Performance and emission trade-off assessment for aero-gas turbine engine

Muhammad Hanafi Azami, Mark Savill

Abstract---- Environmental and performance aspect has emerged as an essential trade-off in the design phase of novel engines. From design's point of view, not only engine performance requirements, external factors such as cost and environmental issues are all required to be in place. At present, there are myriad works on optimization and trade-off performance and environmental impacts are being done. This work provides a systematic trade-off solution to address the performance and emission for aero-gas turbine engine such as RB211. Four types of fuels namely algae biofuel, Jatropha biofuel, Camelina biofuel, and kerosene fuel are studied. Prior to the trade-off assessment, data from performance analysis using in-house software PYTHIA and emission analysis (in-house software: HEPHAESTUS) are compiled to first identify the necessary parameters needed in each computer tool subsequently. A design of experiment (DoE) using general factorial is used in Minitab software to follow an explorative approach, offering an alternative solution to the practicability in this work. Performance and emission parameter that were studied are thrust specific fuel consumption (TSFC) and nitrous oxides emission indices (EINOx). It was found that the contrasting effects of EINOx and TSFC due to speed factor require a trade-off evaluation. High speed results in reduction in TSFC, but not EINOx.

Keywords: Engine Performance; Engine Emission; Trade-off Assessment

1. INTRODUCTION

In recent years, optimization method arose as an essential tool to ensure design system operates at optimal condition under certain constraints. Aviation industry has done tremendous efforts in optimization work ranging from aerodynamics (see Antunes and Azevedo [1] and Buckley and Zingg [2]), shapes and structural designs (see Schmidt et al. [3] and Elham and van Tooren [4]), dynamic and trajectories/routes (see Xu et al [5], engine performance (see Berton and Guynn [6] and Boulkeraa and Ghenaiet [7] for turboprop), technology and economic perspectives (see Curran et al. [8]. Some of the works are very specific on the field but at least in the last four decades, the field of multidisciplinary design optimization (MDO) has been more attractive due to its advances in theory, algorithms, software frameworks and applications.

The main attraction of MDO is interaction between individual discipline [9]. MDO decomposes into two or several levels of sub-problems with upper or system level and lower or subsystem level, that is categorized into two types: hierarchical (parent-childhood relationship) and non-hierarchical (same-level children sub-problems) [10]. A complete survey of all architectures in MDO is explained in-depth by Martins and Lambe [9] covering optimization problem statements, diagrams and detailed algorithms for non-specialists and future references. This certainly pushes aerospace industry in the design of complex system as a whole. Early work of MDO only covers fundamental design formulation, optimization methods, and sensitivity analysis, but now it advances to topics of surrogate modelling, visualization, multi-objective optimization and optimization under uncertainty [11]. Willcox and Haftka [11] further added that MDO communities are struggling with issues related to the efficient sensitivity calculation, surrogate modelling, Pareto frontiers, visualization, and implementations in the industries.

During mid-20th century, Schmit, Haftka and collaborators introduced MDO and built its application around other branches of engineering. For aerospace in particular, Sobieski and Haftka [12] made a complete survey for interaction of structures with other discipline, Rallabhandi and Mavris [13] as well as Bijewitz et al. [14] made studies on the airframe with propulsion cycle, Ghoman et al. [15] focuses on wing shape, structure, and aerodynamics MDO, last but not least, Toal et al. [16] focuses on optimization of a whole engine thermochemical design.

Environmental and performance aspect has emerged as an essential trade-off in the design phase of novel engines. From design's point of view, not only engine performance requirements, external factors such as cost and environmental issues are all required to be in place. At present, there are myriad works on optimization and trade-off performance and environmental impacts are being done, including Antoine and Kroo [17] on aircraft designing within environmental (noise) and cost constraints, Mazlan [18] on optimization assessment on biofuel to find the trade-off between emission (NOx and CO) and thrust and Cavalca et al. [19] on micro turbine performance with consideration of pollutant emission. Much recently, Jimenez and Mavris [20] studied selections of aircraft technologies in response to environmental impacts in the future and put a broader perspective on the performance trade-off between fuel burns, LTO NOx and noise. It is found to be less distinctive in the overall reduction. It seems that these results are, indeed, comparable to this work and discussed later in the section.

Nonetheless, this work excludes an economical viewpoint. Optimization methods select the best set and variables in each case by using iterative numerical calculation [21]. There are many optimization techniques

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involved although two main approaches are non-evolutionary and evolutionary methods. Each approach is divided into several techniques as presented in Figure 1. Aldheeb [21] has described each technique thoroughly and is not repeated here. To provide a meaningful insight on the selection of most preferred optimization techniques, genetic algorithms, differential evolution and particle swarm optimization are often the best choices. Evolutionary optimization techniques are preferred due to their flexibility, robustness and capability of solving complex problems. This is advantageous since complexity of optimization problems dramatically increased as more design variables and objective functions involved [22]. Kipouros [22] further added that not only appropriate selection of optimizations are essential, but modelling and optimization algorithm tuning play important role to capture execution and exploration design problem successfully. Although there is a number of engineering software tools that can be used for optimization purposes, its capabilities of commercially used software in statistics to accommodate problems in aerospace propulsion are certainly worth exploring. The unique ability of factorial design problems in statistics allows interactions between factors given at different levels of the designs.

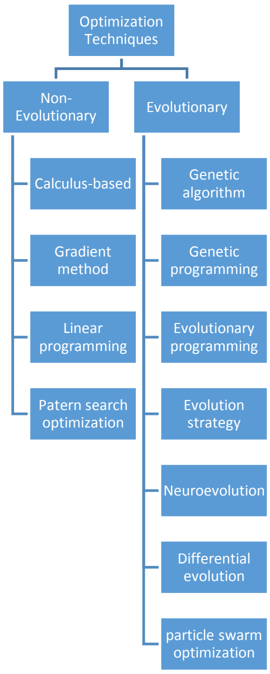

Fig. 1: Flow process of conventional combustor trade-off assessment

Some earlier relevant optimisation studies such as performed by Mazlan [18], the present work attempts to evaluate the trade-off between performance and emission using biofuels under different modes of combustion by applying an explorative Design of Experiment (DoE) method rather than a strict design optimization approach. It follows an explorative approach, offering an alternative solution to the practicability in this field since there are very limited number of studies published. The general factorial problem in the Minitab software is used to capture the main effects between the factors and to obtain a trade-off between the performance and emissions matrices. Such a factorial experiment problem is most effective way to discover the interaction between variables in which one-factor-at-a-time approach may fail, be inefficient and produce incorrect results [23].

As an initial analysis, a parametric study was made to investigate the behaviour of main decision variables for conventional combustor using different four types of fuels namely algae biofuel, Jatropha biofuel, Camelina biofuel, and kerosene fuel (AG, BJ, BC, and KE respectively). The combustor is analysed at different designated case at different factors and levels. The discrete variables trade-off is presented for every case. It is important to stress that the configurations identified are not optimal but are best configurations from the set evaluated in DoE and allow any specific trends that develop between input parameters to be identified. Pareto optimally criteria could then be applied to this information.

2. METHODS

Prior to the trade-off assessment, data from performance analysis using in-house software PYTHIA and emission analysis (in house-software HEPHAESTUS) are compiled to first identify the necessary parameters needed in each computer tool subsequently. Among all parameters calculated, the best solutions are selected from discrete variables by using trade-off assessment in order to achieve targeted objectives of the research. The process flow and parameters needed are illustrated in Figure 2.

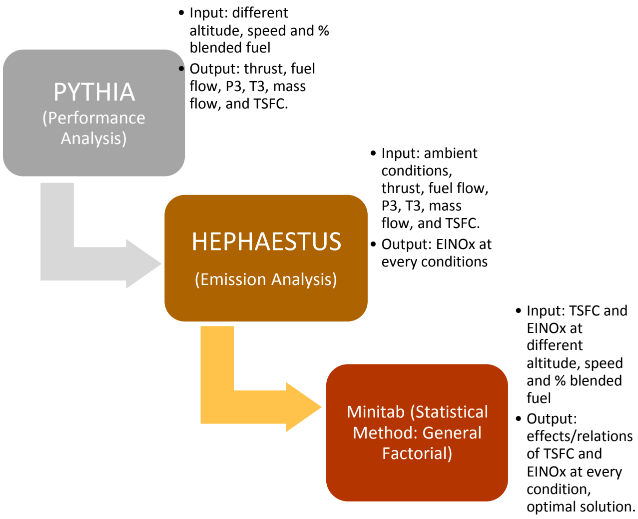

Fig. 2: Flow process of trade-off assessment

In performance analysis, assessments are made according to designated case study, as presented in Table 1. Off-design conditions are calculated at different factors such as different ranges of altitudes, speeds and blended ratio

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percentages. These factors' variations are designed to accommodate HEPHAESTUS requirements. Parameters output from PYTHIA such as mass flow rate of fuel, total mass flow rate through combustor chamber, total pressure and temperature of combustion chamber are put into the emission analysis of EINOx. Thrust specific fuel consumption (TSFC) is also calculated from PYTHIA output. A design of experiment using general factorial is used in Minitab software. General factorial design suits well in case study as the analysis is conducted at factors of different levels. With given number of factors and its' levels, Minitab adjusts case study randomly in a worksheet. Two responses, TSFC and EINOx, are re-arranged according to the factors. All data are, then, entered manually for individual factor.

Table 1: Case study of conventional combustor

Case No	Description	Factors (No of Levels)	Range []	Objectives
1	KE+AG KE+BC KE+BJ	Altitude (3 levels) Speed (4 levels) % Blend (3 levels)	Altitude [500m-1500m] Speed [0.2M-0.8M] % Blend [0.2-1.0]	Minimum TSFC Minimum EINOx
2	Cruise (50% blend)	Type of Fuels (4 levels) Speed (7 levels)	Type of Fuels [KE, KE+AG, KE+BC, KE+BJ] Speed [0-0.8M]	
	Ground (50% blend)		Type of Fuels [KE, KE+AG, KE+BC, KE+BJ] Speed [0-0.3M]	
3	All Blended Fuels	Type of Fuels (3 levels) Altitude (3 levels) Speed (4 levels) % Blend (3 levels)	Type of Fuels [KE+AG, KE+BC, KE+BJ] Altitude [500m-1500m] Speed [0.2M-0.8M] % Blend [0.2-1.0]	

3. MAIN RESULTS AND DISCUSSION

This section discusses results obtained in conventional combustor based on two responses of TSFC and EINOx, which are analysed with different factors such as types of fuels, operating conditions, altitudes (in metres), speeds (in Mach number) and blended ratio percentages. The analysis compares their main effects from the mentioned factors and trade-off that is the presumed solution of the desired objective to the factors given. Note that the minimum constraints for particular flight conditions, such as thrust and fuel flow required are fulfilled and have been taken into considerations.

3.1 Different fuels used (Case 1 - Individual Fuel)

The main effects on TSFC and EINOx and their interactions for Case 1 are illustrated in Table 2. Since the results are almost similar, AG fuel is presented in the text. It is shown that the effects of altitude are less significant (the trends has no gradient) on TSFC (shown in Table 2 (a) and (c)) than EINOx. On the other hand, speed has the most significant changes (large gradient), in which TSFC has opposite trends (refer to Table 2 (a) and (b)) compared to EINOx. As previously discussed, this behaviour is easily explained by taking into account throttling actions from the consumption of burned fuel producing more NOx. TSFC also simultaneously reduces as rate of changes in thrust is higher than fuel flow. Similarly, effect of blending percentage ratios has also resulted in the same trends but is, however, less significant.

The results are further analysed by considering combined effects of the three factors; altitude, speed and percentage blending ratios as depicted in Table 2 (c) and (d). The effects on TSFC for AG fuel illustrate that speed has contributed to the most significant changes, while for EINOx, both altitude and speed affect equally. EINOx emission is shown to result to higher NOx formation at higher speed regardless of blended ratio percentages. The greatest improvement in the TSFC is attained at higher speed, which is contradicting with NOx emission analysis. The results of DoE method interaction lead to identifying a best trade-off solution, which is discussed later. For a clear visualization, the interactions of the factors are contour plotted and presented in Table 3 (a) and (b) for EINOx response and (c) and (d) for TSFC response. Contrasting results of EINOx and TSFC were observed due to the speed factor which require an appropriate trade-off.

Table 2: Main and combined effects of TSFC and NOx for Case 1

TSFC	EINOx
AG fuel	

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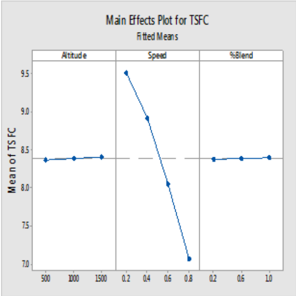
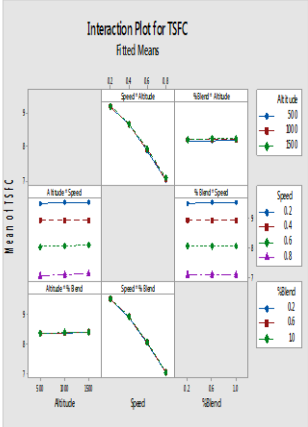
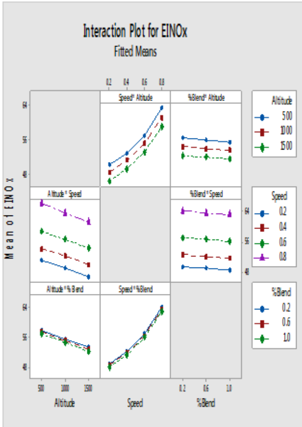


(a)

(b)

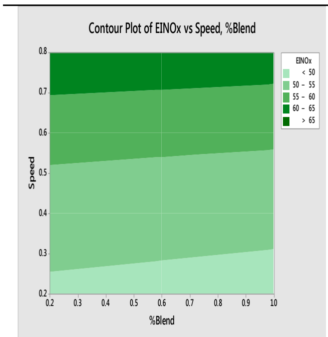
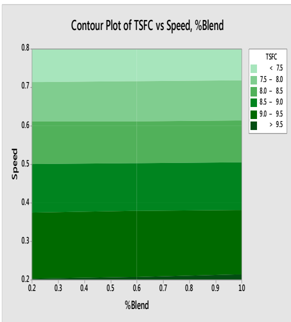
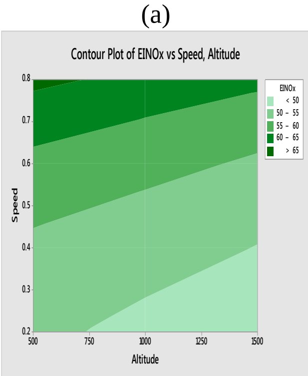
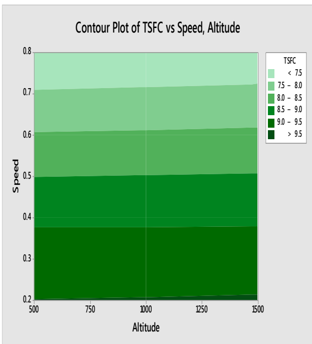


(c)



(d)

Table 3: Contour plots for the interactions of responses and the factors for Case 1

EINOx	TSFC
 (a)	 (c)
 (b)	 (d)

Trade-off (Case 1- Individual Fuel)

Based on the two conflicting responses, a further analysis has been made to obtain the trade-off. Table 4 summarizes the findings, where it can be seen that all fuel types should operate at high altitude of 0.6 Mach number. The best configuration suggests that pure AG fuel is the one to be considered, but not BC and BJ fuels. It is worth noting that the lowest TSFC is preferred, as it reduces other emission as well and is economically sustainable. Figure 3 illustrates distributed compromise plots for each case. The arrows represent the best compromise point for particular fuel.

Table 4: Trade-off solutions for Case 1

Type of Fuel	*Altitude (m)*	*Speed (Mach)*	*%Blend*	*EINOx Fit*	*TSFC Fit*
KE+AG	1500	0.6	1	53.89	8.09
KE+BC	1500	0.6	0.2	57.25	8.04
KE+BJ	1500	0.6	0.2	53.28	8.03

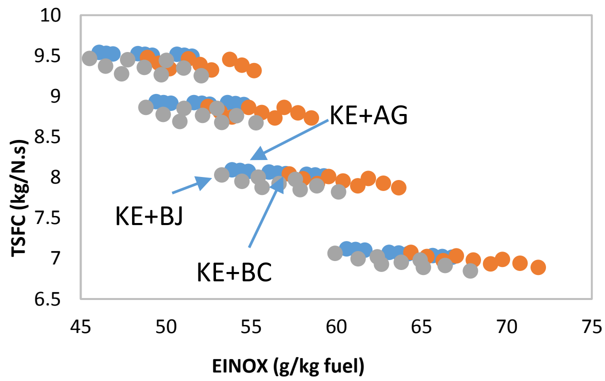


Fig. 3: Trade-off plots for Case 1

3.2 Different operating conditions (Case 2)

In Case 2, further analysis is conducted to evaluate a certified 50% blended ratio fuel at two operating conditions: cruise and ground level, by using KE fuel is used as reference. Similarly, two responses (EINOx and TSFC) with two factors (a type of fuel and speed) are considered. Notably, some performance parameters are not presented because diverging results for biofuels are obtained. The main effects results can be seen in Table 5. The cruise effects are shown on the left side while the effect on ground are shown on the right side of the table. The mean of EINOx for KE+AG fuel is shown to be the lowest in both flight operations (Table 5 (a) and (b)), while KE fuel remains as the highest among all fuels. On the contrary, KE fuel has better TSFC in cruise (Table 5 (c)), but not on the ground (Table 5 (d)). The influence of speed factors is found to be significant and put opposite effects on EINOx and TSFC responses. This proves the consistency of these results altogether.

The trends for overall interaction between factors are illustrated in Table 6 (left: for the effects on cruise, right: effects on the ground). At cruise, results have shown that there is a crossover in the mean of EINOx between KE with KE+BJ (Table 6 (a)), as well as KE+BC at higher speeds for TSFC (Table 6 (c)). KE+AG fuel consistently shows the lowest mean EINOx at every speed. However, KE fuel has significantly improved in TSFC at cruise (Table 6 (c)). In

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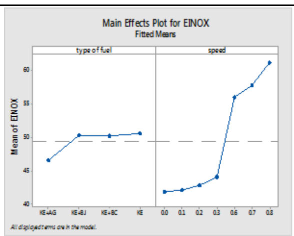
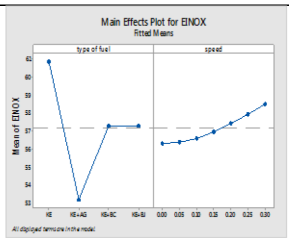
terms of speed, changes of TSFC between the types of fuels are found to be significant, in which KE has the lowest TSFC for speed-type of fuel interaction. On the ground, the trends for EINOx and TSFC have depicted that the change is more gradual for all interaction factors (Table 6 (b) and (d)). Similarly, KE+AG fuel has the lowest EINOx, but KE+BJ fuel has significantly improved in TSFC.

Table 5: Main effects of TSFC and EINOx for Case 2

Cruise	Ground



(a)



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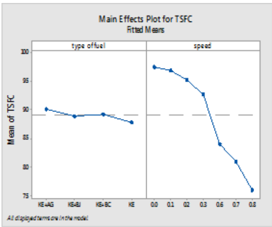

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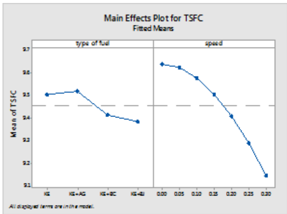
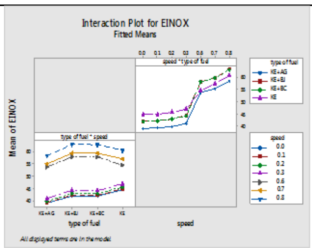


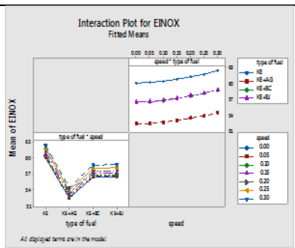
(d)

Table 6: Interaction plot of TSFC and EINOx for Case 2

Cruise	Ground



(a)



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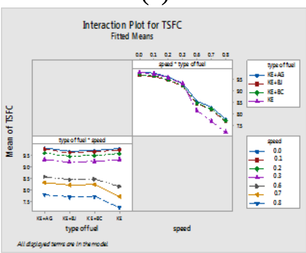
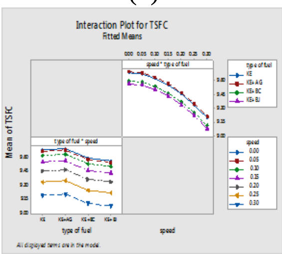


(c)



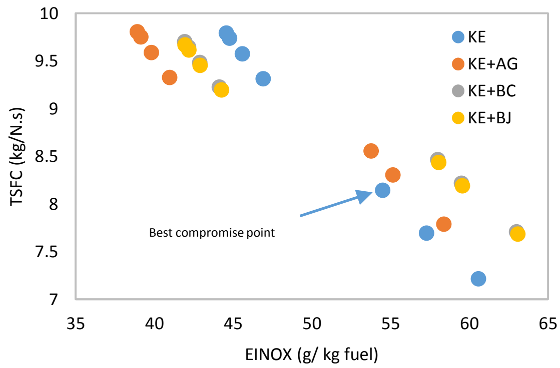
(d)

Trade-off (Case 2)

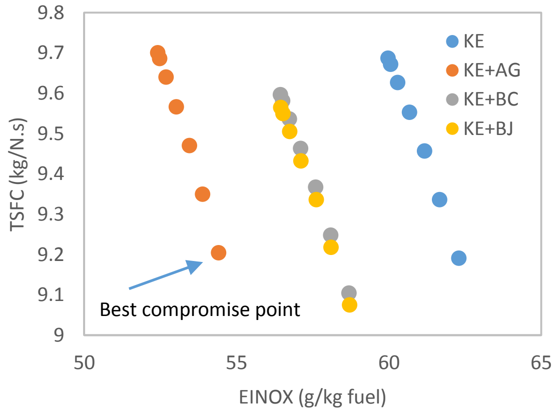
Similar conflicting trends are observed between TSFC and EINOx at different speeds. To compare the trade-off between those two, the same approach is conducted. The trade-off solutions are tabulated in Table 7. At cruise, KE fuel has better trade-off between EINOx (54.51 g/kg fuel) and TSFC (8.14 kg/N.s) at 0.6 Mach number, while at ground, KE+AG fuel has much better trade-off in EINOx (54.42 g/kg fuel) and TSFC (9.2 kg/N.s) at 0.3 Mach number. A scattered plot for visualizing the compromise point for both cases is illustrated in Figure 4 represented by arrows.

Table 7: Trade-off solutions for Case 2

	Type of Fuel	Speed	EINOx Fit	TSFC Fit
Cruise				
	KE	0.6	54.507	8.142
Ground				
	KE+AG	0.3	54.416	9.205



(a)



(b)

Fig. 4: Trade-off plots for (a) Cruise and (b) Ground

3.3 All fuels at different operating conditions (Case 3)

A whole assessment for all fuels using conventional combustor is described in Case 3. Three types of fuel are analysed with three factors such as altitudes, speeds and blended percentage ratios. By using the similar approach as in the previous cases, results for the main effects ((a) and (b)) and interaction plots ((c) and (d)) are illustrated in Table 8. Both KE+AG and KE+BJ fuels have EINOx below the mean value (Table 8 (a)). On the contrary, KE+AG fuel has significantly higher TSFC compared to the mean value. To compare, the three factors (altitude, speed and blended ratio percentage) show opposite effects and trade-off assessment is required.

Table 8: Main effects plots for Case 3

EINOX	TSFC

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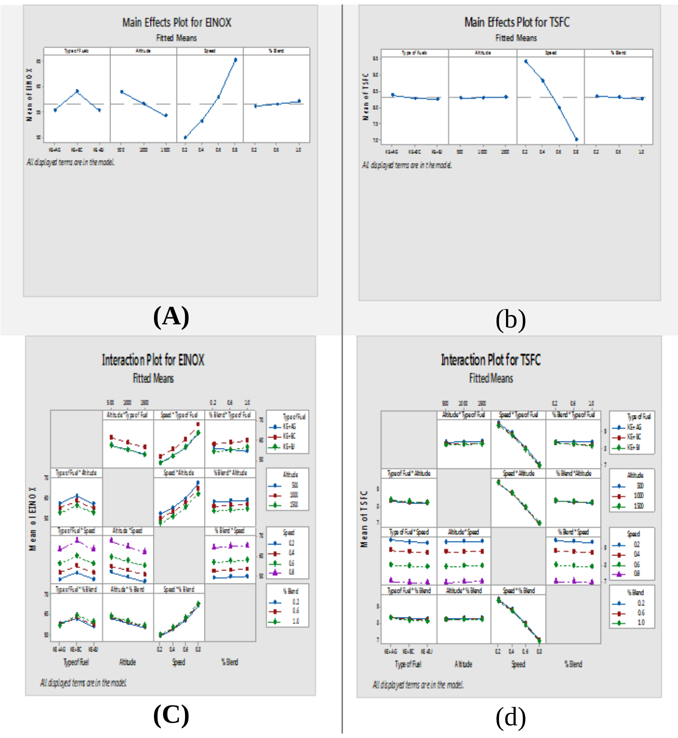

(A) (b)

(C) (d)

Interaction plots show a wider view on the effects of these factors described. The discussion begins with the matrix of mean EINOx in the first column (Table 8 (c)), which is the interaction of type of fuel to other factors. KE+BC fuel produces more EINOx at every blended ratio percentage. In contrast, other factors of interactions (a type of fuel-speed and type of fuel-altitude) have shown a gradual change. As depicted in the second column, generally, EINOx is less produced at higher altitude. KE+AG fuel and KE+BJ fuel produce less EINOx as compared to KE+BC fuel. Meanwhile, in the third column, EINOx has increased exponentially due to the increase in speed. In fourth column, a crossover trend shows between KE+AG and KE+BJ fuels. The matrix interaction in the mean of TSFC (Table 8 (d)) shows different behaviours. There are no significant changes being observed in most of the interactions except for speed, in which a negative is observed. All factors have shown that TSFC can be reduced at higher speed. By comparing both response matrices, the results show that speed is the main contributor compared to other factors involved.

Trade-off (Case 3)

Similarly, further analysis is carried out to obtain trade-off solutions in Case 3. In comparison with other case, Case 3 involves four factors simultaneously. There are five solutions given in DoE and those results are tabulated in Table 9 while Figure 5 illustrates how the solutions are distributed with the circles indicating the best trade-off solutions identified. It is worth highlighting that KE fuel is excluded initially, to keep the number of factors and its levels equally distributed. In short, this case analysis was initially intended to identify the best trade-off between all biofuels and the work is progressing to carry out the comparison with KE fuel. The same conditions as proposed by the solutions are used to analyse KE fuel. As a result, KE+BJ fuel dominates the top three solutions. All suggested solutions have shown better trade-off at higher altitude. KE+BJ fuel at higher speed with lower blended percentage ratio has a better trade-off.

To evaluate on how the biofuels can benefit both trade-off, the comparison with KE fuel is further analysed. The same approach is conducted separately using the same conditions as in the optimal solutions. KE+BJ fuel has shown that high speed with lower blended ratio percentages has the reduction of EINOx and TSFC by 1.07% and 2.06% respectively. However, it seems that the second solution gives a much further reduction of EINOx (2.24%) and TSFC (1.36%). In characterizing the broader, underlying the trade-off between performance and NOx emission, we can find that there is no distinct reduction between those two. This has been noted earlier in one of the literature surveys by Jimenez and Mavris [20].

Table 9: Trade-off solutions for Case 3

Type of Fuels	*Altitude*	*Speed*	*% Blend*	*% Diff wrt KE for EINOx*	*% Diff wrt KE for TSFC*
KE+BJ	1500	0.8	0.2	-1.07	-2.06
KE+BJ	1500	0.6	0.2	-2.24	-1.36
KE+BJ	1500	0.6	0.6	-0.08	-2.32
KE+AG	1500	0.8	1.0	0.03	-1.29
KE+BJ	1500	0.6	1.0	2.11	-3.27

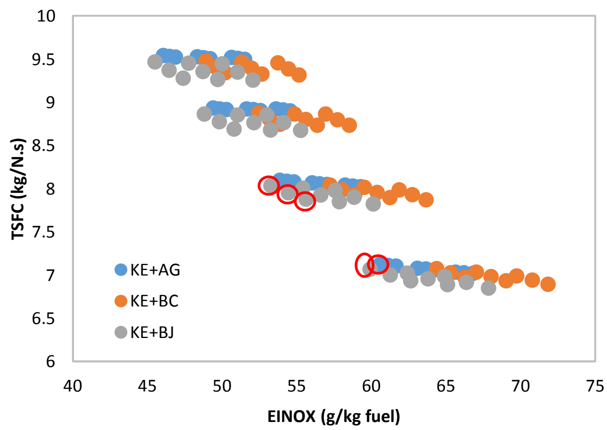

Fig. 5: Trade-off plots for Case 3

4. CONCLUDING REMARKS

This work aims to identify a trade-off between performance and emission of conventional and pressure-rise combustors which has not been attempted so far. By applying Design of Experiment (DoE) method into Minitab tools, main effects, interactions of factors and best solutions are discussed and presented. Two types of the combustors

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are analysed separately due to difference in parameterization analysis involved. As previously clarified, DoE tests are used because of its capability to evaluate factors with different sets of levels and factors interactions. Furthermore, several important conceptual trade-offs can be carried out using DoE methods. Based on the designated case study, results of this work conclude that:

1. Contrasting effects of EINOx and TSFC due to speed factor require a trade-off evaluation. High speed results in reduction in TSFC, but not EINOx.
2. All fuels (Case 1) have better EINOx and TSFC trade-off at high altitude, with KE+BJ fuel dominates the solution suggested in DoE.
3. For 50% blended fuel (Case 2), KE fuel has better trade-off between EINOx (54.51 g/kg fuel) and TSFC (8.14 kg/N.s) at 0.6 Mach number in cruise, while KE+AG fuel has significantly better trade-off in EINOx (54.42 g/kg fuel) and TSFC (9.2 kg/N.s) at 0.3 Mach number on the ground.
4. For an overall analysis (Case 3), KE+BJ fuel has shown that higher speed with lower blended ratio percentages (20%) has better trade-off. A reduction of 1% and 2% of EINOx and TSFC, respectively, is obtained as compared to KE fuel.
5. In identifying trade-off between performance and NOx emission, no significant difference is found between them in the context of design space being considered.

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