A TAGUCHI APPROACH FOR OPTIMIZATION OF PROCESS PARAMETERES IN THERMOACOUSTIC REFRIGERATION

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Abstract- In TAR, pressure wave acoustic energy is converted into thermal energy, without any frictional energy losses. The objective of the study showcased here is to optimize the process parameters viz. stack position, stack material, frequency and acoustic wave type involved in TAR, using the Taguchi approach. An experimental set up is developed. Optimum combination is developed by the Taguchi approach over the results of experiments performed on the experimental set up. Optimized parameters given by the Taguchi approach are: stack position 150 mm, stack material glass fibre stack with capillary tube spacers, 350 Hz acoustic sine wave.

Keywords- TAR (TAR), Taguchi Approach, Process parameters, Stack, Acoustic wave frequency**.**

1. INTRODUCTION

Thermoacoustic refrigeration (TAR) is a technique of generating temperature difference across a thermoacoustic stack using acoustic energy, without the need of eco-sensitive refrigerants or use of moving parts. This heat pumping systems is beneficial over conventional systems. It uses environmentally safe working fluids, no seals, lubrication, frictional losses, facilitates cheap analogue control and design. TAR uses acoustic energy to generate cooling effect. It has sound source attached to an close ended resonator tube filled air, porous stack and two heat exchangers across the stack. The stack, the most vital component of TAR devices, is placed inside the resonator between pressure antinode and velocity antinode of the acoustic wave. The stack material should have low thermal conductivity and higher heat capacity than fluid, as it allows steady thermal gradient across the stack walls. The stack and resonator material should be strong enough and of low thermal conductivity to withstand higher pressure and prevent heat leakage.

The acoustic wave from an acoustic driver makes the gas resonant. The oscillating standing sound wave creates a temperature difference across the length of the stack because of compression and expansion of gas and facilitates heat exchange between fluid and stack[1]. The heat exchangers exchange heat with the surroundings at the cold and hot sides of the stack. The basic parameters affecting the performance of TAR are well under stood.[3]

Nsofor and Ali [2] studied the performance of TAR system of aluminum resonator tubing lined with plastic tubing by changing the frequency, load and pressure. Kartik M. Trivedi[6] studied the effect of thirteen various stack positions on performance of TAR. Thus it is inferred that stack positioning affects the temperature difference across stack ends. Mohammed Awwad Ali [4] undertook a 2D computational simulation of TAR. It identified the optimized parameters for TAR from the study.

Experiments were conducted by Giulio Allesina [5] varying the stack material, Stack geometry to analyze the performance of TAR. He used spiral and parallel stack geometries and conclude that parallel plate stack gives better result than the spiral stack, but parallel plate stack is difficult to manufacture.

The literature referred so far relates to the basic principles and performance augmentation of TAR and the authors came across no literature that specifies design of TAR using Taguchi approach. Therefore, the present study aims to find the optimum input parameters of standing wave TAR using air as a working fluid by Taguchi method. The most vital parameters influencing performance of TAR are frequency, stack position, stack material, and acoustic wave type. Using Taguchi method, the most productive optimum combination is obtained and investigated. The experimental setup of TAR has been developed using values generated from Taguchi for the desired output of temperature difference. Experiments are performed and the results are presented in this paper

2. EXPERIMENTAL SETUP

Figure 1 shows a schematic diagram of the TAR. It consists of an acoustic driver (speaker) which is connected to the resonator through a diverging conical adiabatic member (funnel). The stack is placed at appropriate position inside the resonator with two thermocouples across it for temperature measurement. These stacks forms different configurations and are made from Glass capillary tubes, Glass fibre with capillary spacers and Glass fibre with Nylon spacers. The capillary tubes and spacers are rolled into a bundle with outside diameter just abutting to inside diameter of the Glass resonator tube. The various configurations pertaining to stack material, stack position, frequency and type of acoustic wave are given in the table. Calibrated K type thermocouples and Digital Temperature Indicator are used to measure temperature at hot and cold end of the stack as well as atmospheric temperature. Electrical power input to the speaker is measured using calibrated Ammeter and Voltmeter. The standard frequency generator is put to use and the pressure variations in the resonator tube at appropriate locations are measured using Pressure transducers.

2.1 Stack

The stack is used to convert acoustic power into heat, the amount of acoustic power that can be converted into heat depends on certain features of the stack like material properties, stack dimensions and the position of the stack in the resonator. Figure 2 shows a stack. The stack material should have a high heat capacity and low thermal Conductivity along resonator axis. The length is important for the temperature gradient. The length and cross-Sectional area of the stack determine how much the sound waves are intercepted. We have used three stack configurations viz. Glass capillary tube stacks, Glass fibre with nylon spacers and Glass fibre with glass capillary spacers. The thermal conductivity of the stack is taken as 1.25 W/mK. Figure 2 shows these different stacks.

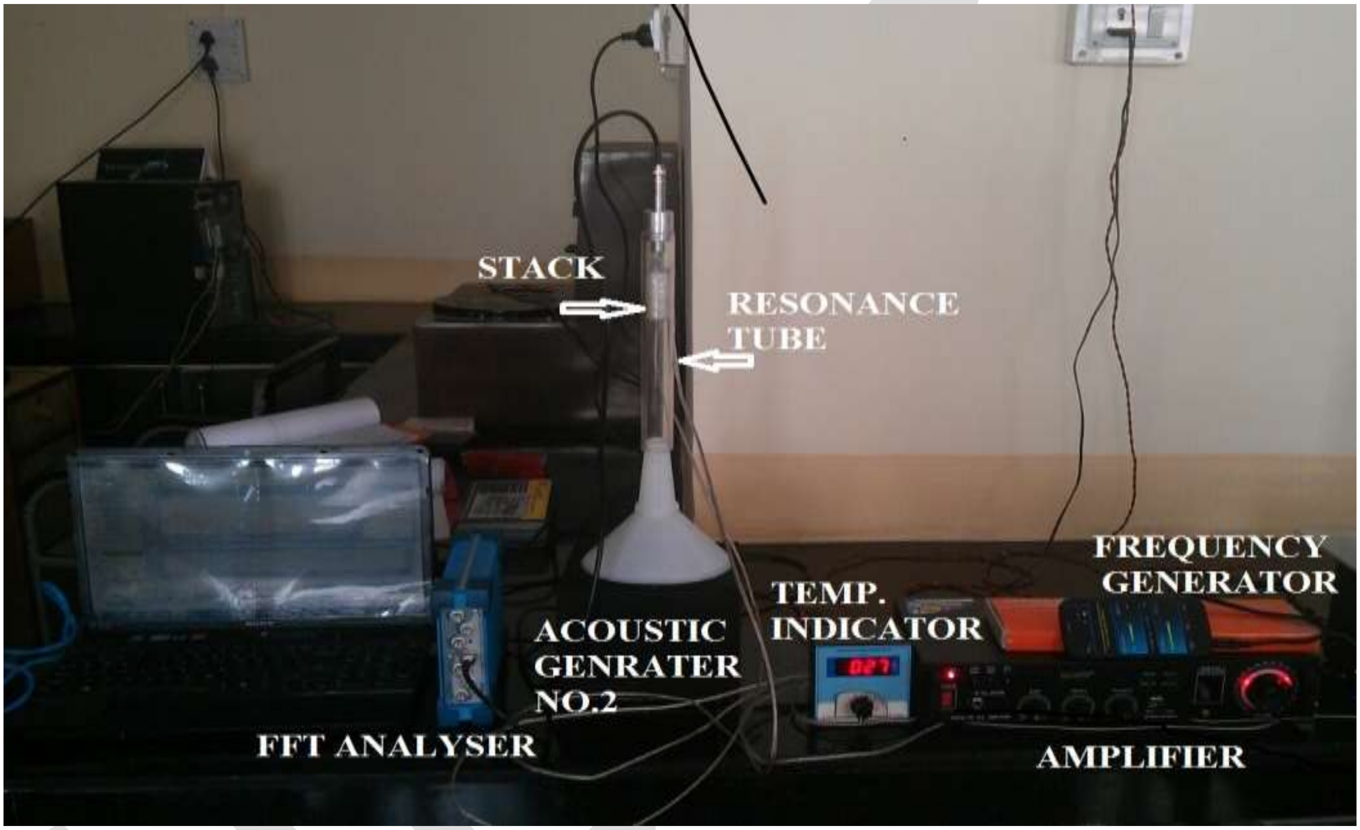

Figure 1: Experimental Set-up of TAR

Figure 2: Rolled Stack

2.2 Working Fluid

High mean fluid pressure, a high velocity of sound and a large cross-sectional area gives more thermo acoustic power. Hence generally, helium is used in thermo acoustic devices. But from low cost perspective, air at atmospheric pressure with low Prandlt number and low viscous losses is used as the working fluid.

2.3 Resonance Tube

The shape, length, weight and the losses are significant parameters in resonator design. Length of resonator is determined by the resonance frequency and minimal losses at the wall of the resonator. The length of resonator tube corresponds to quarter of the wavelength of the standing wave [1]:

Length of resonance tube,

L= v/4f …………………[7,8]

Where,

Velocity of sound in air, v =340 m/s

Frequency of Sound wave, F=350 Hz

L= 340/(4*350)

= 0.242 m

Where, a is the speed of sound,

L is the length

and F is the resonance frequency

For the resonance frequency 350Hz, the length of resonant tube is set equal to 242 mm that corresponds to the quarter wavelength of the acoustic standing wave, the diameter of the resonator tube is set equal to 20mm. The acoustic resonator comprises of a straight acrylic tube of length 242 mm with internal diameter 20 mm and the thickness of the wall, 2.5mm. One end of the tube is attached to the small end of acrylic conical flask. At the other end of the resonator, an aluminum plug is placed which works as reflector wall and heat exchanger.

2.4 Acoustic Generator

Figure 3 shows acoustic generator with resonance tube. Acoustic driver supplies total acoustic power used by the refrigerator. The acoustic driver converts electric power into acoustic power. A loudspeaker with maximum power of 60 watts and 8Ω at the operating frequency of 350 Hz is selected as the acoustic driver for this study.

2.5 Measuring Instruments

Different process parameters viz. pressure, temperature, amperage, voltage are measured using calibrated instrumentation. The locations of measurements are selected judiciously and appropriately.

The pressure wave amplitude is measured using pressure transducer and FFT analyzer shown in figure 4. Calibrated K type thermocouples and calibrated digital temperature indicator are used to measure temperature of hot and cold end of the stack as well as atmospheric temperature. Electrical input to speaker is measured using calibrated 0-20 A, 600V Multimeter.

Figure 3: Resonator a top the acoustic generator

Figure 4: FFT Analyzer for pressure measurment

3. OPTIMIZATION APPROACH

Designs of experiments include the statistical tools used for process planning of experimentation and help collect appropriate data and subsequently minimize the number of experiments. Taguchi is one of such statistical tools, widely used in experimental designing to minimize the variation of noise factors and determine optimal parameters using Signal to Noise (SN) ratio graphs[10].

The aim of this work is to determined optimum parameters using Taguchi method, to get maximum temperature difference across two ends of the stack. Here three different types of quality characteristics are used viz. smaller is better, nominal is best and larger is better. In the experimentation, response is temperature difference across the stack ends for better performance of TAR. Performance of TAR is based on the temperature difference across stack, so we selected Larger the better quality characteristics for Taguchi analysis.

Table : 1 Parameters under investigation

Parameters	Level 1	Level 2	Level 3
Stack position (A)	100 mm	150 mm	190 mm
Stack Material (B)	Capillary tubes	Glass fiber with nylon spacers (GFW/TN)	Glass fiber with glass spacers (GFW/TC)
Frequency (C)	350 Hz	520 Hz	700 Hz
Wave type (D)	Sine	Square	Triangular

In design of experiment, four critical parameters selected are Stack position, Stack length, and Frequency and Wave type with three levels for each parameter. If full factorial analysis is undertaken, number of experiments required to be performed are 3^4=81[12]. To minimize this number Taguchi analysis is put to use. Obviously L_9 array has been selected for the analysis.

Table 2: Response of L_9 array

Test. No.	A	B	C	D	Response			SN ratio	Mean response
					1	2	3		
T_1	1	1	1	1	5	4	4	12.59	4.33
T_2	1	2	2	2	1	2	2	3.01	1.66
T_3	1	3	3	3	3	2	2	6.91	2.33
T_4	2	1	2	3	2	2	1	3.01	1.66
T_5	2	2	3	1	4	5	4	12.59	4.33
T_6	2	3	1	2	8	8	9	18.37	8.33
T_7	3	1	3	2	1	2	2	3.01	1.66
T_8	3	2	1	3	2	2	4	7.27	2.66
T_9	3	3	2	1	3	5	5	11.95	4.33

3.1 Signal to Noise Ratio

Larger the Better (SN) Ratio is used for non-availability of anticipated target value, and larger the value of the characteristic, higher is the temperature difference across the stack.

SN ratio is larger the better,

Find the value of SN ratio by using following formula

$$\text{S/N Ratio} = -10\log_{10}\left(\frac{1}{n}*\left(\sum\frac{1}{y^2}\right)\right)$$

……………………………….(Minitab Start Guide)

SN ratio for trial 1,

$$T_1 = -10\log_{10}\left(\frac{1}{3}\sum\left(\frac{1}{5}\right)^2 + \left(\frac{1}{4}\right)^2 + \left(\frac{1}{4}\right)^2\right) = 12.59$$

Similarly, S/N ratio for T2 to T9 is calculated as shown in the table 2.

3.2 Predicted Taguchi Result

Predicted results of all full factorial design are determined using predicted Taguchi analysis in Minitab software. This predicted results show values of SN ratio and mean (response).It shows total 81 predicted results for 4 factor, 3 level design. Predicted results show that experiment number 46 has maximum predicted response of 8.78 K for A2B3C1D1 combination.

As per orthogonal array, nine experiments are performed. The results are fed as input parameter to Minitab software and same are analytically solved as well. The main effect plot for S/N ratio and mean effect plot for means are obtained which revealed optimum parameters with its level as shown in figure 5, for SN ratio and means.

3.2 Main effect plots

Main effect plots show severity of different levels of the factors on the response. The main effect is evident when the response varies with levels of the factors. The Minitab software is used for the analysis. figure 5 shows that Frequency has the most significant effect on SN ratio. This is evident as the 350Hz run gives higher SN ratios than 525Hz run and 700Hz. 525Hz and 700Hz runs have insignificant effect on SN ratio, as represented by the almost flat line in SN ratio plot. Stack position of 150mm has higher SN ratios than 100 mm and 190 mm stack positions.

Thus, maximum value of response in main effect plot for SN ratio and main effect plot for means helps select optimum combination A2-stack position=150mm, B3-stack material=glass fibre with capillary spacers, C1-Fequency=350Hz, D1-wave type = Sine wave. Taguchi method achieves this by two different ways. The first minimizes variability, and the other hits the target.

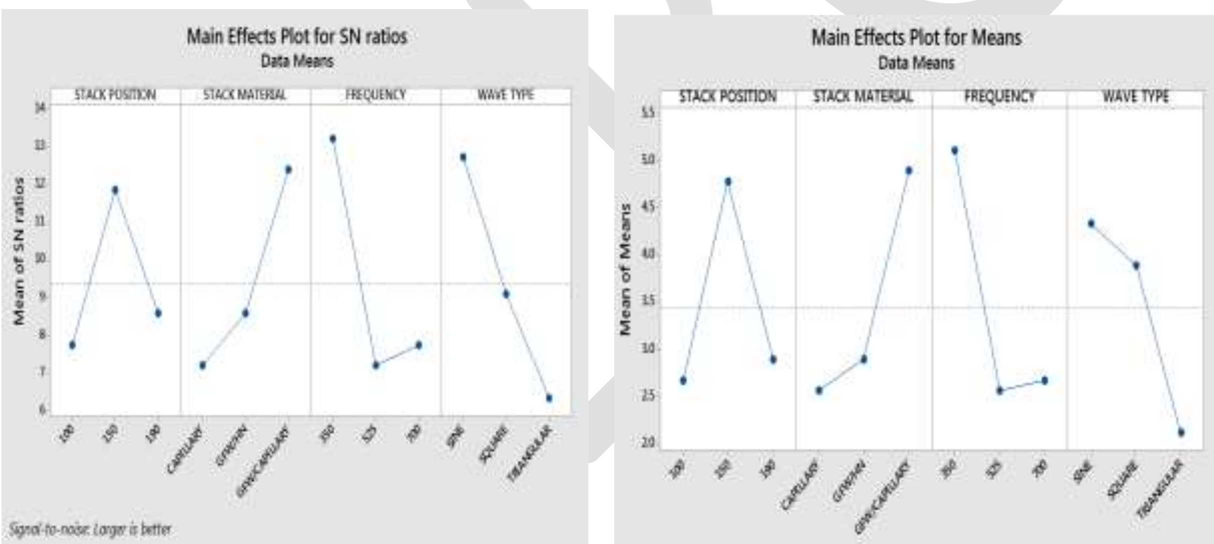

Figure 5: Main effect plot for SN ratios and means

3.3 Contour plots

Contour plots are used to explore the relationship between three variables at a time. Generally, there are two predictors and one response variable. Contour plots are useful for establishing desirable response values and operating conditions. Minitab plots the values for the x and y factors (predictors) on the x and y axes, while contour lines and colored bands represent the values for the z-factor (response).

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Contour plot In Figure 6 shows that the maximum temperature difference occurs near 350 Hz and stack position 150 mm. The lowest temperature differences are found near 550 Hz and 130mm stack position. Contour plot represents functional relationship between stack materials and positions, on response. It is evident that stack material glass fibre with capillary tube spacers and 150mm stack position evokes maximum values of response (temperature difference). Counter plot portrays the effect of frequency and stack material, on response. 350 Hz frequency and glass fibre with capillary tube spacers stack material yields maximum values of response.

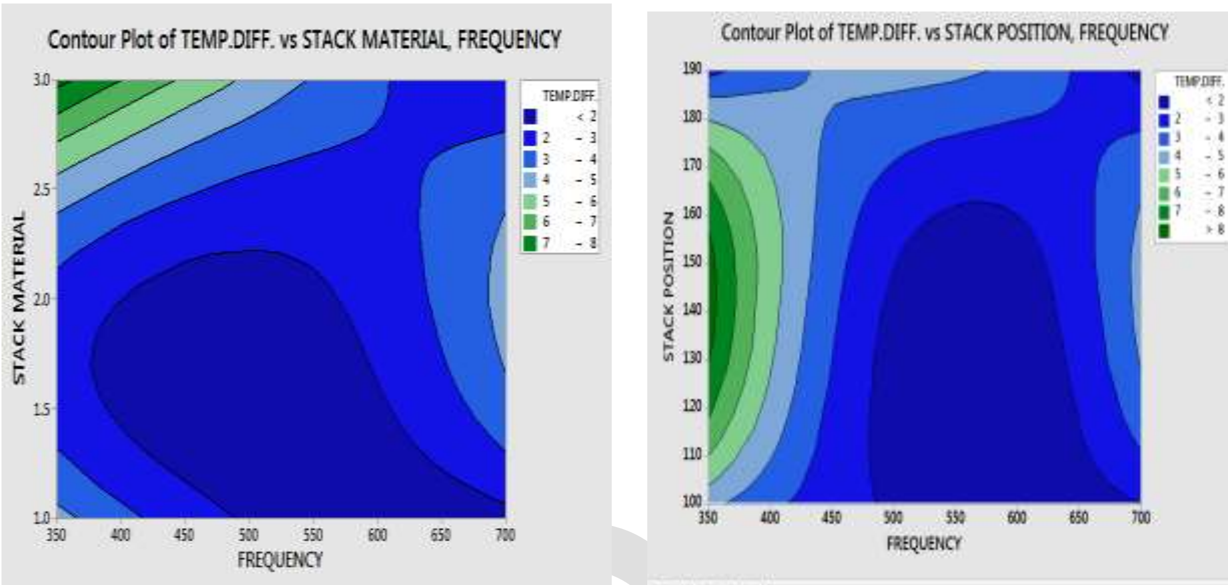


Figure 6: Contour plots of response (temperature difference)

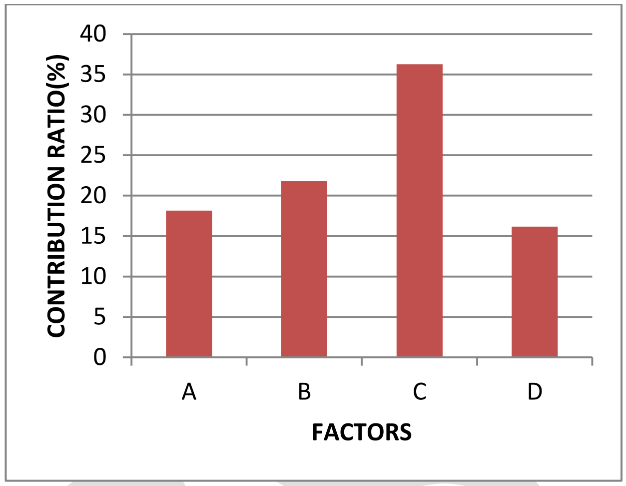
4 ANOVA (Analysis of Variance)

Analysis of variance (ANOVA) is similar to regression and as such is used to investigate and model the relationship between a response variable and one or more predictor variables. Also it is used for multi-factorial study and precise analysis of data. Table 4 shows contribution ratio of individual factor. In figure 6 shows bar chart of all factors and its contribution ratio. Frequency has most contributing factor as compare with other factors.

ANOVA is used to investigate the significance and capability of the model. The ANOVA results of temperature difference across the stack, are presented in Table 4, which effectively represents the relationship between the response (temperature difference) and the significant input variables such as stack material, stack position, frequency and wave type. The mean squares are obtained by dividing the sum by the respective degrees of freedom. The F-value, is calculated by dividing the mean square of the concerned factor variations by variance of error. The F-values of parameter if greater than critical F value selected from F-distribution table, indicates that the factor is statistically significant at 95% of confidence level.

Table 4: ANOVA Table

source of variation	Sum of square	Dof	MS	F value	%P value
A	22.2963	2	11.15	21.49	18.16
B	26.74074	2	13.37	25.78	21.78
C	44.51852	2	22.26	42.92	36.27
D	19.85185	2	9.92	19.14	16.17
ERROR	9.33359	18	0.51		7.60
total	122.741	26	4.72		



F_{18}^{2} (95%) = 3.55 ....From F-value table[11]

ANOVA table shows all values of F value in column, are greater than 3.55, so all factors are significant.

4.1 Verification Run

Predicted Taguchi analysis shows the predicted value of the Temperature difference as optimum value of Temperature difference of 8.78 K.

As per 95% CI = 8.78 K,

For validation of predicted results by Taguchi method, experiments with optimized parameters are to be undertaken.

The experiment for optimum combination of $A_2B_3C_1D_1$ (Stack position 150 mm, Stack material Glass fibre with capillary tube spacers, Frequency 350 Hz and Wave type Sine) produced Temperature difference of 10 K, in close agreement with predicted value.

5. CONCLUSIONS

Using the Taguchi approach, the effect of parameters viz. stack position, stack material, frequency and type of acoustic wave on the TAR performance, in terms of temperature difference has been studied and optimum parameter combination have been obtained.

From the ANOVA results, it is found that the frequency has most contributing factor influencing the performance of TAR.

Confirmation trial is performed for the Taguchi generated optimum combination and thus the predicted response is verified.

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