Thermodynamics 2 Turbojet Lab Report

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Abstract

This report analyses the behaviour of thrust, fuel mass flow rate and efficiency of a turbo jet engine as the throttle setting is linearly increased. The report establishes basic theory plots the observed data using least square approximations. The report concludes that for minimum specific fuel consumption, a throttle of 69% is required.

1 Introduction

This report analyses data from a turbojet wind tunnel experiment by measuring the thrust and fuel mass flow rate at different throttle settings. It examines their relationship to determine an optimal operating point where maximum thrust is produced with minimal fuel consumption.

A turbojet is a propulsion system that enables an aircraft to generate thrust. It consists of multiple thermodynamic and aerodynamic stations, as illustrated in Figure 1. The intake allows air to enter the engine. The compressor then pressurises the incoming air, increasing its potential energy. The pressurised air is subsequently heated and combusted in the combustion chamber, significantly increasing its temperature and pressure while consuming fuel. The high-energy exhaust gases then expand through the turbine, where a portion of the energy is extracted to drive the compressor. The remaining high-energy gases are further expanded through the nozzle, where their remaining potential energy is converted into kinetic energy, generating high, jet velocities. The high velocities push the jet forwards by Newton's third law.

For any system, it is crucial to identify the optimal operating conditions that maximise output work while minimising input consumption. This is particularly important for a turbojet engine, where fuel efficiency must be optimised to maximise thrust while minimising fuel usage, thereby enhancing operational efficiency in both commercial and military applications. This report presents a method for determining the optimal fuel consumption value for a given turbojet.

The report outlines the theoretical background of turbojet engine efficiency in Section 2. Section 3 discusses the results obtained from a wind tunnel experiment, where thrust and fuel mass flow rate were measured at different throttle settings. Finally, Section 4 summarises the findings and conclusions of the report.

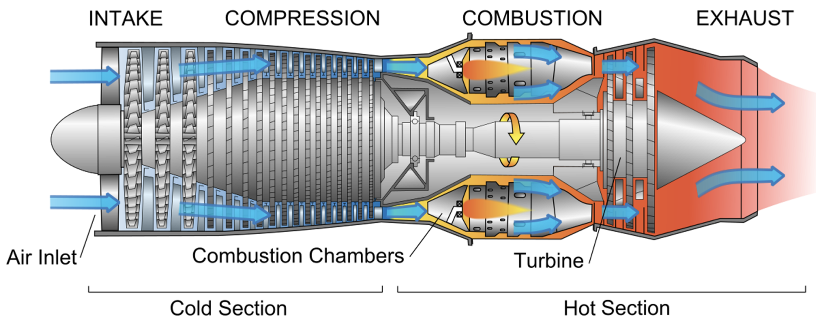

Figure 1: Diagram of a Turbojet Engine

2 Methodology and Theory

For any turbojet engine, an important parameter to consider is the thrust force, F_T [N]. A good approximation for this is found using the momentum conservation principle in a control volume (CV) given as,

$$F_T = \frac{d}{dt}\int_{CV} \rho V \, dV + \sum_i \dot{m} V_{out,i} \ - \sum_j \dot{m} V_{in,j} \tag{1}$$

where $\dot{m}$ [kgs^{-1}] is the mass flow rate, $V_{in,i}$ [ms^{-1}] is the i^{th} intake velocity, $V_{out,j}$ [ms^{-1}] is the j^{th} exit flow velocity, ρ [kgm^{-3}] is the density of fluid and t [s] is time. This equation ignores the atmospheric pressures acting into the cross-sections which is a common approximation. For this experiment, since no changes to the flow is made to the flow other than the rate of combustion, it is possible to assume steady flow, therefore the time derivative term is approximately 0 N. Also for a turbo-jet engine, there is only one intake and one exit, therefore the thrust force equation reduces to,

$$F_T = \dot{m}(V_{out} \ - V_{in}). \tag{2}$$

The experimental set-up allows us to find an accurate value of F_T $[N]$ for a given throttle percentage.

The experiment set-up also allows for the fuel mass flow rate to be measured $\dot{m}_f$ $[kgms^{-1}]$. This is the amount of transported mass per second. A high value for this means that there is a larger fuel consumption.

As the throttle percentage is increased, the fuel mass flow rate increases non-linearly. The increase in combustion rate, causing an increase in the exhaust velocity which speeds up the compressor and turbine, which increases the thrust produced. An optimal value for this can be found using Python's Numpy module.

It is possible to set up a new parameter, specific fuel consumption, sfe $[kgs^{-1}N^{-1}]$ defined as,

$$sfc := \frac{\dot{m}_f}{F_T}. \tag{3}$$

It is important to find the throttle which minimises this ratio.

The experimental data is presented as an array of values for $\dot{m}_f$, F_T, sfc and throttle percentage. Since the data is in discrete points with measurement errors, it is important to do a polynomial approximation, using least squares.

3 Results and Discussion

All data is also shown and processed using a Python script, which is accessible through this GitHub repository. Appendix, 4 shows table of all data points obtained from the wind tunnel experiment for thrust, fuel mass flow rate and throttle percentage. Throttle values ($0\% \rightarrow 16.1\%$ and $90\% \rightarrow 100\%$) are excluded to avoid plotting values while the turbojet is turning on and heating up or turning off and cooling down. In these regions, the flow is non-steady, and therefore (2) does not hold. Values for sfc are obtained using (3).

Figure 2, displays the plots of Thrust(a), fuel mass flow rate (b) and specific fuel consumption (c), respectively against throttle percentage. The plots also contain the polynomial approximation where the polynomial degrees are 1, 2 and 2 respectively.

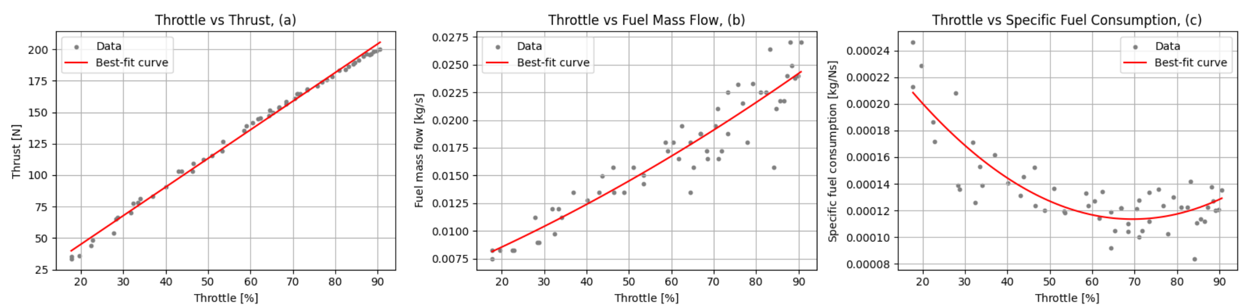

Figure 2: Graphs obtained from the wind tunnel experiment and computed using python. (a) Thrust[N] vs Throttle[%], (b) Fuel-mass-flow-rate[kgs^{-1}] vs Throttle[%]
, (c) specific-fuel-consumption[$\text{kgN}^{-1}\text{s}^{-1}$] vs throttle[%]

It can be see that the relationship between throttle and thrust is linear. The relationship between the throttle and fuel mass flow rate is a convex quadratic, causing the throttle, sfc, graph to also be convex. This convex form, shows that there exists a unique throttle percentage which minimises the specific fuel consumption. The optimal throttle percentage is found to be 69%, providing a thrust of $159.2N$, where the specific fuel consumption is 11.3×10^{-5}.

The medium-high percentage throttle for optimal operation region of the turbojet means that the aircraft will the most efficient at higher velocities therefore allowing less fuel consumption at the cruising speed. However, this also means that at take off and landing, there is a high fuel consumption.

4 Conclusion

This report has analysed the behaviour of a turbojet engine by investigating the relationship between throttle percentage, thrust, and fuel mass flow rate. By applying the momentum conservation principle, an expression for thrust was derived, and specific fuel consumption (sfc) was introduced as a key metric to evaluate engine efficiency.

Experimental data collected from a wind tunnel test was processed using least squares polynomial approximations, revealing that the relationship between throttle and thrust is linear, whereas the relationship between throttle and fuel mass flow rate is quadratic. As a result, the sfe graph exhibited a convex shape, indicating the existence of an optimal throttle setting that minimises fuel consumption while maintaining a high thrust output.

The findings conclude that the most fuel-efficient throttle is 69%, highlighting the efficiency of such turbojet in high speed scenarios.

A Data Table for the Wind Tunnel Experiment

Table 1: Throttle, Thrust, and Fuel Mass Flow Rate

Throttle [%]	**Thrust [N]**	**Fuel Mass Flow Rate [kg/s]**
16.9	27.9	0.010498
17.7	33.5	0.008249
17.7	35.2	0.007500
19.6	36.1	0.008249
22.4	44.2	0.008248
22.8	48.1	0.008249
27.8	54.1	0.011254
28.3	64.9	0.008996
28.7	66.1	0.008999
31.8	70.2	0.011998
32.4	77.3	0.009749
33.4	78.5	0.011999
34.0	81.0	0.011248
36.9	83.4	0.013498
40.1	90.5	0.012747
43.0	102.9	0.013505
43.7	103.2	0.014993
46.3	103.2	0.015749
46.5	109.3	0.013498
48.8	112.2	0.013499
51.0	115.5	0.015748
53.4	119.5	0.014249
53.5	126.7	0.014998
58.5	135.2	0.017998
59.1	139.4	0.017248
60.5	141.8	0.017999
61.7	144.5	0.016499
62.4	145.3	0.019495
64.4	147.4	0.013500
64.5	151.4	0.017998
65.3	149.9	0.015744
66.8	153.6	0.018748
68.4	156.6	0.017249
68.5	158.7	0.016498
70.4	161.1	0.019499

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Throttle [%]	Thrust [N]	Fuel Mass Flow Rate [kg/s]
71.1	164.6	0.016486
71.0	164.9	0.021012
71.8	164.9	0.017249
73.4	167.8	0.018746
73.4	168.4	0.022506
75.7	170.9	0.023239
76.8	174.0	0.021485
77.9	175.7	0.017978
79.2	178.6	0.023253
81.0	183.5	0.022512
82.4	183.9	0.022512
83.2	186.4	0.026395
84.2	188.2	0.015754
84.7	189.5	0.020997
85.6	191.3	0.021751
86.6	194.3	0.021751
87.3	196.4	0.023999
88.1	195.7	0.027000
88.5	196.1	0.024932
89.1	198.0	0.023792
89.8	199.1	0.024000
90.6	199.8	0.027000