

Samuel Simmons

ME 210

Professor Shabany

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Abstract

The effects of adding an economizer that reduced the temperature of the combustion gases for a steam boiler were analyzed. The steam boiler burned methane and air at 1 atm and 25°C with varying amounts of excess air. The economizer reduced the exergy destruction for the steam in the steam boiler but increased the exergy destruction of the combustion gases until the percentage of excess air exceeded about 170%. However, the net effect of adding the economizer was a significant reduction in total exergy destruction from 1450 kJ per kilogram of steam to 1380 kJ per kilogram of steam, with the difference in performance with and without the economizer increasing as the amount of excess air increased. The economizer lowered the difference in flow exergy values for the combustion reactants and products, increased the amount of heat that could be extracted from the same amount of methane, and reduced the amount of methane required to provide the necessary heating for the air. Regardless of the actual amount of air needed to ensure complete combustion of the methane, the boiler with the economizer was found to always outperform the boiler without the economizer.

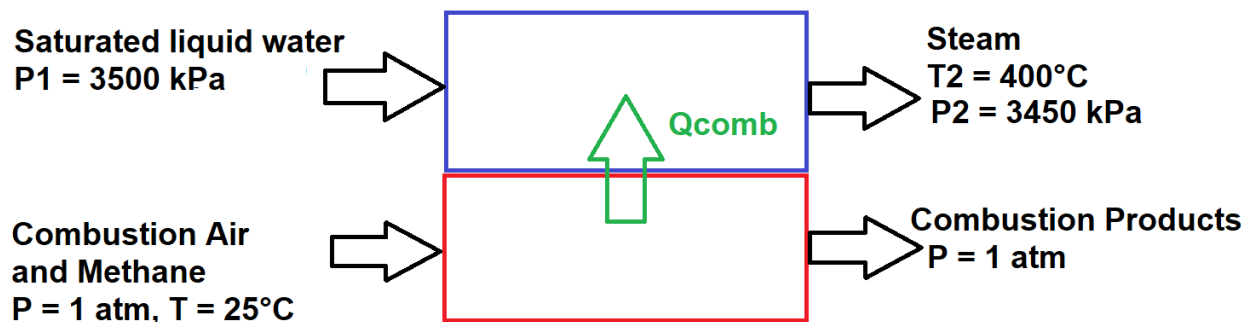
Introduction

A steam boiler was studied that transfers heat from combustion gases to a water stream. The steam boiler converts saturated liquid water at a pressure of 3500 kPa to steam at 400°C and a pressure of 3450 kPa. Methane is burned at a pressure of 1 atm and 25°C and the combustion air needed is supplied at 1 atm and 25°C. For the first case, the combustion products are maintained at a temperature of 300°C. For the second case, an economizer is added to the boiler that reduced the temperature of the

combustion products to 200°C. The change in exergy of the combustion and water streams was evaluated for excess air amounts ranging from 0 to 200 percent per 1 kilogram of steam produced. The exergy lost in the boiler was also plotted in the boiler for the different excess air amounts. A MATLAB program was used to solve the energy and exergy equations and plot the results. Additionally, the results for both cases were compared based on these results. For both cases, it was assumed that the combustion process was constant pressure and not constant volume since this is a steady-flow combustion process. A schematic of the system is shown below in Figure 1 including the combustion heat transfer from the combustion process to the steam.

Figure 1

Schematic of the Steam Boiler System



Methodology

Energy Balance

In order to analyze the steam boiler, the principles of energy balance and exergy balance must be used to determine the exergy change of the combustion reaction and the steam boiler. The enthalpy value for state 1 and state 2 of the water were found to be 1049.7 and 3224.1 kJ/kg respectively. All tabulated values used in this paper were taken from Cengel (2015). The energy balance was done for the water separately, with the heat transferred from the combustion included. Starting with the energy balance:

$$E_{in} - E_{out} = 0$$

$$m_w h_1 + Q_{comb} - m_w h_2 = 0$$

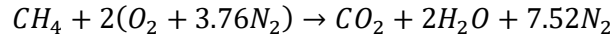
$$\frac{Q_{comb}}{m_w} = (h_2 - h_1)$$

Substituting in the enthalpy values for the water:

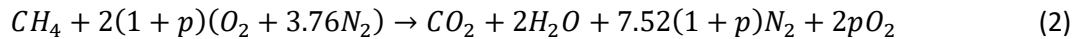
$$\frac{Q_{comb}}{m_w} = (3224.1 - 1049.7)$$

$$\frac{Q_{comb}}{m_w} = 2174.4 \quad (1)$$

This is the final form of the energy equation that will be used for the water. Since the initial and final states of the water needed were already determined, the combustion reaction must provide the desired heating of 2174.4 kJ per kg of steam at different amounts of excess air. For the burning of methane, the balanced combustion reaction with no excess air is:



In order to account for the excess air from 0 to 200%, a variable p was added to represent the percentage of excess air, with a p value of 2 corresponding to 200% excess air. The combustion reaction for an arbitrary percentage of excess air is:



The energy balance must be used to determine the amount of methane and air needed to provide the necessary heating. Since there is 1 kmol of CH_4 in (2), results for the energy balance will be on a per kmol of CH_4 basis. The number of kmol of each product and reactant will be updated in relation to the actual number of kmol of fuel needed to provide the necessary heating found for the energy balance of steam. For the combustion process, the energy balance is:

$$\sum N_{R,i} \overline{h_{R,i}^o} - \sum N_{P,i} \overline{h_{P,i}^o} - \frac{Q_{comb}}{\text{kmol of } CH_4} = 0$$

$$\sum N_{R,i} \overline{h_{R,i}^o} - \sum N_{P,i} \overline{h_{P,i}^o} = \frac{Q_{comb}}{\text{kmol of } CH_4}$$

To determine \bar{h}^o at, the enthalpy of formation and the difference between the enthalpy at the actual temperature and pressure and at the reference temperature and pressure must be evaluated as shown in (3). These values were determined from tabulated values for each chemical and are tabulated below in Table 1. Note that the combustion products were assumed to also be at a pressure of 1 atm, so the enthalpy difference was a function of temperature. In addition the reactants entered at 25°C, the same reference temperature use for the tabulated values of enthalpy of formation, so only the enthalpy of formation is needed for the reactants.

$$\bar{h}^o = \bar{h}_f^o + \bar{h}(T, P) - \bar{h}(T_{ref}, P_{ref}) \quad (3)$$

Table 1

Table of the Enthalpy Values for Each Combustion Product and Reactant for Both Cases

Compound	Temperature (°C)	\bar{h}_f^o	$\bar{h}(T, P)$	$\bar{h}(T_{ref}, P_{ref})$	\bar{h}^o
CH_4	25	-74850	-	-	-74850
$O_{2,R}$	25	0	-	-	0
$N_{2,R}$	25	0	-	-	0
CO_2	300	-393520	21017.1	9364	-381866.9
$H_2O(g)$	300	-241820	19431.4	9904	-232289.6
$N_{2,P}$	300	0	16576.5	8669	8087.5
$O_{2,P}$	300	0	17071.5	8682	8389.5
CO_2	200	-393520	16489.6	9364	-386394.1
$H_2O(g)$	200	-241820	15886.9	9904	-235837.1
$N_{2,P}$	200	0	13785.9	8669	5116.9
$O_{2,P}$	200	0	13949.3	8682	5257.3

Since the enthalpy of the reactant oxygen and nitrogen is 0, they can be omitted from the energy balance equation. Plugging these values into the energy balance equation from earlier produces the following equation:

$$\bar{h}_{CH_4}^o - N_{CO_2}\bar{h}_{CO_2}^o - N_{H_2O}\bar{h}_{H_2O}^o - N_{O_2}\bar{h}_{O_2}^o - N_{N_2,P}\bar{h}_{N_2,P}^o = \frac{Q_{comb}}{kmol \text{ of } CH_4}$$

For the arbitrary percent air values, the number of kmol of each reactant and product can be written as:

$$1\bar{h}_{CH_4}^o - 1\bar{h}_{CO_2}^o - 2\bar{h}_{H_2O}^o - 2p\bar{h}_{O_2}^o - 2(1+p)\bar{h}_{N_2,P}^o = \frac{Q_{comb}}{kmol \text{ of } CH_4} \quad (4)$$

This equation can be solved for both cases using the enthalpy values shown in table 1. Once the heat generated by the combustion process per kmol of CH_4 was determined, the actual number of kmol of CH_4 needed was found by:

$$N_{CH_4} = Q_{comb} \left(\frac{Q_{comb}}{\text{kmol of } CH_4} \right)^{-1} \quad (5)$$

Exergy Balance

Next, the exergy balance equation must be used to determine the rate of exergy destruction for the steam. Starting with the exergy balance equation:

$$\Delta X = Q \left(1 - \frac{T_0}{T} \right) + m_w \psi_1 - m_w \psi_2 - X_{dest}$$

$$0 = Q \left(1 - \frac{T_0}{T} \right) + m_w \psi_1 - m_w \psi_2 - X_{dest}$$

$$\frac{X_{dest}}{m_w} = \frac{Q_{comb}}{m_w} \left(1 - \frac{T_0}{T} \right) + \psi_1 - \psi_2$$

For the flow exergy terms, the ambient temperature will be assumed to be 25°C. The entropy values of the water at state 1 and state 2 are tabulated and were found to be 2.7253 kJ per kg-K and 6.8509 kJ per kg-K, respectively. The difference in flow exergy terms can be determined by the equation below.

$$\psi_1 - \psi_2 = (h_1 - h_2) - T_0(s_1 - s_2)$$

$$\psi_1 - \psi_2 = (1049.7 - 3224.1) - 298.15(2.7253 - 6.8509)$$

$$\psi_1 - \psi_2 = -944.352 \frac{\text{kJ}}{\text{kg}}$$

Plugging the difference in flow exergy terms and the combustion heat transfer in and assuming that the ambient temperature is 25°C, produced the following equation:

$$\frac{X_{dest}}{m_w} = 2174.4 \left(1 - \frac{298.15}{T} \right) - 944.352$$

Note that the temperature value at which the heat transfer occurs was assumed to be 300°C for the first case and 200°C for the second case based on the temperature of the combustion products. The results for case 1 and case 2 are shown below.

$$\left(\frac{X_{dest}}{m_w}\right)_{Case\ 1} = 98.9347 \frac{kJ}{kg\ of\ steam}$$

$$\left(\frac{X_{dest}}{m_w}\right)_{Case\ 2} = -140.1254 \frac{kJ}{kg\ of\ steam}$$

To determine the exergy change of the combustion process, the exergy balance done for the combustion process, starting with the equation below:

$$\Delta X = -Q \left(1 - \frac{T_0}{T}\right) + \sum N_{R,i} \overline{\psi}_{R,i} - \sum N_{P,i} \overline{\psi}_{P,i} - X_{dest}$$

$$0 = -Q \left(1 - \frac{T_0}{T}\right) + \sum N_{R,i} \overline{\psi}_{R,i} - \sum N_{P,i} \overline{\psi}_{P,i} - X_{dest}$$

$$\frac{X_{dest,comb}}{kmol\ of\ CH_4} = -\frac{Q_{comb}}{kmol\ of\ CH_4} \left(1 - \frac{T_0}{T}\right) + \sum N_{R,i} \overline{\psi}_{R,i} - \sum N_{P,i} \overline{\psi}_{P,i}$$

The equation above was derived assuming steady flow. To determine the flow exergy values of the products and reactants, the following equation was used:

$$\overline{\psi}_i = \overline{h}_i^o - T_0 \overline{s}_i^o$$

$$\overline{\psi}_i = \overline{h}_i^o - T_0 \left(\overline{s}_i^o(T, P_{ref}) - \bar{R} \ln \left(\frac{P_i}{P_{ref}} \right) \right)$$

$$\overline{\psi}_i = \overline{h}_i^o - T_0 \left(\overline{s}_i^o(T, P_{ref}) - \bar{R} \ln(X_i) \right) \quad (6)$$

The entropy value of each component at the temperature and partial pressure was determined using (6). Since the total pressure of combustion reactants and products was 1 atm, the same pressure as the reference pressure used in the tabulated values for entropy, the equation was able to be written in terms of the mole fraction of each component X_i . This mole fraction is obtained by dividing the moles of that constituent by the total moles of the products or reactants, depending on whether the

constituent of interest was a product or reactant. Note that for the methane fuel, the entropy value was able to be directly read off of a table.

$$N_{tot,R} = 2(1 + p)(4.76)$$

$$N_{tot,P} = 3 + 2(1 + p)(3.76) + 2p$$

Table 2

Table of the Entropy Values for Each Combustion Product and Reactant for Both Cases

Compound	Temperature (°C)	$\bar{s}^o(T, P_{ref})$	X_i	$\bar{R} \ln(X_i)$	\bar{s}_i^o
CH_4	25	-	-	-	186.16
$O_{2,R}$	25	205.033	$\frac{2(1+p)}{N_{tot,R}}$	$8.3145 \ln \frac{2(1+p)}{N_{tot,R}}$	$205.033 - 8.3145 \ln \frac{2(1+p)}{N_{tot,R}}$
$N_{2,R}$	25	191.502	$\frac{2(1+p)3.76}{N_{tot,R}}$	$8.3145 \ln \frac{2(1+p)3.76}{N_{tot,R}}$	$191.502 - 8.3145 \ln \frac{2(1+p)3.76}{N_{tot,R}}$
CO_2	300	241.045	$\frac{1}{N_{tot,P}}$	$8.3145 \ln \frac{1}{N_{tot,P}}$	$241.045 - 8.3145 \ln \frac{1}{N_{tot,P}}$
$H_2O(g)$	300	211.273	$\frac{2}{N_{tot,P}}$	$8.3145 \ln \frac{2}{N_{tot,P}}$	$211.273 - 8.3145 \ln \frac{2}{N_{tot,P}}$
$N_{2,P}$	300	210.692	$\frac{2(1+p)3.76}{N_{tot,P}}$	$8.3145 \ln \frac{2(1+p)3.76}{N_{tot,P}}$	$210.692 - 8.3145 \ln \frac{2(1+p)3.76}{N_{tot,P}}$
$O_{2,P}$	300	224.883	$\frac{2p}{N_{tot,P}}$	$8.3145 \ln \frac{2p}{N_{tot,P}}$	$224.883 - 8.3145 \ln \frac{2p}{N_{tot,P}}$
CO_2	200	232.371	$\frac{1}{N_{tot,P}}$	$8.3145 \ln \frac{1}{N_{tot,P}}$	$232.371 - 8.3145 \ln \frac{1}{N_{tot,P}}$
$H_2O(g)$	200	204.479	$\frac{2}{N_{tot,P}}$	$8.3145 \ln \frac{2}{N_{tot,P}}$	$204.479 - 8.3145 \ln \frac{2}{N_{tot,P}}$
$N_{2,P}$	200	204.999	$\frac{2(1+p)3.76}{N_{tot,P}}$	$8.3145 \ln \frac{2(1+p)3.76}{N_{tot,P}}$	$204.999 - 8.3145 \ln \frac{2(1+p)3.76}{N_{tot,P}}$
$O_{2,P}$	200	218.881	$\frac{2p}{N_{tot,P}}$	$8.3145 \ln \frac{2p}{N_{tot,P}}$	$218.881 - 8.3145 \ln \frac{2p}{N_{tot,P}}$

The exergy equation can then be written as, noting that the equation is also on a per 1 kg of

steam basis:

$$\frac{X_{dest,comb}}{m_w} = -Q_{comb} \left(1 - \frac{298.15}{T}\right) + N_{CH_4} \left(\sum N_{R,i} \bar{\psi}_{R,i} - \sum N_{P,i} \bar{\psi}_{P,i} \right)$$

$$\frac{X_{dest,comb}}{m_w} = -Q_{comb} \left(1 - \frac{298.15}{T}\right) + N_{CH_4} \left(\bar{\psi}_{CH_4} + N_{O_{2,R}} \bar{\psi}_{O_{2,R}} + N_{N_{2,R}} \bar{\psi}_{N_{2,R}} - N_{CO_2} \bar{\psi}_{CO_2} - N_{H_2O} \bar{\psi}_{H_2O} - N_{N_{2,P}} \bar{\psi}_{N_{2,P}} - N_{O_{2,P}} \bar{\psi}_{O_{2,P}} \right)$$

$$\frac{X_{dest,comb}}{m_w} = -2174.4 \left(1 - \frac{298.15}{T}\right) + N_{CH_4} \left(\bar{\psi}_{CH_4} + 2(1+p) \bar{\psi}_{O_{2,R}} + 7.52(1+p) \bar{\psi}_{N_{2,R}} - \bar{\psi}_{CO_2} - 2 \bar{\psi}_{H_2O} - 7.52(1+p) \bar{\psi}_{N_{2,P}} - 2p \bar{\psi}_{O_{2,P}} \right) \quad (7)$$

MATLAB will be used to solve (7) for each value of percent excess air due to the large number of values that need to be calculated for this problem. Note that each case has different flow exergy values

for the combustion products and different values for T due to the temperature of the combustion products being different. Finally, the total exergy destroyed by the boiler can be calculated by adding together the exergy destruction from heating the water and the exergy destruction from the combustion reaction, producing the equations shown below in (8) and (9). Since all equations were done for a single kilogram of steam, all exergy values are exergy destroyed per kilogram of steam.

$$\frac{X_{dest,total,1}}{m_w} = \left(\frac{X_{dest}}{m_w} \right)_{Case\ 1} + \left(\frac{X_{dest,comb}}{m_w} \right)_{Case\ 1} \quad (8)$$

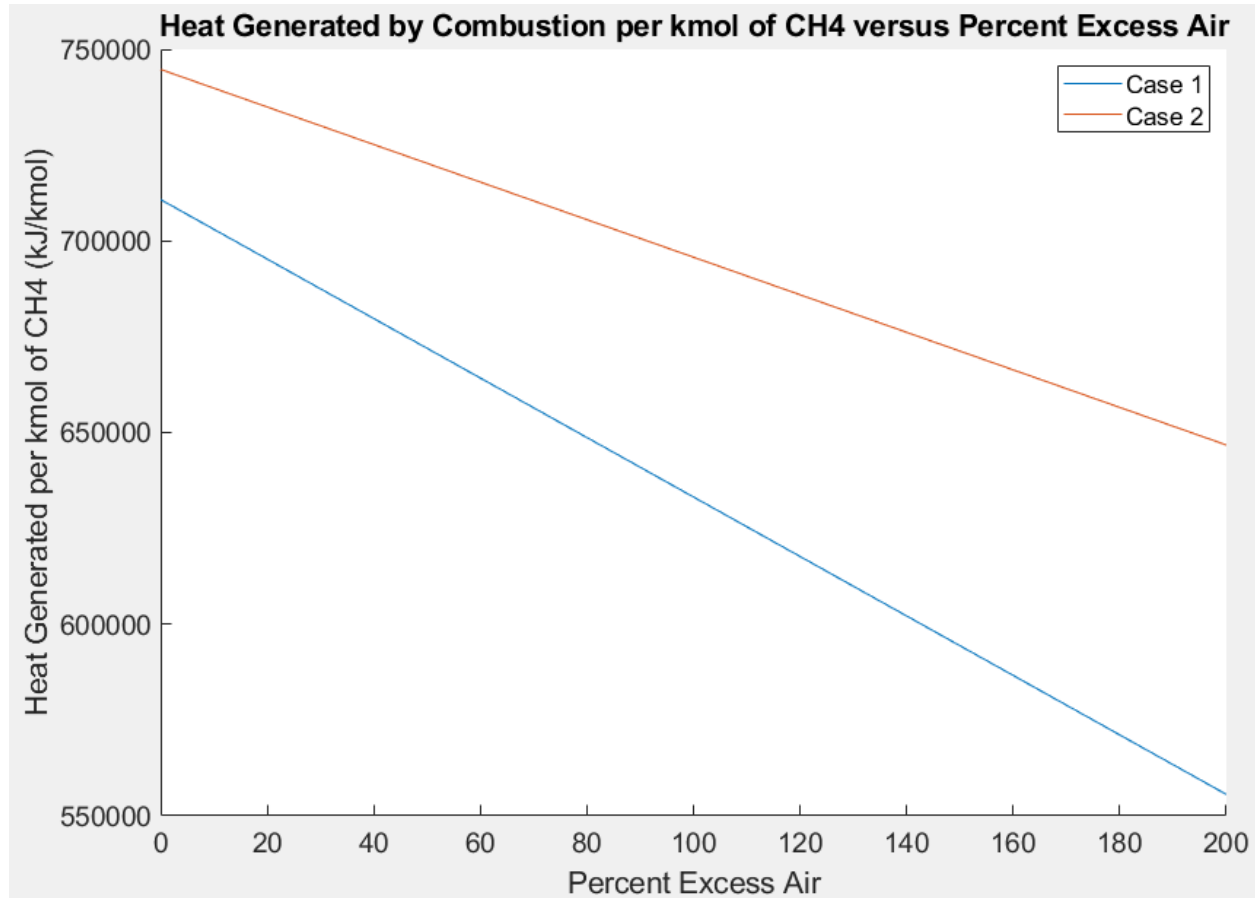
$$\frac{X_{dest,total,2}}{m_w} = \left(\frac{X_{dest}}{m_w} \right)_{Case\ 2} + \left(\frac{X_{dest,comb}}{m_w} \right)_{Case\ 2} \quad (9)$$

Results and Discussion

First, the heat generated from combustion was determined per kmol of CH_4 based on (4). The results are shown below in Figure 2, and it was found adding more excess air reduced the heat generated from the combustion of methane. This is due to some of the heat generated by the combustion process being lost to heating the excess air. The second case where the temperature of the combustion products was reduced to 200°C was found to produce larger amounts of heat per kmol of methane. Reducing the temperature of the products produced more heat from the combustion since more heat was able to be extracted from the combustion due to less energy being used on heating the products. The heat generation results compare similarly to the heat of combustion of methane at standard conditions of 891,000 kJ per kmol ("Combustion Heat"). The heat of combustion at standard conditions assumes that the combustion products are at 25°C and that the water produced is in the liquid phase and no excess air. Due to the different temperatures, assumption that the water produced was a gas, and that up to 200% excess air was provided, the slightly lower heat generation values for the methane was expected.

Figure 2

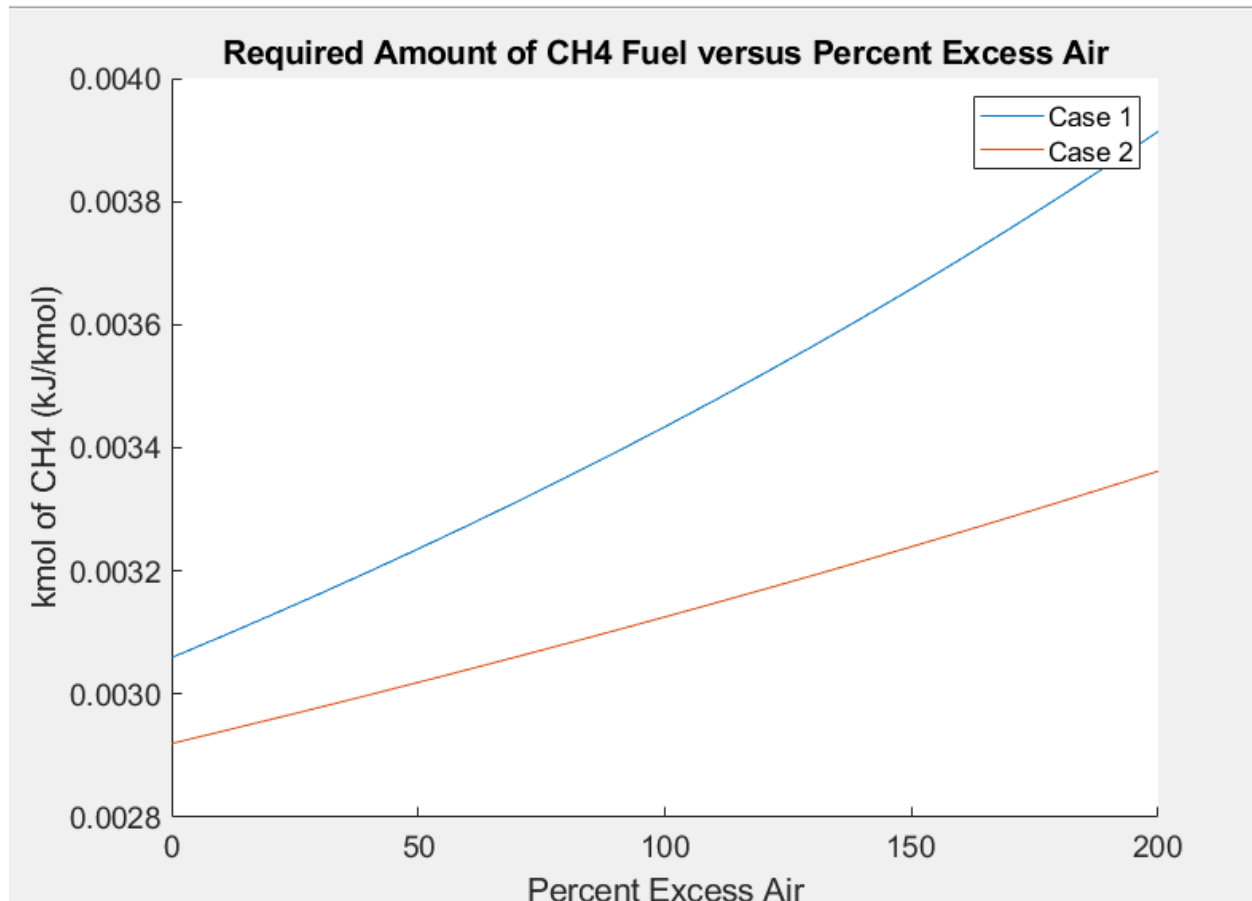
Heat Generated from Combustion per kmol of CH₄ for Both Cases



Due to the heat generated by the methane being lower as more excess air was added, it was found that larger quantities of fuel were needed to produce the necessary amount of heat for the water. The results are shown in Figure 3, with around 3.05 moles of methane being required with no excess air and around 3.9 moles of methane being required for 200% excess air for the first case. For the second case, less methane was required to produce the same amount of heating since the lower temperature of the combustion products allowed for more heat to be extracted. The second case required around 2.9 moles of methane with no excess air and around 3.3 moles of methane when 200% excess air was provided. Flow exergy of the carbon dioxide and water decreased due to this while the flow exergy of the oxygen and nitrogen in the products increased with excess air.

Figure 3

Amount of Methane Required to Provide the Necessary Heat for the Steam for Both Cases



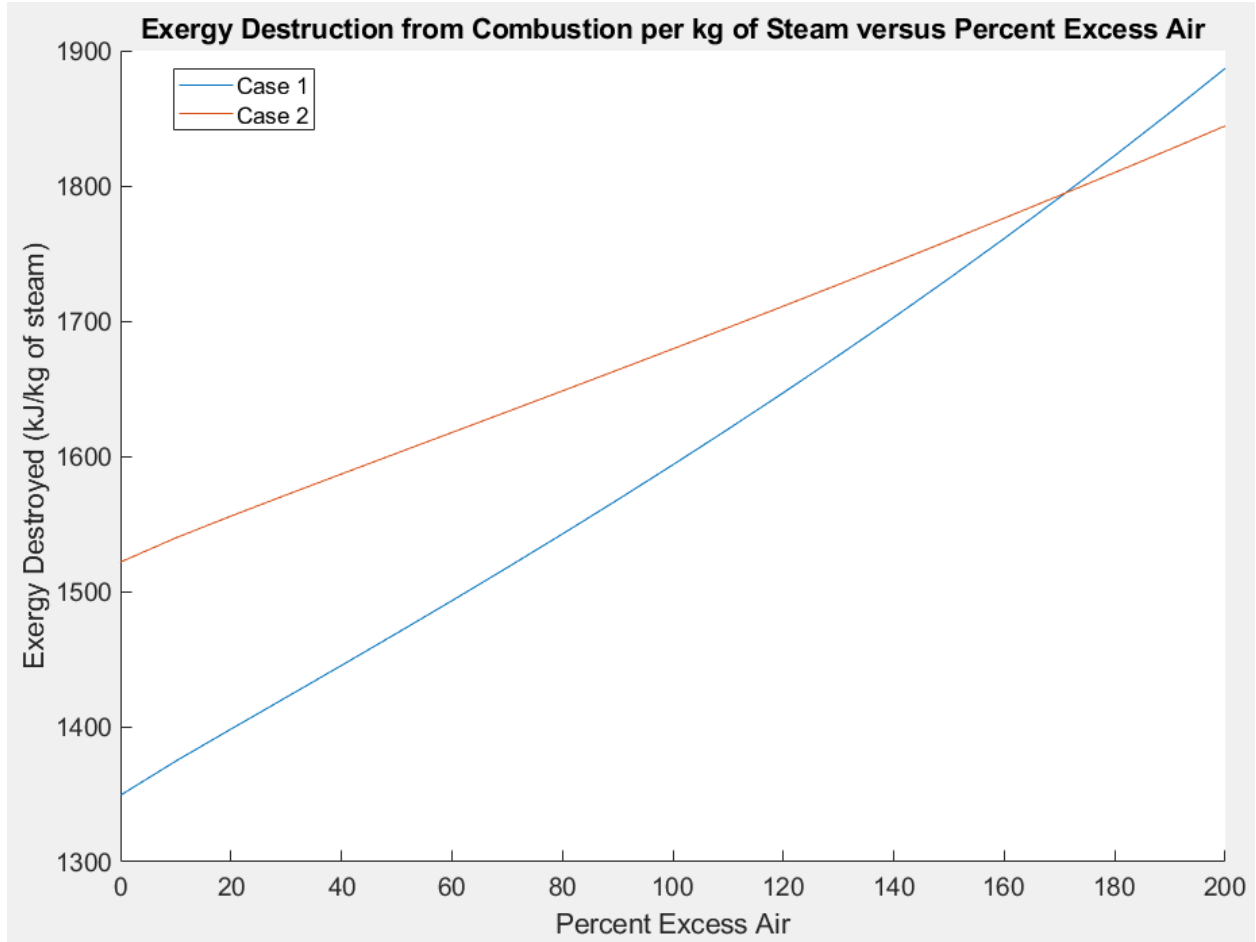
In terms of the exergy destruction of water, the difference in combustion product temperatures between the two cases only effected the temperature at which the heat transfer from the combustion gases occurred. As noted earlier, the exergy destruction for water was found to be 98.9347 and -140.1252 kJ per kilogram of steam, respectively. The difference in flow exergy for the steam was not affected by changing the combustion product temperature since the initial and final state of the steam was the same for both cases. However, the exergy destruction due to the combustion heat transfer was affected by the difference in combustion product temperatures. Lower exergy destruction was caused by the lower combustion product temperature, which is expected since the temperature difference

between the combustion products and the ambient environment was lower so less potential work that could be extracted at this temperature was wasted.

Regarding the exergy destruction for the combustion gases, the exergy destruction was found increase with percent excess air as shown in Figure 4. Higher percentages of excess air require larger amounts of fuel due to the combustion process not producing as much heat. The effects of the increased amount of fuel required due to the increased amounts of oxygen and nitrogen dominated the trends for exergy destruction, which caused the trends for exergy destruction and the trends for amount of fuel required at different excess air percentages to closely resemble each other. For case 2, the exergy destruction by the heat transfer is lower than it is for case 1, increasing the overall exergy destruction based on (7). For the first case, it was found that exergy destruction varied from around 1350 kJ per kg of steam to around 1880 kJ per kg of steam. For the second case, the exergy destruction was found to vary from around 1520 kJ per kg of steam to around 1840 kJ per kg of steam.

Figure 4

Exergy Destruction by the Combustion Process for Both Cases



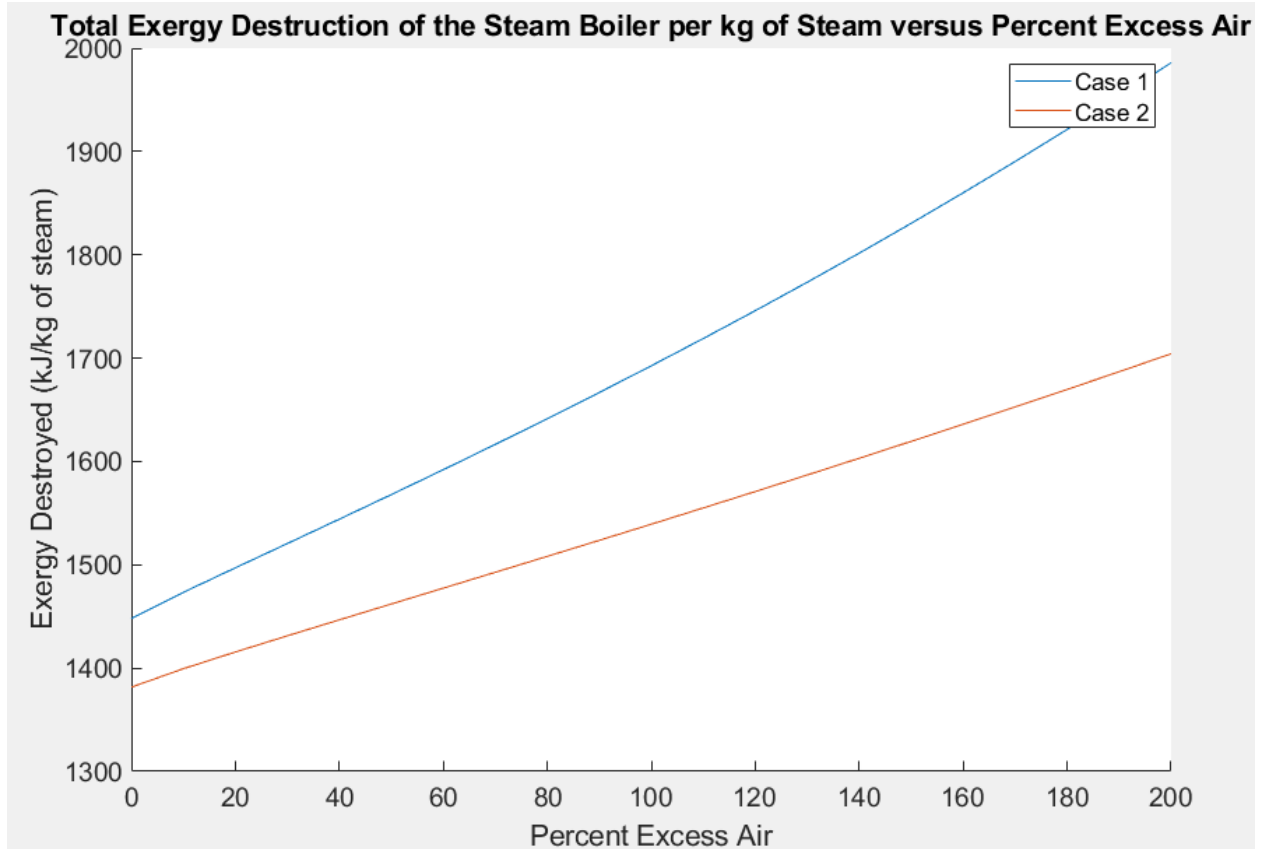
However, as the percentage excess air was varied, it was found that at around 170% excess air the exergy destruction for case 1 becomes lower than the exergy destruction for case 2. This is due to the difference in flow exergies being lower for case 2 than in case 1 due to the temperature of the combustion products being lower for the second case as well as the amount of fuel required for the second case being smaller due to extracting more heat from the same amount of fuel. While the exergy destruction due to heat transfer is higher for the second case, the exergy destruction due to the difference in flow exergy is smaller. This means exergy destruction for the combustion process in the second case increases more slowly as the percentage of excess air increased.

For the total exergy destruction, the second case was found to always have lower exergy destruction than case 1. Adding the exergy destruction of the water increased the total exergy

destruction for case 1 and decreased the total exergy destruction in case 2, causing the difference in the exergy destroyed in both cases to increase 240 kJ per kilogram of steam. Unlike when plotting just the exergy destruction associated with the combustion process, the first case was found to no longer produce less exergy destruction for any amount of excess air as shown in Figure 5. This was expected since more energy was able to be extracted from the methane fuel for the second case. Increasing the amount of excess air still increases the amount of exergy destruction, due to the increased amount of fuel required to provide the same amount of heating and the increased amount of energy needed to heat the additional air. The exergy destruction due to the heat transfer for the steam and the combustion process are equal and opposite for both cases, meaning that the effect of the temperature at which the heat transfer between the steam and combustion gases does not influence the total exergy destruction.

Figure 5

Total Exergy Destruction of the Steam Boiler for Both Cases



Summary and Conclusions

The economizer was found to be a good addition to this steam boiler, as reducing the temperature of the combustion products from 300°C to 200°C decreases the amount of exergy destruction. The exergy destruction is reduced with the combustion products at a lower temperature since more heat can be extracted from the same amount of methane, allowing for less methane to be used to provide the same amount of heating. Additionally, the lower temperature combustion products reduce the exergy destruction by reducing the difference in flow exergies between the 25°C combustion reactants and the combustion products. The exergy destruction for the steam was not dependent on the amount of excess air, since the state of the steam and the total heat transfer needed was not affected. The exergy destruction for the steam was lower with the economizer added, as the heat transfer occurred at a temperature closer to the ambient

temperature and less work that could be potentially extracted from the combustion products was wasted.

Exergy destruction of the combustion process was generally higher for the case with the economizer, as the exergy destruction due to heat transfer was instead increased with the economizer added due to heat being transferred out of the system. The higher the temperature of the combustion products, the lower the amount of exergy destroyed by heat transfer. The effects of the increased amount of methane required was found to dominate the trends for exergy destruction versus excess air, with trends for exergy destruction of the combustion process looking very similar to the trends for the amount of methane needed. Due to the lower difference in flow exergy values and the lower amount of methane required for the same amount of heating, the combustion process has lower exergy destruction values for excess air above around 170%.

Regarding, the total entropy destruction of the steam boiler, the economizer was found to be a complete improvement over the steam boiler without the economizer. The total exergy destruction with the economizer was found to be around 70 kJ per kg of steam with no excess air, with the gap in exergy destruction increasing the excess air was increased due to smaller amount of methane required and the lower difference in flow exergy of the combustion products and reactants with the economizer. The difference between the steam boiler with and without the economizer was around 280 kJ per kg of steam at 200% excess air. The economizer increases the amount of heat extracted from the methane, lowers the amount of methane required, and reduces the difference in flow exergy for the combustion process causing a significant improvement in steam boiler performance. Regardless of the actual amount of excess air needed to ensure the complete combustion of methane, the economizer should be added to this steam boiler for better performance.

References

Cengel, Y. A. (2015). *Thermodynamics: An Engineering Approach* (Eighth Edition). McGraw-Hill Education.

“Combustion Heat,” *Engineering ToolBox* Available:
https://www.engineeringtoolbox.com/standard-heat-of-combustion-energy-content-d_1987.html.