Analytical Performance of Marine Vessel Engines with or without Heat Exchanger

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Abstract— The proficiency of Gas turbine (GT) in the maritime industry for easy navigation and power supply for on-board vessels cannot be over emphasized. Therefore, studying the performance of GT engines in marine vessels for effective power delivery with or without heat exchanger (HE) is the cardinal focus of this paper. Hence, in order to achieve this objectives, an excel mathematical modelling programme is designed in carrying out the study with a General Electric (GE) marine GT with engine model LM500. The programming tool has the capability of analysing design point (DP) and off design point (ODP) performance of GTs. Established results shows the importance of incorporating HE in GTs for effective performance. A confirmed summary result in the study attests an increase in thermal efficiency from 39.67% to 43.04% with an improved index increment of 8.5% for GTs with HEs over the same engine without HEs. Therefore, the adopted approach for the research is considered as an effective and reliable technology.

Index Terms— Design point, Effectiveness, Gas turbine, Gas path, Heat exchanger, Off design point, Performance, Variation

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1 INTRODUCTION

The significance of incorporating HE in engineering machineries can never be over emphasized. HE functions as equipment through which energy flows from either hot source to a cold medium or vice versa. The energy may be in the form of heat which flows from one medium to another [1]. The device controls temperature of the working fluid in the engine. Thus, temperature is one key thermodynamic property that determines the effectiveness, reliability and the efficiency of a machine [2]. In fact, temperature is a design point specification of most engines. For instance, in GT industries, the ambient temperature is a major design factor of the different operation of GTs such as the aero and industrial GTs. The principle behind GTs which is also known as the heat engine converts energy to useful work by the burning of fuel in its combustion chamber (CC). This empowers the GT to propel an aircraft, generate an electric power through a synchronous machine, drill or transport crude oil and its products by a compressor along pipelines or propel a ship or a water jet [3]. Hence, in this research of analysing the marine vessel engines with or without HE; an empirical review of the maritime GTs from different scholars is examined.

Meanwhile, an established fact about GTs is that their major performance measurements are the thermal efficiency and perhaps specific output power. These out-standing parameters are dependent variables on both the pressure ratio (PR) and turbine entry temperature (TET). Thus, an increase in the stoichiometric air and temperature in the CC raises the TET and then the PR which yields a direct increment in the thermal efficiency [4], [5]. This workable phenomenon is made possible with the incorporation of a cooling device to a turbine unit. The recognition of the cooling technology such as Intercoolers and recuperators as used in industrial GTs meanly for power generation and the marine vessels in the GT process is the ideal behind HEs [5], [6]. The incorporation of this technology enhances the thermodynamic cycle efficiency of GTs. In its configuration, the recovered heat is used in the same GT cycle as gas-to-gas recuperation [7]. Mostly, the recuperator HEs are an instrumental design to the success of hybrid fuel cell and gas turbine power plants as reported in a peer review research journal. The only disadvantageous fact to this design is its large size which may add weight and occupy space to the final design product [8]. However, serious research is on-going for the introduction of the HEs in aero-GTs by its different design industries due to the numerous benefits of fuel economy and environmentally friendly operation. Conversely, the only limitation to this incorporation is the fear of additional weight to the jet engine, system complexity, and uncertainty in terms of structural integrity HEs [5].

In another view to research reveals that HEs are aimed to solely create a friendly working conditions and life span maintenance target for the turbine components in their operations. According to a scholarly study, the synergic approach of cooling effect leads to high internal heat transfer coefficient within the gas path of the GT. This process is eventually described as a means of the evolved heat being suppressed by

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the working fluid or the coolant of the HE [9], [10]. Conversely, with the significant importance attached to HE, the cooling effect derived from it is a function of its design. Therefore, the cooling effectiveness of a HE relies on the convective efficiency and the film effectiveness. However, a limiting factor of HE device is the increase of the coolant flow blockage which intensifies the pressure drop of the coolant [11], [12].

2 ENGINE DESIGN POINT SPECIFICATION

The GE GT with engine model LM500 is the considered engine for the study. It is a double spool simply cycle marine GT with a 4-stage aerodynamically coupled power turbine (PT). It is a derivative of GE CF34 turbofan aero GT used initially in the military and commercial applications. Conversely, the high rated efficient LM500 GT has a single spool gas generator of 14-stages. The output shaft to which the load is connected is on the air inlet end of the engine. Research reveals that it has compressor ratio of 14.5:1 with output performance of 6130shp which is equivalent to 4570KW and specific fuel consumption (SFC) rate of 443 lb/shp-hr (269.5 g/kW-hr), off-course with heat rate of 8,140 Btu/shp-hr (11520KJ/S) [13]. Other performance specifications are presented in table 1. The LM500 GT is designed with corrosion-resistant materials for durability, reliability and maximum components life span due to its applied environment.

The LM500 GT model is of 144 inches (3.66m) long, 65 inches (1.65m) high and weighs 6,173 pounds (2,779 kg). Its inlet and exit duct flow area is about 12 square feet ($1.12m^2$) and 7 square feet ($0.65m^2$) respectively. It is an established fact that, the LM500 GT has proven performance record and high reliability in both marine and industrial applications [13]. Thus, for these outstanding reasons, it is also being repowered for on-board power systems. However, the discussed engine model is presented in figures 1 – 2.

Figure 1: LM500 Marine GT
Source: [13].

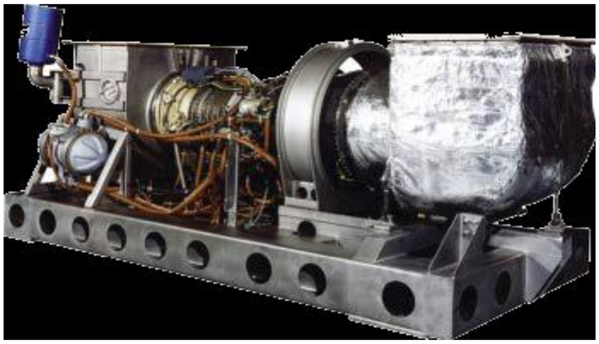


Figure 2: The Housing of LM500 GT
Source: [13].

Table 1: LM500 Marine Gas Turbine Specification.

S/N	Specifications	Symbol	Unit	Performance
1	Pressure Ratio	PR	-	14.5
2	Power Output	UW	KW	4570
3	Heat Rate	Qcc	KJ/S	11520
4	Specific Fuel Consumption	SFC	Kg/KWh	0.2695
5	Exhaust Gas Temperature	$T_{exhaust}$	K	838.15
6	Exhaust Gas Flow	$M_{exhaust\ gas}$	Kg/S	16.4
7	Shaft Numbers	-	-	1
8	Power Turbine Speed	N	rpm	7000
9	Relative Humidity	RH	%	60

Source: [13].

Table 2. Fixed Parameters at Design Point.

S/N	Parameters	Symbol	Unit	Performance
1	Ambient temperature	P_{amb}	K	288.15
2	Ambient pressure	T_{amb}	Kpa	101.33
3	Compressor Efficiency	-	%	86
4	Turbine Efficiency	-	%	88
5	Specific heat for cold air	Cp_{cold}	KJ/Kg/K	1.005
6	Specific heat for hot air	Cp_{hot}	KJ/Kg/K	1.15
7	Gamma for cold air	γ_{cold}	-	1.4
8	Gamma for hot air	γ_{hot}	-	1.333
9	% Increase in ambient	-	KPa	2
10	% Pressure Loss at P_5	-	%	5
11	Exhaust Pressure loss	-	KPa	1

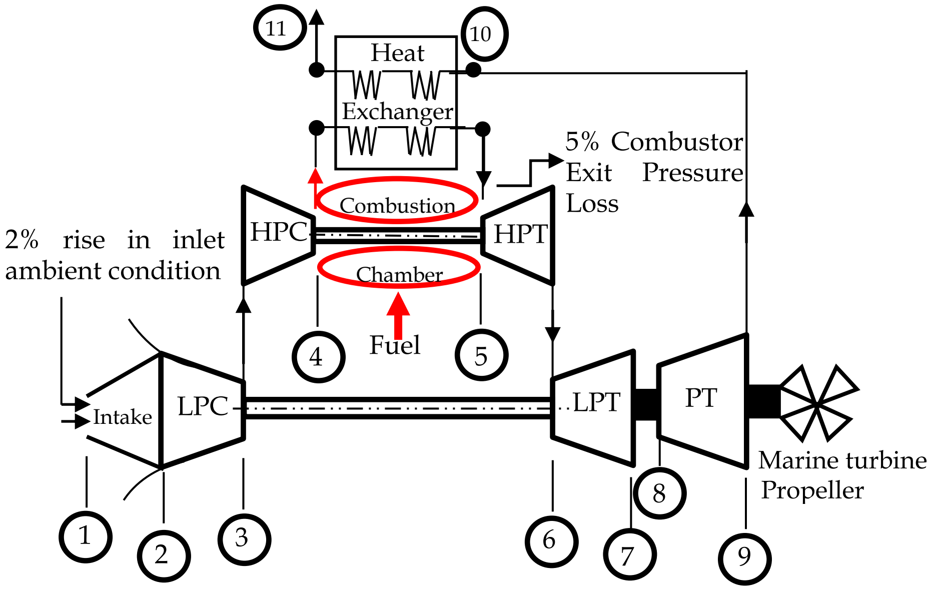


Figure 3: LM500 Marine Gas Turbine

3 Mathematical Modelling

Modelling the engine mathematically gives an insight of the design analysis involved in the design process of the GT under consideration. This is carried out with the design specification of the engine alongside with some fixed parameters as presented in table 2 to march the performance specification which enhances the DP calculations. Thus, in order to fulfil this objective, the engine model schematics is well presented as shown in figure 3 for proper guide in the analysis.

4 Components Analysis at Design Point

As described above, each component of the GT is analysed with the corresponding governing equations presented in equations (1) – (29). Conversely, the engine model schematics is of double spool marine GT, hence it is expected to have a low pressure compressor (LPC) driving a low pressure turbine (LPT); consequently, a high pressure compressor (HPC) is designed to drive a high pressure turbine (HPT) as illustrated in the figure. However, an incorporation of HE is inserted in the engine model since the research is focused on the performance of the GT with or without a HE.

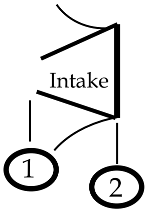
GT Air Intake System:

$$T_1 = T_{amb} \quad (1)$$

$$P_1 = P_{amb} \quad (2)$$

$$T_2 = T_1 + (2\% \text{ of } T_1) \quad (3)$$

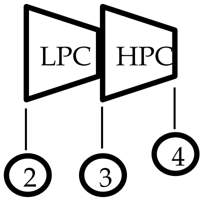
$$P_2 = P_1 + (2\% \text{ of } T_1) \quad (4)$$



GT Compressor System (LPC and HPC):

$$\frac{P_{out}}{P_{in}} = \frac{P_3}{P_2} = PR \quad (5)$$

$$T_3 - T_2 = \frac{T_2}{\eta_c}\left[(PR)^{\gamma-1/\gamma} - 1\right] \quad (6)$$



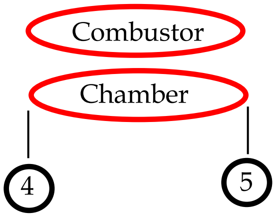
$$LPCW = \dot{m}_{cold} \times C_{P_{cold}} (T_3 - T_2) \quad (7)$$

$$HPCW = \dot{m}_{cold} \times C_{P_{cold}} (T_4 - T_3) \quad (8)$$

GT Combustor System:

$$SFC = \frac{FF}{UW} \quad (9)$$

$$FF = \dot{m}_{hot} - \dot{m}_{cold} \quad (10)$$



$$Q_{CC} = \dot{m}_{cold} \times C_{P_{hot}} (T_5 - T_4) \quad (11)$$

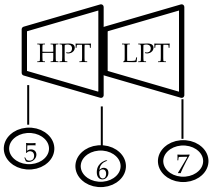
$$P_5 = P_4 \times (5\% \, of \, P_4) \quad (12)$$

GT Turbine System (LPT and HPT):

$$HPTW = \dot{m}_{hot} \times C_{P_{hot}} (T_5 - T_6) \quad (13)$$

$$LPTW = \dot{m}_{hot} \times C_{P_{hot}} (T_6 - T_7) \quad (14)$$

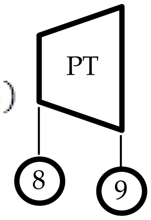
$$HPTW = HPCW \quad (15)$$



$$LPTW = LPCW \tag{16}$$

$$\eta_T = \frac{1-\frac{T_6}{T_5}}{1-\left[\frac{P_6}{P_5}\right]^{\frac{\gamma-1}{\gamma}}} \tag{17}$$

Power Turbine System:



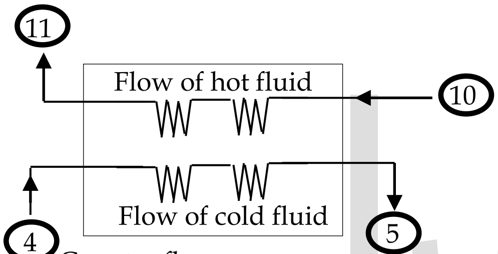
$$UW = \dot{m}_{hot} \times C_{P_{hot}} (T_8 - T_9) \tag{18}$$

$$P_9 = P_1 + (1\% \text{ of } P_1) \tag{19}$$

Thermal Efficiency without heat exchanger, (η_{Th})

$$\eta_{Th} = \frac{UW}{Q_{cc}} \times 100\% \tag{20}$$

GT Heat Exchanger System:



Counter flow arrangement

$$\left[\frac{T_{out}}{T_{in}}\right]_{HE} = \left[\frac{T_{out}}{T_{in}}\right]_{Turb} \tag{21}$$

$$\epsilon_H = \frac{\text{Actual heat transfer } (Q_{Actual})}{\text{Maximum possible heat transfer } (Q_{Max})} \tag{22}$$

$$Q_{Actual} = \dot{m}_{cold} \times C_{P_{cold}} (T_4 - T_5) \tag{23}$$

$$Q_{Max} = \dot{m}_{cold} \times C_{P_{cold}} (T_{10} - T_5) \tag{24}$$

Thermal Efficiency with heat exchanger, $(\eta_{Th_{HE}})$

$$\eta_{Th_{HE}} = \frac{UW}{Q_{cc} - Q_T} \times 100\% \tag{25}$$

$$Q_T = Q_{hot} + Q_{cold} \tag{26}$$

$$Q_{hot} = T_{10} - T_{11} \tag{27}$$

$$Q_{cold} = T_5 - T_4 \tag{28}$$

$$\text{Variation } (\%) = \frac{DP \text{ values} - ODP \text{ value}}{DP \text{ value}} \tag{29}$$

5 Off Design Point Calculations

Calculation analyses on ODP are based on the different operating conditions of the marine GT under study. The GT is expected to cruise on water bodies with varying temperatures and pressures different from its design parameters. Conversely, in the process the gas path of the GT will be deteriorated. Meanwhile, the degradation action of the system is usually studied under different variation of the ambient condition of the GT. Similarly, the environmental operating condition such as the medium at which the marine vessel operates also tends to cause some catastrophes to the engine. This always leads to components failure to fouling and erosion. Some possible prognostics steps to these components limitations are ODP analysis based on variation test on component isentropic efficiencies and flow capacities. Therefore, in order to monitor the health condition of the GT components against these unforeseen circumstances is the introduction of an excel mathematical modelling programme. This is the design methodology in carrying out both the DP and ODP investigation of the gas path in this research paper.

5 Results Presentation and Discussion

Results presented here for discussion are in two sets; the first is the DP results which gives a clear analysis of the GT at its DP from the manufacturing industry. While, the second set of results are classified as ODP results. They are prognostics results which forecast the GT condition at different operations. They can also be considered as GT health condition monitoring results. It helps GT operators and users for GT components routine check and maintenance. Hence, table 3 is DP results while tables 4 – 7 and figures 4 – 7 are ODP results. It helps GT operators and users for GT components routine check and maintenance. Hence, table 3 is DP results while figures 4 – 7 are ODP results with correspondings tables 4 -7 shown in appendix A

Table 3: LM500 GT Design Point Parameters

S/N	Parameters	Symbols	Unit	Values
1	Ambient Condition	T_{amb}	K	288.15
2	Ambient Condition	P_{amb}	Kpa	101.33
3	Intake Temperature	T_1	K	288.15
4	Intake Pressure	P_1	Kpa	101.33
5	LPC Inlet Temperature	T_2	K	293.91
6	LPC Inlet Pressure	P_2	Kpa	103.36
7	HPC Inlet Temperature	T_3	K	685.89
8	HPC Inlet Pressure	P_3	Kpa	1498.67
9	HPC Exit Temperature	T_4	K	1600.63
10	HPC Exit Pressure	P_4	Kpa	21730.73
11	HP Turbine Entry Temperature	T_5	K	2314.46

Continuation of Table 3

S/N	Parameters	Symbols	Unit	Values
12	HP Turbine Inlet Pressure	P_5	Kpa	20644.19
13	LPT Inlet Temperature	T_6	K	1531.74
14	LPT Inlet Pressure	P_6	Kpa	2962.3
15	LPT Exit Temperature	T_7	K	1196.33
16	LPT Exit Pressure	P_7	Kpa	942.33
17	PT Inlet Temperature	T_8	K	1080.46
18	PT Inlet Pressure	P_8	Kpa	332.25
19	PT Exhaust Temperature	T_9	K	838.15
20	PT Exhaust Pressure	P_9	Kpa	102.34
21	Heat Exchanger Inlet Temperature	T_{10}	K	838.15
22	Heat Exchanger Exit Temperature	T_{11}	K	650.18
23	Thermal Eff. (GT without HE)	ηTh	%	39.67
24	Thermal Eff. (GT with HE)	ηTh (HE)	%	43.04
25	Effectiveness of HE	E_H	%	48.35

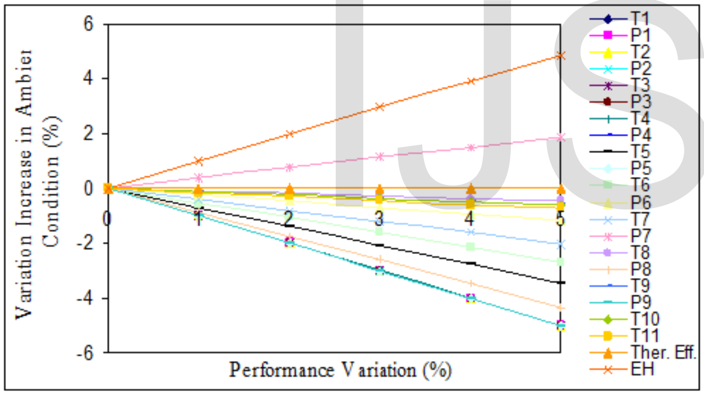


Figure 4: Graph plot of increase Ambient Condition

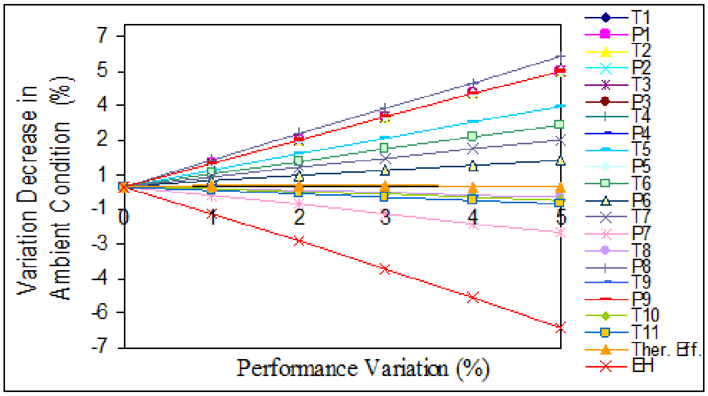


Figure 5: Graph plot of decrease Ambient Condition

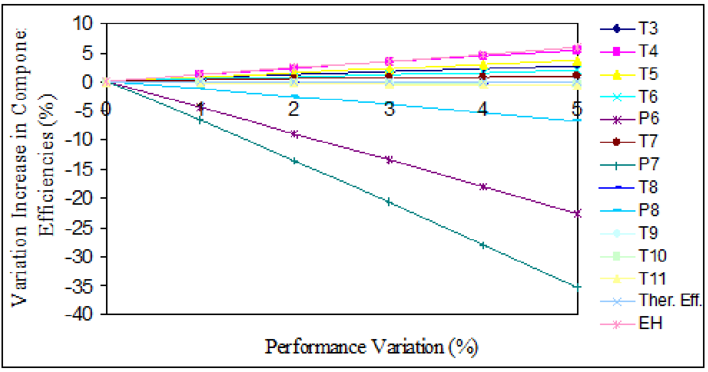


Figure 6: Graph plot of increase in Components Efficiencies

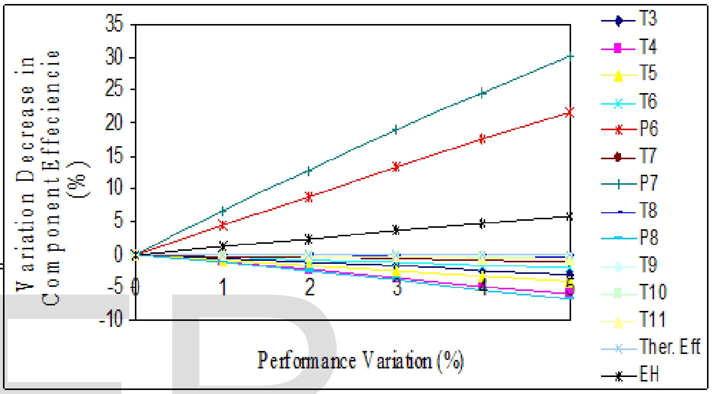


Figure 7: Graph plot of decrease in Components Efficiencies

Obviously, the results show effects of deviation in ambient conditions and change in components efficiencies as a catastrophe to GT's performance. This confirmation is apparently noticed in the comparison of the DP and ODP results display. The DP results are the clean performance results of the engine as obtainable from the design and manufacturing industries of GTs, though it is modelled mathematically in this research. In the close march of these sets of results to the different operating ambient conditions gives a reflection of the intrinsic parametric behaviour of the engine gas path. Conversely, this is indicated in the temperatures and pressures of the various components of the engine as the working fluid passes via the intake to the power turbine to do work as required. By and large, the corresponding performance index as indicated in the thermal efficiency and heat effectiveness is affected. Also, it causes components failure due to fouling, erosion and perhaps corrosion as regards to corresponding reduction and rise in component isentropic efficiencies and flow capacities.

Consequently, the result analysis of the marine GT LM500 cruising at an increase ambient condition of (1 – 5)% shows a corresponding rise in components temperatures and pressures which leads to decrease in heat effectiveness from of the engine even with the incorporation of HE to the system. This is affirmed in both graph plot of figure 4 and table 4 as the DP heat effectiveness decreases from 48.35% to 46.01%. Meanwhile, as the isentropic efficiency of components are both increased and reduced subsequently at the considered percentage range; the heat effectiveness tends to decrease along the gas stream of the GT. It is observed that both tow the same pattern of value reduction of the heat effectiveness from 48.35% to 45.49% as shown in figures 6 and 7 with the corresponding tables in 6 and 7 respectively.

However, the graphical results in figure 5 with corresponding values in table 5 are indication of reduction in ambient conditions. At this phase, the incorporated HE helps in reduces the excessive heat from the engine thereby increasing the output performance of the heat effectiveness from 48.35% to 51.31%. Similar scenario is observed for the thermal efficiency mostly in comparing its performance based on non- integration and integration of HE to the GT. Values of this development reveals 39.67% against 43.04%. This index shows an improved percentage increment of 8.5% with the integration of HE to GT over without HE incorporation. Hence, the thermodynamic merit of HE incorporation in GTs is an outstanding fact to enhance performance improvement of the engine. Therefore, GT users and operators keying into this knowledgeable path for its productivity will increase the engine availability.

6 Conclusion

The analytical research of GT engine performance with or without HE is an unveiled summary of the benefits of HE in GTs. It is an embodiment of cooling mechanism to the engine which enhances its performance. Thus, the following conclusions are reached in respect to the research.

- The application of HE reduces the level of component degradation such as fouling, erosion, corrosion, etc.
- The effectiveness of a GT system is a function of an effective HE. An established scholarly reviewed literature reveals that high rate of HE effectiveness increases the performance of the engine.
- Moderation and control of GTs in different operating ambient conditions for stable and effective performance could be adjusted by the aid of HE.
- The research reveals the relevance of the programmed mathematical modelling approach carried out for the study.

Therefore, this application can be extended to other engine models for efficient service delivery.

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Nomenclature

UW	*Useful Work*
m_{cold}	*Cold or Inlet Mass Flow of Air*
m_{hot}	*Hot or Exhaust Mass Flow of Air*
Q_{hot}	*Hot Heat Flow*
Q_{cold}	*Cold Heat Flow*
Q_T	*Total Heat Flow*

Appendix A

Table 4: ODP Analysis for Increased Variation in Ambient Condition

Parameters	Increase in Ambient Temperature and Pressure					
	DP	1%	2%	3%	4%	5%
T_1	288.15	291.03	293.9	296.79	299.68	302.56
P_1	101.33	102.34	103.4	104.37	105.38	106.4
T_2	293.91	296.85	299.8	302.73	305.67	308.61
P_2	103.36	104.39	105.4	106.46	107.49	108.53
T_3	685.89	692.74	699.6	706.46	713.33	720.19
P_3	1498.67	1513.61	1529	1543.63	1558.57	1573.66
T_4	1600.63	1616.62	1633	1648.62	1664.67	1680.67
P_4	21730.7	21947.3	22166	22382.7	22599.27	22818.01
T_5	2314.46	2330.46	2346	2362.45	2378.51	2394.51
P_5	20644.2	20850	21058	21263.5	21469.3	21677.11
T_6	1531.74	1539.91	1548	1556.26	1564.46	1572.64
P_6	2962.3	2969	2976	2982.68	2989.29	2996.26
T_7	1196.33	1201.15	1206	1210.8	1215.64	1220.46
P_7	942.33	938.68	935.2	931.63	928.11	924.77
T_8	1080.46	1081.46	1082	1083.46	1084.46	1085.46
P_8	332.25	335.14	338.1	340.92	343.79	346.68
T_9	838.15	839.15	840.2	841.15	842.15	843.15
P_9	102.34	103.36	104.4	105.41	106.43	107.46
T_{10}	838.15	839.15	840.2	841.15	842.15	843.15
T_{11}	650.18	651.13	652.1	653.03	653.98	654.93
ηTh (HE)	43.04	43.0395	43.04	43.0399	43.0401	43.0403
E_H	48.35	47.87	47.39	46.92	46.46	46.01

Table 5: ODP Analysis for Decreased Variation in Ambient Condition

Parameters	Reduction in Ambient Temperature and Pressure					
	DP	1%	2%	3%	4%	5%
T_1	288.15	285.27	282.4	279.51	276.62	273.74
P_1	101.33	100.32	99.3	98.29	97.28	96.26
T_2	293.91	290.975	288	285.1	282.1524	279.2148
P_2	103.36	102.326	101.3	100.256	99.2256	98.1852
T_3	685.89	679.034	672.2	665.324	658.4445	651.5892
P_3	1498.67	1483.73	1469	1453.71	1438.771	1423.685
T_4	1600.63	1584.63	1569	1552.63	1536.578	1520.58
P_4	21730.7	21514.1	21295	21078.8	20862.18	20643.44
T_5	2314.46	2298.46	2282	2266.47	2250.413	2234.415
P_5	20644.2	20438.4	20231	20024.8	19819.07	19611.27
T_6	1531.74	1523.56	1515	1507.21	1499.01	1490.835
P_6	2962.3	2955.58	2949	2941.83	2935.165	2928.105
T_7	1196.33	1191.51	1187	1181.86	1177.023	1172.201
P_7	942.33	946.048	949.7	953.568	957.5183	961.3854
T_8	1080.46	1081.46	1082	1083.46	1084.462	1085.462
P_8	332.25	328.522	324.8	321.064	317.365	313.6436
T_9	838.15	839.15	840.2	841.15	842.15	843.15
P_9	102.34	101.323	100.3	99.2729	98.2528	97.2226
T_{10}	838.15	839.15	840.2	841.15	842.15	843.15
T_{11}	650.18	651.131	652.1	653.03	653.9803	654.9304
ηTh (HE)	43.04	43.0395	43.04	43.0399	43.04014	43.04034
E_H	48.35	48.9159	49.49	50.0826	50.68906	51.30835

Table 6: ODP Analysis for Increase in Component Efficiencies

Parameters	Increase in Compressor and Turbine Efficiencies					
	DP	1%	2%	3%	4%	5%
T_1	288.15	288.15	288.15	288.15	288.15	288.15
P_1	101.33	101.33	101.33	101.33	101.33	101.33
T_2	293.91	293.91	293.91	293.91	293.91	293.91
P_2	103.36	103.36	103.36	103.36	103.36	103.36
T_3	685.89	682.01	678.2	674.47	670.81	667.22
P_3	1498.67	1498.67	1498.67	1498.67	1498.67	1498.67
T_4	1600.63	1582.56	1564.95	1547.78	1531.03	1514.69
P_4	21730.73	21730.73	21730.73	21730.73	21730.73	21730.73
T_5	2314.46	2296.4	2278.79	2261.62	2244.87	2228.53
P_5	20644.19	20644.19	20644.19	20644.19	20644.19	20644.19
T_6	1531.74	1525.81	1520.01	1514.34	1508.79	1503.36
P_6	2962.3	3094.6	3227.8	3361.76	3496.37	3631.52
T_7	1196.33	1193.72	1191.18	1188.7	1186.29	1183.93
P_7	942.33	1005.33	1070.24	1137	1205.56	1275.87
T_8	1080.46	1081.46	1082.46	1083.46	1084.46	1085.46
P_8	332.25	336.45	340.81	345.33	350.03	354.9
T_9	838.15	839.15	840.15	841.15	842.15	843.15
P_9	102.34	102.34	102.34	102.34	102.34	102.34
T_{10}	838.15	839.15	840.15	841.15	842.15	843.15
T_{11}	650.18	651.13	652.08	653.03	653.98	654.93
ηTh (HE)	43.04	43.0395	43.0397	43.0399	43.0401	43.0403
E_H	48.35	47.79	47.22	46.64	46.07	45.49

Table 7: ODP Analysis for Decrease in Component Efficiencies

Parameters	Decrease in Compressor and Turbine Efficiencies					
	DP	1%	2%	3%	4%	5%
T_1	288.15	288.15	288.15	288.15	288.15	288.15
P_1	101.33	101.33	101.33	101.33	101.33	101.33
T_2	293.91	293.91	293.91	293.91	293.91	293.91
P_2	103.36	103.36	103.36	103.36	103.36	103.36
T_3	685.89	689.849	693.8891	698.0126	702.222	706.52
P_3	1498.67	1498.67	1498.67	1498.67	1498.67	1498.67
T_4	1600.63	1619.158	1638.179	1657.707	1677.76	1698.36
P_4	21730.73	21730.73	21730.73	21730.73	21730.73	21730.73
T_5	2314.46	2332.993	2352.014	2371.542	2391.6	2412.2
P_5	20644.19	20644.19	20644.19	20644.19	20644.19	20644.19
T_6	1531.74	1537.8	1544.002	1550.349	1556.84	1563.5
P_6	2962.3	2830.997	2700.84	2571.96	2444.496	2318.59
T_7	1196.33	1199.004	1201.749	1204.568	1207.462	1210.43
P_7	942.33	881.2786	822.2194	765.1962	710.2475	657.41
T_8	1080.46	1081.462	1082.462	1083.462	1084.462	1085.462
P_8	332.25	336.4529	340.8109	345.3326	350.027	354.9
T_9	838.15	839.15	840.15	841.15	842.15	843.15
P_9	102.34	102.34	102.34	102.34	102.34	102.34
T_{10}	838.15	839.15	840.15	841.15	842.15	843.15
T_{11}	650.18	651.1305	652.0803	653.0303	653.9803	654.9304
ηTh (HE)	43.04	43.03953	43.03974	43.03994	43.04014	43.04034
E_H	48.35	47.78515	47.21557	46.64395	46.07036	45.49485