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Performance Estimation of a Solar Box Cooker by Approaching Taguchi Technique

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Abstract - **Demand of energy is increasing day by day in this developing world in every sector of life. Many alternative energy sources are supporting us, in which, cooking by solar energy is pretty familiar to everyone. According to various International societies, promoting solar cookers, in progressively active mode, solar box cookers are very popular in the field of cooking due its economical and ecological benefits. An attempt is made to evaluate the performance of a solar box cooker by using Taguchi method. Among the important operating and system parameters, three parameters have been selected viz. ambient temperature (Tamb), solar radiation (H) and medium (particles spreaded). Based upon experiments their confirmatory equations have been developed and compared with the obtained experimental values for a good satisfaction.**

Keywords : **Box cooker, Performance, Solar energy, Taguchi**

Nomenclature

A	Aperture area (m^2)
C_W	Specific heat of water (J/kg-K)
F_1	First figure of merit
F_2	Second figure of merit
H	Solar radiation (W/m^2)
M_W	Mass of water (kg)
t	Time difference between readings (s)
U_L	Overall heat loss coefficients (J/s-K)
T_{w1}	Initial water temperature (^oC)
T_{W2}	Final water temperature (^oC)
T_p	Plate temperature (^oC)
T_{sc}	Stagnation temperature (^oC)
T_{amb}	Ambient temperature (^oC)
η	Overall efficiency of solar box cooker
SBC	Solar box cooker

1. Introduction

Solar thermal energy finds its simplest application in the form of solar cooking, which in itself has enormous potential for reducing dependence on conventional fuels in the various households worldwide. The different types of solar cookers developed for cooking are, a box type, a concentrator type, and an indirect type [1-2]. The detailed design, performance test procedures, theory and utility of solar cookers are well developed. An indirect solar cooker uses a fluid to transfer heat from a solar collector to the cooking pots via a heat pipe [3], but it has more advantages than a box type or concentrator cookers because it provides high thermal power and temperatures without tracking and allows cooking in the shade or even in a conventional kitchen. One exception is that cooking of food is not possible in the evening [4].

Well, the other major fact is that cooking is an activity that must be carried out almost on a daily basis for the sustenance of life. An enormous amount of energy is thus expended regularly on cooking. In most of the rural homes and many urban homes, the traditional and most popular source of energy for cooking is firewood. There has been a considerable recent interest in thedesign, development and testing of various types of solar cookers like box type [5–7], concentrator type [8-9] and oven type [10-11] around the globe. Out of these types of solar cookers, only the box type solar cookers have so far been disseminated at the mass level in India [12-13]. Box type solar cooker, is the simplest in terms of operation and fabrication and the temperature of around 100^0C is achieved. This range of temperature is suitable for cooking by boiling, which is prevalent in most parts of India. A few attempts have been made in the past to introduce and popularize solar cookers. The most extensive attempt was perhaps made with the help of solar scientists and anthropologists to introduce solar cookers in Mexico. These cookers had rigid plastic reflectors with reflective films bonded to the front surfaces; they were not successful due to mechanical failures. Later, the cooker was redesigned, modified and found to be the most successful [14]. In India the design is approved by the Ministry of Non-conventional Energy Sources (MNES), which consists of inner and outer boxes made of aluminium and fiber-glass respectively. The dimensions of inner box are generally 45 x 45 x 8 cm^3. All types of foods like cereals, pulses, vegetables, roots (Like potato etc.), eggs, soup can be easily cooked in this cooker. 3.66 $x10^5$ solar cookers were sold in the local markets since March 1995 [15] but now, these cookers has touch the limit of around 6.5 lakhs to be sold out [16].

Universal principles of thermodynamics can be applied to the cookers to realize their differing performances qualitatively with respect to heat transfer and energy transformation. Solar cookers are systems that via reflector attentiveness allow an arrival of energy through their transmissive surfaces. Upon absorption visible light wavelengths become tainted producing heat that becomes trapped until the cookers reach thermal equilibrium with their surrounds. Although solar energy does not decrease (1st Law) it has tainted from ~6000K solar radiation to the aluminum block temperatures recorded (~350K). Exergy accounts for the change in value of energy experienced as a temperature change and therefore is a more significant measurement for solar cooker efficacy. Heat transfer into and out of the system produces augmented entropy as put forth by the second law of thermodynamics [17-19]. Generally cookers are thermally rated according to the stagnation plate temperature, time required for cooking different food substance and the time required to raise the temperature of a known amount of water to its boiling point [20]. The design parameters of solar cooker are among the several other important parameters that influence its thermal performance. Therefore, the knowledge of these design parameters is essential for evaluation and comparison of different cooker designs, in addition to providing a basis for the selection of proper materials for the construction of cooker. In order to investigate the thermal performance of a box- type solar cooker in a better qualitative manner, it is therefore necessary to have the knowledge of design parameters optical efficiency and heat capacity of the cooker.

Taguchi's technique has been fined popular for parameters optimization in the design of various engineering applications. Many of researchers and scientists have already been successfully applied this method for optimization of problems. Sahin *et al.* used Taguchi method for optimizing the design parameters of heat exchanger [21]. Yakut *et al.* employed Taguchis method to optimize the design parameters of heat exchangers having hexagonal fins [22]. Win *et al.* applied Taguchi method for optimizing the diesel engine operation and injection system parameters for low noise emissions and fuel consumption [23]. Ganapathy *et al.* used Taguchi method for optimization of various performance parameters of an I.C engine [24]. Beside this, Taguchi technique has also been used for various types of solar flat plate collectors and other related applications [25-28]. Beyond this if we have look towards the world of solar cookers than, in the past decade a few techniques have already been effectively applied to evaluate the thermal performance parameters estimation of box cookers or thermal behavior of them [29-32]. In the present case the sensitivity analysis has been carried out to test the parameters of solar box cooker for the performance, on the basis of two figures of merits and verified by the Taguchi method. The first figure of merit, F1 of a box-type solar cooker is defined as the ratio of optical efficiency to overall heat loss coefficient and is obtained by relation; [33].

$$\eta_o \text{ x } H = U_L \text{ x } (T_p - T_{amb}) \qquad [1]$$

Hence, first figure of merit becomes

$$F_1 = \eta_o / U_L = (T_p - T_{amb}) / H \qquad [2]$$

The second figure of merit, F_2 of a box-type solar cooker can be obtained by operating the cooker on load (putting some substance inside the cooker usually water), hence Second figure of merit:

$$F_2 = \frac{F_1 (MC)_w}{At} \ln \left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w1} - T_{amb}}{H}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w2} - T_{amb}}{H}\right)} \right] \qquad [3]$$

By using the Equations 2 and 3, the obtained value for the figures of merits F_1 and F_2 have been evaluated. By using the Eqs.1 and 2, the obtained value for the figures of merits F_1 and F_2 have been evaluated.

II. Experimental Set up

A series of out-door experiments was carried out for the determination of two figures of merit F_1 and F_2 during the month of May 2011. Performance testing of a SBC is shown in Fig 2. In the design construction of a SBC, a rubber gasket of 1.5 mm was provided between the tray and the open-able frame to make it leak proof. One 4mm thick plane mirror reflector was fixed over it. The reflector can be placed over the cooker and acts as a lid as well as facilate to track the sun accordingly, during the cooking process. The cooker was placed towards the south during conduction of experiments. The key feature of this cooker was it high heat absorbing capacity. A mixture of sand and granular carbon was introduced as the heat absorbing material on the surface of absorber plate in SBC and the thickness of the mixture layer was 1 mm, which was completely sealed with a float glass [34]. A commercially cooker has been modified to introduce high sensible heat storage, and to evaluate the performance testing with given specifications.

Specifications of Box type solar cooker taken for performance evaluation

Dimensions of outer box	540 × 540 × 160 mm^3
Material for outer casing of the cooker Fiberglass	
Dimension of tray shaped absorber plate	(i) Top 455 × 435 mm^2
	(ii) Bottom 380 ×400 mm^2
Depth of the tray	80 mm
Emissivity of the absorber plat	0.90
Material for absorber plate material	Aluminum (Blackened)
Specific heat of absorber plate material	938 J/kg °C
Thickness of absorber plate	0.60
mm Thickness of glass covers	2 mm
Spacing between the glazing	10 mm
Emissivity of glass	0.86
Specific heat of water	4200 J/kg°C
Type of insulation	Glass-wool
Thermal conductivity of insulation	0.05 W/m°C
Thickness of insulation at the bottom	50 mm
Pot height	65 mm
Pot diameter	160 mm
Mirror booster (single)	460 x 460 mm^2

The variations of temperature in the solar cooker are measured at a regular time interval of ten minutes. The ambient temperature is measured by using a, six wires, K-type thermocouple meter with an accuracy of ±1°C. The solar insolation (mW/cm^2) on the horizontal surface is directly measured by a solari meter, "SURYA-MAPI" (CEL-201) with an accuracy of 1 mW/cm^2. The thickness of the glasses, glazing, and the absorber tray was measured by a micrometer with a least count of 0.01 mm.

Many International standards, like ISO, are mainly used to determine the collector efficiency by means of least square method while using such standards, it becomes essential to have a certain level of accuracy in sensors, instrumentations, and control systems. But the fact remains that there is no prescribed methodology is available to determine the uncertainty of the efficiency curve parameters [35]. Beside this, for the box cookers, the level of accuracy in sensors and instrumentations is not exceeding than a value of 2.5% for F1 and 5% for F_2 to evaluate the thermal behavior of a SBC [36-37]. Hence, only the sensitivity analysis has been carried out to estimate the performance of a SBC in this article. Other major side of the solar cooking process that the present International standards for solar cookers are the trademark or guarantee of acceptance of the product at international level, it does mean that the product is working good or not. Many of the people self, made the efficient box cookers and regularly use on it at different places of this world. Likely cooker does not follow any national or international standard but are in use [38-40].

A. Taguchi Method

The Taguchi method is a commonly adopted approach for optimizing design parameters. The method was originally proposed as a means of improving the quality of products through the application of statistical and engineering concepts [41-42].Since experimental procedures are generally expensive and time consuming, the need to satisfy the design objectives with the least number of tests is clearly an important requirement. The Taguchi method involves laying out the experimental conditions using specially constructed tables known as orthogonal arrays. The use of these tables ensures that the experimental design is both straightforward and consistent. Adopting the Taguchi approach, the number of analytical explorations required to develop a robust design is significantly reduced, with the result that both the overall testing time and the experimental costs are minimized [43-45].

B. Implementation of an Experiment

The L16 (3^3) inner orthogonal array permits the analysis of three four-level factors [46-47]. The array comprises three columns, within which each entry can be assigned to one of four different levels. Additionally, the array consists of sixteen rows, where each row represents a trial condition with a particular combination of factor level settings. In other words, the information required to fully analyze factors and their respective level settings can be obtained from just nine experimental trials, each trial having many repetitions with outer array. In the Taguchi approach, the controllable factors are assigned to particular columns of the inner orthogonal array [48]. Accordingly, the present study assigns the ambient temperature (factor A), solar radiation (factor B), and medium type (factor C) to columns 1, 2 and 3 of the adopted L16 (3^3) inner orthogonal array, respectively (Table I) and each trial will be replicated several times with different level settings of adopt forecasting methods parameters of the outer arrays. In practice, these factors can be assigned arbitrarily to any of the arrays columns, provided that all combinations are included. After assigning appropriate level settings, the S/N analysis [49] is needed to evaluate experiment results. In S/N analysis, the greater the S/N, the better the experimental results:

$$\eta = -10 \log (\text{M.S.D.}) \qquad [4]$$

where, M.S.D. is the mean-square deviation for the output characteristic.

As mentioned earlier, there are three categories of quality characteristics, i.e. lower-the-better, higher-the-better, and nominal-the-better. To obtain optimal performance, higher-the-better quality characteristic must be taken. The mean-square deviation (M.S.D.) for higher-the-better quality characteristic can be expressed as:

$$\text{M.S.D} = \frac{1}{m}\sum_{i=1}^{m}\frac{1}{T_i^2} \qquad [5]$$

where m is the number of tests and Ti is the value of experimental results and the ith test.

Furthermore, a statistical analysis of variance (ANOVA) is performed to see which process parameters are statistically significant [50-51]. With the S/N and ANOVA analyses, the optimal combination of the process parameters can be predicted. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the parameter design.

To summarize, the parameter design of the Taguchi method includes the following steps: (1) identification of the quality characteristics and selection of design parameters to be evaluated; (2) determination of the number of levels for the design parameters and possible interactions between the design parameters; (3) selection of the appropriate orthogonal array and assignment of design parameters to the orthogonal array; (4) conducting of the experiments based on the arrangement of the orthogonal array; (5) analysis of the experimental results using the S/N and ANOVA analysis; (6) selection of the optimal levels of design parameters; and (7) verification of the optimal design parameters through the confirmation experiment. Therefore, three objectives can be achieved through the parameter design of the Taguchi method, i.e: (1) determination of the optimal design parameters for a process or a product; (2) estimation of each design parameter to the contribution of the quality characteristics; and (3) prediction of the quality characteristics based on the optimal design parameters.

III. Results and Discussion

A. Analysis of Experimental Results

In Table II, the fifth column, seventh column, ninth column and eleventh column represents S/N ratio of the water temperature (Tw), Stagnation temperature (Tsc), First figure of merit (F1) and second figure of merit (F2) respectively. The overall mean for the S/N ratio of water temperature (Tw), Stagnation temperature (Tsc), First figure of merit (F1) and second figure of merit (F_2) are found to be 36.65db, 40.39db, -21.04db and -14.08db respectively for solar box cooker. The analysis was made using the popular software specifically used for design of experiment applications known as MINITAB 14 [52]. Analysis of the result leads to the conclusion that factor combination of factor A_2, B_1 and C_3 gives maximum water temperature (Fig 2), A_4, B_1 and C_3 gives maximum Stagnation temperature (Fig 3), A_1, B_1 and C_3 gives maximum First figure of merit (Fig 4) and A_4, B_2 and C_3 gives maximum second figure of merit (Fig 5) respectively.

B. Analysis of Variance

Analysis of Variance (ANOVA) is performed on experimental data to identify the parameters and interactions that influence the output variable. Tables III a, b, c, and d show the ANOVA result for water temperature (Tw), Stagnation temperature (Tsc), First figure of merit (F_1) and second figure of merit (F_2) for solar box cooker respectively.

The F-ratio, which is used to measure the significance of factor at the desired significance level, is the ratio between variance due to the effect of a factor and variance due to error term. This analysis is undertaken for a level of confidence of significance of 5%. The last column of the table indicates that the main effects are highly significant (all have very small p-values) [53].

From Table IIIa, it can be observed that medium ($p = 0.014$) and radiation ($p = 0.571$), have great influence on water temperature whereas ambient temperature ($p = 0.699$) has relatively lesser effect on the output. But the factor ambient temperature cannot be omitted from the list, as ambient temperature is considered as a major factor in order to find the water temperature.

Similarly, from Table IIIb, it can be observed for the medium ($p = 0.007$) and ambient temperature ($p = 0.292$) show significant control factor in the order of their increasing order for maximizing the Stagnation temperature. Between the three control factors radiation is less significant as compare to other two factors. But from this analysis factor radiation is not omitted as radiation is one of the major control factors in order to find out the Stagnation temperature. Similarly, from Table IIIc and Table IIId, it can be observed that for the medium ($p = 0.009$) is more significant for first figure of merit and ambient temperature is important significant control factor for second figure of merit.

IV. CONFIRMATION OF EXPERIMENT

The optimal combination of control factors has been determined in the previous section. However, the final step in any design of experiment approach is to predict and verify improvements in observed values through the use of the optimal combination level of control factors. The confirmation experiment is performed by conducting a new set of factor combination $A_3B_4C_2$ on water temperature as evident from Table IV. As for as Stagnation temperature concerned the following factors $A_2B_2C_1$ are taken into account, similarly for prediction of First figure of merit and Second figure of merit the following factor combinations are taken into considerations as: $A_2B_3C_1$, $A_3B_1C_4$ respectively. The estimated S/N ratio for all the out puts is calculated with the help of following prediction equation:

$$\hat{\eta}_{\text{water temp.}} = \bar{T} + (\bar{A}_3 - \bar{T}) + (\bar{B}_4 - \bar{T}) + (\bar{C}_2 - \bar{T}) \qquad (6)$$

$$\hat{\eta}_{Stagnation\ temp.} = \bar{T} + (\bar{A}_2 - \bar{T}) + (\bar{B}_2 - \bar{T}) + (\bar{C}_3 - \bar{T}) \qquad (7)$$

$$\hat{\eta}_{\text{First figure of merit}} = \bar{T} + (\bar{A}_2 - \bar{T}) + (\bar{B}_3 - \bar{T}) + (\bar{C}_3 - \bar{T}) \qquad (8)$$

$$\hat{\eta}_{\text{Second figure of merit}} = \bar{T} + (\bar{A}_3 - \bar{T}) + (\bar{B}_1 - \bar{T}) + (\bar{C}_4 - \bar{T}) \qquad (9)$$

$\bar{\eta}_{\text{water temp.}}$, $\bar{\eta}_{\text{Stagnation temp.}}$, $\bar{\eta}_{\text{First figure of merit}}$ and $\bar{\eta}_{Second\ figure\ of\ merit}$, Predicted average, and $\bar{T}$ Overall experimental average, $\bar{A}_2, \bar{A}_3, \bar{B}_1, \bar{B}_2, \bar{B}_3, \bar{B}_4$ and $\bar{C}_2, \bar{C}_3, \bar{C}_4$, Mean response for factors at designated levels.

A new combination of factor levels is used to predict water temperature through prediction equation and it is found to be $\bar{\eta}_{\text{water temp}} =$ 34.88db, similarly for stagnation temperature $\bar{\eta}_{\text{Stagnation temp.}} =$ 41.34db, for first figure of merits $\bar{\eta}_{\text{First figure of merit}} =$ -19.89db and for second figure of merits $\bar{\eta}_{\text{Second figure of merit}} =$ -28.43db respectively. For each performance measure, an experiment is conducted for different factors of combination and then compared with the result obtained from the predictive equation as shown in Table IV.

The resulting model seems to be capable of predicting First figure of merit and Second figure of merit to a reasonable accuracy. An error of 4.56%, 3.78%, 2.14% and 3.25 % for the S/N ratio of water temperature, stagnation temperature, first figure of merit and second figure of merit are observed. However, the error can be further reduced if the number of measurements is increased. This validates the development of the mathematical model for predicting the measures of performance based on knowledge of the input parameters.

V. CONCLUSION

The contributions of all the operational parameters (ambient temperature, solar radiation, and medium) in SBC performance have identical importance. The results from this study show successful performance of the experimental plane reflector augmented box type solar cooker. The results justify the modifications made to the design of traditional solar box cookers. The solar cooker performance has been observed better improved with the plane reflector in place. The analysis confirms the first and second figures of merit as reliable design and performance rating criteria for solar cookers. The results obtained in this study, of which only a small part is presented here, form a useful database for the validation of theoretical models in addition to their intrinsic value of characterizing the cooker.

Inlet fluid temperature, Difference between inlet & outlet fluid temperature

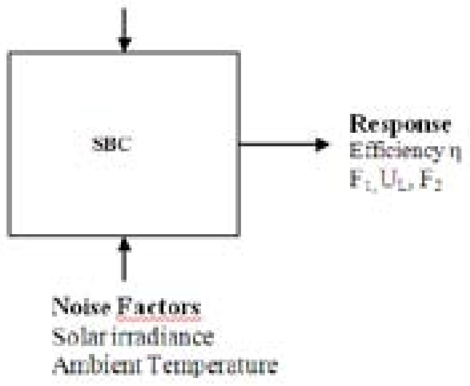

Fig. 1 Design Parameters of a solar box cooker

Fig. 2 Thermal performance testing of a SBC

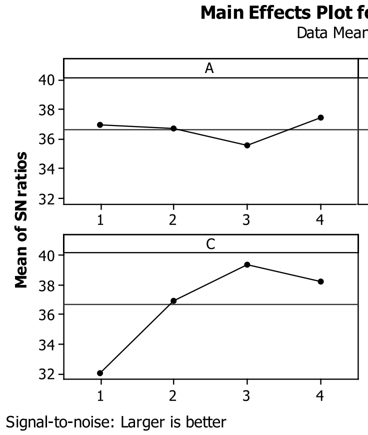

Fig. 3 Effect of control factors on water temperature

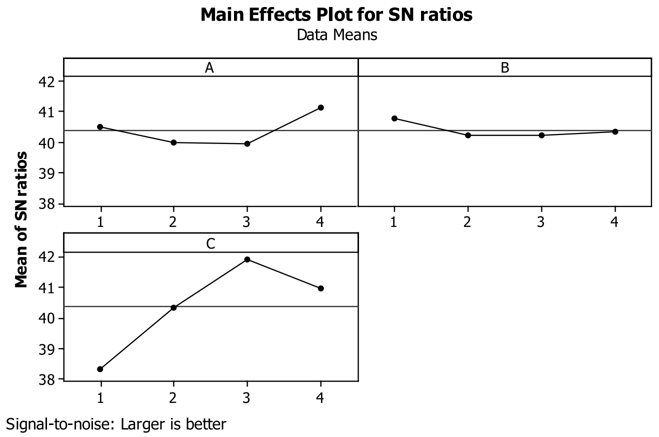

Fig. 4 Effect of control factors on Stagnation temperature

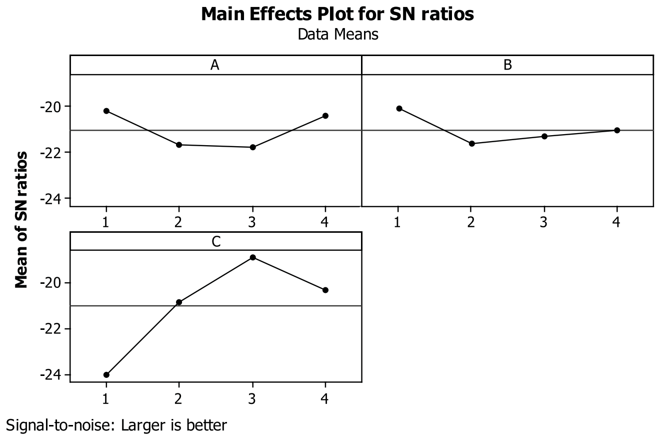

Fig. 5 Effect of control factors on First figure of control factors

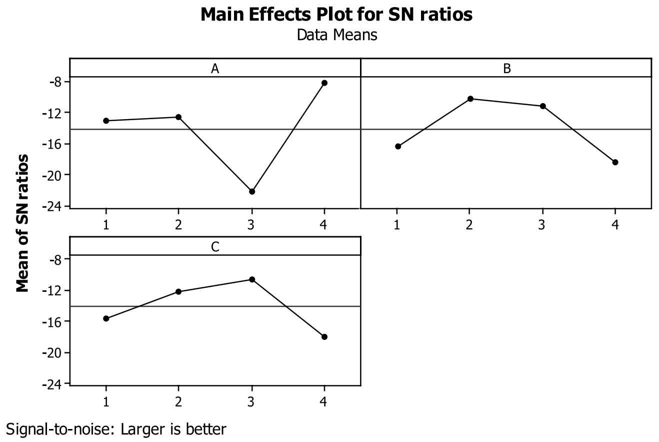

Fig. 6 Effect of control factors on second figure of control factors

TABLE I LEVELS FOR VARIOUS CONTROL FACTORS

Control factor	Level				
	1	2	3	4	Units
A: Ambient temperature	30	31	32	33	^0C
B: Radiation	740	750	760	780	W/m^2
C: Medium	Nothing	Sand	Carbon	Sand+Carbon	

TABLE II EXPERIMENTAL DESIGN USING L16 ORTHOGONAL ARRAY (SOLAR BOX COOKER)

S. No.	A	B	C	Tw	S/N ratio (Tw)	Tsc	S/N ratio (Tsc)	F_1	S/N ratio (F_1)	F_2	S/N ratio (F_2)
1	1	1	1	45	33.0643	89	38.9878	0.075	-22.4988	0.340	-9.3704
2	1	2	2	65	36.2583	105	40.4238	0.096	-20.3546	0.420	-7.5350
3	1	3	3	90	39.0849	120	41.5836	0.120	-18.4164	0.540	-5.3521
4	1	4	4	93	39.3697	112	40.9844	0.105	-19.5762	0.030	-30.4576
5	2	1	2	88	38.8897	96	39.6454	0.088	-21.1103	0.070	-23.0980
6	2	2	1	47	33.4420	80	38.0618	0.057	-24.8825	0.403	-7.8939
7	2	3	4	55	34.8073	96	39.6454	0.073	-22.7335	0.150	-16.4782
8	2	4	3	95	39.5545	135	42.6067	0.124	-18.1316	0.700	-3.0980
9	3	1	3	92	39.2758	120	41.5836	0.105	-19.5762	0.030	-30.4576
10	3	2	4	90	39.0849	105	40.4238	0.082	-21.7237	0.080	-21.9382
11	3	3	1	35	30.8814	80	38.0618	0.063	-24.0132	0.091	-20.8192
12	3	4	2	45	33.0643	96	39.6454	0.081	-21.8303	0.164	-15.7031
13	4	1	4	98	39.8245	140	42.9226	0.136	-17.3292	0.720	-2.8534
14	4	2	3	95	39.5545	125	41.9382	0.105	-19.5762	0.650	-3.7417
15	4	3	2	93	39.3697	120	41.5836	0.098	-20.1755	0.780	-2.1581
16	4	4	1	35	30.8814	81	38.1697	0.058	-24.7314	0.060	-24.4370

TABLE III A: ANOVA TABLE FOR WATER TEMPERATURE

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	3	7.253	7.253	2.418	0.49	0.699
B	3	10.704	10.704	3.568	0.73	0.571
C	3	124.303	124.303	41.434	8.47	0.014
Error	6	29.361	29.361	4.893		
Total	15	171.621				

TABLE III B ANOVA TABLE FOR STAGNATION TEMPERATURE

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	3	3.8677	3.8677	1.2892	1.57	0.292
B	3	0.8739	0.8739	0.2913	0.35	0.789
C	3	28.0737	28.0737	9.3579	11.37	0.007
Error	6	4.9390	4.9390	0.8232		
Total	15	37.7543				

TABLE III C ANOVA TABLE FOR FIRST FIGURE OF MERIT

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	3	8.169	8.169	2.723	1.48	0.313
B	3	5.085	5.085	1.695	0.92	0.486
C	3	55.762	55.762	18.587	10.08	0.009
Error	6	11.066	11.066	1.844		
Total	15	80.082				

TABLE III D: ANOVA TABLE FOR SECOND FIGURE OF MERIT

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	3	410.9	410.9	137.0	1.05	0.438
B	3	188.8	188.8	62.9	0.48	0.707
C	3	131.0	131.0	43.7	0.33	0.802
Error	6	785.0	785.0	130.8		
Total	15	1515.7				

TABLE IV RESULTS OF THE CONFIRMATION XXPERIMENTS FOR OUTPUT PERFORMANCE.

Performance output	Optimal control factor settings	S/N ratio Predictive values (dB)	S/N ratio Experimental values (dB)	Error (%)
1. Water temperature	$A_3B_4C_2$	34.88	33.28	4.56
2. Stagnation temperature	$A_2B_2C_1$	41.34	39.77	3.78
3. First figure of merit	$A_2B_3C_1$	-19.89	-19.46	2.14
4. Second figure of merit	$A_3B_1C_4$	-28.43	-27.51	3.25

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