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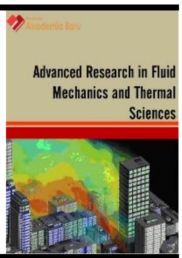

On-Design Operation and Performance Characteristic of Custom Engine

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ABSTRACT

The purpose of this study is to investigate the design point performance of a custom engine via GasTurb software. In this study, a turbojet engine model is simulated without afterburners and limited to design point (DP) simulation at a speed of 15,000 rpm. The input parameters such as pressure ratio (PR) for the main components, the mechanical and burner efficiency, and isotropic PR for compressor and turbine have been identified for a custom engine as a design point. The results compared at different levels of the condition using GasTurb-13 and GSP-11 software. It was found that each software was able to provide similar results at various conditions tested. There are small differences in the values for the fuel flow and specific fuel consumption. Also, the same results were obtained at the baseline point. Furthermore, the heating value has a primary effect on specific fuel consumption. It was also found that the optimal thrust value was at 34.2 kN, and the best value for optimal specific fuel consumption was 20.9 g/kN.s. The main factors affecting biofuel properties are calorific value and viscosity. When the calorific value of the fuel is reduced, the thrust FN and specific fuel consumption increase. For example, Methanol and Ethanol recorded the highest amount of fuel consumption, which is 54.72 g/KN.s and 47.56 g/(KN.s), respectively. This is because they have the highest mass fuel flow (1.79 kg/s for Methanol, and 1.54 kg/s for Ethanol) than other types of fuel, while the mass fuel flow for green diesel (0.78 kg/s) was lower than other fuels, so its specific fuel consumption (22.11 g/(KN.s) was lesser than other fuels.

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1. Introduction

Simulation on cost and risk are the two most important activities in the engine development phase. Meanwhile, engine health monitoring is considered very important during the operation phase [1]. One of the aspects to develop the Engine Health Management (EHM) system is an engine simulation model [2]. There are considerable advantages of simulating the models, such as (i) to understand the performance of the gas turbine engine running on different operation conditions, (ii) to generate required data for a gas turbine engine at an intermediate stage which cannot be acquired analogy [2].

GasTurb is one of a computer-aided system developed by Dr. Joachim Kurzke that enables gas turbine engine on-design performance [3,4]. It equips with some features to estimate (emission, dimensions, and weight) for the engine, real-time and flight simulation, and strength analysis for the integrated components. On the other hand, the National Aerospace Laboratory (NLR) has developed the CAE-system, which is known as GSP. GSP software able to estimate the emission, and it has all the parameters and settings for each module similar to GasTurb. Both of these programs have a simple intuitive interface [4]. The cycle parameters determine which minimizes specific fuel consumption (SFC) subject to constraints series by optimization feature, which provides into GasTurb 12.

Moreover, NASA computer program Chemical Equilibrium with Applications (CEA) generated a tabulated value of the gas properties which are used in GasTurb. Fuel-to air ratio injection, the inlet to the burner of pressure and temperature, and the fuel chemical composition are affected by increasing the temperature in the burner [5]. There are two types of cycle analysis which includes; (i) parametric cycle analysis (also known as design point DP or On-design) which determines engine performance at design choice values (as pressure ratio PR for compressor), fuel performance, and specific thrust with diverse flight conditions, and limits of design parameters (such as exit temperature of the combustor), (ii) engine performance analysis or as known off-design which determines specific engine performance at throttle settings and all flight conditions [6].

The traditional scaling method is compared between the data for the design point of the original maps with a new design point to derive the scale factors [1]. The off-design point map data scale then be multiplied with the original performance maps with scale factors to obtain the scale maps [1]. In the GSP simulation program, the engine performance definition is fixed at DP (Design Point) condition, which has to run before off-design and accelerate or decelerate the engine cycles because of the reference parameters generated from it [2]. GSP program also allows the user to perform cycle analysis from several compressor maps for the aero-engine [7]. The DP calculation in the GasTurb program for the isentropic efficiency, pressure ratio PR, and mass flow of the component be similar to the original map scaling reference point [1]. The demanded engine performance is achieved when selected PR, the efficiency of the components, and maximum temperature for the cycle at the DP for the gas turbine. The demanded power is given when the airflow rate and the thermal efficiency determine at DP [8].

For the data validity, Sankar *et al.*, [2] validated the results for the virtual engine model with engine testbed data (Twin Spool Turbo Jet Engine) at DP because the similar engine test data were not available. Leylek *et al.*, [7] was repeated the tests and error analysis to validate the data. Leylek *et al.*, [7] used different methods to predict the performance for the engine components such as computational fluid dynamics (CFD) analysis, standard empirical performance models, flow codes, and mean-line. They also used GasTurb software to predict dynamic and steady-state performance for a 12-pound thrust turbojet engine and compared it with test results at 15,556 rpm/s rate.

Anosike [9] compared the DP results for engine model with OEM's (Original Equipment Manufacturer's) and compared the data against a known commercial quality natural gas with associated gas. The results were found to have small variations between simulation and OEM test, which may be due to the difference in natural gas qualities. Kong *et al*., [1] compared the performance analysis between GAs map, scaled map, and experimental data. Nasir [8] used a GasTurb to carry out the GT of 40.7 MW SCTS (Simple Cycle Two Shaft), and found the performance for GT drops with reduces the mas flow when the ambient temperature increase. Krishnaraj and Wessley [6] used MATLAB and GSP to perform a parametric analysis of the micro turbofan engine at different bypass ratios. Abu Talib *et al*., [10] uses GasTurb-11 to perform a simulation of performance evaluation of a small scale turbojet engine running on palm oil biodiesel blends. Bayona-Roa [11] indicates that the simulation in the GasTurb software program has three levels, which are the thermodynamic method, the engine's performance mode, and the advanced simulation of the engine performance by determining the geometry of the turbine engines. Use the engine performance simulation method to simulate two-spools turboprop. It was also reported that the factor that has the most influence on the specific fuel consumption (SFC), thrust, and fuel flow in the different flight conditions and the various micing rations is when adjusting the low heating value (LHV). Frhan et al., [12] uses ANSYS 18 software to study the effects of n-Heptane and diesel fuels on the combustion process of a four-stroke diesel engine.

The purpose of this study is to investigate the design point performance of a custom engine via GasTurb software. In this study, a turbojet engine model is simulated without afterburners and limited to design point (DP) simulation at a speed of 15,000 rpm. The input data were identified from previous studies as a reference point. Parameters such as pressure ratio (PR) for the main components, the mechanical and burner efficiency, isotropic PR for compressor and turbine were used. The output parameters such as thrust, fuel mass flow, and SFC for various levels were presented. Furthermore, the effect of changing the fuel type based on the heating value was also investigated.

2. Simulating the Engine Parameters

Both GSP-11 and GasTurb-13 programs need to determine the input parameters and identify the design point DP before simulating the off-design point for any engines. The reference model into GSP is TJET, while GasTurb-13 is using Demo_jet.CYC. The DP is used in GSP and GasTurb simulation programs as a reference point for further analysis. Moreover, the DP simulation was carried out by control in the parameters of the component for a custom engine. Table 1 shows the input parameters for various components of the custom engine which included the specific heat constant pressure for the compressor and turbine (C_{pc}, C_{pt}), specific heat ratio for turbine and compressor (γ_t, γ_c), turbine temperature (T_{t4}), mass flow ($\dot{m}_0$), spool speed (N), turbine and burner efficiency (η_m, η_b), pressure ratio for inlet, compressor, burner, and nozzle (π_d, π_c, π_b, π_n), compressor and polytropic turbine efficiency (e_c, e_t), and the fuel heating value (h_{PR}) [13].

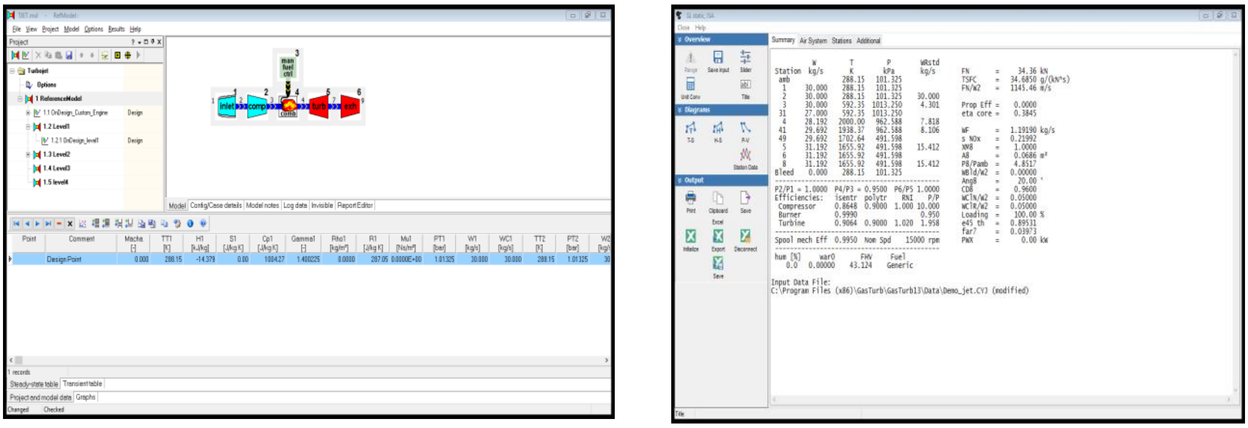
The design point DP for the custom engine now can be established using different component parameters used to compare on-design performance, as shown in Table 2. The interfaces for each program are shown in Figure 1. The DP simulations at sea level static indicated that the Mach number and altitude are zero.

Table 1
The input data at the design point DP

Design Parameter	Units	Value	Design Parameter	Unit	Value
C_{pc}	kJ/kg.K	1.004	π_d	-	1
C_{pt}	kJ/kg.K	1.235	π_c	-	10
γ_t	-	1.4	π_b	-	0.95
γ_c	-	1.3	π_n	-	1
T_{t4}	K	1,800	P_0/P_9	-	1
$\dot{m}_0$	kg/s	30	e_c	-	0.9
N	rpm	15,000	e_t	-	0.9
η_m	-	0.99	h_{PR}	MJ/kg	42.0755
η_b	-	0.99			

Table 2
The input data at the design point DP

Design Parameters	level1	level2	level3	level4
Burner Design Efficiency	0.880	0.940	0.990	0.999
Burner Pressure Ratio	0.900	0.920	0.940	0.950
Mechanical Efficiency	0.950	0.970	0.990	0.995
Burner Exit Temperature [K]	1110	1390	1780	2000
Polytr.Turbine Efficiency	0.880	0.850	0.890	0.900
Polytr.Compr.Efficiency	0.800	0.840	0.880	0.900



(a) (b)

Fig. 1. (a) GSP-11 interface (b) GasTurb-13 output interface

3. Design Point Simulation

The same simple turbojet engine model has been simulated in both GasTurb-13 and GSP-11 software. The parameters used for the simulation using a normal JP-10 fuel for this engine are shown in Table 2. The results for different four levels and baseline for JP-10 fuel into GSP-11 and GasTurb-13 have been illustrated in Table 3, respectively. Simple turbojet engine performances at baseline were found to be similar in the two programs with an only small variation.

Table 3
GSP-11 and GasTurb-13 software output data for JP-10 Fuel at different levels

Performance parameters	Net Thrust [kN]		Thrust Specific Fuel Consumption [g/kN.s]		Total Fuel Flow W_f_b [kg/s]	
	GSP	GasTurb	GSP	GasTurb	GSP	GasTurb
baseline	32.4965	31.3112	34.8333	32.5070	1.1323	1.0178
level1	13.3832	12.5522	32.9722	31.5075	0.4416	0.3954
level2	23.7375	22.0032	30.0000	29.0684	0.7123	0.6396
level3	31.8251	30.5857	34.6111	32.4047	1.1019	0.9911
level4	35.4383	34.2389	38.1111	35.5363	1.3513	1.2167

Figure 2 shows that at a lower technology setting, GSP-11 calculates the impetus higher than GasTurb-13 by 6.2% for the first level. However, at high technology setting, GSP-11 calculates a 3.38% lower trend for the fourth level. This shows that the efficiency levels have a direct impact on the comparison between the calculations of ideal fuel. The component maps were not used in this study, so the result of these differences in the trend is due to the difference in the calorific value of the fuel in both programs. These differences are complemented by the increase burner exit temperature from level one to level four. Therefore, thrust value in level four higher than the value in level one.

Figure 3 shows that the GSP-11 and GasTurb-13 are produced approximately fuel flow results. However, unlike thrust comparison, there are more distinct between GSP-11 and GasTurb-13. At level 1, the difference is 10.4%, but the difference in level 4 is 9.96%. Fuel flow increases due to the decrease in the calorific fuel value and indicates the overall efficiency of the engine is dropped, as well as that leads to increased fuel consumption.

The fuel efficiency for the turbojet engine refers to the thrust specific fuel consumption, which is a ratio between thrust and fuel flow rate. Therefore, the fuel consumption in the turbojet engine is higher than values calculated by GSP-11 for all levels of technology due to the high flow rate. Figure 4 shows that the GSP-11 has a higher SFC than the values calculated by GasTurb-13 due to the higher mass flow. The difference between GSP-11 and GasTurb-13 is 4.52% at level 1, while at level 4, the difference between them is 6.76%. As previously mentioned, when the calorific value decreases, the engine increases the amount of fuel flow rate as a result of the overall efficiency decrease, and an increase in fuel consumption accompanies this. Unlike thrust, fuel consumption increases when it increases the burn exit temperature (this will be noticed in section 4).

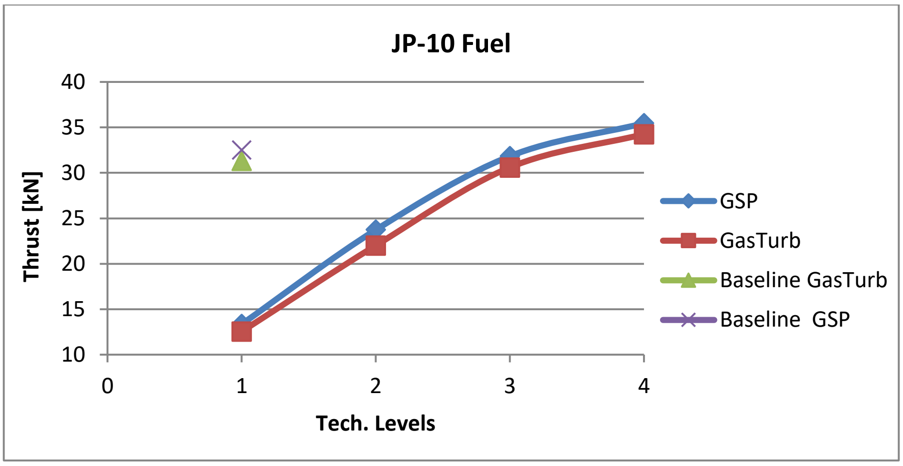


Fig. 2. Thrust comparison at DP for JP-10

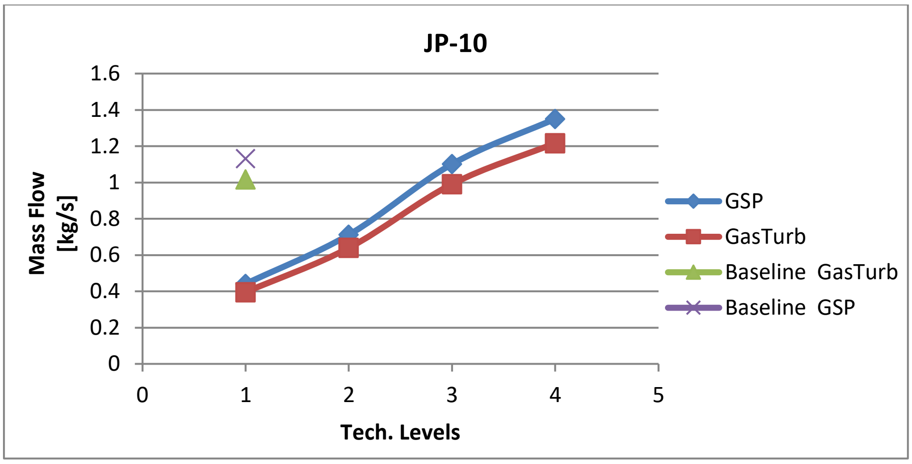


Fig. 3. Mass flow comparison at DP for JP-10

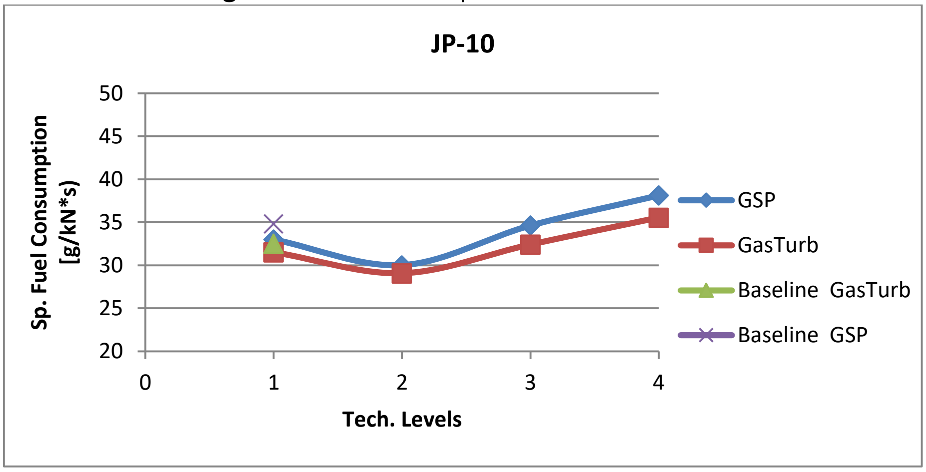


Fig. 4. SFC comparison at DP for JP-10

Table 4 summarizes the design simulation results. The results between the GasTurb-13 and GSP-11 are noticeably close, indicating that the two programs on the performance of the turbojet engine with an affinity for real gas effects. The results from the GasTurb-13 shows the thrust and fuel flow rate slightly lower. As a result, GasTurb-13 produced lower fuel consumption in terms of propulsion. This is probably due to component maps that are not used for on-design analysis that resulted in the outcome of the differences of variations in specific heat.

Table 4
Comparative DP performance of the custom engine for JP-10 Fuel

Performance Parameters	GasTurb-13	GSP-11	Difference %
Thrust [KN]	31.31	32.49	3.65
Mass Flow [kg/s]	1.01	1.13	10.64
TSFC [g/KN*s]	32.50	34.84	6.71

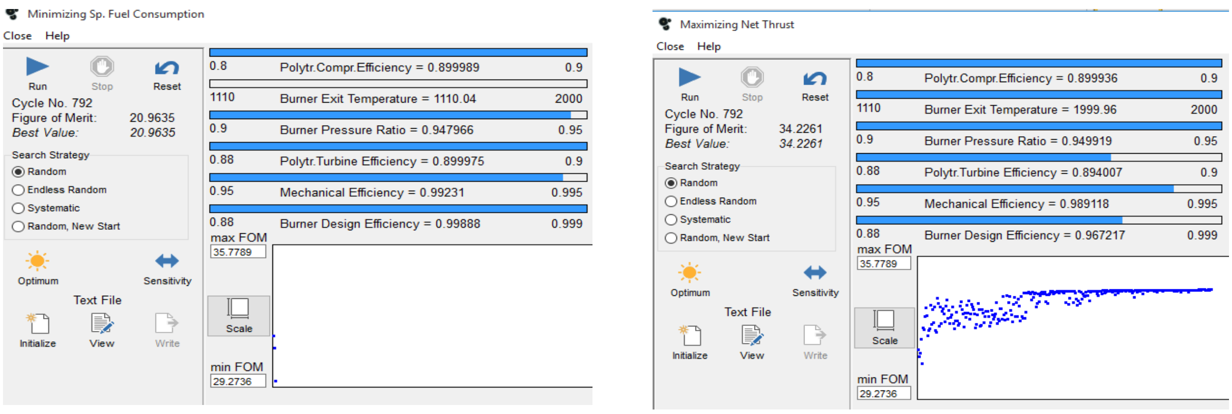
Based on the design simulations, it is clear that the two programs follow the same trend. However, the performance of the turbojet engine is greatly amplified by the impact of different gas assumptions due to efficiency changes. It can be seen that the more significant this difference, the lower the efficiency.

4. Optimization Variable

In this paper, there are four levels of technology setting used, as shown in Table 2. This section illustrates how to optimize these four levels to get the best value for thrust and specific fuel consumption (SFC). Based on that, the GasTurb-13 was used to determine the optimum value for thrust and SFC based on the component variables in Table 5. Furthermore, the variables range, as shown in Figure 5, as follows; Polytr. Compressor efficiency range (0.8-0.9), Polytr.Turbine efficiency (0.8-0.9), burner exist temperature (1,110-2,000K), mechanical efficiency (0.95-0.995), pressure ratio (0.9-0.95), and burner efficiency (0.88-0.999). However, the best value for SFC was 32.56 g/(kN.s) and 31.31 kN for the thrust as shown in Table 4 before running the random strategy on the variables, but after the strategy applied on the variables, so the thrust is 34.22 kN at optimum input values as η_m, π_b, T_{t4}, e_c, and e_t are (0.9891, 0.9499, 1999.96 K, 0.8999, and 0.8940) as shown in Column A. As well as, the best value for SFC became 20.96 g/(kN.s) at optimum input values such as η_m is 0.9923, π_b is 0.9479, T_{t4} is 1110.03K, e_c is 0.899989, and e_t is 0.899975 as illustrate in Colum B, respectively.

Table 5
The optimum values for the components

Design Parameters	A	B
Mechanical Efficiency	0.9891	0.9923
Burner Pressure Ratio	0.9499	0.9479
Burner Exit Temperature (K)	1999.96	1110.03
Polytr. Compr. Efficiency	0.8999	0.8999
Polytr. Turbine Efficiency	0.8940	0.8999
Performance parameters	**Best Thrust value**	**Best SFC value**
Net Thrust (kN)	34.2261	18.4428
Sp. Fuel Consumption g/(kN.s)	36.7158	20.9635
NOx Severity Index	0.2199	0.2199
Total Fuel Flow (kg/s)	1.2566	0.3866



(a) (b)

Fig. 5. (a) Minimizing the Specific Fuel Consumption (b) Maximize Net Thurst

5. Fuel Properties Simulation

In order to study the mechanism of the effect of fuel property such as the calorific value of fuel on the engine performance, so the thrust, SFC, and flow of fuel are presented with the heating value of different fuels taken from previous studies. Furthermore, Kurzke [14] mentioned that most of the hydrocarbons (which have the chemical composition C_nH_n) such as Kerosene and JP-10 (chemical composition $C_{10}H_{16}$) and other fuels used to run the gas turbine. Fuel properties are essential for the design and operation of alternative fuel combustion, such as caloric value, humidity, and oxygen [15].

The heating value (HV) of biomass is one of the parameters to compare the difference between fuels [16]. Based on that, a further simulation was conducted on the custom engine using GasTurb-13 with the same parameters in Table 1, but the heating value has been changed based on different types of fuels used, as shown in Table 6. The GasTurb-13 simulation was performed using the same fuel flow rate, and the design parameters under on-design condition, so the heat energy is emitted from various types of fuel due to varying the calorific value of different fuels can be evaluated.

Figure 6 illustrated the effect of heating values for each fuel on thrust, SFC, and fuel flow. It can be seen that the waste cooking oil (WCO)-based green diesel has the lowest TSFC but having the highest thrust compared to the other fuels because of the oxygen content is zero. In contrast, ethanol and methanol have the highest TSFC because the caloric value is lower than the other fuels. In contrast, the Jet-A1, HFFA R-8, Green Diesel, Kerosene, Jatropha SPK, and Camelina SPK have a similar thrust, SFC, and mass flow values.

Table 6
Heating value for different fuels

References	Fuel	Fuel Heating Value (MJ/kg)
	Diesel fuel	41.59
[17]	PO5	37.40
	PO10	38.72
	Jet A-1	43.20
[18]	HEFA R-8	44.10
	Green Diesel	43.70
	kerosene	43.10
[19]	Ethanol	26.81
	Methanol	19.92
[20]	Jatropha SPK	44.30
	Camelina SPK	44.00
[21]	WCO-based green diesel	44.80

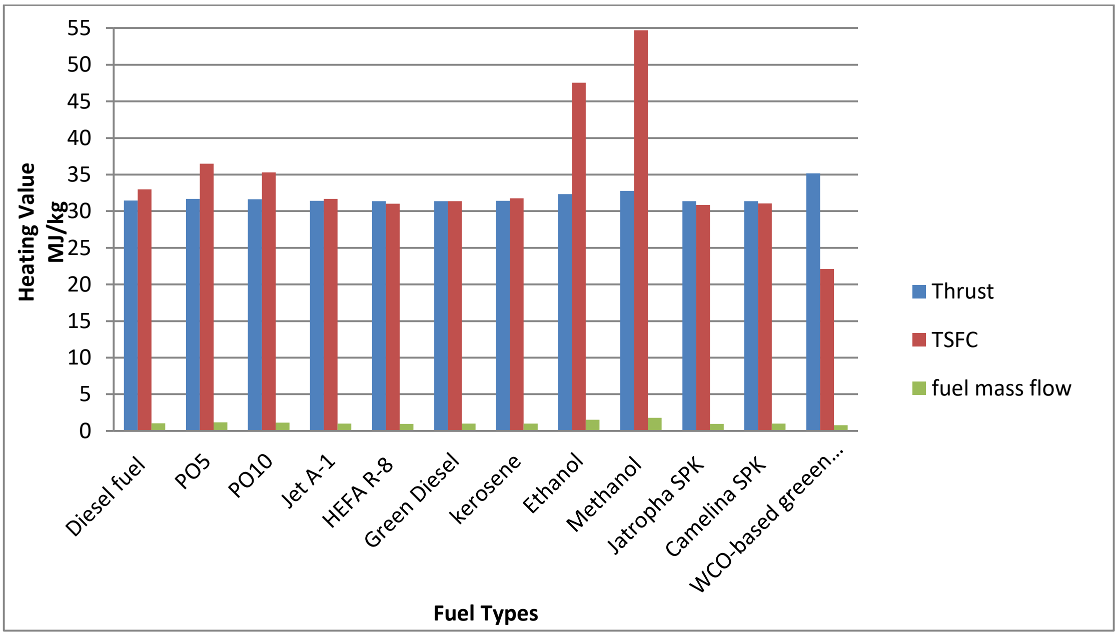


Fig. 6. Effect type of fuel on the engine performance

Compared to previous studies, the results obtained in this study correspond well to the other researchers [14-17]. Zhou *et al.*, [19] used GSP software to find the effect of heating value on the engine performance. It was found that the lower calorific value of methanol and ethanol compared to kerosene led to the reduction of engine thrust (FN), and therefore the specific fuel consumption (TSFC) is increased and to maintain the performance of the engine itself must increase the overall flow rate of fuel. This corresponds to the results of Figure 6 as noted, the highest value for fuel consumption was 54.72 g/KN.s for methanol, followed by 47.56 g/KN.s for ethanol, accompanied by a higher fuel flow, and this is a result of a decrease in the calorific value of these types of fuels, as follows 19.92 MJ/kg and 26.81 MJ/kg, respectively. Also, the high turbine temperature has an impact on this high fuel consumption (SFC).

However, Gaspar *et al.*, [18] confirmed that specific fuel consumption was saved by 4% when alternative fuels were used to improve engine performance compared to conventional jet fuel. Besides, Tobib *et al.*, [17] mentioned that palm oil blends led to increasing BSFC (Break Specific Fuel Consumption) on the HCCI-DI engine compared to diesel fuel within the experimental data. Also, Yuons [20] found that fuel consumption was reduced by 3%, and the fuel flow rate was 2.7% compared with Jet-A; this is seen in Figure 6.

As for waste cooking oil-based green diesel, it resulted in less fuel consumption 22.11 g/KN.s and also a higher thrust of 35.18 KN, which means that the fuel flow rate is 0.78 kg/s, and this is because it contains the highest heat value 44.80 MJ/kg compared to other fuels. There is no research on studying its impact on fuel engines.

6. Recommendation

As a future work, this paper did not use the off-design operation for this type of engine. Besides, comparing between GSP-11 and GasTurb-13 need more studies by applying different cases such as simulating turbojet or turbofan engines with afterburning or without and using different conditions and study the differences between them.

7. Conclusions

GSP-11 and GasTurb-13 are the most popular software for engine performance on-design simulation. At on-design calculations, the thrust obtained were almost the same for both programs at all levels. However, there are apparent differences in fuel mass flow and specific fuel consumption. The reasons for these differences due to the fuel properties in each program, for example, the JP-10 heating value is 42.10 MJ/kg in GSP, but it is 42.07 MJ/kg in GasTurb-13. Furthermore, the change in fuel types did not show a big difference in the results.

Noticed at optimum values that the temperature has to increase with increasing on the other parameters to get the best value for thrust, but the best value for specific fuel consumption (SFC) needs to decrease the temperature with increasing of the other parameters. Moreover, when fixed the efficiency for mechanical and burner with decrease temperature, as shown in level 3, so the thrust and SFC were similar to baseline values.

The main factor affecting engine performance in general and fuel consumption, in particular, is the caloric value of fuel in the same line it affects the amount of fuel mass flow. Based on that, the best type of fuel which is studied in this paper was WCO-based green diesel.

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