MCG 5344 Final project: Gas Turbine System Evaluations

As a gas turbine engineer, you are tasked to design a gas turbine system. Based on the information given below, generate a well-presented report that addresses following design parameters.

1. The gas turbine is designed to meet NOx emission regulation as set by Environment and Climate Change Canada (ECCC). Assume the gas turbine that you are designing is a frame engine with more than 70 MW output for base-load applications. https://www.canada.ca/en/environment-climate-change/services/canadian-environmental-protection-act-registry/guidelines-objectives-codes-practice/reduction-nitrogen-oxide-combustion-turbines-guidelines.html#_Toc393204295 (Table 2). Note that the NOx upper limit set by ECCC is in ppmv that's corrected to 15% O2 (dry).

   The following chart is the best emission performance that can be achieved for complete burning of natural gas (assume 100% methane). You have learnt from MCG5344 that the best emission performance can be achieved when fuel and air are perfectly pre-mixed. Assume that you can extrapolate the linear correlation between log([NOx]) and Flame Temperature presented below.

   As the NOx limit in regulation is corrected to 15% O2 (dry), your first task is to correct the correlation between NOx and Flame Temperature shown below to 15% O2. Hint: Use the flame temperature calculator that you have used in the second assignment to map flame temperatures to equivalence ratios of the methane/air combustion: https://elearning.cerfacs.fr/combustion/tools/adiabaticflametemperature/index.php. Once the equivalence ratio is determined for a flame temperature, you can assume complete reaction between methane and air so that you can determine the composition of combustion products. Use the definition of [NOx]_15 to convert [NOx] in ppmv to [NOx]_15.

$$[NOx]\_15\ (ppmv) = [NOx](ppmv)\,\frac{20.95\% - 15\%}{20.95\% - [O2]\_dry}$$

   where 20.95% is the oxygen content in standard air and $[O2]\_dry$ is the oxygen content in % in dry combustion exhaust, meaning that the water as a product for combusting methane has been removed before measuring oxygen content.

   Note: For this part of calculations, assume the gas turbine has a pressure ratio of 20, and efficiency is at 90% for both compressor and turbine. Be sure to update both pressure and initial temperature when you use the adiabatic flame temperature calculator.

   a) Make a plot of [NOx]_15 vs. Flame Temperature.
   b) What's the theoretical flame temperature limit for meeting the emission regulation as set forth by ECCC?
   c) In practical, perfect mixing cannot be achieved either due to limitations in mixing length or due to combustion dynamics. To make sure that the emission standard can be met, what's the flame temperature if we choose a more conservative emission target of [NOx]_15 = 10 ppmv?

[1] Boyce, P. M, 2002, "Gas turbine engineering handbook", Gulf Professional Publishing, 2nd edition, Huston, Texas, USA.

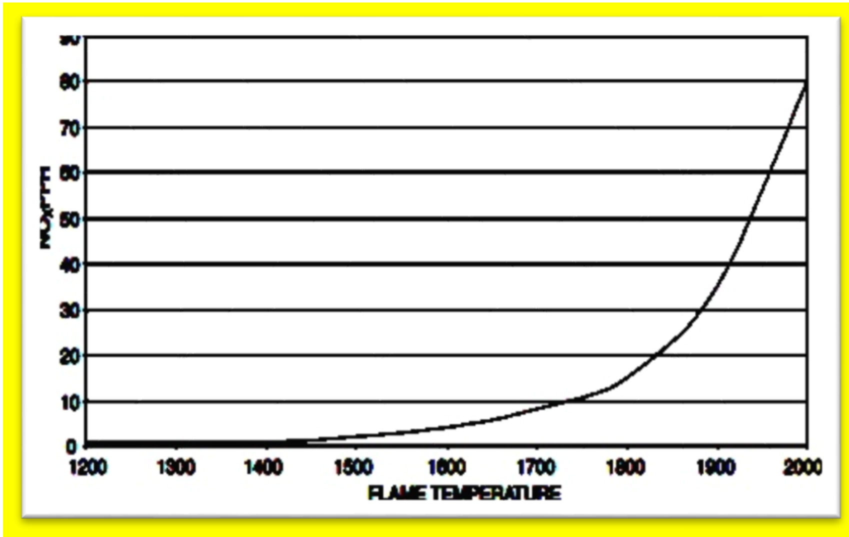

Figure 1. Adiabatic flame temperature in K versus NOx emissions [1]

2. With the flame temperature determined from 1(c) and assuming that the flame temperature is the same as TIT (turbine inlet temperature), determine design pressure ratios for following scenarios. Note 2: an iterative process is needed as a change in PR/compressor efficiency results in a different pair of pressure/initial temperature for the combustion process, consequently the adiabatic flame temperature.
   (a) Best engine efficiency when both compressor and turbine have 90% efficiency? What's engine efficiency as calculated using non-ideal Brayton cycle?
   (b) Largest engine power density when both compressor and turbine have 90% efficiency? What's engine efficiency as calculated using non-ideal Brayton cycle?
   (c) Best engine efficiency when both compressor and turbine have 85% efficiency? What's engine efficiency as calculated using non-ideal Brayton cycle?
   (d) Largest engine power density when both compressor and turbine have 85% efficiency? What's engine efficiency as calculated using non-ideal Brayton cycle?
3. Now consider the use of cooling air for hot-gas path components, including combustor, transition piece and turbine blades and stators. Assume the max. flame temperature is set by 1(c) and assume 70% of compressor discharge air is used for combustion and 30% for cooling.
   (a) What's the new TIT temperature? Hint: combustion products at flame temperature mixes with cooling air at compressor discharge temperature before entering turbine; therefore you can calculate the new TIT temperature. Here assume compressors and turbines are of 90% efficiency and the same PR as determined in 2(a).
   (b) In fact, the lowered TIT as a result of mixing with cooling air in 3(a) results in a lowered PR for best efficiency. Again, assume 90% efficient compressors and turbines, determine the PR for best engine efficiency and the corresponding TIT. Hint: this may require a few iterations to get the proper PR or TIT.
   (c) What's the best engine efficiency under conditions 3(b)? What's efficiency deficiency in comparison to 2(a) as a result of using 30% compressor discharge air for cooling therefore lowering the TIT.

[1] Boyce, P. M, 2002, "Gas turbine engineering handbook", Gulf Professional Publishing, 2nd edition, Huston, Texas, USA.

(d) Repeat steps 3(a) to 3(c) by assuming 85% efficient compressors and turbines. Compare best engine efficiency with cooling to that of 2(c) and report efficiency gap as a result of engine cooling air.

4. The PR calculations in steps 2-3 were assuming that the gas turbine is to be run in the simple-cycle mode. Now assume the gas turbine was designed to run in the combined-cycle mode with a bottoming steam turbine. To avoid using expensive super alloys for exhaust duct and stream turbine, the exhaust gas temperature is limited to 655C. Practically, the gas turbine exhaust temperature is expected to be between 450 C and 650C. Assuming 90% efficient compressors and turbines, and assume TIT is the same as that was determined in 3(b). What's the PR range of the gas turbine engine in combined cycle so that the engine exhaust is between 450C and 650C (assuming engine exhaust is fully expanded to 1 atm).
5. Again, assume 90% efficient compressors and turbine. By setting the gas turbine exhaust temperature to be 550C and TIT as determined in 3(b)
   (a) Determine PR of the gas turbine engine and compressor discharge temperature
   (b) Assume ignition delay is insensitive to pressure change, use proper charts from the course notes to determine the mixing length of a natural gas nozzle.

[1] Boyce, P. M, 2002, "Gas turbine engineering handbook", Gulf Professional Publishing, 2nd edition, Huston, Texas, USA.