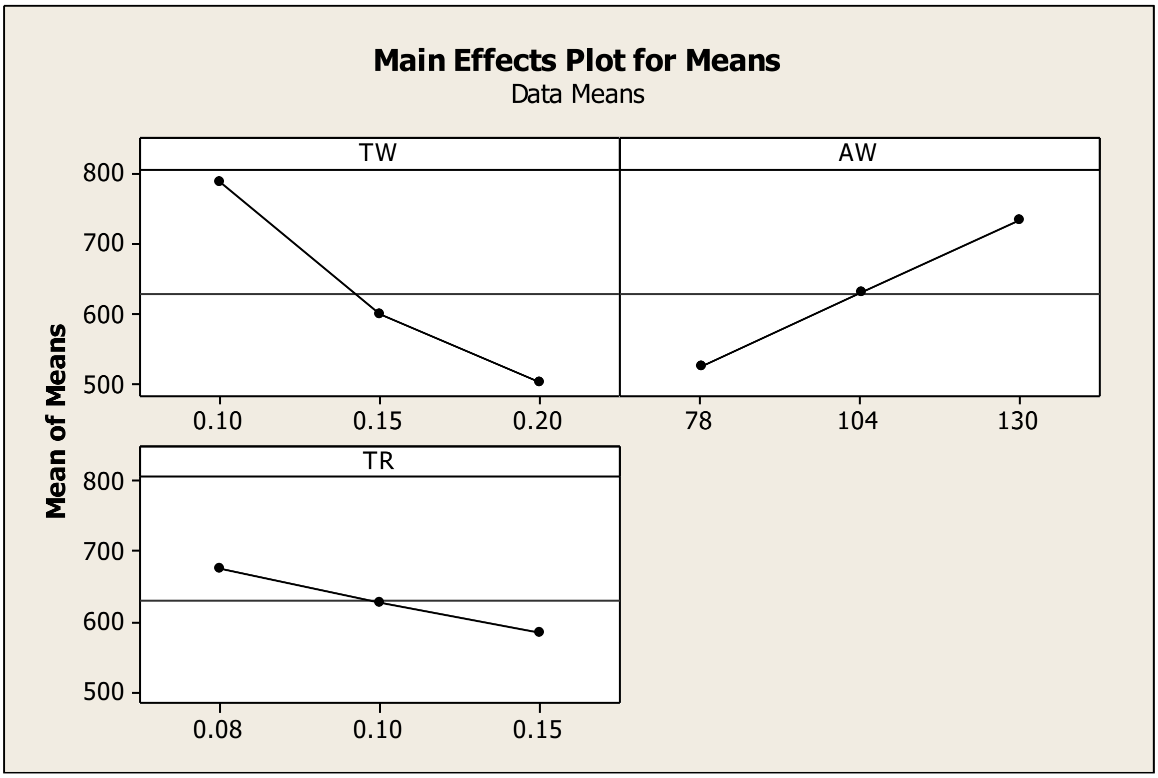


Fig. 2. Variation of mean of means with TW, AW, TR for heat gain in the cold room (Q) for conduction process

3.2 For convection and condensation process

Fig. 3. Shows the main effect plot for S/N ratio for heat transfer in the evaporator space of the cold room (Q)

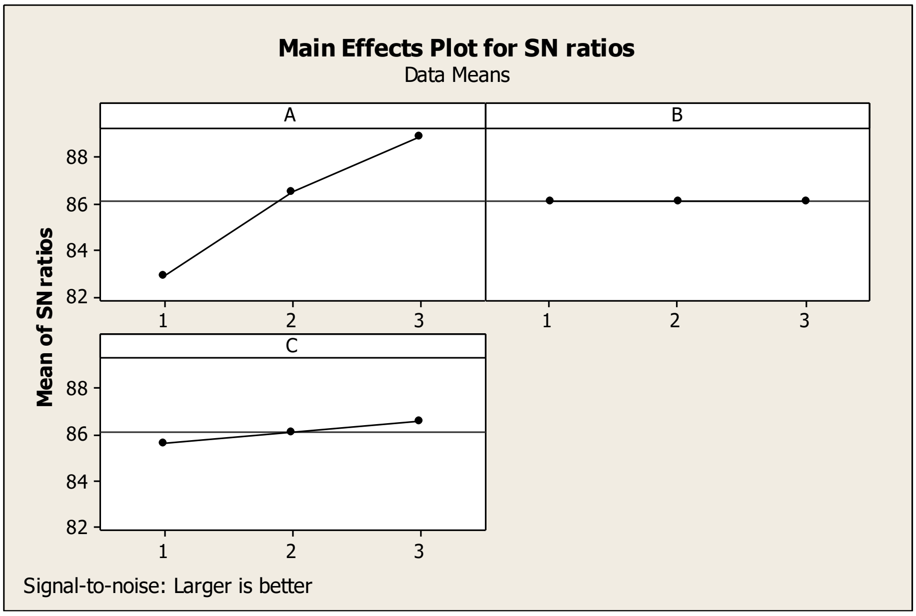


Fig. 3. Variation of mean of S/N ratio with TW (A), AW (B), TR(C) for heat transfer in the evaporator space of the cold room (Q) for convection and condensation process

Fig. 4. Shows the main effect plot for Means for heat transfer in the evaporator space of the cold room (Q) for convection and condensation process

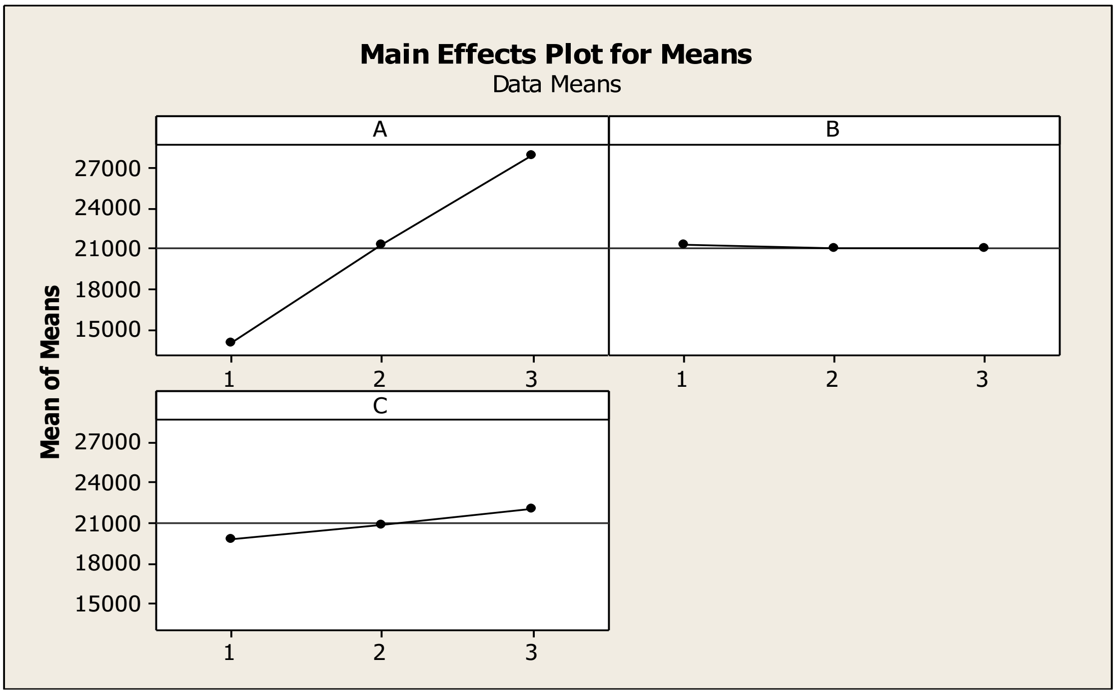


Fig. 4. Variation of mean of means with TW (A), AW (B), TR(C) for heat transfer in the evaporator space of the cold room (Q) for convection and condensation process

3.3 Analysis of the S/N ratio

For conduction process overall mean S/N ratio= - 55.7041

For convection and condensation process overall mean S/N ratio= 86.1020

4. Validation Process

4.1 For Conduction Process

In initial condition,

We have taken the control parameters as: TW2 AW2 TR2

Values of those control parameters are: 0.150 m, 104 $m^{2,}$ and 0.100 m

From experiment we get the value of Q;

Q=518.50 KJ

Then S/N ratio = -54.2949

We get this S/N ratio table from the graph:

TW	AW	TR
-57.9091	-54.0944	-56.5153
-55.3836	-55.8337	-55.7944
-53.8197	-57.1843	-54.8027

In Optimized Condition,

We get the control parameters as: TW3 AW1 TR3

Values of those control parameters are 0.200 m, 78 m^2 and 0.150 m

In this condition the value of Q = 362.48 KJ

S/N ratio = -51.1857

So, here we get the optimized value of Q by the validation process

4.2 For convection process

In initial condition,

We have taken the control parameters as: V2 dT2 RH2

Values of those control parameters are: 1.25 m/s, 4^{o}c and 0.90

From experiment we get the value of Q;

Q= 21650.80 KJ

S/N ratio= 86.7095

We get this S/N ratio table from the graph:

V	dT	RH
82.8770	86.0943	85.6154
86.5242	86.1020	86.1110
88.9050	86.1098	86.5798

In optimized condition we get the control parameters as: V3 dT3 RH3

Values of those control parameters are: 1.76 m/s, 6 °c and 0.95

From experiment we get the value of Q;

In this condition the value of Q = 29466.83 KJ

S/N ratio= 88.9897

So, here we get the optimized value of Q by the validation process

Now we added both optimized value of heat (Q) taking as optimized heat through combined conductive and convective heat transfer process.

Total optimized heat through conduction and convection process= (29,466.83+362.48) KJ

= 29,829.31 KJ

Previously we got one equation for showing the combined effect through conduction and convection process;

The equation is;

$QT = K*A*dT/X+7.905V^{0.8}(dT+2490RH)$

The maximum value of heat (Q) we get from this equation is= 29,316.10 KJ

By Comparing both optimized value and the value of heat we get from the equation is on a acceptable range and the range is (29,829.31-29,316.10)=513.22 or ±5.13%

Conclusion

Following conclusions are drawn from this analysis

a. Here we use the Taguchi S/N ratio to get the combined effect through conduction and convection process and also use the validation process to compare both optimized value and the value we get from previously proposed equation. The value we get by comparing those values is quite an acceptable range.

b. Here we can minimize the heat enter into the cold storage through wall and roof by conduction process as well as we can maximize the heat transfer in evaporator space through convection and condensation process. Therefore we can minimize the energy loss as a result we can minimize the cost of a cold storage.
c. So we can use this paper for the development of a cold storage.

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