Substitution of Electricity with Natural Gas Burners for Industrial Dryers

Hayden Youngs, University of Michigan

Abstract

Throughout the country, there is a vast amount of manufacturing plants, in which there is an automated drying process. Often times, these plants use electric heaters to preheat the high velocity air prior to it being propelled towards the product during the drying process. An example of a facility that uses an electric heater is the MIWI (Midbrook Industrial Washers Inc.) washers manufacturing plant in Jackson, Michigan. Thus, a graduate student, Kumar Aanjaneya, and I researched the substituting of electric heaters for low-cost and potentially faster-heating natural gas burners. In this investigation it is investigated how to control temperature, flame stability, incomplete combustion, pollutant formation, and air quality issues in the dryer air flow because of the burning of natural gas. Furthermore, a propane fueled physical model was constructed to prove the concept developed in a CFD simulation with a limited set of experimental results. Additionally, the potential benefits are estimated such as cost savings, increase in production speed, as well as the environmental pollution from potential impurities in the products of combustion in the hot air stream due to the burning of natural gas.

Keywords: Combustion, Efficiency, Factory Air Quality Issues, Flame Stability, Heating Process, Incomplete Combustion, Industrial Drying, Natural Gas Heater, Temperature Control

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1 Introduction

There is a large amount of manufacturing plants in this country. In these industries, many perform automated manufacturing processes in which a wash and subsequent drying of the production specimens happens. In these facilities, electric heaters are frequently used to preheat the air flowing at high velocities before it is directed towards the product specimens. In automated production lines, the rate at which the product can be manufactured depends on the pace of the slowest process. Often times, the drying process is the step that slows down production. So, for this project we are taking aim on the drying process; post wash. Furthermore, this project builds off an initial assessment performed by the Industrial Assessment Center, and a former ME 490 Project [1] [2]. Finally, the goal of this research was to investigate the potential for MIWI, and other companies, to switch their electrical dryers into natural gas dryers for the systems they manufacture in order to save the plant money, time, and hopefully to reduce unnecessary pollution.

1.1 Overview of the MIWI drying process

MIWI, a manufacturing plant in Jackson, MI, constructs systems for drying of plastic and metallic components after a wash. Additionally, MIWI provides washing and drying services for industrial customers. The process involves the electric heater heating the air after it is pushed by the blower, then the air is funneled into an air knife, and rapidly dries the parts progressing on the conveyor belt; ending the washing and drying process (Figure 1). The electricity usage in this process is used to heat the ambient air. Although this procedure makes it easier to regulate the temperature, it is much more expensive.

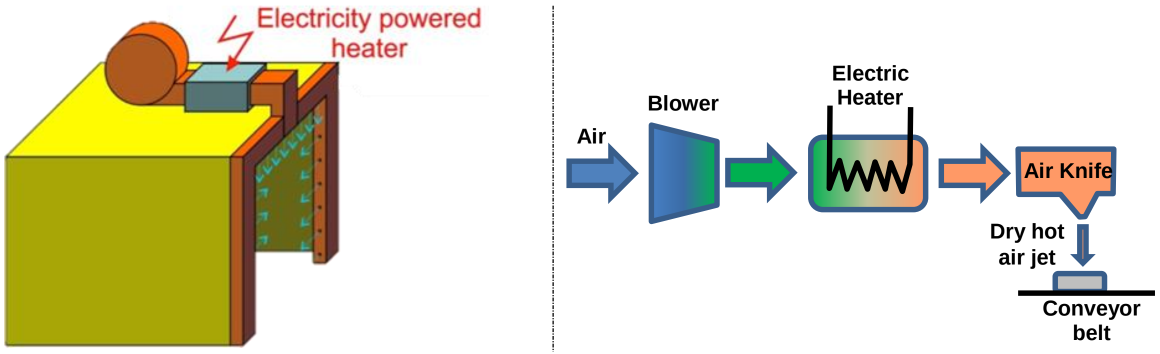


Figure 1: Current Setup of MIWI's dryer

1.2 Plant Specifications

The Industrial Assessment Survey that was performed preceding this project provided our system with the specific conditions that the operation had to function at (Table 1) [1].

Parameters	**Value**
Ambient air temperature T_{AMB} [K]	298.15
Relative Humidity of air RH_{AMB}	70%
Outpute air temperature T_{OUT} [K]	363.15
Mass of exiting air m_{AIR} [kg/s]	0.229

System Power Q_{EL} [kW]	15
Curent Elecrical Costs AELC [$/yr]	3,750
Outpute Relative Humidity RH_{OUT}	3.16%
Current Carbon Emissions CO_2 [ton/yr]	64.5

Table 1: Plant specifications/Operating conditions

1.3 Technical Considerations

Before we switch to natural gas from the original electricity, we first have to meet the specifications of the plant in addition to performance restrictions. When dealing with natural gas, a major focus needs to be on the emissions of the gas in order that the dried parts do not contain remnants from the diluted combustion. Furthermore, we have to take into consideration the use of a heat exchanger to protect the integrity of the part if the air would ever become mitigated. This will allow us to provide purified hot air to the drying process. However, this would present an additional step in the system, lowering the efficiency of the heating process. Additionally, some other causes for concern is heat regulation, and the dryer settings within the combustion chamber to ensure safety. Moreover, we would like to design a system that allows for an easy assembly by utilizing the existing air ducts so that we can prevent unnecessary modifications to the dryer itself, and ultimately lower installation costs.

1.4 Setup Proposal

By using the current structure of the drying unit, we aimed for the removal of the electric heater in exchange for a burner apparatus with accessible air flow and fuel injector. This proposition allows for the utilization of the existing air ducts, and limited costs. The design contains the same makeup of the air flow to the blower which accelerates the soon to be heated air, drying the part. However, instead of the electric heater, there is a natural gas burner (Figure 2).

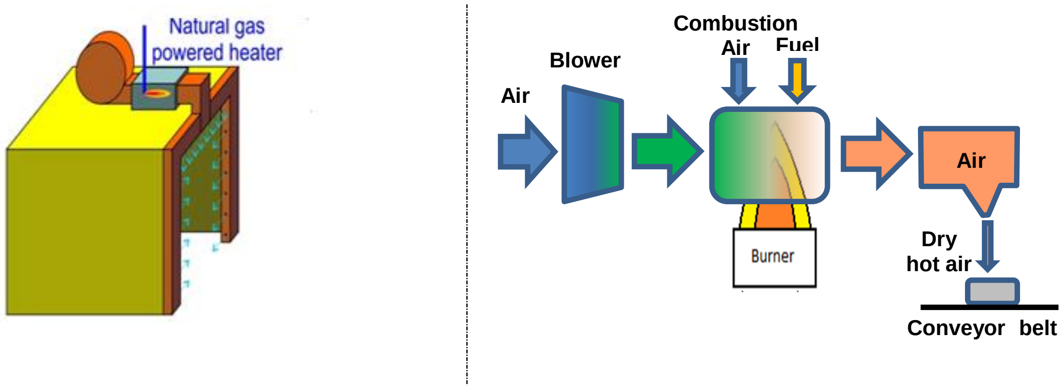


Figure 2: Proposed Setup of MIWI's dryer

2 Fuel and air combustion

To perform the goal of the project, investigating the feasibility of switching to natural gas dryers from electrical dryers, we must analyze the challenges of the theoretical and analytical. Firstly, we need to ensure that natural gas is a possible fuel. As a result, the first thing that we did, was to prove natural gas as a viable fuel. This required that we verify that the required mass of natural gas could be properly combusted while minimizing the flame temperatures, and sufficiently adding secondary air to cool down the system to a fully mixed 90°C.

2.1 Fuel Stoichiometry

Methane is a hydrocarbon made up of 98% natural gas [3]. The combustion equation for natural gas is:

$$CH_4 + 2(O_2+3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2 \qquad \text{(Eq. 1)}$$

From a stoichiometric analysis of fuel combustion as shown in Appendix A, it was determined that in order to combust the required 1.08 kg/hr of Natural Gas, we would need to add 18.57 kg of primary air for stoichiometric combustion.

2.2 Flame Temperature

The temperature in the combustion chamber was of interest to MIWI. In reference to the safety, we needed to confirm that the flame temperature was as low as possible. A potential way to relegate flame temperature is by allowing excess secondary air (Figure 3) [4].

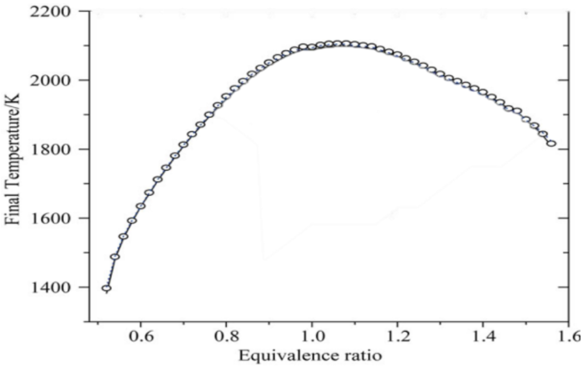


Figure 3: Flame Temperature vs. Equivalence ratio
An Equivalence ratio of 0.8 was determined to be ideal for this application [4]

From the above figure, the minimum fuel-air ratio that is permitted for combustion is 0.55. However, to avoid flame out, we decided that a fuel-air ratio of 0.8 would be ideal. This ratio of 0.8 would decrease the flame temperature from 2100 K at stoichiometric combustion, to a more innocent 1800 K. This is further discussed in Section 3, describing the reduced emissions produced by combustion. In order to change the equivalency ratios, one would need to allow more primary and secondary air flows as revealed below.

2.3 Mass Flow Rates

To confirm that the air was cooled to 90°C before it was blown onto the parts, additional secondary air would be mixed to reduce the combustion temperature. These values of enthalpy of combustion for the natural gas and the amount of secondary air required can be seen in Appendix B.
The necessary mass flow rates are:

- Fuel Flow Rate = 1.08 kg/hour
- Primary Air Flow = 5.014 kg/hour
- Secondary Air flow = 687.6 kg/hour

2.4 Mixing

One of the most significant factors that had to be discussed for this project, was the mixing of the combustion fuel and secondary air flow. Notably, the ideal situation produces full mixing to create uniform temperature in the air being driven to ensure evenly dried products (Figure 4).

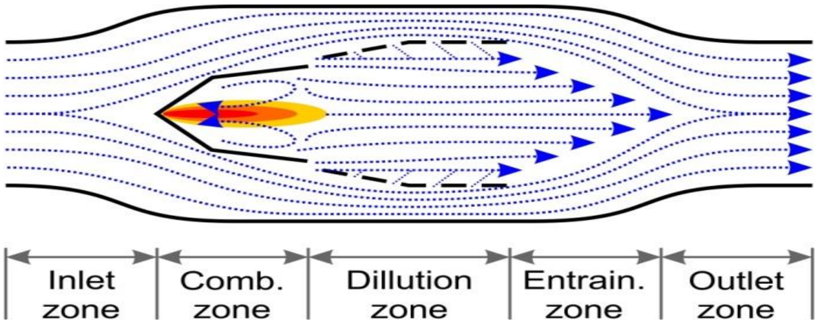


Figure 4: Recirculation zones in design [5]

In research done in prior years at the University of Michigan, the idea of co-annular tubes for a burner is one conclusion to obtaining sufficient mixing [5]. The inlet zone bends around the combustion zone and generates re-circulation inside of the dilution zone until it exits at an optimum mix of uniform temperatures. So, in our design we created a “sandwich” of the fuel by overlapping the fuel inlets with two sets of air flow (Figure 5). The primary air plow was between the fuel streams, with secondary air flow surrounding the fuel on the outside in order to promote mixing.

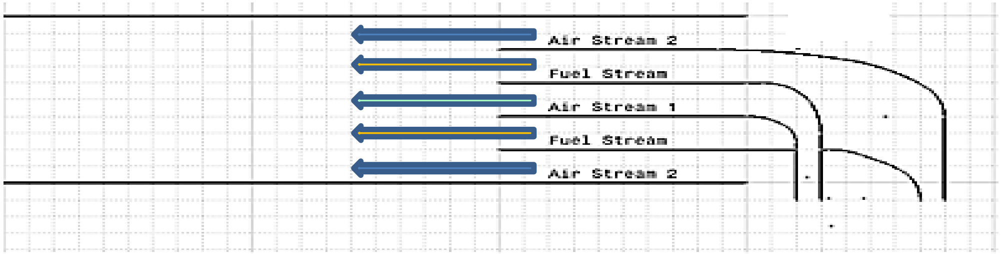


Figure 5: Experimental Design of the Burner

For additional mixing, obstacles were added within the apparatus to ensure that there was even temperature at the outlet zone. As a result, we created multiple obstacles in our design so that we could be confident in our mixing (Figure 6). The first obstacle was a “lip” on both the inside and outside of the burners exit chamber. This created turbulence with both the primary and secondary air, causing flow paths that were not direct. The next obstacle was positioned shortly after the combustion occurred, and this was to direct the flow towards are next obstacle, the “spider”. The “spider” is the last obstacle, and it is positioned near the center of the cylinder in order to cause a massive alteration in the flow, hopefully creating optimal mixing.

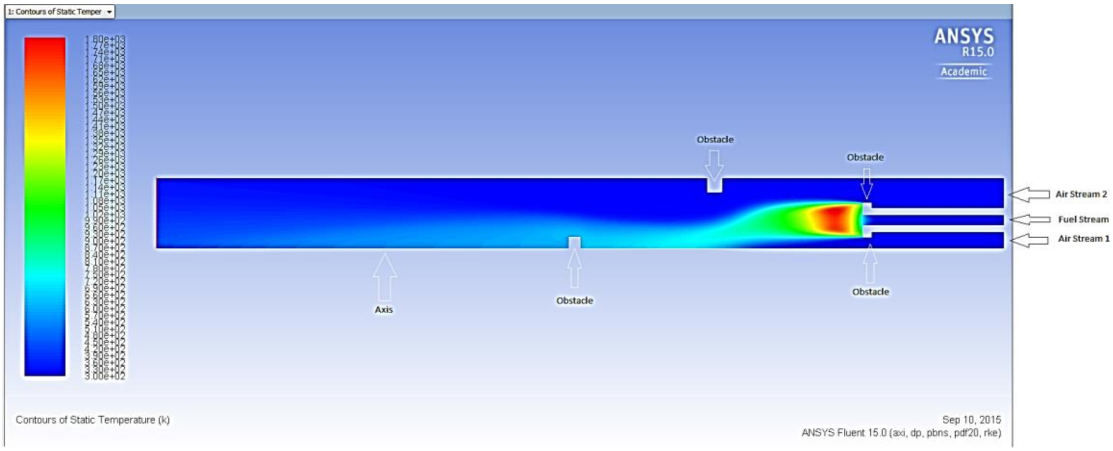


Figure 6: Fluent Design, optimal mixing (2D axisymmetric model)

3 Emissions

A major concern with switching to a natural gas burner from an electric heater, is the emissions produced in the combustion process. These pollutants not only are dangerous, but can end up diluting the drying process and ultimately corrupting the future treatments. In this project, we will take into consideration the three main forms of emission: soot, CO, and NOx.

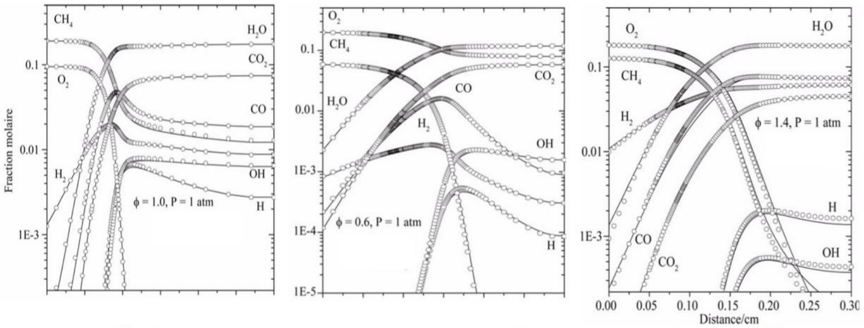
3.1 Soot

Soot is the result of incomplete combustion, and is an impure carbon particle that can contaminate the product. Often times, soot is emitted when diffusion flames exist, mixing with the hydrocarbons. Due to the limited mixing by the rate of diffusing, there is generally not enough oxygen in the combustion to fully complete the process, resulting in an impure excess. For pre-mixed flames, the fuel and oxidizer have been fully mixed prior to combustion. However, for the pre-mixed flame the question is whether or not there was enough oxygen mixed with the fuel. Theoretically, the development of soot in a combustion of hydrocarbons should only happen when the C/O ratio is greater than 1 [6]. From equation 1 (Eq. 1), stoichiometric equation, a complete combustion of pre-mixed flames occur when an air/ CH_4 mole ratio of 9.52 is obtained. The more air in the mixture, the less soot created. Additionally, the leaner the pre-mixture, the greater possibility of oxygen combining with the hydrocarbons to shape complete combustion. On the other hand, a more fuel rich mixture will lessen the completeness of the combustion (Figure 7). With the proposed ϕ (air/fuel ratio/stoichiometric air/fuel ratio) of 0.8, it is believed that there will be more than enough air that sooting can be considered minimal.

Figure 7: The left is a rich fuel mixture with no pre-mixed oxygen, producing a sooty diffusion flame. On the right is a full oxygen premixed flame, producing no soot [6]

3.2 Pollutant gases CO, N_2O, and NO_X

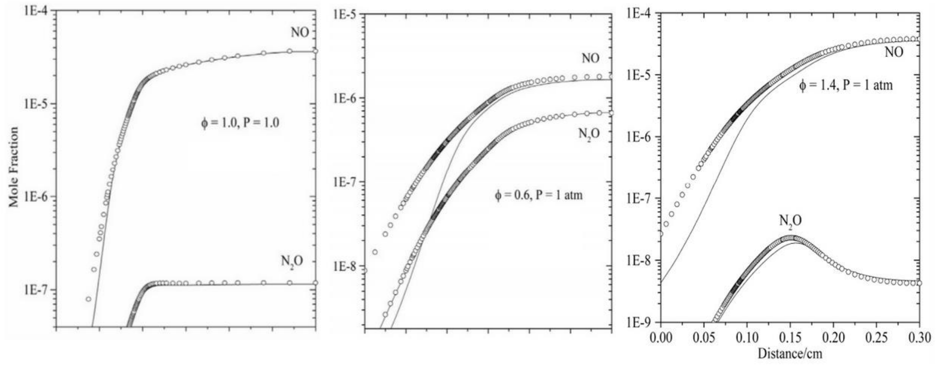
Because sooting is unlikely with the use of a lean pre-mixed flame, the largest concern for combustion products is CO which will be produced from combustion. For an ideal combustion, the methane's carbon atoms will react with the oxygen in the air producing only CO_2, balancing the stoichiometric equation. However, the more probable reaction will yield an incomplete combustion that will not be fully oxidized. Thus, the production of CO. The amount of CO generated is dependent on ϕ [3]. The more air in the process, the greater the probability for the formation of CO_2 instead of CO. The amount of CO produced from the combustion can be reduced by a magnitude of two by using a ϕ of 0.8 versus 1.0 (Figure 8). For $\phi = 0.8$, the mole fraction of CO is just under 1/1000, which is almost negligible



Stoichiometric Lean (excess air) Rich (air deficit)

Figure 8: Methane combustion as a function of distance through flame for different values of ϕ [3]

Since the oxidizer in the premixed flame is not pure oxygen, the nitrogen in the air should be taken into consideration. NO_X, is produced during combustion when nitrogen and oxygen are present. In our case, because air has a much larger amount of nitrogen than oxygen, N_2O could also be a product of combustion, and this can be the case even with perfect combustion. The imperfect combustion still does play a role in the formation of NO and N_2O, as it will be produced even when ϕ is greater than 1 (Figure 10). However, a lean mixture is still the ideal choice when considering the potential for NO_X and N_2O formation (Figure 9). Fortunately, the formation of NO and N_2O in a $\phi = 0.8$ mixture are negligent enough that they can be ignored.



Stoichiometric Lean (excess air) Rich (air deficit)

Figure 9: NO and N_2O fractions as a function of distance through flame for multiple values of ϕ [3]

With the large amount of secondary air that will be added to the combustion products (including soot), it can be assumed that the minimal amount of emissions that are produced will be so diluted that they will have little to no effect on any further processes the dried parts might go through. However, something that we did not take into account, but should have in future work is the generation of NO_X when dealing with recirculation zones.

3.3 Carbon Footprints

Currently, the industry is operating the dryers for 3120 hr/yr. At this rate, the company will produce a conservative 23 tons/year of CO_2. Whereas, if the company were to operate at the same amount of hours with a natural gas dryer, the company would only produce 9.2 tons/year of CO_2. So, by switching over to natural gas, the company will reduce the carbon footprints in the atmosphere by over 13.8 tons/year (Appendix C).

4 Experimental Results

After generating the design through calculations and fluent, we then began the building our project. However, in order to fit the lab space, while keeping the integrity of the project itself, we had to scale down our model. The scaling down of the project is not directly 1:1, and the equivalent values can be seen in Table 2, with the calculations in Appendix D.

Power (kW)	MMBtu/hr	Mass of Fuel (kg/s)	Mass of Fuel (kmol/s)	Primary Air (kg/s)	Secondary Air (kg/s)	CFM
1	3412.142	2E-05	1.25E-06	0.000381	0.012752	22.71673
15	51182.13	0.0003	1.87E-05	0.005713	0.191287	340.751

Table 2: Equivalent Experimental Values for a scaled down apparatus

Following the generation of the specifications we would be using to prove the validity that the substitution of a natural gas dryer for an electric heater, we created the model. Our model was created at the specs listed below by the glass blower at the University of Michigan, Harald Eberhart (Figure 10).

- Outer Tube: 1.8” Dia
- Fuel Tube: 0.9” Dia
- Inner (Air) Tube: 0.125’ Dia
- Fuel and Inner Tubes: 2” Long
- Outer Tube: 1’ Long

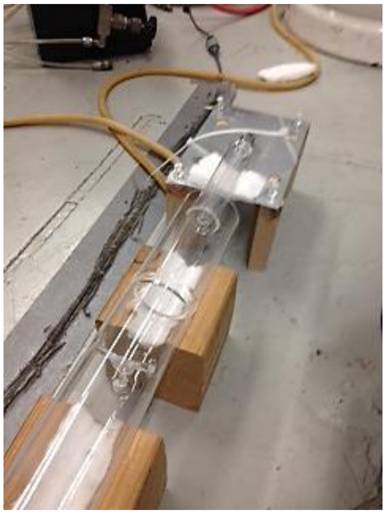


Figure 10: Laboratory Apparatus with Specs

The model was created in glass so that we could see the flame for both its existence as well as the color. In case of the trials we would be able to observe whether the flame blew out, in addition to witnessing whether the flame was lean or not; determined by the color. Additionally, there was a computer fan, 35 CFM, connected to the system in order to get the desired secondary air flow. Also, there was an opening following the combustion reaction so that three radial positions could be measured for their temperatures in order to determine even heating (Figure 11).

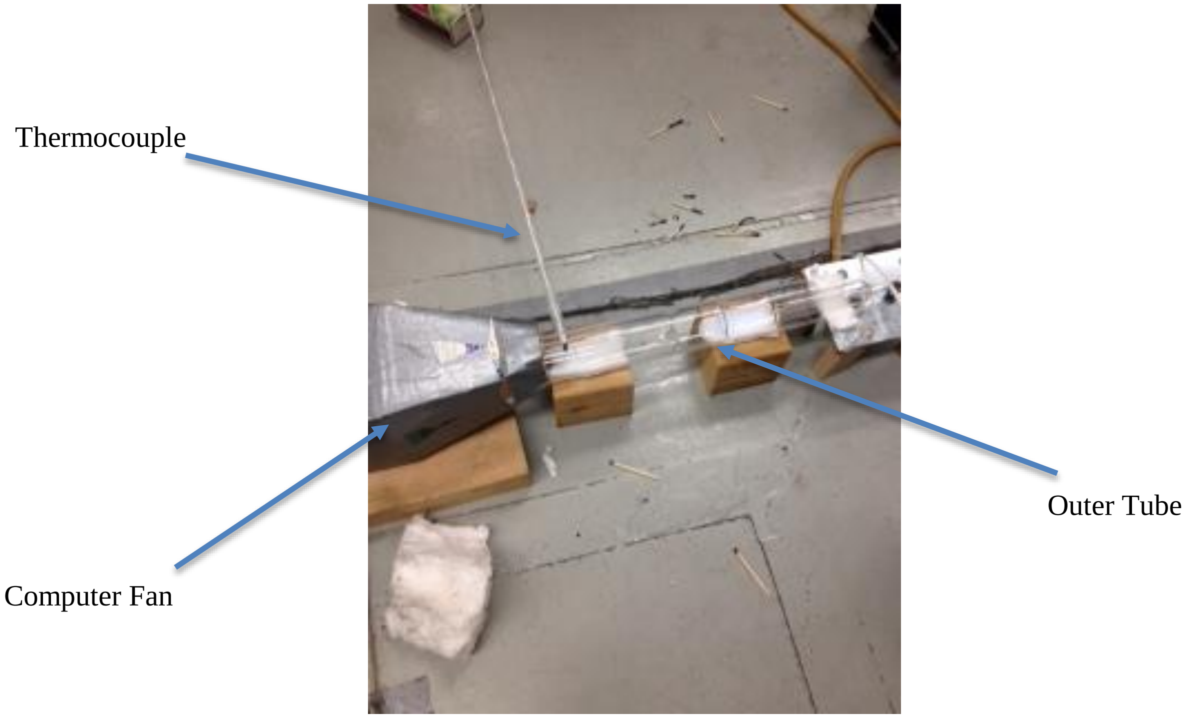


Figure 11: Laboratory Apparatus

The project proved to be a big success, meeting all the concerns generated when first initializing the research. There were four cases, none of which produced a blown out flame. In addition, the model generated better results than the fluent design. This could be attributed to two separate things; the first being that the computer fan created turbulence through its circular flow instead of having a direct line flow, and secondly the "spider" obstacle had structural obstacles created in the outer tube which added additional mixing (Figure 12).

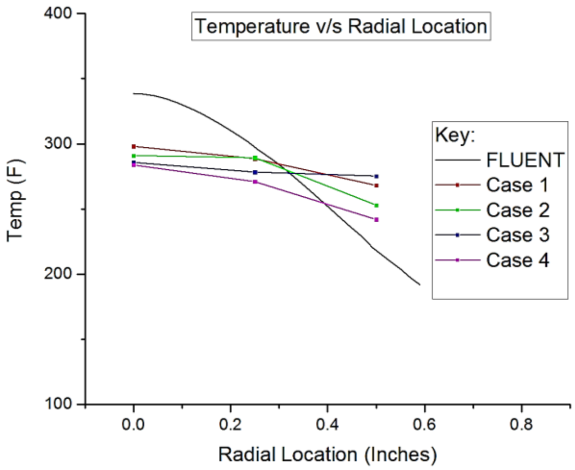


Figure 12: Experimental Results

As seen in Figure 12, there was even temperatures in the cylinder outlet throughout all the cases. Again, this can be attributed to the optimized mixing created by the co-annular burner, multiple obstacles, and circular secondary air. Although the actual temperatures were lower than predicted, it can be explained to the heat loss at the walls. Throughout the four cases, there was never any generation of soot, thus proving natural gas dryers as an ample drying process. In addition, there was no recognition of any increase in humidity which would again defeat the purpose of the drying process.

5 Financial Analysis

Despite the reduction of carbon emissions by exchanging an electric dryer for a natural gas dryer, the decision to make the change is strictly financial. In order to convince firms such as MIWI to make the conversion, one must prove the opportunity costs of switching. When taking the financial considerations into account, there are two costs; energy savings and installation plus maintenance costs.

According to the energy information administration [7], the current industrial prices in Michigan are \$0.08 per kW-hr for electricity and \$5.5 per MMBTU for natural gas. Under the assumption that the MIWI plant runs for 3120 hours during the year, the cost for using a 15 kW electrical heater is \$3,750 per year for a single machine. For a natural gas burner using our mass flow rate of 1.08 kg/hr, the price of natural gas for a single burner would be \$858 per year. As a result, for each natural gas burner the plant substitutes for an electrical one, they would save \$2,892 per year. So, assuming the plant operates 3 dryers, this would save the plant \$8,676 per year. Financially, the energy savings cost is an easy decision to switch over (Appendix E).

By performing the switch from electrically powered dryers to natural gas dryers, MIWI will save a large sum of money. Using the cost of natural gas in terms of energy equivalencies, we were able to determine the potential cost savings specified by the temperature and air flow rate of the dryer (Figure 13).

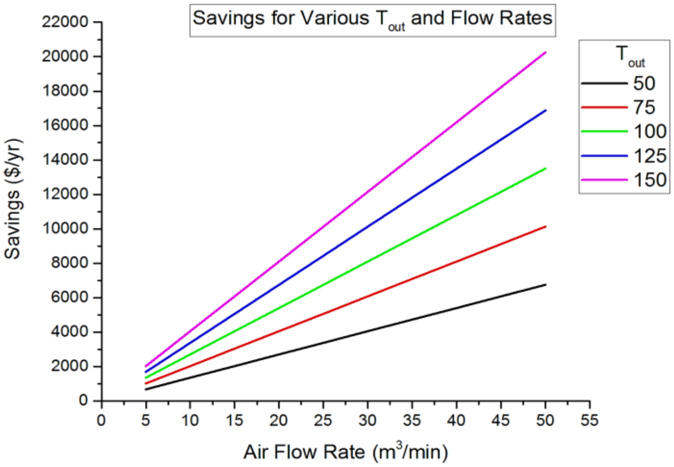


Figure 13: Potential for cost saving in respect to current flow rates and temperatures in °C

By using the current temperature of 90°C and output volume of 11 m^3/min, we have the potential to save almost \$3,000 annually per dryer if we were to exchange for natural gas burners.

However, there is the initial costs of implementation and the additional costs of maintenance. The proposed purchase for a natural gas burner is the Kromschroder BIC 50 industrial burner (Figure 14) [8]. The BIC 50 burner costs \$1,332 each, and the average maintenance and replacement parts for these burners cost ~\$700 a year (as quoted from Combustion 911 customer service representatives). This means that the first year costs for the burners would be \$2,302 (for one burner) each and subsequent year costs would be $700 each ($4,696 and $2,100 for the 3 dryer assumption). While these numbers seem large, the amount of money being saved in energy costs would allow for the plant to reach its payback period in just under 10 months. Provided the plant has the fund, this would be an easy decision to make.

Figure 14: Proposed Burner (Kromschroder BIC 50) [11]

6 Conclusions and Recommendations

By substituting natural gas for electrical dryers results in a cheaper, cleaner, and faster drying process. If the company operates 3 dryers on a yearly basis, they can save up to $8,676 per year by switching, and the payback period for the initial costs is less than 10 months.

As shown through the experiments and calculations, the ideology is sound. The process is cheaper by using natural gas versus electricity. It is cleaner by emitting less carbon to the environment, while producing no soot similarly to a normal electric dryer. Furthermore, the process is faster because the company will no longer have to preheat the air, as the air is heated directly. All in all, the switch to natural gas has been proven time and again. However, for future projects, there are some things that can be researched in order to make this idea become a living reality. First, is to create an industry model instead of the porotype created at a lab scale model. Secondly, is to use the burner recommended with multiple fuel jets to achieve better mixing and combustion in higher power regimes. Also, a detailed gas analysis of the exhaust would be beneficial. Moreover, providing a better way to increase and decrease control flow would allow for minimal error when achieving desired temperatures, and it would allow for consistent flame stability. Lastly, for safety and production purposes, the inclusion of flame sensor and ignitor would permit the re-ignition if the flame were to ever blow out, the initial ignition, and the ability to turn the fuel off in case of emergency.

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Appendix A: Fuel Stoichiometry

$$\dot{m}_{\mathrm{Fu}} = \frac{Q_{heater}}{LHV_{fuel}} = 15\text{ kW} / 50\,010\text{ kJ/kg fuel} = 1.08\text{ kg/hour}$$

$$\dot{m}_{\mathrm{air}} = (\mathrm{A/F})_{\mathrm{mass}}\, \dot{m}_{\mathrm{Fu}} = (n_{\mathrm{air}}\, M_{\mathrm{air}}/M_{\mathrm{Fu}})\, \dot{m}_{\mathrm{Fu}} = \frac{2*4.76*28.97}{16.04} * 1.08 = 18.57\text{ kg/hour}$$

We need at least 18.57 kg air an hour in order to get stoichiometric combustion

Appendix B: Secondary Air

As shown in equation 1, each mole of fuel requires 2 moles of primary air for combustion. For reducing the flame temperature to 90°C, assume x times as much secondary air is added to the total gas flow which consists of

$$CO_2 + 2H_2O + 7.52N_2 + x(3.76N_2 + O_2) \text{ per mole of fuel combusted.}$$

Heat generated from combustion of Methane:

Lower heating value = 50 010 kJ/kg fuel

Molar Mass * LHV = 16.043 kg/kmol fuel * 50 010 kJ/kg fuel
= 802 310 kJ/kmol fuel

This amount of energy gets transferred to the product gasses. Therefore the energy equation states,

Energy = LHV*Molar Mass = 802 310 kJ/kmol fuel
= energy in the products
= $\Delta h_{CO2} + 2\Delta h_{H20} + 7.52\,\Delta h_{N2} + x(\Delta h_{O2} + 3.76\,\Delta h_{N2})$ per kmol fuel

Assuming all the gas components are ideal gases, then at 90°C target we get :

Δh_{CO2} = 2429.4 kJ/kmol ; Δh_{H20} = 2094.8 kJ/kmol
Δh_{N2} = 1804.2 kJ/kmol ; Δh_{02} = 1837.8 kJ/kmol

Since for every 2 moles of primary air, x moles of secondary air are required:

$\dot{m}(secondary, air) = \frac{x}{2} * \dot{m}(primary, air)$

$\dot{m}(secondary, air)$ = 687.6 kg/hour

Appendix C: Carbon Footprints

Combustion of Natural Gas:

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2$$

$$CO_2 \text{ emissions per kg of Natural Gas} = \frac{M_{CO2}*1}{M_{CH4}*1} = \frac{44}{16} = 2.75\text{ kg}$$

$$\text{Fuel rate for a 15 kW dryer} = \frac{15}{HV} = \frac{15}{50010} \times 3600 = 1.08\,\frac{kg}{\mathrm{hr}}$$

CO_2 production rate for the dryer = 1.08 x 2.75 = 2.97 kg/hr

Annual CO_2 production = 2.97 x 3120 = 9.2 tons/year

Assuming Similar Energy produced by a Power plant (~40% efficient):

CO_2 production rate = $9.2/0.40 = 23$ tons/year

Appendix D: Specification Scaling

Power of 1 kW was decided on for the burner based on the CFM we could achieve for the secondary air with the computer fan we had:

Energy Generated:

Power * 34142.142
= 34142.142 [MMBu/hr]

Mass Flow rate of Fuel:

Energy / 50010
= $1.9996*10^{-5}$ [kg/s]
= $1.2498*10^{-6}$ [kmol/s]

Primary Air:

$\dot{m}_{Fu}$ * 2.22
= $2.774*10^{-6}$ [kmol/s]
= 0.000381 [kg/s]
= 1.3716 [kg/hr]

Secondary Air:

$\dot{m}_{Fu}$ * 74.33
= $9.2894*10^{-5}$ [kmol/s]
= 0.01275 [kg/s]
= 45.9 [kg/hr]

Total Volume Flow Rate:

$$\frac{\dot{m}(secondary,air)+\dot{m}(primary,air)}{1.225}$$

= 0.01072 [m^3/s]
= 38.596 [m^3/hr]
= 22.717 [CFM]

Appendix E: Cost Savings

Using a 15kW dryer, running for 3120 hrs/year

Variables:
W_{el}: Power rating (kW or MMBtu/hr)
HR: Hours of use per year (3120 hrs)

C_e: Cost of electricity ($/kWh)
C_{NG}: Cost of electricity ($/MMBtu)

For Electricity powered dryer, annual electricity cost:

$$Cost_{elec\ dryer} = W_{el} \text{ x } HR \text{ x } C_e = 15 \text{ x } 3120 \text{ x } 0.08 = \$3,750$$

For gas powered dryer, annual fuel cost:

$$Cost_{NG\ dryer} = W_{el} \text{ x } HR \text{ x } C_{NG} = 0.05 \text{ x } 3120 \text{ x } 5.5 = \$858$$

Cost Savings = $2892/dryer