Final Report

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Purina Dryer Efficiency

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Problem Statement

Introduction

Nestlé Purina is one of the top manufactures of pet food in the United States. The Flagstaff, AZ plant produces about 1,000 tons of pet food each day. When the food is done cooking it contains 35% moisture content. Therefore, all of the food produced needs to be properly dried to meet the 11.5% moisture content requirement. This requirement was set forth to reduce the risk of mold growth due to the build-up of condensation in the bags while cooling. To dry the food, the Flagstaff plant has five steam powered dryers, each responsible for about 20%. However, dryer three is not running as efficient as the other dryers. Dryer 3, shown in Figure 1, should be capable of producing 200 tons per day, but has recently been producing only 150 tons per day, while still using the same amount of energy as the other four dryers.

Figure 1 – Dryer 3

After the product enters the dryer, it is passed through four sections. The first three sections are responsible for removing moisture from the product, and the fourth section is responsible for cooling the product. Each section has its own dedicated air flow, temperature control, and steam coils. The steam coils are used to heat up the air that moves through each section, as hot air can contain much more moisture than cool air. The lack of productivity is largely due to the condensation in the steam used for drying the pet food. Because of the large scale of production, this degree of inefficiency costs our client a large amount of money in terms of unmade product. Our goal is to increase the efficiency and throughput of dryer 3 for Nestlé Purina.

Objectives

Table 1 is a list of the objectives and measurement basis we have come up with for the implementation of this project to increase the efficiency of dryer 3. This table also includes all of the units for each of the individual objectives.

Table 1 – Objectives broken into how they are measured

Objectives	Basis for Measurement	Units
Inexpensive	Implementation costs	$
Production output	Weight of product	Tons
Moisture content	Amount of water	%
Efficiency	Energy used	BTU/ ton
Condensation	Weight of water in the steam	Kg water/ kg steam

Constraints

Overall, we were given three constraints to meet during the project. The first constraint is that the moisture content must be less than 11.5% to avoid the growth of mold in the product. The second constraint is that the payback period should be less than three years to justify the cost of the project. The last constraint is there must be no condensation in the steam coils so heat transfer can occur optimally.

Criteria Tree

In order to show how each of the criterion related to each other, a criteria tree was developed (As seen in Figure 2). The criterion was split into three different categories: costs, moisture control, and production. The most important criteria to consider with the designs of the dryer are the amount of money that will be spent. The total cost includes the payback period which is the amount of time that it takes for the money spent to pay for itself. The next category is moisture control. This category was then split into the amount of water that is still in the product, and the amount of condensation that is in the steam. The final category is the total production of the dryer. This includes the total amount of product that can be pushed through the dryer in a span of an hour and how much power we need to push that much product through. We also need to compare the new efficiency of the dryer to the efficiency of the old dryers.

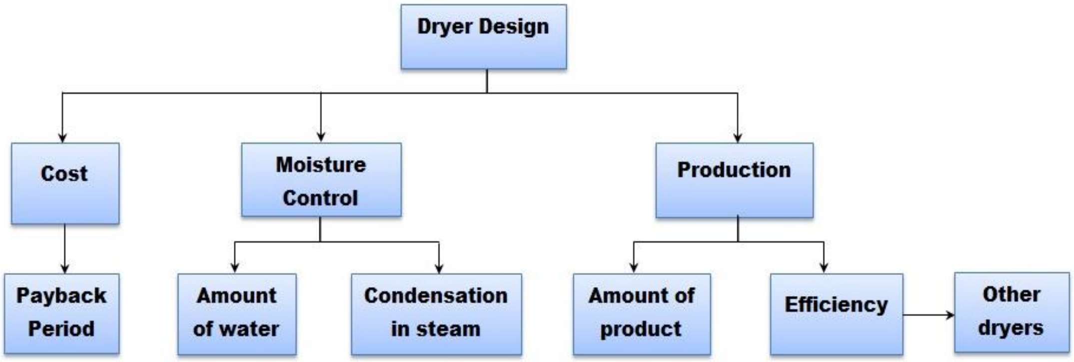


Figure 2 – Criteria Tree

Functional Diagram

To better understand the process of the dryer and where to perform our engineering analysis, a functional diagram of dryer 3 was made. This is shown in Figure 3 below. The dryer runs on steam in conjunction with an air circulation system. The plant produces its own steam in a natural gas boiler. This steam is then pumped at approximately 100 psi to the dryer unit. In the dryer, steam is continually pumped through steam coils. The air circulation system blows air over the steam coils to heat the air to around 280 degrees Fahrenheit. Hot air has a larger capacity to remove moisture than air at a lower temperature. This air passes through the moist product and removes moisture from it. After this, the air is re-heated and passed through the product twice more. The product enters the fourth and final section of the dryer where it is cooled to about 100 degrees Fahrenheit before it is sent to further processing.

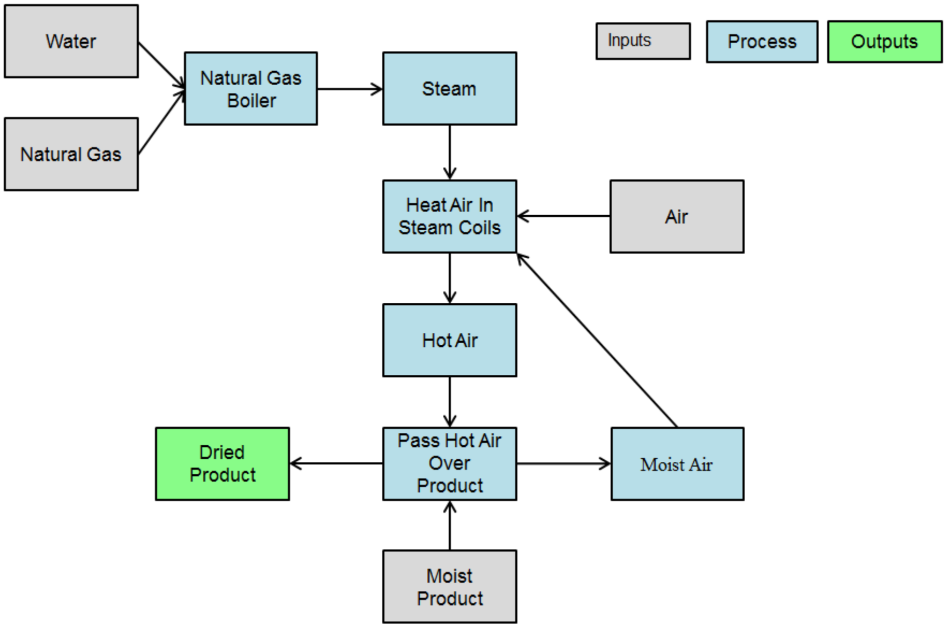
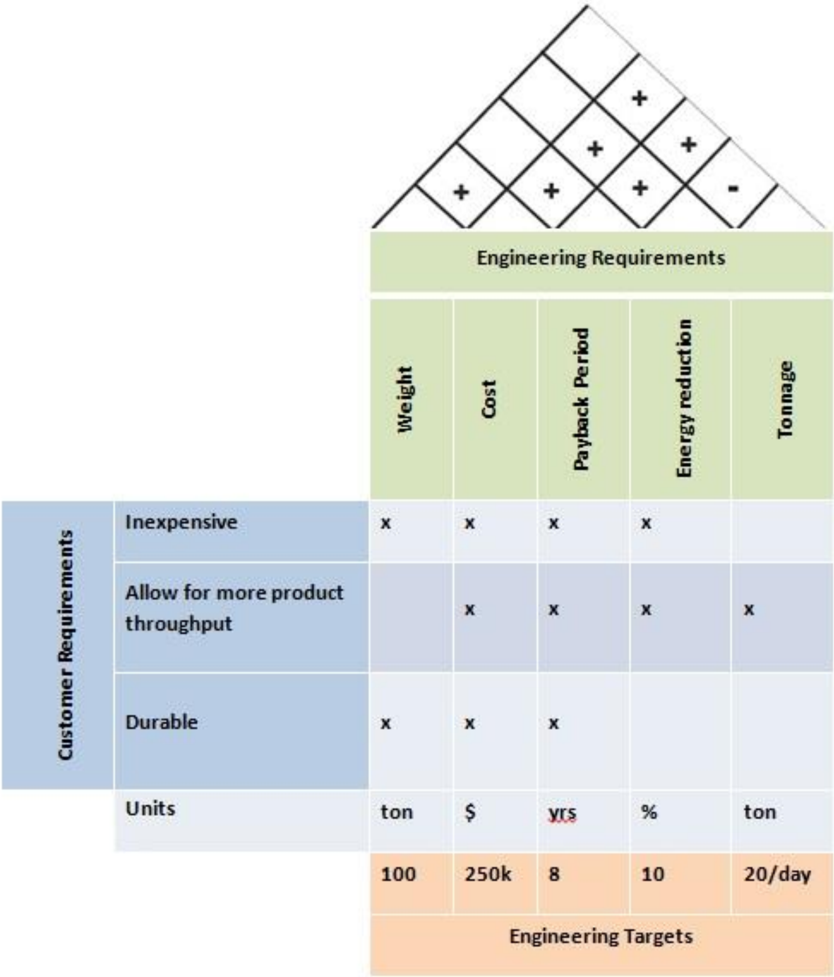


Figure 3 – Function Diagram

Quality Function Deployment

A quality function deployment table, Figure 4, compares customer needs to engineering needs. It relates overall design to reasonable engineering specifications. From the figure, cost relates to all of the customer requirements. To make the dryer more efficient for allowing more product throughput, the cost will increase. To be more durable, there will be more materials used or longer lasting parts which will be more expensive. This also affects the overall weight of the dryer and energy reduction. Ideally, the output should be 10% more efficient than the dryers already in use which gives us the engineering targets. The house of quality refers to how the engineering requirements relate to each other. There is a positive correlation (+) between cost and energy reduction. This means that by increasing the cost, the energy reduction should be larger. By increasing the energy reduction, the output tonnage decreases. This is a negative correlation (-).



		Engineering Requirements				
		Weight	Cost	Payback Period	Energy reduction	Tonnage
Customer Requirements	Inexpensive	x	x	x	x	
	Allow for more product throughput		x	x	x	x
	Durable	x	x	x		
	Units	ton	$	yrs	%	ton
		100	250k	8	10	20/day
		Engineering Targets				

Figure 4 – Quality Function with House of Quality

Concept Generation

Before we were able to select a design to move forward with, we first had to generate a multitude of concepts to choose from. We accomplished this by breaking the concept generation section into multiple stages. These stages are: defining the problem, defining the system, brainstorming, using Osborn's Checklist to expand these ideas, and then refining the ideas to prepare for concept selection. Through our previous work, we were able to interpret our client's need and generate a concrete problem statement. We determined that the problem was: Dryer 3 at Nestle Purina uses significantly more energy than the other four dryers to extract moisture from the product.

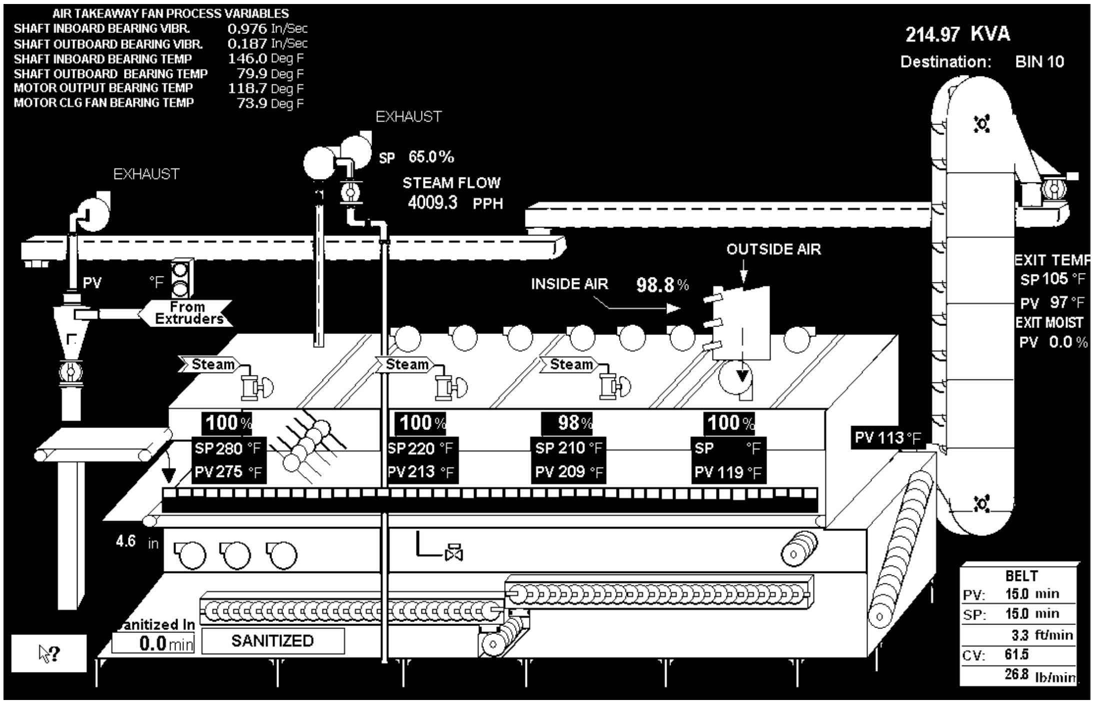
The next step in our concept generation and selection process was to define the system and understand it as completely as possible. We were able to meet with Chad Girvin, the processing maintenance team leader at the Nestle Purina plant in Flagstaff. Chad was able to provide us detail about the system that one would only learn by spending years with a specific system.

We realize now that the drying process at Nestle Purina is very complicated, but we were able to take note of the most critical pieces of the system and its operation. The first step of the drying process is bringing the product to the front of the dryer from the exit of the extruder, or product cooker. This is done with a vacuum conveyance system. Each dryer has a dedicated blower that creates a vacuum to pull the product to the dryer. The vacuum conveyance system is a very important part of the drying process as it provides about ¼ of the moisture removal as a fraction of the entire drying process.

Once the product is pulled through the vacuum conveyance system, it is deposited onto the dryer bed by an oscillating belt. This belt speed can be controlled, and helps to control the product depth and uniformity. The belt speed also affects the time the product spends in the dryer. After the product enters the dryer, it is passed through 4 sections of the dryer. The first 3 sections are responsible for removing moisture from the product, and the fourth section is responsible for cooling the product. Each section has its own dedicated air flow, temperature control, and steam coils. The steam coils are used to heat up the air that moves through each section, as hot air can contain much more moisture than cool air.

In addition to using Chad Girvin as a resource for information, we were also able to use Nestle Purina’s process monitoring system called iFix to gather information on the system. The computer interface with this system is shown in Figures 5 and 6. Figure 5 depicts all of the relevant information for dryer 3, which is the focus of our project. iFix provides a large amount of data, and we focused on a few key details to determine the relative efficiency of dryer 3. We used dryer 1 as a reference; data for dryer 1 can be found in Figure 6.

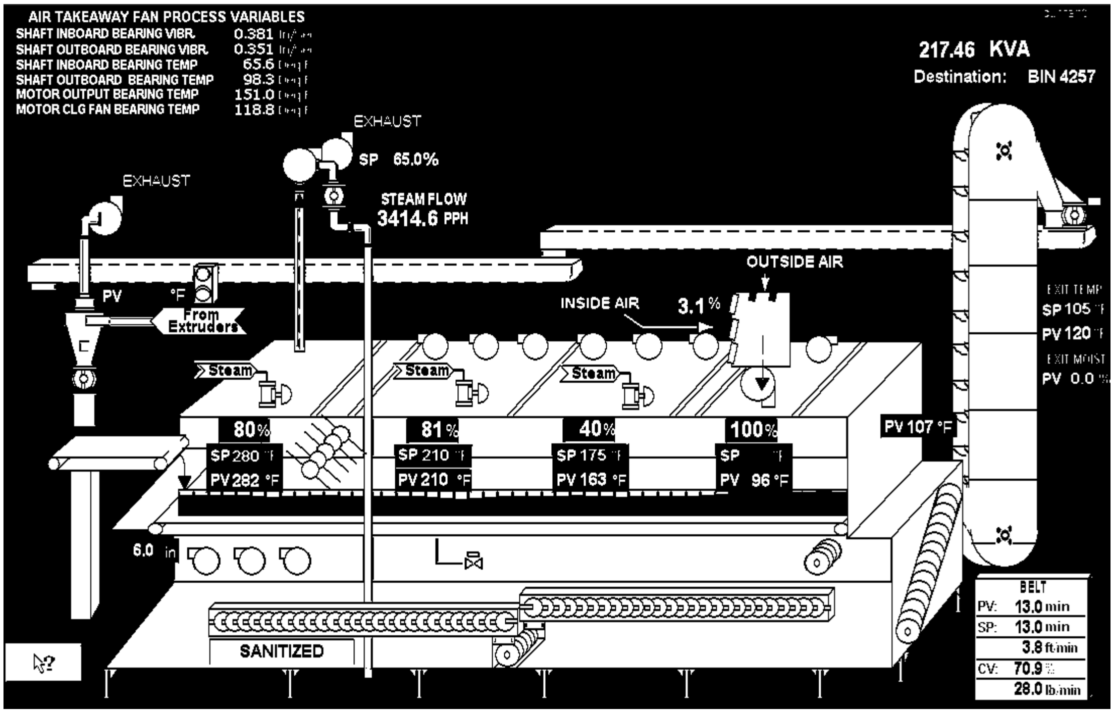
The percentages displayed along the dryer bed represent the percentage of dryer steam usage as a comparison to the dryer capacity. Figures 5 and 6 show that dryer 3 is running at near capacity, while dryer 1 is running at approximately 70% capacity. To quantify the dryer steam usage, we were able to access the steam flow rate for each dryer, in terms of pounds of steam per hour, or pph. The steam flow rate for dryer 3 was 4009.3 pph at the time of measurement and the steam flow rate for dryer 1 was 3414.6 pph.



AIR TAKEAWAY FAN PROCESS VARIABLES

SHAFT INBOARD BEARING VIBR.	0.976	In/Sec
SHAFT OUTBOARD BEARING VIBR.	0.187	In/Sec
SHAFT INBOARD BEARING TEMP	146.0	Deg F
SHAFT OUTBOARD BEARING TEMP	79.9	Deg F
MOTOR OUTPUT BEARING TEMP	118.7	Deg F
MOTOR CLG FAN BEARING TEMP	73.9	Deg F

Figure 5 – Dryer 3 Source: Nestle Purina Process Monitoring System



AIR TAKEAWAY FAN PROCESS VARIABLES

SHAFT INBOARD BEARING VIBR.	0.381
SHAFT OUTBOARD BEARING VIBR.	0.351
SHAFT INBOARD BEARING TEMP	65.6
SHAFT OUTBOARD BEARING TEMP	98.3
MOTOR OUTPUT BEARING TEMP	151.0
MOTOR CLG FAN BEARING TEMP	118.8

Figure 6 – Dryer 1 Source: Nestle Purina Process Monitoring System

We also needed a way to quantify the product throughput through the dryer. iFix provides the product bed depth, and the dryer bed operates at a constant speed, so we decided to define a dryer efficiency index as inches of product depth per steam flow rate in pounds per hour. The indexes were small, so we made them easier to read by multiplying by 1000. The efficiency index of dryer 3 was determined to be 1.147 while the efficiency index of dryer 1 was 1.7516. The percent difference between the efficiency index of dryer 3 and 1 was 34.7%, with dryer 1 displaying a significantly higher efficiency rating. We used all of this information to aide our brainstorming, concept generation, and concept selection.

In the brainstorming stage, we came up with any and all solution ideas to achieve better efficiency in dryer 3 compared to the other 4 dryers. There were no bad ideas or negative feedback in this stage, as one idea can lead to another. Some ideas range from outright buying a new boiler from off the shelf to redesigning the existing boiler to changing the insulation and fuel for the boiler itself. Initial research and price quotes for these solutions range upward of half a million dollars so a careful inspection of these ideas are necessary.

To further generate concepts from the brainstorming stage, we used Osborn’s Checklist shown in Table 1 in the Appendix. This method allows one to expand the list of ideas by asking how to adapt, modify, magnify, minify, substitute, rearrange, and combine. By following this procedure, we obtain many more concepts; some good and some unreasonable. For example, by taking the original concept of insulation, we can increase the amount of insulation around main pipes, decrease insulation around other pipes, use different insulation material, or a combination of these designs. Then, to refine the list for top, viable concepts, we used a weighted criteria tree with a decision matrix.

Concept Selection

Since there are three criteria, the team needs to determine the overall importance for the criteria. So the team can make a decision matrix for the concepts. Therefore the Analytical Hierarchy Process is applied to determine the overall importance. Table 2 describes the overall scale to judge the overall importance of each category.

Table 2 – Scale of the Judgment of Importance

Judgment of Important	Equally important		Moderately more important		Strongly more important		Very strongly more important		Extremely more important
Numerical Rating	1	2	3	4	5	6	7	8	9

In the Pairwise Comparison Matrix (Table 3), the team determines that the moisture control is moderately more important that the cost. The production is strongly more important than the cost and moisture control. So the values are put in the matrix. The total value is the sum of the values in each column. The value of each criterion in the matrix is divided by the total value in that column. The normalized values are shown in Table 4. By taking the average of the normalized value in the row, the team gets the overall importance for the criteria. The overall importance of the cost, moisture control, and production is 0.211, 0.102, and 0.686 respectively.

Table 3 – Pairwise Comparison Matrix

	Cost	Moisture Control	Production
Cost	1	3	1/5
Moisture Control	1/3	1	1/5
Production	5	5	1
Total	19/3	9	7/5

Table 4 – Normalized Importance and Overall Importance

	Cost	Moisture	Production	Overall Importance
Cost	0.158	0.333	0.143	0.211
Moisture Control	0.053	0.111	0.143	0.102
Production	0.789	0.556	0.714	0.686

Each criterion was given a relative weight of how important they are to each other for each category. Cost was determined by our client to be of twenty-five percent importance, while moisture control was ten percent importance and production was sixty-five percent. In each of the three categories; cost, moisture control, and production were broken down into their sub criteria and ranked on importance of each other. Under cost, the payback period was rated as an overall seventy percent while the energy to run the dryer was ranked as thirty percent important. The same technique was applied to the other categories. After each of the criteria received their specific weight, they were then multiplied by the overall weight for that category. This allowed for an overall ranking of how important each of the criteria was to the overall design (shown in Figure 7).

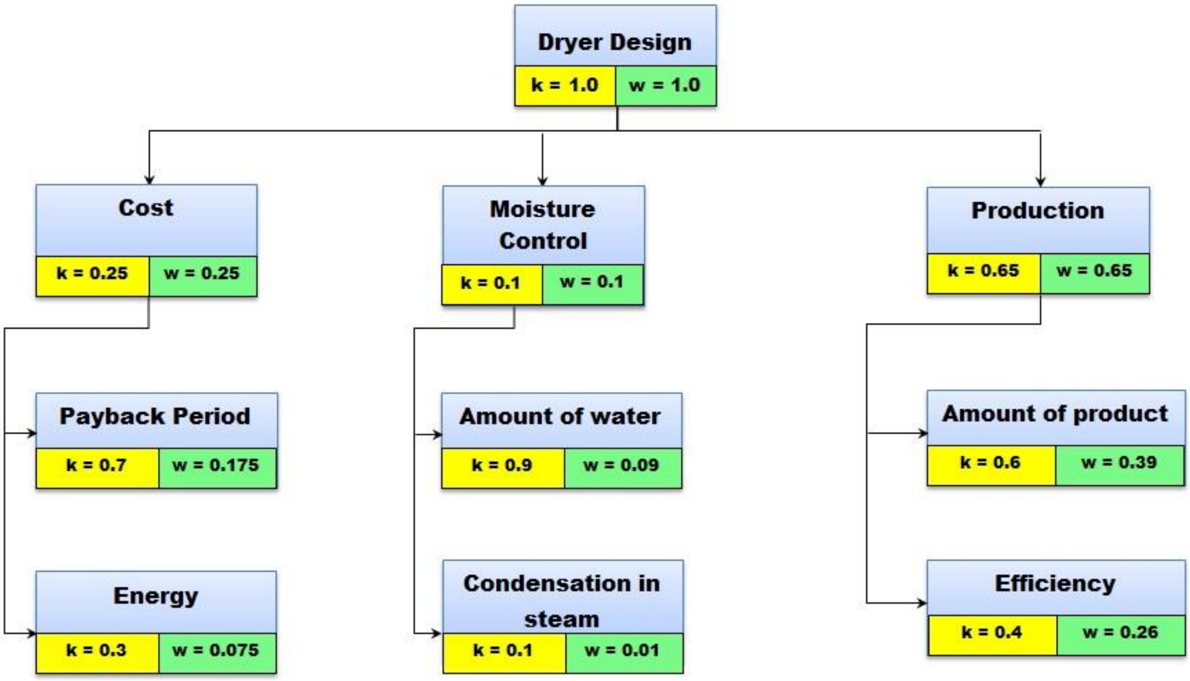


Figure 7 – Weighted Criteria Tree

We used a clearly defined strategy to generate concepts to solve this problem, and also to select which concepts we would be pursuing in our engineering analysis. This strategy was to clearly define our problem, clearly define our system, brainstorm ideas, and then use Osborn's checklist (seen in Table 1 in the Appendix) to expand and refine these raw ideas. Then, we used a weighted criteria tree as well as an analytic hierarchy process to determine our best solution options from our refined idea list. As a result, we were able to conclude that our best three solution options are: Analyzing the steam characteristics, analyzing the air flow inside the dryers, and re-designing the dryer air flow. These three ideas will be our basis when we begin to look into the engineering analysis section of our design process.

Engineering Analysis

Current System

After the product enters the dryer, it is passed through 4 sections of the dryer. Figure 8 shows a schematic of how the dryer operates. The first 3 sections are responsible for removing moisture from the product, and the fourth section is responsible for cooling the product. Each section has its own dedicated air flow, temperature control, and steam coils. The steam coils are used to heat up the air that moves through each section, as hot air can contain much more moisture than cool air.

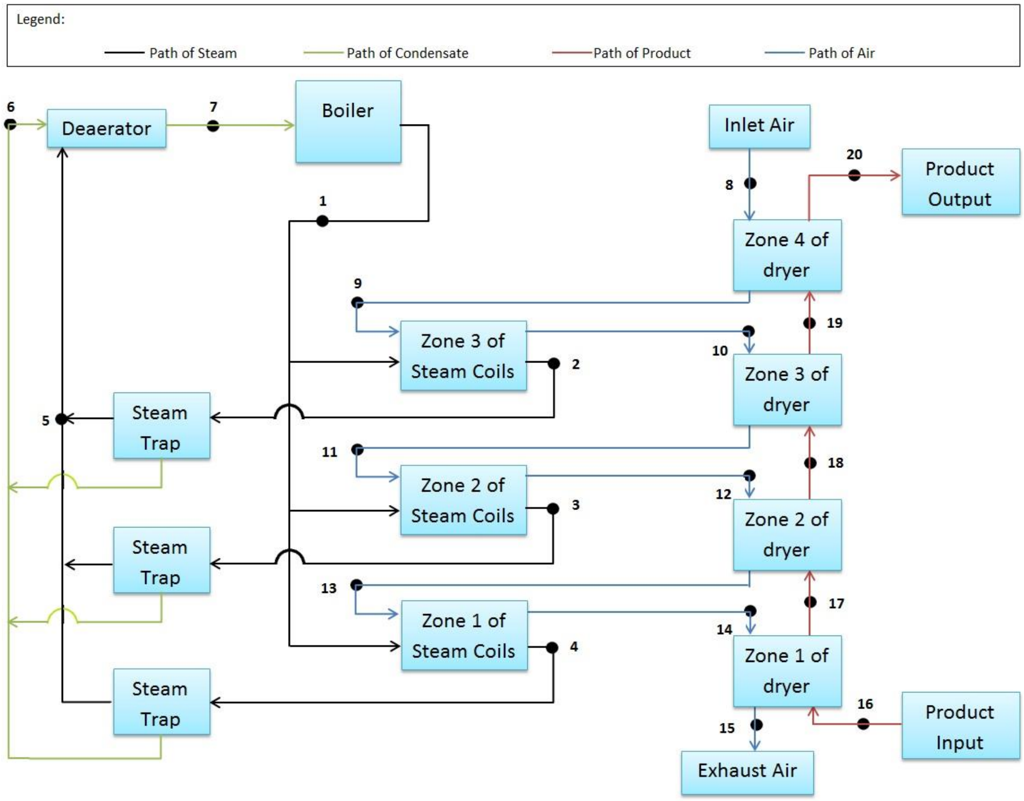


Figure 8 – Schematic of Steam Dryer

Analysis of Steam

In order to ensure the system is operating correctly, the operation of the subcomponents must be analyzed. The analysis conducted below is for an individual steam coil. Each steam coil acts as a heat exchanger where an input of steam heats up air in a cross flow pattern. The energy balance for the control volume is as follows:

$$\frac{dE}{dt} = Q_{in} - W_{out} + \sum \dot{m}\imath \left[h_i + \frac{{V^2}_i}{2} + gz_i\right] - \sum \dot{m}\imath \left[h_e + \frac{{V^2}_e}{2} + gz_e\right] \tag{1}$$

Where:	h	Enthalpy
	Q_{in}	Heat in
	W_{out}	Work done
	$\dot{m}$	Mass flow rate
	V	Velocity of fluid
	g	Gravitational constant
	z	Elevation

The above equation is simplified with the assumptions that kinetic and potential energy can be neglected. Furthermore no work is done by the system; however loss of energy must be accounted for. Thus equation 1 can be rewritten as:

$$E_{Loss} = \dot{m}_{steam}(h_1 - h_2) + \dot{m}_{air}(h_3 - h_4) + \dot{m}_{vapor}(h_3 - h_4) \tag{2}$$

In order to solve the above equation, the properties of the steam and drying air at every node must be known. All of the properties for the steam are known, however the mass flow rate for the air is not determined by the facilities software. Therefore the mass flow rate of air is estimated by using the known power of the motors that move the air. The following equation relates power to mass flowrate:

$$P = \frac{\dot{m}gh}{33000\eta\eta_e} \tag{3}$$

Where:	$\dot{m}$	Mass flow rate
	g	Gravitational constant
	h	Total head
	η	Efficiency of the motor
	η_e	Mechanical energy (converting electricity)

Since the values for the amount of power for the motor is known (10 horsepower), we can determine the overall expected mass flow rate once we get the data about the overall efficiency of the motor, the mechanical energy, and the total head caused by the velocity and pipe frictions. Once we have calculated the mass flow rate, we need to determine how much of the mass is made up of water vapor and how much is made up of air. By using the equation for moisture content it allows us to determine the ratio of vapor to air:

$$\omega = \frac{m_{vapor}}{m_{air}} \tag{4}$$

Equation 2 will be utilized to determine the operational condition of each independent heat exchanger of the dryer. Those values will be compared to each of the heat exchangers in another dryer found in the plant. This will allow us to determine how differently dryer three is operating from dryer one.

The only data that we have collected so far is listed in Table 6, where each point was defined earlier in Figure 8. This data in combination with the data from the other dryers will allow us to determine if there is a discrepancy with the heat exchangers.

Table 6 – Collected Thermodynamic Properties

Point	**Description**	**Property**	**Others**
1	Stream inlet	T = 273F P = 50psi	should be saturated steam
2	zone 3 steam outlet	T = 230F	
3	zone 2 steam outlet	No Data Collected	
4	zone1 steam outlet	No Data Collected	
5	steam trap outlet	T = 100F	
6	condensate return	T = 180F	
7	Boiler inlet	P = 148psi	efficiency: 84.09%
9	zone 4 air outlet	T = 63F	
10	zone 3 air inlet	T = 187F	
11	zone 3 air outlet	T = 184F	
12	zone 2 air inlet	T = 226F	
13	zone 2 air outlet	T = 178F	
14	zone 1 air inlet	T = 216F	
15	exhaust	P = atmospheric	standard pressure
16	product inlet (cyclone exit)	T = 150F	22% moisture content
17	zone 1 (inlet)	T = 215F	22% moisture content
18	zone 2 (inlet)	T = 200F	15.5% moisture content
19	zone 3(inlet)	T = 180F	11.5% moisture content
20	zone 4 (inlet)/ dryer outlet	T = 100F	9% moisture content

After our analysis, we are going to determine the best way to fix whatever is causing the problem. To determine the best way of fixing the problem, we are going to perform a cost analysis. This will allow us to determine exactly how much the increase in cost will be, and how long it will take for the increase in productivity to pay for the increase in costs.

Natural Gas Conversion

Another idea that we are looking into is converting the steam dryer over to a dryer that runs on natural gas. This would replace the use of steam to this dryer therefore eliminating the issue of the problematic drying. Instead of using the three different steam coils and steam traps, all of that would be replaced by a natural gas burner which heats the air directly drying the product as a result. Figure 9 shows a schematic of how the natural gas dryer operates.

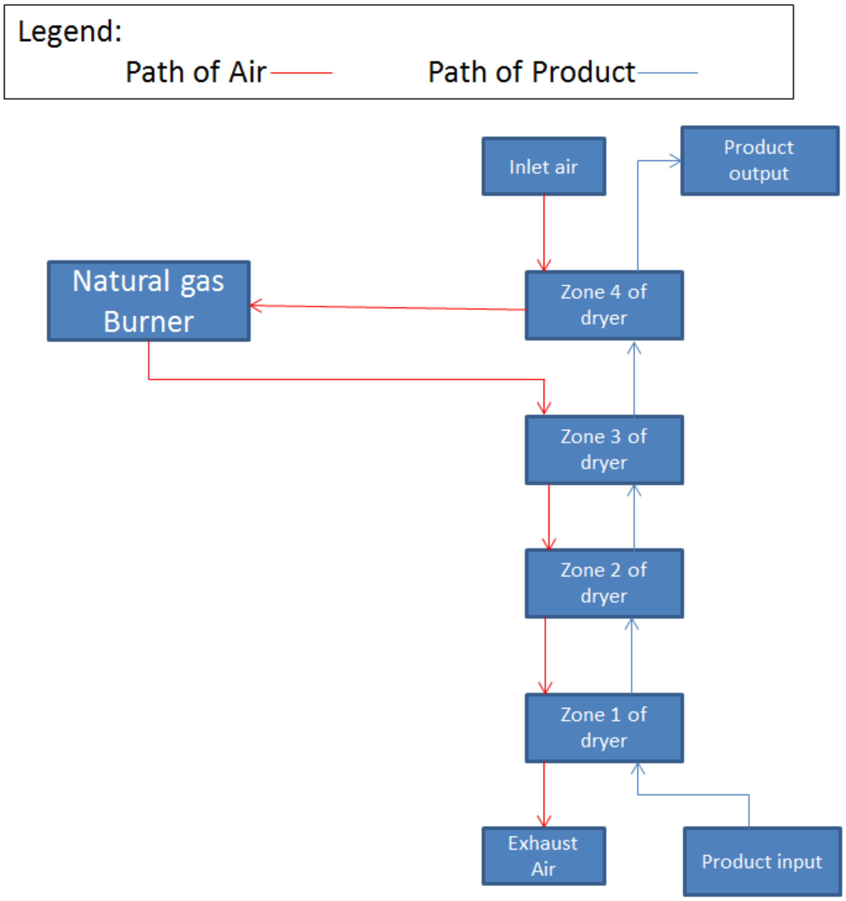


Figure 9 – Schematic of the Natural Gas Dryer.

After the product enters the dryer, it is passed through 4 sections of the dryer. Air enters the fourth zone to cool the product down. Then the air will be heated up by the natural gas burner. After air being heated up, it enters the other 3 sections of the dryer which will remove the moisture from the product.

$$Q_{Combustion} = \dot{m}_{air} * (h_1 - h_2) + \dot{m}_{vapor}(h_1 - h_2) + E_{Loss} \tag{5}$$

$$Q_{Combustion} = \dot{m}_{gas} * \Delta H_{comb} * \eta \tag{6}$$

Where:	h	Enthalpy
	Q_{Comb}	Heat
	W	Work done
	$\dot{m}$	Mass flow rate
	ΔH_{comb}	Heat of combustion
	η	Burner Efficiency

The energy released by the burning of natural gas is given in equation 6, which is used in equation 5 to find the energy lost to entropy generation. The mass flow rates are determined either using the flow to power relationship given in equation 3 or are measured.

These dryers have a much higher efficiency than the steam dryers, reducing the overall amount of cost for fuel while greatly increasing the amount of product that can go through the dryer at any given time. However, this conversion is a very significant cost so it ultimately would depend on whether our client would want to go that route. If they do decide to go that route, the payback period is only a couple of years due to the increase in efficiency and throughput.

In order to do analysis on this, we would have to consult with a sister Purina plant in Clinton, IA. They are currently implementing a similar conversion in their plant and should be up and running in the near future. We would be able to see the direct effect of the increase in productivity for this type of dryer and present this to our client for his considerations.

Natural Gas Heat Exchanger Design

The progress up to this point has led the team to split into two design groups. Similar to the work that was completed last semester, we brainstormed and refined our ideas down to two natural gas fueled designs.

The first design includes replacing the steam coils in the dryer with a natural gas fire heat exchanger. The team received specifications for this heat exchanger from a heat exchanger that is in use in a Purina facility in Clinton, IA. It was determined from the manufacturer specifications that the heat exchanger would transfer heat at a rate of 1,028 BTU per cubic foot of natural gas used.

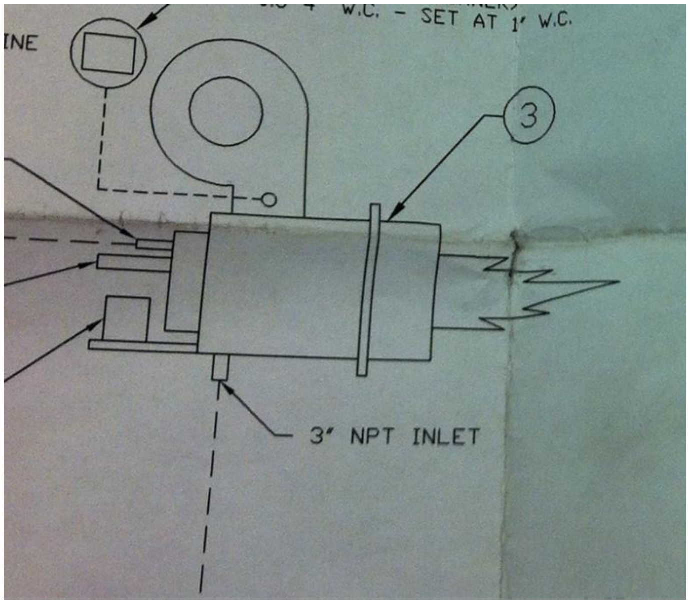


Figure 10 – Natural Gas Burner

Figure 3 shows a drawing of this existing design. The flange denoted by section 3 in the figure is the wall between the fire chamber and the outside of the device.

Exhaust Gas Design

To gather an estimate on how much energy it uses to run the dryer, a thermodynamic analysis was ran on Dryer 3 by using the Interactive Thermodynamics software (see code and full results in Appendix). To make analysis a little easier, it was decided to only do the analysis on a single simplified heat exchanger, Figure 4, in the first section of the dryer. The first section was analyzed because the air temperatures are the hottest there and therefore use the most energy.

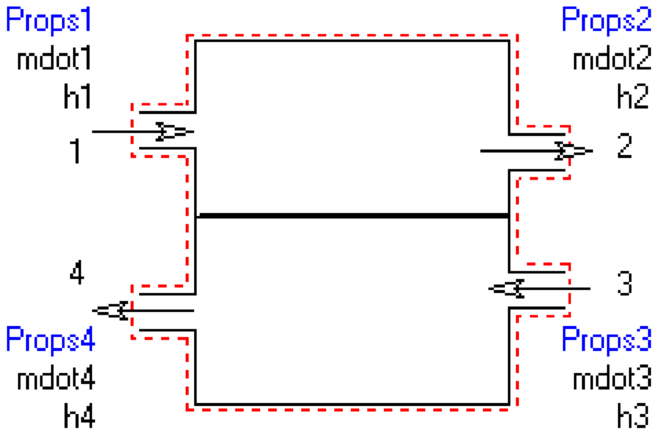


Figure 11 – Simplified Heat Exchanger

For the purpose of our calculations, the analysis was run under steady state conditions (no mass accumulations, so inlet mass flow rate equals the mass flow rate at the outlet). It was assumed that the pressure does not drop over the length of the heat exchanger. Because the exhaust of the natural gas fire is completely theoretical, a starting temperature of 500F was used and an ending temperature of 345F to provide enough energy to heat the air to the 280F temperature. Steam has a much higher capability of transferring heat due to an enthalpy of 1212 BTU/lb at 350 degrees Fahrenheit, while air at 500 degrees Fahrenheit has an enthalpy value of 231 BTU/lb (Table 2 and Table 3). Calculations showed that the energy the steam loses is 21740 BTU/lb. At a cost of $6.19/MBTU, the total cost per day comes out to be $193.80. Calculations showed that the energy the air loses is 21290 BTU/lb. At a cost of $5.16/MBTU the total cost per day comes out to be $158.12. The major difference in the cost is due to a 20% transmission loss from transferring the steam from the natural gas boiler to the heat exchanger across the plant. Also we could tell that the heat exchangers are not that efficient because they are losing quite a bit of energy. Between the steam and air, a total of 458.7 BTU are being lost during the heat transfer. This would equate to a cost of $4.09 per day.

Since each dryer has 3 heat exchangers, the approximate cost per day to run the dryer on steam would be $581.40 per day and on exhaust would cost $474.36. However, due to the lack of production of these dryers as compared to the natural gas dryers, the total cost is actually quite a bit more.

Table 7 – Results of analysis on the heat exchanger for steam

Measurement	Value
Temperature of steam at inlet	350 F
Pressure of steam at inlet	40 psi
Enthalpy of steam at inlet	1212 BTU/lb
Mass flow rate of steam	22.27 lb/min
Temperature of steam at outlet	267 F
Enthalpy of steam at outlet	235.8 BTU/lb
Temperature of air at inlet	120 F
Pressure of air at inlet	10 psi
Mass flow rate of air	552 lb/min
Enthalpy of air at inlet	138.6 BTU/lb
Temperature of air at outlet	280 F
Enthalpy of air at outlet	177.2 BTU/lb
Energy extracted from steam	21740 BTU
Energy from steam into air	21280 BTU
Energy lost between steam and air	458.7 BTU
Cost	775.20 $/day

SolidWorks Flow Simulation

To accomplish our goal of showing the benefit of switching to a natural gas system, we will fully define the natural gas system using Computational Fluid Dynamics (CFD) analysis. CFD software's enable quick, efficient simulation of fluid and heat transfer. The Solidworks Flow simulation extension was chosen as the choice of software due to the availability and experience with the software. The software allows conjugate heat transfer, which is an added benefit. (add in what you put in the presentation)

Heat Transfer Model

The current heat exchanger present in the dryer has dimensions of 10'x4'x4'. The intent is to design a heat exchanger using 2 inch piping as the exhaust tubing to replace the current heat exchanger. In Figure 12 below, the SolidWorks model shows the new heat exchanger with the same dimensions with 15 individual partitions with the 3 barrier design. The primary design requirements are in earlier sections; however in detail specifications needed to be determined, such as the spacing between pipe and wall and the number of barriers. A counter flow heat exchanger was chosen because of the higher output temperature than a parallel flow heat exchanger. The partition width was chosen based on avoiding an excessive Reynolds number; the narrower the partition the quicker the air must move past the exhaust tubing.

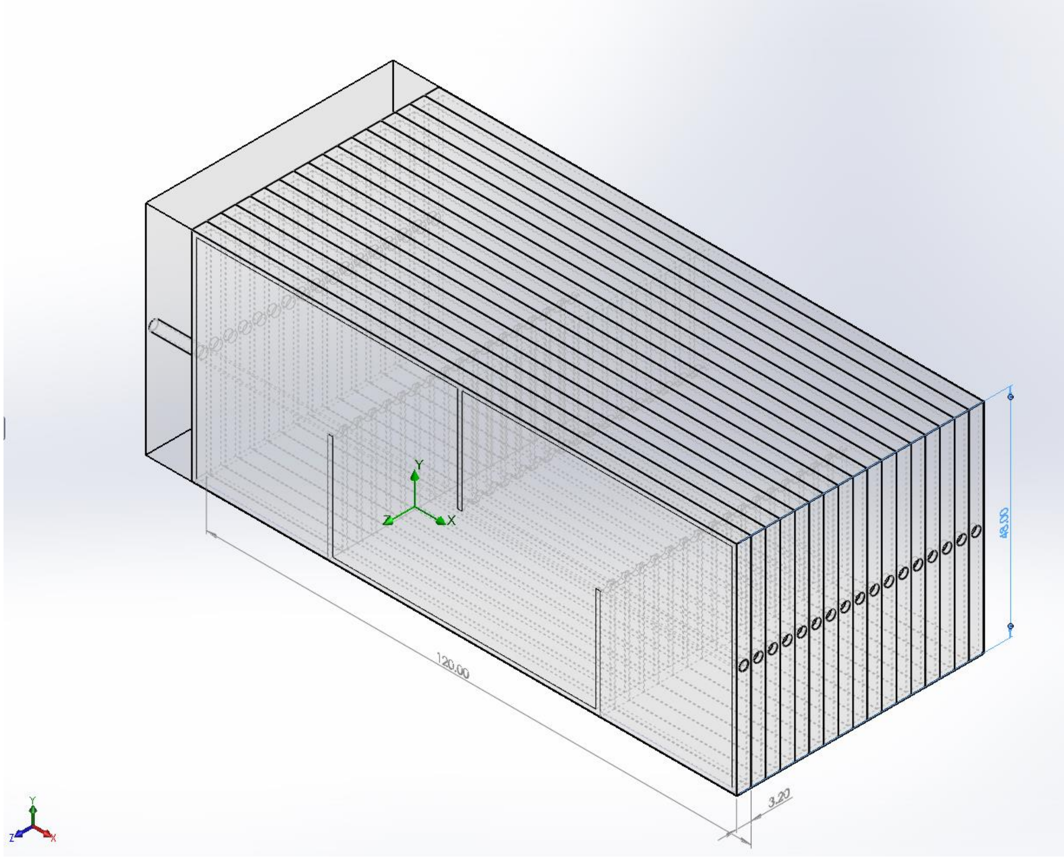


Figure 12 – Heat Exchanger Design

In order to determine the most efficient design an individual portion is analyzed to simplify simulation and computational time. To simulate partitions on each side, an adiabatic wall condition for the outer walls of the partition was imposed on the model. A conjugate analysis was chosen with stainless steel as the material of most solids. The input parameters of the fluids were determined earlier using the thermodynamic model. To determine the suitable amount of barriers, the efficiency of each is compared. In order to rate their efficiencies and draw conclusions based thereupon, the simulations must be run using the same parameters. Following are temperature contour cut plots of an individual partition with flow trajectories for the different amounts of barrier heat exchangers.

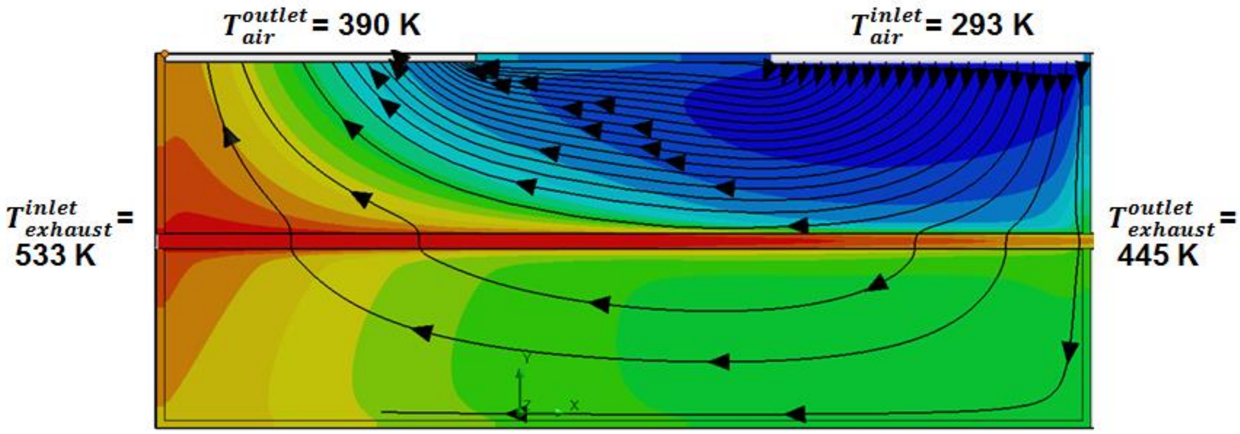


Figure 13 – No Barrier Heat Exchanger Design

The design without any barriers, (shown above), displayed poor performance. The majority of the streamlines never cross the exhaust tube; furthermore there is a large temperature gradient across the air exit, about 12 contours. The large spacing between streamlines indicates extreme slow velocities. The exhaust should not have a temperature gradient across the exit, this indicates incomplete heat transfer. The single barrier partition below shows impressive improvement. The velocity across the tube is fairly constant with a slight increase in-between crossing. All stream lines cross the tubing and the temperature gradient across the air exit is significantly smaller with only 4 contours, furthermore the exhaust exit shows a lower temperature.

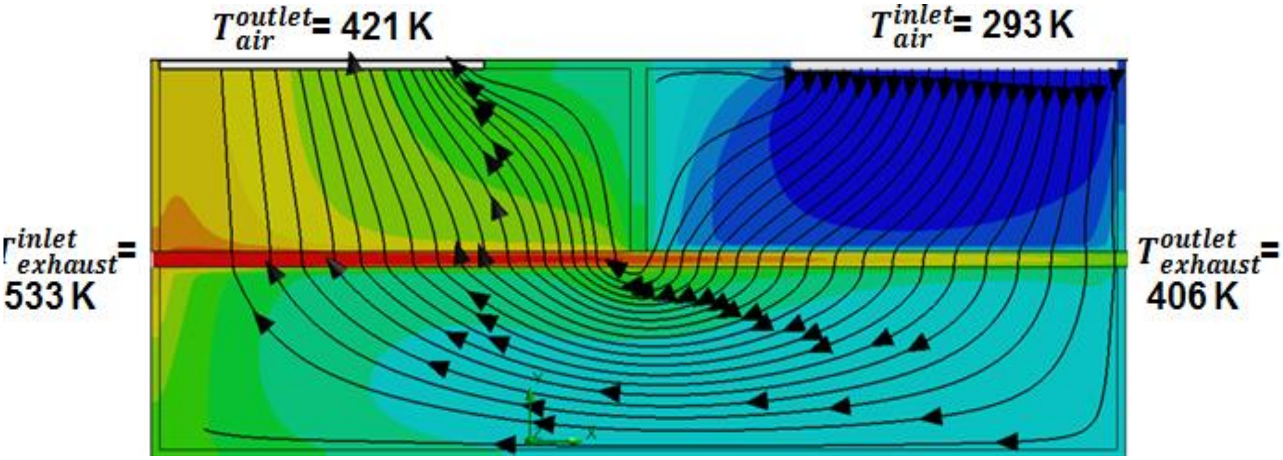


Figure 14 – Single Barrier Heat Exchanger Design

Since the single barrier showed such improvement, the dual barrier design is expected to behave similarly, shown in Figure 15. The stream lines cross the tubing three times reducing the width causing the velocity to increase, which is illustrated by the spacing between the stream lines being narrower. The gradient across the air exit continued to decrease to only 3 contours.

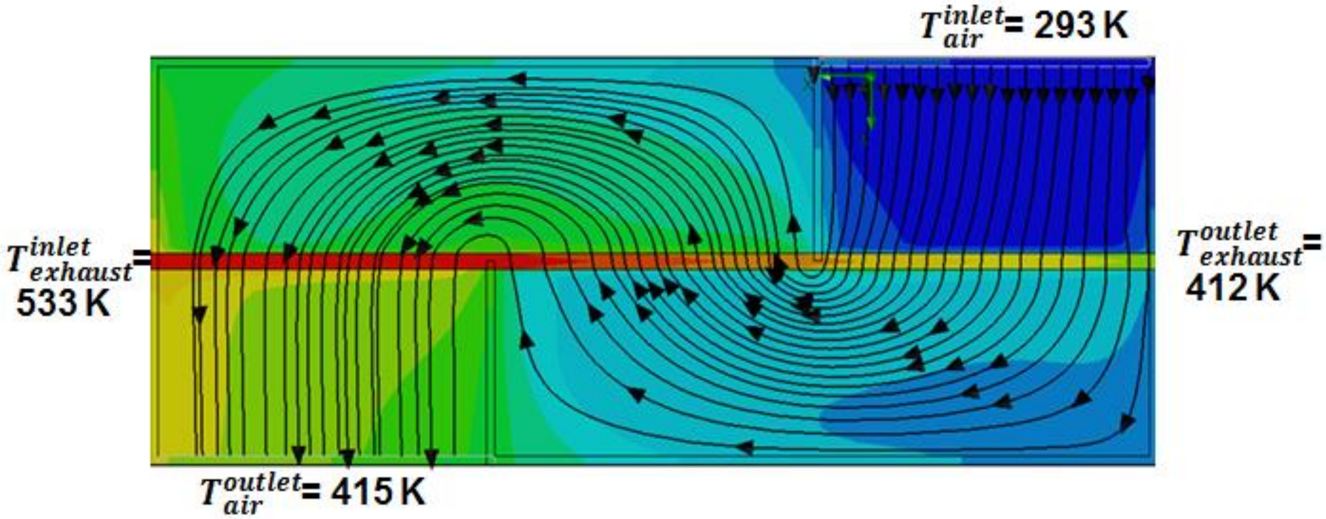


Figure 15 – Two Barrier Heat Exchanger Design

Both the 3 and 4 barrier designs showed similar behavior with respect to their streamlines. The air flow is very turbulent and therefore the streamlines collide and intersect, resulting in the lowest temperature gradient across the exit. The increased velocity causes the flow to contract together hence does not occupy the entire partitions cavities. The slight blue corner in the 3 barrier partition is due to vortices crossing in form the exterior boundary. Overall, the 3 and 4 barrier design showed low to no improvement, although the exit air is at a more uniform temperature. Intuitively the more barriers the heat exchanger is equipped with, the higher the heat transfer should be. However the 4 barrier heat exchanger exhibited lower performance due to the flow being faster across the tubing, resulting in less heat transfers

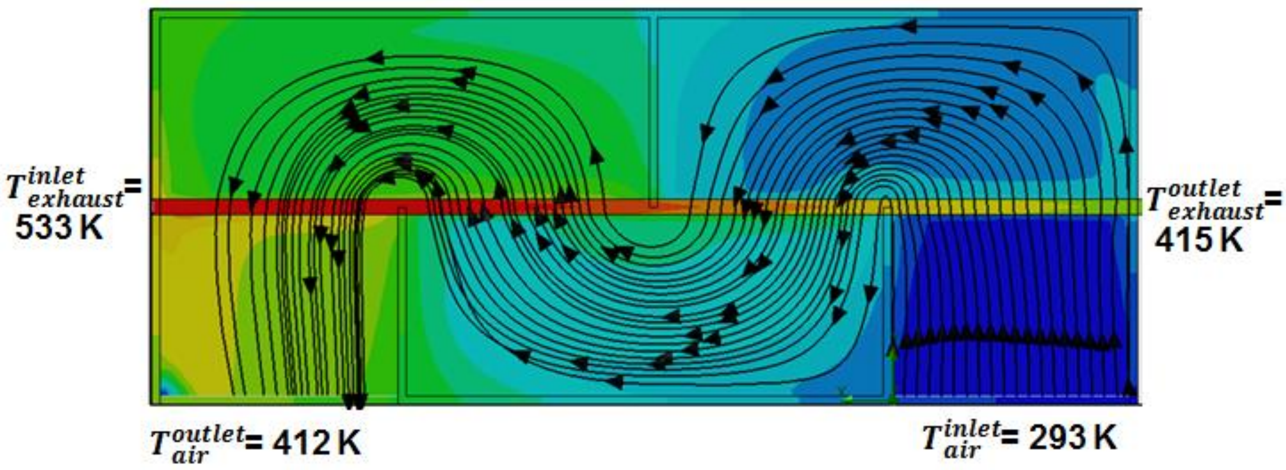


Figure 16 – Three Barrier Heat Exchanger Design

Results

There are five models described in the previous section. The outlet temperatures of exhaust and air have been calculated from the simulation for each heat exchanger. The temperature of all heat exchanger designs are shown in the table below.

Table 8 – The inlet and outlet temperature of all heat exchanger designs

Type	Air inlet Temperature [K]	Air Outlet Temperature [K]	Exhaust Inlet Temp [K]	Exhaust Outlet Temperature [K]
No barrier	293	390	533	445
1 Barrier	293	421	533	406
2 Barriers	293	415	533	412
3 Barriers	293	412	533	415
4 Barriers	293	405	533	420

The heat exchanger efficiency can be calculated by the following equation when the temperature values are available:

$$\varepsilon = \frac{T_{air}^{Inlet} - T_{air}^{outlet}}{T_{air}^{Inlet} - T_{exhaust}^{inlet}} \tag{7}$$

Where:

ε is the heat exchanger efficiency

T_{air}^{Inlet} is the inlet temperature of the cold air, [K]

T_{air}^{outlet} is the outlet temperature of the cold air, [K]

$T_{exhaust}^{inlet}$ is the inlet temperature of the hot exhaust, [K]

According to the equation above, the heat exchanger efficiencies have been calculated and listed in the following table:

Table 9 – Efficiency of Heat Exchangers

Type	No barrier	1 Barrier	2 Barriers	3 Barriers	4 Barriers
Efficiency	0.37	0.53	0.5	0.49	0.47

From the efficiency table, the design with one barrier is the most efficient heat exchanger when comparing with other four heat exchangers. The efficiency values of five designs are very close except the no barrier design. In reality, the values may vary and the design with one barrier may not be the best design. However, the design with one barrier is the best design from the simulations.

Another way to find the best design is to show the temperature difference between the inlet and outlet. The temperature increase of the cold air and the temperature drop of the exhaust are shown in Figure 17 below.

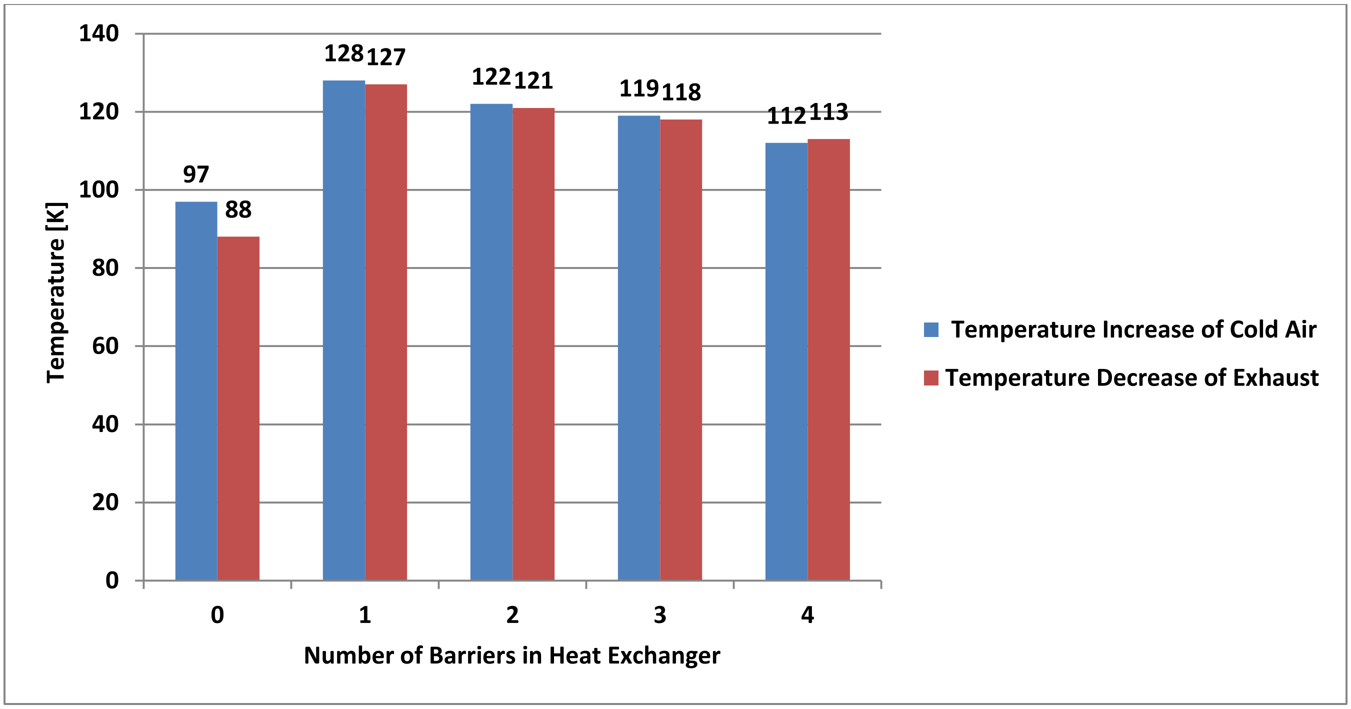


Figure 17 – Temperature Comparisons of Cold Air and Exhaust

From the figure above, the temperature increase in the cold air is 128 K in the design with one barrier, which is the most temperature increase among five designs. The temperature differences in the two barrier design and three barrier design are close to the one barrier design. Overall, the design with one barrier will be considered as the best design.

Natural Gas Burner Design

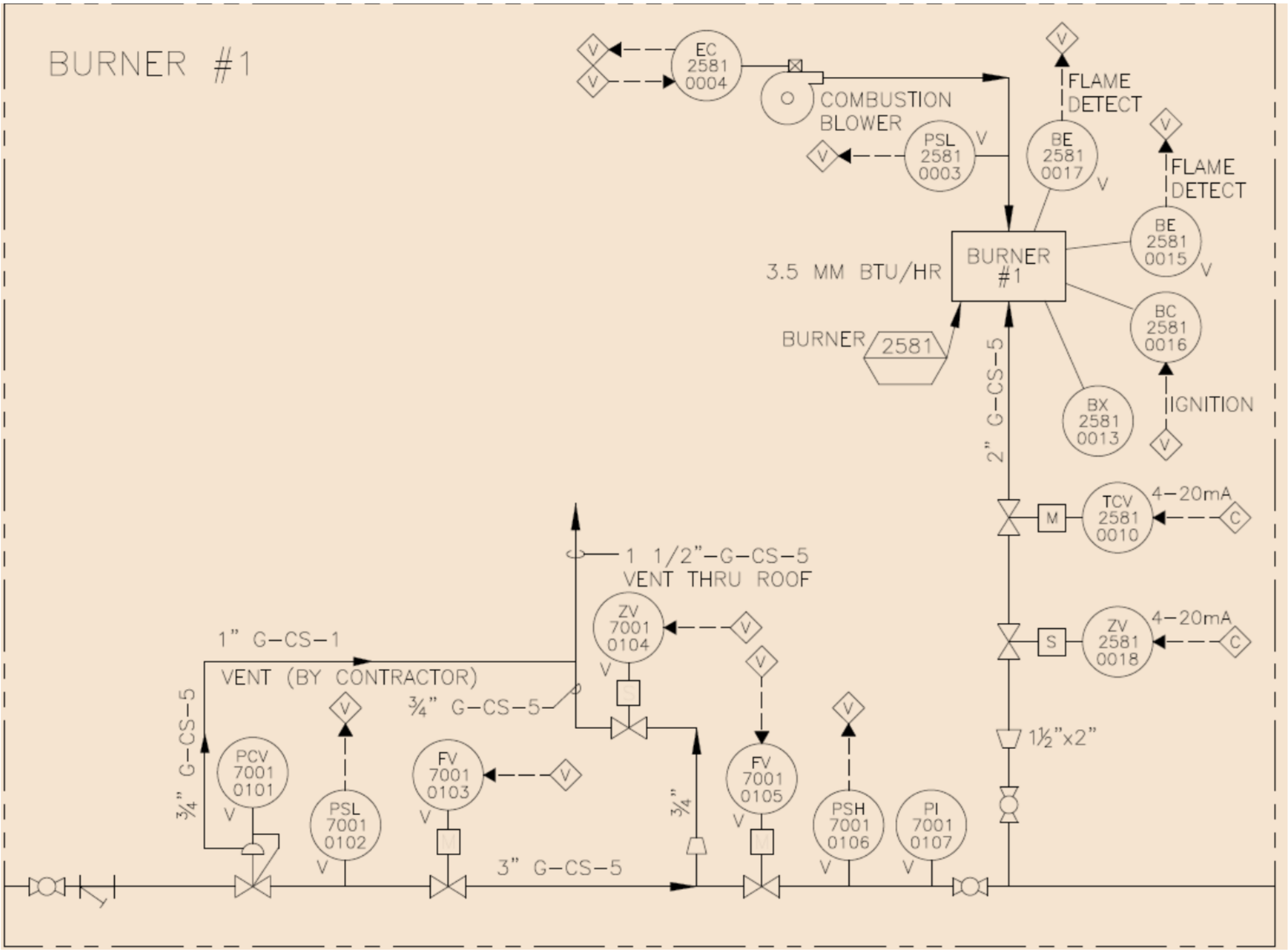


Figure 18 – Natural Gas Burner Design Drawing 757-963A-SKF3-A

Figure 18 shows the gas burner design that our team will use in conjunction with our heat exchanger design. The lower, horizontal section is an entirely vendor controlled portion of the burner. It contains flow and pressure sensors that are connected to a vendor supplied control interface. This interface interacts with itself as well as Nestlé's control interfaces to monitor the conditions of the natural gas as it approaches the burner. The main natural gas header is a 3 inch carbon steel line, with two ¾ inch pipes merging into a 1.5 inch vent to the roof. These pipes have solenoid valves that can open and close by inducing an electric current from the control interface. These solenoid valves operate in a ‘normally closed’ state. This 3 inch natural gas header is then reduced to a 2 inch carbon steel line that acts as the supply to the burner. On this 2 inch line, there is a motor operated temperature control valve as well as another solenoid valve. These valves are linked to the plant programmable logic controllers. This allows us to control the temperature of the inlet natural gas. Also, in the event of combustion within the line, the motor operated valve will automatically shut off, preventing a dangerous natural gas explosion. The solenoid valve allows us to control the flow of natural gas to the burner. We had concerns with the backpressure created when combustion occurred in the burner. We did not want the natural gas fire to flow back into the supply line, and we also wanted to avoid exposing our blower to high heat. The highest operating temperature blower we could find operated much below the possible temperatures created by the natural gas combustion. The control valves are capable of operating at a high frequency, so we are able to achieve a near-continuous flow of natural gas to the burner without exposing the upstream components to these high temperatures. The chamber will fill with natural gas and air, the inlet valves will shut, and then the ignition source will spark. The burner as well as the outlet tubing will be constructed of 304 – Stainless Steel. This material decision was based off of the high melting point and the low maintenance of stainless steel. It also contributes to a Nestlé Purina initiative called the kitchen concept initiative.

Conclusion

Nestle Purina in Flagstaff produces pet food and is experiencing problems with one of their food dryers. These energy inefficiencies have led to increased costs and decreased throughput for dryer 3. To combat this, we used an iterative design process to diagnose the issues with dryer 3, mainly the steam coil heat exchangers, and propose a design to solve the problems that we have identified. Our team designed a new heat exchanger that uses hot exhaust gasses from a natural gas burner as the high energy fluid. The design with one barrier is the best design from Solidworks simulation. We also researched and included specifications for the natural gas burner, blower, and safety instrumentation associated with the burner. Our natural gas design requires approximately 72,000 cubic feet of natural gas per day, which at industrial pricing for natural gas translates to $196.65 per day. We used our thermodynamic model as well as information from the company to find a steam usage of approximately $775.2 per day. This savings translates to $196,707 per year. One of the design constraints was a 3 year maximum payback period. To meet this requirement, the total investment should less than $590,000. Using this new heat exchanger design, we hope to improve the energy efficiency and product throughput at the Nestlé Purina facility in Flagstaff, Arizona.

References

Clint Chadwick
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Bergman, T. L., and Frank P. Incropera. *Fundamentals of Heat and Mass Transfer*.Hoboken, NJ: Wiley, 2011. Print.

Figliola, R. S., and Donald E. Beasley. *Theory and Design for Mechanical Measurements*. Hoboken, NJ: J. Wiley, 2011. Print.

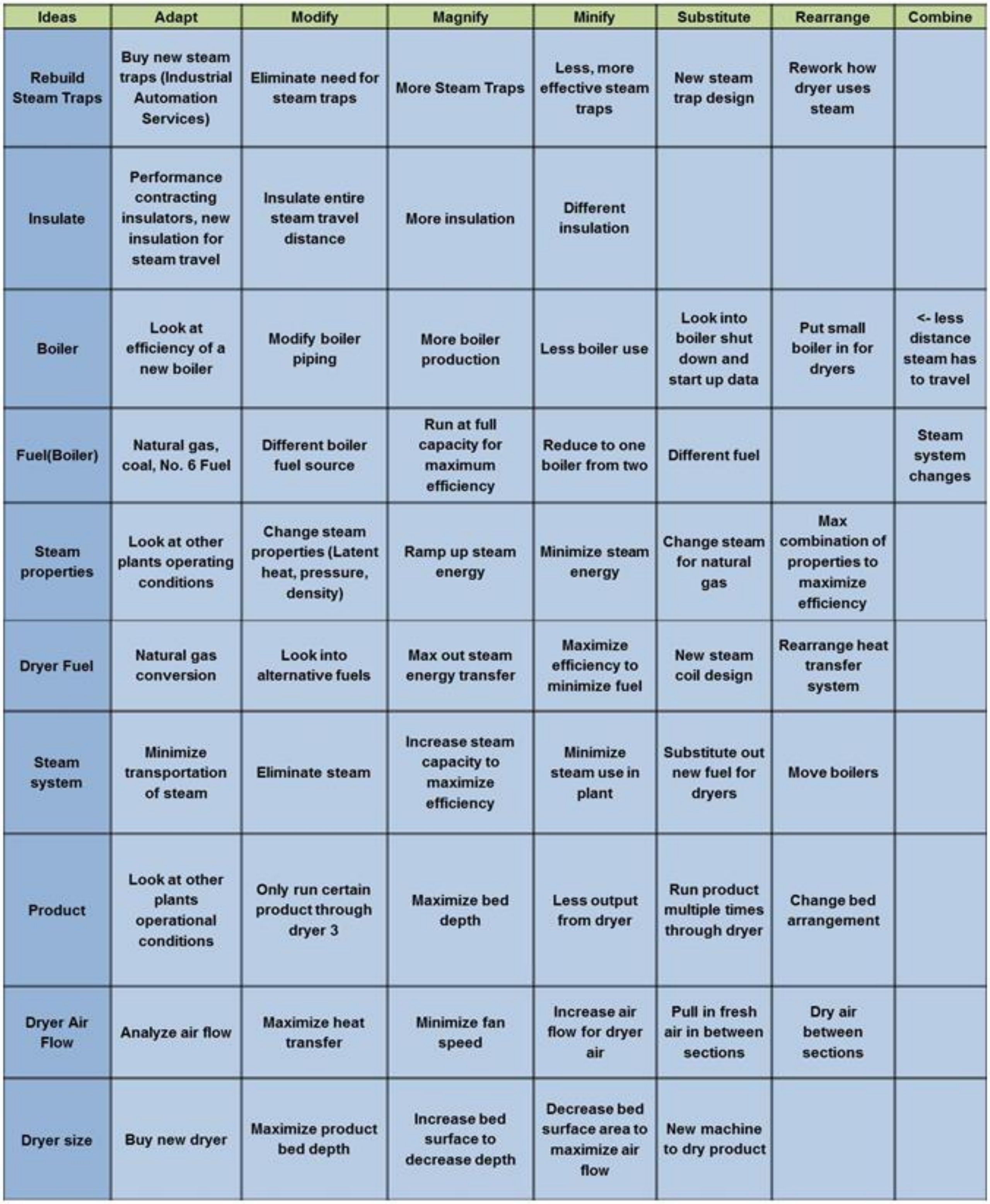
Baumeister, Theodore, Ali M. Sadegh, and Eugene A. Avallone. *Marks' Standard Handbook for Mechanical Engineers*. New York: McGraw-Hill, 2007. Print.
White, Frank M. *Fluid Mechanics*. New York, NY: McGraw Hill, 2011. Print.

J.P. Holman. “Heat Transfer.” Eighth edition.

Appendix:

Osborn’s Checklist

Table 1 - Osborn’s Checklist



Ideas	Adapt	Modify	Magnify	Minify	Substitute	Rearrange	Combine
Rebuild Steam Traps	Buy new steam traps (Industrial Automation Services)	Eliminate need for steam traps	More Steam Traps	Less, more effective steam traps	New steam trap design	Rework how dryer uses steam	
Insulate	Performance contracting insulators, new insulation for steam travel	Insulate entire steam travel distance	More insulation	Different insulation			
Boiler	Look at efficiency of a new boiler	Modify boiler piping	More boiler production	Less boiler use	Look into boiler shut down and start up data	Put small boiler in for dryers	<- less distance steam has to travel
Fuel(Boiler)	Natural gas, coal, No. 6 Fuel	Different boiler fuel source	Run at full capacity for maximum efficiency	Reduce to one boiler from two	Different fuel		Steam system changes
Steam properties	Look at other plants operating conditions	Change steam properties (Latent heat, pressure, density)	Ramp up steam energy	Minimize steam energy	Change steam for natural gas	Max combination of properties to maximize efficiency	
Dryer Fuel	Natural gas conversion	Look into alternative fuels	Max out steam energy transfer	Maximize efficiency to minimize fuel	New steam coil design	Rearrange heat transfer system	
Steam system	Minimize transportation of steam	Eliminate steam	Increase steam capacity to maximize efficiency	Minimize steam use in plant	Substitute out new fuel for dryers	Move boilers	
Product	Look at other plants operational conditions	Only run certain product through dryer 3	Maximize bed depth	Less output from dryer	Run product multiple times through dryer	Change bed arrangement	
Dryer Air Flow	Analyze air flow	Maximize heat transfer	Minimize fan speed	Increase air flow for dryer air	Pull in fresh air in between sections	Dry air between sections	
Dryer size	Buy new dryer	Maximize product bed depth	Increase bed surface to decrease depth	Decrease bed surface area to maximize air flow	New machine to dry product		

Decision Matrix

Table 2 – Decision Matrix

Design Type	Cost		Moisture Control		Production		Total
	Value	Normalized Value	Value	Normalized Value	Value	Normalized Value	
Change steam properties.	9	1.899	7	0.714	8	5.488	8.101
Analyze air flow	10	2.11	5	0.51	7	4.802	7.422
Pull in fresh air between section	7	1.477	5	0.51	7	4.802	6.789
Natural Gas Conversion	1	0.211	10	1.02	8	5.488	6.719
New steam coil design	7	1.477	8	0.816	6	4.116	6.409
Dry air between sections	5	1.055	5	0.51	7	4.802	6.367
New steam trap design	7	1.477	5	0.51	6	4.116	6.103
Buy new steam traps	3	0.633	6	0.612	6	4.116	5.361
Other plants operating conditions	10	2.11	4	0.408	3	2.058	4.576
Increase bed surface area	3	0.633	4	0.408	5	3.43	4.471
New insulation for steam travel	5	1.055	5	0.51	4	2.744	4.309
Minimize transportation of steam	4	0.844	6	0.612	4	2.744	4.2
Run product multiple times through dryer	1	0.211	5	0.51	3	2.058	2.779
Scale 1-10		0.25		0.3		0.45	
Overall Importance		0.211		0.102		0.686	

Combustion Calculations

Mass flow rate of combustion reactants is $0.001\ \frac{kg}{s}$, or $0.1323\ \frac{lb}{min}$

Reactants of Combustion Reaction = 24 molecules of Air and 1 molecule of Methane

Density of Air at NTP = $0.0752\ \frac{lb}{ft^3}$

Density of Methane at NTP = $0.0417\ \frac{lb}{ft^3}$

Total Density = $(24 * 0.0752) + (1 * 0.0417)$ = 1.8465 $\frac{lb}{ft^3}$

Flow rate of Reactants = $\frac{0.1323\frac{lb}{min}}{1.8465\frac{lb}{ft^3}} = 0.071811\frac{ft^3}{min}$

Overall Ratio of Methane to Air = $\frac{0.0417}{1.8465} = 0.02258$

Actual Amount of Methane Used = $0.02258 * 0.07111 = 2.335248\frac{ft^3}{day}$

Total BTU/day = $\frac{1020\ BTU}{1\ ft^3} * 2.335248\ \frac{ft^3}{day} = 2381.95\frac{BTU}{day}$

Cost for one tube = $\frac{\$5.16}{1000\ BTU}\ *\ 2381.95\frac{BTU}{day} = \frac{\$12.29}{day}$

Cost for all tubes = $\frac{\$12.29}{day} * 16\ tubes = \frac{\$196.65}{day}$

Interactive Thermodynamics Code

(Steam Analysis Code)

```
//*Neglect Kinetic Energy

//Steam Inlet
T1 = 350
p1 = 40
mdot1 = ((4009.3/3)/60)
h1 = h_PT("Water/Steam", p1, T1)

//Steam Outlet
T2 = 267
p2 = p1
mdot1 = mdot2
h2 = h_PT("Water/Steam", p2, T2)

//Air Inlet
T3 = 120
p3 = 10
density3 = 0.115
//0.115 [lb/ft^3] at 120F and 10psi
mdot3 = 4800*density3
h3 = h_T("Air",T3)

//Air Outlet
T4 = 280
p4 = p3
mdot4 = mdot3
h4 = h_T("Air",T4)

//Balance
Qdot_steam = mdot1*(h1-h2)
Qdot_air = mdot3*(h4-h3)
Qloss = Qdot_steam - Qdot_air

Price = 6.19 //$/BTU
Cost = (Qdot_steam/1000000)*Price*60*24
//Cost = $/day
```

(Natural Gas Fire Exhaust Code)

```
//*Neglect Kinetic Energy

//Exhaust Inlet
T1 = 500
p1 = 10
density1 = 0.070
mdot1 = 8000*density1
h1 = h_T("Air",T1)

//Exhaust Outlet
T2 = 345
p2 = p1
mdot1 = mdot2
h2 = h_T("Air",T2)

//Air Inlet
T3 = 120
p3 = 10
density3 = 0.115
//0.115 [lb/ft^3] at 120F and 10psi
mdot3 = 4800*density3
h3 = h_T("Air",T3)

//Air Outlet
T4 = 280
p4 = p3
mdot4 = mdot3
h4 = h_T("Air",T4)

//Balance
Qdot_exhaust = mdot1*(h1-h2)
Qdot_air = mdot3*(h4-h3)
Qloss = Qdot_exhaust - Qdot_air

Price = 5.16 //$/MBTU
Cost = (Qdot_exhaust/1000)*Price*60*24
//Cost = $/day
```

(Steam Analysis Results from IT Software)

```
Cost     775.20
h1       1212
h2       235.8
h3       138.6
h4       177.2
mdot2    22.27
mdot3    552
mdot4    552
p2       40
p4       10
Qdot_air          2.128E4
Qdot_steam        2.174E4
Qloss    458.7
density3          0.115
mdot1    22.27
p1       40
p3       10
Price    6.19
T1       350
T2       267
T3       120
T4       280
```

(Natural Gas Fire Exhaust Results from IT Software)

```
Cost      632.48
h1        231
h2        193
h3        138.6
h4        177.2
mdot1     560
mdot2     560
mdot3     552
mdot4     552
p2        10
p4        10
Qdot_air            2.128E4
Qdot_exhaust        2.129E4
Qloss     9.337
density1            0.07
density3            0.115
p1        10
p3        10
Price     5.16
T1        500
T2        345
T3        120
T4        280
```

(Natural Gas Combustion Code for Theoretical Air)

```
// Known quantity
TR = 25 + 273  //  Temperature of reactants (K)

//The energy balance reduces to
hR = hP
hR = hCH4_R + 2*(hO2_R + 3.76*hN2_R)        // reactants
hP = hCO2_P + 2*(hH2O_P + 3.76*hN2_P)      // products

//  Enthalpy data
hCH4_R = -74850  // kJ/kmol (Value from Table A-25)
hO2_R = h_T("O2",TR)
hN2_R = h_T("N2",TR)
hCO2_P = h_T("CO2",TP)
hH2O_P = h_T("H2O",TP)
hN2_P = h_T("N2",TP)
```

(Natural Gas Combustion Results for Theoretical Air)

hCO2_P	-2.821E5
hH2O_P	-1.522E5
hN2_P	6.803E4
hN2_R	-4.371
hO2_R	-4.407
hP	-7.489E4
hR	-7.489E4
TP	2328
hCH4_R	-7.485E4
TR	298

(Natural Gas Combustion Code for Theoretical Air)

```
/*
For combustion of methane with the theoretical amount of air
CH4 + 2(O2 + 3.76 N2)  ===>  CO2 + 2 H2O + 7.52 N2

For 400% excess air
CH4 + 4*2(O2 + 3.76 N2)  ===>  CO2 + 2 H2O + 6 O2 + 30.08 N2

For 800% excess air
CH4 + 8*2(O2 + 3.76 N2)  ===>  CO2 + 2 H2O + 14 O2 + 60.16 N2

For 1200% excess air
CH4 + 12*2(O2 + 3.76 N2)  ===>  CO2 + 2 H2O + 22 O2 + 90.24 N2
*/

// Known quantity
TR = 25 + 273  //  Temperature of reactants (K)

//The energy balance reduces to
hR = hP
hR = hCH4_R + 12*2*(hO2_R + 3.76*hN2_R)       // reactants
hP = hCO2_P + 2*hH2O_P + 22*hO2_P + 90.24*hN2_P      // products

//  Enthalpy data
hCH4_R = -74850  // kJ/kmol (Value from Table A-25)
hO2_R = h_T("O2",TR)
hN2_R = h_T("N2",TR)
hCO2_P = h_T("CO2",TP)
hO2_P = h_T("O2",TP)
hH2O_P = h_T("H2O",TP)
hN2_P = h_T("N2",TP)
```

(Natural Gas Combustion Results for 1200% Excess Air)

hCO2_P	-3.838E5
hH2O_P	-2.338E5
hN2_P	6868
hN2_R	-4.371
hO2_P	7099
hO2_R	-4.407
hP	-7.535E4
hR	-7.535E4
TP	532.2
hCH4_R	-7.485E4
TR	298