Derated Thrust: Method Analysis for Optimizing Turbofan Engine Takeoff Performances (SFC, EGT) Due to Lower Maximum Takeoff Weight (MTOW) Requirement

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Abstract. Reduced thrust or derate has been practiced commonly nowadays as a standard procedure of takeoff. Since power is being used at maximum during takeoff phase, the practice has many benefits for the operation of aircraft. Not only it reduced fuel consumption during the takeoff phase, but also reduced engine's wear and tear that caused by stress and a very high temperature. Exhaust Gas Temperature (EGT) is one of the most important parameters that used to monitor the engine deterioration. There is a definite correlation between reducing takeoff thrust and EGT reduction, where both values are contradicting one another. However, there must be some calculation by the flight crew on how much percentage of derate is eligible prior to takeoff. The goal of this paper is to find the effectiveness of derate to reduce EGT in order to improve performance, prolong engine life and reduce operating costs of the operators.

1. Introduction
Every airplane has its thrust setting based on the design of what the airplane meant for. For a long-range wide-body twin-engine aircraft, it was built purposely to carry a heavy load and fly in a very long-distance flight. To do that, it requires an engine that could generate enormous thrust to lift the aircraft. In the modern era, most of the commercial aircraft are equipped with an efficient high bypass ratio turbofan.

The high temperature in the hot section of the engine could deteriorate and shorten the engine’s life. Exhaust Gas Temperature (EGT) is used as a reference to monitor the engine condition at the High-Pressure Turbine (HPT) outlet [1]. EGT level is proportional to how much thrust inputted, meaning if an airplane uses almost its maximum thrust, then the EGT will be high and approaching its near maximum allowable level.

In the takeoff phase, a full rated thrust is applied only if aircraft carries a load in its maximum takeoff weight (MTOW). It is the ultimate design limit of the aircraft where the aircraft carries a maximum payload, applied its full thrust and the temperature inside of the engine peak almost to the limit. However, in some cases such as the runway conditions is limited, which is still many in Indonesia mostly in the remote regions [2], the airplanes are not allowed to takeoff with its specified MTOW. It means that the airplane should also
reduce its thrust to perform efficiently. Otherwise, the high temperature from the excessive thrust could wear and tear the engine.

That is where reduced takeoff thrust or derate technique comes. This technique reduces the thrust of the airplane during takeoff sufficiently, thus reduce the stress inside of the engine during takeoff. This could prolong the engine’s life, therefore saving cost for maintaining the engine [3]. There is a definite correlation between weight, thrust, and EGT level in terms of aircraft performance during takeoff.

By applying reduced thrust, not only the decreasing EGT could be calculated thermodynamically, but also every temperature at each section using The Brayton cycle calculation. The assumed temperature will be inputted to the flight management computer (FMC) to ‘trick’ engine to perform a reduced-thrust takeoff can also be predicted.

2. Methodology

![Flowchart of the methodology](image)

The whole process of this research is illustrated in figure 1. A long-range wide-body twin-engine aircraft uses a high bypass ratio turbofan engine as shown in Figure 2. A turbofan engine consists of two flow; primary flow that goes through the hot core, and secondary flow that bypass through the fan. The airflow that goes through the engine will experience a change of temperature and pressure due to how the engine was designed and constructed. In this paper, the analysis is particularly based on the typical high bypass ratio turbofan engine of a long-range wide-body twin-engine aircraft.

To conduct the thermodynamic calculation using The Brayton cycle, a variety of data with different circumstances must be set first. Five samples are used in this calculation. The first sample is when the aircraft carries a maximum takeoff weight (MTOW), that is 351,533 kg, with a maximum takeoff thrust of 513.9 kN. The other three samples were from real flight data that was obtained from one of Indonesian
airline’s fleet with three different flight. The last sample is when the aircraft performs a 25% of derated takeoff thrust with an assumed takeoff weight based on the regression method from the other four data. 25% is the maximum reduction thrust allowed for an aircraft based on the FAA’s Advisory Circular 25-13 [4].

The calculation took place at the rotation speed (VR), where aircraft have gained enough momentum and speed to lift off. Table 1 displays the data of the aircraft in VR during takeoff phase with the information of takeoff weight (TOW), derated takeoff thrust, EGT, and the outside air temperature (OAT) during that time.

The ambient pressure is set constant for this calculation since the three data was taken from the same departing runway and the same flight destination that is Jakarta (CGK) to Jeddah (JED).

Table 1. Flight data of the aircraft during takeoff phase (VR)

| TOW  | TO Thrust | Derate Thrust | TOW  | TO Thrust | VR | EGT | OAT |
|------|-----------|---------------|------|-----------|----|-----|-----|
| kg   | kN        | %             | kg   | kN        | KTAS | M/S | M   |
| 35153 | 513.9 | 0 | 100 | 100 | 191 | 98.25 | 0.286 | 1090 | 1363.15 |
| 318167.8 | 464.63 | 90.5 | 90.4 | 177.22 | 91.16 | 0.266 | 995 | 1268.15 | 31.5 |
| 294798.8 | 423.94 | 17.5061 | 83.86 | 82.49 | 167.49 | 86.16 | 0.251 | 954 | 1227.15 | 34.2 |
| 294508.5 | 416.27 | 18.9977 | 83.78 | 81 | 165.66 | 85.23 | 0.248 | 947 | 1220.15 | 32.95 |
| 282148.3 | 385.43 | 25 | 80.26 | 75 | 154.46 | 79.45 | 0.232 | 937 | 1210.96 |

The Brayton cycle calculation is based on the design of a typical high bypass ratio turbofan engine [5]. The changes of temperature and pressure of the airflow are divided into 10 sections as shown in Figure 2 followed by the information of the airflow in Table 2. Various values can be calculated from the pressure and temperature changes, and variables from Table 1. Those values are: Air-to-Fuel ratio (AFR), Jet Velocity, Fan Velocity, Thrust, Thrust-Specific Fuel Consumption (TSFC), Work Net, Heat Addition (Qin), Thermal and Propulsive Efficiency [6].

Table 2. Section of Turbofan Engine

| Stage | Flow          |
|-------|---------------|
| 1     | Ambient       |
| 2     | Diffuser      |
| 3     | Fan Out       |
| 4     | LPC Out       |
| 5     | HPC Out       |
| 6     | CC Out        |
| 7     | HPT Out       |
| 8     | LPT Out       |
| 9     | Nozzle Hot Core |
| 10    | Nozzle Fan    |

The calculation was done on a spreadsheet and the Brayton cycle calculation is specific for the typical High Bypass Ratio Turbofan Engine model, referencing from A.F. El-Sayed’s formula for Forward Fan Unmixed Double-Spool Configuration [6].

After the calculation is done and the necessary values are calculated, the next step is to calculate a new set of takeoff thrust from a different set of air inlet temperature that will act as the ‘Assumed Temperature’ but with a constant EGT from four takeoff weight variations. The goal of this method is to find a linear line of EGT that could explain the relationship between temperature and thrust.
3. Results and Discussion

The results from the Brayton cycle calculation are presented in table 3. The results are determined based on a collective set of values that have been previously mentioned. A full rated thrust of the particular aircraft is 513.9 kN, so there is no way that the thrust will be exceeding that number. However, in this case, since the goal is to find a linear EGT line, a hypothetical result is necessary.

Table 3. Thrust, TSFC, Thermal and Propulsive Efficiency from a different set of Air Inlet Temperature

| Air Inlet Temperature (°C) | MTOW; EGT = 1090 °C | TOW = 318168 kg; EGT = 995 °C | TOW = 294799 kg; EGT = 954 °C | TOW = 294508 kg; EGT = 947 °C |
|---------------------------|---------------------|-------------------------------|-------------------------------|-------------------------------|
| Thrust (kN)               | 521.5275            | 518.9875                      | 516.4379                      | 513.9                        |
|                           | 20                   | 25                            | 30                            | 35                            |
| TSFC (Kg/kN Hr)           | 200.382              | 200.324                       | 200.268                       | 200.430                      |
|                           | 200.167              | 200.122                       |                               |                               |
| Thermal Efficiency (%)    | 26.538               | 27.227                        | 27.928                        | 28.711                       |
|                           | 29.364               |                               |                               |                               |
| Propulsive Efficiency (%) | 30.219               | 30.319                        | 30.421                        | 30.523                       |
|                           | 30.627               |                               |                               |                               |

The increasing temperature of the air inlet will result in a smaller thrust, smaller TSFC, higher thermal, and propulsive efficiency. When the air inlet temperature is increased, the air-to-fuel ratio is decreased due to the small temperature difference in the inlet and the outlet of the combustion chamber. Therefore, the fuel that is injected to the combustion chamber is smaller than the ratio of air, creating a smaller thrust and more efficient fuel consumption. Less fuel injected to the combustion chamber means less heat energy is added to the system. When the air inlet temperature is increased, it increases all temperature at each section inside of the engine. The compressor work will increase, and the turbine will also receive higher work, resulting in a higher total work (Wnet). Consequently, when the work done is getting higher and higher while the heat supplied to the system is getting smaller and smaller, the thermal efficiency increases. For the
propulsive efficiency, a higher air inlet temperature will result in a slower jet velocity. The slower the jet velocity, the higher the propulsive efficiency.

Figure 3 is a combined visual representation of Table 1 and Table 3. The left side of the chart presents the relationship between the Takeoff Weight (x-axis) and the Takeoff Thrust (y-axis), while the right side of the chart presents the relationship between the Takeoff Thrust (y-axis) and the OAT (x-axis) that can be used as a reference to choose an “Assumed Temperature” that will be inputted to the Flight Management Computer (FMC). When performing a full rated thrust, the OAT must be 30°C or below to guarantee its maximum thrust.

The way this chart is read is by starting it from the Takeoff Weight axis, decide how much payload the aircraft will be carrying, then pull a straight line until it touches the curved line, then pull a perpendicular line to the Takeoff Thrust. That is how much thrust required for the aircraft to fly. Most of the time, airplanes do not carry a full payload, therefore, it is not necessary to deliver a full 100% of thrust. Then the next step is to choose the assumed temperature that will be inputted to the FMC by simply pull a straight line until it touches the design limit line, then pull a perpendicular line downward, and that is the assumed temperature of the air inlet temperature.

These assumed temperature values are the upper limit to be inputted to the FMC. External factor such as wind speed and wet surface runway can be a consideration for the pilot to decide a lower assumed temperature than the values that have been mentioned above since it is a matter of safety issue.

An additional line is added and that is the EGT line. EGT line is obtained from the Brayton cycle calculation on the engine during takeoff, however, the value of EGT is set constant while the air inlet temperature that acted as the assumed temperature is varied. This linear line can be used similar to the design limit line, simply pull a straight line from the Takeoff Thrust axis, until it reaches the line then pull a straight line down to the value of the outside air temperature.

Traditionally, the selection of the assumed temperature is higher than the actual air temperature on the runway. Therefore, choosing an assumed temperature lower than the actual air temperature is very unlikely in the day-to-day operation and has no benefit whatsoever to improve the performance of the aircraft during takeoff.
4. Conclusion
The plotted graphic of the analysis results shows how the effect of reduced takeoff thrust lowers temperature level at each section, especially EGT. By performing reduced takeoff thrust, it also decreasing TSFC, making it more efficient. Performing reduced takeoff thrust does not necessarily mean lowering the performance of the engine, instead, it improves it by making it more effective. Therefore, inputted power is delivered base on how much power required. Finally, it is undeniably beneficial for long-term usage as engine deterioration is retarded. The plotted graphic can be used as a guide for the pilot in determining the assumed engine inlet temperature for inputting the FMC.

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