Monitoring Of Carbon Dioxide Production In A Carbonated Beverage Company Using Factorial Design Technique

P.Y. Andoh, F. Davisand Y.A.K. Fiagbe

ABSTRACT: Carbon dioxide is used as a preservative and taste parameter in the soft drink industry. It has many other commercial uses with new applications continually being created. Carbon dioxide may be used in either a vapor, liquid, solid or supercritical state in a given applications such as carbonation of beverages. Improper combustion of air-to-fuel ratio in the combustor during carbon dioxide production can result in high cost of production and also affect quality of product. In this work, factorial design technique is utilized in studying the effects of fuel rate, air pressure and fuel quality on carbon dioxide production. A model is then developed to monitor the level of carbon dioxide produced in the flue gas of a carbon dioxide production plant at a coca cola bottling company. It can be concluded that all the three process parameters have significant effects on the production of carbon dioxide gas. The model obtained can be used to predict and monitor the quantity of fuel and air required, thus improving the efficiency and quality of the carbon dioxide produced.

KEYWORDS: Carbon Dioxide, Coca Cola, Factorial Design, Diesel Fuel

1 INTRODUCTION

Factorial design is a strategy of planning, conducting, analyzing and interpreting experiments so that sound and valid conclusion can be drawn efficiently, and economically. It provides the experimenters a greater understanding and power over the experimental procedure. It has seen an increased application over fifteen years as both manufacturing and service industries have attempted to refine and improve product, process and service quality [1]. Factorial design methodology has seen increased application where new products are designed, existing product designs improved, and industrialized processes optimized, this is often the key to overall product success. This principle has been established in many different industries, including electronics and semiconductors, aerospace, automotive, medical devices, food and pharmaceuticals, and the chemical and process industries. Through its application, a greater understanding and power over the actual experiment procedure is gained by experimenters.

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Factorial design technique has been successfully used in monitoring machining operations [4] delamination caused by drilling of composite laminates [5, 6] and optimization response variables [3]. In this study, factorial design technique is used to complement the effort of technicians in the production of carbon dioxide. Carbon Dioxide is used as a preservative in several carbonated beverage companies in Ghana. Most of these companies produce their own carbon dioxide using the direct-fired system, which is a self-contained system, designed to produce carbon dioxide through complete combustion of diesel fuel. The diesel fuel is fed into the combustor from the fuel pump through a regulation valve. The valve is subsequently regulated manually with the intention of achieving complete combustion of the diesel fuel. The resulting flue gas devoid of smoke is the carbon dioxide. To ensure accurate regulation of diesel fuel, two tests namely, exit gas analysis and smoke test are conducted periodically. The exit gas analysis is performed after the combustor is in full operation. Exit gas is collected with the analyzer to determine the percentage of the carbon dioxide produced. The tolerable percentage of carbon dioxide in the exit gas should be about fifteen percent (15%), otherwise the technician will have to intervene by manually adjusting the regulation valve. The smoke gun test is carried out with a special test paper in the smoke gun. The gun is inserted into a gate located at the end of the combustor. On withdrawing the smoke gun after a few minutes the test paper must be clear of traces of smoke. Traces of smoke on the test paper indicate incomplete combustion, necessitating manual adjustment of the valve in order to increase fuel flow. It is clear from the above description of carbon dioxide production, that, the process heavily depends on human interventions. This happening is extremely subjective and has the tendency of not meeting the desired quantity (15%) and quality of the product [2]. Accurate estimation of the process parameters will go a long way to improve the efficiency of the carbon dioxide production plant and also the quality of carbon dioxide gas produced. This work intends to continuously monitor the quantity of fuel and air required for the production of carbon dioxide using factorial design technique. This will circumvent the intermittent interventions made by the technicians at the production plant. The objective is to identify the process parameters that affect the production of carbon dioxide and as a result develop a quantitative relationship between the process parameters and the efficiency and quality of carbon dioxide produced.

2 MATERIAL AND METHODMETHODOLOGY

2.1 EXPERIMENTAL SET UP AND PROCEDURE

The fuel of varying quality at set periods from the fuel tank is regulated into the combustor or re-boiler using a pump and flow meter to take readings. Ambient air from the blower is regulated into the combustor by means of a regulator and the pressure readings noted. The experimental set up is given in a schematic diagram as shown in Fig. 1.

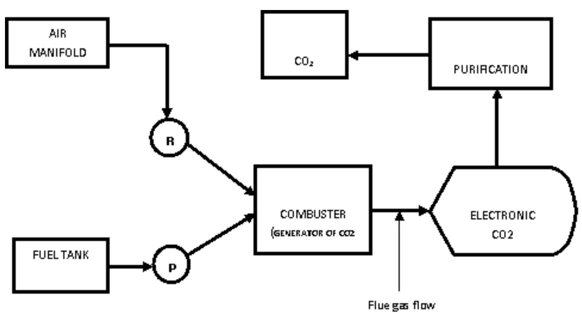

Fig. 1: Schematic Diagram of Experimental Set-Up

The fuel quality was varied based on samples supplied by the company vendor. Only one quality characteristic (i.e. density - kg/m3) was used for the experiment. (It was practically difficult judging from the project and hence experiment constrains to use other notable diesel fuel properties as benchmark for fuel quality). A carbon dioxide gas detector measuring device (electronic analyzer) is placed just after the combustor to measure the percentage of carbon dioxide in the flue gas before it goes to the Scrubber for commencement of the purification processes and thence to storage.

2.2 EXPERIMENTAL DESIGN METHOD

Factorial design provides both quantitative and qualitative means of investigating variable responses. It also provides a systematic approach that optimizes the number of experiments. Full coverage of the experimental space is provided with clear boundaries defined. Factorial design allows for main effects and interactions of factors to be easily separated and their significance judged, thus addressing the questions asked above. In this work, a factorial design is applied in investigating the quality or percentage of carbon dioxide gas in flue gas as determined by three variables namely: Air Pressure (psi), Fuel Flow (liters/hr.) and quality of diesel fuel (i.e. density)(Kg/m3). The design matrix is as shown in Fig. 2, which shows the variables in ranges of two points such that the points take on high (+) and low (-) values for each variable.

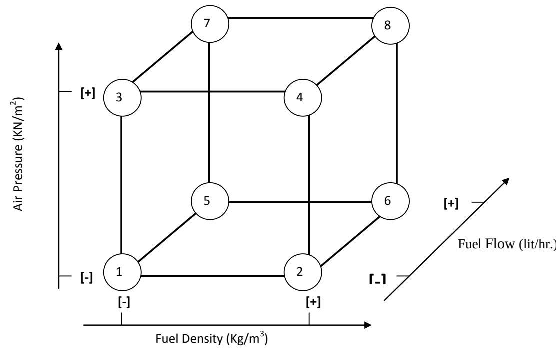

Fig. 2: 2^3 Factorial Design

2.3 EXPERIMENT PARAMETERS, LEVELS AND DATA COLLECTION

The three quantitative variables, namely, fuel rate (lit/hr), air pressure (KN/m^2), and fuel quality (i.e. density) (kg/m3) are used to study the response in terms of percentage of carbon dioxide in flue gas during combustion in the re-boiler. Table 1 presents the levels of the variable used in this work.

Table 1: The experimental matrix

Variables	Lower Level (-)	Upper Level (+)
Fuel Rate f (liters/hr.)	60	80
Air Pressure a (KN/m^2)	10	30
Fuel Quality - density q (Kg/m^3)	830	880

The fuel rate and the air pressure are selected to correspond to typical range of values used during the combustion process and also according to data provided by manufacturer of the CO2 production plant. Fuel quality was varied based on samples supplied by the company vendor as requested for the purposes of the experiment. Only one quality characteristic or property (i.e. density) was used and measured for the representation of fuel quality (as it was practically difficult, judging from the experimental constrains, to use a combination of or other fuel properties as benchmark for fuel quality). The experiment is performed at each combination of the fuel rate, air pressure and fuel quality. Thus, there are $2^3 = 8$ experimental conditions. For each parameter setting conditions, the percentage and quality of CO2 in flue gas is obtained. Each experiment is replicated at each point. The measurable quantities for the responses are recorded. The averages of the two runs are computed for each set of conditions. Tables 2 and 3 show the experimental matrix and the magnitude of efficiency and quality of CO2 gas respectively.

Table 2: The Measured Values for Efficiency of Carbon Dioxide Gas

Pts	Code			Efficiency of Carbon Dioxide Gas (%)		
	f	a	q	Run 1	Run 2	Mean
1	-	-	-	2.04	2.04	E1=2.04
2	+	-	-	18.72	18.72	E2=18.72
3	-	+	-	4.05	4.2	E3=4.12
4	+	+	-	10.49	10.87	E4=10.68
5	-	-	+	7.31	7.3	E5=5.01
6	+	-	+	15.37	18.72	E6=17.04
7	-	+	+	15.2	15.81	E7=15.50
8	+	+	+	17.36	17.9	E8=17.63

Note: (-) represents the lower level of the variables, (+) represents the upper level of the variables

Table 3: The Measured Values for Quality of Carbon Dioxide Gas

Pts	Code			Quality of Carbon Dioxide Gas (%)		
	f	a	q	Run 1	Run 2	Mean
1	-	-	-	65	61.5	Q1=63.25
2	+	-	-	82.5	73	Q2=77.75
3	-	+	-	60	68	Q3=64.00
4	+	+	-	69	65	Q4=67.00
5	-	-	+	76	83	Q5=79.50
6	+	-	+	70.5	73	Q6=71.75
7	-	+	+	72	68	Q7=70.00
8	+	+	+	81.5	87	Q8=84.25

Note: (-) represents the lower level of the variables, (+) represents the upper level of the variables

The results obtained are used to determine the effects of the process parameters on the CO2 output responses. A model will then be generated and used to monitor the carbon dioxide response.

2.4 Calculation of Effects

The main effect of each of the process variables reflects the changes of the response as the process variables change from a low to a high level. The main effect of the fuel rate (f) is

$$E_f = \tfrac{1}{4}\{(C_2 + C_4 + C_6 + C_8) - (C_1 + C_3 + C_5 + C_7)\}$$

For the air pressure (a) is

$$E_a = \tfrac{1}{4}\{(C_3 + C_4 + C_7 + C_8) - (C_1 + C_2 + C_5 + C_6)\}$$

Andfor the fuel quality (q) (density) is

$$E_q = \tfrac{1}{4}\{(C_5 + C_6 + C_7 + C_8) - (C_1 + C_2 + C_3 + C_4)\}.$$

Two or more of the variables may jointly influence the responses. These joint influences are referred to as interactions. The interaction between the fuel rate and the air pressure is

$$I_{fa} = \tfrac{1}{4}\{(C_1 + C_4 + C_5 + C_8) - (C_2 + C_3 + C_6 + C_7)\}$$

between the fuel rate and the fuel quality is

$$I_{fq} = \tfrac{1}{4}\{(C_1 + C_3 + C_6 + C_8) - (C_2 + C_5 + C_5 + C_7)\}$$

and between the air pressure and the fuel is

$$I_{aq} = \tfrac{1}{4}\{(C_1 + C_2 + C_7 + C_8) - (C_3 + C_4 + C_5 + C_6)\}$$

The three-factor interaction is expressed as

$$I_{faq} = \tfrac{1}{4}\{(C_2 + C_3 + C_5 + C_8) - (C_1 + C_4 + C_6 + C_7)\}$$

and the mean of the runs is defined as

$$E_M = \left[\sum_{1}^{8} C_i / 8\right].$$

where Ci are the carbon dioxide gas responses. The estimates for the two carbon dioxide percentage responses are shown in Table 4.

Table 4: Effects of Process Parameters on Efficiency and Quality of Carbon Dioxide Gas

Effects/Interactions	Carbon Dioxide Gas Responses	
	Efficiency	Quality
E_M	11.63	72.19
E_f	8.77	6
E_a	0.7	-1.75
E_q	5.48	8.38
I_{fa}	-4.43	2.63
I_{fq}	-2.84	-2.75
I_{aq}	3.69	3.25
I_{faq}	0.62	8.38

The results suggest that increasing the fuel rate from 60 to 80 lit / hr results in an increase of efficiency of 8.77 and an increase of quality of 6.00%; increasing the air pressure from 10 to 30 KN/m2 results in an increase of efficiency of 0.70% and a decrease of quality of 1.75%. Increasing the fuel quality (i.e. density) from 830 to 880 kg/m3 results in an increase of efficiency of 5.48% and an increase of quality of 8.38%. These results may be confirmed by the application of the experimental error as discussed in [Box, 1978].Using the results obtained for carbon dioxide gas responses during the combustion process as presented in Tables 2 and 3, the di and the di2/2 are computed for each ith condition. These values are used to compute the corresponding standard errors for efficiency and quality of carbon dioxide gas. The results are presented in Table 5.

Table 5: Standard Errors for Efficiency and Quality of Carbon dioxide gas

Parameters	Responses	
	Efficiency	Quality
Variance, $s^2 = \sum \left(d_i^2 / 2 \right) / g$	0.75	17.75
Variance of an effect $V(effect) = \frac{4}{N} s^2$	0.19	4.44
Standard Error, $s_e = \sqrt{V(effect)}$	0.44	2.11

3 DISCUSSION OF RESULTS

3.1 The Effects of the Process Variables

The combination of the main effects or the interactions and the standard error gives the range (Es ± Se) for the effect or interaction of each process parameter. For instance, the main effect of the fuel rate has a range of 8.77 ± 0.44 for the efficiency while that of the quality is 6.00 ± 2.1. However, it is not clear which of the effects or interactions are important and which are unimportant. By examining the range or the confidence intervals of each result, it can be determined if each effect or interaction is significant. It has been determined that any effect or interaction is considered as significant if its range does not include zero. Therefore, the combination of these results and the values in Tables 4 and 5 produce the final results for the factorial analysis. This is illustrated in Table 6.

Table 6: Summary of the Factorial Experimental Results.

Effects	Responses			
	Efficiency		Quality	
	Results	Remarks	Results	Remarks
E_M	11.63 ± 0.44		72.19 ± 2.1	
E_f	8.77 ± 0.44	Real	6.00 ± 2.1	Real
E_a	0.70 ± 0.44	Real	-1.75 ± 2.1	Not Real
Eq	5.48 ± 0.44	Real	8.38 ± 2.1	Real
I_{fa}	-4.43 ± 0.44	Real	2.63 ± 2.1	Real
I_{fq}	-2.84 ± 0.44	Real	-2.75 ± 2.1	Real
I_{aq}	3.69 ± 0.44	Real	3.25 ± 2.1	Real
I_{faq}	0.62 ± 0.44	Real	8.38 ± 2.1	Real

The comparison of the estimates with the standard errors requires some interpretation. The main effect of a variable may be individually interpreted only if there is no evidence that the variable interacts with other variables. When there is evidence of one or more interactions, the interacting variables must be considered together. Comparison of the efficiency and quality of the carbon dioxide gas responses estimates with their standard errors (Table 6) and use of the normal probability limits suggests that the fuel rate, (f), air pressure (a) and the fuel quality (q) have effects on the efficiency of the carbon dioxide gas, whereas fuel rate, (f) and the fuel quality (q) have effects on the quality of the carbon dioxide gas. However, since the fuel rate interacts with both the air pressure and the fuel quality ($I_{fa} = -4.43 \pm 0.44$ and $I_{fq} = -2.84 \pm 0.44$ respectively) for the efficiency and ($I_{fa} = 2.63 \pm 2.1$ and $I_{fq} = 2.75 \pm 2.1$, respectively) for the quality. Similarly, the fuel quality interacts with the air pressure ($I_{aq} = 3.69 \pm 0.44$) for the efficiency and ($I_{aq} = 3.25 \pm 2.1$) for the quality of the carbon dioxide gas, then, the fuel rate, air pressure and fuel quality should not be treated separately. Hence, the two-way interaction between the fuel rate and the air pressure for both responses are presented in Fig. 3.

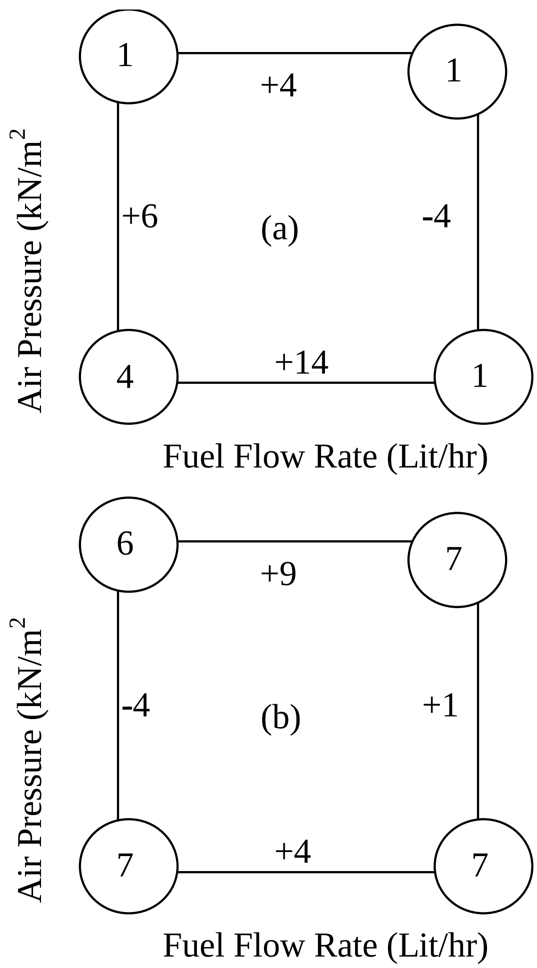

Fig. 3: Two-way interaction between fuel rate and air pressure for (a) efficiency and (b) the quality of the carbon dioxide gas

From Fig. 3, it can be seen that increasing the air pressure increases the efficiency of the carbon dioxide gas at a low fuel rate whereas the quality of the carbon dioxide gas decreases. However, the efficiency of the carbon dioxide gas decreases at a higher fuel rate while the quality increases. Increasing the fuel rate increases the both the efficiency and the quality of the carbon dioxide gas, irrespective of the air pressure. The two-way interaction between the fuel rate and the fuel quality for both responses are presented in Fig. 4.

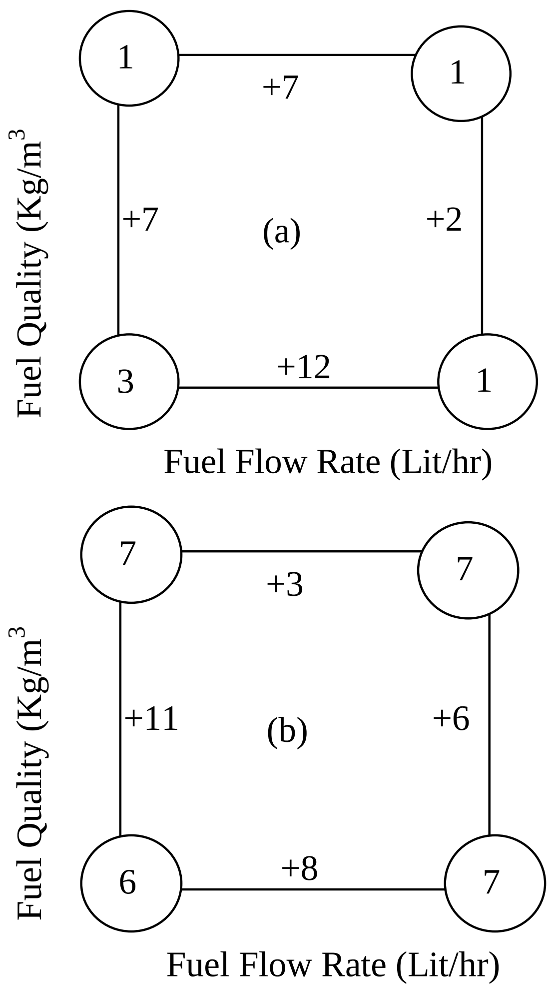

Fig. 4: Two-way interaction between fuel rate and air pressure for (a) efficiency and (b) the quality of the carbon dioxide gas

From Fig. 4, irrespective of both fuel rate and fuel quality, increasing the fuel rate or fuel quality increases both the efficiency and the quality of the carbon dioxide gas. The two-way interaction between the air pressure and the fuel quality (density) is as presented in Fig. 5.

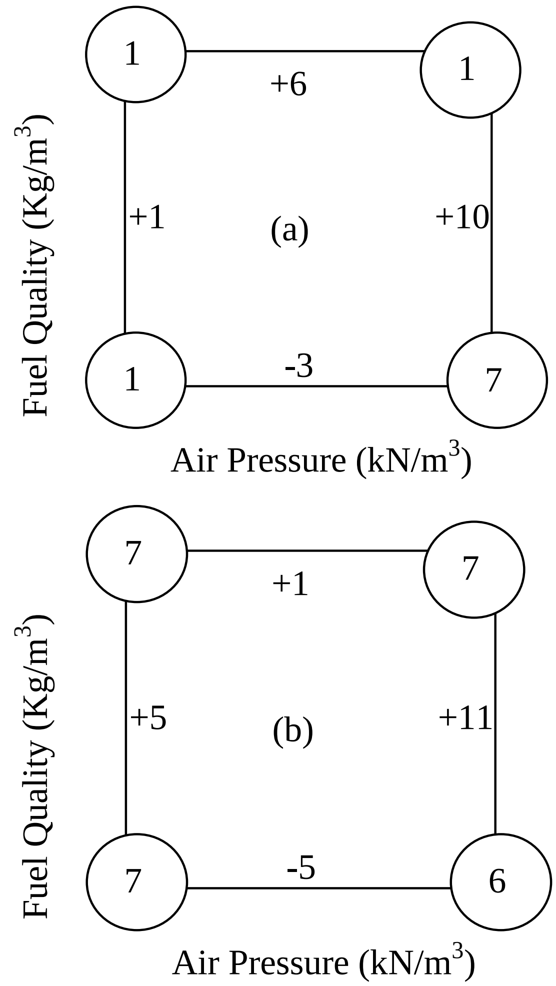

Fig. 5: Two-way interaction between air pressure and fuel quality (density) for (a) efficiency and (b) quality of carbon dioxide gas

Fig. 5 shows that increasing the air pressure decrease both the efficiency and the quality of the carbon dioxide gas at a lower fuel quality (density). However, both the efficiency and quality of carbon dioxide increases at a higher fuel quality (density). In addition, the efficiency and quality of the carbon dioxide gas increases as the fuel density increases, irrespective of the air pressure. There is evidence of three-factor interactions among the three process parameters for both the efficiency and the quality of the carbon dioxide gas $I_{faq} = 0.62 \pm 0.44$ and $I_{faq} = 8.38 \pm 2.1$ respectively. Thus, these three variables must be considered together. An interpretation of the results under such conditions is very difficult in the deterministic approach. Other approaches, such as the stochastic approach or modeling, may be used for further analysis and interpretation of these results. The discussion so far suggests that a model can be developed to predict and monitor the efficiency and quality of the carbon dioxide gas during the production process.

3.2 Modeling and Verification of the Results

A full model may consist of three main effects, three two-factor interaction and a three-factor interaction. This is defined as:

$$C = \begin{bmatrix} \alpha_0 + \alpha_1 f + \alpha_2 a + \alpha_3 q + \alpha_4 fa \\ + \alpha_5 fq + \alpha_6 aq + \alpha_7 faq \end{bmatrix} \quad (1)$$

where $\alpha_0, \alpha_1, \ldots, \alpha_7$ are the constants and f, a, and q are the fuel rate, air pressure and fuel quality, respectively.
It can be shown that

$$\alpha_0 = mean, \quad \alpha_1 = \frac{E_f}{2}, \quad \alpha_2 = \frac{E_a}{2}, \quad \alpha_3 = \frac{E_q}{2},$$

$$\alpha_4 = \frac{I_{fa}}{2}, \quad \alpha_5 = \frac{I_{fq}}{2}, \quad \alpha_6 = \frac{Iaq}{2}, \quad \alpha_7 = \frac{I_{faq}}{2}$$

and C is the carbon dioxide gas responses evaluated. The significant effects and interactions are used to develop the empirical model for each response with the use of Equation 1. But since all the effects and interactions of the process parameters have significant effects on the efficiency of the carbon dioxide gas produced, then the model is given as

$$E = \begin{bmatrix} 11.63 + 4.39 f + 0.35a + 2.74q - 2.22 fa \\ -1.42 fq + 1.85aq + 0.31 faq \end{bmatrix} \ldots (2)$$

Similarly, the model for the quality of the carbon dioxide is given as

$$Q = \begin{bmatrix} 72.2 + 3 f + 4.2q + 1.3 fa \\ -1.4 fq + 1.6aq + 4.2 faq \end{bmatrix} (3)$$

Since the process parameters (f, a, and q) are coded, their values are noted as (-1 to +1) in these models. The value of efficiency and quality of carbon dioxide gas E and Q respectively can be calculated at each experimental condition. For example, at the lower values of f, a, and q, (i.e. -1, -1, and -1), E is computed as

$$E = \begin{bmatrix} 11.63 + 4.39(-1) + 0.35(-1) + 2.74(-1) \\ -2.22(-1)(-1) - 1.42(-1)(-1) \\ +1.85(-1)(-1) + 0.31(-1)(-1)(-1) \end{bmatrix} = 2.05\%$$

and Q is given as

$$E = \begin{bmatrix} 72.2 + 3(-1) + 4.2(-1) \\ +1.3(-1)(-1) - 1.4(-1)(-1) \\ +1.6(-1)(-1) + 4.2(-1)(-1)(-1) \end{bmatrix} = 62.38\%$$

This process is then repeated for the remaining combustion conditions. It was found out that the percentage error is within a range of 0% and 0.50% for the efficiency of the carbon dioxide gas while that of the quality is within the range of 1.00% and 1.40%. This finding means that the two sets of values are in close agreement or within the experimental error. Since the fuel flow rate and fuel density have large positive effects on both responses, it could be increased by running both factors at the high level. But the air pressure can be run at both low and high level, since it has less positive effect on the efficiency and no effect on the quality of the carbon dioxide. However, since the density of the fuel is mostly controlled by the supplier, it can then be treated as a constant. Hence the model can be modified to improve both the efficiency and the quality; therefore, the fuel quality can be set at high level. At constant fuel quality, and using the results shown in Tables 2 and 3, it was determined that, the two main effects and the interaction have significant effect on the efficiency whereas the fuel rate and its interaction have significant effect on the quality. Therefore, when the fuel quality is kept constant, the models for both the efficiency and the quality of the carbon dioxide gas are given as $E = 11.34 + 6.68 f + 0.64a - 2.50 fa$ and $Q = 72.18 + 3.00 f + 1.32 fa$ respectively. These two models were verified and fall within experimental error. Plots were then generated using the two models and the two factors, air pressure and fuel flow rate. The results obtained are presented in Fig. 6

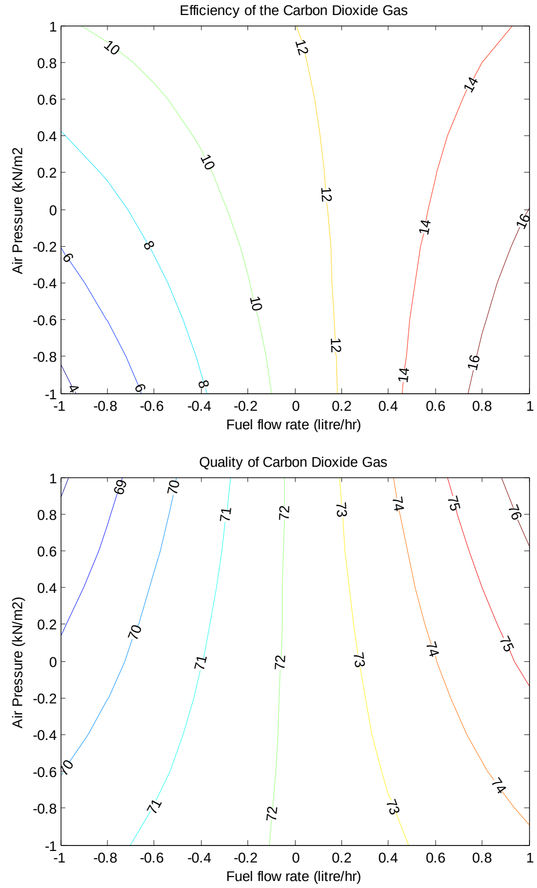

Fig. 6: Graph of air pressure and fuel rate for the two carbon dioxide gas responses using the models

From the graph, it can be seen that the maximum efficiency for the carbon dioxide gas is obtained when the fuel flow rate falls within the range of 0.70 and 1.00 whereas the air pressure falls within the range of -1.0 and 0. Similarly, when the fuel flow rate falls within the range of 0.70 and 1.00 and the air pressure falls within the range of -0.2 and 1.0, then a high quality of the carbon dioxide gas is obtained. Hence to obtain the maximum efficiency and high quality of carbon dioxide, the two factors are to be run between 0.8 and 1.0 for the fuel flow rate and -0.02 and 0 for the air pressure. To ascertain this, series of experiments were performed varying the fuel flow rate and the air pressure whereas the fuel density is kept constant. The results obtained is shown in Fig. 7.

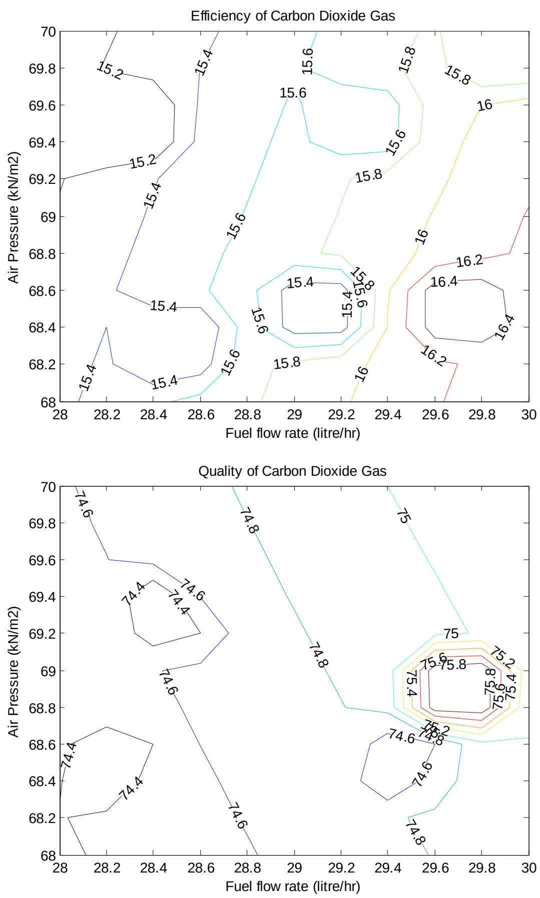

Fig. 7: Graph of air pressure and fuel rate for the two carbon dioxide gas responses from experiment

It can be deduced that, the maximum efficiency and high quality of the carbon dioxide is achieved when the fuel rate is ran at a range of 29.6 to 29.8 litres per hour while the air pressure is ran at a range of 68.6 and 69.0 kN/m^2. These results conformed to the model results; hence, the two factors should be run at the ranges mentioned above to achieve maximum production efficiency and high quality of the carbon dioxide gas.

4 CONCLUSIONS AND RECOMMENDATION

This work has identified the process parameters that affect the production of carbon dioxide as fuel rate, air pressure and fuel quality. An experimental design technique utilized to determine the effects of fuel rate, air pressure and fuel quality on the efficiency and quality of carbon dioxide, revealed that the identified process parameters have significant effects on the efficiency and quality of carbon dioxide produced. Consequently, a quantitative relationship between the process parameters and the efficiency and quality of the carbon dioxide produced has been developed. The following conclusions and recommendation are made based on the results obtained. That: (1) the process parameters have significant effects on the production of carbon dioxide gas, (2) the developed model could be used to predict and monitor the amount of fuel and air required for optimum amount and quality of carbon dioxide during the production process, (3) an automated control system be developed to replace the manual regulation of air and fuel valve.

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