



MSC AEROSPACE ENGINEERING

1MAE605 - AEROENGINE ARCHITECTURES AND PERFORMANCE

Intercooled Engine Modeling and Parametric Sizing Studies

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Item	Breakdown
Set up the model Inputs	1
Setup the formula and iterations	1
Choose the mail equations and explain them using the engine Dofs, setup the iterations, Check constraints	4
Parametric studies and explain	5
Optimize and explain	1
Intercooler: sizing at iso-OPR or iso-T3	3
Intercooler: Parametric studies	2
Intercooler: Optimize	1
Technological influence and explain	1
Overall presentation, report clarity and organization	1
Total	20

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1 Introduction

The aim of this project is to design a 3-shaft bypass engine, based on several specifications and assumptions, using the software GasTurb. This engine should be able to power a short to medium range aircraft, resembling the LEAP engine developed by CFM International, the joint venture between airplane engine manufacturers Safran and General Electric. The Entry Into Service of this fictional engine is 2025 so it will be assumed that it is equipped with the latest technologies.

As a second stage, an inter-cooler will be added to the model to compare several design options and perform engine sizing parametric studies, with the ultimate goal of finding the design strategy differences induced by the addition of this component. Efficiency and pressure losses are the main focus of this type of parametric studies. The best potential concept of an inter-cooler should be identified, in addition to its impact on the high pressure core.

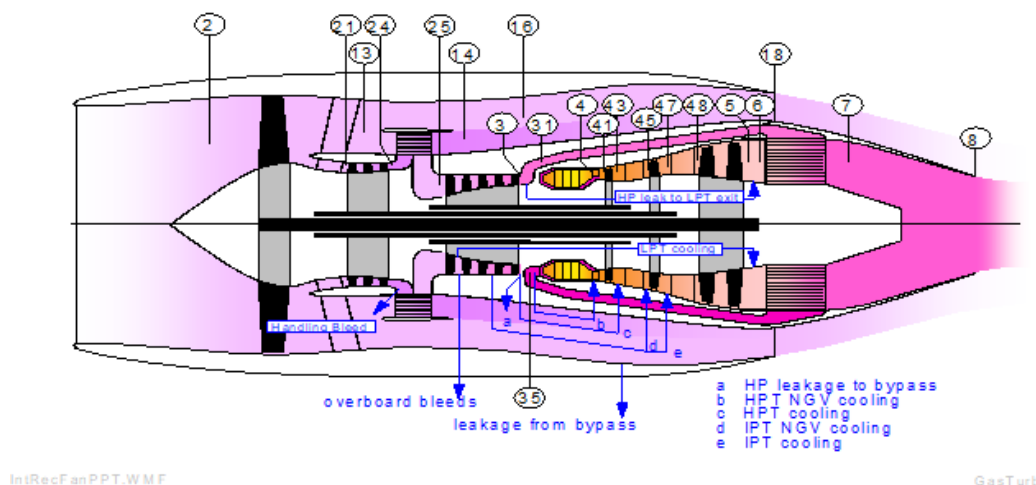


Figure 1: Engine Model

2 Engine Model Inputs

The aircraft's requirements must be considered. It is of uppermost importance to know the altitude at which the aircraft will fly and its weight since the engine must provide thrust to ensure lift production under these conditions. The speed of flight, the bleeding and, of course, the necessary thrust are detailed by the aircraft manufacturer and the engine must fulfill the demands. The requirements data is given in Table.1

It must be noted that GasTurb, unlike other programs, is limited to a unique design point. This means that only one operational situation can be studied at a time. The Top Of Climb point has been chosen for the design since it represents the best compromise between fuel consumption optimization and maximum thrust capacity in altitude. Other points such as Take-Off or Maximum Cruise Speed should not be neglected in real life scenarios but will not be included in this report.

The engine to be developed has a bypass immediately downstream of the fan, which is driven by the

Alt (ft)	Mach	ISA (c)	Rating	Thrust (lbf)	Hp offtake (hp)	Bleed (lbm/s)
0	0.25	15	Take-off	26000	230	0
35000	0.79	10	Max climb	7100	255	1.14
35000	0.8	10	Max cruise	3900	255	1.14
10000	0.45	10	Max continuous	6300	420	1.82

Table 1: Specifications for the Engine.

low-pressure turbine (LPT). The inner part of the fan deals with core flow and the outer part with secondary flow. Analogously, the intermediate turbine (IPT) and the high-pressure turbine (HPT) drive the intermediate compressor (IPC) and high-pressure compressor (HPC) respectively. They are connected, as previously mentioned, by means of three independent shafts. Two separate nozzles eject the primary and secondary flows, which do not mix after the low pressure turbine. As a side note, the intermediate and high pressure compressors were considered as pressure enhancers with a given efficiency.

Technology features such as the components isentropic efficiencies and pressure losses, and the characteristics of the secondary air system were set using the provided data. The inter-cooler efficiency was set to zero initially and modified for the second part of the task.

3 Main Sizing Parameters

It must always be ensured that the constraints specified are respected. For instance, as mentioned before, the thrust is a strict requirement from the aircraft manufacturer. However, there are other parameters such as the Overall Pressure Ratio (OPR) or the different turbine thermal loads, which must remain within reasonable ranges. The main equations chosen refers to the engine's degree of freedom and it is most essential as the cycle convergence depends on it.

The number of degrees of freedom limits the amount of equations that can be used. Hence, some restrictions will have to be checked after iterating. Moreover, the parameters available as inputs in GasTurb can be directly modified, whereas the rest must be imposed indirectly by means of iterations using connecting parameters and equations which describes the physical effect.

The constraints that concern directly a certain input variable of the cycle are the high-pressure compressor pressure ratio (P3Q25) of 21 and the turbine inlet temperature (T4) less than 1800 K. As for T4, the default temperature of 1725K is taken after checking constraint T48 which should be less than 1200K. See Tab.2

The iterations are used in the software to define new equations of the model. By setting a target value for a particular parameter, an internal variable iterates within a range defined in order to reach the targeted value. That is to say, a certain figure can be inserted to satisfy a particular constraint, and a chosen degree of freedom modifies its value until the cycle converges fulfilling it. Hence, it is necessary not only to perform a selection of constraints, but also a subsequent assessment of the suitability of each relationship. As some of the limiting parameters or relations are not present in GasTurb, to associate a value to them, they have to be created in advance.

Enter formula:

<input type="radio"/> cp_val1:	$CONSTEFF = (E213is-1)/(E221is-1)$
<input type="radio"/> cp_val2:	$CONSTP = (ZP13q2-1)/(ZP21q2-1)$
<input type="radio"/> cp_val3:	$W25R3 = W25*(T3/288.15)^{0.5} / (P3/101.325)$
<input type="radio"/> cp_val4:	$TLoad41 = PW_{HT}/W41/T41$
<input type="radio"/> cp_val5:	$TLoad47 = PW_{LT}/W48/T47$
<input type="radio"/> cp_val6:	$TLoad43 = PW_{IT}/W45/T43$
<input type="radio"/> cp_val7:	$ConvertedNetThrust = FN*224.809$
<input type="radio"/> cp_val8:	$ConvertedSFC = SFC*0.00036$
<input type="radio"/> cp_val9:	$FanDIAinch = d_t_{LC}*39.3701$

Figure 2: Composed Formulae

To designate the main equations of the cycle, several formulas have been implemented, as can be seen in Figure. These formulas have been used to define new parameters and relations that represent in a more meaningful manner the given constraints, i.e. the core size. Additionally, they also convert the units from lbs to metric system for easiness.

3.1 Assessment of Constraints

The constraints can be directly imposed if the parameter is available as an input in GasTurb. If not available, then via iteration variable that is in input list and can be traded against the desired parameter. Selecting the iteration variable is a key step and it has to be effectively related to constraint input.

The chosen input variable to fix thrust has been the corrected inlet air mass flow, or W2R. This choice can be explained by the fact that net thrust is directly proportional to the mass flow that comes into the engine. Moreover, a variation of the amount of flow does not change the quality of the transformation in the engine. It remains in homothety to the original cycle and scaled up or down. As for CONSTP and CONSTEFF, they have been set making use of the Inner Fan Pressure Ratio (P13Q2) and isentropic efficiency (E13D2) respectively.

The fan diameter is limited due to the aircraft integration constraint. The associated sizing variable should be the Bypass Ratio (BPR), since their relation is straight forward: the higher the BPR, the higher must be the diameter of the engine to allocate a bigger fan. This assessment is made by assuming that the core-size cannot be reduced for now because, if the core-size is changed it effects the engine-cycle temperatures and other constraints may not be met.

The acoustic features of the aircraft are very relevant too, with engines generating a great amount of the noise associated to airplanes. That is why, as the last equation, the ratio of bypass to core pressure ratio (P16Q6) has been fixed to make sure that this constraint is satisfied. A medium value of 1.1 has been chosen. the outer fan pressure ratio, that determines the pressure on the bypass channel has been utilized as a variable for it.

Thrust (lbf)	CONSTEFF	CONSTP	OPR	P16Q6	T4 (K)	T48 (K)
7100	0.29	1.74	45-60	0.9-1.3	<1820	<1200

The Fan is limited to 80inch in diameter due to integration constraints.

Thermal Load of Turbines (DH/T) (J/Kg/K)	DH41/T41 <400	DH45/T43 <150	DH48/T48 <450
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Table 2: Constraints

The significance of the overall pressure ratio is also very high, as it implies multiple changes in almost every stage of the engine. A value from given range, of 46, is selected at this stage of design process. The only accessible main flow pressure ratio left, the one from the IPC, has been used to iterate for the OPR constraint.

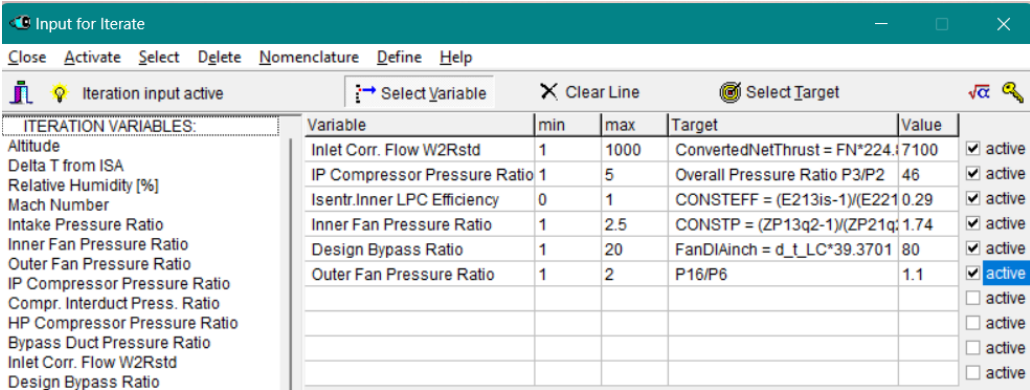


Figure 3: Parameters for Iterations

The low pressure turbine inlet temperature (T48) and the maximum turbine thermodynamic loads restraints, they are consequences of the characteristics of previous engine stages, which have already been defined. Consequently, their integration on the equations would be redundant, and so their fulfillment will be checked after the iterations. All the parameters and their corresponding iterations can be observed in Fig.3

Station	W	T	P	WRstd	FN	=	31.58
amb		228.81	23.842		TSFC	=	15.8250
2	220.936	257.43	35.887	589.608	WF	=	0.4998
13	198.288	297.40	57.778		s NOx	=	1.0251
14	39.658	297.40	57.200		BPR	=	8.7553
16	198.288	297.40	57.663		P16/P13	=	0.9980
21	22.648	286.57	48.468	47.216	Core Eff	=	0.5316
24	22.648	345.24	87.189	28.809	Prop Eff	=	0.7702
25	22.648	345.24	85.445	29.397	P25/P24	=	0.9800
3	22.195	847.14	1794.350	2.149	P3/P2	=	50.0000
31	19.753	847.14	1794.350				
4	19.120	1725.00	1713.604	2.766	P5/P2	=	1.3822
41	20.252	1680.10	1713.604	2.892	P4/P3	=	0.95500
42	20.252	1207.36	316.740		P44/P43	=	0.98000
43	21.611	1186.13	316.740		P48/P47	=	0.99000
44	21.611	1186.13	310.406		P6/P5	=	0.99500
45	22.064	1176.00	310.406	14.550			
46	22.064	1125.74	252.163		P16/P13	=	0.99800
47	22.291	1121.32	252.163		P16/P6	=	1.16828
48	22.291	1121.32	249.642	17.847			
49	22.291	790.96	49.605		V8	=	511.5
5	22.517	790.23	49.605	76.168	V18	=	315.6
6	22.630	790.52	49.357		V18/V8,id=	=	0.66094
8	22.630	790.52	49.357	76.949	A8	=	0.32976
18	198.288	297.40	56.971	358.283	A18	=	1.52145
Efficienciers:	isent	polytr	RNI	P/P	XM8	=	1.00000
Outer LPC	0.9400	0.9439	0.428	1.610	XM18	=	1.00000
Inner LPC	0.7931	0.8017	0.428	1.351	ZWBld	=	0.51710
IP Compressor	0.8900	0.8987	0.483	1.799	FWX	=	190.2
Intercooler	1.000E-5			0.9800	T14	=	297.40
HP Compressor	0.9000	0.9315	0.621	21.000	WHDB1/W21=	=	0.00000
Burner	0.9995			0.9550	Loading %=	=	100.00
HP Turbine	0.8800	0.8573	0.894	5.410	W NGV/W25=	=	0.05000
IP Turbine	0.8900	0.8876	0.292	1.231	WHc1/W25 =	=	0.06000
LP Turbine	0.9000	0.8799	0.254	5.033	WIC1N/W25=	=	0.02000
HP Spool mech	0.9940	Nominal Spd	16000		WIC1/W25 =	=	0.01000
IP Spool mech	0.9960	Nominal Spd	7500		WLc1/W25 =	=	0.01000
LP Spool mech	0.9985	Nominal Spd	3807		WHPLk/W25=	=	0.00500
Fuel	FHV	humidity	war2				
Generic	43.124	0.0	0.0000				
Composed Values:							
1: CONSTEFF		=	0.289999				
2: CONSTP		=	1.740004				
3: W25R3		=	2.192808				
4: LoadHPT		=	0.354281				
5: LoadLPT		=	0.345173				
6: LoadIPT		=	0.051350				
7: ConvertedNetThrust		=	7100.000000				
8: ConvertedSFC		=	0.005697				
9: FandIAinch		=	79.000000				

Figure 4: Reference Cycle with Constraints

The above fig.4 shows the values of temperature, pressure and mass-flow at each station and other parameters of interest along with composed values. The cycle follows all the constraints that are imposed and the SFC of the reference cycle is (ConvertedSFC) 0.005697 to be noted further.

4 Parametric Study of Reference Engine

In order to assess if the selection of variables carried out in the previous section was adequate, some of the sizing parameters have been altered to see their effect on the overall performance of the engine. Before proceeding with the analysis, it is important to understand what concerns the different efficiencies which are going to be studied.

• Propulsive Efficiency

The propulsive efficiency is the efficiency of the conversion of the kinetic energy of air into propulsive power when it passes through the engine. As a result, it is inversely proportional to the kinetic energy gained by the airflow. Its mathematical expression can be found in eqn.1 where it is clearly appreciated how increasing the exhaust speed (V8) decreases the propulsive efficiency. If a compound modification of both exhaust velocities is expected, the one of the core flow and the one of the bypass(V18), the more comprehensive expression contained in eqn.2 should be considered.

$$\eta_{\text{prop}} \approx \frac{2}{1 + \frac{V_8}{V_0}} \quad (1)$$

$$\eta_{\text{prop}} = \frac{2V_0 [V_8 + \text{BPR} \times V_{18} - (1 + \text{BPR})V_0]}{(V_8)^2 [V_8 + \text{BPR} \times (V_{18})^2 - (1 + \text{BPR})(V_0)^2]} \quad (2)$$

- **Thermal Efficiency**

Thermal efficiency is the efficiency in the conversion of chemical energy of fuel into kinetic energy of the fluid passing through the engine. In other words, it is the ratio between the kinetic energy added to the flow and the power introduced by the fuel. It is related, as a result, to the exhaust speed in as can be seen in eqn.3. Note that the OPR is present in this expression, which will be important further on in this section, and also the thermal efficiency is inversely proportional to the Specific Fuel Consumption (SFC).

$$\eta_{th} \approx 1 - \frac{1}{\text{OPR}^{\frac{\gamma-1}{\gamma}} (1 + \frac{\gamma-1}{2} M_0^2)} \quad (3)$$

- **Core Efficiency**

The core efficiency of a jet engine is a measure of how efficiently the engine is converting the chemical energy in the fuel into useful mechanical energy. It is typically defined as the ratio of the kinetic energy of the exhaust gases leaving the engine's core to the power added during the combustion process:

$$\eta_{core} = \frac{\text{Kinetic energy at exit}}{\text{Power added during combustion}} = \frac{W_{core} \cdot (dH_{is} - \frac{V_0^2}{2})}{FN \cdot W_f} \quad (4)$$

The kinetic energy of the exhaust gases is a function of the exhaust velocity and the mass flow rate of the gases. The power added during combustion is the product of the fuel flow rate and the heat of combustion of the fuel. The core efficiency can also be expressed in terms of the specific fuel consumption (SFC), which is the fuel flow rate per unit of thrust produced:

$$\eta_{core} = \frac{\text{Thrust} \times \text{Exhaust velocity}}{\text{SFC} \times \text{Heat of combustion of fuel}} \quad (5)$$

4.1 Influence of BPR

To perform a parametric study on it, the iteration fixing the fan diameter has been deactivated and the OPR, P16Q6 and T4 have been kept constant so as to isolate the effect of BPR.

As the bypass ratio increases, The diameter increases linearly, accounting for the fact that more air mass flow has to be allowed into the engine. The diameter goes well beyond the 80 inches limitation because of this reason. The greater quantity of air also allows for a lower fan pressure ratio, having that any change of pressure on a larger volume of gas will produce a more notable change in momentum. (See fig.5)

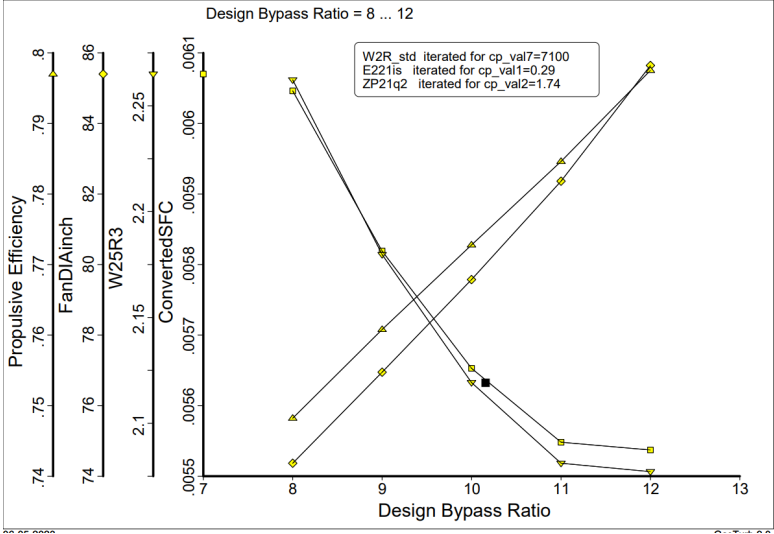


Figure 5: Influence of BPR

The specific fuel consumption decreases, as well as the amount of flow going into the core of the engine (core size or W25R3). In-fact it can be analysed in two ways. One is the fact that engine diameter is increasing which allows more air inside and the flow is diverted more into bypass duct comparatively. Other way is, assuming the core size is decreasing only with an assumption that diameter of the engine is constant, which is not in this case.

As the bypass ratio increases, since the ratio outlet-to-inlet velocity has decreased, the propulsive efficiency has increased accordingly, keeping the same core efficiency because of the trade-off between less kinetic energy at the exhaust and less fuel flow. This means that the core energy is mostly extracted by the turbines and propulsive thrust from the core is less which is balanced by the thrust from the bypass-nozzle. (See fig.6)

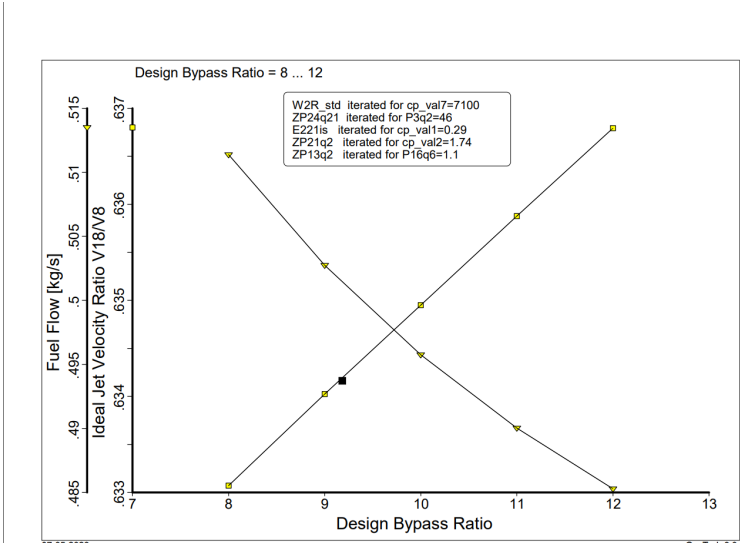


Figure 6: Influence of BPR

4.2 Influence of OPR

To study the effects of changing the OPR, the fan diameter has been fixed, as well as P16Q6 and T4. Since the OPR is not a model input in GasTurb, the IPC pressure ratio has been used as a variable instead. Respecting the constraint defined by the problem description, the OPR is adjusted in range of 45 to 60.

Given that P3Q25 was kept at the design value, the enthalpy changes in the HPC and HPT remained constant. No changes are applied to the LPC, used in the CONSTP equation, It is therefore the IPC which has been iterated for the targeted OPR range.

The pressure ratio increase in the intermediate pressure compressor (IPC) is maintained by expanding more air in the intermediate pressure turbine (IPT) to keep the intermediate pressure (IP) shaft balanced. However, this results in less energy available for the low pressure turbine (LPT) to extract due to a constant extraction ratio. The enthalpy change in the first compressor remains constant, while that of its respective turbine decreases, causing an increase in the LPT exhaust pressure. To maintain the power balance in the low pressure (LP) shaft, the bypass ratio (BPR) needs to be decreased, which increases the amount of airflow through the core and allows the turbines to extract more energy to feed the compressors.

$$PWLPC = PWLPT$$

$$W_{total}\Delta H_{LPC} = W_{core}\Delta H_{LPT} \rightarrow W_{total}\Delta H_{LPC} = \frac{W_{total}}{1 + BPR}\Delta H_{LPT}$$

$$(1 + BPR)\Delta H_{LPC} = \Delta H_{LPT}$$

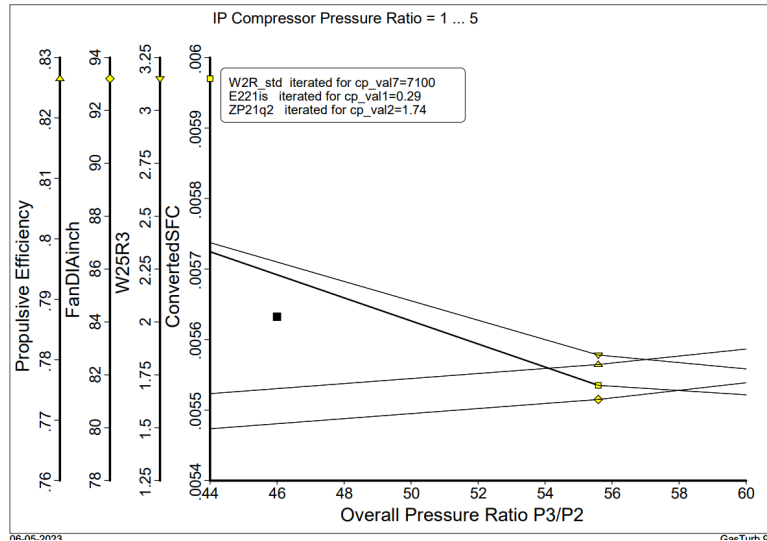


Figure 7: Influence of OPR

As the OPR increases so do W25 and the temperature at the HPC outlet (T3), but the pressure at this stage (P3) grows at a faster rate and, as it is in the denominator, the overall core size decreases. It must be noted that even though the temperature rise is higher along the compression phase the drop is also larger through the expansion phase, therefore the total amount of heat added is constant and so is the nozzle temperature. Nonetheless, there is a rise in nozzle pressure because turbine expansion

ratio increases more slowly than the overall pressure ratio. Due to energy conservation the increase in exhaust pressure at constant temperature results in lower exhaust speed.

Since the BPR is reduced, more air flows through the core, increasing its temperature much more than if that air flowed through the bypass channel, resulting in an exhaust flow which has more enthalpy. The increased amount of energy before the expansion at the core nozzle means that there is higher expansion potential which has a positive effect on thrust. As previously mentioned thrust is the rate of change of momentum of the flow, hence the increase in core mass flow results in a larger momentum at the exit of the engine, overcompensating for the fact that the exhaust speed is lower.

Consequently, thermal efficiency is also improved through primary compression because the higher the compression and the more core flow, the higher the area ratio nozzle to be fitted on the engine. This means that more of the heat energy is converted to jet speed, and thermal efficiency is enhanced and thereby, SFC improves. Propulsive efficiency should decrease because more air flows through the core and is accelerated further than that flowing through the secondary channel as BPR drops. However, this effect is counteracted by a lower exhaust speed of the core flow as OPR increases. The propulsive efficiency is maximum when the exhaust speed matches V_8 , but of course this is incompatible with thrust generation due to momentum conservation.

The overall core efficiency increases but it reaches a point where there is no noticeable gain as the OPR is further increasing. As the OPR is further increased, the core size continues to decrease, eventually reaching a point where it limits the power output of the engine cycle, resulting in decrease in the thrust. But the thrust should be kept constant which means the BPR should be increased by not further decreasing the core flow but by increasing the diameter, which counteracts to the whole process resulting in no more improvement in core efficiency.

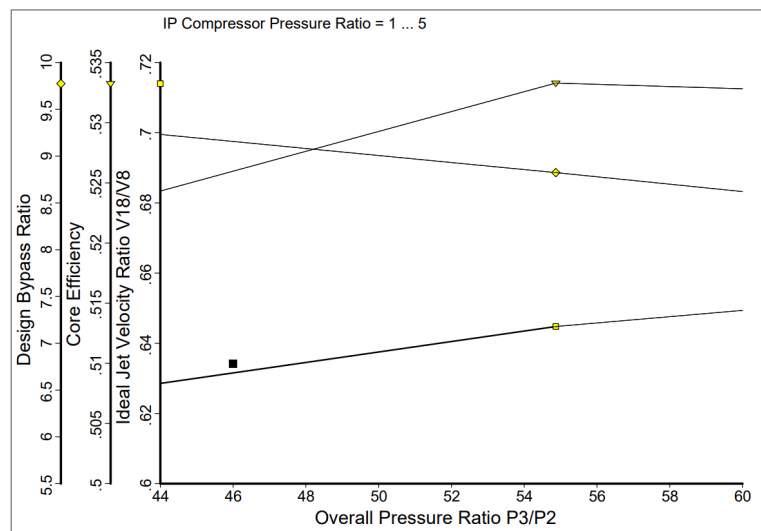


Figure 8: Influence of OPR

One other reason for which OPR is not further increased to achieve better efficiencies is that as the air is compressed it heats up and beyond a given point the material may not withstand and the core efficiency of turbo-machinery decreases.

4.3 Influence of Turbine Entry Temperature (T4)

To perform a parametric study on it OPR, P16Q6 and Fan diameter have been kept constant so as to isolate the effect of BPR. In a 3 shaft bypass engine architecture, the turbine entry temperature (T4) refers to the temperature of the hot gases entering the high pressure turbine just after exiting the burner after combustion. A higher T4 enables the engine to extract more energy from the combustion process, which increases the engine’s efficiency. This is due to a higher T4 allows for a greater pressure drop across the turbine, which in turn means more energy is extracted from the combustion gases. On the flipside, very high T4 can lead to blades to deform or in rare cases even fail due to thermal stresses. Hence it of utmost importance to us to maintain this delicate tradeoff between improving the efficiency of the engine while maintaining its structural integrity.

From fig.9 we can infer that with an increase in Burner Exit Temperature clearly leads to a decrease in the corrected mass flow rate. We know mass flow rate is a function of the density of the air and the velocity of the air. As the burner exit temperature increases, the temperature of the air entering the turbine section of the engine also increases. According to the ideal gas law, an increase in temperature causes a decrease in density, assuming constant pressure and mass. Therefore, as the air entering the turbine section becomes hotter, its density decreases. As the density of the air passing through the engine decreases, the mass flow rate through the engine also decreases.

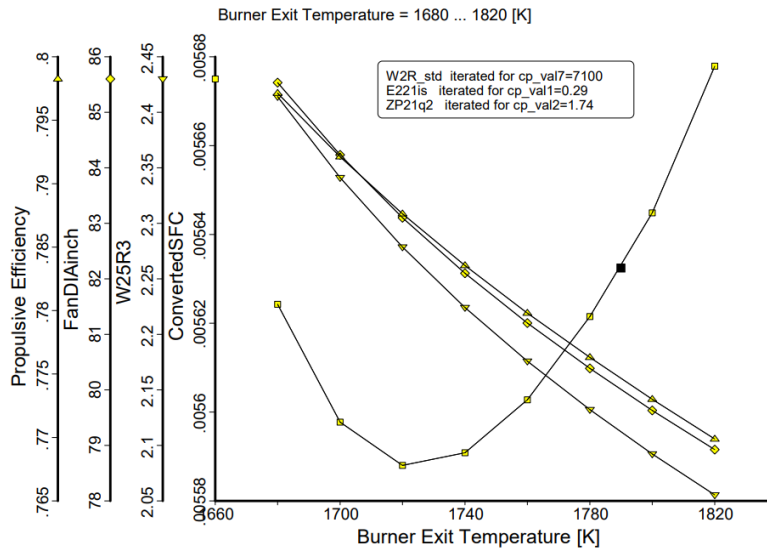


Figure 9: Influence of T4

As a consequence of that there is a reduction in the engine’s thrust output, which needs to be balanced and so to maintain the same level of thrust with a lower mass flow rate, the velocity of the air must be increased. This can be achieved by reducing the diameter of the fan and increasing the rotational speed of the fan blades. The reduction in fan diameter allows the fan to operate at a higher speed, which increases the velocity of the air passing through the engine and compensates for the reduction in mass flow rate.

Also, the propulsive efficiency of a turbofan engine is the ratio of the thrust produced by the engine to the energy expended by the engine. As the burner exit temperature increases, the exhaust gases leaving the engine have a higher velocity and a lower density. This reduces the thrust produced by the engine, which in turn reduces the propulsive efficiency of the engine.

Initially, the increase in pressure ratio and turbine inlet temperature can lead to a reduction in SFC. This is because the engine is able to extract more energy from the fuel, leading to a higher

thermal efficiency. However, as the temperature and pressure in the engine continue to increase, the engine may start to experience higher levels of internal losses, such as friction and leakage losses. This can offset the initial gains in thermal efficiency and cause the SFC to increase again.

Additionally, reducing the fan diameter to increase the engine’s velocity can also increase the engine’s specific thrust, which is the thrust produced by the engine divided by the mass flow rate of air passing through the engine. An increase in specific thrust can lead to a decrease in SFC, as the engine is producing more thrust for a given mass flow rate of fuel.

4.4 Influence of P16Q6

Here we vary the bypass flow pressure and study its effect on our engine. As we increase the bypass-flow pressure (Shown in graph by increase in Fan Diameter), this leads to an increase in stagnation pressure at the secondary nozzle, which in turn leads to an increase in expansion ratio and furthermore resulting an increase in velocity from the secondary channel. For the same thrust level, given our more air passes through the bypass than the core as exhibited in our graph by an decrease in the core flow, less air is forced to enter and burn the core and hence as a result of this the SFC decreases.

The propulsive efficiency of the engine seems to increase this could be attributed to the increase in the pressure of the bypass flow which can increase the velocity of the bypass air, which in turn can increase the thrust generated by the bypass flow. This leads to an increase in the engine’s total thrust output which is responsible for a large part of the engine’s propulsive efficiency. Also, by improving the pressure recovery in the exhaust nozzle, and improving the mixing of the bypass and core flows engine’s propulsive efficiency could increase.

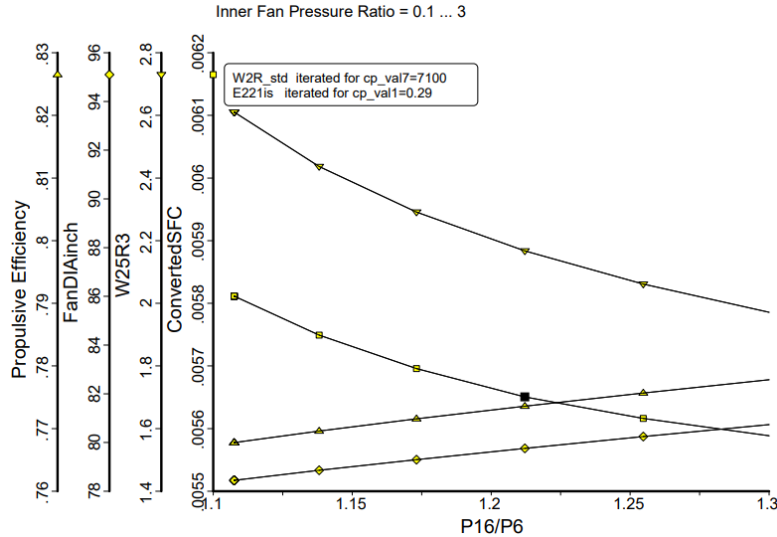


Figure 10: Influence of P16/Q6

5 Optimization of Reference Engine

The reference engine cycle is optimized for minimum fuel consumption. To perform the optimization study, all the limitations have been fixed: fan diameter, turbine loads, OPR and P16/Q6, as well as their associated variables, including BPR and T4 (See Fig.11). After that, an endless iteration is done and it is stopped when residuals line is flat and obtained the cycle which provided best results for SFC while remaining within the constraint range.

```

Optimization Variables:
  IP Compressor Pressure Ratio      1...3
  Outer Fan Pressure Ratio          1...3
  Design Bypass Ratio              8...12
  Burner Exit Temperature           K    1680...1820

Constraints:
  FanDIAinch = d t LC*39.3701      70...80
  P16/P6                            0.9...1.3
  Overall Pressure Ratio P3/P2     45...60
  LoadHPT = PW HT/W41/T41         0.3...0.4
  LoadIPT = PW IT/W45/T43         0.04...0.15
  LoadLPT = PW LT/W48/T47         0.35...0.45

Minimize ConvertedSFC = SFC*0.00036
    
```

Figure 11: Variables and Constraints

The first thing to notice in the results is that the overall pressure ratio ($P3/P2$), the Fan diameter (FanDIAinch) and the bypass/core pressure ratio ($P16/P6$) are at their respective maximums. These trends coincide with the ones observed in preceding sections, since increasing them produces a rise in overall efficiency, on which the specific fuel consumption is directly dependent.

Station	W	T	P	WRstd	FN	=	31.58
amb		228.81	23.842		TSFC	=	15.3682
2	226.563	257.43	35.887	604.626	WF	=	0.4854
13	205.980	298.29	58.352		s NOx	=	1.3624
14	41.196	298.29	57.769		BPR	=	10.0072
16	205.980	298.29	58.236		P16/P13	=	0.9980
21	20.583	287.26	48.798	42.673	Core Eff	=	0.5428
24	20.583	364.14	103.273	22.702	Prop Eff	=	0.7746
25	20.583	364.14	101.207	23.166	P25/P24	=	0.9800
3	20.172	889.26	2125.353	1.689	P3/P2	=	59.2235
31	17.905	889.26	2125.353				
4	17.361	1813.48	2029.712	2.174	P5/P2	=	1.2450
41	18.390	1766.25	2029.712	2.273	P4/P3	=	0.95500
42	18.390	1273.06	374.597		P44/P43	=	0.98000
43	19.625	1250.50	374.597		P48/P47	=	0.99000
44	19.625	1250.50	367.105		P6/P5	=	0.99500
45	20.037	1239.86	367.105	11.472			
46	20.037	1174.65	283.072		P16/P13	=	0.99800
47	20.243	1170.06	283.072		P16/P6	=	1.30995
48	20.243	1170.06	280.242	14.748			
49	20.243	789.99	44.680		V8	=	511.2
5	20.449	789.63	44.680	76.765	V18	=	316.1
6	20.551	790.12	44.457		V18/V8,id=	=	0.71428
8	20.551	790.12	44.457	77.564	A8	=	0.33278
18	205.980	298.29	57.537	369.069	A18	=	1.56725
Efficiencies:	isent	polytr	RNI	P/P	XM8	=	0.99996
Outer LPC	0.9400	0.9440	0.428	1.626	XM18	=	1.00000
Inner LPC	0.7931	0.8019	0.428	1.360	ZWBld	=	0.51710
IP Compressor	0.8900	0.9009	0.484	2.116	PWX	=	190.2
Intercooler	1.000E-5			0.9800	T14	=	298.29
HP Compressor	0.9000	0.9313	0.673	21.000	WHDB1/W21=	=	0.00000
Burner	0.9995			0.9550	Loading %	=	100.00
HP Turbine	0.8800	0.8576	0.973	5.418	W NGV/W25=	=	0.05000
IP Turbine	0.8900	0.8869	0.316	1.297	WHc1/W25 =	=	0.06000
LP Turbine	0.9000	0.8770	0.265	6.272	Wlcln/W25=	=	0.02000
HP Spool mech	0.9940	Nominal Spd	16000		Wlcl/W25 =	=	0.01000
IP Spool mech	0.9960	Nominal Spd	7500		WLcl/W25 =	=	0.01000
LP Spool mech	0.9985	Nominal Spd	3760		WHPlk/W25=	=	0.00500
Fuel	FHV	humidity	war2				
Generic	43.124	0.0	0.0000				
Composed Values:							
1: CONSTEFF	=	0.289999					
2: CONSTP	=	1.740002					
3: W25R3	=	1.723868					
4: LoadHPT	=	0.355225					
5: LoadLPT	=	0.383123					
6: LoadIPT	=	0.063895					
7: ConvertedNetThrust	=	7100.000488					
8: ConvertedSFC	=	0.005533					
9: FanDIAinch	=	79.999763					

Figure 12: Optimized Cycle by GasTurb

However, it is important to note that the bypass ratio has only increased slightly, from 8.21 to 8.56, despite the fact that increasing it has been shown in parametric studies to result in the greatest reduction in specific fuel consumption. This is because the size of the engine is constrained by its diameter, which has already been maximized.

$$SFC = \frac{W_{fuel}}{F_N} = \frac{V_0}{\eta_{thp} F_{HV}} = \frac{k}{\eta_{thp}} = \frac{k}{\eta_{pr} \eta_t}$$

Lastly, in terms of the thermodynamic loads on each turbine, all three have been increased to varying degrees depending on the shaft they are attached to. The HPT experienced the smallest increase, as the pressure ratio on the compressor it is associated with was kept constant to maintain power balance on that shaft. Therefore, the burden of increasing the overall pressure ratio is on IP and LP shafts, particularly the IPT, resulting in an almost 30 point increase in load. These combined effects resulted in a 2.87 percent reduction in fuel consumption compared to the reference engine. (The SFC of optimised cycle is 0.005533. See Fig.12)

6 Intercooler

After the optimization process, an intercooler was introduced into the compression phase. This component is a heat exchanger that is positioned before the high-pressure compressor. The function of an intercooler before the high-pressure compressor is to remove waste heat from the compressed air and lower its temperature. This makes compression less energetically expensive and expected to improve the volumetric efficiency of the engine.

6.1 Sizing at iso-OPR and iso-T3

The engine cycle with intercooler is adjusted to have the same overall pressure ratio(OPR) as the optimised cycle without intercooler and also satisfying all the constraints. The resulting thermodynamic cycle is plotted for comparison against that of the reference engine, which can be observed in the fig.13.

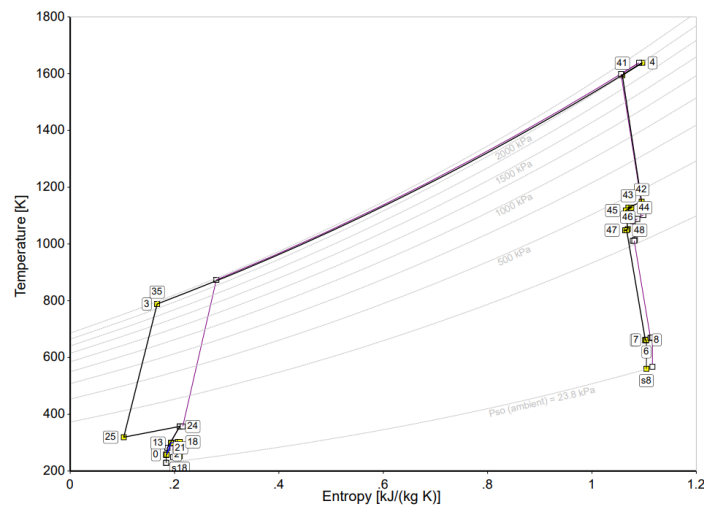


Figure 13: T-S diagram of cycle with and without intercooler at iso-OPR

As previously explained, the compression of colder air requires less energy since the isobaric lines are closer to each other. This implies that with an intercooler, less work is required by the compressor

for the same overall pressure ratio compared to a scenario without an intercooler. However, T_4 , which is an input in the model, remains constant, resulting in the same extraction ratio. Therefore, there is extra energy available at the turbines. As the thrust is fixed, this extra core energy can be utilized to drive more air into the engine and decrease the core-flow to balance.

The addition of the intercooler leads to a small enhancement in thermal and core efficiencies, leading to a decrease in SFC. The intercooler does not have a direct effect on the burner exit temperature (T_4). This temperature is primarily determined by the combustion process and fuel-air mixture ratio, which are independent of the intercooler. However, since the intercooler reduces the temperature of the air entering the combustion process and the T_4 is fixed which results for a higher fuel-air ratio mixing and burning the fuel completely and reducing NOx emissions.

A new iteration was added to set T_3 to the optimized reference engine value, while the iteration that fixed the OPR was removed. The resulting thermodynamic cycle is then compared to the optimized reference engine without an intercooler. (See Fig.14)

By cooling the air, the intercooler reduces the temperature of the air before it enters the high-pressure compressor, which leads to an increase in air density. Since the pressure in the intercooler remains constant, the decrease in temperature results in a decrease in the volume of the air. This, in turn, leads to an increase in the air pressure as due to increase in core-flow. If the temperature of the air entering the high-pressure compressor is increased to the same level as it would be in the absence of an intercooler, a higher pressure will be reached due to the convergence of isobaric lines, which means higher OPR.

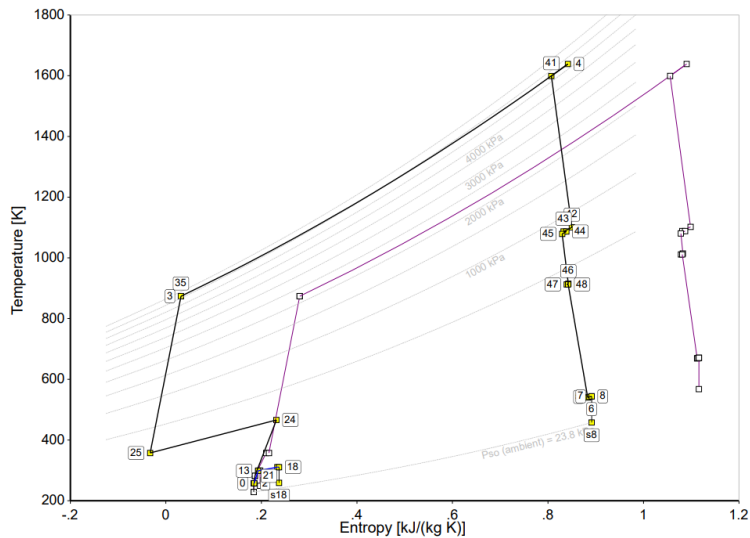


Figure 14: T-S diagram of cycle with and without intercooler at iso- T_3

The significant increase in OPR leads to a direct improvement in thermal efficiency as defined in eqn.3. This increase in thermal efficiency results in a reduction in SFC and an increase in the core efficiency, which can be seen as a measure of the thermal efficiency of the core. However, one of the main drawbacks of this model is, as the combustion temperature is constant the fuel is not completely burned and leads to increased NOx emissions.

Comparing the two intercooler cycle options, the Iso- T_3 case has a significant advantage of better SFC due to the higher OPR. However, regulatory limitations on NOx emissions must be considered, and a very high overall pressure ratio can increase the weight of the core, reducing the fuel savings achieved by carrying a heavier engine. Hence, a compromise must be found between the two cycles.

Parameter	Reference Engine	ISO-OPR	ISO-T3
NOx emission	1.3624	0.9522	1.8611
SFC (Kg/h/daN)	0.5533	0.5442	0.5325
BPR	10.0072	11.3051	10.7154
OPR	59.2235	59.2235	140.22
Core efficiency (%)	54.28	55.29	54.31

Table 3: Comparison of Reference, Iso-OPR and Iso-T3 cycles

7 Parametric Study of Engine with Intercooler

7.1 BPR

P16Q6, T4, OPR are the fixed parameters and their corresponding iterations are to be left active. BPR was to be varied within the range of 8 to 12. The study showed that adjusting the BPR (bypass ratio) resulted in similar trends as in reference engine parameter study. Obviously changes in the magnitudes of the variables due to the addition of an intercooler and modifications to OPR, T4, and P16Q6 after optimizing the reference engine. (See fig.5)

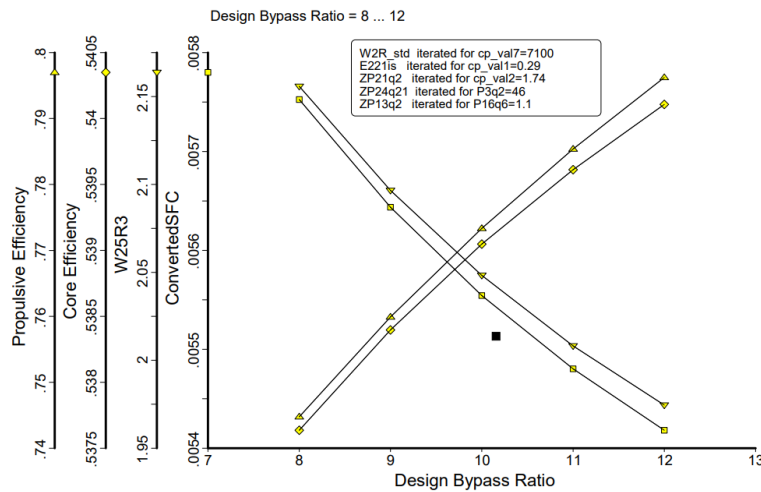


Figure 15: Influence of BPR

The unique characteristic of this new study is the behavior of the core nozzle velocity (V_8). As shown in the fig.6 V_8 decreases consistently. The reason for this can be attributed to the higher value of P16Q6. When the bypass pressure ratio increases, more air mass flows through the bypass duct. To maintain the same bypass/core pressure ratio, the pressure on the engine core must also be reduced, resulting in a lower V_8 . However, it's essential to consider that the core static pressure cannot decrease indefinitely because the core jet velocity relies on the flow's expansion in the nozzle, which cannot go beyond the ambient pressure.

This is precisely what occurred in this case: the core nozzle static pressure reached the ambient pressure, which is around 24 kPa. To continue decreasing the total pressure inside the core, the dynamic pressure must decline at a faster rate. Since dynamic pressure is a function of air velocity and density (the latter remaining constant due to the static pressure limit), this implies that V_8 must decrease even more, as shown in the 6 which is why the core efficiency is also increasing.

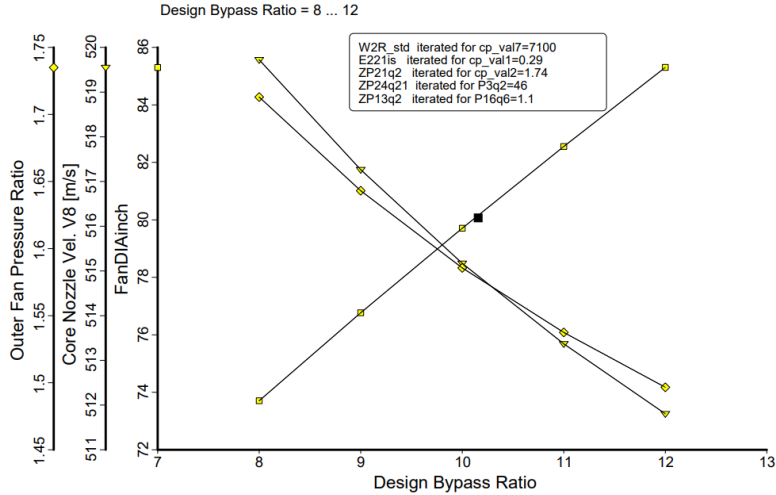


Figure 16: Influence of BPR

7.2 OPR

Fan diameter, T4, P16Q6 are the fixed parameters and their corresponding iterations are to be left active. OPR was to be varied within the range of 45 to 60. The are largely the same when compared to section 4.2.

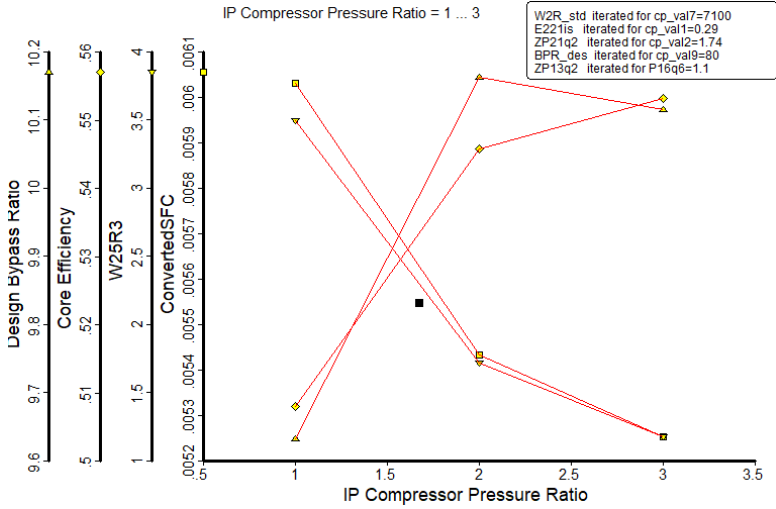


Figure 17: Influence of OPR

What’s particularly noteworthy is that the BPR exhibits a significant change in its trend when the OPR is increased with the introduction of an intercooler. This can be attributed to the interaction between two factors. Firstly, a slight increase in compression becomes increasingly energy-intensive at the high temperatures at which turbines operate, necessitating more core flow to maintain shaft balance and leading to a decrease in BPR. Secondly, due to isobaric line divergence, turbine work grows more rapidly as the OPR increases, causing the BPR to decrease more quickly for higher OPR values. However, up to a certain, the BPR increases rather than decreasing due to a second trend: since the intercooler reduces the energy required for compression, the compressors require less energy from the turbines, allowing the BPR to increase. The maximum BPR is attained once this second trend is no longer powerful enough to counteract the first one.

7.3 Turbine Entry Temperature

Fan diameter, P16Q6, OPR are the fixed parameters and their corresponding iterations are to be left active. T4 was to be varied within the range of 1680K to 1820K. The trends followed here are similar, with SFC showing noticeable change in behaviour when compared to the ones section 4.3.

From the graph it can be inferred that an increase in burner exit temperature can lead to a decrease in the mass flow rate of air through the engine core so as to accommodate for increase in bypass flow in order to maintain the thrust balance within the engine, which can reduce the engine’s thrust output and increase the specific fuel consumption of the engine. From eqn.5 we can see the linear relation between core efficiency and core nozzle velocity both of which are inversely proportional to SFC, and from the graph similar trends can be inferred of SFC decreasing and Core nozzle velocity and core efficiency increasing.

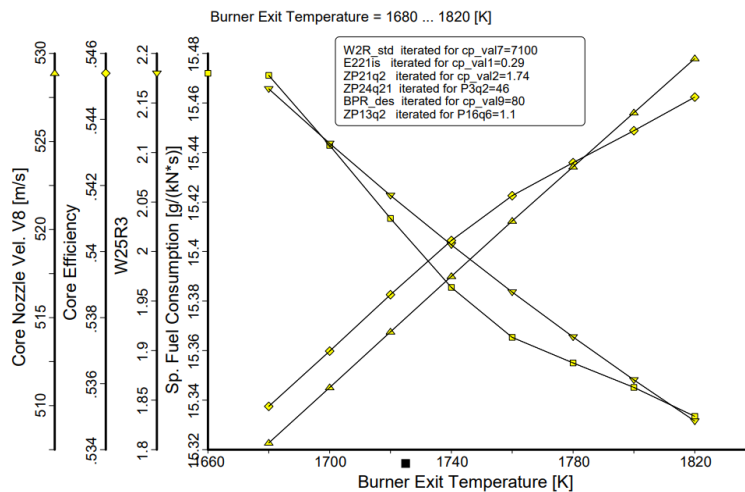


Figure 18: Influence of T4

7.4 P16Q6

Fan diameter, T4, OPR are the fixed parameters and their corresponding iterations are to be left active. P16Q6 was to be varied within the range of 0.9 to 1.3. The trends followed are the same as section 4.4.

From the graph it can be inferred that as the outer fan pressure ratio increases we observe decrements in core efficiency and core mass flow as due to most of the air now being bypassed, the core would decrease and as a result have to less work and hence by extension SFC also decreases. Also, in support to the previous statements on referring to fig.20 it clearly shows in increase in BPR to accommodate for an increase in FPR and conversely a decrease in core nozzle velocity as expected.

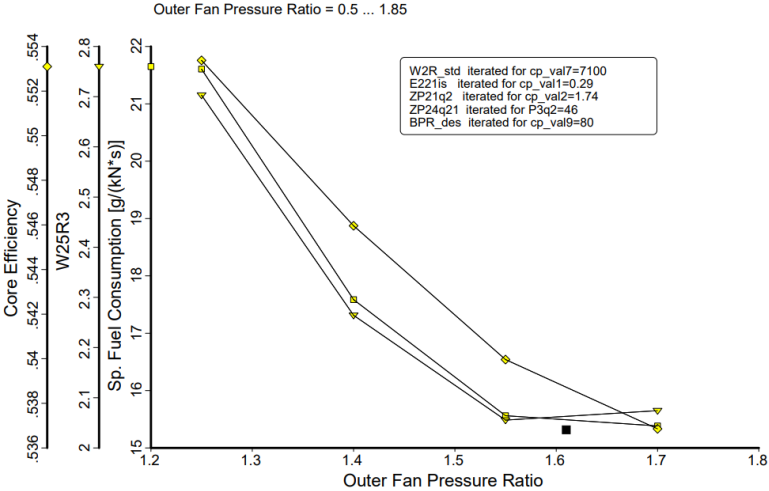


Figure 19: Influence of P16Q6

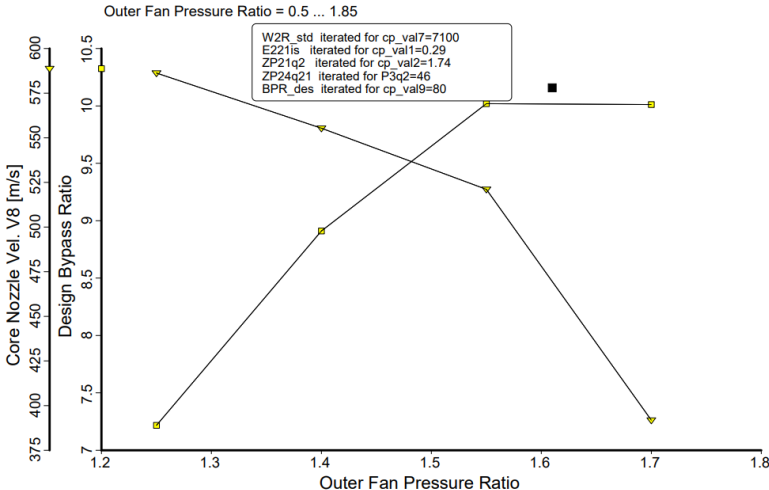


Figure 20: Influence of P16Q6 on BPR and V8

7.5 Cold Flow into Intercooler

Fan diameter, T4, P16Q6, OPR are the fixed parameters and their corresponding iterations are to be left active. Cold flow was to be varied within the range of 5 to 30 %.

From the graph we can infer that with an increase in Cold flow the core mass flow decreases as compressed air is cooled (also the reason why bypass ratio increases), its density increases, and so the BPR is increased as a consequence of that to maintain constant thrust. Also, cooling of the compressed air can reduce the temperature of the air entering the combustion chamber, which can lead to a more efficient combustion process. This can result in a decrease in the specific fuel consumption of the engine.

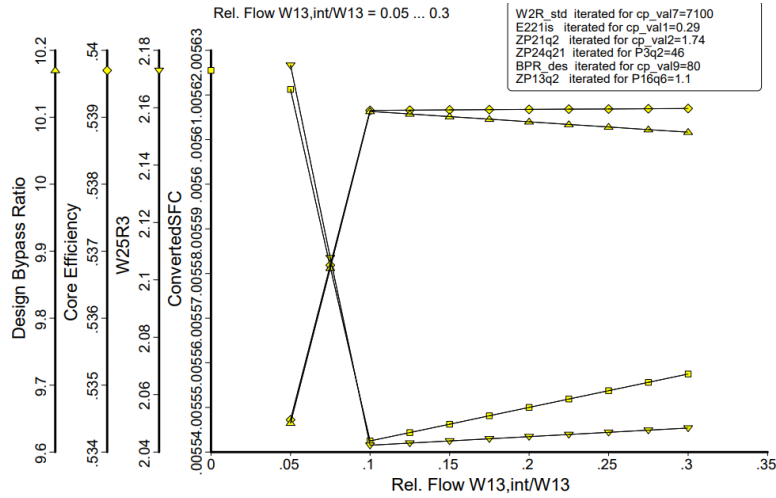


Figure 21: Influence of Cold Flow Percentage

8 Optimization of Engine with Intercooler

Optimization for the engine with intercooler is done in the same way as the optimization done previously, with the addition of cold flow percentage as a variable. The following table presents a comparison between the two optimizations.

	Without Intercooler	With Intercooler
BPR	8.7553	10.5936
OPR	50.0000	59.9805
T4 (K)	1725.00	1739.93
P16Q6	1.16828	1.31578
W13	198.288	209.596
Propulsive Efficiency	0.7702	0.7767
Core Efficiency	0.5316	0.5491
SFC	0.005657	0.005334
NO _x	1.0251	0.8363

Table 4: Comparison between Optimized Engines with and without Intercooler

From the table it can be inferred that with the addition of intercooler a clear decrement in SFC of 5.7%, NO_x also shows decrement of 18.4%, both Propulsive and Core efficiencies show increments which is what we expected to happen, the other parameters don't show substantial changes w.r.t our original optimization. Hence, our intentions to employ SFC have come to fruition as they have delivered decrements in SFC and NO_x emissions which help us achieve our environmental goals, while not heavily compromising on performance.

Intercooled Recuperated Turbofan Alt=10668m / Mn=0.790 ISA +10 C

Station	W	T	P	WRstd	FN	=	
amb							31.58
2	229.381	228.81	23.842		TSFC	=	14.8155
13	209.596	297.56	57.877	612.146	WF	=	0.4679
14	24.866	332.90	57.298		s NOx	=	0.8363
16	209.596	301.76	57.808		BPR	=	10.5936
21	19.785	286.69	48.525		P16/P13	=	0.9988
24	19.785	365.51	104.593	41.209	Core Eff	=	0.5491
25	19.785	321.34	102.501	21.587	Prop Eff	=	0.7767
3	19.389	793.40	2152.520	20.654	P25/P24	=	0.9800
31	17.191	793.40	2152.520	1.515	P3/P2	=	59.9805
4	16.669	1739.93	2055.657		P5/P2	=	1.2304
41	17.659	1691.84	2055.657	2.019	P4/P3	=	0.95500
42	17.659	1250.91	437.115		P44/P43	=	0.98000
43	18.846	1224.24	437.115		P48/P47	=	0.99000
44	18.846	1224.24	428.373		P6/P5	=	0.99500
45	19.241	1212.76	428.373	9.337			
46	19.241	1145.46	325.949		P16/P13	=	0.99881
47	19.439	1140.47	325.949		P16/P6	=	1.31578
48	19.439	1140.47	322.689	12.143			
49	19.439	743.53	44.155		V8	=	491.3
5	19.637	742.82	44.155	72.350	V18	=	317.9
6	19.736	743.07	43.935		V18/V8_id	=	0.74489 <-
8	19.736	743.07	43.935	73.092	AR	=	0.31338
18	209.596	301.76	57.115	380.518	A18	=	1.61588
Efficiencies:	isent	polytr	RNI	P/P	XM8	=	0.98841
Outer LPC	0.9400	0.9439	0.428	1.613	XM18	=	1.00000
Inner LPC	0.7931	0.8018	0.428	1.352	ZWBld	=	0.51710
IP Compressor	0.8900	0.9012	0.483	2.155	PWX	=	190.2
Intercooler	0.6500			0.9800	T14	=	332.90
HP Compressor	0.9000	0.9318	0.842	21.000	WHDB1/W21	=	0.00000
Burner	0.9995			0.9550	Loading %	=	100.00
HP Turbine	0.8800	0.8596	1.059	4.703	W NGV/W25	=	0.05000
IP Turbine	0.8900	0.8868	0.383	1.314	WHcl/W25	=	0.06000
LP Turbine	0.9000	0.8745	0.319	7.308	Wlcl/W25	=	0.02000
HP Spool mech	0.9940	Nominal Spd		16000	Wlcl/W25	=	0.01000
IP Spool mech	0.9960	Nominal Spd		7500	WLcl/W25	=	0.01000
LP Spool mech	0.9985	Nominal Spd		3736	WHPLk/W25	=	0.00500
Fuel Generic	FHV	humidity	war2				
	43.124	0.0	0.0000				
Composed Values:							
1: CONSTEFF	=		0.289999				
2: CONSTP	=		1.740002				
3: W25R3	=		1.545422				
4: HPTLoad	=		0.330086				
5: LPTLoad	=		0.407428				
6: IPTLoad	=		0.066974				
7: ConvertedNetThrust	=		7100.000000				
8: ConvertedSFC	=		0.005334				
9: FanDIAinch	=		80.495743				

Figure 22: Optimization with Intercooler

9 Technology Influences

In order to assess the relative impact of the technology on the SFC level, from all the previous studies, the following intercooler technology assumptions are considered:

- Heat exchanger efficiency: +0.01
- Hot flow pressure ratio P25/P24: +1 point (+0.01 absolute value)
- Cold flow pressure ratio P14/P13: +1 point (+0.01 absolute value)

The table.5 shows information on relative variation of each of the technology items as well as their influence on SFC. It can be seen that reducing the cold flow pressure losses has the highest impact on the SFC. This is because reducing the bypass flow pressure losses results in an increase in the effective bypass ratio. The effective bypass ratio is the ratio of the mass flow rate of air that bypasses the engine core to the mass flow rate of air that passes through the engine core.

Increasing the effective bypass ratio means that a greater proportion of the air that is being ingested by the engine is not involved in the combustion process, which means that less fuel needs to be burned to generate a given amount of thrust. This results in a reduction in specific fuel consumption, which is a key metric of engine efficiency. Nevertheless, intensifying the pressure ratio of the hot flow produces a SFC variation of the same order of magnitude, as the temperature gradient to be provided in the combustion chamber is smaller to achieve the desired T4 value.

Increasing the effectiveness of the intercooler do not reduce the specific fuel consumption (SFC) significantly because the intercooler is only responsible for cooling the air flowing through the compressor. Therefore, while a more effective intercooler may improve the compressor efficiency and reduce the amount of work required to compress the air, it does not directly reduce the SFC because the amount of fuel required to generate a given amount of thrust is primarily determined by the mass flow rate of air passing through the combustor. In fact, very small drop of T25, approximately 1K is observed. The work done by the HPC to compress the flow barely changes.

Parameter	Impact on SFC
Effectiveness	-0.0375
P25/P24	-0.1884
P14/P13	-0.1966

Table 5: Influence on SFC (Converted-SFC*100)

From this Technological influences study, we can come to understanding of in which areas of the engine architecture it is better to invest resources if a reduction on the SFC is desired. Among the turbomachinery, the low-pressure ones present the bigger influence with respect to the high-pressure ones. Focusing on the offtakes variables, to reduce their amount to reduce the fuel consumption, aircraft pressurization offtakes and LPT guide vane cooling can be employed, while mechanical offtake has a negligible effect hence can be omitted. Pressure losses in the combustion chamber and engine inlet have a detrimental effect on performance hence should be kept as high as possible.

10 Conclusion

An engine cycle which follows the constraints has been designed and influence of different parameters of interest is analyzed. Further, the reference engine is added with an effective intercooler, and parametric study is done to understand effect of each parameter on the cycle. The differences induced by the addition of the intercooler with iso-OPR same as the reference cycle and one more cycle with constant HPC exit temperature is done to understand which parameter has more effect on SFC. The cycle with better SFC is further optimized with the constraints with aim to minimize the SFC.

BPR is a crucial factor in designing an engine as increasing it can significantly decrease fuel consumption. However, the maximum size of the engine's fan is a limiting factor for BPR growth, resulting in sub-optimal values. Therefore, it's essential to consider how BPR interacts with other variables, including its relationship with P16Q6. While a high core pressure ratio also reduces fuel consumption and helps with noise control, setting it too high in high OPR situations can cause severe drops in exhaust velocity due to excessive depressions on the core flow. In summary, the engine's design must carefully balance these variables to optimize performance.

Raising the burner exit temperature (T4) and OPR has been found to crucial in reducing the SFC of the engine cycle. Using an iso-T3 intercooler engine cycle can significantly reduce fuel consumption by increasing the OPR. However, other factors such as NOx emissions must also be considered, making iso-OPR intercooler cycle more attractive. In any case, engine cycle with an intercooler benefit from the divergence of isobaric lines, which helps improve thermal efficiency. By combining various T3 and OPR values, promising engine models can be designed by using optimization in GasTurb and a 3.5 percent reduction in SFC has been found comparing with reference cycle without intercooler.