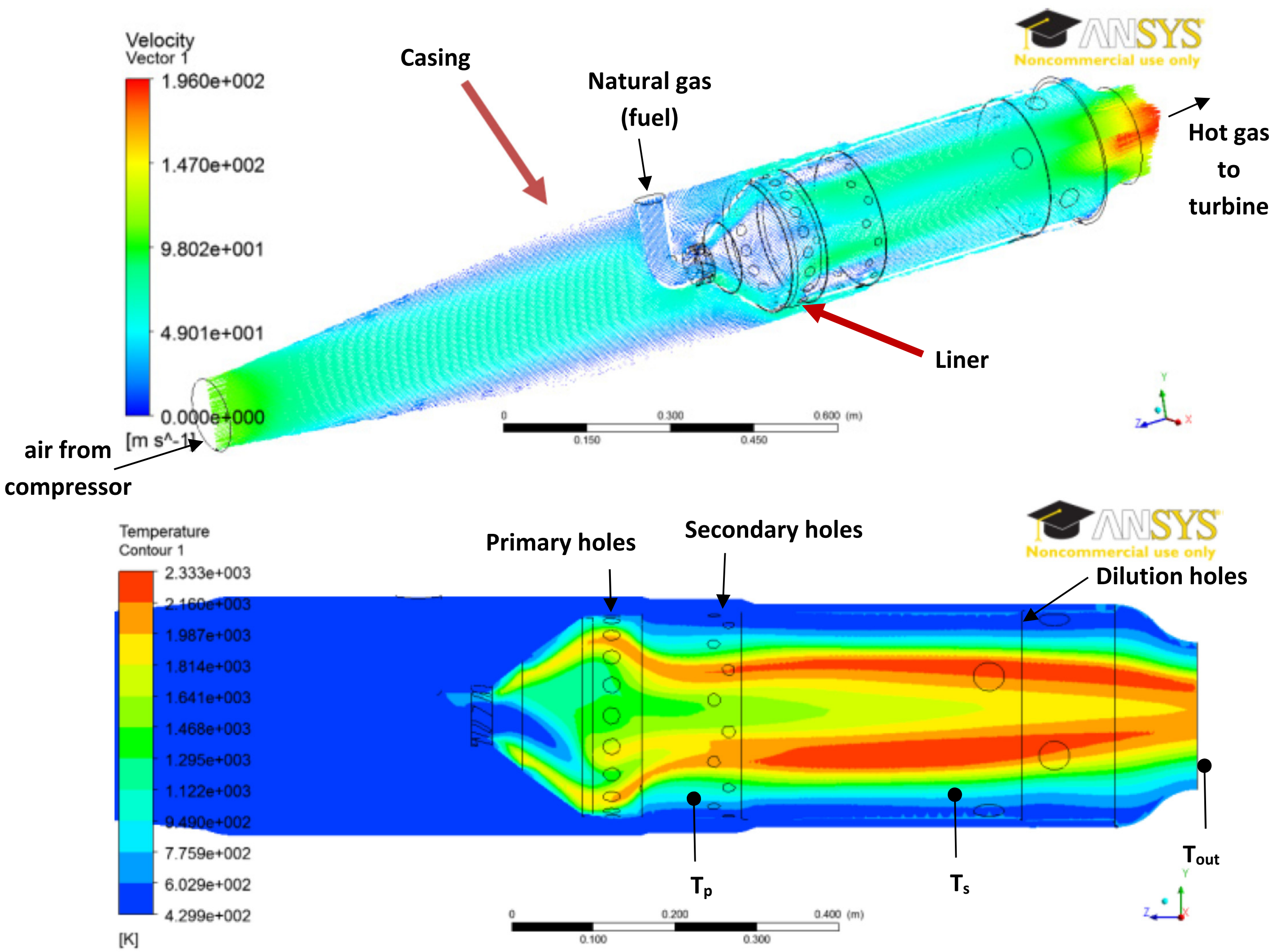
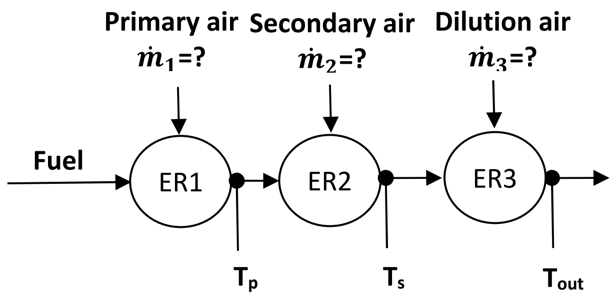
Project #1: Preliminary design of a gas turbine combustor

Part I:

The following figure shows the combustion chamber (combustor) of a gas turbine.



Fuel which is Natural gas, composed of *90%* (volumetric) methane (CH_4) and *10%* ethane (C_2H_6), i.e. 1 mole fuel = 0.9 CH_4 +0.1 C_2H_6 , enters the liner at *0.07 kg/s*. It is desired to design the total air flow rate from the compressor to the casing and the fraction of this flow which enters the liner through each rows of holes, primary, secondary, and dilution holes. The total flow rate is calculated such that the outlet temperature equals a specific value (T_{out}=TIT). TIT is chosen as the maximum temperature tolerated by the turbine blades. Here TIT=*1300 K*. The fraction of air entering through primary holes and secondary holes is computed knowing the desired value of temperatures T_p and T_s, respectively. T_p is chosen as *1700 K* based on pollutant emission considerations and T_s is assumed to be *1600 K*.



Assume that the flow is at equilibrium state at sections T_p, T_s, and T_{out}. The inlet air and fuel temperatures are *460 K* and 430 K, respectively. The combustor pressure is 10 bar. Determine the total air flow rate and the fractions mentioned above:

Problem 1: Assuming complete combustion.

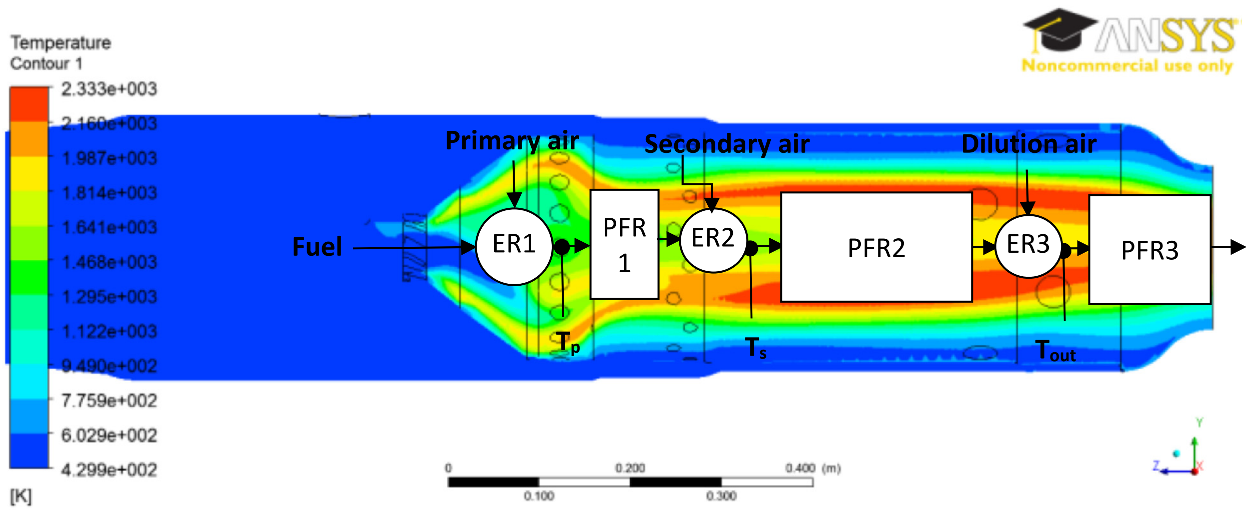
Problem 2: Assuming combustion product to be compose of 10 species N_2, N, O_2, O, H_2, H, OH, H_2O, CO, and CO_2 which are in chemical equilibrium at each section as:

$$N_2 \leftrightarrow 2N$$
$$O_2 \leftrightarrow 2O$$
$$H_2 \leftrightarrow 2H$$
$$O_2 + H_2 \leftrightarrow 2OH$$
$$O_2 + 2CO \leftrightarrow 2CO_2$$
$$O_2 + 2H_2O \leftrightarrow 4OH$$

Note: the proper choice of 3 control volumes needed can simplify the amount of coding required.

Part II:

In this part, it is intended to determine the combustor NOx emission. NOx is mainly composed of NO species for conventional combustors. This species cannot be considered in chemical equilibrium and have to be determined using chemical kinetics. For this purpose, the liner is decomposed into several reactors (control volumes) as follows:



It is assumed that NO mole fraction is so small that does not affect the composition (mole fraction) of other species. Therefore, each circle in the figure represents an equilibrium reactor (ER) with equilibrium composition at the outlet which is obtained in part I. It means the temperature and composition of 10 species N_2, N, O_2, O, H_2, H, OH, H_2O, CO, and CO_2 at the inlet of each plug-flow reactor (PFR) is assumed to be exactly the same as the ones obtained in part I (problem2). The PFRs are added to this model to calculate the amount of NO formed in each zone of the combustor. The temperature and composition of the 10 species (all species except NO) in each PFR is assumed constant and equal to its inlet value obtained in part I. Only NO concentration changes as flow passes each PFR.

1) Determine the concentration of NO at the outlet of each PFR.
2) What is total NOx emission of the combustor (in ppm=$X_{NO,out}\times10^6$)?

Reaction rate of NO can be determined by Zeldovich mechanism as:

$$O + N_2 \Leftrightarrow NO + N \qquad (N.1)$$

$$N + O_2 \Leftrightarrow NO + O, \qquad (N.2)$$

$$N + OH \Leftrightarrow NO + H. \qquad (N.3)$$

$$k_{N.1f} = 1.8 \cdot 10^{11} \exp[-38{,}370/T(\mathrm{K})] \qquad [=]\ \mathrm{m^3/kmol\text{-}s},$$

$$k_{N.1r} = 3.8 \cdot 10^{10} \exp[-425/T(\mathrm{K})] \qquad [=]\ \mathrm{m^3/kmol\text{-}s},$$

$$k_{N.2f} = 1.8 \cdot 10^{7}\, T \exp[-4680/T(\mathrm{K})] \qquad [=]\ \mathrm{m^3/kmol\text{-}s},$$

$$k_{N.2r} = 3.8 \cdot 10^{6}\, T \exp[-20{,}820/T(\mathrm{K})] \qquad [=]\ \mathrm{m^3/kmol\text{-}s},$$

$$k_{N.3f} = 7.1 \cdot 10^{10} \exp[-450/T(\mathrm{K})] \qquad [=]\ \mathrm{m^3/kmol\text{-}s},$$

$$k_{N.3r} = 1.7 \cdot 10^{11} \exp[-24{,}560/T(\mathrm{K})] \qquad [=]\ \mathrm{m^3/kmol\text{-}s}.$$

For each PFR, the residence time of flow is calculated based on combustor sizing and mass flow rates:

$$t_R = \frac{L}{v}, v = \frac{\dot{m}}{\rho A_L},$$

where, L is the PFR length (which is 120 mm, 340 mm, and 300 mm for the 3 PFRS, respectively), and $\dot{m}$ and ρ are the mass flow rate and mixture density which are assumed constant within each PFR and equal to the values calculated in part I at the inlet of each PFR. $A_L = 0.0471\ m^2$ is the liner cross-section area.