Desirability Analysis to Optimize the Performance of Castor-Diesel Blends Using ANNOVA

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Abstract

By using optimized engine parameters, this work seeks to maximize the performance of castor-diesel blends in a Variable Compression Ratio (VCR) diesel engine. Engine optimization takes operational factors such as engine load, fuel blends, and compression ratio into account. Performance metrics such as indicated thermal efficiency (ITHE), brake thermal efficiency (BTHE), and mechanical efficiency, on the other hand, are taken into consideration for responses. Research is carried out using the experimental design of the Box - Behnken Design (BBD). The Desirability approach is utilized in engine operating parameter optimization. According to the results, the VCR diesel engine performs better than the diesel engine at full load when it is run at a compression ratio of 18 and 40% fuel blend (Diesel 60% by volume and 40% by volume mixed with castor oil). Blending optimization yields 56.81% mechanical efficiency, 28.72% brake thermal efficiency, and 51.87% indicated thermal efficiency. Ultimately, the engine parameters with the best efficiency and lowest emissions for biodiesel blends are found in the mathematical models and experimental data.

Keywords: - Variable Compression Ratio, Diesel Blends, Engine Performance, and ANOVA

Introduction

Biomass refers to the organic matter that can be used as a substitute for energy. It encompasses various types of biofuels, including solid, gaseous, and liquid fuels. These can be obtained from biomass[1,2].

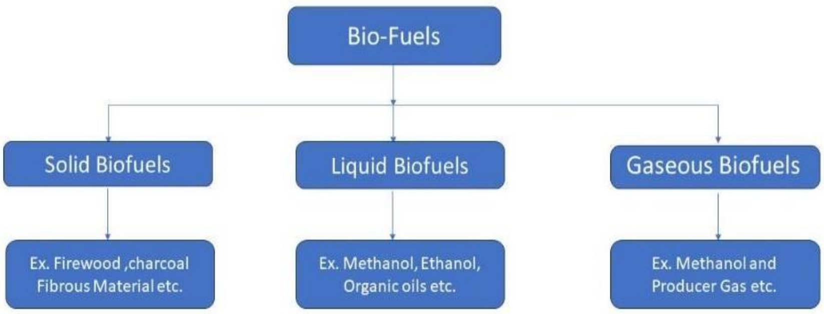

Fig.1: -Systematic Layout of Different Biofuels

In contemporary times, it is crucial to deliberate upon the optimal utilization of biofuels and fossil fuels in our daily lives, as both play a vital role in shaping our future generations [3].The cost of essential commodities, such as oil, is experiencing a significant increase. In this case, biofuel would be the most advantageous substitute to meet the need for fuel in human necessities. It replaces fossil energy sources and the depleting reserves of fossil fuels. The outcome serves as a means to mitigate the impacts of climate change and establish a sustainable and dependable energy source. Biofuels are considered perpetual and sustainable resources as they are continuously replenished. Fossil fuels are non-renewable resources that deplete over time as they require millions of years to form and are extracted from underground reserves [4].

The study's primary objective is to comprehend and analyse various characteristics of bio- diesel. Biodiesel is an environmentally friendly, widely available fuel and not dependent on geography. Like diesel, biodiesel comprises mono-alkyl esters of long-chain fatty acids derived from renewable natural sources like vegetable or animal fats. Significantly reducing the utilization of fossil fuels can greatly decrease the harmful emissions. It can be achieved by replacing fossil fuels with renewable fuels. The future global energy demand will be largely met by renewable energy sources[5]. Biodiesel is a clean and sustainable bioenergy that can be produced from various sources such as single edible oil (SEO), hybrid edible oils (HEO), single nonedible oil (SNEO), and hybrid nonedible oil (HNEO). It can be used as fuel for diesel engines without requiring engine modifications [6]. To enhance the production of biodiesel, numerous innovative technologies are being embraced in the field of bioenergy research [7].Biodiesel is primarily derived from edible vegetable oil, nonedible vegetable oil, waste or recycled oil, and animal fats. It is relatively less flammable than regular diesel. Biodiesel can be readily blended with conventional diesel fuel. Bio-diesel is biodegradable, thereby rendering it less environmentally hazardous. It lacks sulfur, the primary cause of acid rain. Biodiesel is suitable for application in catalytic converters in numerous instances. The engines, which utilize bio-diesel as a fuel source, typically exhibit high durability. The refineries are relatively less complex and environmentally friendly. Biofuels show higher octane levels and lubricity scores than uncontaminated petroleum-based diesel fuel. It can enhance the engine's efficiency and prolong the machine's operational lifespan [8].

Recent studies have examined biodiesel engines' operational and exhaust properties under various engine speeds, loads, and ratios [9,10].Benefits of using biodiesel as a substitute fuel for diesel engines include lower or nonexistent exhaust gas emissions of carbon monoxide, sulfur dioxide, and unburned hydrocarbons. The oxygen in biodiesel molecules generally leads to a more thorough burning process and decreased environmental pollution [11].Optimizing the biodiesel engine's performance is the primary goal of the research. Design software can be used to calibrate the engine performance. Internal combustion engine (ICE) calibration is defined as finding the ideal combinations of several engine configurable parameters, like air-to-fuel ratio (AFR), spark advance, and variable valve timings (VVT), for all the points of the range of operations in order to attain the prescribed performance requirements in terms of maximum output power, minimum fuel consumption (FC), minimum pollutant emissions, and noise. In the real world, the engine calibration problem becomes a crucial optimization problem since an appropriately calibrated engine produces fewer greenhouse gas emissions and is therefore preferred over an engine that is not. Thus, engineers and researchers alike are interested in engine calibration. Unfortunately, dyno performance evaluation takes a lot of time, which makes engine calibration a costly optimization issue. The conventional manual method has reached its limit since engine calibration issues have typically been more complex than in the past few decades. On the one hand, as engine technology advances, more and more engine parameters can be adjusted [12].

Experimental Set-Up

A problem-solving method called One factor at a Time (OFAT) separates the important causes of an effect from a group of possible causes. Many organizations use the OFAT approach to identify the primary factors when conducting experiments. Finding the performance characteristics with the OFAT approach requires selecting the appropriate range of input variables. A specific range of input variables is determined and fixed before the performance characteristics start, followed by an organized arrangement of the experimental performance. The variables chosen for the inputs are listed in Table 1 to achieve the best results. The appropriate ranges of the variables are also fixed. Pure castor oil was bought from the market for this investigation. Transesterification is the process that turns castor oil, which has less than 2% free fatty acids (FFA) and 27% alkaline, into biodiesel [13-15].The mechanical efficiency of the biodiesel is optimized using the Design-expert 13model. The output values are obtained using a diesel engine with a displacement of 87.50mm, stroke length of 110.00mm, connecting rod length of 234.00mm, and compression ratio 18. The engine has a power of 350KW @1500 rpm.

Run Order	**Torque**	**Brake Power**	**Indicated Power**	**Mechanical Efficiency**	**Brake Thermal Efficiency**	**Indicated Thermal Efficiency**
1	0.62	1.67	1.84	5.28	2.15	40.98
2	0.6	0.1	3.5	5.34	2.1	40.9
3	0.65	3.23	3.45	5.15	2.09	40.87
4	11.25	0.12	1.84	5.11	23.27	52.17
5	11.20	3.00	5.60	44.61	23.19	52
6	11.27	3.24	1.80	44.59	23.25	51.90
7	21.80	2.99	3.55	44.40	30.32	48.45
8	11.2	1.65	3.48	62.59	23.19	52
8	11.21	.10	5.16	43.94	23	51.95
10	21.81	.12	3.45	44.72	30.30	48.34
Run Order	**Torque**	**Brake Power**	**Indicated Power**	**Mechanical Efficiency**	**Brake Thermal Efficiency**	**Indicated Thermal Efficiency**
11	21.8	1.67	5.10	62.40	30.00	48
12	21.87	1.6	1.82	62.30	30.25	48.25
13	0.64	1.59	5.09	5.20	2.18	40.95

Table-1: Design Matrix

Fig. 2 shows the systematic layout of the diesel engine used in the analysis of the result outcomes of the ANNOVA model.

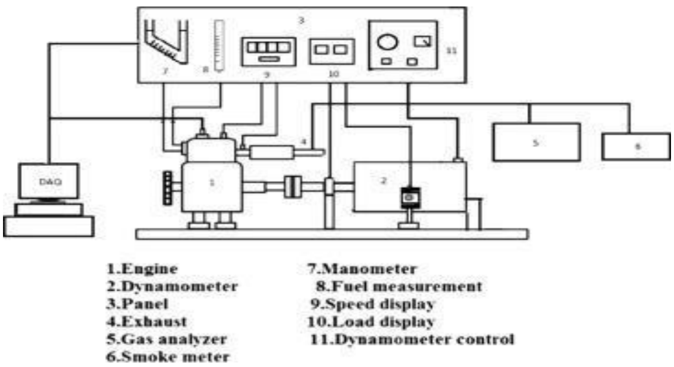

Fig.2 Systematic Engine Layout Diagram [16]

Experimental Methodology

Three levels of experiment design based on the BBD technique are generated to determine the optimal value of the output parameters selected for analysis. These levels include speed, load, indicated power, and brake power as input parameters, as shown in Fig.3.

Factors

Factor	Name	Units	Type	SubType	Minimum	Maximum	Coded Low	Coded High	Mean	Std. Dev.
A	Speed	RPM	Numeric	Continuous	1433.00	1493.00	-1 ↔ 1433.00	+1 ↔ 1493.00	1463.00	19.64
B	I.P	KW	Numeric	Continuous	2.28	3.93	-1 ↔ 2.28	+1 ↔ 3.93	3.10	0.5401
C	B.P	KW	Numeric	Continuous	0.1000	2.51	-1 ↔ 0.10	+1 ↔ 2.51	1.30	0.7889
D	Load	Kg	Numeric	Continuous	0.3600	9.20	-1 ↔ 0.36	+1 ↔ 9.20	4.78	2.89

Table-2: Details of factors chosen for Research Analysis

This study looked at torque, load, indicated power, and brake power as input factors that could impact the engine's indicated thermal efficiency, mechanical efficiency, and brake thermal efficiency.For the experimentation, full factorial designs of Design of Experiments (DOEs) are considered, where each factor varies at levels of 3x3x5, respectively. The complete factorial design from the software "Design Expert" trial version 13, which included 17 runs, served as the basis for creating the design matrix.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	6915.68	9	768.41	93423.62	< 0.0001	significant
A-torque	6557.99	1	6557.99	7.973E+05	< 0.0001	
B-I.P	0.0001	1	0.0001	0.0061	0.9428	
C-B.P	0.0021	1	0.0021	0.2568	0.6472	
AB	0.0000	1	0.0000	0.0000	1.0000	
AC	0.0132	1	0.0132	1.61	0.2943	
BC	0.0000	1	0.0000	0.0000	1.0000	
A²	265.56	1	265.56	32286.64	< 0.0001	
B²	0.0002	1	0.0002	0.0213	0.8933	
C²	3.571E-06	1	3.571E-06	0.0004	0.9847	
Residual	0.0247	3	0.0082			
Cor Total	6915.71	12				

Table-3: -Quadratic Model of the ANNOVA

The quadratic model of the ANOVA technique is displayed in the table above.

Result & Discussion

The foundation of analysis is analysis of variance (ANOVA), which yields the p-value numerically. The alternative term for rejection points that indicates the lowest level of significance at which the null hypothesis would be rejected is the p-value. The maximum value of p is 0.05, and model terms with p-values greater than 0.05 are considered unimportant. Since the p-values for the different responses are less than 0.05, it is determined that the models are significant.

The actual Regression Analysis for different values is as follows:

Mech. Efficiency= 2.307 + 4.836 x Torque - 0.0237 x I.P -0.0302 x B.P -0.000403 x Torque x I.P +0.003458 x Torque x B.P + .0000269 x I.P x B.P -0.0954 x Torque^2 + 0 .00317 x I.P ^{2} + 0.000510 x B.P^2 **(1)**

BTHE =0.6274 + 2.720 x Torque -0.0970 x I.P -0.01588 x B.P -0.000047 Torque x I.P +0.000451 x Torque x B.P -0.003849 I.P x B.P -0.062018 x Torque^2 + 0.013155 x I.P ^{2} + 0.005614 x B.P ^{2} **(2)**

ITHE = 40.191 +1.81469 x Torque -0.13534 x I.P -0.11562 x B.P + 0.000951 x Torque X I.P +0.003157 x Torque X B.P +0.02021 x I.P x B.P -0.06533 x Torque ^{2} + 0.012701 x I.P^2 - 0.001021 B.P^2 **(3)**

Model Evaluation

ANOVA modeling is used to analyze the stability of the model, as shown in the table below.

Model	Mean	SD	R-Square	Model Degree	Adj.R^2
Mechanical Efficiency	37.96	.09	1.00	Quadratic	.99
Brake Thermal Efficiency	18.91	.036	1.00	Quadratic	.98
Indicated Thermal Efficiency	47.48	.09	.99	Quadratic	.99

Table-4: Model Evaluation

The model fits the data well because, according to regression statistics, the difference between goodness of fit and prediction is less than 0.2, and the value of p is less than 0.0500, indicating that the model terms are significant.

Input Parameter	Goal	Lower Limit	Upper Limit	Importance
Torque	In Range	0.62	21.87	3
Indicated Power	In Range	1.84	5.16	3
Brake Power	In Range	0.1	3.23	3

Table 5: Analysis of Constraints

The **Model F-value** of 93423.62 implies the model is significant. There is only 0.01% chance that the F-value can increase due to noise. Model terms are adequate if the P-value are less than 0.05. In this case, A and A^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.

Actual Vs Predicted Values

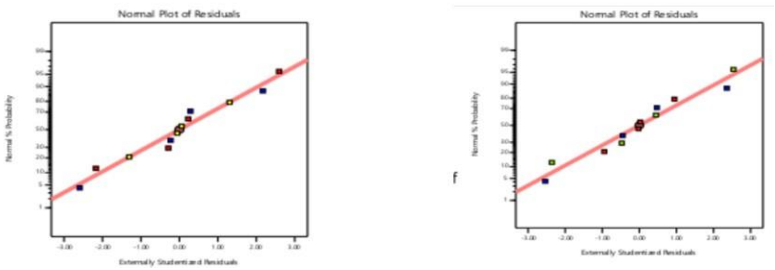

Fig.3 Actual Value Vs. Predicted Values for the ITHE and BTHE

The experimental analysis of the graph in Figure 4 provides easy validation of the values by comparing the spread between the predicted and actual values for the ITHE and BTHE for the 40% blended solution operated at predefined conditions with a compression ratio18.The graph unequivocally demonstrates that the developed existing models of BTHE and ITHE are adjacent to and close to the theoretical values predicted during the experimental performance. This can be readily verified by observing the spread of the actual values to the predicted existing line.

Fig. 4 Desirability Diagram at variable conditions

Optimization

The table displays the optimization criteria that were used in this investigation. Three input variables and three output variables are chosen for the model to take into account each output and use optimization techniques to maximize the output variables. Each response in the desirability approach can be given a value between 1 and 5. Mechanical efficiency, BTHE, and ITHE are assigned the highest importance for this study. Maximum desirability is achieved with engine parameters such as a compressibility ratio 18, 40% of fuel blend, and a complete load condition.

	Number	torque	I.P	B.P	Mechanical Efficieny	BTHE	ITHE	Desirability	
	1	*16.931*	*3.611*	*1.417*	56.818	28.727	51.879	1.000	Selected

Optimized Result

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A: Torque	is in range	0.62	21.87	1	1	3
B: I. P	is in range	1.84	5.16	1	1	3
C: B. P	is in range	0.1	3.23	1	1	3
Mechanical Efficiency		5.11	62.59	1	1	3
BTE		2.09	30.32	1	1	3
ITE		40.8	52.17	1	1	3

Table-6: Optimization Criteria

Conclusion

The following conclusion is noted after optimization is done to determine the idealparameters for a biodiesel blend with castor oil:

- The software-designed experiments aided in the precise prediction of the responses.
- The highest desirability of 1 is attained using the RSM's desirability approach using Design Expert.
- As per the study, Indicated Thermal Energy should be higher than Brake Thermal Energy; it is observed from experimentation that the value of ITE is higher than BTE.
- During the analysis, maximum Mechanical Efficiency was observed as 56.818, Indicated Thermal Energy as 51.897, and Brake Thermal Energy as 28.727.
- The engine's efficiency increased during the process, and the optimal value for the blended mixture was achieved during the analysis.
- It is observed that the increased value is obtained for the 40 % blended mixture of castor oil in diesel in a VCR diesel engine at a compression ratio of 18 as compared toa pure diesel engine.

It is shown that the ANOVA analysis can be used to identify the variables needed for any IC engine to meet its goals. The current study determines the compression ratio, load, and blend percentage to achieve the highest mechanical and thermal efficiency levels. This approach was discovered to be successful for multi-objective IC engine optimization.

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