

# ME 146 Project 3:

## Hybrid Solar Gas Turbine - Design and Analysis

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## Introduction

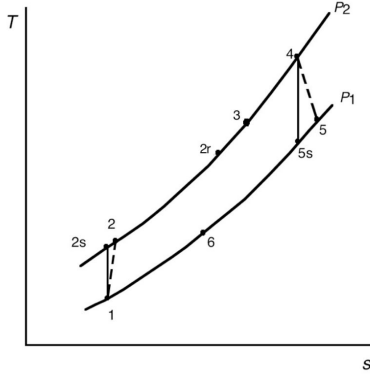


Fig. 1: T-S Diagram of Turbine System

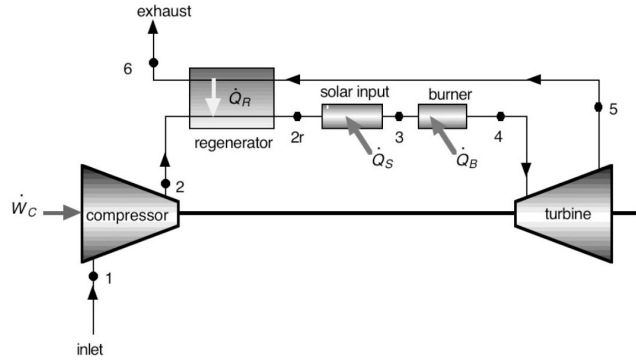


Fig. 2: Schematic of Turbine System

The purpose of this project is to construct a computer simulation of the performance of the gas turbine system shown in Figure 1 and 2 above. Using MATLAB, we built our own codes to calculate the values of constants in Task 1, 2 and 3. Then, by utilizing our results from task 1, 2 and 3, it was possible to implement and answer the questions on task 4 and 5.

## Combustor Governing Equations

In the combustor,

$$\left(\frac{\alpha}{4.76}\right)(O_2 + 3.76N_2) + [\gamma C_3H_8 + (1-\gamma)CH_4] \Rightarrow \left(\frac{3.76\alpha}{4.76}\right)N_2 + \left(\frac{\alpha}{4.76} - 3\gamma - 2\right)O_2 + (2+2\gamma)H_2O + \left(\frac{3.76\alpha}{4.76}\right)N_2 + \left(\frac{\alpha}{4.76} - 3\gamma - 2\right)O_2 + (2+2\gamma)H_2O + (1+2\gamma)CO_2 \quad [\text{Eqn. 1}]$$

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

$$\sum_{\text{reactants}} \dot{n}_r \hat{h}_r = \sum_{\text{products}} \dot{n}_p \hat{h}_p \quad [\text{Eqn. 3}]$$

$$\left(\frac{\alpha}{4.76}\right)\hat{h}_{O_2}[T_r] + \left(\frac{3.76\alpha}{4.76}\right)\hat{h}_{N_2}[T_r] + \gamma\hat{h}_{C_3H_8}[T_r] + (1-\gamma)\hat{h}_{CH_4}[T_r] \downarrow$$

$$\left(\frac{\alpha}{4.76} - 3\gamma - 2\right)\hat{h}_{O_2}[T_p] + (2+2\gamma)\hat{h}_{H_2O}[T_p] + (1+2\gamma)\hat{h}_{CO_2}[T_p] \quad [\text{Eqn. 4}]$$

$$\hat{h}_i(T) = \hat{h}_i(T^\circ) + \hat{c}_{p,i}(T_{avg})(T - T^\circ), \text{ where } T_{avg} = 0.5(T_r + T_p) \quad [\text{Eqn. 5}]$$

$$\alpha = \frac{4.76[-\gamma\hat{h}_{C_3H_8}[T_r] - (1-\gamma)\hat{h}_{CH_4}[T_r] - (3\gamma+2)\hat{h}_{O_2}[T_p] + (2+2\gamma)\hat{h}_{H_2O}[T_p] + (1+2\gamma)\hat{h}_{CO_2}[T_p]]}{[\hat{h}_{O_2}[T_r] + 3.76\hat{h}_{N_2}[T_r] - 3.76\hat{h}_{N_2}[T_p] - \hat{h}_{O_2}[T_p]]} \quad [\text{Eqn. 6}]$$

$$\hat{c}_v = \hat{c}_p - \bar{R} \quad (\text{kJ/kmolK}) \quad [\text{Eqn. 7}]$$

$$\hat{c}_{p,product} = y_{H_2O}\hat{c}_{p,H_2O} + y_{CO_2}\hat{c}_{p,CO_2} + y_{N_2}\hat{c}_{p,N_2} + y_{O_2}\hat{c}_{p,O_2} \quad [\text{Eqn. 8}]$$

$$\hat{c}_{v,prod} = \hat{c}_{p,prod} - \bar{R} \quad (\text{kJ/kmolK}) \quad [\text{Eqn. 9}]$$

## System Analysis Governing Equations

- $\epsilon_{regen} = \frac{\dot{n}\hat{c}_{p,air}(T_{2r}-T_2)}{(\dot{n}\hat{c}_p)_{min}(T_5-T_2)}$  [Eqn.10]
- $\eta_{class} = \frac{\eta_r[1-(P_1/P_2)^{(k-1)/k}]-1/\eta_c(T_1/T_4)[(P_2/P_1)^{(k-1)/k}-1]}{1-\epsilon_r[1-\eta_r+\eta_r[1-(P_1/P_2)^{(k-1)/k}]]-(1-\epsilon_r)(T_1/T_4)[1-(1/\eta_c)+(1/\eta_c)(P_2/P_1)^{(k-1)/k}-1]}$  [Eqn 11]
- $n_{prod} = \alpha + \gamma + 1$  [Eqn 12]
- $m_{prod} = \overline{M}_{N_2} \frac{3.76\alpha}{4.76} + \overline{M}_{O_2} \left( \frac{\alpha}{4.76} - 3\gamma - 2 \right) + \overline{M}_{H_2O} (2 + 2\gamma) + \overline{M}_{CO_2} (1 + 2\gamma)$  [Eqn 13]
- $\dot{n}_{air} = \frac{\dot{m}_{air}}{\overline{M}_{air}}$  [Eqn 14]
- $\dot{n}_{prod} = \frac{\dot{m}_{air}}{\overline{M}_{prod}/n_{prod}}$  [Eqn 15]
- $\eta_{system} = \frac{\dot{W}}{\dot{Q}} = \frac{\dot{W}_t - \dot{W}_c}{\dot{Q}_b} = \frac{n_{products} \cdot c_{p,f} \cdot (T_4 - T_5) - \eta_{air} \cdot c_{p,c} \cdot (T_2 - T_1)}{n_{burner} \cdot c_{p,burner} \cdot (T_4 - T_3)}$  [Eqn 16]
- Net Power:  $\dot{P}_{out} = \dot{W}_{turbine, out} - \dot{W}_{req}$  [Eqn 17]
- Heat Input into Combustor:  $\dot{Q}_{burner} = \dot{n}_{prod} \hat{c}_{p,prod} (T_4 - T_3)$  [Eqn 18]
- System efficiency:  $\eta_{system} = \dot{P}_{out} / (\dot{Q}_{burner} + \dot{Q}_{solar})$  [Eqn 19]

## Constants and Variables

- $P_1$  : Air at atmospheric pressure.
- $T_1$  : Inlet temperature
- $T_2$  : Compressor temperature.
- $\overline{M}$  : The effective molecular mass
- $\dot{m}$  : Mass flow of air at the inlet.
- $T_{af}$  : Adiabatic flame(exit) temperature
- $T_r$  : Reactant temperature
- $T_p$  : Product temperature
- $\alpha$  : Molar air-to-fuel ratio
  - (Moles of air) / (moles of propane and methane mixture) in inlet flow to burner
- $\gamma$  : Fuel propane molar fraction
  - (Moles of Propane) / (moles of propane and methane in fuel mixture)
- $\hat{c}_v$  : Specific heat at constant volume.
- $\hat{c}_p$  : Specific heat at constant pressure.
- $\overline{R}$  : The universal gas constant.
- $\hat{c}_{v,prod}$  : Average specific heat of product at constant volume.
- $\hat{c}_{p,prod}$  : Average specific heat of product at constant pressure.
- $\epsilon_{regen}$  : Regenerator effectiveness.
- $\dot{n}$  : Molar flow
- $\hat{h}$  : enthalpy per kmol.
- $\dot{Q}_{solar}$  : Solar heat input.

- $\eta_{turb}$  : Turbine efficiency
- $\eta_{comp}$  : Compressor efficiency.

## Responsibilities

This section provides a summary of how the project work was divided between the teammates when preparing this report.

### **Charles Lin:**

- Introduction
- Task 4
- Task 5

### **Jung Hwan Ha:**

- Task 1
- Task 2
- Task 3

# Design Task Documentation

## Task 1

### Task Description:

The main objective of the task 1 is to build up our own computer program which has the ability to calculate the the molar air-to-fuel ration  $\alpha$  that will occur in specified combustor adiabatic flame temperature( $T_{af}$ ) for given reactant temperature( $T_r$ )

### Assumptions/Idealizations:

- The values of  $\alpha$  and  $\gamma$  are greater than or equal to the stoichiometric value.
- We assume  $P_1 = 101$  kPa.
- We assume  $T_1 = 25^\circ\text{C}$  which also can be  $T_1 = 298.15$  K.
- We assume  $\overline{M} = 28.97$  kg/kmol.
- We assume  $\dot{m} = 6.0$  kg/s.
- We assume air as an ideal gas.
- We assume the stoichiometric mixture has enough oxygen to burn all propane and methane, and make them convert to oxygen and carbon dioxide.
- We assume the regenerator heated air and injected fuel to be at the same temperature.
- We assume water exists as water vapor in the exhaust gas.
- $T_{avg} = 0.5(T_r + T_p)$ .
- $T_{af}$  is greater than  $T_{af, stoich}$ .
- $\alpha$  is greater than  $\alpha_{stoich}$ .
- $T^\circ = 25^\circ\text{C}$ .
- $T_r = 550\text{K}$ .
- $T_p = 1900\text{K}$ .

### Algorithm Summary of the Program:

1. After the air flows into the inlet, the mixture of propane( $C_3H_8$ ) and methane( $C_3H_4$ ) will be injected to the burner. And those will be completely burned.
2. Due to the combustion process of propane and methane, the chemical reaction of the combustion will be occurred. And, the balanced chemical reaction can be written as [Eqn 1].
3. For stoichiometric conditions, the  $\alpha$  can be determined as [Eqn 2].
4. Based on the [Eqn 3], [Eqn 4] can be derived in order to find the value of the molar air-to-fuel ratio  $\alpha$ .
5. Before calculating the enthalpy of each gas species, refer to the [Table 2] at [Appendix B], evaluate specific heat of each gas species.
6. After determining specific heat of each gas species, according to [Table 1] at [Appendix B], [Eqn 5] is used to determine each enthalpy of each gas species at reference temperature.

7. Rearranging [Eqn 1], it is possible to derive [Eqn 6] to solve for the air-to-ratio.

**Required Deliverables for Given Conditions:**

1. Value of  $\alpha$  when the gas mixture is only composed with pure propane.
2. Value of  $\alpha$  when the gas mixture is only composed with pure methane.
3. Value of  $\alpha$  when the gas mixture is 50% mole fraction mixture.

**Results:**

Conditions of Gas Mixture	Value of $\alpha$
Pure propane	39.5023
Pure methane	15.2750
50% mole fraction mixture	27.3887

## Task 2

**Task Description:**

Build up our own computer program to compute the exit condition from the compressor and the work required per kilogram of air.

**Assumptions/Idealizations:**

- We assume  $P_1 = 101 \text{ kPa}$ .
- We assume  $T_1 = 25^\circ\text{C}$  which also can be  $T_1 = 298.15 \text{ K}$ .
- We assume  $\bar{M} = 28.97 \text{ kg/kmol}$ .
- We assume  $\dot{m} = 6.0 \text{ kg/s}$ .
- We assume air as an ideal gas.
- $T_{avg} = 0.5(T_r + T_p)$ .
- At  $T_1 = 25^\circ\text{C}$ , the molar enthalpy is zero.
- $P_2 = 130 \text{ Kpa}$ .
- $\eta_{comp} = 1$

**Algorithm summary of the program:**

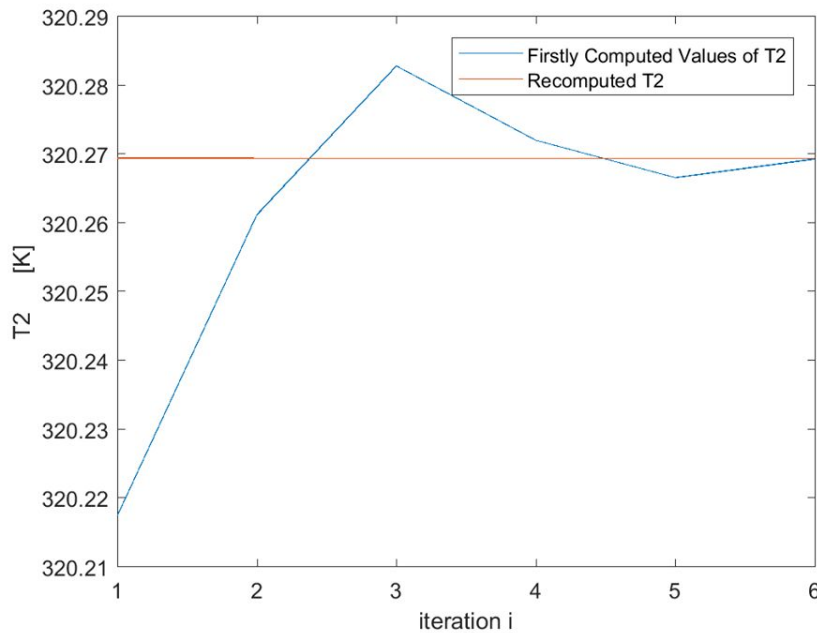
1. Guess the exit temperature,  $T_2$ .
2. Compute specific heat of the product at the average temperature by using [Table 2] at [Appendix B].
3. Compute  $\hat{c}_v$  by using [Eqn 7].

4. Using constant  $\hat{c}_p$  and  $\hat{c}_v$ , determine the enthalpy per kmol of air and the temperature at the exit from the compressor  $T_2$ .
5. Recalculate the average temperature using the newly computed  $T_2$  value and repeat the calculation of the outlet condition.
6. If the difference between  $T_2$  and  $T_{2,new}$  is less than 0.2, terminate the iterative calculation. If not, repeat the iteration from step 1-5 again.

Results:

Our resulting compressor temperature is 320.2694[K], shown in [Fig. 3].

The work required per kilogram of air is 134.3031[kW/kg of air]



**[Fig. 3]:  $T_2$ [K] over the Number of Iterations [i]  
at  $P_2 = 130 \text{ kPa}$  and  $\eta_{comp} = 1$**

## Task 3

### Task Description:

Task 3 is independent computer program which calculates  $\hat{c}_{p,prod}$  for the gas mixture as the mole-fraction computed average of the  $\hat{c}_p$  values for the individual species ( $CO_2, O_2, H_2O, N_2$ ) in the gas mixture that can be expressed as a function of molar-air-fuel ratio  $\alpha$ .

### Assumptions/Idealizations:

- We assume  $P_1 = 101 \text{ kPa}$ .
- We assume  $T_1 = 25^\circ\text{C}$  which also can be  $T_1 = 298.15 \text{ K}$ .
- We assume  $\bar{M} = 28.97 \text{ kg/kmol}$ .

- We assume  $\dot{m} = 6.0 \text{ kg/s}$ .
- We assume air as an ideal gas.
- $\gamma = 0.25$
- $T_p = 600K$

#### Algorithm Summary of the Program:

1. Calculate the total moles of product: which is equal to  $n_{total} = \alpha + \gamma + 1$
2. Compute each molar fraction of each gas species in the gas mixture.
  - a.  $y_{N_2} = \frac{3.76\alpha}{4.76n_{total}}$
  - b.  $y_{O_2} = (\frac{\alpha}{4.76} - 3\gamma - 2) / n_{total}$
  - c.  $y_{H_2O} = \frac{2+2\gamma}{n_{total}}$
  - d.  $y_{CO_2} = \frac{1+2\gamma}{n_{total}}$

For the value of  $\alpha$ , We use  $\alpha_{stoich} = 4.76(2 + 3\gamma) = 4.76(2 + 3(0.25)) = 13.09$  due to the condition in Task 3.

3. Bring the calculated values of specific heats of each species in the gas mixture in Task 1.
4. Plug the result of step 2 and step 3 into the [Eqn 8], then it is possible to get the value of  $\hat{c}_{p,prod}$  at temperature =  $600K$ .
5. Refer to the [Table 2] at [Appendix B], compute  $\hat{c}_p$  for pure air at the same temperature.

#### Results:

At product gases at  $T_p = 600K$ , the following results are achieved from our own computer program.

$\hat{c}_{p,prod}$ for stoichiometric combustion	33.0953 [kJ/kmol · K]
$\hat{c}_p$ for pure air at $T_p = 600K$	30.5943[kJ/kmol · K]

## Task 4

#### Task description:

In this task, we bring together our programs from Tasks 1, 2, and 3 to conduct overall system analysis. That is, given a  $P_1, T_1, P_2, T_4, \gamma, \dot{Q}_{solar}, \eta_{comp}, \eta_{turb}$ , and  $\epsilon_{regen}$ , we may compute system net power output  $\dot{P}_{out}$ , heat input into the combustor  $\dot{Q}_{burner}$ , and system efficiency  $\eta_{system}$ . This system efficiency  $\eta_{system}$  is to be compared against  $\eta_{class}$ , an efficiency found by derivation in class from the constant specific heat relation.

#### Assumptions/Idealizations:

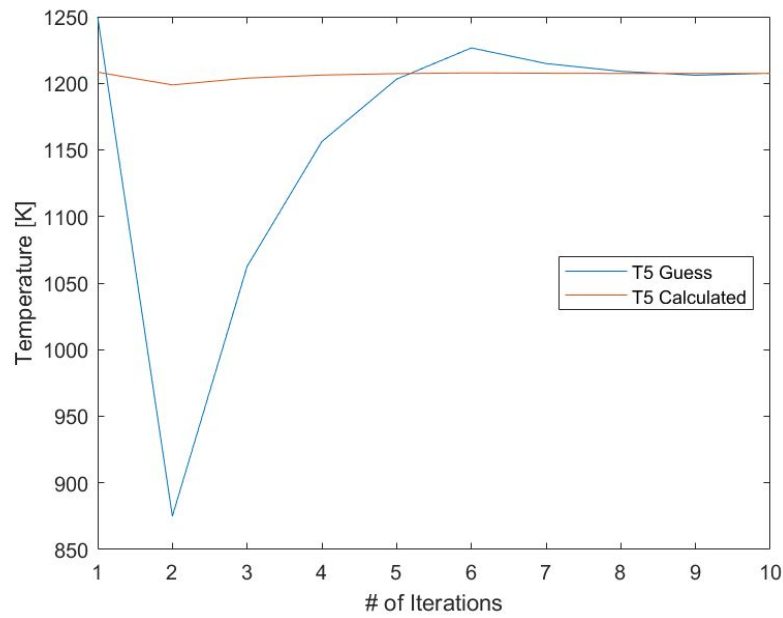


- We assume  $P_1 = 101 \text{ kPa}$ .
- We assume  $T_1 = 25^\circ\text{C}$  which also can be  $T_1 = 298.15 \text{ K}$ .
- We assume  $\bar{M} = 28.97 \text{ kg/kmol}$ .
- We assume  $\dot{m} = 6.0 \text{ kg/s}$ .
- We assume air as an ideal gas.
- $T_{avg} = 0.5(T_r + T_p)$ .
- At  $T_1 = 25^\circ\text{C}$ , the molar enthalpy is zero.
- $P_2 = 500 \text{ kPa}$ .
- $T_4 = 1600 \text{ K}$ .
- $\eta_{comp} = 0.85$
- $\eta_{turb} = 0.85$
- $\dot{Q}_{solar} = 0$
- $\epsilon_{regen} = 0.75$
- $\gamma = 0.25$
- Initial  $\alpha$  ratio is stoichiometric as given by [Eqn 2]

#### Algorithm summary of the program:

1. Initialize constants and assumptions
2. Initiate a for-loop with 2 iterations:
  - a. Call the Task2 program as a function to find the enthalpy, temperature, and work input required  $\dot{W}_{req}$  at State 2.
  - b. Guess  $T_{5,guess}$ . For the turbine expansion process, calculate  $\hat{c}_{p,prod}$ . Use constant  $\hat{c}_p$  and  $\hat{c}_v$  analysis [Eqn 7] and [Eqn 9] in order to calculate  $T_5$ . Implement bisection method to converge upon a  $T_5$  value with error  $|T_5 - T_{5,guess}| < 0.2^\circ\text{C}$ .
  - c. For the regenerator, find the  $\hat{c}_{p,air}$  and  $\hat{c}_{p,prod}$  values at  $T_{avg} = 0.5(T_2 + T_5)$ . Solve for  $T_{2r}$  using [Eqn 10] and thermodynamic equations.
  - d. Find  $T_3$  using an energy balance with  $\dot{Q}_{solar}$ . Because  $\dot{Q}_{solar} = 0$ ,  $T_3$  will be equal to  $T_{2r}$ ; the relevant  $\hat{c}_{p,air}$  may also be found using Task 3 at  $T_{2r}$ .
  - e. Utilize the Task 1 program (implemented as “Task4supp”) to find the corrected  $\alpha$  value using  $T_4$  and the  $T_3$  we found. Go through steps (b) through (d) in the second iteration to recalculate the aforementioned values.
3. Upon completing the for-loop, solve for  $\dot{P}_{out}$ ,  $\dot{Q}_{burner}$ , and  $\eta_{system}$  using Eqns. [Eqn 17], [Eqn 18], and [Eqn 19]. Compare  $\eta_{system}$  to  $\eta_{class}$ , which is found using [Eqn 11].
  - a.  $\dot{P}_{out} = \dot{W}_{turbine, out} - \dot{W}_{req}$
  - b.  $\dot{Q}_{burner} = \dot{n}_{prod} \hat{c}_{p,prod} (T_4 - T_3)$
  - c.  $\eta_{system} = \dot{P}_{out} / (\dot{Q}_{burner} + \dot{Q}_{solar})$
  - d.  $\eta_{class}$

#### Results:



**Fig. 4: Convergence of  $T_5$**

We see that in Figure 4 that our bisection method  $T_5$  indeed converges. Our resulting deliverable values are as follows:

- $\dot{P}_{out} = 2070.3 \text{ kW}$
- $\dot{Q}_{burner} = 4735.0 \text{ kW}$
- $\eta_{system} = 0.4372$
- $\eta_{class} = 0.4284$

Additionally, we found the following intermediate or state values:

- $\alpha_{stoich} = 13.0900$
- $\alpha_{corrected} = 51.2669$
- $T_2 = 497.4372 \text{ K}$
- $T_3 = 1000.8 \text{ K}$
- $T_5 = 1207.5 \text{ K}$
- $\dot{W}_{turbine, out} = 3290.0 \text{ kW}$
- $\dot{W}_{req} = 1219.7 \text{ kW}$

## Task 5(a) and (b)

### Task description:

(a): Using the system analysis program created in Task 4, we are to take into account variation of  $\dot{Q}_{solar}$  during the day from 0 MW (nighttime) to 2.0, 2.5, and 3.0 MW. We are to determine the resulting

changes in net power output  $\dot{P}_{out}$ , heat input into the combustor  $\dot{Q}_{burner}$ , and system efficiency  $\eta_{system}$  compared to  $\eta_{class}$ .

(b): Using the system analysis program created in Task 4, we are to take into account variation of the mole fraction of propane  $\gamma$  within a range of 0 to 0.5 and understand the impact upon system performance.

### Assumptions/Idealizations:

All assumptions from Task 4 hold, with the following changes for parts (a) and (b):

(a)  $\dot{Q}_{solar} = 0, 2.0, 2.5, 3.0 \text{ MW}$ ,  $\gamma = 0.25$

(b) Assume  $\dot{Q}_{solar} = 0$ ,  $\gamma = 0, 0.25, 0.5$

### Algorithm summary of the program:

The algorithm summary is identical to that of Task 4, with one exception - because  $\dot{Q}_{solar}$  changes,  $T_3$  is no longer equal to  $T_{2r}$ . As a result,  $T_3$  must also be guessed and solved using the bisection method as with finding  $T_5$ .

### Results:

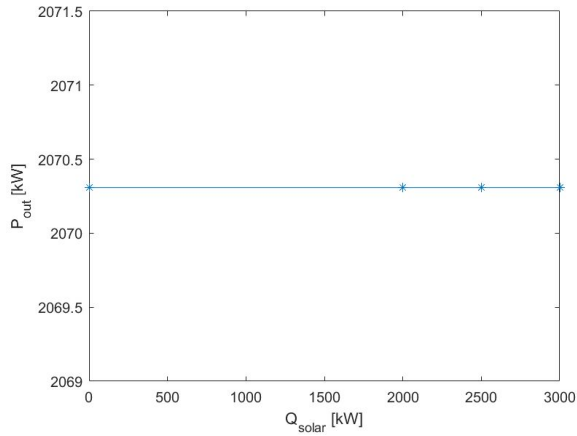
(a)

$\dot{Q}_{solar}$ [kW]	$\dot{Q}_{burner}$ [kW]	$\dot{P}_{out}$ [kW]	$\eta_{system}$	$\eta_{class}$
0	4734.633591	2070.308434	0.4372689869	0.4283605165
2000	2432.743426	2070.308434	0.4670490112	0.4283605165
2500	1882.982015	2070.308434	0.4723515695	0.4283605165
3000	1341.885428	2070.308434	0.4768224469	0.4283605165

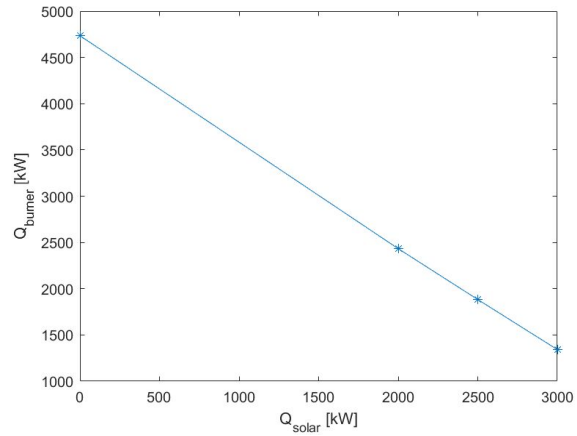
**Table 1**

Our deliverables are tabulated in Table 1 above.  $\dot{P}_{out}$  stays constant throughout variation in  $\dot{Q}_{solar}$ . As seen in Eqn. [17],  $\dot{P}_{out}$  is only dependent upon  $\dot{W}_{turbine, out}$  and  $\dot{W}_{req}$ . As  $\dot{W}_{turbine, out}$  is primarily dependent on the difference between the constant  $T_4$  and  $T_5$  (which also turns out to be constant across varying  $\dot{Q}_{solar}$  values),  $\dot{W}_{turbine, out}$  is constant throughout the day. Additionally,  $\dot{W}_{req}$  is dependent upon the assumed constants  $P_2$  and  $\eta_{comp}$ , and is therefore itself constant. Thus, it makes sense for  $\dot{P}_{out}$  to be constant throughout the day, as seen in Figure 5.

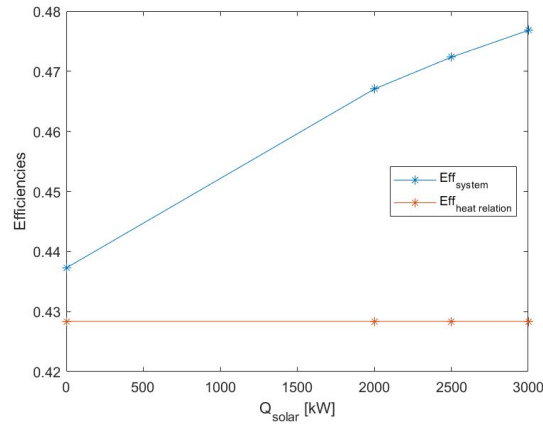
However, system efficiency actually increases as  $\dot{Q}_{solar}$  increases (Figure 6). We also note that the required heat input into the combustor  $\dot{Q}_{burner}$  decreases as  $\dot{Q}_{solar}$  increases (Figure 7). As efficiency is the net power output over the total heat input, we see that the increases in system efficiency is due to the decrease in required  $\dot{Q}_{burner}$ , not because of an increase in  $\dot{P}_{out}$ .



**Fig. 5:**  $\dot{P}_{out}$  over  $\dot{Q}_{solar}$



**Fig. 6:**  $\dot{Q}_{burner}$  over  $\dot{Q}_{solar}$



**Fig. 7:**  $\dot{P}_{out}$  over  $\dot{Q}_{solar}$

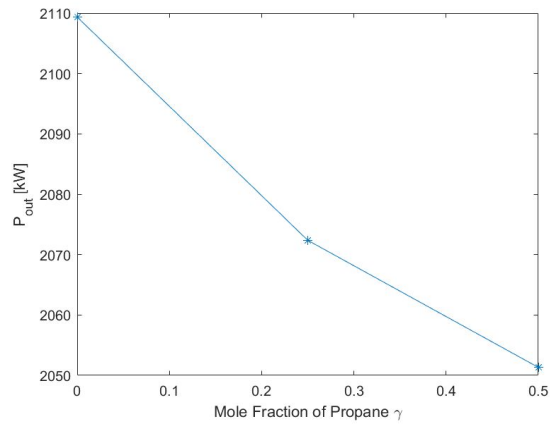
(b)

Propane Mole Fraction Ratio $\gamma$	$\dot{Q}_{burner}$ [kW]	$\dot{P}_{out}$ [kW]	$\eta_{system}$	$\eta_{class}$
0	4738.746897	2109.342238	0.4451265881	0.4285166515
0.25	4739.410797	2072.368703	0.4372629409	0.4283605165
0.5	4708.183244	2051.3234	0.435693195	0.4282737671

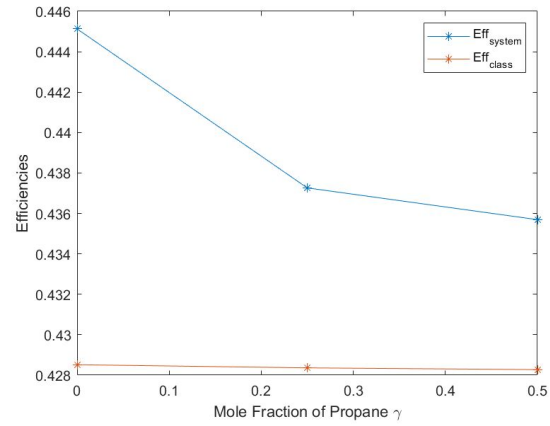
**Table 2**

System performance across variation of the propane mole fraction ratio  $\gamma$  is tabulated above in Table 2.

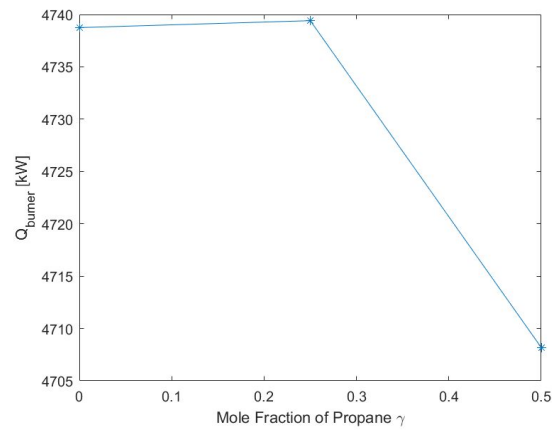
As Figure 8 demonstrates, as  $\gamma$  increases,  $\dot{P}_{out}$  decreases. Meanwhile, as  $\gamma$  increases, the required heat input  $\dot{Q}_{burner}$  decreases. However, this decrease is not enough to maintain system efficiency  $\eta_{system}$  levels, and it thus decreases over  $\gamma$ .



**Fig. 8:  $\dot{P}_{out}$  over  $\gamma$**



**Fig. 9:  $\dot{Q}_{burner}$  over  $\gamma$**



**Fig. 10:  $\dot{P}_{out}$  over  $\gamma$**

## **Appendix A: MATLAB Code**

## Task1.m

```

%% Task 1 Problem Statement
% Find molar air-to-fuel ratio alpha for i) pure propane, ii) pure
methane,
%   iii) 50% mixture

%% Initializing Constants/Assumptions

Tr = 550; %[K]
Tp = 1900; %[K]
Tavg = (Tr + Tp)/2;
To = 25+273; %[K] from 25 oC

% Fuel Propane ratios for i) pure propane, ii) pure methane,
%   iii) 50 percent mixture
g1 = 1;
g2 = 0;
g3 = 0.5;

%% Finding h_i(T) Molar Enthalpy for Gas Species i
% cp = a + bT + cT^2 + dT^3, for T = Tavg
% 6 Gas species:
%   1) C3H8
%   2) CH4
%   3) O2
%   4) H2O
%   5) CO2
%   6) N2

a = [-4.04 19.89 25.48 32.24 22.26 28.90];
b = [30.48 5.024 1.520 0.1923 5.981 -0.1571].*10^-2;
c = [-15.72 1.269 -0.7155 1.055 -3.501 0.8081].*10^-5;
d = [31.74 -11.01 1.312 -3.595 7.469 -2.873].*10^-9;

cp=zeros(1,6);
for i=1:length(cp)
    cp(i) = a(i) + b(i)*Tavg + c(i)*Tavg^2 + d(i)*Tavg^3; %[kJ/(kmol*K)]
end

ho = [-103850 -74850 0 -241820 -393520 0]; %[kJ/kmol]
h = @(n,T) ho(n) + cp(n)*(T-To); %Molar Enthalpy

```

```

%% Finding alpha_i for Cases (i), (ii), (iii)

a1 = 4.76*(-g1*h(1,Tr) - (1-g1)*h(2,Tr) - (3*g1+2)*h(3,Tp) + ...
      (2+2*g1)*h(4,Tp) + (1+2*g1)*h(5,Tp)) / ...
      (h(3,Tr) + 3.76*h(6,Tr) - 3.76*h(6,Tp) - h(3,Tp));

a2 = 4.76*(-g2*h(1,Tr) - (1-g2)*h(2,Tr) - (3*g2+2)*h(3,Tp) + ...
      (2+2*g2)*h(4,Tp) + (1+2*g2)*h(5,Tp)) / ...
      (h(3,Tr) + 3.76*h(6,Tr) - 3.76*h(6,Tp) - h(3,Tp));

a3 = 4.76*(-g3*h(1,Tr) - (1-g3)*h(2,Tr) - (3*g3+2)*h(3,Tp) + ...
      (2+2*g3)*h(4,Tp) + (1+2*g3)*h(5,Tp)) / ...
      (h(3,Tr) + 3.76*h(6,Tr) - 3.76*h(6,Tp) - h(3,Tp));

results = [g1 g2 g3; a1 a2 a3]'; %Left is fuel propane fraction, right is
alpha

```

## Task2.m

```

%% Task 2 Problem Statement
% Compute exit condition from compressor and work required per kg of air
function [h2_out, T2_out, W_req] = Task2(P2, eff_comp)
    %% Initialize Constants/Assumptions
%     P2 = 130;
%     eff_comp = 1;
    T1 = 298;
    P1 = 101; %[kPa]
    R = 8.314; %[kJ/(kmol*K)]
    h1 = 0; %enthalpy of air = 0 at 25oC
    mdot = 6.0; %[kg/s]
    M_molar = 28.97; %[kg/kmol]

    %% Iteration
    error = [1000 1000 1000]; %Initialize error
    T2 = [298 0 1200]; %Initial guess range of T2
    tol = 0.2; %Tolerance of 0.2 oC

    i=1;
    while abs(error(2))>tol %|| (error(1)*error(3)<0)

        mid(i) = (T2(1)+T2(3))/2;
    end

```



```

T2(2) = mid(i);
Tavg1 = (T1+T2)./2;

%(iii-iv): Compute T2_calc1
cp1 = 28.11 + Tavg1.*0.1967e-2 + Tavg1.^2.*0.4802e-5 +
Tavg1.^3.*-1.966e-9;
cv1 = cp1-R;
k1 = cp1./cv1; %Array
T2s_1 = T1*(P2/P1).^((k1-1)./k1);
T2_calc1 = T1 + (T2s_1-T1)./eff_comp; %array

%(v-vii): Compute T2_calc2, Recomputation using T2_calc1 for Tavg
Tavg2 = (T1+T2_calc1)./2; %Array

%(iii-iv): Compute T2_calc1
cp2 = 28.11 + Tavg2.*0.1967e-2 + Tavg2.^2.*0.4802e-5 +
Tavg2.^3.*-1.966e-9;
cv2 = cp2-R;
k2 = cp2./cv2; %Array
T2s_2 = T1*(P2/P1).^((k2-1)./k2);
T2_calc2 = T1 + (T2s_2-T1)./eff_comp;

%Error for Higher and Lower Bounds
error = T2_calc2-T2_calc1; %array

if error(1)*error(2)<0
    T2(3) = T2(2);
else
    T2(1) = T2(2);
end

%For plotting/debugging
T2_result1(i) = T2_calc1(2);
T2_result2(i) = T2_calc2(2);
errorPlot(i) = error(2);
cp_result = cp2(2);
i=i+1;
end

T2_out = T2_result2(end);
h2_out = cp_result*(T2_out-T1)+h1; %[kJ/kmol]
W_req = mdot*cp_result/M_molar*(T2_out-T1); %[kW]

% Plots
%    plot(T2_result1); hold on; plot(T2_result2);

```

```
%      xlabel("Iterations i");
%      ylabel("Temperature [K]");

end
```

## Task3.m

```
%% Task 3 Problem Statement
% Compute cp_prod for product gas mixture as mole-fraction weighed average
% of the cp values. Assume stoichiometric conditions.

function cp_prod = Task3(a)
    %% Initializing Constants/Assumptions
    g = 0.25;
    Tavg = 600; %[K]

    % Test Case:
    % a_stoich = 4.76*(2+3*g);
    % a = a_stoich;

    mol_total = (3.76*a/4.76) + (a/4.76 - 3*g - 2) + (2 + 2*g) + (1 +
2*g);

    %% Molar Relations
    y_N2 = [3.76*a/4.76] / mol_total;
    y_O2 = [a/4.76 - 3*g - 2] / mol_total;
    y_H2O = [2 + 2*g] / mol_total;
    y_CO2 = [1 + 2*g] / mol_total;

    % 1) O2
    % 2) H2O
    % 3) CO2
    % 4) N2

    a = [25.48 32.24 22.26 28.90];
    b = [1.520 0.1923 5.981 -0.1571].*10^-2;
    c = [-0.7155 1.055 -3.501 0.8081].*10^-5;
    d = [1.312 -3.595 7.469 -2.873].*10^-9;

    cp_O2 = a(1) + b(1)*Tavg + c(1)*Tavg^2 + d(1)*Tavg^3; %[kJ/(kmol*K)]
    cp_H2O = a(2) + b(2)*Tavg + c(2)*Tavg^2 + d(2)*Tavg^3;
    cp_CO2 = a(3) + b(3)*Tavg + c(3)*Tavg^2 + d(3)*Tavg^3;
```

```

cp_N2 = a(4) + b(4)*Tavg + c(4)*Tavg^2 + d(4)*Tavg^3;

cp_prod = y_H2O*cp_H2O + y_CO2*cp_CO2 + y_N2*cp_N2 + y_O2*cp_O2;
%[kJ/(kmol*K)]

%% Comparison to cp_air [Table pg. 7]
cp_air = 28.11 + 0.1967e-2*Tavg + 0.4802e-5*Tavg^2 - 1.966e-9*Tavg^3;

fprintf("At T = 600 K: \n    cp_prod = " + cp_prod + " [kJ/(kmol*K)]
\n" + ...
        "    cp_air = " + cp_air + " [kJ/(kmol*K)]");
end

```

## Task4.m

```

%% Task 4 Problem Statement

%% Constants/Assumptions

mdot_air = 6.0;
M_air = 28.97;
P1 = 101; %[kPa]
T1 = 298; %[K], 25oC
P2 = 500; %[kPa]
T4 = 1600; %[K]
g = 0.25;
Qs = 0;
eff_comp = 0.85;
eff_turb = 0.85;
e_regen = 0.75;

h1 = 0; %[kJ/kmol] - find enthalpies at other states by determining change
in enthalpy
R = 8.314; %[kJ/(kmol*K)]

a_stoich = 4.76*(2+3*g);
a = a_stoich;

for z = 1:2

```

```

%% (i) Compressor
[h2, T2, W_req] = Task2(P2, eff_comp);

%% (ii)
% Implement Task3 where necessary

%% (iii & iv): Turbine Expansion Process
error = [1000 1000 1000];
T5_guess = [500 0 2000];
tol = 0.2;

i=1;
while(abs(error(2))>tol)
    mid = (T5_guess(1)+T5_guess(3))/2;
    T5_guess(2) = mid;

    Tavg = 0.5*(T4+T5_guess);
    cp_prod_turbine = Task3(a,g,Tavg);
    cv_prod_turbine = cp_prod_turbine - R;
    k = cp_prod_turbine./cv_prod_turbine;
    T5_s = T4*(P1/P2).^((k-1)./k);
    T5_calc = eff_turb.*(T5_s - T4) + T4;

    error = T5_calc - T5_guess;

    %Tighten the T5_guess bounds
    if error(1)*error(2)<0
        T5_guess(3) = T5_guess(2);
    else
        T5_guess(1) = T5_guess(2);
    end

    T5_result(i) = T5_guess(2);
    T5_constant(i) = T5_calc(2);
    cp_prod_turbine_result(i) = cp_prod_turbine(2);
    i=i+1;
end
T5 = T5_result(end);
cp_prod_turbine_out = cp_prod_turbine_result(end);

%% (v): Regenerator

Tavg_regen = 0.5*(T2 + T5_result(end));
[cp_air_regen, cp_prod_regen] = Task3(a,g,Tavg_regen);

```

```

M_N2 = 28.01;
M_O2 = 32.00;
M_H2O = 18.02;
M_CO2 = 44.01;

n_prod = 3.76/4.76*a + (a/4.76-3*g-2) + (2+2*g) + (1+2*g);
m_prod = M_N2*3.76/4.76*a + M_O2*(a/4.76-3*g-2) + M_H2O*(2+2*g) + ...
    M_CO2*(1+2*g);

ndot_prod = mdot_air/(m_prod/n_prod); % [kmol/s]
ndot_air = mdot_air/M_air; % [kmol/s]

n_cp_air = ndot_air*cp_air_regen;
n_cp_prod = ndot_prod*cp_prod_regen;
n_cp_min = min([n_cp_air n_cp_prod]);

syms T2_r
eqn1 = e_regen == (n_cp_air)*(T2_r - T2)/(n_cp_min*(T5-T2));
T2_r_ans = double(solve(eqn1)); % [K]

%% (vi): Find T3

[f, cp_air] = Task3(a,g,T2_r_ans);
T3 = Qs/(ndot_air*cp_air) + T2_r_ans;

% can only evaluate cp_air at T2_r_ans if T2_r_ans = T3;
% this is the case for Task 4; however, for Task 5, T2_r_ans != T3;
% For Task 5, cp_air must be evaluated at Tavg of T2_r and T3.

%% (vii) Compute a
% Eq. 3
a_corrected = Task4supp(g, T3, T4);
a_result(z) = a_corrected;
end
a_result = a_result(1);

%% Performance Calculations
W_out = ndot_prod*cp_prod_turbine_out*(T4-T5);
%Tavg_burner = 0.5*(T4-T3);
Tavg_burner = T4;
cp_prod_burner = Task3(a_result,g,Tavg_burner);

Qburner = ndot_prod*cp_prod_burner*(T4-T3); %Q for combustor
power_out = W_out-W_req; %[W]

```

```

eff_sys = power_out/(Qs + Qburner);

eff_class = (eff_turb*(1-(P1/P2)^((k-1)/k)) -
(1/eff_comp*T1/T4*((P2/P1)^((k-1)/k)-1)))/...
    (1-e_regen*(1-eff_turb+eff_turb*(P1/P2)^((k-1)/k)) - ...
    (1-e_regen)*(T1/T4)*(1-(1/eff_comp) +
(1/eff_comp)*(P2/P1)^((k-1)/k)));

%% Plot
% plot(T5_result);
% hold on;
% plot(T5_constant);
% xlabel("# of Iterations");
% ylabel("Temperature [K]");
% legend("T5 Guess","T5 Calculated","Location","east");

```

## Task4supp.m

```

%% Task 4 Support: Implementing Task 1 as function
% Find molar air-to-fuel ratio alpha for i) pure propane, ii) pure
methane,
%   iii) 50% mixture

%% Initializing Constants/Assumptions

function [a_out] = Task4supp(g, Tr, Tp)
    % Tr = 550; %[K]
    % Tp = 1900; %[K]
    Tavg = (Tr + Tp)/2;
    To = 25+273; %[K] from 25 oC

    %% Finding h_i(T) Molar Enthalpy for Gas Species i
    % cp = a + bT + cT^2 + dT^3, for T = Tavg
    % 6 Gas species:
    %   1) C3H8
    %   2) CH4
    %   3) O2
    %   4) H2O
    %   5) CO2
    %   6) N2

```

```

a = [-4.04 19.89 25.48 32.24 22.26 28.90];
b = [30.48 5.024 1.520 0.1923 5.981 -0.1571].*10^-2;
c = [-15.72 1.269 -0.7155 1.055 -3.501 0.8081].*10^-5;
d = [31.74 -11.01 1.312 -3.595 7.469 -2.873].*10^-9;

cp=zeros(1,6);
for i=1:length(cp)
    cp(i) = a(i) + b(i)*Tavg + c(i)*Tavg^2 + d(i)*Tavg^3;
%[kJ/(kmol*K)]
end

ho = [-103850 -74850 0 -241820 -393520 0]; %[kJ/kmol]
h = @(n,T) ho(n) + cp(n)*(T-To); %Molar Enthalpy

%% Finding alpha_i for Cases (i), (ii), (iii)

a_out = 4.76*(-g*h(1,Tr) - (1-g)*h(2,Tr) - (3*g+2)*h(3,Tp) + ...
    (2+2*g)*h(4,Tp) + (1+2*g)*h(5,Tp)) / ...
    (h(3,Tr) + 3.76*h(6,Tr) - 3.76*h(6,Tp) - h(3,Tp));
end

```

## Task5\_ab.m

```

%% Constants/Assumptions

mdot_air = 6.0;
M_air = 28.97;
P1 = 101; %[kPa]
T1 = 298; %[K], 25oC
P2 = 500; %[kPa]
T4 = 1600; %[K]
g = 0.5;
Qs = 0;
eff_comp = 0.85;
eff_turb = 0.85;
e_regen = 0.75;

h1 = 0; %[kJ/kmol] - find enthalpies at other states by determining change
in enthalpy
R = 8.314; %[kJ/(kmol*K)]

```

```

a_stoich = 4.76*(2+3*g);
a = a_stoich;

for z = 1:2
    %% (i) Compressor
    [h2, T2, W_req] = Task2(P2, eff_comp);

    %% (ii)
    % Implement Task3 where necessary

    %% (iii & iv): Turbine Expansion Process
    error = [1000 1000 1000];
    T5_guess = [500 0 2000];
    tol = 0.2;

    i=1;
    while(abs(error(2))>tol)
        mid = (T5_guess(1)+T5_guess(3))/2;
        T5_guess(2) = mid;

        Tavg = 0.5*(T4+T5_guess);
        cp_prod_turbine = Task3(a,g,Tavg);
        cv_prod_turbine = cp_prod_turbine - R;
        k = cp_prod_turbine./cv_prod_turbine;
        T5_s = T4*(P1/P2).^((k-1)./k);
        T5_calc = eff_turb.*(T5_s - T4) + T4;

        error = T5_calc - T5_guess;

        %Tighten the T5_guess bounds
        if error(1)*error(2)<0
            T5_guess(3) = T5_guess(2);
        else
            T5_guess(1) = T5_guess(2);
        end

        T5_result(i) = T5_guess(2);
        T5_constant(i) = T5_calc(2);
        cp_prod_turbine_result(i) = cp_prod_turbine(2);
        i=i+1;
    end

    T5 = T5_result(end);
    cp_prod_turbine_out = cp_prod_turbine_result(end);

```



```

%% (v): Regenerator

Tavg_regen = 0.5*(T2 + T5_result(end));
[cp_air_regen, cp_prod_regen] = Task3(a,g,Tavg_regen);

M_N2 = 28.01;
M_O2 = 32.00;
M_H2O = 18.02;
M_CO2 = 44.01;

n_prod = 3.76/4.76*a + (a/4.76-3*g-2) + (2+2*g) + (1+2*g);
m_prod = M_N2*3.76/4.76*a + M_O2*(a/4.76-3*g-2) + M_H2O*(2+2*g) + ...
    M_CO2*(1+2*g);

ndot_prod = mdot_air/(m_prod/n_prod); % [kmol/s]
ndot_air = mdot_air/M_air; % [kmol/s]

n_cp_air = ndot_air*cp_air_regen;
n_cp_prod = ndot_prod*cp_prod_regen;
n_cp_min = min([n_cp_air n_cp_prod]);

syms T2_r
eqn1 = e_regen == (n_cp_air)*(T2_r - T2)/(n_cp_min*(T5-T2));
T2_r_ans = double(solve(eqn1)); % [K]

%% (vi): Find T3 iteratively - use cp_air
error3 = [1000 1000 1000];
T3_guess = [400 0 1600];

j=1;
while(abs(error3(2))>tol)
    mid = (T3_guess(1)+T3_guess(3))/2;
    T3_guess(2) = mid;

    Tavg = 0.5*(T2_r_ans+T3_guess); %array
    [cp_prod, cp_air] = Task3(a,g,Tavg); %arrays
    T3_calc = Qs./(ndot_air.*cp_air) + T2_r_ans;

    error3 = T3_calc - T3_guess;

    %Tighten the T3_guess bounds
    if error3(1)*error3(2)<0
        T3_guess(3) = T3_guess(2);
    else
        T3_guess(1) = T3_guess(2);
    end
end

```

```

        end
        error_out = error3(2);
        T3_result(j) = T3_guess(2); % Require resetting from
        T3_constant(j) = T3_calc(2);
        cp_prod_result(j) = cp_prod(2);
        j=j+1;
    end

    T3 = T3_result(end);
    cp_prod_out = cp_prod_result(end);

    %% (vii) Compute a
    % Eq. 3
    a_corrected = Task4supp(g, T3, T4);
    a_result(z) = a_corrected;
end
a_result = a_result(1);

%% Performance Calculations
W_out = ndot_prod*cp_prod_turbine_out*(T4-T5);
%Tavg_burner = 0.5*(T4-T3);
Tavg_burner = T4;
cp_prod_burner = Task3(a_result,g,Tavg_burner);

Qburner = ndot_prod*cp_prod_burner*(T4-T3); %Q for combustor
power_out = W_out-W_req; %[W]
eff_sys = power_out/(Qs + Qburner);

eff_class = (eff_turb*(1-(P1/P2)^((k-1)/k)) -
(1/eff_comp*T1/T4*((P2/P1)^((k-1)/k)-1)))/...
    (1-e_regen*(1-eff_turb+eff_turb*(P1/P2)^((k-1)/k)) - ...
    (1-e_regen)*(T1/T4)*(1-(1/eff_comp) +
(1/eff_comp)*(P2/P1)^((k-1)/k)));

%% Results and Plot
%
% % Part (a)
% % resultsAdd = [Qs; Qburner; power_out; eff_sys; eff_class];
%
% % Part (b)
% resultsAdd = [g; Qburner; power_out; eff_sys; eff_class];
% results = [results resultsAdd];

%% Part (a)
% results =

```

```

[0,2000,2500,3000;4734.63359107193,2432.74342603970,1882.98201537437,1341.
88542803099;2070.30843392204,2070.30843392204,2070.30843392204,2070.308433
92204;0.437268986944631,0.467049011174485,0.472351569470268,0.476822446892
826;0.428360516508602,0.428360516508602,0.428360516508602,0.42836051650860
2];
% % Row 1: Qs Values
% % Row 2: Qburner
% % Row 3: Power Out
% % Row 4: System Efficiency
% % Row 5: Efficiency from Class Relation
% Qs_vec = results(1,:);
%
% % Plot of Qburner over Varying Qs
% plot(Qs_vec, results(2,:), '*-');
% xlabel("Q_{solar} [kW]");
% ylabel("Q_{burner} [kW]");
%
% % Plot of Net Power Out over Varying Qs
% figure;
% plot(Qs_vec, results(3,:), '*-');
% xlabel("Q_{solar} [kW]");
% ylabel("P_{out} [kW]");
%
% % Plot of Efficiencies
% figure;
% plot(Qs_vec, results(4,:), '*-'); hold on;
% plot(Qs_vec, results(5,:), '*-');
% xlabel("Q_{solar} [kW]");
% ylabel("Efficiencies");
% legend("Eff_{system}", "Eff_{class}", "Location", "east");
%
%% Part (b)
%
% results =
[0,0.250000000000000,0.500000000000000;4738.74689668427,4739.41079682154,4
708.18324435581;2109.34223807536,2072.36870310773,2051.32340021501;0.44512
6588117901,0.437262940890787,0.435693194965200;0.428516651524242,0.4283605
16508602,0.428273767100242];
% % Row 1: g Values
% % Row 2: Qburner
% % Row 3: Power Out
% % Row 4: System Efficiency
% % Row 5: Efficiency from Class Relation
%
% g_vec = results(1,:);

```

```

%
% % Plot of Qburner over Varying Qs
% plot(g_vec, results(2,:), '*-');
% xlabel("Mole Fraction of Propane \gamma");
% ylabel("Q_{burner} [kW]");
%
% % Plot of Net Power Out over Varying Qs
% figure;
% plot(g_vec, results(3,:), '*-');
% xlabel("Mole Fraction of Propane \gamma");
% ylabel("P_{out} [kW]");
%
% % Plot of Efficiencies
% figure;
% plot(g_vec, results(4,:), '*-'); hold on;
% plot(g_vec, results(5,:), '*-');
% xlabel("Mole Fraction of Propane \gamma");
% ylabel("Efficiencies");
% legend("Eff_{system}", "Eff_{class}", "Location", "northeast");

```

## **Appendix B: Thermodynamic Tables**

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

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

[Table 1]

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 <sub>2</sub>	28.90	$-0.1571 \times 10^{-2}$	$0.8081 \times 10^{-5}$	$-2.873 \times 10^{-9}$	273–1800	0.59	0.34
Oxygen	O <sub>2</sub>	25.48	$1.520 \times 10^{-2}$	$-0.7155 \times 10^{-5}$	$1.312 \times 10^{-9}$	273–1800	1.19	0.26
Air	—	28.11	$0.1967 \times 10^{-2}$	$0.4802 \times 10^{-5}$	$-1.966 \times 10^{-9}$	273–1800	0.72	0.33
Hydrogen	H <sub>2</sub>	29.11	$-0.1916 \times 10^{-2}$	$0.4003 \times 10^{-5}$	$-0.8704 \times 10^{-9}$	273–1800	1.01	0.26
Carbon monoxide	CO	28.16	$0.1675 \times 10^{-2}$	$0.5372 \times 10^{-5}$	$-2.222 \times 10^{-9}$	273–1800	0.89	0.37
Carbon dioxide	CO <sub>2</sub>	22.26	$5.981 \times 10^{-2}$	$-3.501 \times 10^{-5}$	$7.469 \times 10^{-9}$	273–1800	0.67	0.22
Water vapor	H <sub>2</sub> O	32.24	$0.1923 \times 10^{-2}$	$1.055 \times 10^{-5}$	$-3.595 \times 10^{-9}$	273–1800	0.53	0.24
Nitric oxide	NO	29.34	$-0.09395 \times 10^{-2}$	$0.9747 \times 10^{-5}$	$-4.187 \times 10^{-9}$	273–1500	0.97	0.36
Nitrous oxide	N <sub>2</sub> O	24.11	$5.8632 \times 10^{-2}$	$-3.562 \times 10^{-5}$	$10.58 \times 10^{-9}$	273–1500	0.59	0.26
Nitrogen dioxide	NO <sub>2</sub>	22.9	$5.715 \times 10^{-2}$	$-3.52 \times 10^{-5}$	$7.87 \times 10^{-9}$	273–1500	0.46	0.18
Ammonia	NH <sub>3</sub>	27.568	$2.5630 \times 10^{-2}$	$0.99072 \times 10^{-5}$	$-6.6909 \times 10^{-9}$	273–1500	0.91	0.36
Sulfur	S <sub>2</sub>	27.21	$2.218 \times 10^{-2}$	$-1.628 \times 10^{-5}$	$3.986 \times 10^{-9}$	273–1800	0.99	0.38
Sulfur dioxide	SO <sub>2</sub>	25.78	$5.795 \times 10^{-2}$	$-3.812 \times 10^{-5}$	$8.612 \times 10^{-9}$	273–1800	0.45	0.24
Sulfur trioxide	SO <sub>3</sub>	16.40	$14.58 \times 10^{-2}$	$-11.20 \times 10^{-5}$	$32.42 \times 10^{-9}$	273–1300	0.29	0.13
Acetylene	C <sub>2</sub> H <sub>2</sub>	21.8	$9.2143 \times 10^{-2}$	$-6.527 \times 10^{-5}$	$18.21 \times 10^{-9}$	273–1500	1.46	0.59
Benzene	C <sub>6</sub> H <sub>6</sub>	-36.22	$48.475 \times 10^{-2}$	$-31.57 \times 10^{-5}$	$77.62 \times 10^{-9}$	273–1500	0.34	0.20
Methanol	CH <sub>3</sub> O	19.0	$9.152 \times 10^{-2}$	$-1.22 \times 10^{-5}$	$-8.039 \times 10^{-9}$	273–1000	0.18	0.08
Ethanol	C <sub>2</sub> H <sub>5</sub> O	19.9	$20.96 \times 10^{-2}$	$-10.38 \times 10^{-5}$	$20.08 \times 10^{-9}$	273–1500	0.40	0.22
Hydrogen chloride	HCl	30.33	$-0.7620 \times 10^{-2}$	$1.327 \times 10^{-5}$	$-4.338 \times 10^{-9}$	273–1500	0.22	0.08
Methane	CH <sub>4</sub>	19.89	$5.024 \times 10^{-2}$	$1.269 \times 10^{-5}$	$-11.01 \times 10^{-9}$	273–1500	1.33	0.57
Ethane	C <sub>2</sub> H <sub>6</sub>	6.900	$17.27 \times 10^{-2}$	$-6.406 \times 10^{-5}$	$7.285 \times 10^{-9}$	273–1500	0.83	0.28
Propene	C <sub>3</sub> H <sub>6</sub>	-4.04	$30.48 \times 10^{-2}$	$-15.72 \times 10^{-5}$	$31.74 \times 10^{-9}$	273–1500	0.40	0.12
n-Butane	C <sub>4</sub> H <sub>10</sub>	3.96	$37.15 \times 10^{-2}$	$-18.34 \times 10^{-5}$	$35.00 \times 10^{-9}$	273–1500	0.54	0.24
i-Butane	C <sub>4</sub> H <sub>10</sub>	-7.913	$41.60 \times 10^{-2}$	$-23.01 \times 10^{-5}$	$49.91 \times 10^{-9}$	273–1500	0.25	0.13
n-Pentane	C <sub>5</sub> H <sub>12</sub>	6.774	$45.43 \times 10^{-2}$	$-22.46 \times 10^{-5}$	$42.29 \times 10^{-9}$	273–1500	0.56	0.21
n-Hexane	C <sub>6</sub> H <sub>14</sub>	6.938	$55.22 \times 10^{-2}$	$-28.55 \times 10^{-5}$	$57.69 \times 10^{-9}$	273–1500	0.72	0.20
Ethylene	C <sub>2</sub> H <sub>4</sub>	3.95	$15.64 \times 10^{-2}$	$-8.344 \times 10^{-5}$	$17.67 \times 10^{-9}$	273–1500	0.54	0.13
Propylene	C <sub>3</sub> H <sub>6</sub>	3.15	$23.83 \times 10^{-2}$	$-12.18 \times 10^{-5}$	$24.62 \times 10^{-9}$	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, 7<sup>th</sup> edition, McGraw Hill, 2011.Here, the universal gas constant =  $\bar{R} = 8314 \text{ J/kmolK}$ 

[Table 2]