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Optimizing the Temperature of Cold-outlet Air of Counter-Flow Vortex Tube using Response Surface Methodology

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ABSTRACT

Vortex tube is a device that separates pressurized inlet gas into hot and cold streams. Its main applications are in spot cooling. Hence cold temperature of outlet gas, as a response variable, is of much concern for experimentation. There are various input controllable parameters, the values (levels) of which may affect the cold temperature of outlet gas. Some studies were carried out on vortex tube hitherto, considering different input controllable parameters. The present work analyses the effect of five input controllable parameters viz., inlet gas (air) Pressure, Length of the vortex (hot)tube, Diameter of the vortex(hot) tube, Diameter of the orifice / diaphragm, and Diameter of the nozzle on the response variable-Temperature of cold-outlet stream of air. Response Surface Methodology (RSM) approach is used to optimize the response. L-27 Orthogonal Array (OA) is used for experimentation. Response is of "Smaller the Better" type. Regression equation is obtained. All the parameters considered but the Length of the vortex tube, are found to be significant from the Analysis of Variance (ANOVA) table. Optimum levels for factors are predicted, confirmatory test is run and the experimental results are validated.

Introduction

A vortex tube separates the input compressed gas into hot and cold streams. Using a conical valve built into the hot air exhaust, the volume and temperature of these two air streams can be altered. A nozzle is located in the vortex chamber. Air from a compressor is supplied to the vortex tube and passes through the nozzle tangentially. Thus vortex motion is given by nozzle to the air. This stream of air passes down the hot tube in the form of a spinning shell. A conical valve at the other (hot) end of the tube allows some of the heated air to escape. Remaining air heads back as a smaller second vortex, inside the low-pressure area of the larger vortex. This inner vortex loses heat and comes out as cold air through the orifice kept in the cold tube after the vortex chamber as shown in Fig. 1. The outer vortex is under higher pressure than the inner vortex (because of centrifugal force) and therefore the temperature of the outer vortex air is higher than that of the inner vortex air.

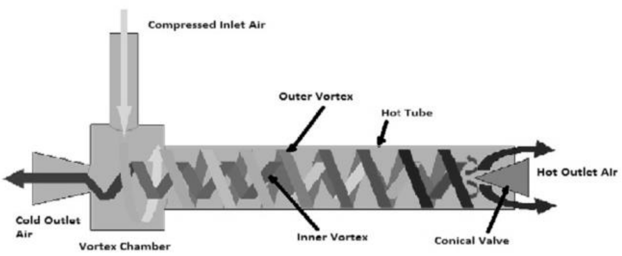

Fig. 1: Working of Counter flow Vortex tube

The main parts of the vortex tube used as shown in Fig. 2 are:

1. Hot and Cold tubes 2. Vortex Chamber 3. Orifice/ Diaphragm 4. Nozzle 5. Conical Valve

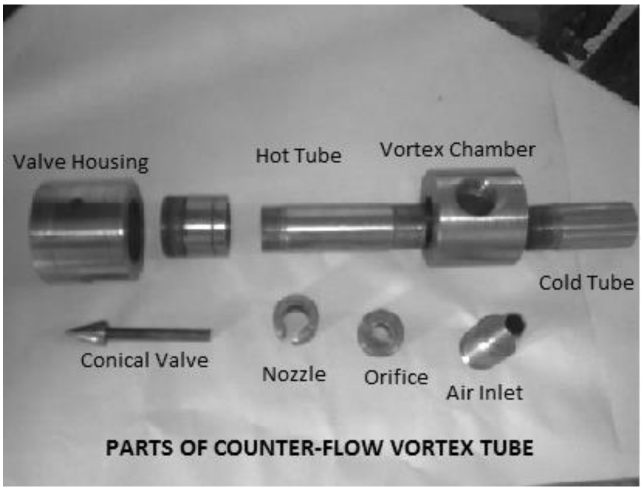

Fig. 2: Construction and Parts of Counter flow Vortex tube

Many researches focused on optimizing the performance of the vortex tube with respect to its construction design features, input parameters and so on. Other studies tried to analyze the heat transfer phenomenon within the vortex tube using Computational Fluid Dynamics (CFD) and other numerical procedures. Vortex tube is mainly used for spot cooling and hence optimization of cold outlet temperature of the vortex tube has been the major concentration of these studies. Some studies attempted to optimize the temperature difference between the hot and cold outlet temperatures considering different input parameters. A.M. Pinar et.al. [1], in their studies, tried to maximize the temperature difference between the hot and cold outlet temperatures using Taguchi method. That study revealed all the three parameters considered and their two way interactions to be significant on the response, statistically. To

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analyze the effect of vortex angle on the efficiency and performance of the vortex tube, Y. Xue et.al. [5] used vortex angle generator to form different vortex angles. It is concluded that the vortex angle plays an important role in both the separation of cold and hot flows and vortex tube performance. A smaller vortex angle demonstrated a larger temperature difference and better performance for the heating efficiency of the vortex tube. Again, A.M. Pinar et. al. [4] in their other work, considered inlet pressure, nozzle number and cold mass fraction as affecting factors, each at three levels. It is observed that the quality characteristic-temperature difference increased with the increase of inlet pressure and cold mass fraction and decreased with the increase in nozzle number. L27 OA is used for experimentation and Taguchi method is used for parameter optimization. The effect of cooling the vortex tube on the temperature separation (Ti – Tc) is studied by S. Eiamsa-ard et. al. [6]. It is observed that cooling efficiency in the vortex tube is higher when the tube is externally cooled than when it is not cooled, operating under similar conditions. Prabakaran et. al. [8] used Response Surface Methodology to optimize temperature difference with pressure, orifice diameter and nozzle diameter as the factors. Pressure, and nozzle diameter are shown to be significant factors affecting the temperature difference.

Response surface Methodology is a collection of statistical and mathematical techniques useful for developing, improving and optimizing the process parameters. The RSM can be used when many input variables potentially influence few performance measures or quality characteristics of the process. Thus the performance measure is called as response. The input variables are called independent variables. The response can be modelled appropriately by a linear function or a curvilinear function of independent variables. The objective of using the RSM is not only to investigate the response over the entire factor space, but also to locate the region of interest where the response reaches its optimum or near optimum value. The Design of Experiments with optimization of control parameters to obtain best results can be achieved by Response Surface Methodology (RSM). "Orthogonal Arrays" (OA) provide a set of well balanced (minimum) experiments and experimentation may be carried in accordance with the OA selected. Results thus obtained are analyzed using RSM. Response surface plots / contour plots are drawn and regression equation, that describes the relationship between the response variable and the controllable factors, is developed. Effect of the controllable factors on the response can be studied using the graphs and their statistical significance through ANOVA table. Optimum factor settings and corresponding optimum response value is predicted. Confirmation test is run with the optimum factor level settings, to validate the experimental results.

Objective of Present Study:

To study the influence of the controllable parameters selected, viz., inlet air Pressure, Length of the vortex (hot) tube, Diameter of the vortex(hot) tube, Diameter of the orifice / diaphragm, and Diameter of the nozzle, on the Temperature of cold-outlet air (T_c °C) of the vortex tube.

Experimental work

The vortex tube used in the present work is of counter flow type using one nozzle. The standard L-27 Orthogonal Array (OA) layout in coded form is taken and the level values of the five factors selected are appropriately substituted. One column is added to the right side for noting the response values. Experimental runs order is taken to be the same as given by the table. Experimentation is carried out and response (T_c °C) values are noted for all the 27 run conditions as shown in Table 1.

Results Analysis and Discussion:

The results obtained after experimentation are analyzed. The ANOVA table as shown in Table 2 gives the statistical significance of factors. Those terms that have the P value < 0.05 are significant and others are not in Table 2. Thus, except Length of the hot tube, other linear factors are significant.

Assuming full quadratic relationship, regression coefficients are estimated and are presented in Table 3.

R-Sq = 98.66% R-Sq(pred) = 91.39% R-Sq(adj) = 97.09%

Regression Equation developed from the above Table 3, for the terms is:

$$T_c = 144.617 - 0.102 * L - 7.975 * D_t - 10.049 * D_n + 4.250 * D_o - 7.889 * P + 0.272 * (D_t)^2 + 0.346 * (D_n)^2 - 0.222 * (D_o)^2 + 0.111 * P^2 + 0.111 * P * D_t + 0.056 * P * D_n + 0.125 * P * D_o$$

Graphs:

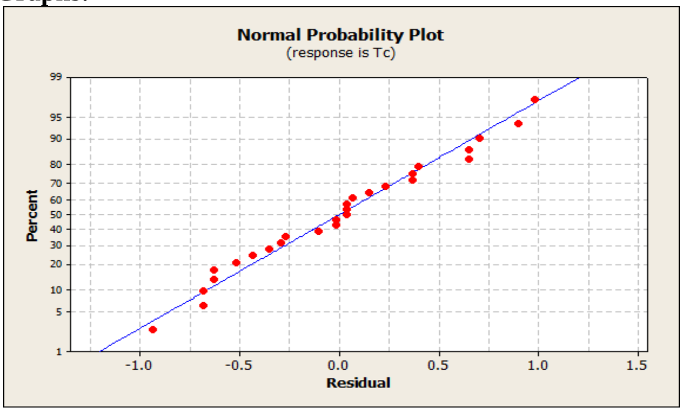

Fig. 3a: Normal Probability Plot

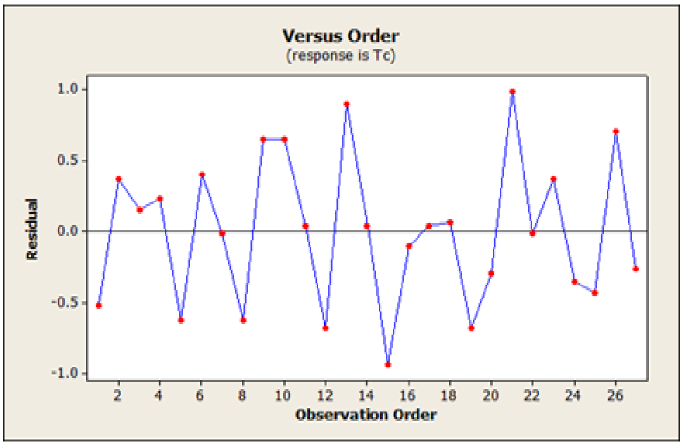

Fig. 3b: Residuals vs. Observation order Plot

Fig. 3 a shows that the data values obtained for the response follow normal distribution. From the fig. 3 b, since the points are randomly scattered about the 0-line, it can be concluded that there is no effect of observation order on response values obtained.

From the Surface / Contour plots, effects of change of levels of pair of any two factors on the response variable, i.e., the cold outlet temperature can be studied. Surface plots as depicted in Fig. 4 are three dimensional and show the response surfaces, whereas the contour plots as depicted in Fig. 5 are two dimensional response surfaces. For instance, lower response values (cold outlet air temperature) less than 10 °C are possible with D_o around 6 mm and inlet air pressure > 3 Kgf/cm^2 , as can be interpreted from the first plot of Fig. 5. Fig. 6 gives the optimal setting of factors with the corresponding optimal response value.

Table 1: L-27 Orthogonal Array with uncoded level values and Response column

Trial No.	L (cm)	D_t (cm)	D_n (cm)	D_o (cm)	P(Kgf/cm^2)	T_c (°c)
1	120	11	11	6	1	25
2	120	11	11	6	2	21
3	120	11	11	6	3	16
4	120	14	14	8	1	21
5	120	14	14	8	2	16
6	120	14	14	8	3	13
7	120	17	17	10	1	25
8	120	17	17	10	2	22
9	120	17	17	10	3	19
10	150	11	14	10	1	25
11	150	11	14	10	2	20
12	150	11	14	10	3	15
13	150	14	17	6	1	21
14	150	14	17	6	2	15
15	150	14	17	6	3	11
16	150	17	11	8	1	26
17	150	17	11	8	2	22
18	150	17	11	8	3	18
19	180	11	17	8	1	25
20	180	11	17	8	2	21
21	180	11	17	8	3	18
22	180	14	11	10	1	25
23	180	14	11	10	2	21
24	180	14	11	10	3	17
25	180	17	14	6	1	19
26	180	17	14	6	2	16
27	180	17	14	6	3	11

Table 2: Analysis of Variance (ANOVA) for Means:

Analysis of Variance(ANOVA) for Tc(°c)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	14	485.898	485.898	34.7070	62.91	0.000
Linear	5	384.278	109.524	21.9047	39.70	0.000
L	1	1.389	0.547	0.5474	0.99	0.339
Dt	1	3.556	38.400	38.4004	69.60	0.000
Dn	1	10.889	60.970	60.9704	110.51	0.000
Do	1	64.222	6.535	6.5352	11.85	0.005
P	1	304.222	6.371	6.3709	11.55	0.005
Square	5	99.204	99.204	19.8407	35.96	0.000
L*L	1	0.463	0.463	0.4630	0.84	0.378
Dt*Dt	1	35.852	35.852	35.8519	64.98	0.000
Dn*Dn	1	58.074	58.074	58.0741	105.26	0.000
Do*Do	1	4.741	4.741	4.7407	8.59	0.013
P*P	1	0.074	0.074	0.0741	0.13	0.720
Interaction	4	2.417	2.417	0.6042	1.10	0.403
L*P	1	0.000	0.000	0.0000	0.00	1.000
Dt*P	1	1.333	1.333	1.3333	2.42	0.146
Dn*P	1	0.333	0.333	0.3333	0.60	0.452
Do*P	1	0.750	0.750	0.7500	1.36	0.266
Res. Error	12	6.620	6.620	0.5517		
Total	26	492.519				

Table 3: Estimated Regression Coefficients for Tc(^c)

Term	Coeff.	SE Coef	T	P
Constant	144.617	13.3165	10.860	0.000
L	-0.102	0.1022	-0.996	0.339
Dt	-7.975	0.9559	-8.343	0.000
Dn	-10.049	0.9559	-10.513	0.000
Do	4.250	1.2348	3.442	0.005
P	-7.889	2.3215	-3.398	0.005
L*L	0.000	0.0003	0.916	0.378
Dt*Dt	0.272	0.0337	8.061	0.000
Dn*Dn	0.346	0.0337	10.260	0.000
Do*Do	-0.222	0.0758	-2.931	0.013
P*P	0.111	0.3032	0.366	0.720
L*P	-0.000	0.0071	-0.000	1.000
Dt*P	0.111	0.0715	1.555	0.146
Dn*P	0.056	0.0715	0.777	0.452
Do*P	0.125	0.1072	1.166	0.266

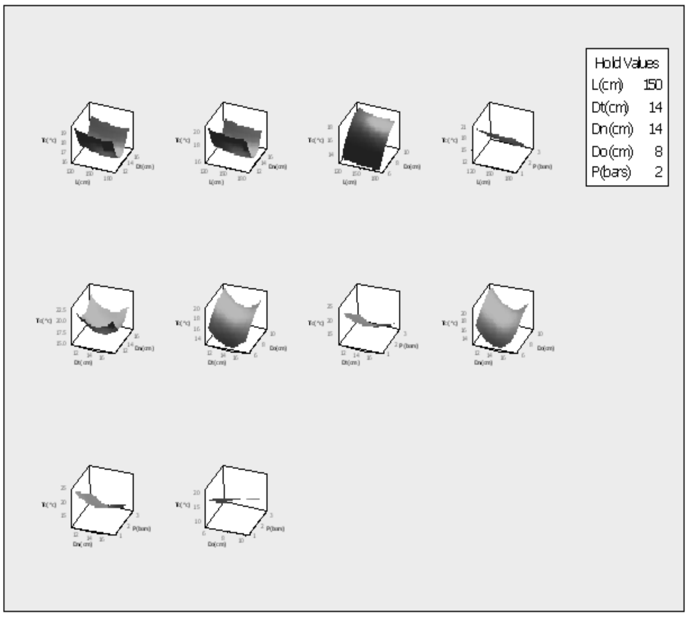

Fig. 4: Surface Plots between two factors and the Response variable

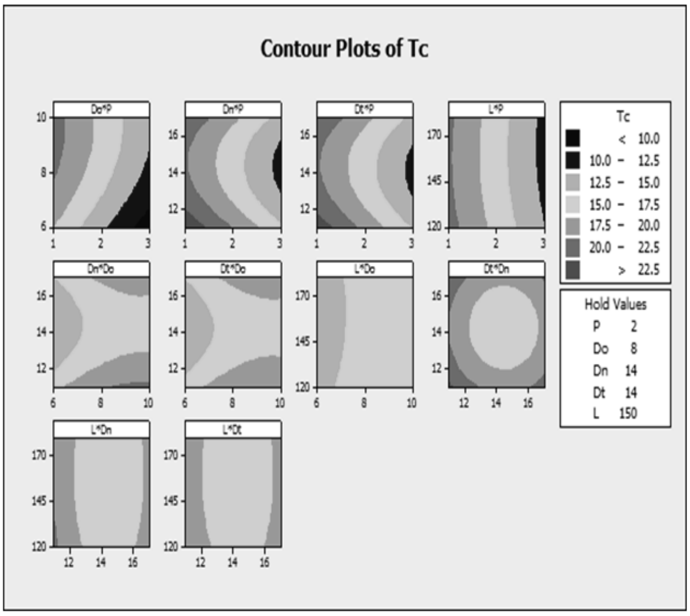

Fig. 5: Contour Plots between two factors and the Response variable

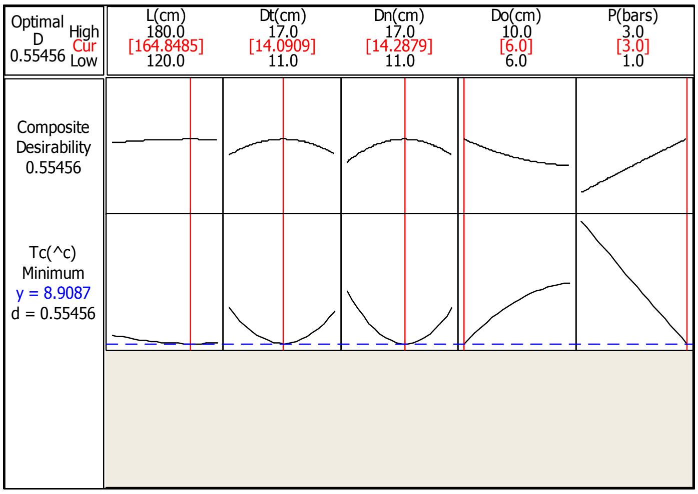

Fig. 6: Response Optimizer

Prediction of Optimal levels / settings for factors:

From Fig. 7, L = 165 mm, D_t = 14 mm, D_n = 14 mm (rounded to an mm), D_o = 6 mm, and P = 3 Kgf / cm^2 are the optimal settings for the factors predicted and the corresponding optimized response value is 8.91 ^oC

A confirmatory test is run and results are presented in Table 4. The mean response value is 9.2 ^oC with a standard deviation of 0.837 ^oC.

Table 4: Confirmatory test results

Trial No.	1	2	3	4	5
T_c (^{o}C)	10.0	8.0	9.0	10.0	9.0

Average T_c = **9.2 ^{o}C** with a Standard deviation = **0.837 ^{o}C**

The % Error calculated = (9.2 - 8.9) / 8.9 = 3.26

As the % error is smaller in magnitude, the experimental results are validated.

Conclusions:

It is concluded that all the factors selected but the Length of the hot tube have significant effect on the response variable – temperature of cold outlet air, statistically. With the optimal factor settings of L = 165 mm, D_t = 14 mm, D_n = 14 mm, D_o = 6 mm, and P = 3 Kgf / cm^2, a cold temperature of around **9 ^{o}C** achievable.

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