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Optimisation of the Performance of Ethanol-Gasoline Fuel Blend for Internal Combustion Engines

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ABSTRACT : *In the pursuit of enhanced automotive performance without compromising the environment, researchers and manufacturers explore alternative fuels. Ethanol, as a substitute for gasoline in spark ignition engines, have received significant attention. This study utilized Ricardo wave software to simulate a 4-cylinder spark ignition engine, maintaining a constant compression ratio of 10. Various fuel blends (ranging from E0 to E100) were analysed at different speeds (1500, 3000, 4500, and 6000rpm), evaluating parameters like brake power, fuel consumption, thermal efficiency, and emissions (CO, NOx, UHC). The investigation highlighted the impact of different ethanol-gasoline blends on engine performance and emissions. Using Design Expert software for parameter optimization, the study revealed that E85 emerged as the optimal blend across all speeds considered. E85 showcased superior performance among the blends, suggesting its viability as an optimal fuel choice for spark ignition engines. These findings hold potential implications for automotive design and policy, indicating a promising pathway towards improved performance with reduced environmental impact*

KEYWORDS: e*thanol; gasoline; design expert software; optimisation; emissions.*

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I. INTRODUCTION

The pursuit of improved performance in internal combustion engines has long relied on fossil fuels, driving both transportation and electricity for generations (Ekpu and Obadina, 2020). However, the detrimental emissions linked to fossil fuel combustion such as nitrogen oxides (NOx), sulphur oxides (SOx), carbon monoxide (CO), and unburnt hydrocarbons (UHC) have contributed significantly to global warming, air pollution, and the environmental challenges facing today (Amsal et al., 2023; Abouemara and Fikry 2020; Oguclu, 2019). Research, such as that conducted by the World Health Organization, has shown the widespread impact on urban air quality, with nearly 90% of residents in cities breathing unhealthy air (Sihaloho et al., 2023). In particularly, the use of heavy fuel oil (HFO) in maritime vessels accounts for approximately 20-30% of total NOx emissions, in addition to contributing to CO and particulate matter (PM) pollution (Sihaloho et al., 2023).

In the context of energy sectors of developing nations, a pressing challenge revolves around the environmental degradation linked to fossil fuel usage (Rahmani et al., 2020). Highlighting this, Dahham et al. (2022) demonstrated that internal combustion engines fuelled by fossil resources not only generate a quarter of power worldwide, but also contribute 10% of global greenhouse gas (GHG) emissions. Consequently, legislative actions at various governance levels in numerous countries have aimed to mandate or encourage the adoption of alternative fuels, spurred by the limited availability and adverse environmental impact of fossil fuels. These efforts underscore the urgent search for more environmentally sustainable and higher-performing fuel alternatives. The technological advancements of the automotive and engine industries are anchored in the pursuit of enhancing thermal efficiency, reducing fuel consumption, and reducing GHG emissions. Research investigating the impact of fuel additives has affirmed the success of substances such as alcohol, hydrogen, and metal oxides in improving engine performance or mitigating emissions (Paluri and Patel, 2022; Daud et al., 2021; Costa and Piazzullo, 2018; Dantas-Neto et al., 2014; Schifter et al., 2011).

Recent focus has been toward ethanol as a prospective substitute for gasoline in spark ignition engines. Ethanol, available in various forms worldwide, can be employed in its pure form or blended with gasoline or diesel. Its oxygenated properties allow for heightened engine compression ratios, facilitating faster flame propagation and ultimately contributing to reduced GHG emissions, thereby fostering cleaner air (Emeniru et al., 2022; Lin et al., 2021). Fuel producers tailor blend specifications to accommodate local legislation, vehicle types, weather patterns, consumer habits, and market conditions, necessitating the optimisation of ethanol-gasoline blends to ascertain the most advantageous composition. Optimisation methodologies, such as statistical analysis software employing optimiser functions and visual optimisation plots, are pivotal in determining the most exhaustive experimental solutions, a position supported by (Ekpu, 2020; Ekpu et al., 2013).

This study aims to optimise various mixtures ethanol and gasoline fuels (E0, E10, E25, E40, E55, E70, E85, and E100) at different engine speeds (1500, 3000, 4500, and 6000rpm). The results of the brake power (BP), brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), UHC, CO, and NOx simulations, derived from a 4-cylinder spark ignition engine model simulated using Ricardo Wave software, serve as critical input parameters. This quest of optimisation was emphasized by the findings of Carissimo and Korecki, (2023) which states that optimisation can discern the most fitting choice based on an objective function, although requiring clear objective selection. Additionally, Ijaz-Malik et al. (2023) underscore the robustness of response surface methodology (RSM) based optimisation in identifying optimised conditions, altering input factors to achieve desirable outputs, and outlining detailed trends. Thus, this study strives to pinpoint the most favourable solutions within a solution space, where the objective function achieves its minimal or maximal value, an essential feature of optimisation (Tunay and Abiyev, 2022).

II. MATERIALS AND METHODS

A. MATERIALS

The materials and equipment/tools used in this study include gasoline, ethanol, Ricardo Wave software, and Design Expert software. Gasoline is derived from the distillation of petroleum by the fractionation method, which consists mainly of chemical substances that are enriched with various additives. However, ethanol is a renewable fuel made from various plant materials collectively known as biomass. Ricardo Wave software was used to design the engine model and run the simulation. While Design Expert was used for the optimisation of the simulation results.

B. METHODS

A 4-cylinder spark ignition naturally aspirated engine model was built using Ricardo Wave software. Fig. 1 presents the engine model used in this study. The engine was made up of an engine block, four engine cylinders, eight valves, four injector nozzles, and intake and exhaust channels. The engine specifications and parameters are presented in Table 1. The stoichiometric air fuel ratio for one of the fuel blends (E25 – 75% gasoline and 25% ethanol) was calculated as 13.7 employing Eq. (1-5). Similar steps were followed to calculate the stoichiometric air fuel ratio for other blends of ethanol-gasoline.
From the fuel blend of E25,

$$Molecular\ formular = C_{5.28}H_{12.57}O_{0.45} \quad (1)$$

The percentages of carbon, hydrogen, and oxygen are 0.7621 (76.21%), 0.1512 (15.12%), and 0.0866 (8.66%) respectively. Eq. 2 and 3 are used to calculate the oxygen required for complete combustion of carbon and hydrogen.

$$for\ C: C + O_2 \rightarrow CO_2 \quad (2)$$

$$O_{2,\ c}\ required\ \ 2.0322kg\ of\ fuel$$

$$for\ H: 2H_2 + O_2 \rightarrow 2H_2O \quad (3)$$

$$O_{2,h}\ required\ \ 1.2096\ kg\ of\ fuel$$

Let $O_{2,t}$ $be\ the\ total\ oxygen\ required$

$$O_{2,t} = (O_{2,\ c} + O_{2,h} - 0.0866) \quad (4)$$

$$A/F = (O_{2,t})/0.23 \quad (5)$$

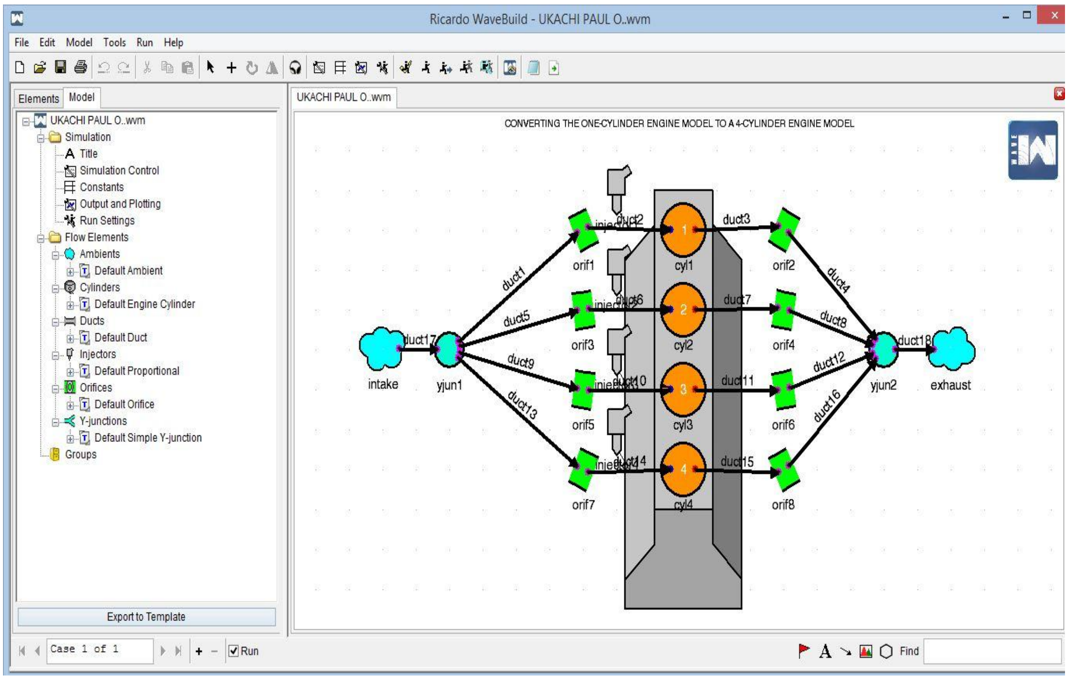

Fig. 1: 4-Cylinder Spark Ignition Engine Model

Table 1: Engine Model Specifications

Parameters	Symbols	Units	Values
Bore x Stroke	D x L	mm	78.1x82
Number of cylinders	K	-	4
Compression ratio	r	-	10
Engine Type	4-Stroke spark ignition	-	-
Engine speed	N	rpm	1500,3000,4500,6000
Number of power strokes	n	rpm	N/2
Clearance Height	C1	mm	2
Intake Pressure	Pi	bar	1.0
Intake Temperature	Ti	K	300
Exhaust Pressure	Pe	bar	1.05
Exhaust Temperature	Te	K	300
Connecting Rod Length	CR	mm	150
Valve Type	Valve lift	-	-
Combustion Model	Wiebe Model	-	-
Heat Transfer Model	Woschni Model	-	-
Piston top temperature	Tp	K	520
Cylinder liner temperature	Ti	K	400
Cylinder head temperature	Th	K	520
Intake valve temperature	Tiv	K	420
Exhaust valve temperature	Tev	K	480

C. Optimisation Criteria

The optimisation criteria employed in this study through Design Expert software revolved around a multi-criteria approach, conducted across a range of engine speeds (1500, 3000, 4500, and 6000 rpm). To steer this optimisation process, the simulation outputs of BP, BSFC, BTE, UHC, CO, and NOx were used as crucial input parameters. The primary aim of this optimisation was threefold: first, to reduce fuel consumption; second, to enhance overall engine performance; and third, to reduce emissions. Consequently, the optimisation strategy focused on maximising BP and BTE, while simultaneously minimising BSFC, UHC, CO, and NOx.

By focusing on maximisation of BP and BTE, the study sought to achieve greater power output and improved engine efficiency, thus improving engine performance. At the same time, reducing BSFC aimed to decrease the fuel consumed per unit of power produced, aligning with the goal of reducing overall fuel consumption. Additionally, minimising the emission of UHC, CO, and NOx aimed to mitigate the environmental impact by curbing the release of these harmful pollutants into the atmosphere. This multi-criteria approach to optimisation underscores the study's commitment to striking a balance between enhancing engine performance, reducing fuel usage, and mitigating emissions for a more efficient and environmentally friendly operation.

III. Results and Discussion

The analysis of results obtained from the Ricardo Wave software is depicted in Tables 2 – 5. These tables show data on BP, BSFC, BTE, UHC, CO, and NOx at speeds of 1500, 3000, 4500, and 6000 rpm. When these tables are examined, certain observations can be made regarding blends containing gasoline-ethanol mixtures.

E85 exhibits the highest BP and BTE, along with the lowest UHC, CO, and NOx at all speeds considered. On the contrary, E25 demonstrates the lowest BSFC for each of the speeds studied. Moreover, an increase in speed correlates with an increase in BP, BSFC, and CO, while UHC decreases. Remarkably, the highest BTE is observed at 3000 rpm, whereas the lowest occurs at 6000 rpm. Similarly, the highest and lowest NOx values are observed at 1500 rpm and 4500 rpm, respectively. These findings from Tables 2 – 5 serve as the basis for the optimisation carried out at speeds of 1500, 3000, 4500, and 6000 rpm.

Table 2: Simulation results at 1500rpm

Fuel Blend	BP (hp)	BSFC (kg/kWhr)	BTE (%)	UHC (ppm)	CO (ppm)	NOx (ppm)
E0	26.68	0.2381	34.03	488.5	45210	26.01
E10	28.12	0.2946	34.75	481.5	40440	23.27
E25	27.22	0.262	34.32	486.9	43050	25.58
E40	27.8	0.2792	34.48	487.4	42930	19.39
E55	28.29	0.2983	34.73	481.3	41410	19.03
E70	28.84	0.3205	34.99	468	39570	18.57
E85	29.54	0.3458	35.32	448	37370	17.9
E100	30.44	0.3755	35.73	431.7	34590	17.97

Table 3: Simulation results at 3000 rpm

Fuel Blend	BP (hp)	BSFC (kg/kWhr)	BTE (%)	UHC (ppm)	CO (ppm)	NOx (ppm)
E0	65.17	0.2268	35.72	107.6	57710	26.17
E10	68.69	0.2815	36.37	96.31	52660	22.17
E25	66.55	0.2497	36.61	102.3	55360	25.51
E40	68	0.2662	36.17	99.62	55140	19.43
E55	69.19	0.2847	36.38	96.28	53210	18.93
E70	70.63	0.3059	36.65	92.49	51090	18.4
E85	72.35	0.3307	36.94	90.19	48830	17.73
E100	74.47	0.3598	37.29	89.19	45410	17.39

Table 4: Simulation results at 4500 rpm

Fuel Blend	BP (hp)	BSFC (kg/kWhr)	BTE (%)	UHC (ppm)	CO (ppm)	NOx(ppm)
E0	87.02	0.2339	34.64	58.43	62450	19.99
E10	91.76	0.2904	35.25	57.94	57340	17.37
E25	88.88	0.2576	34.91	58.15	60810	19.59
E40	90.84	0.2746	35.06	58.38	59810	14.95
E55	92.41	0.2938	35.26	58.17	57940	14.78
E70	94.31	0.3158	35.51	57.94	55860	14.45
E85	96.55	0.3413	35.79	57.66	53400	14.13
E100	99.17	0.3717	36.1	57.34	50450	13.62

Table 5: Simulation results at 6000 rpm

Fuel Blend	BP (hp)	BSFC (kg/kWhr)	BTE (%)	UHC (ppm)	CO (ppm)	NOx (ppm)
E0	105.2	0.254	31.9	59.06	66770	20.11
E10	110.6	0.3153	32.47	58.56	61670	17.4
E25	107.3	0.2797	32.15	58.77	64330	19.8
E40	109.5	0.2982	32.29	58.99	64180	15.2
E55	111.3	0.3189	32.49	58.79	62320	14.85
E70	113.4	0.3428	32.71	58.55	59920	14.54
E85	116	0.3706	32.97	58.28	57610	14.16
E100	119.1	0.4035	33.25	57.95	54740	13.65

A. Optimisation at 1500 rpm

The surface response analysis conducted at a speed of 1500 rpm for the various fuel blends is visually represented in Fig. 2. The obtained desirability value stands at 0.097, indicating that certain parameters could be further optimized. The predicted values for key performance indicators are as follows: 29.8015 hp, 0.3540 kg/kWhr, 35.4229%, 448.1510 ppm, 36813.5 ppm, and 17.1083 ppm for BP, BSFC, BTE, UHC, CO, and NOx, respectively.

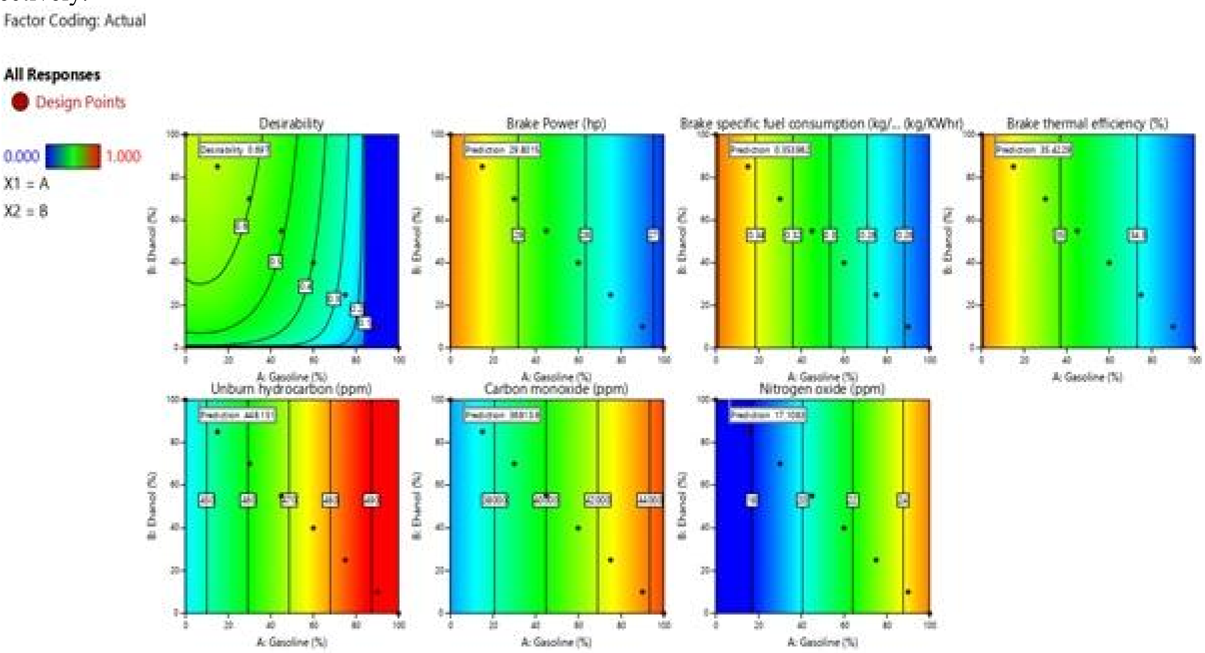

Fig. 2: Surface response at 1500 rpm

B. Optimisation at 3000 rpm

Fig. 3 illustrates the surface response corresponding to each fuel blend at a speed of 3000 rpm. It presents a desirability score of 0.730, signalling a relatively higher level of favourable outcomes. The predicted values for the key parameters are as follows: 72.8584 hp, 0.3371 kg/kWhr, 37.0206%, 89.9057 ppm, 48119.1 ppm, and 16.9495 ppm for BP, BSFC, BTE, UHC, CO, and NOx, respectively.

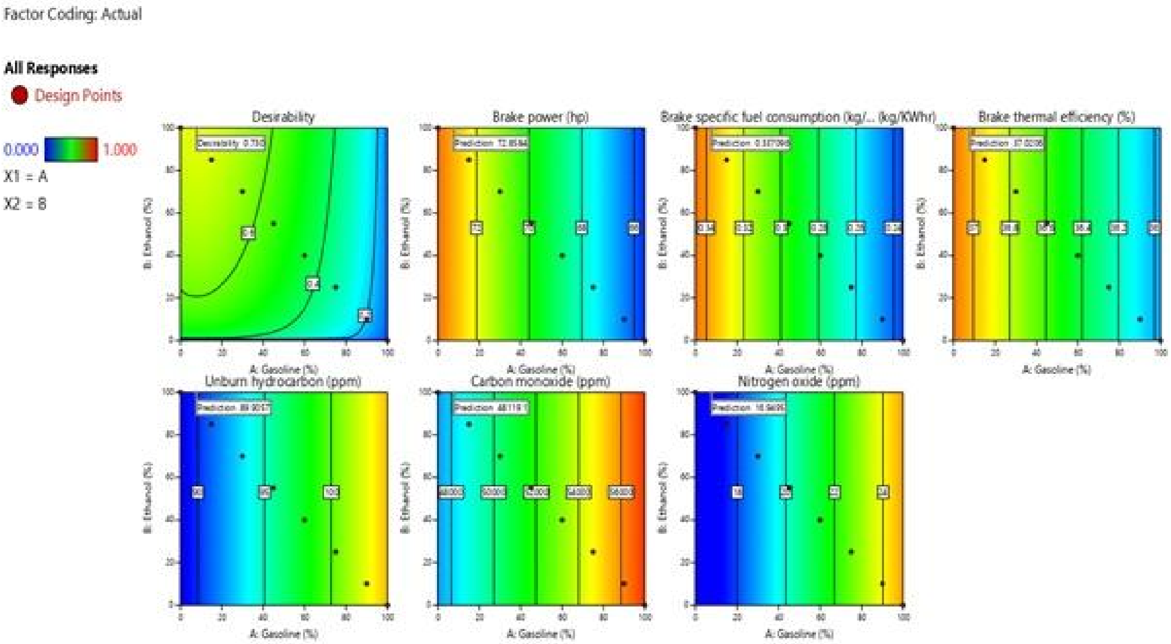

Fig. 3: Surface response at 3000 rpm

C. Optimisation at 4500 rpm

Fig. 4 displays the surface response of each fuel blend at a speed of 4500 rpm. It reveals a desirability rating of 0.712, indicating a relatively favourable overall outcome. The predicted values for essential parameters are: 97.5338 hp, 0.3521 kg/kWhr, 35.8960%, 57.5651 ppm, 52470.2 ppm, and 13.7274 ppm for BP, BSFC, BTE, UHC, CO, and NOx, respectively.

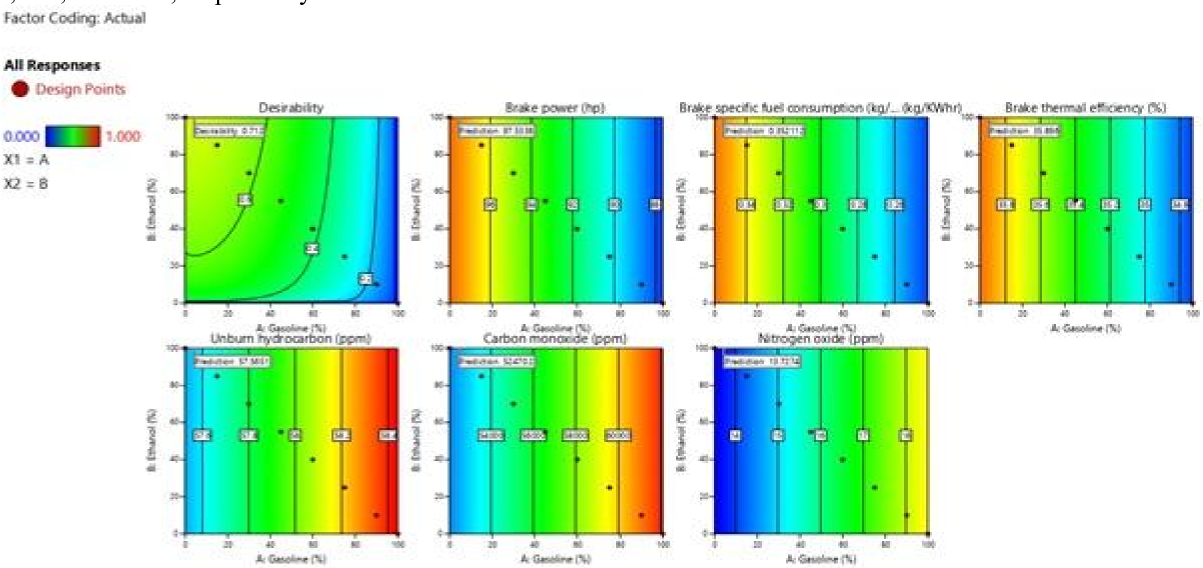

Fig. 4: Surface response at 4500 rpm

D. Optimisation at 6000 rpm

Fig. 5 shows the surface response corresponding to each fuel mixture at a speed of 6000 rpm. The analysis indicates a desirability score of 0.708, suggesting a reasonably favourable overall outcome. Anticipated values for key parameters are as follows: 116.839 hp, 0.3790 kg/kWhr, 33.0348%, 58.2514 ppm, 57063.6 ppm, and 13.3856 ppm for BP, BSFC, BTE, UHC, CO, and NOx, respectively.

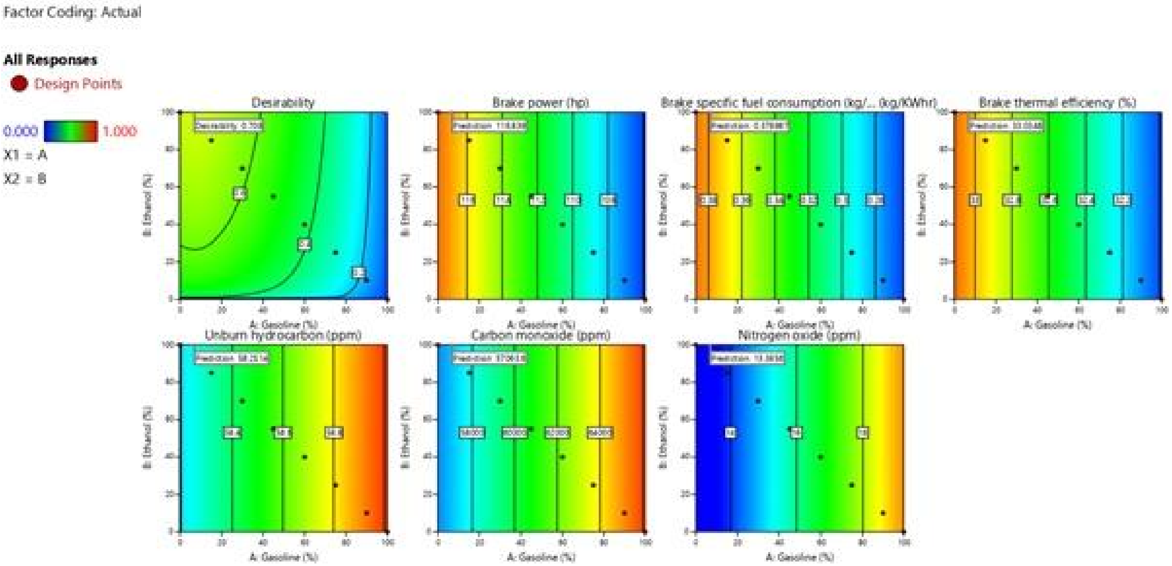

Fig. 5: Surface response at 6000rpm

E. Discussion of Optimisation Analysis

Optimisation was carried out at speeds of 1500, 3000, 4500, and 6000 rpm, and the findings are summarized in Table 6. The results of this table strongly advocate for the superiority of the E85 fuel blend among all the blends and speeds considered. This position reiterates the results of previous studies: Koç et al. (2009) demonstrated E85 outperforms E0 and E50 blends in engine performance and emissions. Similarly, Paloboran et al. (2021) optimised a spark ignition engine using RSM and nonlinear programming, confirming superior engine parameters for E85 within a speed range of 2000 - 8000 rpm, although specific fuel consumption and thermal efficiency were noted as less preferable when compared to E0.

Furthermore, insights from Serrano and Chalaça (2018) proposed the development of engine hypotheses from scratch to accommodate high concentration ethanol such as E85, reinforcing its future potential. The prevalence of E85 in more than 3000 fuel stations in the United States is attributed to its ability to enhance engine efficiency compared to pure gasoline (Tornatore et al., 2019). Furthermore, Yontar (2018) conducted a mapping study evaluating the performance of dual sequential spark ignition engines using ethanol (E100) and E85. Their findings favoured E85 over ethanol in a Honda L13A4 i-DSI engine designed for gasoline use, adding weight to E85's superiority. In this context, E85 emerges as the optimal fuel blend, consistent with various studies highlighting its superior performance across a spectrum of engine parameters and speeds.

Table 6: Optimisation Response at 1500, 3000, 4500, and 6000 rpm

Speed (rpm)	Response to Brake Power (hp)	Response to Brake Specific Fuel Consumption (kg/kWhr)	Response to Brake Thermal Efficiency (%)	Response to Unburn Hydrocarbon (ppm)	Response to Carbon Monoxide (ppm)	Response to Nitrogen Oxide (ppm)
1500	29.8015	0.3540	35.4221	448.1510	36813.5	17.10
3000	72.8584	0.3371	37.0206	89.9057	48119.1	16.9495
4500	97.5338	0.3521	35.896	57.5651	52470.2	13.7274
6000	116.839	0.3790	33.0348	58.2514	57063.6	13.3856

IV. CONCLUSION

Researchers and automotive manufacturers continuously explore alternative fuels that not only enhance performance, but also prioritise environmental sustainability. Taking into account the global imperative to limit the temperature increase to 1.5 degrees Celsius, a shift away from fossil fuels becomes imperative. Emissions resulting from fossil fuel combustion directly contribute to air pollution, global warming, and environmental issues such as droughts and floods. In pursuit of improved engine performance, fuel efficiency and reduced emissions, this study meticulously optimised parameters such as BP, BSFC, BTE, UHC, CO, and NOx across various fuel blends E0, E10, E25, E40, E55, E70, E85, and E100. Consequently, optimisation strongly indicates that the E85 fuel blend is the most favourable among the tested blends, showcasing superior attributes in engine performance, efficiency, and emission reduction.

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