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Mathematical Modeling and Optimization for Emission Parameter SO_2 of Dual Fuel CI Engine using Mustard Stalk

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ABSTRACT

Background: Punjab (India) an agricultural state with twelve major crops sown round the year, produces 14.53 MT as crop residue. This huge quantity of crop residue poses a serious problem of stubble burning in the fields, leading to an alarming level of air pollution across the state, along with a potential loss of fuel usable for power generation. About 1000 MW of electricity can be generated from this crop residue by the proper utilization (Singh *et al.* 2015).

Methods: Characteristics of various crop residues were evaluated experimentally and further investigations have been carried out to study the performance of producer gas derived from mustard stalk using a downdraft gasifier in combination with diesel oil in dual fuel diesel engine, where effect of various input parameters such as type of fuel, equivalence ratio and load on engine were studied on emission component SO_2. Results were modeled and optimized through central composite design (CCD) of response surface methodology (RSM) using design of experiments technique to determine the most desirable mode of utilization.

Result: It has been found that fixed carbon (40.55%), sulphur (0.367%), moisture contents (6.88%) and nitrogen contents (1.314%) in mustard stalk is almost same as in coal, where as hydrogen (6.124%), oxygen (43.965%), volatile matter (68.93%), gross calorific values (3933 kcal/kg) of mustard stalk are more and ash content (6.65%) is less as compared to corresponding values for coal. In all the three modes of operations, SO_2 increases with increase in load on the engine. ER has no effect in diesel alone mode but in dual modes with increase in ER further increases SO_2 as high temperature producer gas and air along with sulphur enters the engine which further increases the value of SO_2.

Key words: Central composite design, Crop residue, Design of experiments, Downdraft gasifier, Environmental pollution, Producer gas, Response surface methodology, Stubble burning.

INTRODUCTION

Punjab is an agricultural state with only 1.5% of the geographical area of India, producing 22.5% wheat, 12% rice and 13% of cotton of the annual productions in India and producing a large amount of crop residue (http://punjabgovt.nic.in). Even biomass production in less favoured areas has been investigated considering the energy impacts, soil ecosystem services and productivity under circumstances of climate change (Polakova *et al.* 2021). Crop residues in the mechanized farms in state are burned in the fields, as this management has the lowest cost and minimum labour requirements (Aggarwal 1994). The stubble burning in fields results the loss of potential fuel, organic matter and nutrients of soil with increases in pollution. The increase in pollution is evident from the fact that one tonne of straw burning releases 3 kg of particulate matter, 60 kg of CO, 1460 kg of CO_2, 199 kg of ash and 2 kg of sulphur (Jenkins and Bhatnagar 1991). Although burning of crop residue is easy and cheapest method being practiced globally, but this influences the air quality and human health adversely, so this should be discontinued and rather be used for energy production through different processes (Singh *et al.* 2013). Gradual depletion of fossil fuels coupled with present problem of stubble burning inspired the exploration of alternative renewable energy sources like producer gas derived from crop residue. At the present level of technology the gasifiers are more suited for heat applications than for shaft power applications (Alkorta *et al.* 2001). The high contents of K^+ and CL^{-1} in crop straw makes it difficult to burn (Jorapur *et al.* 1995). Biomass quality can be improved by agricultural management (Jorgesen and Sander 1997). Open core gasifier has been designed for the comparison of different biofuels (Bhoi *et al.* 2006). The effect of equivalence ratio (ER) affects the gas composition from gasifier derived from wood and wood chips (Quadir *et al.* 2002). The emission data varies with producer gas derived from wood pallets and wood briquettes in small combustor (Johansson *et al.* 2003). VCR engine behavior has been studied at different compression ratio at different parameters by pouring different biofuels (Chauhan *et al.* 2020). In dual fuel CI engine using rice husk, 31% of the diesel can be replaced with producer gas and emission parameters like

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CO, HC and smoke density have been found to be higher in dual mode (Pandey 2010). Further using pigen pea stalks, corn cob and wood chips, the replacement of diesel in CI engine was 64%, 63% and 62% respectively (Das *et al*. 2011). The power output of CI engine with producer gas was almost comparable with diesel power with marginal higher efficiency and CO_2 emission was more at higher load condition (Akhtar *et al*., 2016). CI engines operated on 60% biogas and 40% diesel performed better in terms of brake thermal efficiency with minimum fuel consumption as compared to diesel (Senthikumar and Vivekanandan 2016). The producer gas derived from sugarcane baggasse and carpentry waste reduced 51% diesel and 71% NOx emissions with slight reduction in power output (Singh *et al*. 2016). Mathematical models were developed for dual fuel CI engine performance and emission for producer gas derived from rice husk using response surface methodology with design of experiments technique, were successfully Validated with ANOVA (Baraskar *et al*. 2015).

In all the referred work, very little has been reported regarding the utilization of crop residue for power production using dual fuel CI engine coupled with gasifier. Further no specific work has been found to be done regarding the modeling and optimization of various input variables and output responses of gasifier coupled with CI engine using mustard stalk as feedstock, although it has sufficient high calorific value. In this study the effects of various input variables (load, ER, type of fuel) on output responses (SFC, power output, emission components) using CCD of RSM through DOE has been studied, along with mathematical modeling and optimization. The models were validated using ANOVA and optimized solutions were verified experimentally.

MATERIALS AND METHODS

Materials and experimental procedure

Mustard stalk and mustard stalk briquettes (crop residue) were used as the gasifier feed.Various properties of the mustard stalk has been given in Table 1 and Table 2. The diesel engine gasifier test rig was used for experimentation purpose. A downdraft gasifier was used to produce the producer gas using mustard stalk as the gasifier fuel. The gasifier is directly connected to CI engine, which is further connected to a 5 kW generator system with a provision to put variable load on generator. The load on the generator was varied with the help of electric heaters each of 1 KW. Producer gas from the gasifier enters the CI engine through inlet manifold through control valve.

The gasifier was charged from the top with mustard stalk fuel in batch modes. Air enters the gasifier through two nozzles fitted at the circumference of the gasifier. The producer gas generated leaves the gasifier at the bottom. It is then supplied to the CI engine after its cleaning through a series of filters. The load of generator and equivalence ratio (ER) of the gasifier along with type of engine fuel were varied for various output responses. Specific fuel consumption was measured directly with the help of calibrated burette and exhaust gas emission components like CO, CO_2, NO, NOx, SO_2,O_2, Atmospheric Temperature (AT), Flue Gas Temperature (FT) were measured with the help of exhaust gas analyzer “Testo 350”.

Design of experiments

The input design variables, output design responses using CCD of RSM through DOE technique of experiments employed for the experiments has been described as follows:

Input design variables

Input design variables considered in the present work were load on engine, type of fuel and equivalence ratio (ER). The various experimental conditions are shown in Table 3. In this work the effect of load on engine, type of fuel and ER have been studied on the performance and emissions of the engine.

Output responses

The various output responses studied were; specific fuel consumption (SFC), exhaust gas emission components CO, CO_2, NO, NOx, SO_2, O_2, atmospheric temperature (AT), flue gas temperature (FT) were measured with the help of exhaust gas analyzer “Testo 350”. In the present research paper only SO_2 has been incorporated.

Response surface methodology (RSM)

Response surface methodology is a collection of mathematical and statistical techniques useful for analyzing

Table 1: Properties of mustard stalk (proximate analysis).

Biomass name	Moisture % age	Ash % age	Volatile matter % age	Gross calorific Value(kcal/kg)
Mustard stalks	6.88	6.65	68.93	3933

Table 2: Properties of mustard stalk (ultimate analysis).

Biomass name	Nitrogen % age	Carbon % age	Sulphur % age	Hydrogen%age	Oxygen % age
Mustard stalks	1.314	40.55	0.367	6.124	43.965

problems having several independent variables which influence a dependent variables or response and the goal is to optimize the response variable. In most of the problems, relationship between response and independent variables is not known. The eventual objective of RSM is to determine the optimum operating conditions for the system, or to determine a region of the factor space in which the operating specifications are satisfied. Central composite design (CCD) gives over determined second order polynomial approximations. In second order polynomial approximations, there are more design points in the design than the undetermined coefficients. So CCD technique of RSM has been used in the design of experiments. Total 39 experiments have been conducted as per the design matrix.

Modeling response variables

For each response with given variables, the mathematical models had been developed using the software (Design Expert-10) for all the three modes of engine operation with various input variables and output responses (gaseous components of emission are discussed here). The ANOVA and Fishers statistical test (F test) were performed to check the adequacy of models as well as the significance of individual parameters. The various models developed are as follows in equations 1-3:

SO_2 concentration

Fuel I

$$SO_2 = 69.94 - 3.22 \times LOAD - 245.77 \times ER + 2.22 \times LOAD^2 + 390.12 \times ER^2 \quad ....1$$

Fuel II

$$SO_2 = -224.60 + 6.09 \times LOAD + 1565.45 \times ER - 0.29 \times LOAD^2 - 2348.50 \times ER^2 \quad ....2$$

Fuel III

$$SO_2 = -221.43 - 1.22 \times LOAD + 1607.95 \times ER + 26.92 \times LOAD \times ER - 0.10 \times LOAD^2 - 2466.84 \times ER^2 \quad ....3$$

Adequacy of model for SO_2

ANOVA results for the developed model of SO_2 are shown in Table 4. The lack of fit non significant, high value of R^2 (0.9976), sound agreement of R^2 adjusted (0.9956) and R^2 predicted (0.9930 values, high F value, high adequate precision value (84.730), low value of CV (1.75%), low value of standard deviation (0.87) and low value of PRESS (45.80) validates the model.

Optimization

Optimization is the combination of various factor levels that simultaneously satisfy the requirements as per the selected criteria for each of the responses and the variables. Usingthe optimization criteria, the various optimization solutions have been obtained as shown in Table 5.

Table 3: Experimental conditions.

Variables	Levels with range		
	Level 1	Level 2	Level 3
Type of fuel	Fuel I (Diesel)	Fuel II (Diesel + mustard stalks)	Fuel III (Diesel + Mustard stalk briquettes)
Load (kW)	1	3	5
ER	0.25	0.315	0.38

Table 4: Analysis of variance for SO_2 (ppm).

Source	Sum of squares (SS)	DF	Mean square	F value	p-value prob > F	
Model	6522.82	17	383.70	508.54	<0.0001	Significant
A-Load	3556.06	1	3556.06	4713.10	<0.0001	
B-ER	410.89	1	410.89	544.58	<0.0001	
C-Fuel	848.78	2	424.39	562.47	<0.0001	
AB	16.33	1	16.33	21.65	0.0001	
AC	408.36	2	204.18	270.62	<0.0001	
BC	235.53	2	117.76	156.08	<0.0001	
A^2	49.11	1	49.11	65.09	<0.0001	
B^2	321.82	1	321.82	426.53	<0.0001	
Residual	15.84	21	0.75			
Lack of fit	3.66	9	0.41	0.40	0.9120	Not significant
Pure error	12.19	12	1.02			
Cor. total	6538.67	38				

Std. Dev.	0.87	R-squared	0.9976
Mean	49.52	Adj R-squared	0.9956
C.V. %	1.75	Pred R-squared	0.9930
Press	45.80	Adeq precision	84.730

RESULTS AND DISCUSSION

The influence of various input parameters on selected response variables were assessed during experimentation. ANOVA was used to check the adequacy of the model. The developed RSM based mathematical models have been discussed below.

Analysis of SO_2

Variation of SO_2 with ER and load for fuel I, II and III is shown in Fig 1.

It is observed from the Fig 2 that as expected the concentration of SO_2 increases with increase in load on engine. SO_2 concentration has no effect of ER as in this mode engine is running in single fuel mode *i.e* with diesel fuel.

It is observed from the Fig 2 that as expected the concentration of SO_2 increases with increase in load on engine in duel fuel mode. With increase in ER, the high temperature producer gas and air along with sulphur enters the engine which further increases the value of SO_2.

It is observed from the Fig 3 that as expected the concentration of SO_2 increases with increase in load on engine in duel fuel mode. With increase in ER, the high temperature producer gas and air along with sulphur enters the engine which further increases the value of SO_2. The reduced emission of SO_2 is recommended as per Table 6.

Optimization and validation

After the selection of the optimization criteria for all the input variables and output responses, the 42 optimization results have been obtained according to the decreasing order of their

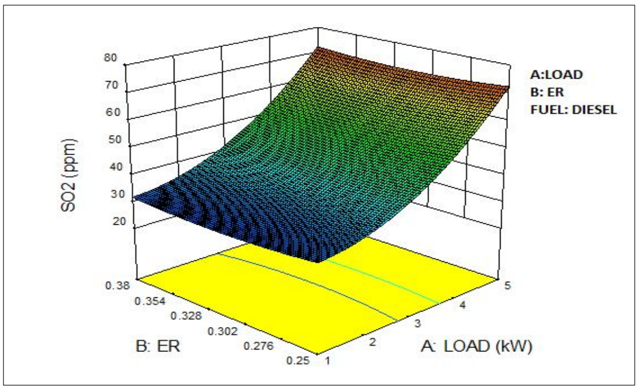

Fig 1: Variation of SO_2 concentration with load and ER for fuel I.

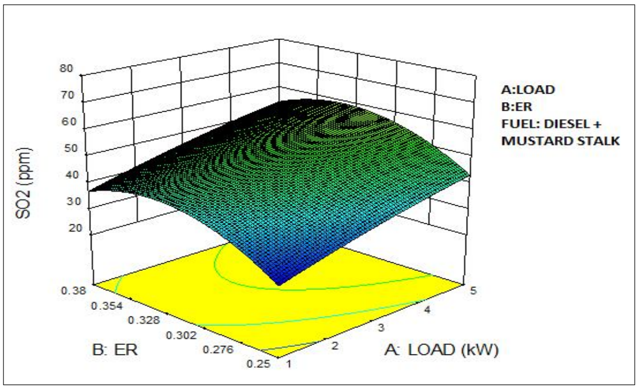

Fig 2: Variation of SO_2 concentration with load and ER for fuel II.

Table 5: Optimization solutions.

Load	ER	Fuel	SFC	POUT	O_2	CO	NO	CO_2	FT	NO_X	SO_2	AT	Dr
3.2	0.25	Fuel III	3.7	3.2	19.64	1525.50	45.09	1.90	81.08	54.13	42.97	40.64	0.662
3.2	0.25	Fuel III	3.7	3.2	19.64	1525.24	45.04	1.90	81.01	54.09	42.92	40.64	0.662
3.2	0.25	Fuel III	3.7	3.2	19.63	1525.90	45.16	1.90	81.19	54.21	43.04	40.65	0.662
3.1	0.25	Fuel III	3.7	3.1	19.65	1524.80	44.96	1.90	80.89	54.02	42.85	40.63	0.662
3.2	0.25	Fuel III	3.7	3.2	19.62	1526.28	45.24	1.90	81.32	54.29	43.12	40.66	0.662

*POUT= Power output; Dr= Desirability.

Table 6: Recommendation of gasifier fuels at different values of ER and load.

ER	Load (kW)	Fuel recommended	Maximum "Down" and Minimum "Up" (SO_2 %age)
0.25	1	Fuel II	19 (down)
	3	Fuel II	20 (down)
	5	Fuel II	40 (down)
0.315	1	Fuel II	37 (up)
	3	Fuel II	24 (up)
	5	Fuel II	19 (down)
0.38	1	Fuel II	33 (up)
	3	Fuel II	7 (up)
	5	Fuel II	24 (up)

Table 7: Validation of optimized results.

Number	Load	ER	Fuel	SFC	Power output	O_2	CO	NO	CO_2	FT	NO_X	SO_2	AT	Desir -ability
							Optimized solution							
1	3.2	0.250	D+MSB	3.7	3.0	19.64	1525	45.09	1.90	81.08	54.13	42.97	40.64	0.662
							Experimental results							
1	3.2	0.250	D+MSB	3.5	3.0	18.00	1529	46.00	1.80	83.00	56.00	43.00	42.00	-
2	3.2	0.250	D+MSB	3.8	3.0	20.00	1528	48.00	1.85	82.00	55.00	44.00	43.00	-
3	3.2	0.250	D+MSB	3.9	3.0	21.00	1530	47.00	1.90	80.00	57.00	42.90	41.00	-

Table 8: Response error (Comparison with experimental results).

Response	SFC	O_2	CO	NO	CO_2	FT	NO_X	SO_2	AT
Max. % age error	5.40	6.92	0.32	6.45	5.26	2.36	5.30	2.39	5.8

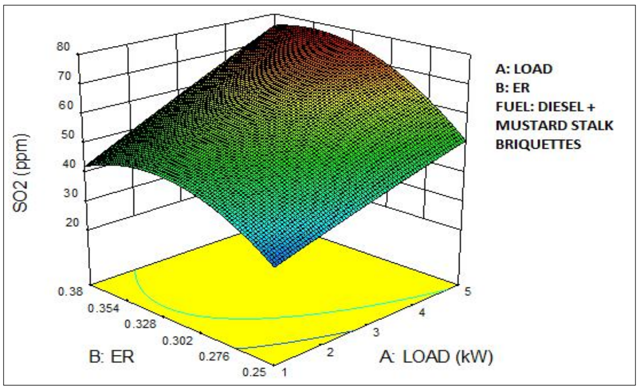

Fig 3: Variation of SO_2 concentration with load and ER for dual fuel III.

desirability. The best solution and its experimental validation has been given in Table 7 and response error in Table 8.

CONCLUSION

It has been observed that in most of the crop residue (and in particular mustard stalk) fixed carbon, sulphur, moisture and nitrogen contents are almost same as in coal. But hydrogen, oxygen, volatile matter and calorific values of mustard stalk are higher as compared to coal and ash content is less. Thus crop residue can be a good alternative to coal for power generation.

The successful models have been developed for all the output responses in the three modes of operations. The effects of various performance parameters on different responses were found as follows:

In all the three modes of operations, SO_2 increases with increase in load on the engine. ER has no effect in diesel alone mode but in dual modes with increase in ER further increases SO_2 as high temperature producer gas and air along with sulphur enters the engine which further increases the value of SO_2.

Results were optimized through mathematical modelling and validated experimentally and it was found that fuel III with ER=0.25 at 3.2 kW load have highest desirability.

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