Design of Thermal Systems
Professor Weisensee
DHW4

Natural Gas Car Engine

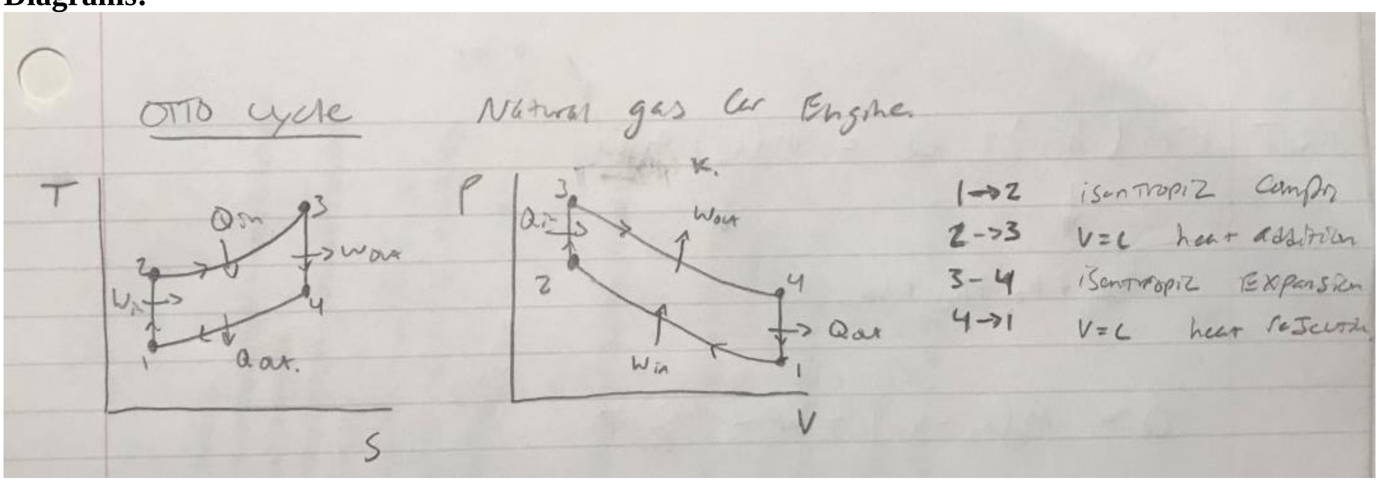
Assumptions/ Boundary Conditions:

- Compression ratio is 12:1, so the volume at state 2 is 12 time bigger than state 1, which allows us to solve for T2 to get enthalpies from tables [3].
- Reversible/Adiabatic process, which allows us to use polytropic relations to solve for temperatures and compression ratio [8].
- Assume max operating temperature is 900 K because when looking up materials used for a car engine, aluminums melting temperature was about 933 K, so I chose a temperature under that because aluminum seemed to have one of the lower melting points [7].
- The power output is 74.57 kW (100 hp) for car engine, this was given.
- Methane is in liquid state, so we need to include latent heat in the energy balance, also given.[8]
- State 1 is at STP, so temperature is 298 K and pressure is 100kPa. This can be assumed if you have the intake of air from the outside.
- Assume theoretical air is at 130%, I chose this because in the problem statement it said that the theoretical air needed to be 130% percent or greater [8].
- The latent heat of methane is 8.19 kJ/mol. I need this value when finding the amount of heat generated in the combustion [5].

Discussion of Maximum Temperature and Environmental Impact:

When researching maximum temperatures, I found that the melting temperature of aluminum, which is in a car engine, is about 933K. What I was not so sure about was the fact that also found online that the maximum operating temperature of a car engine was about 400K. But I did not use this value in my design homework because I was calculating a temperature at state 2 to be 800 K, so I thought that there was no way the max operating temperature would be that low. But the material used in the engine still seemed to be the limiting factor because the temperature which NOx starts to form is around 2800 ˚F (~1800 K) [4]. The two most common NOx gases are nitrogen dioxide and nitric oxide. When the NOx is released into the air it will break apart due to the UV rays in sunlight. This break down causes O_3 to form in the atmosphere, which traps heat in the atmosphere causing an increase in temperature. Another negative effect NOx has on the environment is when it starts to rain, the NOx mixes with the air and forms acidic rain. Lastly, when NOx gets into the oceans it causes an increase in algae grow [6].

Diagrams:



Combustion Reaction:

Stoichiometric Equation:

$$1\, CH_4 + 2\,(O_2 + 3.76N_2) \rightarrow 1\, CO_2 + 2H_2O + 7.52N_2$$

Non-Stoichiometric Equation:

$$1\, CH_4 + 2.6\,(O_2 + 3.76N_2) \rightarrow 1\, CO_2 + 2H_2O + 11.52N_2 + 0.6O_2$$

Calculations:

The percent theoretical air is the amount of air you have over the amount of air needed in a reaction, as shown below:

$$\%\, Theoretical\ air = \frac{N_{air}}{N_{air,s}}$$

And solving for the AF ratio you have:

$$AF = \frac{m_{air}}{m_{fuel}} = \frac{n * m_{air}}{n * \ m_{fuel}} = \frac{2.6 * 4.76 * 60}{16.04} = 46.3$$

Before solving for the heat generated first the temperature at state 2 needs to be calculated. From the assumption that the process is adiabatic and reversible the polytropic relation below can be used.

$$T_2 = \ T_1 * {r_v}^{k-1}$$

Since we assumed that state 1 is just air coming in from outside, we know the temperature (T1) is around 298 K. Also, I assumed that the compression ratio is 12:1. From this T2 = 800K. (note; it was actually slightly great than this, but it made the table A.9 easier).

Now if assuming a theoretical are of 130% the amount of actual air (N_{air}) can be solved for to get:

$$N_{air} = \%\, Theoretical\ ait * \ N_{air,s} = 1.3 * 2\ mol = 2.6\ moles$$

Now since the amount of air is known, the amount of excess oxygen and the amount of nitrogen can be found in the non-stoichiometric equation. With this information the amount of heat generated in this reaction can be solved for using an energy balance from state 2 to state 3:

$$Q + \sum(n_i h_i)_{reactants} = \sum\left(n_j h_j\right)_{products}$$

So, when solving for Q you get:

$$Q = \sum(n_i h_i)_{products} - \sum\left(n_j h_j\right)_{reactants}$$

From this I looked up the enthalpies of the products at 900 K (state 3) and 800 K (state 2) and subtracted them. This was because the enthalpies that I had in table A.9 where from a reference temperature. I also kept the latent heat out of the heat generated because the latent heat was only changing the methane from liquid to gas, not adding additional heat to the system. From this I got that:

$$Q = n_{CO2} * \left(h_p - h_r\right) + n_{H20} * \left(h_p - h_r\right) + n_{O2} * \left(h_p - h_r\right) + n_{N2} * \left(h_p - h_r\right)$$

$$Q = (1\ kmol)(28.03 - 22.8)\frac{MJ}{kmol} + (2\ kmol)(21.937 - 18.002)\frac{MJ}{kmol}$$
$$+ (0.6\ kmol)(19.241 - 15.836)\frac{MJ}{kmol}$$
$$+ (11.28 kmol)(18.223 - 15.046)\frac{MJ}{kmol}$$

Q = 50.98 MJ

Once the heat generated was found, the mass flow rate could be solved for assuming all the heat is transferred to work. So, you have:

$$\dot{m} = \frac{\dot{w}}{Q}$$

The only difference is now the latent heat has to be added to the Q in order to get the actual mass flow needed to produce at least 74.57 kW (100 hp) to the engine and we will keep the Q in MJ/kmol. With the latent heat of methane being 8.19 kJ/mol, and converting that to 8.19 MJ/kmol, we have that:

$$Q = \sum (h_i)_{products} - \sum (h_j)_{reactants} - h_l$$

$$Q = (28.03 - 22.8)\frac{MJ}{kmol} + (21.937 - 18.002)\frac{MJ}{kmol} + (19.241 - 15.836)\frac{MJ}{kmol} + (18.223 - 15.046)\frac{MJ}{kmol} - 8.19\ MJ/kmol$$

Leaving Q = 7.557 MJ/kmol. Now we can calculate the mass flow of the fuel to be

$$\dot{m} = \frac{74.57\ kW}{7.57\ MJ/kmol} = 0.0099\frac{kmol}{s}$$

Knowing that the molar mass of methane is 16.04 g/mol and doing dimensional analysis will lead to the mass flow rate being:

$$\dot{m} = 0.0099\frac{kmol}{s} * \frac{16.04\ kg}{1\ kmol} = 0.1588\frac{kg}{s}$$

Final Answers:

Mass Flow Rate: 0.1588 kg/s
Percent Theoretical Air: 130%
AF = 46.3:1
Heat Generated: 44.65 MJ
Compression Ratio: 12:1

Discussion of Final Answers:

Looking at my answers, the compression ratio should make sense because I assumed one for my calculations based on online sources [3]. For the percent theoretical air by assuming it is 130%, it meets the requirement set in the design homework. But by looking at the air-fuel ratio from my answer I think it is not the best representation because from x-engineers they say the air-fuel ratio should be about 17:1[9] Next looking at the mass flow rate, I calculated it to be 0.1588 kg/s. This value is a lot higher than what I have seen online, although what I did find online was from experiment where they varied the flow rate, all the flow rates were lower than the one calculated in this homework. The highest mass flow rate used in the experiment on

CNG(compressed natural gas) fuel did start out at 0.8 kg/hr. Lastly, the mass flow rate calculated in the design homework was 0.1588 kg/s. I was not able to find a value for mass flow of methane, but comparing it to the mass flow rate of gasoline(C_4H_{10} and C_8H_{18}) has a mass flow ratio of about 0.1024 kg/s[11] which is a lot closer than I thought it would be.

References:

[1]
http://www.chemistry.pomona.edu/chemistry/periodic_table/Elements/Aluminum/aluminum.htm

[2] https://www.engineeringtoolbox.com/methane-d_1420.html

[3]
https://www.researchgate.net/post/What_is_the_maximum_compression_ratio_achieved_so_far_for_a_compression_ignition_engine

[4]
https://www.google.com/search?q=temperature+NOx+starts+to+form&oq=temperature+NOx+starts+to+form&aqs=chrome..69i57j33.7973j1j9&sourceid=chrome&ie=UTF-8

[5]
https://www.engineeringtoolbox.com/methane-d_1420.html

[6]
https://www.thoughtco.com/what-is-nitrogen-oxide-pollution-1204135

[7]
http://www.chemistry.pomona.edu/chemistry/periodic_table/Elements/Aluminum/aluminum.htm

[8] Design Homework 4

[9] https://x-engineer.org/automotive-engineering/internal-combustion-engines/performance/air-fuel-ratio-lambda-engine-performance/

[10] http://www.sphinxsai.com/2017/ch_vol10_no7/1/(228-240)V10N7CT.pdf

[11]
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