

The Evaluation of the Performance of the Gas Turbine System

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Introduction

In today's rapidly development of science and technology, countless products and systems have been invented and combined with others to achieve more promising results. The purpose of this project was to examine such an operation, a hybrid solar fossil-fuel gas turbine system (shown in Fig. 1 and 2 below), and to establish a computational method of its performance.

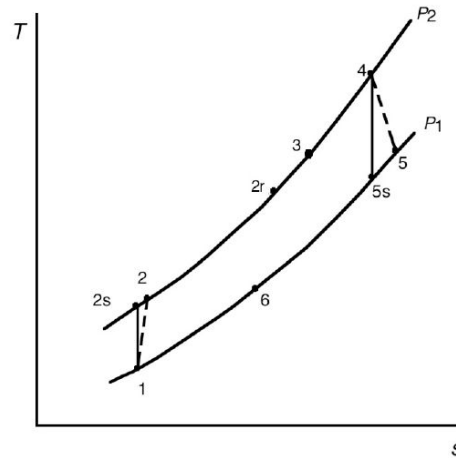


Figure 1. A S-T cycle illustration of various stages in the gas turbine system

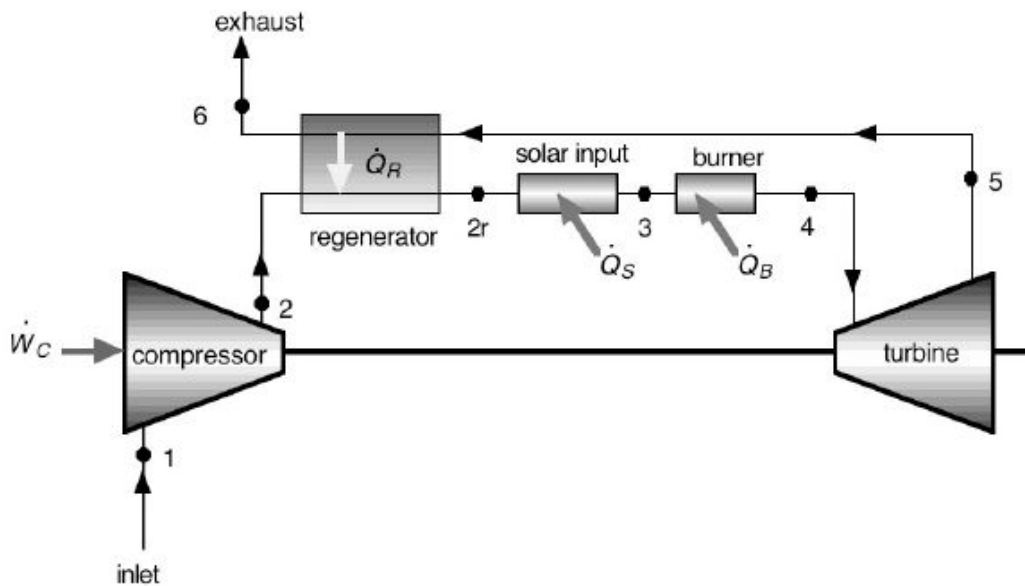


Figure 2. A detailed scheme of the gas turbine system.

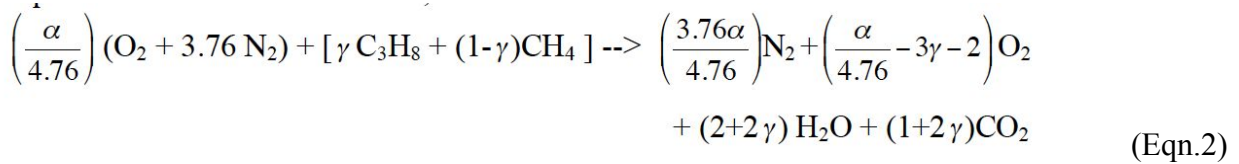
Initially, it's known that the atmospheric pressure of air is $P_1 = 101 \text{ kPa}$ at a temperature $T_1 = 25 \text{ }^\circ\text{C}$. The inlet of air to the system had a flow rate of 6.0 kg/s . Moreover, it's considered as an ideal gas with an effective molecular mass M of 28.97 kg/kmol .

Task 1 (III)

Given that a mixture of propane (C_3H_8) and methane (CH_4) was injected into and burned in the burner with air, the molar air-to-fuel ratio α and the fuel propane mole fraction γ were defined:

$$\begin{aligned}\alpha &= (\text{moles of air})/(\text{moles of propane and methane mixture}) \text{ in inlet flow to burner} \\ \gamma &= (\text{moles of propane})/(\text{moles of propane and methane in fuel mixture})\end{aligned}\quad (\text{Eqn.1})$$

Moreover, the mixture had just enough stoichiometric values that converted all the propane and methane to H_2O and CO_2 with no oxygen left over. The balanced equation for arbitrary α and γ greater than or equal to the stoichiometric values was also provided below:



And the stoichiometric condition for α was given:

$$\alpha = \alpha_{stoich} = 4.76(2 + 3\gamma) \quad (\text{Eqn.3})$$

The goal of this task was to calculate the molar air-to-fuel ratio α for specific combustor adiabatic flame (exit) temperature T_{af} and reactant temperature T_r . According to definition, T_{af} is the temperature that balances the combustor energy with no additional heat reactions:

$$\sum_{reactants} \dot{n}_r \hat{h}_r = \sum_{products} \dot{n}_p \hat{h}_p \quad (\text{Eqn.4})$$

The following equation with α , T_r , T_p was shown:

$$\begin{aligned}\left(\frac{\alpha}{4.76}\right) \hat{h}_{O_2}(T_r) + \left(\frac{3.76\alpha}{4.76}\right) \hat{h}_{N_2}(T_r) + \gamma \hat{h}_{C_3H_8}(T_r) + (1-\gamma) \hat{h}_{CH_4}(T_r) &= \left(\frac{3.76\alpha}{4.76}\right) \hat{h}_{N_2}(T_p) \\ + \left(\frac{\alpha}{4.76} - 3\gamma - 2\right) \hat{h}_{O_2}(T_p) &+ (2+2\gamma) \hat{h}_{H_2O}(T_p) + (1+2\gamma) \hat{h}_{CO_2}(T_p)\end{aligned} \quad (\text{Eqn.5})$$

where the molar enthalpy can be obtained from the heat of formation and the specific heat:

$$\hat{h}_i(T) = \hat{h}_i^\circ(T^\circ) + \hat{c}_{p,i}(T_{avg})(T - T^\circ) \quad \text{where } T_{avg} = 0.5(T_r + T_p) \quad (\text{Eqn.6})$$

In the exhaust gas, the water was assumed to be vapor. And α was isolated but only applied when $T_{af} < T_{af,stoich}$ and $\alpha > \alpha_{stoich}$:

$$\alpha = \frac{4.76 \left[-\gamma \hat{h}_{C_3H_8}(T_r) - (1-\gamma) \hat{h}_{CH_4}(T_r) - (3\gamma + 2) \hat{h}_{O_2}(T_p) + (2+2\gamma) \hat{h}_{H_2O}(T_p) + (1+2\gamma) \hat{h}_{CO_2}(T_p) \right]}{\left[\hat{h}_{O_2}(T_r) + 3.76 \hat{h}_{N_2}(T_r) - 3.76 \hat{h}_{N_2}(T_p) - \hat{h}_{O_2}(T_p) \right]} \quad (\text{Eqn.7})$$

In order to find α , the heat of formation of different species was first found at reference temperature $T^\circ = 25^\circ C$ in the attached table. Various specific heat were also calculated, at T_{avg}

using Eqn. 6, based on the equation provided in the attached table. Hence, the molar enthalpy of different compounds were obtained.

Further, a function of α could be created according to Eqn.7. In this task, T_p was given to be 1900 K, and T_r was 550 K. The fuel propane mole fraction γ depended on the circumstance given: (i) pure propane, (ii) pure methane, and (iii) a 50% mole fraction mixture. The results were calculated and shown below:

Table 1. The values of the molar air-to-fuel ratio α at $T_r = 550$ K and $T_p = 1900$ K for different mole fractions of mixture.

	Pure propane	Pure methane	A 50% mole fraction mixture
α	39.5022	15.2750	27.3886

Task 2 (IV)

In this part, we examined the exit condition of the compressor and the work required per kilogram of air. First, we guessed the exit temperature T_2 was the product temperature given in Task 1, 1900K. Then, an average temperature of T_1 and guessed T_2 was calculated and used to find c_p (based on the attached table). For air, its molar enthalpy was given to be 0 at reference temperature. The specific heat at constant volume, c_v , was found using the constant relationship:

$$\hat{c}_v = \hat{c}_p - \bar{R} \quad (\text{Eqn.8})$$

For a compressor, its exit temperature is known to be a function of k (the ratio of c_p to c_v), T_1 , P_2 , and the efficiency η_{comp} :

$$T_2 \approx T_1 \left[1 + \frac{\left(\frac{P_2}{P_1} \right)^{\left(\frac{k-1}{k} \right)} - 1}{\eta} \right] \quad (\text{Eqn.9})$$

In a similar manner, this exit temperature was now taken to be another guess of the outlet temperature. The step was repeated to measure the real exit temperature. And the difference between the successive T_2 values were measured. This whole process was iterated until the difference agreed within 0.2 °C.

Moreover, for the compressor, its work was equal to the changed of enthalpy between 2 states. Since the inlet state was 0, work was the exit stage. The molar enthalpy was measured using Eqn. 6, and then converted from kmol to kg of air by dividing 28.97.

Task 3 (V)

This task was first intended to calculate the mole fraction of all exhaust species with respect to the molar air-to-fuel ratio α . Generally, the mole fraction was obtained by dividing the molar coefficient of the particular species by the total number of moles of all species in the inlet or outlet. In our case, we relied on Eqn.2 provided. The total mole of products (n_{ex}) was found by summing the molar coefficients of N_2 , O_2 , H_2O , and CO_2 . The mole fraction of each species was then calculated as mentioned above. For example, the mole fraction of H_2O was $(2+2\gamma)/n_{ex}$. It's also given that γ was 0.25 in the mixture. The second objective of this task was to find the specific heat of products, $c_{p,prod}$, as a function of the mole-fraction weight average of the specific heat of all species involved., as shown in the equation below:

$$\hat{c}_{p,prod} = y_{H_2O} \hat{c}_{p,H_2O} + y_{CO_2} \hat{c}_{p,CO_2} + y_{N_2} \hat{c}_{p,N_2} + y_{O_2} \hat{c}_{p,O_2} \quad (\text{Eqn.9})$$

The method of finding the specific heat was provided on the attached tables, and T_p was given to be 600 K. At the same temperature, c_p of pure air was also measured and compared with $c_{p,prod}$, and should be smaller than it. At 600K, the cp_{prod} was found to be 33.0904 kJ/kmol K and $cp_{air} = 30.5943$ kJ/kmol K.

Task 4 (VI)

Now that we had the ability to find the temperature at step 2, the cp for air at the average temperature of step 1 and 2, and the specific heat of products at step 4, it was time to combine all of the previous tasks to create a whole cycle.

1. First we started at step 1 and used task 2 to find the Temperature at step 2.
2. We then found the mole fractions of products and molar flow rates using the equations below. Equation 10 gives the ability to us to calculate the mass of the products while equation 11 gives us the ability to calculate the moles of products flowing. Equation 13 gives us is the kmol per second of product gases flowing as a result of burning the propane/methane fuel mixture to achieve the specified α for the air flow of 6.0 kg/s (mass flow rate of air).

$$m_{prod} = \bar{M}_{N_2} \frac{3.76\alpha}{4.76} + \bar{M}_{O_2} \left(\frac{\alpha}{4.76} - 3\gamma - 2 \right) + \bar{M}_{H_2O} (2 + 2\gamma) + \bar{M}_{CO_2} (1 + 2\gamma) \quad (\text{Eqn 10})$$

$$n_{prod} = \frac{3.76\alpha}{4.76} + \left(\frac{\alpha}{4.76} - 3\gamma - 2 \right) + (2 + 2\gamma) + (1 + 2\gamma) \quad \text{(Eqn. 11)}$$

$$\dot{n}_{air} = \frac{\dot{m}_{air}}{M_{air}}$$

$$\dot{n}_{prod} = \frac{\dot{m}_{air}}{m_{prod}/n_{prod}} \quad \text{(Eqn. 12, 13)}$$

3. Next before we could move on to step 2r and 3, we had to find T5, for taking the regenerator into account. For this we guessed T5 and use a similar program as task 2 to reach a final T5. An average temperature of T₄ (1600K) and guessed T₅ was calculated and used to find c_p using task 3 and α_{stoich} for the first iteration. The specific heat at constant volume, c_v, was found using the constant relationship:

$$\hat{c}_v = \hat{c}_p - \bar{R} \quad \text{(Eqn.14)}$$

For a compressor, its exit temperature is known to be a function of k (the ratio of c_p to c_v), T₄, P₂, and the efficiency $\eta_{turbine}$:

$$T_5 = T_4 * \left(1 + \left(\left(\frac{P_1}{P_2} \right)^{\frac{k-1}{k}} - 1 \right) * \eta_{turbine} \right) \quad \text{(Eqn.15)}$$

In a similar manner, this exit temperature was now taken to be another guess of the outlet temperature. The step was repeated to measure the real exit temperature. And the difference between the successive T₅ values were measured. This whole process was iterated until the difference agreed within 0.2 °C.

4. After this T5 was found, it was time to incorporate the regenerator into the big picture. For this we determined the cp_{air} and cp_{products} at the average temperature of T2 and T5, and then we used these values for calculating T2r using this formula:

$$\varepsilon_{regen} = \frac{\dot{n}\hat{c}_{p,air}(T_{2r} - T_2)}{(\dot{n}\hat{c}_p)_{min}(T_5 - T_2)} \quad \text{(Eqn. 16)}$$

, where (n*cp)_{min} is the minimum of {(n*cp)_{air} , (n*cp)_{prod} }. This gives us T2r.

5. After this, we find T3 using the solar heat input. We use the first law of thermodynamics to find this Temperature. But we need the cp at the average temperature of T3 and T2r to find T3. For this we created a root_finder and using the two equations of finding cp and T3, we solved for T3. These equations are given below

$$cp_{23} = 28.11 + 0.1967 * 10^{-2} * (0.5 * (T_3 + T_{2r})) + 0.4802 * 10^{-5} * (0.5 * (T_3 + T_{2r}))^2 - 1.966 * 10^{-9} * (0.5 * (T_3 + T_{2r}))^3 \quad \text{Eqn(17)}$$

$$T_3 = Qs / (n_{dot_air} * cp_{23}) + T_{2r} \quad \text{(Eqn(18))}$$

6. We then used task 1 and T3, T4 to find a new alpha. After finding the new alpha, we then used this alpha to restart the process from step 1 of Task 4. We repeated this for 2 iterations.

7. After finding the right value of alpha, T5, T2, T2r, T3, molar flow rates of products and air, we find the Power output and the heat input to the combustor along with the overall efficiency of the cycle. We do this using the formulas given below.

$$W_{net} = W_t - W_c = \dot{n}_{products} * c_{p,t} * (T_4 - T_5) - \dot{n}_{air} * c_{p,c} * (T_2 - T_1)$$

Eqn 19

$$Q_{net} = Q_b + Q_{solar} = \dot{n}_{dotprod} * c_{p,products} * (T_4 - T_3) + Q_{solar} \quad \text{Eqn 20}$$

$$\eta_{computed} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_t - \dot{W}_c}{\dot{Q}_b} = \frac{\dot{n}_{products} * c_{p,t} * (T_4 - T_5) - \dot{n}_{air} * c_{p,c} * (T_2 - T_1)}{\dot{n}_{burner} * c_{p,burner} * (T_4 - T_3)}$$

Eqn 21

8. We then compared this efficiency to a constant cp efficiency whose formula is given below.

$$\eta_{class} = \frac{\eta_t * \left[1 - (P_1/P_2)^{(k-1)/k}\right] - (1/\eta_c) * (T_1/T_4) * \left[(P_2/P_1)^{(k-1)/k} - 1\right]}{1 - \epsilon_r * \left[1 - \eta_t + \eta_t * (P_1/P_2)^{(k-1)/k}\right] - (1 - \epsilon_r) * (T_1/T_4) * \left[1 - (1/\eta_c) + (1/\eta_c) * (P_2/P_1)^{(k-1)/k}\right]}$$

We then ran the computation for $\gamma = 0.25$, $Q_s = 0$, $P_2 = 500$ kPa, $T_4 = 1600$ K, $\eta_{comp} = 0.85$, $\eta_{turb} = 0.85$, $\epsilon_{regen} = 0.75$ and found the results given below.

Power	1.9268e+03 kW
Heat	4.3481e+03 kW
T5_f	1.1826e+03 K
alpha_f	54.6895
W_c	1.2233e+03 kW
W_t	3.1501e+03 kW
n_comp	0.4431
n_constant cp	0.5740

Table 2: Results from running the computation of task 4 for different values.

n_prod was found at a k value of averaged k values of air and product values determined at $T_p=0$. The efficiency at constant cp, is much higher than the achieved calculating cp at averaged temperatures at every step. This is because the averaged cp just goes from the first step to the last with one step. But if the cp is found at every step it gives a more accurate representation of how the efficiency will work.

Task 5 (VII)

For this Task, we considered a system with $\eta_{\text{comp}} = 0.85$, $\eta_{\text{turb}} = 0.85$, $\varepsilon_{\text{regen}} = 0.75$, $P_2 = 500$ kPa, $\gamma = 0.25$, and $T_4 = 1600$ K. Because the incident angle of the sun's rays varies with time over the peak collection hours of the day, Q_s varies from 2.0 to 3.0 MW over the peak collection period of the daytime. We then used the program developed in Task 4 to find the α 's and the variations of of the net power output, the heat input in the combustor, and the efficiency of the cycle with varying Q_s . We ran task_4 for 4 different values of Q_s - 0, 2, 2.5, 3 MW. We found the values for α , power output, heat input to the combustor and efficiency of given below.

Q_s (kW)	0	2000	2500	3000
α	54.6895	114.0972	155.8688	244.8664
Power (kW)	1.9268e+03	1.9063e+03	1.9013e+03	1.8962e+03
Heat (kW)	4.3481e+03	2.2043e+03	1.6673e+03	1.1310e+03
Efficiency	0.4431	0.4534	0.4562	0.4590

Table 3: Results for different values of α , Power, Heat and Efficiency for different values of Q_s

This table is summarized with the graphs given below.

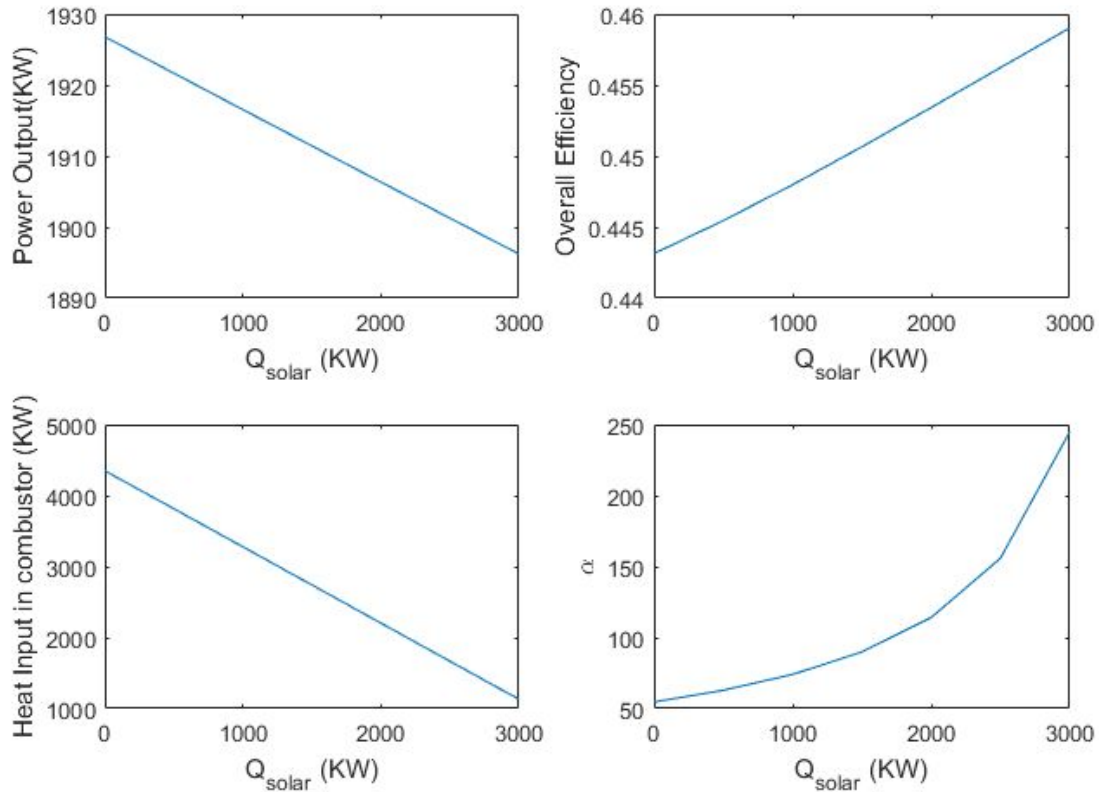


Figure 3: Subplots of changing Q_s and its variations on Power, Heat, Efficiency, and alpha. The table and the graphs show that as the solar heat input increases, the Power output, heat input to the combustor increase. But the efficiency and alpha increase. The graph of alpha vs Q_s is peculiar as the moles of air increases in an exponential manner rather than a linear manner. This may be because of the less heat provided to the combustor and the increased heat provided to heat the air. The temperature difference results in a small amount of methane and propane being burnt and hence the increase in alpha.

Task 5b (VIII)

In this task we asked the question that if the mole fraction of propane (γ) in the fuel increases to 0.5 or decreases to 0, how will the system performance change? We assumed that the Q_s value is 0 MW for this specific case. We ran task 4 for different values of γ - 0, 0.125, 0.25, 0.375, 0.5 and tabulated the results, given below.

γ	0	0.125	0.25	0.375	0.5
Power(kW)	1.9364e+03	1.9308e+03	1.9268e+03	1.9238e+03	1.9214e+03
n_comp	0.4451	0.4440	0.4431	0.4425	0.4420
alpha_f	39.4117	47.0505	54.6895	62.3285	69.9675
Heat (kW)	4.3500e+03	4.3489e+03	4.3481e+03	4.3475e+03	4.3470e+03

Table 4: Results of Power, Efficiency, Heat with different values of gamma

This shows that the efficiency, heat to the combustor and power output doesn't change much with changing gamma while they do decrease. So if the gamma were to decrease to zero, or only methane was being burnt, the power output is the highest as compared to when 50% of propane and methane were burnt. This is because propane combustion requires more amounts of oxygen and hence there is less moles of total gas burned. The heat input to the combustor, decreases as well but not as much as the power input. This results in the efficiency decreasing.

Conclusion

In this project, we analysed the hybrid solar fossil-fuel gas turbine system, to construct a computer simulation of the performance of the system. For this we first developed a program that found the value of the molar air-to-fuel ratio α that would result in a product temperature T_p for specified reactant temperature T_r . We then wrote a computer program to compute the exit condition from the compressor and the work required per kilogram of air from 1 to 2 using a constant c_p and c_v analysis. Next, using the chemical reaction for this propane and methane mixture with air ($O_2 + 3.76 N_2$) with possible products being CO_2 , H_2O , O_2 and N_2 , we derived relations for the mole fraction of each exhaust gas species as a function of molar air to fuel ratio α . Using these relations we set up a computer program to compute $c_{p,prod}$ for the product gas mixture as the mole-fraction weighted average of the c_p values for the individual species.

We then combined all these steps into one to recreate a cycle computationally and analyse its overall performance. We then ran the computation for $\gamma = 0.25$, $Q_s = 0$, $P_2 = 500$ kPa, $T_4 = 1600$ K, $\eta_{comp} = 0.85$, $\eta_{turb} = 0.85$, $\epsilon_{s_{regen}} = 0.75$ and found the results given in table 2. We then looked at how changing Q_s input and gamma change the efficiency, power input, and heat input. We found that the efficiency at constant c_p , is much higher than the achieved calculating c_p at averaged temperatures at every step. This is because the averaged c_p just goes from the first step to the last with one step. But if the c_p is found at every step it gives a more accurate representation of how the efficiency will work. As the solar heat input increases, the Power output, heat input to the combustor increase. But the efficiency and alpha increase.

Appendix I

Table A-25 Thermochemical Properties of Selected Substances at 298K and 1 atm

Substance	Formula	Molar Mass, <i>M</i> (kg/kmol)	Enthalpy of Formation, \bar{h}_f° (kJ/kmol)	Gibbs Function of Formation, \bar{g}_f° (kJ/kmol)	Absolute Entropy, \bar{s}° (kJ/kmol · K)	Heating Values	
						Higher, HHV (kJ/kg)	Lower, LHV (kJ/kg)
Carbon	C(s)	12.01	0	0	5.74	32,770	32,770
Hydrogen	H ₂ (g)	2.016	0	0	130.57	141,780	119,950
Nitrogen	N ₂ (g)	28.01	0	0	191.50	—	—
Oxygen	O ₂ (g)	32.00	0	0	205.03	—	—
Carbon monoxide	CO(g)	28.01	−110,530	−137,150	197.54	—	—
Carbon dioxide	CO ₂ (g)	44.01	−393,520	−394,380	213.69	—	—
Water	H ₂ O(g)	18.02	−241,820	−228,590	188.72	—	—
Water	H ₂ O(l)	18.02	−285,830	−237,180	69.95	—	—
Hydrogen peroxide	H ₂ O ₂ (g)	34.02	−136,310	−105,600	232.63	—	—
Ammonia	NH ₃ (g)	17.03	−46,190	−16,590	192.33	—	—
Oxygen	O(g)	16.00	249,170	231,770	160.95	—	—
Hydrogen	H(g)	1.008	218,000	203,290	114.61	—	—
Nitrogen	N(g)	14.01	472,680	455,510	153.19	—	—
Hydroxyl	OH(g)	17.01	39,460	34,280	183.75	—	—
Methane	CH ₄ (g)	16.04	−74,850	−50,790	186.16	55,510	50,020
Acetylene	C ₂ H ₂ (g)	26.04	226,730	209,170	200.85	49,910	48,220
Ethylene	C ₂ H ₄ (g)	28.05	52,280	68,120	219.83	50,300	47,160
Ethane	C ₂ H ₆ (g)	30.07	−84,680	−32,890	229.49	51,870	47,480
Propylene	C ₃ H ₆ (g)	42.08	20,410	62,720	266.94	48,920	45,780
Propane	C ₃ H ₈ (g)	44.09	−103,850	−23,490	269.91	50,350	46,360
Butane	C ₄ H ₁₀ (g)	58.12	−126,150	−15,710	310.03	49,500	45,720
Pentane	C ₅ H ₁₂ (g)	72.15	−146,440	−8,200	348.40	49,010	45,350
Octape	C ₈ H ₁₈ (g)	114.22	−208,450	17,320	463.67	48,260	44,790
Octane	C ₈ H ₁₈ (l)	114.22	−249,910	6,610	360.79	47,900	44,430
Benzene	C ₆ H ₆ (g)	78.11	82,930	129,660	269.20	42,270	40,580
Methyl alcohol	CH ₃ OH(g)	32.04	−200,890	−162,140	239.70	23,850	21,110
Methyl alcohol	CH ₃ OH(l)	32.04	−238,810	−166,290	126.80	22,670	19,920
Ethyl alcohol	C ₂ H ₅ OH(g)	46.07	−235,310	−168,570	282.59	30,590	27,720
Ethyl alcohol	C ₂ H ₅ OH(l)	46.07	−277,690	174,890	160.70	29,670	26,800

Source: Based on JANAF Thermochemical Tables, NSRDS-NBS-37, 1971; *Selected Values of Chemical Thermodynamic Properties*, NBS Tech. Note 270-3, 1968; and *API Research Project 44*, Carnegie Press, 1953. Heating values calculated.

II

TABLE A-2

Ideal-gas specific heats of various common gases (Concluded)

(c) As a function of temperature

$$\bar{c}_p = a + bT + cT^2 + dT^3$$

(T in K, \bar{c}_p in kJ/kmol·K)

Substance	Formula	a	b	c	d	Temperature range, K	% error	
							Max.	Avg.
Nitrogen	N ₂	28.90	-0.1571×10^{-2}	0.8081×10^{-5}	-2.873×10^{-9}	273–1800	0.59	0.34
Oxygen	O ₂	25.48	1.520×10^{-2}	-0.7155×10^{-5}	1.312×10^{-9}	273–1800	1.19	0.28
Air	—	28.11	0.1967×10^{-2}	0.4802×10^{-5}	-1.966×10^{-9}	273–1800	0.72	0.33
Hydrogen	H ₂	29.11	-0.1916×10^{-2}	0.4003×10^{-5}	-0.8704×10^{-9}	273–1800	1.01	0.26
Carbon monoxide	CO	28.16	0.1675×10^{-2}	0.5372×10^{-5}	-2.222×10^{-9}	273–1800	0.89	0.37
Carbon dioxide	CO ₂	22.26	5.981×10^{-2}	-3.501×10^{-5}	7.469×10^{-9}	273–1800	0.67	0.22
Water vapor	H ₂ O	32.24	0.1923×10^{-2}	1.055×10^{-5}	-3.595×10^{-9}	273–1800	0.53	0.24
Nitric oxide	NO	29.34	-0.09395×10^{-2}	0.9747×10^{-5}	-4.187×10^{-9}	273–1500	0.97	0.36
Nitrous oxide	N ₂ O	24.11	5.8632×10^{-2}	-3.562×10^{-5}	10.58×10^{-9}	273–1500	0.59	0.26
Nitrogen dioxide	NO ₂	22.9	5.715×10^{-2}	-3.52×10^{-5}	7.87×10^{-9}	273–1500	0.46	0.18
Ammonia	NH ₃	27.568	2.5630×10^{-2}	0.99072×10^{-5}	-6.6909×10^{-9}	273–1500	0.91	0.36
Sulfur	S ₂	27.21	2.218×10^{-2}	-1.628×10^{-5}	3.986×10^{-9}	273–1800	0.99	0.38
Sulfur dioxide	SO ₂	25.78	5.795×10^{-2}	-3.812×10^{-5}	8.612×10^{-9}	273–1800	0.45	0.24
Sulfur trioxide	SO ₃	16.40	14.58×10^{-2}	-11.20×10^{-5}	32.42×10^{-9}	273–1300	0.29	0.13
Acetylene	C ₂ H ₂	21.8	9.2143×10^{-2}	-6.527×10^{-5}	18.21×10^{-9}	273–1500	1.46	0.59
Benzene	C ₆ H ₆	-36.22	48.475×10^{-2}	-31.57×10^{-5}	77.62×10^{-9}	273–1500	0.34	0.20
Methanol	CH ₃ O	19.0	9.152×10^{-2}	-1.22×10^{-5}	-8.039×10^{-9}	273–1000	0.18	0.08
Ethanol	C ₂ H ₅ O	19.9	20.96×10^{-2}	-10.38×10^{-5}	20.05×10^{-9}	273–1500	0.40	0.22
Hydrogen chloride	HCl	30.33	-0.7620×10^{-2}	1.327×10^{-5}	-4.338×10^{-9}	273–1500	0.22	0.08
Methane	CH ₄	19.89	5.024×10^{-2}	1.269×10^{-5}	-11.01×10^{-9}	273–1500	1.33	0.57
Ethane	C ₂ H ₆	6.900	17.27×10^{-2}	-6.406×10^{-5}	7.285×10^{-9}	273–1500	0.83	0.28
Propane	C ₃ H ₈	-4.04	30.48×10^{-2}	-15.72×10^{-5}	31.74×10^{-9}	273–1500	0.40	0.12
n-Butane	C ₄ H ₁₀	3.96	37.15×10^{-2}	-18.34×10^{-5}	35.00×10^{-9}	273–1500	0.54	0.24
i-Butane	C ₄ H ₁₀	-7.913	41.60×10^{-2}	-23.01×10^{-5}	49.91×10^{-9}	273–1500	0.25	0.13
n-Pentane	C ₅ H ₁₂	6.774	45.43×10^{-2}	-22.46×10^{-5}	42.29×10^{-9}	273–1500	0.56	0.21
n-Hexane	C ₆ H ₁₄	6.938	55.22×10^{-2}	-28.65×10^{-5}	57.69×10^{-9}	273–1500	0.72	0.20
Ethylene	C ₂ H ₄	3.95	15.64×10^{-2}	-8.344×10^{-5}	17.67×10^{-9}	273–1500	0.54	0.13
Propylene	C ₃ H ₆	3.15	23.83×10^{-2}	-12.18×10^{-5}	24.62×10^{-9}	273–1500	0.73	0.17

Source: B. G. Kyle, *Chemical and Process Thermodynamics* (Englewood Cliffs, NJ: Prentice-Hall, 1984). Used with permission.

Table A-2 from Thermodynamics by Y.A. Cengel and M.A. Boles, 7th edition, McGraw Hill, 2011.
Here, the universal gas constant = $\bar{R} = 8314 \text{ J/kmolK}$

III

```

function [alpha] = task_1(Tp, Tr, gamma)

%the heat of formation from table, [kJ/kmol]
h0_c3h8 = -103850;
h0_ch4 = -74850;
h0_o2 = 0;
h0_h2o = -241820;
h0_co2 = -393520;
h0_n2 = 0;

%specific heat from table, [kJ/kmol*K]
T_avg = 0.5 * (Tr+Tp);
cp_c3h8 = -4.04 + 30.48*10^(-2)*T_avg - 15.72*10^(-5)*(T_avg)^2 + 31.74*10^(-9)*(T_avg)^3;
cp_ch4 = 19.89 + 5.024*10^(-2)*T_avg + 1.269*10^(-5)*(T_avg)^2 - 11.01*10^(-9)*(T_avg)^3;
cp_o2 = 25.48 + 1.520*10^(-2)*T_avg - 0.7155*10^(-5)*(T_avg)^2 + 1.312*10^(-9)*(T_avg)^3;
cp_h2o = 32.24 + 0.1923*10^(-2)*T_avg + 1.055*10^(-5)*(T_avg)^2 - 3.595*10^(-9)*(T_avg)^3;
cp_co2 = 22.26 + 5.981*10^(-2)*T_avg - 3.501*10^(-5)*(T_avg)^2 + 7.469*10^(-9)*(T_avg)^3;
cp_n2 = 28.9 - 0.1571*10^(-2)*T_avg + 0.8081*10^(-5)*(T_avg)^2 - 2.873*10^(-9)*(T_avg)^3;

%enthalpy
h_c3h8 = h0_c3h8 + cp_c3h8 * (Tr-298.15);
h_ch4 = h0_ch4 + cp_ch4 * (Tr-298.15);
h_o2_i = h0_o2 + cp_o2 * (Tr-298.15);
h_o2_o = h0_o2 + cp_o2 * (Tp-298.15);
h_h2o = h0_h2o + cp_h2o * (Tp-298.15);
h_co2 = h0_co2 + cp_co2 * (Tp-298.15);
h_n2_i = h0_n2 + cp_n2 * (Tr-298.15);
h_n2_o = h0_n2 + cp_n2 * (Tp-298.15);

alpha = 4.76*(-gamma*h_c3h8 - (1-gamma)*h_ch4 - (3*gamma+2)*h_o2_o + (2+2*gamma)*h_h2o +
(1+2*gamma)*h_co2)/(h_o2_i + 3.76*h_n2_i - 3.76*h_n2_o - h_o2_o);

```

```

end

```

Appendix IV

```

function [T2_f, W] =task_2(T1,P1,P2, eta_comp)

%guess T2=T2_g to be average, Tf was taken from task 1
Tf=1900;
T2_g=Tf;
R=8.314;

err=1;
while err >0.2
    T_avg = 0.5*(T1+T2_g);
    cp = 28.11+ 0.1967*10^(-2)*(T_avg) + 0.4802*10^(-5)*(T_avg)^2 - 1.966*10^(-9)*(T_avg)^3;
    cv = cp-R;
    k= cp/cv;
    %first T2 to calculate difference
    T2 = T1* (1+((P2/P1)^((k-1)/k) -1)/eta_comp);
    %try to get second T2 for difference calculation
    T_avg_1 = 0.5*(T1+T2);
    cp_1 = 28.11+ 0.1967*10^(-2)*( T_avg_1) + 0.4802*10^(-5)*( T_avg_1)^2 - 1.966*10^(-9)*(
T_avg_1)^3;
    cv_1 = cp_1-R;
    k_1= cp_1/cv_1;
    T2_1 = T1* (1+((P2/P1)^((k_1-1)/k_1) -1)/eta_comp);
    err= abs(T2-T2_1);
    if err <= 0.2
        break
    else
        T2_g = T2;
    end
end
T2_f = T2_g;
H2= 0 + cp * (T2_f-T1)/(28.97);
%W=H2-H1, and H1=0
W=H2;

end

```

```
function [y_h20, y_co2, y_n2, y_o2, cp_prod, cp_air] = task_3(Tp, gamma,alpha)
```

Appendix V

```
%based on the equation given on page1
```

```
n_ex = (3.76*alpha/4.76) + (alpha/4.76-3*gamma-2) + (2+2*gamma) + (1+2*gamma);
```

```
y_h20 = (2+2*gamma) / n_ex;
```

```
y_co2 = (1+2*gamma)/ n_ex;
```

```
y_n2 = ((3.76*alpha)/4.76)/ n_ex;
```

```
y_o2 = ((alpha/4.76)-3*gamma-2) / n_ex;
```

```
%cp of each product
```

```
cp_o2 = 25.48 + 1.520*10^(-2)*Tp - 0.7155*10^(-5)*(Tp)^2 + 1.312*10^(-9)*(Tp)^3;
```

```
cp_h20 = 32.24 + 0.1923*10^(-2)*Tp + 1.0551*10^(-5)*(Tp)^2 - 3.595*10^(-9)*(Tp)^3;
```

```
cp_co2 = 22.26 + 5.981*10^(-2)*Tp - 3.501*10^(-5)*(Tp)^2 + 7.469*10^(-9)*(Tp)^3;
```

```
cp_n2 = 28.9 - 0.1571*10^(-2)*Tp + 0.8081*10^(-5)*(Tp)^2 - 2.873*10^(-9)*(Tp)^3;
```

```
%cp of whole product
```

```
cp_prod = y_h20*cp_h20 + y_co2*cp_co2 + y_n2*cp_n2 + y_o2*cp_o2;
```

```
cp_air = 28.11+ 0.1967*10^(-2)*( Tp) + 0.4802*10^(-5)*( Tp)^2 - 1.966*10^(-9)*( Tp)^3;
```

```
end
```

```

function [Power, Heat, T5_f, alpha_f, W_c, W_t, n_comp, Work_Class, Heat_Class, n_class]= task_4
(~)
P1= 101;
T1=298;
P2=500;
T4=1600;
gamma= .25;
alpha_stoich = 4.76*(2+3*gamma);
Qs=0;
eff_comp=0.85;
eff_turb=0.85;
eps_regen=0.75;
i = 1;
T5_f(1,:) =1000;
alpha(1,:) = alpha_stoich;
while i<4
    m_prod(i,:) = 28.014*3.76*alpha(i,+)/4.76 + 15.9999*2 *(alpha(i,+)/4.76 - 3*gamma -2)+18.
01528*(2+2*gamma)+44.01*(1+2*gamma);
    m_air = 6;
    n_dot_air(i,:)= m_air/28.97;
    n_prod(i,:) = 3.76*alpha(i,+)/4.76 + (alpha(i,+)/4.76 - 3*gamma -2)+(2+2*gamma)+(1+2*gamma);
    n_dot_prod(i,:) = m_air/(m_prod(i,+)/n_prod(i,));
    [T2_final(i,:), W(i,:), cp_2(i,:)] = task_2(T1,P1,P2,eff_comp,1900);
    [T5_f(i+1,:), W_5(i,:), cp_5(i,:)] =task_2a(T4,P1,P2, eff_turb,T5_f(i,:), gamma,alpha(i,:));
    T_avg_25= 0.5*(T2_final(i,)+T5_f(i,));
    [y_h2o(1,:), y_co2(i,:), y_n2(i,:), y_o2(i,:), cp_prod(i,:), cp_air(i,:)] = task_3(T_avg_25,
gamma,alpha(i,:));
    ncp_min = min(cp_prod(i,)*n_dot_prod(i,:), cp_air(i,)*n_dot_prod(i,:));
    T2_r(i,:) = T2_final(i,)+ (ncp_min* eps_regen* (T5_f(i,)- T2_final(i,)))/(n_dot_air(i,)*
*cp_air(i,));
    [T3, cp_23] = root_finder(Qs,T2_r(i,:),n_dot_air(i,:));
    i = i+1;
    alpha(i,:)= task_1(T4, T3, gamma);
end

alpha_f = alpha(3,:);
W_t = n_dot_prod(3,)*cp_5(3,)*(T4-T5_f(3,));
W_c = n_dot_air(3,)*cp_2(3,)*(T2_final(3,)-T1);
Power= n_dot_prod(3,)*cp_5(3,)*(T4-T5_f(3,))- n_dot_air(3,)*cp_2(3,)*(T2_final(3,)-T1);
[~, ~, ~, ~, cp_burn, ~] = task_3(.5*(T3+T4), gamma,alpha(3,));
Heat =(n_dot_prod(3,)*cp_burn*(T4-T3))+ Qs;

k=(28.11/(28.11-8.314)+ (28.3369/(28.3369-8.314)))/2;

Work_Class =(eff_turb*(1-(P1/P2)^((k-1)/k))- (1/eff_comp)*(T1/T4)*((P2/P1)^((k-1)/k)-1));
Heat_Class = (1-eps_regen*(1-eff_turb+eff_turb*((P1/P2)^((k-1)/k)))-(1-eps_regen)*(T1/T4)*(1-
(1/eff_comp)+(1/eff_comp)*(P2/P1)^((k-1)/k)));
n_comp = (n_dot_prod(3,)*cp_5(3,)*(T4-T5_f(3,))- n_dot_air(3,)*cp_2(3,)*(T2_final(3,)-T1))/
(n_dot_prod(3,)*cp_burn*(T4-T3));
n_class = (eff_turb*(1-(P1/P2)^((k-1)/k))- (1/eff_comp)*(T1/T4)*((P2/P1)^((k-1)/k)-1))/(1-
eps_regen*(1-eff_turb+eff_turb*((P1/P2)^((k-1)/k)))-(1-eps_regen)*(T1/T4)*(1-(1/eff_comp)+
(1/eff_comp)*(P2/P1)^((k-1)/k)));
end
function [T2_f, W,cp] =task_2(T1,P1,P2, eta_comp, T_guess)

%guess T2=T2_g to be average, Tf was taken from task 1

```

Appendix VI


```

T2_g=T_guess;
R=8.314;

err=1;
while err >0.2
    T_avg = 0.5*(T1+T2_g);
    cp = 28.11+ 0.1967*10^(-2)*(T_avg) + 0.4802*10^(-5)*(T_avg)^2 - 1.966*10^(-9)*(T_avg)^3;
    cv = cp-R;
    k= cp/cv;
    %first T2 to calculate difference
    T2 = T1* (1+((P2/P1)^((k-1)/k) -1)/eta_comp);
    %try to get second T2 for difference calculation
    T_avg_1 = 0.5*(T1+T2);
    cp_1 = 28.11+ 0.1967*10^(-2)*( T_avg_1) + 0.4802*10^(-5)*( T_avg_1)^2 - 1.966*10^(-9)*(
T_avg_1)^3;
    cv_1 = cp_1-R;
    k_1= cp_1/cv_1;
    T2_1 = T1* (1+((P2/P1)^((k_1-1)/k_1) -1)/eta_comp);
    err= abs(T2-T2_1);
    if err <= 0.2
        break
    else
        T2_g = T2;
    end
end
T2_f = T2_g;
H2= 0 + cp * (T2_f-T1)/(28.97);
%W=H2-H1, and H1=0
W=H2;

end
function [T2_f, W,cp] =task_2a(T1,P1,P2, eta_comp, T_guess, gamma,alpha)
%guess T2=T2_g to be average, Tf was taken from task 1
T2_g=T_guess;
R=8.314;

err=1;
while err >0.2
    T_avg = 0.5*(T1+T2_g);
    [~, ~, ~, ~, cp_prod, ~] = task_3(T_avg, gamma,alpha);
    cp = cp_prod;
    cv = cp-R;
    k= cp/cv;
    %first T2 to calculate difference
    T2 = T1* (1+((P1/P2)^((k-1)/k) -1)*eta_comp);
    err= abs(T2-T2_g);
    if err <= 0.2
        break
    else
        T2_g = T2;
    end
end
T2_f = T2_g;
H2= 0 + cp * (T1-T2_f)/(28.97);
%W=H2-H1, and H1=0
W=H2;

```

end

```
function [y_h20, y_co2, y_n2, y_o2, cp_prod, cp_air] = task_3(Tp, gamma,alpha)
```

%based on the equation given on page1

```
n_ex = (3.76*alpha/4.76) + (alpha/4.76-3*gamma-2) + (2+2*gamma) + (1+2*gamma);
y_h20 = (2+2*gamma) / n_ex;
y_co2 = (1+2*gamma)/ n_ex;
y_n2 = (3.76*alpha/4.76)/ n_ex;
y_o2 = (alpha/4.76-3*gamma-2) / n_ex;
```

%cp of each product

```
cp_o2 = 25.48 + 1.520*10^(-2)*Tp - 0.7155*10^(-5)*(Tp)^2 + 1.312*10^(-9)*(Tp)^3;
cp_h20 = 32.24 + 0.1923*10^(-2)*Tp + 1.0551*10^(-5)*(Tp)^2 - 3.595*10^(-9)*(Tp)^3;
cp_co2 = 22.26 + 5.981*10^(-2)*Tp - 3.501*10^(-5)*(Tp)^2 + 7.469*10^(-9)*(Tp)^3;
cp_n2 = 28.9 - 0.1571*10^(-2)*Tp + 0.8081*10^(-5)*(Tp)^2 - 2.873*10^(-9)*(Tp)^3;
```

%cp of whole product

```
cp_prod = y_h20*cp_h20 + y_co2*cp_co2 + y_n2*cp_n2 + y_o2*cp_o2;
cp_air = 28.11+ 0.1967*10^(-2)*( Tp) + 0.4802*10^(-5)*( Tp)^2 - 1.966*10^(-9)*( Tp)^3;
end
```

```
function [alpha] = task_1(Tp, Tr, gamma)
```

%the heat of formation from table, [kJ/kmol]

```
h0_c3h8 =-103850;
h0_ch4 = -74850;
h0_o2 = 0;
h0_h2o = -241820;
h0_co2 = -393520;
h0_n2 = 0;
```

%specific heat from table, [kJ/kmol*K]

```
T_avg = 0.5 * (Tr+Tp);
cp_c3h8 = -4.04 + 30.48*10^(-2)*T_avg - 15.72*10^(-5)*(T_avg)^2 + 31.74*10^(-9)*(T_avg)^3;
cp_ch4 = 19.89 + 5.024*10^(-2)*T_avg +1.269*10^(-5)*(T_avg)^2 - 11.01*10^(-9)*(T_avg)^3;
cp_o2 = 25.48 + 1.520*10^(-2)*T_avg - 0.7155*10^(-5)*(T_avg)^2 + 1.312*10^(-9)*(T_avg)^3;
cp_h2o = 32.24 + 0.1923*10^(-2)*T_avg + 1.055*10^(-5)*(T_avg)^2 - 3.595*10^(-9)*(T_avg)^3;
cp_co2 = 22.26 + 5.981*10^(-2)*T_avg - 3.501*10^(-5)*(T_avg)^2 + 7.469*10^(-9)*(T_avg)^3;
cp_n2 = 28.9 - 0.1571*10^(-2)*T_avg + 0.8081*10^(-5)*(T_avg)^2 - 2.873*10^(-9)*(T_avg)^3;
```

%enthalpy

```
h_c3h8 =h0_c3h8 + cp_c3h8 *(Tr-298.15);
h_ch4 = h0_ch4 + cp_ch4 *(Tr-298.15);
h_o2_i = h0_o2 + cp_o2 *(Tr-298.15);
h_o2_o = h0_o2 + cp_o2 *(Tp-298.15);
h_h2o = h0_h2o + cp_h2o *(Tp-298.15);
h_co2 = h0_co2 + cp_co2 *(Tp-298.15);
h_n2_i = h0_n2 + cp_n2 *(Tr-298.15);
h_n2_o = h0_n2 + cp_n2 *(Tp-298.15);
```

```
alpha = 4.76*(-gamma*h_c3h8 - (1-gamma)*h_ch4 - (3*gamma+2)*h_o2_o + (2+2*gamma)*h_h2o +
(1+2*gamma)*h_co2)/(h_o2_i + 3.76*h_n2_i - 3.76*h_n2_o - h_o2_o);
```

```
end
function [T3_f, cp23] = root_finder(Qs, T2_r, n_dot_air)
syms cp_23 T3
eqn = [cp_23 == 28.11+ 0.1967*10^(-2)*(0.5*(T3+T2_r)) + 0.4802*10^(-5)*(0.5*(T3+T2_r))^2 - 1.966
*10^(-9)*(0.5*(T3+T2_r))^3, T3 == Qs/(n_dot_air*cp_23)+T2_r];
v = solve(eqn, [cp_23, T3]);
cp_23= vpa(v.cp_23);
T3 = vpa(v.T3);
p = find(T3 >800& T3 < 1500);
T3_f = double(T3(p));
cp23 = double(cp_23(p));
end
```

```

function [Power, Heat, T5_f, alpha, W_c, W_t, n_comp, T3, T2_r, cp_23]= task_5(~)
Qs= [0,500,1000,1500,2000,2500,3000];
gamma= 0.25;
P1= 101;
T1=298;
P2=500;
T4=1600;
alpha_stoich = 4.76*(2+3*gamma);
eff_comp=0.85;
eff_turb=0.85;
eps_regen=0.75;
for l = 1:length(Qs)
    i = 1;
    T5_f(1,l) =1000;
    alpha(1,l) = alpha_stoich;
    while i<4
        m_prod(i,l) = 28.014*3.76*alpha(i,l)/4.76 + 15.9999*2 *(alpha(i,l)/4.76 - 3*gamma -2)+18. ✓
        01528*(2+2*gamma)+44.01*(1+2*gamma);
        m_air = 6;
        n_dot_air(i,l)= m_air/28.97;
        n_prod(i,l) = 3.76*alpha(i,l)/4.76 + (alpha(i,l)/4.76 - 3*gamma -2)+(2+2*gamma)+(1+2*gamma);
        n_dot_prod(i,l)= m_air/(m_prod(i,l)/n_prod(i,l));
        [T2_final(i,l),W(i,l),cp_2(i,l)] = task_2(T1,P1,P2,eff_comp,1900);
        [T5_f(i+1,l), W_5(i,l),cp_5(i,l)] =task_2a(T4,P1,P2, eff_turb,T5_f(i,l), gamma,alpha(i,l));
        T_avg_25= 0.5*(T2_final(i,l)+T5_f(i,l));
        [y_h2o(i,l), y_co2(i,l), y_n2(i,l), y_o2(i,l), cp_prod(i,l), cp_air(i,l)] = task_3(T_avg_25, ✓
        gamma,alpha(i,l));
        ncp_min = min(cp_prod(i,l)*n_dot_prod(i,l), cp_air(i,l)*n_dot_prod(i,l));
        T2_r(i,l) = T2_final(i,l)+ (ncp_min* eps_regen* (T5_f(i,l)- T2_final(i,l)))/(n_dot_air(i,l) ✓
        *cp_air(i,l));
        %disp(i);
        %disp(n_dot_air(i,l));
        %[T3(i,l), cp_23(i,l)] = root_finder(Qs(l),T2_r(i,l),n_dot_air(i,l));
        cp_23(i,l) = 28.11+ 0.1967*10^(-2)*((T2_r(i,l))) + 0.4802*10^(-5)*((T2_r(i,l)))^2 - 1.966*10^ ✓
        (-9)*((T2_r(i,l)))^3;
        T3(i,l) = Qs(l)/(n_dot_air(i,l)*cp_23(i,l))+T2_r(i,l);
        i = i+1;
        alpha(i,l)= task_1(T4, T3(i-1,l), gamma);
    end
    alpha_f(1,l) = alpha(3,l);
    W_t(1,l) = n_dot_prod(3,l)*cp_5(3,l)*(T4-T5_f(3,l));
    W_c(1,l) = n_dot_air(3,l)*cp_2(3,l)*(T2_final(3,l)-T1);
    Power(1,l)= n_dot_prod(3,l)*cp_5(3,l)*(T4-T5_f(3,l))- n_dot_air(3,l)*cp_2(3,l)*(T2_final(3,l)- ✓
    T1);
    [~, ~, ~, ~, cp_burn, ~] = task_3(.5*(T3(i-1,l)+T4), gamma,alpha(3,l));
    Heat(1,l) =(n_dot_prod(3,l)*cp_burn*(T4-T3(i-1,l)));
    n_comp(1,l) = (n_dot_prod(3,l)*cp_5(3,l)*(T4-T5_f(3,l))- n_dot_air(3,l)*cp_2(3,l)*(T2_final(3,l)- ✓
    T1))/(Heat(1,l)+Qs(l));
end
subplot(2,2,1)
plot(Qs, Power )
xlabel('Q_{solar} (KW)')
ylabel('Power Output (KW)')
subplot(2,2,3)
plot(Qs, Heat)
xlabel('Q_{solar} (KW)')

```

```

ylabel('Heat Input in combustor (KW)')
subplot(2,2,2)
plot(Qs, n_comp)
xlabel('Q_{solar} (KW)')
ylabel('Overall Efficiency')
subplot(2,2,4)
plot(Qs, alpha_f)
xlabel('Q_{solar} (KW)')
ylabel('{\alpha}')

end

function [T2_f, W,cp] =task_2(T1,P1,P2, eta_comp, T_guess)

%guess T2=T2_g to be average, Tf was taken from task 1
T2_g=T_guess;
R=8.314;

err=1;
while err >0.2
    T_avg = 0.5*(T1+T2_g);
    cp = 28.11+ 0.1967*10^(-2)*(T_avg) + 0.4802*10^(-5)*(T_avg)^2 - 1.966*10^(-9)*(T_avg)^3;
    cv = cp-R;
    k= cp/cv;
    %first T2 to calculate difference
    T2 = T1* (1+((P2/P1)^((k-1)/k) -1)/eta_comp);
    %try to get second T2 for difference calculation
    T_avg_1 = 0.5*(T1+T2);
    cp_1 = 28.11+ 0.1967*10^(-2)*( T_avg_1) + 0.4802*10^(-5)*( T_avg_1)^2 - 1.966*10^(-9)*(
T_avg_1)^3;
    cv_1 = cp_1-R;
    k_1= cp_1/cv_1;
    T2_1 = T1* (1+((P2/P1)^((k_1-1)/k_1) -1)/eta_comp);
    err= abs(T2-T2_1);
    if err <= 0.2
        break
    else
        T2_g = T2;
    end
end

T2_f = T2_g;
H2= 0 + cp * (T2_f-T1)/(28.97);
%W=H2-H1, and H1=0
W=H2;

end

function [T2_f, W,cp] =task_2a(T1,P1,P2, eta_comp, T_guess, gamma,alpha)
%guess T2=T2_g to be average, Tf was taken from task 1
T2_g=T_guess;
R=8.314;

err=1;
while err >0.2
    T_avg = 0.5*(T1+T2_g);
    [~, ~, ~, ~, cp_prod, ~] = task_3(T_avg, gamma,alpha);
    cp = cp_prod;

```

```

    cv = cp-R;
    k= cp/cv;
    %first T2 to calculate difference
    T2 = T1* (1+((P1/P2)^( (k-1)/k) -1)*eta_comp);
    err= abs(T2-T2_g);
    if err <= 0.2
        break
    else
        T2_g = T2;
    end
end
T2_f = T2_g;
H2= 0 + cp * (T1-T2_f)/(28.97);
%W=H2-H1, and H1=0
W=H2;

end

function [y_h20, y_co2, y_n2, y_o2, cp_prod, cp_air] = task_3(Tp, gamma,alpha)

%based on the equation given on page1
n_ex = (3.76*alpha/4.76) + (alpha/4.76-3*gamma-2) + (2+2*gamma) + (1+2*gamma);
y_h20 = (2+2*gamma) / n_ex;
y_co2 = (1+2*gamma)/ n_ex;
y_n2 = (3.76*alpha/4.76)/ n_ex;
y_o2 = (alpha/4.76-3*gamma-2) / n_ex;

%cp of each product
cp_o2 = 25.48 + 1.520*10^(-2)*Tp - 0.7155*10^(-5)*(Tp)^2 + 1.312*10^(-9)*(Tp)^3;
cp_h20 = 32.24 + 0.1923*10^(-2)*Tp + 1.0551*10^(-5)*(Tp)^2 - 3.595*10^(-9)*(Tp)^3;
cp_co2 = 22.26 + 5.981*10^(-2)*Tp - 3.501*10^(-5)*(Tp)^2 + 7.469*10^(-9)*(Tp)^3;
cp_n2 = 28.9 - 0.1571*10^(-2)*Tp + 0.8081*10^(-5)*(Tp)^2 - 2.873*10^(-9)*(Tp)^3;

%cp of whole product
cp_prod = y_h20*cp_h20 + y_co2*cp_co2 + y_n2*cp_n2 + y_o2*cp_o2;
cp_air = 28.11+ 0.1967*10^(-2)*( Tp) + 0.4802*10^(-5)*( Tp)^2 - 1.966*10^(-9)*( Tp)^3;
end

function [alpha] = task_1(Tp, Tr, gamma)

%the heat of formation from table, [kJ/kmol]
h0_c3h8 =-103850;
h0_ch4 = -74850;
h0_o2 = 0;
h0_h2o = -241820;
h0_co2 = -393520;
h0_n2 = 0;

%specific heat from table, [kJ/kmol*K]
T_avg = 0.5 * (Tr+Tp);
cp_c3h8 = -4.04 + 30.48*10^(-2)*T_avg - 15.72*10^(-5)*(T_avg)^2 + 31.74*10^(-9)*(T_avg)^3;
cp_ch4 = 19.89 + 5.024*10^(-2)*T_avg +1.269*10^(-5)*(T_avg)^2 - 11.01*10^(-9)*(T_avg)^3;
cp_o2 = 25.48 + 1.520*10^(-2)*T_avg - 0.7155*10^(-5)*(T_avg)^2 + 1.312*10^(-9)*(T_avg)^3;
cp_h2o = 32.24 + 0.1923*10^(-2)*T_avg + 1.055*10^(-5)*(T_avg)^2 - 3.595*10^(-9)*(T_avg)^3;

```

```
cp_co2 = 22.26 + 5.981*10^(-2)*T_avg - 3.501*10^(-5)*(T_avg)^2 + 7.469*10^(-9)*(T_avg)^3;  
cp_n2 = 28.9 - 0.1571*10^(-2)*T_avg + 0.8081*10^(-5)*(T_avg)^2 - 2.873*10^(-9)*(T_avg)^3;
```

```
%enthalpy
```

```
h_c3h8 = h0_c3h8 + cp_c3h8 * (Tr-298.15);  
h_ch4 = h0_ch4 + cp_ch4 * (Tr-298.15);  
h_o2_i = h0_o2 + cp_o2 * (Tr-298.15);  
h_o2_o = h0_o2 + cp_o2 * (Tp-298.15);  
h_h2o = h0_h2o + cp_h2o * (Tp-298.15);  
h_co2 = h0_co2 + cp_co2 * (Tp-298.15);  
h_n2_i = h0_n2 + cp_n2 * (Tr-298.15);  
h_n2_o = h0_n2 + cp_n2 * (Tp-298.15);
```

```
alpha = 4.76*(-gamma*h_c3h8 - (1-gamma)*h_ch4 - (3*gamma+2)*h_o2_o + (2+2*gamma)*h_h2o +  
(1+2*gamma)*h_co2)/(h_o2_i + 3.76*h_n2_i - 3.76*h_n2_o - h_o2_o);
```

```
end
```

```

function [Power, Heat, T5_f, alpha, W_c, W_t, n_comp, T3, T2_r, cp_23] = task_5b(~)
Qs= 0;
gamma= [0,0.125,0.25,0.375,0.5];
P1= 101;
T1=298;
P2=500;
T4=1600;

eff_comp=0.85;
eff_turb=0.85;
eps_regen=0.75;
for l = 1:length(gamma)
    i = 1;
    T5_f(1,l) =1000;
    alpha_stoich = 4.76*(2+3*gamma(l));
    alpha(i,l) = alpha_stoich;
    while i<4
        m_prod(i,l) = 28.014*3.76*alpha(i,l)/4.76 + 15.9999*2 *(alpha(i,l)/4.76 - 3*gamma(l) ^-2)+18.
01528*(2+2*gamma(l))+44.01*(1+2*gamma(l));
        m_air = 6;
        n_dot_air(i,l)= m_air/28.97;
        n_prod(i,l) = 3.76*alpha(i,l)/4.76 + (alpha(i,l)/4.76 - 3*gamma(l) ^-2)+(2+2*gamma(l))+
(1+2*gamma(l));
        n_dot_prod(i,l)= m_air/(m_prod(i,l)/n_prod(i,l));
        [T2_final(i,l),W(i,l),cp_2(i,l)] = task_2(T1,P1,P2,eff_comp,1900);
        [T5_f(i+1,l), W_5(i,l),cp_5(i,l)] =task_2a(T4,P1,P2, eff_turb,T5_f(i,l), gamma(l),alpha(i,
l));
        T_avg_25= 0.5*(T2_final(i,l)+T5_f(i,l));
        [y_h2o(i,l), y_co2(i,l), y_n2(i,l), y_o2(i,l), cp_prod(i,l), cp_air(i,l)] = task_3(T_avg_25,
gamma(l),alpha(i,l));
        ncp_min = min(cp_prod(i,l)*n_dot_prod(i,l), cp_air(i,l)*n_dot_prod(i,l));
        T2_r(i,l) = T2_final(i,l)+ (ncp_min* eps_regen* (T5_f(i,l)- T2_final(i,l)))/(n_dot_air(i,l)
*cp_air(i,l));
        %disp(i);
        %disp(n_dot_air(i,l));
        [T3(i,l), cp_23(i,l)] = root_finder(Qs,T2_r(i,l),n_dot_air(i,l));
        %cp_23(i,l) = 28.11+ 0.1967*10^(-2)*((T2_r(i,l))) + 0.4802*10^(-5)*((T2_r(i,l)))^2 - 1.966
*10^(-9)*((T2_r(i,l)))^3;
        %T3(i,l) = Qs/(n_dot_air(i,l)*cp_23(i,l))+T2_r(i,l);
        i = i+1;
        alpha(i,l)= task_1(T4, T3(i-1,l), gamma(l));
    end
    alpha_f(1,l) = alpha(3,l);
    W_t(1,l) = n_dot_prod(3,l)*cp_5(3,l)*(T4-T5_f(3,l));
    W_c(1,l) = n_dot_air(3,l)*cp_2(3,l)*(T2_final(3,l)-T1);
    Power(1,l)= n_dot_prod(3,l)*cp_5(3,l)*(T4-T5_f(3,l))- n_dot_air(3,l)*cp_2(3,l)*(T2_final(3,l)-
T1);
    [~, ~, ~, ~, cp_burn, ~] = task_3(.5*(T3(i-1,l)+T4), gamma(l),alpha(3,l));
    Heat(1,l) =(n_dot_prod(3,l)*cp_burn*(T4-T3(i-1,l)));
    n_comp(1,l) = (n_dot_prod(3,l)*cp_5(3,l)*(T4-T5_f(3,l))- n_dot_air(3,l)*cp_2(3,l)*(T2_final(3,l)-
T1))/(Heat(1,l));
end
end

function [T2_f, W,cp] =task_2(T1,P1,P2, eta_comp, T_guess)

```



```

%guess T2=T2_g to be average, Tf was taken from task 1
T2_g=T_guess;
R=8.314;

err=1;
while err >0.2
    T_avg = 0.5*(T1+T2_g);
    cp = 28.11+ 0.1967*10^(-2)*(T_avg) + 0.4802*10^(-5)*(T_avg)^2 - 1.966*10^(-9)*(T_avg)^3;
    cv = cp-R;
    k= cp/cv;
    %first T2 to calculate difference
    T2 = T1* (1+((P2/P1)^((k-1)/k) -1)/eta_comp);
    %try to get second T2 for difference calculation
    T_avg_1 = 0.5*(T1+T2);
    cp_1 = 28.11+ 0.1967*10^(-2)*( T_avg_1) + 0.4802*10^(-5)*( T_avg_1)^2 - 1.966*10^(-9)*(
T_avg_1)^3;
    cv_1 = cp_1-R;
    k_1= cp_1/cv_1;
    T2_1 = T1* (1+((P2/P1)^((k_1-1)/k_1) -1)/eta_comp);
    err= abs(T2-T2_1);
    if err <= 0.2
        break
    else
        T2_g = T2;
    end
end
T2_f = T2_g;
H2= 0 + cp * (T2_f-T1)/(28.97);
%W=H2-H1, and H1=0
W=H2;

end
function [T2_f, W,cp] =task_2a(T1,P1,P2, eta_comp, T_guess, gamma,alpha)
%guess T2=T2_g to be average, Tf was taken from task 1
T2_g=T_guess;
R=8.314;

err=1;
while err >0.2
    T_avg = 0.5*(T1+T2_g);
    [~, ~, ~, ~, cp_prod, ~] = task_3(T_avg, gamma,alpha);
    cp = cp_prod;
    cv = cp-R;
    k= cp/cv;
    %first T2 to calculate difference
    T2 = T1* (1+((P1/P2)^((k-1)/k) -1)*eta_comp);
    err= abs(T2-T2_g);
    if err <= 0.2
        break
    else
        T2_g = T2;
    end
end
T2_f = T2_g;
H2= 0 + cp * (T1-T2_f)/(28.97);
%W=H2-H1, and H1=0

```

W=H2;

end

function [y_h2o, y_co2, y_n2, y_o2, cp_prod, cp_air] = task_3(Tp, gamma,alpha)

%based on the equation given on page1

```
n_ex = (3.76*alpha/4.76) + (alpha/4.76-3*gamma-2) + (2+2*gamma) + (1+2*gamma);
y_h2o = (2+2*gamma) / n_ex;
y_co2 = (1+2*gamma)/ n_ex;
y_n2 = (3.76*alpha/4.76)/ n_ex;
y_o2 = (alpha/4.76-3*gamma-2) / n_ex;
```

%cp of each product

```
cp_o2 = 25.48 + 1.520*10^(-2)*Tp - 0.7155*10^(-5)*(Tp)^2 + 1.312*10^(-9)*(Tp)^3;
cp_h2o = 32.24 + 0.1923*10^(-2)*Tp + 1.0551*10^(-5)*(Tp)^2 - 3.595*10^(-9)*(Tp)^3;
cp_co2 = 22.26 + 5.981*10^(-2)*Tp - 3.501*10^(-5)*(Tp)^2 + 7.469*10^(-9)*(Tp)^3;
cp_n2 = 28.9 - 0.1571*10^(-2)*Tp + 0.8081*10^(-5)*(Tp)^2 - 2.873*10^(-9)*(Tp)^3;
```

%cp of whole product

```
cp_prod = y_h2o*cp_h2o + y_co2*cp_co2 + y_n2*cp_n2 + y_o2*cp_o2;
cp_air = 28.11+ 0.1967*10^(-2)*( Tp) + 0.4802*10^(-5)*( Tp)^2 - 1.966*10^(-9)*( Tp)^3;
end
```

function [alpha] = task_1(Tp, Tr, gamma)

%the heat of formation from table, [kJ/kmol]

```
h0_c3h8 =-103850;
h0_ch4 = -74850;
h0_o2 = 0;
h0_h2o = -241820;
h0_co2 = -393520;
h0_n2 = 0;
```

%specific heat from table, [kJ/kmol*K]

```
T_avg = 0.5 * (Tr+Tp);
cp_c3h8 = -4.04 + 30.48*10^(-2)*T_avg - 15.72*10^(-5)*(T_avg)^2 + 31.74*10^(-9)*(T_avg)^3;
cp_ch4 = 19.89 + 5.024*10^(-2)*T_avg +1.269*10^(-5)*(T_avg)^2 - 11.01*10^(-9)*(T_avg)^3;
cp_o2 = 25.48 + 1.520*10^(-2)*T_avg - 0.7155*10^(-5)*(T_avg)^2 + 1.312*10^(-9)*(T_avg)^3;
cp_h2o = 32.24 + 0.1923*10^(-2)*T_avg + 1.055*10^(-5)*(T_avg)^2 - 3.595*10^(-9)*(T_avg)^3;
cp_co2 = 22.26 + 5.981*10^(-2)*T_avg - 3.501*10^(-5)*(T_avg)^2 + 7.469*10^(-9)*(T_avg)^3;
cp_n2 = 28.9 - 0.1571*10^(-2)*T_avg + 0.8081*10^(-5)*(T_avg)^2 - 2.873*10^(-9)*(T_avg)^3;
```

%enthalpy

```
h_c3h8 =h0_c3h8 + cp_c3h8 *(Tr-298.15);
h_ch4 = h0_ch4 + cp_ch4 *(Tr-298.15);
h_o2_i = h0_o2 + cp_o2 *(Tr-298.15);
h_o2_o = h0_o2 + cp_o2 *(Tp-298.15);
h_h2o = h0_h2o + cp_h2o *(Tp-298.15);
h_co2 = h0_co2 + cp_co2 *(Tp-298.15);
h_n2_i = h0_n2 + cp_n2 *(Tr-298.15);
h_n2_o = h0_n2 + cp_n2 *(Tp-298.15);
```

```
alpha = 4.76*(-gamma*h_c3h8 - (1-gamma)*h_ch4 - (3*gamma+2)*h_o2_o + (2+2*gamma)*h_h2o +
```

```
(1+2*gamma)*h_co2)/(h_o2_i + 3.76*h_n2_i - 3.76*h_n2_o - h_o2_o);
```

```
end
```

```
function [T3_f, cp23] = root_finder(Qs, T2_r, n_dot_air)
syms cp_23 T3
eqn = [cp_23 == 28.11+ 0.1967*10^(-2)*(0.5*(T3+T2_r)) + 0.4802*10^(-5)*(0.5*(T3+T2_r))^2 -
1.966*10^(-9)*(0.5*(T3+T2_r))^3, T3 == Qs/(n_dot_air*cp_23)+T2_r];
v = solve(eqn, [cp_23, T3]);
cp_23= vpa(v.cp_23);
T3 = vpa(v.T3);
p = find(T3 >800& T3 < 1500);
T3_f = double(T3(p));
cp23 = double(cp_23(p));
end
```

Appendix IX