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BOILER BUSTERS BUST THE PLANT MYSTERY

Objective: The Boiler Busters were tasked to evaluate and improve the efficiency of the Mines Steam Plant boiler through thermodynamic analysis, using parametric simulations to assess the impact of operational changes such as air temperature, flue gas recirculation, and economizer performance.

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Section E

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Introduction/Background

The Colorado School of Mines Steam Plant is a crucial piece of infrastructure that supports nearly all aspects of campus functionality and student life. The plant produces and distributes essential heating and hot water across the Mines campus. In the mid-1900s, the original heating systems for campus buildings relied on steam purchased from the neighboring Coors Brewery. This partnership efficiently utilized surplus steam from the brewery; however, as the campus expanded and its demand for steam increased, it became evident that Mines was purchasing a significant amount of steam. To reduce long-term costs, the university decided to build its own on-campus steam plant. This change proved financially beneficial, reportedly saving Mines nearly \$500,000 [1] in its first year of operation. Beyond cost savings, having a dedicated plant enables the integration of energy-efficient technologies, enhances environmental initiatives, and provides tighter control over energy production and consumption.

By analyzing the Mines Steam Plant more closely, the team can evaluate its current performance and identify potential improvements to reduce environmental impact. Since Rankine cycles (steam power systems) are foundational to many energy systems globally, increasing their efficiency can lead to substantial energy and financial savings. A notable example is Denver's Steam System, which has been in operation since 1880 [2]. As one of the oldest systems in the U.S., it continues to supply heat to numerous buildings in downtown Denver, highlighting the resilience and long-term value of efficient district heating.

This project focuses on evaluating the Mines Steam Plant's thermodynamic performance and investigating ways to improve its productivity. According to the U.S. Department of Energy, "Broadening attention to all the components in a steam system—boiler water treatment, generation, distribution, end-use equipment, and steam and condensate recovery—creates much larger opportunities for savings, even as high as 20 to 30% of energy costs" [3]. By giving thermodynamics students the opportunity to analyze the Mines Steam Plant using real data, the project not only deepens student understanding of the Rankine cycle but may also reveal actionable improvements for the plant itself. One such group, the Boiler Busters, hypothesizes that increasing the incoming combustion air (flue gas) using exhaust gases will help to retain thermal heat and improve the insulation/design of the system, ensuring less energy is wasted to the surrounding environment.

Approach/Methodology

To begin this project, students were given a PDF divided into three parts. In Part 1, the team was tasked with defining the system and deriving the thermodynamic equations. Part 2 involved solving for key values using those equations along with table look-ups and provided data. In Part 3, which is the focus of this report, various system parameters were modified to analyze how they affect the steam plant's efficiency. The team then organized the findings into this report and developed recommendations based on the results.

In Part 1, the Boiler Busters created a control volume that highlighted energy transfer into and out of the system. From this control volume, the team derived steady-state energy, entropy, and continuity (mass) equations. A simplified diagram of the Mines Steam Plant was annotated to define each thermodynamic state (Figure 1).

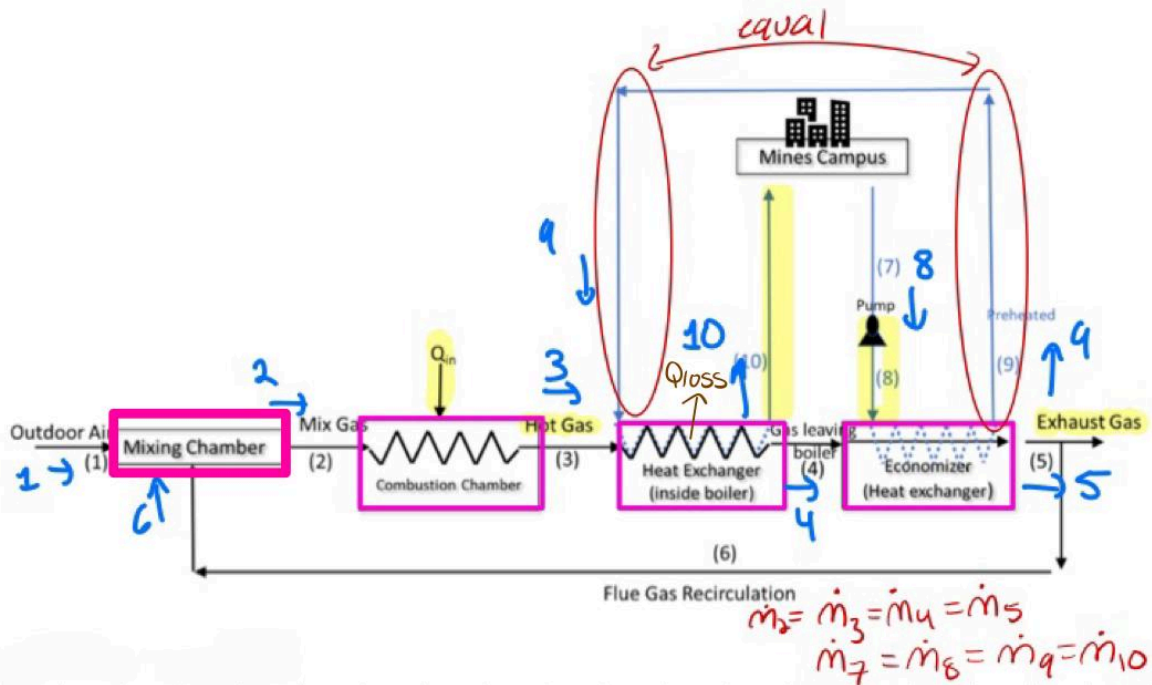


Figure 1: Annotated Control Volume

These states were grouped by component: States 1-2 represent the mixing chamber; 2-3, the combustion chamber; 3-4, the boiler (heat exchanger); and 4-5, the economizer (heat exchanger).

The assumptions (Figure 2) made were based on the physical role of each component and the working fluid flowing through it. The mixing chamber combines outside air with recirculated flue gas to create a mixed gas. This chamber is assumed to be adiabatic, with no heat loss or gain. The mixed gas flows into the combustion chamber, where energy is added through combustion, raising the gas temperature. This heated gas continues into the boiler, where it runs in a pipe adjacent to a water pipe.

Heat is transferred across the pipe walls, converting water into steam. Because heat exits the system at this point, the team assumed some heat loss in the boiler. After the boiler, the mixed gas enters the economizer.

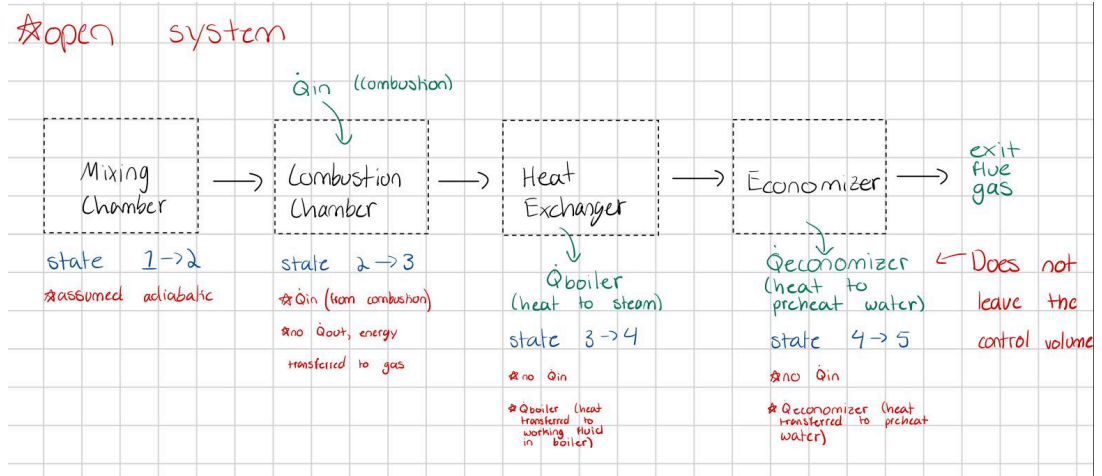


Figure 2: System Definition and Assumptions

The purpose of the economizer is to recover some of the residual heat that would otherwise be lost in typical Rankine cycles. This heat is used to preheat the water before entering the boiler, reducing the heat input required from combustion and thereby improving system efficiency. Because each control volume surrounds a specific component and both gas and water pipes cross its boundaries, the system was treated as open.

Using these assumptions, the team derived equations with state-specific subscripts corresponding to Figure 1. All temperatures, mass flow rates, enthalpies, and entropies were defined as either inputs to or outputs from each component (Figure 3).

Component	Continuity Equation: $\sum \dot{m}_{in} = \sum \dot{m}_{out}$ <i>(mass conservation)</i>	Energy Conservation: $\sum \dot{Q} + \sum \dot{m}h_{in} + \sum \dot{W} = \sum \dot{m}h_{out} + \sum \dot{Q}_{out}$ <i>(First Law of Thermodynamics)</i>	Entropy Balance: $\sum \dot{S}_{in} + \dot{S}_{gen} = \sum \dot{S}_{out}$
Mixing Chamber	$\dot{m}_1 + \dot{m}_6 = \dot{m}_2$	$\dot{m}_2 h_2 = \dot{m}_1 h_1 + \dot{m}_6 h_6$	$\dot{m}_2 s_2 + \dot{S}_{gen,2} = \dot{m}_1 s_1 + \dot{m}_6 s_6$
Combustion Chamber	$\dot{m}_2 = \dot{m}_3$	$\dot{Q}_{in} = \dot{m}_2 (h_3 - h_2)$	$\dot{m}_2 s_2 + \frac{\dot{Q}_{in}}{T_b} = \dot{m}_3 s_3 + \dot{S}_{gen,3}$
Boiler Heat Exchanger	$\dot{m}_3 = \dot{m}_4$	$\dot{m}_3 h_3 + \dot{m}_8 h_8 = \dot{m}_4 h_4 + \dot{m}_{10} h_{10} + \dot{Q}_{loss}$	$\dot{m}_3 s_3 + \dot{m}_8 s_8 - \frac{\dot{Q}_{out}}{T_s} = \dot{m}_4 s_4 + \dot{m}_{10} s_{10} + \dot{S}_{gen,4}$
Economizer	$\dot{m}_4 = \dot{m}_5$ $\dot{m}_7 = \dot{m}_8 = \dot{m}_9 = \dot{m}_{10}$	$\dot{m}_4 h_4 + \dot{m}_8 h_8 = \dot{m}_5 h_5 + \dot{m}_9 h_9$	$\dot{m}_4 s_4 + \dot{m}_8 s_8 = \dot{m}_5 s_5 + \dot{m}_9 s_9 + \dot{S}_{gen,5}$

Figure 3: Balanced equations

In Part 2, these equations were implemented in Engineering Equation Solver (EES) to calculate:

- a) boiler efficiency,
- b) the missing temperatures at various states, and
- c) steam quality at state 10.

State	T (Temperature, °F)	Pressure (psia)
1	40	14
2		14
3		14.2
4	340	14.1
5		14
6	=T ₅	14
7		50
8	222	180
9		150
10		75

Figure 4: Given Chart for Part 2

States 1 through 6 use air/flue gas as the working fluid, while states 7 through 10 use steam. Because state 9 did not have sufficient independent properties to determine enthalpy directly, the team used the provided economizer

effectiveness equation in place of an energy balance equation to solve for T[9], which was then used to find h[9].

The pump (states 7-8) presented a unique challenge. Normally, when given an isentropic efficiency, calculations begin with known inlet conditions to find the outlet. However, in this project, the outlet conditions were given and the inlet conditions were unknown. To solve this, the team used the isentropic efficiency equation in reverse: they performed look-ups for both the actual and isentropic

The team documented the equations used to calculate these values and determined which properties were needed at each state. Data provided included temperatures for states 1, 4, and 8, and pressures for all states (Figure 4). It was also specified that T[5] = T[6]. For states where both temperature and pressure were known, enthalpy was calculated using table look-ups (either air or steam tables). Where only one property was known, the team used energy balance equations to solve for enthalpy and then used the result to find the corresponding temperature (Figure 5).

Sort	1 T _i [F]	2 P _i [psia]	3 ṁ _i [lb/hr]	4 h _i [Btu/lbm]	5 h _{s,i} [Btu/lbm]	6 s _i
[1]	40	14	16250	119.5		
[2]	128.8	14	25000	140.8		
[3]	2981	14.2	25000	920.8		
[4]	340	14.1	25000	191.9		
[5]	292.9	14	25000	180.4		
[6]	292.9	14	8750	180.4		
[7]	221.7	50	19000	190.1		0.3266
[8]	222	180	19000	190.6	190.5	
[9]	237	150	19000	205.7		
[10]	307.6	75	19000	1062		

Figure 5: Solved Array

enthalpy values at state 8, then solved the efficiency equation as a system to find the inlet enthalpy at state 7.

Once all state properties were found, the team calculated pump work using the appropriate enthalpy difference and converted it to horsepower. Boiler efficiency was then computed using the net energy added to the steam and accounting for known boiler losses. Finally, the steam quality at state 10 was found through table look-up based on its enthalpy and pressure.

Unit Settings: Eng F psia mass deg

boiler _{eff} = 83.46 [%]	boiler _{loss} = 0.1 [%]	C _p _{air} = 0.2435 [Btu/lbm-R]	C _p _{water} = 1.008 [Btu/lbm-R]	eff _{econ} = 0.4 [%]	eff _{pump} = 0.7 [%]	Flue _{gas} = 0.35 [%]
Q̇ _{in} = 1.950E+07 [MMBtu/hr]	Q̇ _{steam} = 1.627E+07 [MMBtu/hr]	Q̇ _{loss} = 1.950E+06 [MMBtu/hr]	Ẇ _{pump2} = 4.308 [hp]	x ₁₀ = 0.8675		

Figure 6: Final Solutions for Part 2

The results found for the three values (highlighted in Figure 6), are feasible. According to *Maintenance and Engineering*, an engineering magazine, the industrial standard for boiler efficiency is around 85% [4], which is close to the determined 83.46% the team obtained. In typical steam plants, “pump work is minimal—usually between 1 and 10 horsepower, or less than 0.1% of total boiler heat input” [5], due to the relatively small enthalpy change required to pressurize incompressible liquid water. The team’s 4.308 horsepower does fall within the 1 to 10 horsepower range. Lastly, the average quality of steam for the steam leaving a steam plant should be between 0.95 and 1.00 to operate safely [6]. Anything less than 0.9 is considered “wet” steam. The team’s quality of the steam going out to the Mines campus is approximately 87%, which means that the steam is approximately 13% liquid by mass, which is far too high for industry standards. This inaccuracy suggests that there is an issue, such as:

- a) The boiler may not be providing enough energy to fully vaporize the water, leading to a higher moisture content in the steam. *VRcoolertech* notes that “low-quality or contaminated steam may reduce heating efficiency, leading to insufficient heating.” [7]
- b) Sudden increases in steam demand can cause temporary drops in steam quality if the boiler cannot respond quickly enough. The U.S. Department of Energy’s Steam Challenge report states, “A rapid, short-term steam demand increase of only 15% can cause high entrainment of water in the boiler.” [8]
- c) *ChemAqua* states that “poor steam purity is typically the result of one of the following: boiler water carryover, accelerated corrosion rates in steam lines, process contamination.” [9]

The next step, in part 3, was to vary the parametric parameters to create the highest possible efficiency at the Mines steam plant.

Results/Discussion

To tackle the problem, the Boiler Busters took varying simulations regarding a steam plant and its efficiency. Done throughout Engineering Equation Solver (EES), the team came to some interesting conclusions.

When varying the temperature at state 1, we can understand results when outdoor air temperatures vary. Summarized in Figure 7, as T1 increased from 40°F to 120°F, the boiler efficiency rose ~1.5 %. The quality of the exit steam also showed a consistent increase.

The graph to the right (Figure 8) suggests a direct relationship between an increased inlet temperature₁ and slightly improved boiler efficiency. This observation aligns with thermodynamic expectations: Warmer incoming air requires less heat input to reach the target conditions, reducing energy losses and improving efficiency. The temperature of the mixed gases entering the combustion chamber increased in tandem with the temperature of the incoming air. The data supports this line of reasoning, with boiler efficiency and quality both increasing.

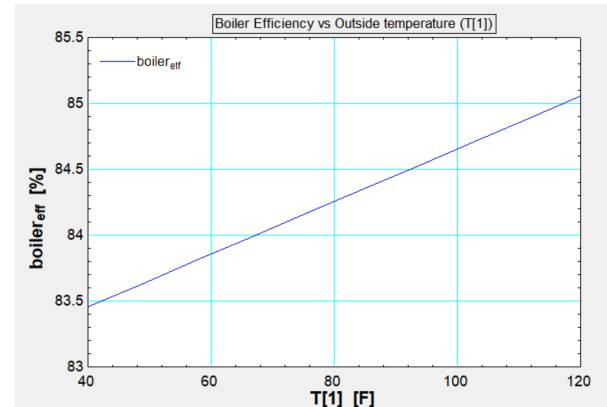


Figure 8: Boiler Efficiency vs. Outside Temperature

Outside temperature T[1]	Flue Gas recirculation	Economizer effectiveness	Pressure Steam P[10]	Boiler Losses	Flue Gas and Boiler Losses							
T ₁ [F]	Flue _{gas} [%]	eff _{econ} [%]	P ₁₀ [psia]	boiler _{loss} [%]	T ₉ [F], h _g [Btu/lbm], Q _{in} [MMBtu/hr], Q _{loss} [MMBtu/hr], boiler _{eff} [%], W _{pump2} [hp], x ₁₀							
Run 1	40	0.35	0.4	75	0.1	237	205.7	1.950E+07	1.950E+06	83.46	4.308	0.8675
Run 2	48.89	0.35	0.4	75	0.1	237	205.7	1.950E+07	1.950E+06	83.63	4.306	0.8695
Run 3	57.78	0.35	0.4	75	0.1	237	205.7	1.950E+07	1.950E+06	83.81	4.306	0.8715
Run 4	66.67	0.35	0.4	75	0.1	237	205.7	1.950E+07	1.950E+06	83.99	4.306	0.8735
Run 5	75.56	0.35	0.4	75	0.1	237	205.7	1.950E+07	1.950E+06	84.17	4.306	0.8755
Run 6	84.44	0.35	0.4	75	0.1	237	205.7	1.950E+07	1.950E+06	84.34	4.306	0.8775
Run 7	93.33	0.35	0.4	75	0.1	237	205.7	1.950E+07	1.950E+06	84.52	4.306	0.8795
Run 8	102.22	0.35	0.4	75	0.1	237	205.7	1.950E+07	1.950E+06	84.7	4.306	0.8816
Run 9	111.11	0.35	0.4	75	0.1	237	205.7	1.950E+07	1.950E+06	84.88	4.306	0.8836
Run 10	120	0.35	0.4	75	0.1	237	205.7	1.950E+07	1.950E+06	85.06	4.306	0.8856

Figure 7: Outside Temperature

The Boiler Buster team also simulated if the flue gas recirculation was increased from 35 to 100%. When calculated, the boiler efficiency rose almost 5%, and the exit steam quality increased significantly.

With other variables being held constant, increasing the flue gas recirculation resulted in higher values than increasing the inlet temperature. The data shows this in figure 9 and 10. When conceptualizing the difference, the team would expect that when recirculating flue gas air, it pre-warms combustion air. Recirculating more of this air means more CO₂ enters the combustion chamber as a result of the oxygen

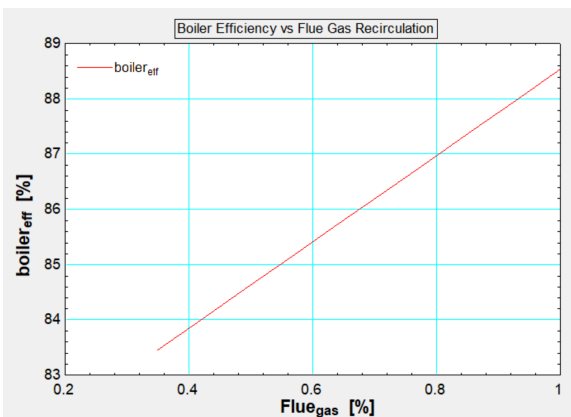


Figure 9: Boiler Efficiency vs. Flue Gas Recirculation

concentration drops, lowering the combustion temperature. The system can function with less heat from the boiler when the combustion temperature is lower. Increasing recirculation from 35% to 100%, however, is a little impractical because it eliminates any possibility of operational error. Given that a

	Outside temperature T[1]	Flue Gas recirculation	Economizer effectiveness	Pressure Steam P[10]	Boiler Losses	Flue Gas and Boiler Losses
	T ₁ [F]	Flue _{gas} [%]	eff _{econ} [%]	P ₁₀ [psia]	boiler _{loss} [%]	T ₉ [F], h ₉ [Btu/lbm], Q _{in} [MMBtu/hr], Q _{loss} [MMBtu/hr], boiler _{eff} [%], W _{pump2} [hp], x ₁₀
Run 1	40	0.35	0.4	75	0.1	237, 205.7, 1.950E+07, 1.950E+06, 83.46, 4.308, 0.8675
Run 2	40	0.4222	0.4	75	0.1	237, 205.7, 1.950E+07, 1.950E+06, 84.02, 4.306, 0.8739
Run 3	40	0.4944	0.4	75	0.1	237, 205.7, 1.950E+07, 1.950E+06, 84.58, 4.306, 0.8803
Run 4	40	0.5667	0.4	75	0.1	237, 205.7, 1.950E+07, 1.950E+06, 85.15, 4.306, 0.8867
Run 5	40	0.6389	0.4	75	0.1	237, 205.7, 1.950E+07, 1.950E+06, 85.71, 4.306, 0.8931
Run 6	40	0.7111	0.4	75	0.1	237, 205.7, 1.950E+07, 1.950E+06, 86.27, 4.306, 0.8995
Run 7	40	0.7833	0.4	75	0.1	237, 205.7, 1.950E+07, 1.950E+06, 86.84, 4.306, 0.9059
Run 8	40	0.8556	0.4	75	0.1	237, 205.7, 1.950E+07, 1.950E+06, 87.4, 4.306, 0.9123
Run 9	40	0.9278	0.4	75	0.1	237, 205.7, 1.950E+07, 1.950E+06, 87.97, 4.306, 0.9187
Run 10	40	1	0.4	75	0.1	237, 205.7, 1.950E+07, 1.950E+06, 88.53, 4.306, 0.9251

Figure 10: Flue Gas Recirculation

65% increase in flue gas recirculation only leads to a ~5% gain in boiler efficiency, achieving zero exhaust leaving the system would be extremely difficult. Even though higher recirculation values result in higher boiler efficiency, we must take into account real-world application rather than simulated data.

Surprisingly, the team came to a different conclusion when looking at the economizer. Making the economizer work better might actually make the boiler less efficient. When the economizer increased from 0.4 to 0.7, the steam exit temperature (T9) and the enthalpy (h9) increased. Despite these changes, the boiler efficiency slightly decreased. This is shown in the figure below.

	Outside temperature T[1]	Flue Gas recirculation	Economizer effectiveness	Pressure Steam P[10]	Boiler Losses	Flue Gas and Boiler Losses
	T ₁ [F]	Flue _{gas} [%]	eff _{econ} [%]	P ₁₀ [psia]	boiler _{loss} [%]	T ₉ [F], h ₉ [Btu/lbm], Q _{in} [MMBtu/hr], Q _{loss} [MMBtu/hr], boiler _{eff} [%], W _{pump2} [hp], x ₁₀
Run 1	40	0.35	0.4	75	0.1	237, 205.7, 1.950E+07, 1.950E+06, 83.46, 4.308, 0.8675
Run 2	40	0.35	0.4333	75	0.1	238.3, 207, 1.950E+07, 1.950E+06, 83.41, 4.306, 0.8684
Run 3	40	0.35	0.4667	75	0.1	239.5, 208.3, 1.950E+07, 1.950E+06, 83.37, 4.306, 0.8693
Run 4	40	0.35	0.5	75	0.1	240.8, 209.5, 1.950E+07, 1.950E+06, 83.33, 4.306, 0.8702
Run 5	40	0.35	0.5333	75	0.1	242, 210.8, 1.950E+07, 1.950E+06, 83.28, 4.306, 0.8711
Run 6	40	0.35	0.5667	75	0.1	243.3, 212, 1.950E+07, 1.950E+06, 83.24, 4.306, 0.872
Run 7	40	0.35	0.6	75	0.1	244.5, 213.3, 1.950E+07, 1.950E+06, 83.2, 4.306, 0.8729
Run 8	40	0.35	0.6333	75	0.1	245.8, 214.6, 1.950E+07, 1.950E+06, 83.15, 4.306, 0.8738
Run 9	40	0.35	0.6667	75	0.1	247, 215.8, 1.950E+07, 1.950E+06, 83.11, 4.306, 0.8747
Run 10	40	0.35	0.7	75	0.1	248.3, 217.1, 1.950E+07, 1.950E+06, 83.07, 4.306, 0.8757

Figure 11: Economizer Effectiveness

When the economizer is more effective, it heats the air going into the boiler to a higher temperature. But this hotter air means the boiler's heat exchanger can't transfer as much heat. Since the amount of energy going into the system stays the same, the boiler ends up doing less useful work. This results in lower overall efficiency, as shown in the graphed figure 12.

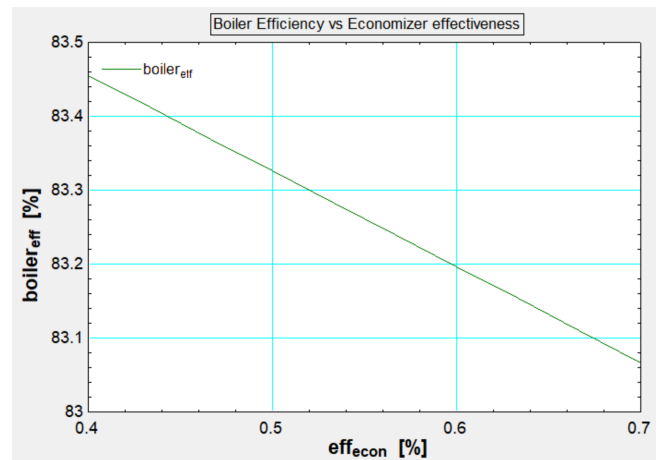


Figure 12: Boiler Efficiency vs. Economizer Effectiveness

The Boiler Busters also took a closer look at decreasing steam pressure. Following an evaluation, the team concluded that this option had no impact on the boiler's overall efficiency. The boiling point temperature was altered by lowering the pressure, but the energy required to convert water to steam remained unchanged. As a result, the boiler's efficiency remained constant since the enthalpy differential between the heat exchanger's inlet and outflow remained roughly constant. For example, when steam pressure (P10) was reduced from 75 psia to 50 psia, the boiler efficiency stayed steady at 83%, and the enthalpy (h9) remained fixed at 205 Btu/lbm. This rendered the alternative unrelated to resolving the issue the team was concentrating on, as illustrated in the figure 13 and 14.

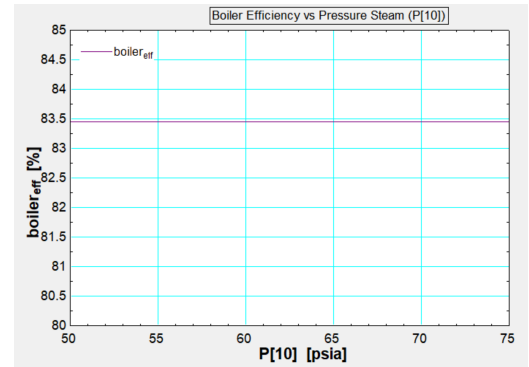


Figure 13: Boiler Efficiency vs. Pressure Steam

	Outside temperature T[1]	Flue Gas recirculation	Economizer effectiveness	Pressure Steam P[10]	Boiler Losses	Flue Gas and Boiler Losses
	T ₁ [F]	Flue_gas [%]	eff_econ [%]	P ₁₀ [psia]	boiler_loss [%]	T _g [F], h _g [Btu/lbm], Q _{in} [MMBtu/hr], Q _{loss} [MMBtu/hr], boiler_eff [%], W _{pump2} [hp], x ₁₀
Run 1	40	0.35	0.4	75	0.1	237, 205.7, 1.950E+07, 1.950E+06, 83.46, 4.308, 0.8675
Run 2	40	0.35	0.4	72.22	0.1	237, 205.7, 1.950E+07, 1.950E+06, 83.46, 4.306, 0.8685
Run 3	40	0.35	0.4	69.44	0.1	237, 205.7, 1.950E+07, 1.950E+06, 83.46, 4.306, 0.8697
Run 4	40	0.35	0.4	66.67	0.1	237, 205.7, 1.950E+07, 1.950E+06, 83.46, 4.306, 0.8708
Run 5	40	0.35	0.4	63.89	0.1	237, 205.7, 1.950E+07, 1.950E+06, 83.46, 4.306, 0.872
Run 6	40	0.35	0.4	61.11	0.1	237, 205.7, 1.950E+07, 1.950E+06, 83.46, 4.306, 0.8733
Run 7	40	0.35	0.4	58.33	0.1	237, 205.7, 1.950E+07, 1.950E+06, 83.46, 4.306, 0.8746
Run 8	40	0.35	0.4	55.56	0.1	237, 205.7, 1.950E+07, 1.950E+06, 83.46, 4.306, 0.8759
Run 9	40	0.35	0.4	52.78	0.1	237, 205.7, 1.950E+07, 1.950E+06, 83.46, 4.306, 0.8773
Run 10	40	0.35	0.4	50	0.1	237, 205.7, 1.950E+07, 1.950E+06, 83.46, 4.306, 0.8788

Figure 14: Pressure Steam

One of the more obvious trials the team ran was decreasing the amount of the boiler losses. Reducing waste heat in the system would improve efficiency and lower energy costs and CO2 emissions. If less heat was lost, the starting temperature would rise, requiring less work from the system to reach the temperature of combustion. Recovering the usable kinetic energy from waste heat can reduce the amount of fuel needed to operate the system. The team found that efficiency rose by the same amount when they simulated less heat loss from the system, demonstrating

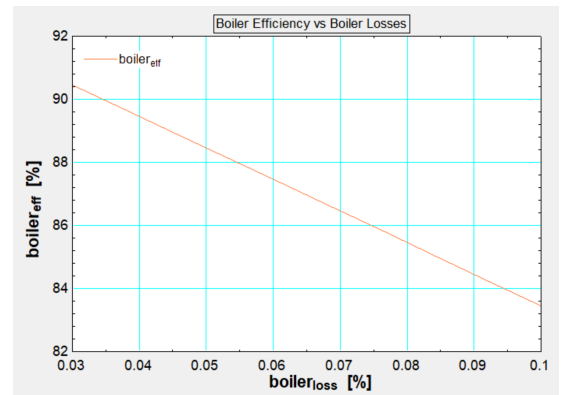


Figure 15: Boiler Efficiency vs. Boiler Losses

a linear relationship between the two. As shown in the graphed simulation results (figure 15), when boiler losses were reduced from 10% to 3%, boiler efficiency increased significantly from 83% to 90%, confirming this trend.

	Outside temperature T[1]	Flue Gas recirculation	Economizer effectiveness	Pressure Steam P[10]	Boiler Losses	Flue Gas and Boiler Losses
	T ₁ [F]	Flue_gas [%]	eff_econ [%]	P ₁₀ [psia]	boiler_loss [%]	T _g [F], h _g [Btu/lbm], Q _{in} [MMBtu/hr], Q _{loss} [MMBtu/hr], boiler_eff [%], W _{pump2} [hp], x ₁₀
Run 1	40	0.35	0.4	75	0.1	237, 205.7, 1.950E+07, 1.950E+06, 83.46, 4.308, 0.8675
Run 2	40	0.35	0.4	75	0.09222	237, 205.7, 1.950E+07, 1.798E+06, 84.23, 4.306, 0.8763
Run 3	40	0.35	0.4	75	0.08444	237, 205.7, 1.950E+07, 1.647E+06, 85.01, 4.306, 0.8851
Run 4	40	0.35	0.4	75	0.07667	237, 205.7, 1.950E+07, 1.495E+06, 85.79, 4.306, 0.8939
Run 5	40	0.35	0.4	75	0.06889	237, 205.7, 1.950E+07, 1.343E+06, 86.57, 4.306, 0.9028
Run 6	40	0.35	0.4	75	0.06111	237, 205.7, 1.950E+07, 1.192E+06, 87.34, 4.306, 0.9116
Run 7	40	0.35	0.4	75	0.05333	237, 205.7, 1.950E+07, 1.040E+06, 88.12, 4.306, 0.9204
Run 8	40	0.35	0.4	75	0.04556	237, 205.7, 1.950E+07, 888333, 88.9, 4.306, 0.9292
Run 9	40	0.35	0.4	75	0.03778	237, 205.7, 1.950E+07, 736667, 89.68, 4.306, 0.9381
Run 10	40	0.35	0.4	75	0.03	237, 205.7, 1.950E+07, 585000, 90.46, 4.306, 0.9469

Figure 16: Boiler Losses

Additionally, steam quality (X10) rose from 0.86 to 0.94, indicating a higher proportion of dry steam, which improves energy transfer and system performance. At the same time, heat losses dropped from 1.950E+06 MMBtu/hr to 586,000 MMBtu/hr, showing that a substantial portion of previously wasted energy was effectively retained and reused within the system. These changes highlight the strong potential of waste heat recovery to improve overall efficiency and reduce fuel consumption.

To explore the most impactful simulation, the team focused on combining two key parameters: increasing the flue gas recirculation and reducing the boiler losses. Flue gas preheats the incoming combustion air using exhaust gasses, helping to retain thermal heat. Boiler efficiency increased by ~5% in this primary simulation. Reducing boiler losses targets the insulation and design of the system, ensuring more energy stays within the system. (Efficiency of ~7%) Among all previously tested configurations, both of these parameters changed the boiler loss percentage and yielded the greatest positive impact on the system. These parameters were chosen as a final simulation based on their massive roles in improving boiler efficiency and positively affecting similar dependents. The results show that combining these parameters led to the highest simulated boiler efficiency. The Boiler Busters hypothesis was proven correct, seen in the table below. (Figure 17) Boiler efficiency increased from 83% to 95%, a 12 percentage point gain. At the same time, exit steam quality (X10) almost reached 100% (excluding run 10). This further indicates a perfectly dry saturated steam, which is a theoretical ideal for maximizing energy transfer.

Outside temperature T[1]	Flue Gas recirculation	Economizer effectiveness	Pressure Steam P[10]	Boiler Losses	Flue Gas and Boiler Losses							
T ₁ [F]	Flue_gas [%]	eff_econ [%]	P ₁₀ [psia]	boiler_loss [%]	T _g [F]	h _g [Btu/lbm]	Q _{in} [MMBtu/hr]	Q _{loss} [MMBtu/hr]	boiler_eff [%]	W _{pump2} [hp]	x ₁₀	
Run 1	40	0.35	0.4	75	0.1	237	205.7	1.950E+07	1.950E+06	83.46	4.308	0.8675
Run 2	40	0.4222	0.4	75	0.09222	237	205.7	1.950E+07	1.798E+06	84.8	4.306	0.8827
Run 3	40	0.4944	0.4	75	0.08444	237	205.7	1.950E+07	1.647E+06	86.14	4.306	0.8979
Run 4	40	0.5667	0.4	75	0.07667	237	205.7	1.950E+07	1.495E+06	87.48	4.306	0.9131
Run 5	40	0.6389	0.4	75	0.06889	237	205.7	1.950E+07	1.343E+06	88.82	4.306	0.9284
Run 6	40	0.7111	0.4	75	0.06111	237	205.7	1.950E+07	1.192E+06	90.16	4.306	0.9436
Run 7	40	0.7833	0.4	75	0.05333	237	205.7	1.950E+07	1.040E+06	91.51	4.306	0.9588
Run 8	40	0.8556	0.4	75	0.04556	237	205.7	1.950E+07	888333	92.85	4.306	0.974
Run 9	40	0.9278	0.4	75	0.03778	237	205.7	1.950E+07	736667	94.19	4.306	0.9893
Run 10	40	1	0.4	75	0.03	237	205.7	1.950E+07	585000	95.53	4.306	100

Figure 17: Flue Gas and Boiler Losses

The synergy between these two variables is crucial. Together, the parameters create a compounding effect, where more energy is retained in the system, and thus less is lost, producing very promising results. However, this configuration is almost too good to be true. In a real-world application, it is nearly impossible to achieve 100% flue gas recirculation. Along similar lines, achieving such low boiler losses would require near-perfect insulation and advanced materials. Even though this combination is inimitable, this simulation highlights an ideal path for maximizing boiler efficiency and offers valuable insight in combined strategies and their possible outcomes. As such, it is the Boiler Busters recommendation to optimally incorporate these parameters to the Colorado School of Mines Steam Plant.

Conclusion

The Boiler Busters' hypothesis - that increasing flue gas recirculation and reducing boiler losses would enhance the Colorado School of Mines Steam Plant's efficiency - has been substantiated through comprehensive thermodynamic analysis and simulation. By recirculating flue gases, the system preheats incoming combustion air, reducing the energy required for heating and improving overall boiler efficiency. Simultaneously, minimizing boiler losses through improved insulation and conservation of resources ensures that more generated heat is utilized effectively, further boosting efficiency.

Simulation results demonstrated that combining these two strategies could elevate boiler efficiency from 83% to 95%, with a corresponding increase in steam quality from 87% to nearly 100%. These findings underscore the potential of targeted modifications to significantly enhance energy performance. While achieving such optimal conditions in practice may present challenges, the insights gained provide a valuable roadmap for future improvements to the Mines Steam Plant, aligning with broader goals of energy efficiency and sustainability.

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