Warsaw University of Technology

FACULTY OF
POWER AND AERONAUTICAL ENGINEERING

Institute of Heat Engineering

in the field of study Aerospace Engineering
and specialisation Aircraft Propulsion

Half-semester Project
“Simplified simulation of bypass engine in Cantera environment.”

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Contents

Chapter 1

Introduction

1.1. Cantera

Cantera is an open-source suite of tools for problems involving chemical kinetics, thermodynamics, and transport processes. Cantera automates the chemical kinetic, thermodynamic, and transport calculations so that the users can efficiently incorporate detailed chemical thermo-kinetics and transport models into their calculations. Cantera utilizes object-oriented concepts for robust yet flexible phase models, and algorithms are generalized so that users can explore different phase models with minimal changes to their overall code.In this project, Cantera is used to model a simple flow through a bypass jet engine. Fuel used in this model is C3H8. The reason for that is because Cantera doesn't model the combustion of a liquid fuel. That is why in this project engine fuel is in a gas state.

1.2. Turbofan Engine

The turbofan is a type of airbreathing jet engine that is widely used in aircraft propulsion. The word "turbofan" is a portmanteau of "turbine" and "fan": the turbo portion refers to a gas turbine engine which achieves mechanical energy from combustion, and the fan, a ducted fan that uses the mechanical energy from the gas turbine to accelerate air rearwards. Thus, whereas all the air taken in by a turbojet passes through the turbine (through the combustion chamber), in a turbofan some of that air bypasses the turbine. A turbofan thus can be thought of as a turbojet being used to drive a ducted fan, with both of these contributing to the thrust.

The ratio of the mass-flow of air bypassing the engine core divided by the mass-flow of air passing through the core is referred to as the bypass ratio. The engine produces thrust through a combination of these two portions working together; engines that use more jet thrust relative to fan thrust are known as low-bypass turbofans, conversely those that have considerably more fan thrust than jet thrust are known as high-bypass. Most commercial aviation jet engines in use today are of the high-bypass type, and most modern military fighter engines are low-bypass. Afterburners are not used on high-bypass turbofan engines but may be used on either low-bypass turbofan or turbojet engines.

Turbofans were invented to circumvent an awkward feature of turbojets, which was that they were inefficient for subsonic flight. To raise the efficiency of a turbojet, the obvious approach would be to increase the burner temperature, to give better Carnot efficiency and fit larger compressors and nozzles. However, while that does increase thrust somewhat, the exhaust jet leaves the engine with even higher velocity, which at subsonic flight speeds, takes most of the extra energy with it, wasting fuel.

Instead, a turbofan can be thought of as a turbojet being used to drive a ducted fan, with both of those contributing to the thrust. Whereas all the air taken in by a turbojet passes through the turbine (through the combustion chamber), in a turbofan some of that air bypasses the turbine.

Because the turbine has to additionally drive the fan, the turbine is larger and has larger pressure and temperature drops, and so the nozzles are smaller. This means that the exhaust velocity of the core is reduced. The fan also has lower exhaust velocity, giving much more thrust per unit energy (lower specific thrust). The overall effective exhaust velocity of the two exhaust jets can be made closer to a normal subsonic aircraft's flight speed. In effect, a turbofan emits a large amount of air more slowly, whereas a turbojet emits a smaller amount of air quickly, which is a far less efficient way to generate the same thrust (see efficiency section below).

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Modern turbofans have either a large single-stage fan or a smaller fan with several stages. An early configuration combined a low-pressure turbine and fan in a single rear-mounted unit.

Chapter 2

Review of the literature.

This project is based on knowledge form three main sources. First of which are Cantera tutorials and examples. Tutorials helped me understand the propeties of Cantera. It's advantages, disadvantages and functions that helped with thermodynamic propeties of a gas. Cantera code examples helped with making reactors for mixing gas and combustion. "Mix1.py" has a code for mixing gases and was modified to get a third gas out of two. "reactor1.py" has a code for simple combustion and in this project was modified so a gas can reach stable state before turbine. Another source are internet python tutorials that helped me understand this programming launguage and propeties of numpy and matplotlib packages. Last source is knowledge from "Turbine Engine" course in Institute of Heat Engineering in witch I learned thermodynamic equations used in inlet, outlet and fan, compressor and turbine.

Chapter 3

Model description.

The program uses input data to calculate output propeties of a stream of gas and the engine propeties like temperature before turbine, thrust, exhaust velocity and efficiencies. Input data contains information about atmosphere in which the engine is located, the Mach number and the propeties of the engine itself. After that is the “core”.

In the beginning the stream of gas is created using Cantera enviroment. This gas goes through fan, gets splitted in two and goes through compressor. The gas properties are calculated based on thermodynamics equations. Next the stream of fuel is created. Using Cantera reactor two streams are mixed together. Program assumes that the two stream are fully mixed before combustion begins. And combustion is also modelled with different Cantera reactor. Before going through turbine the combustion advances to steady state. Transition through turbine is modelled with thermodynamic equations. Before nozzle the is often found in bypass engines mixer. This mixes two streams that were splitted before compressor and uses the same reactor used in mixing fuel with air. This uniform gas goes through nozzle and its final properties are calculated using approximated nozzle equations. Exhaust gas by using Cantera gives us every data to calculate efficiencies and properties of the engine.

This “core” is run several times in the program. It is to gather data from multiple cases and use this data to find optimal parameters and to make plots showing how engine operates in different situations.

3.1. Data set.

One set of input data is used in all simulations. Three variables have been chosen to show the results of this program. Input data contains:

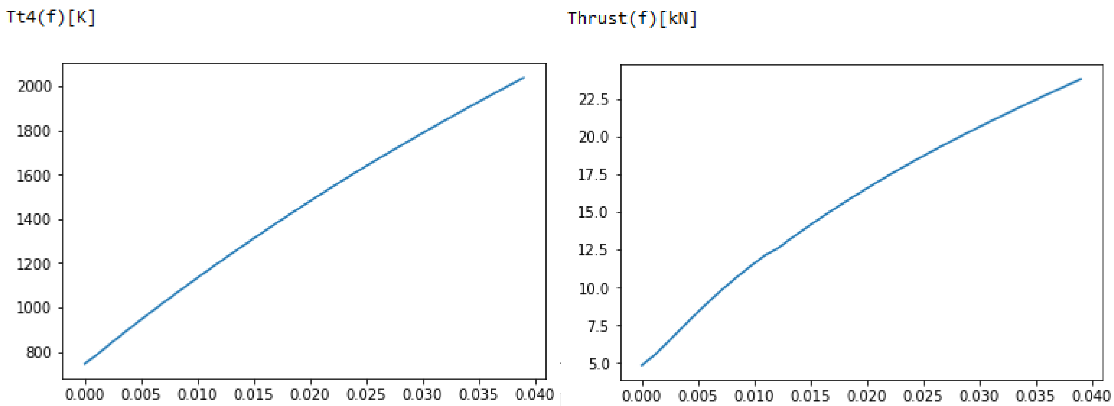
Temperature at sea level = 15 Degrees Celsius
Intake compress = 0,98
Intake Diameter = 0,5 m
Stationary mass flow rate = 50 kg/s
Bypass ratio = 1,5
Fan compress = 3,5
Fan efficiency = 0,97
Compressor compress = 15
Compressor efficiency = 0,92
vc=0,02 (adiabatic efficiency)
Turbine mechanical efficiency = 0,99
Turbine thermal efficiency = 0,95
Nozzle efficiency - On=0,95
Combustion Chamber compress = 0,98
Fuel temperature = 15 Degrees Celsius
Air = O2:0.21, N2:0.78, AR:0.01
Fuel = C3H8
Variables:
f = (0;0,04)
H = (0 m;11000 m)
M = (0;1)

Chapter 4

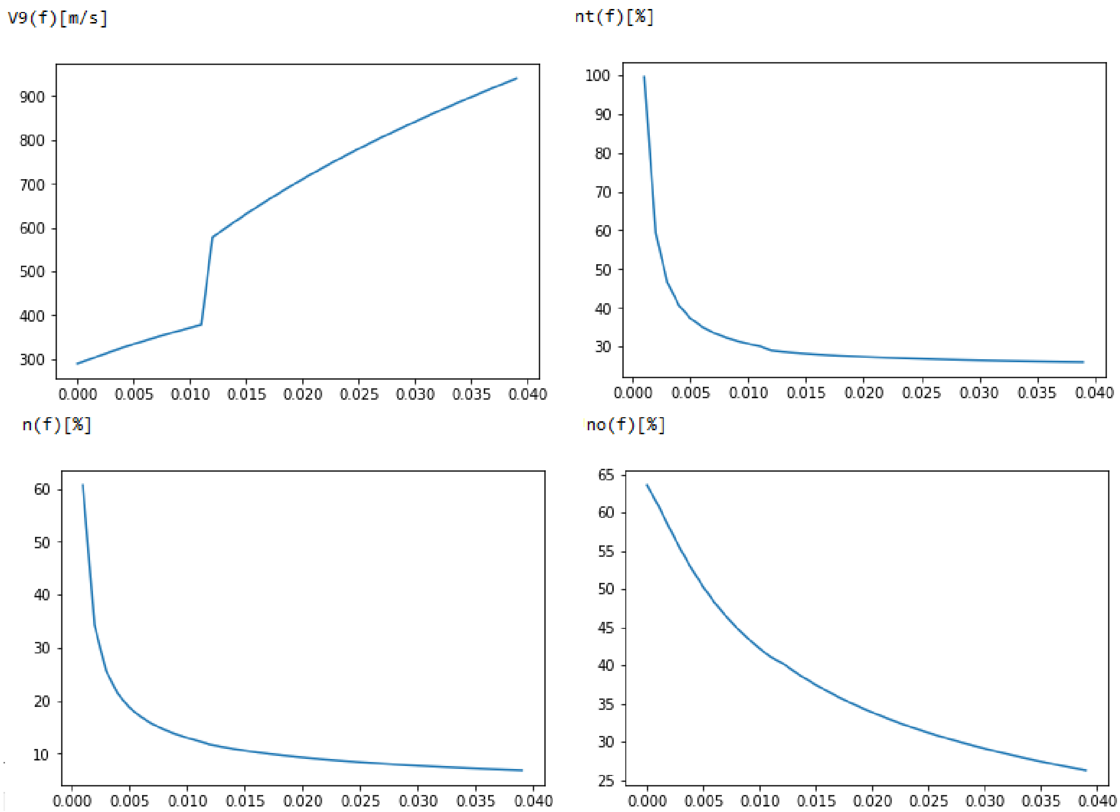
Results review.

4.1. Variable f (fuel to air ratio).

Mach number = 0,5 (constant)
Altitude = 11000m (constant)



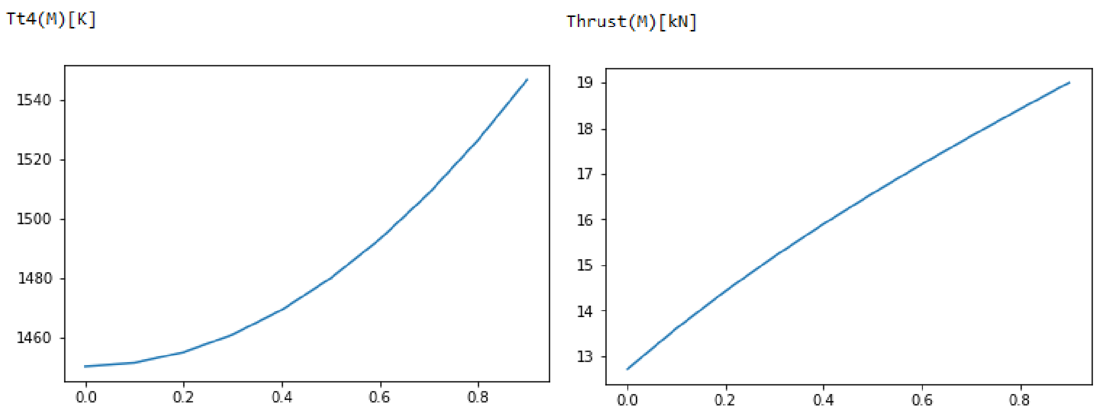
In the plots above we can see how temperature before turbine (Tt4) and engine thrust changes under the influence of fuel to air ratio. We can see that more fuel engine gains more thrust, but temperature is also rising. With the upper limit of 1700 degrees Kelvin we can achieve about 20 kN of thrust.



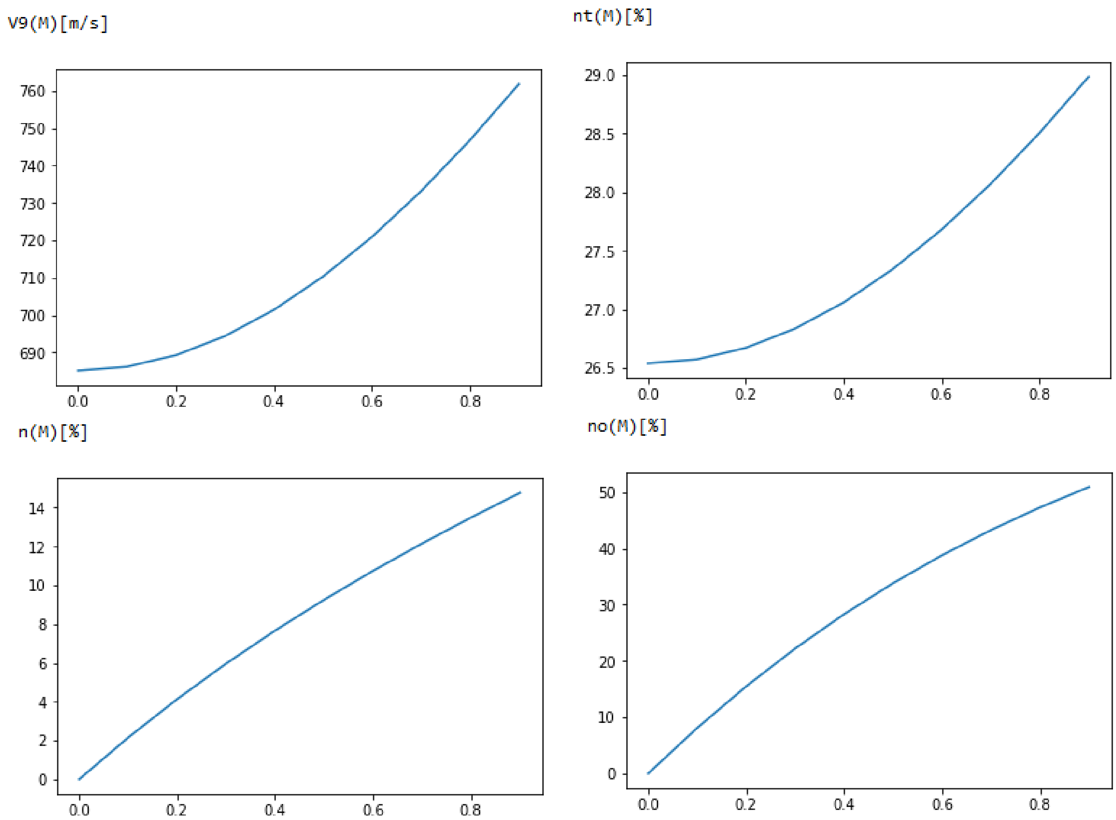
In the plots above we can see that the exhaust gas velocity (V9) has a sudden drop. This means that nozzle stopped working properly and cannot change the gas presuure to the ambient pressure. This means that below f=0,012 this model cannoc accurately predith the outcome. We can see that below that point the thermal efficiency (nt) is rising rapidly below that point, witch is not realistic. Overall efficiency of this engine (n) is about 11 percent in working conditions.

4.2. Variable M (Mach number).

f = 0,02 (constant)
Altitude = 11000m (constant)



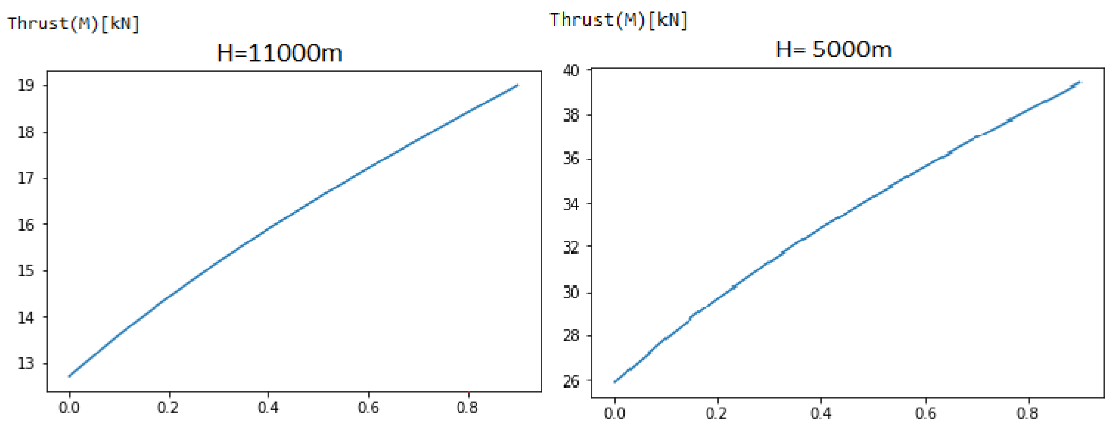
Plots above shows that with increasing Mach number temperature before turbine increases slightly and the thrust increases significantly.

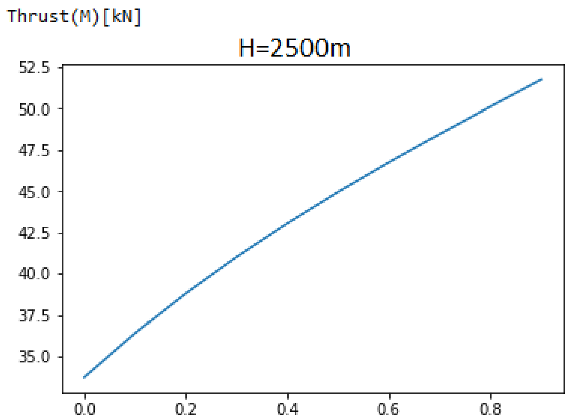


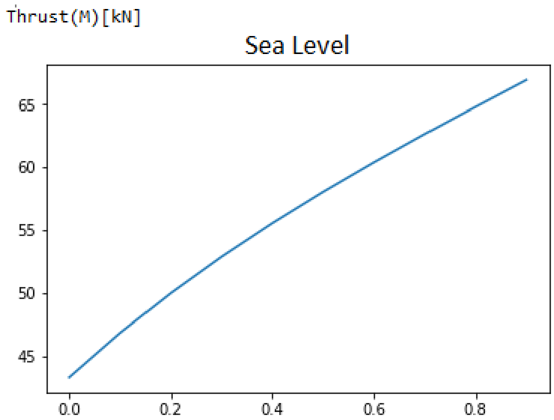
With the plots above we can see that exhaust velocity rises with Mach number. Also every efficiency of the engine rises with Mach number. Thermal efficiency from 26.5 percent to 29 percent and propulsive efficiency rises from 0 percent to around 52 percent.

4.3. Variable Mach number and Altitude.

f = 0,02 (constant)
Altitude = 11000m, 5000m, 2500m, 0m







In the four plots above and on the previous page we can see a significant increase in thrust the lower the altitude. At sea level (Altitude = 0m) we have the highest thrust, reaching about 65 kN at Mach 0,8. At every altitude the trust increases with increasing Mach number and the increace is in a same rate.

4.4. Example of the exhaust gas.

```
gri30:

       temperature          627.967  K
          pressure           166924  Pa
           density         0.923873  kg/m^3
  mean mol. weight          28.8978  amu

                          1 kg             1 kmol
                       -----------      ------------
          enthalpy          -43925       -1.269e+06     J
   internal energy      -2.246e+05       -6.491e+06     J
           entropy          7539.7        2.179e+05     J/K
    Gibbs function     -4.7786e+06       -1.381e+08     J
 heat capacity c_p          1070.7        3.094e+04     J/K
 heat capacity c_v          782.97        2.263e+04     J/K

                           X                 Y          Chem. Pot. / RT
                     -------------     ------------     ------------
  O2               0.181804          0.201314          -26.6752
  H2O             0.0208029         0.0129689          -73.3061
  CO2             0.0156027         0.0237622          -105.821
   N2              0.771881          0.748262          -23.5679
   AR            0.00989598         0.0136801          -23.2756
```

Here we can see increased amount of CO2 and H2O, witch means that combustion of C3H8 indeed took place and the exhaust gas is no longer air. Pressure is equal to the ambient pressure witch means that nozzle worked correctly and the temperature is way higher that inlet temperature.

Chapter 5

Summary

This simple model can give us estimated values that this engine needs to have to work properly. For example at f >=0,03 The temperatures are too high for turbine (above 1700K) and at f<=0,011 the nozzle stops working properly, the nominal compress become too high for nozzle to handle and as a result gives us results. The efficiencies are similar to what a real engine would produce.

The fact that the composition of the exhaust gas and the results being reasonable to what we should expect from a turbofan engine means that this program can be used to predict in some approximation the properties of this type jet engine. The fact that this model does not take into account all possible factors mean that this should be used only in fast and approximate calculations and not for exact and detailed information about a real turbofan engine.

List of Sources.

- https://cantera.org/tutorials/python-tutorial.html
- https://cantera.org/examples/python/reactors/mix1.py.html
- https://cantera.org/examples/python/reactors/reactor1.py.html
- https://cantera.org/documentation/docs-2.4/sphinx/html/cython/thermo.html
- https://matplotlib.org/
- https://docs.scipy.org/doc/numpy-1.15.0/user/basics.creation.html
- http://cs231n.github.io/python-numpy-tutorial/
- https://treyhunner.com/2016/04/how-to-loop-with-indexes-in-python/
- https://en.wikipedia.org/wiki/Turbofan