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HIGH TEMPERATURE PIZZA OVEN

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ABSTRACT

The High Temperature Pizza Oven Team is developing an oven that cooks pizzas quickly and efficiently. During the 2003-2004 academic year, a multidisciplinary design team of senior undergraduate engineering students from Rochester Institute of Technology was chosen to develop the oven as their capstone design project. The oven reaches temperatures higher than most commercial ovens in the marketplace today and incorporates the methods of cooking used in traditional coal ovens without the use of coal. This paper outlines the design process and challenges that the team encountered during the project's duration.

INTRODUCTION

Abraham Fansey of the VP of Finance and Administration office at the Rochester Institute of Technology requested that an oven be designed for the proposed pizza parlor on R.I.T.'s campus. He wanted to replicate the taste of coal ovens; however, due to the use of coal ovens being banned in Rochester, NY, he needed to seek an alternate oven. He theorized that the high temperatures of the coal oven provided much of the unique flavor and texture of the pizzas produced in the coal oven. Our project focuses on building a prototype of a designed oven to prove that his theory is correct and construction of a full size oven will yield the desired results. The oven is broken down into three design systems in order to thoroughly focus on specific design criteria. In order to achieve a successful design, the team implemented common structured design processes and utilizes contemporary techniques, methods, procedures and organization models. The structure system includes the frame to support the dome and the dome itself. The thermal system includes the conduction, convection, and radiation aspects of the oven. The electrical system contains the control systems for gas inputs and temperature measurements.

This paper is based on work conducted by a multidisciplinary team of four, fifth year mechanical and electrical engineering undergraduate students from the Rochester Institute of Technology located in Rochester, New York, U.S.A. The project serves as the students' capstone design. A ten-phase design process, taught to the R.I.T. engineering students during their fifth year, serves as the framework for all capstone projects. Refer to Figure 1 for a schematic representation of the said design methodology.

The project is spread out over two-ten week blocks. Phases one through seven are completed in the first ten week block. The second ten-week block is used for Phase Eight along with prototype development and testing. The team's mission is to assemble a working prototype oven that meets the design objectives within the available time frame. The goal of the High Temperature Pizza Oven design was to complete design phases one through eight. Phases nine and ten and a refinement of phase eight can be completed by either another Senior Design team or by Abraham Fansey himself.

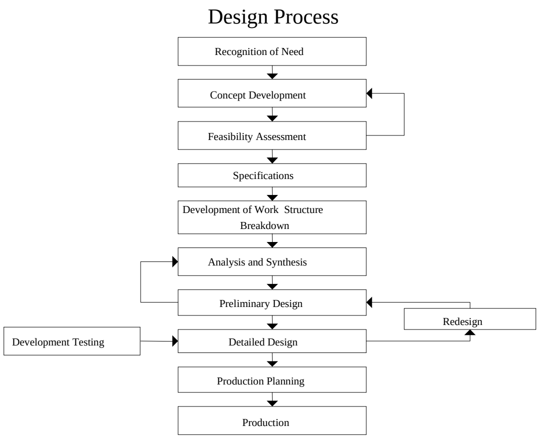

Figure 1 - Design Process Schematic

NOMENCLATURE

HHV – Higher Heating Value
HTPO – High Temperature Pizza Oven

HEATING SYSTEM

Our team took a great amount of time developing and researching the heating system the HTPO will use. The sponsor specified that he wanted a high internal temperature to be reached, similar to the temperatures reached in the coal ovens in New York City. After contacting Lombardi's, a very popular pizzeria in New York City that uses a coal oven to cook their pizzas, we decided that the best internal air temperature for our oven is 727.6K (850°F). There were a plethora of choices for the heating method, but to make a final decision, we invested hours of research into coal ovens.

The coal oven's heat transfer methods are fairly simple. Coal is heated in the back of the oven, which in turn heats the stone deck through conduction and a large air mass through convection. The deck conducts heat into the pizza and the air mass heats the pizza through convection. The heated air mass transfers heat into the surrounding walls which in turn radiate heat back down to the pizza. Unfortunately, due to a lack of time, the team was unable to travel down to New York City or a city that has legally operating coal ovens to investigate further contributions of the different heat transfer methods to the cooking of the pizza.

We decided that the air should obtain a temperature of 727.6 K, but the cooking stone should be kept at a lower 616.5K (650°F). This is due to the fact that conduction is the dominant heat transfer method of the HTPO and the system's modes of heat transfer needed to be adequately distributed in order to produce an evenly cooked pizza. We tried to model our system around the coal oven system as much as possible. Our final design incorporates the use of infrared burners to heat up the pizza stone and a gas burner in the rear of the oven to heat up a large air mass. This system replicates the "look and feel" of a coal oven as much as possible.

In the design requirements, Abraham also specified that the oven should have a "high tech, yet traditional" look and feel to it. We felt that the incorporation of a rotating deck would be one way to satisfy this requirement. As much as we have strived to make the oven a fairly constant temperature throughout, there are going to be some spots where the temperature is either higher or lower than the majority of the oven (Namely the front by the door and the rear by the gas burner). The rotating deck will serve to ensure that the pizza is evenly heated with minimal operator judgment being involved.

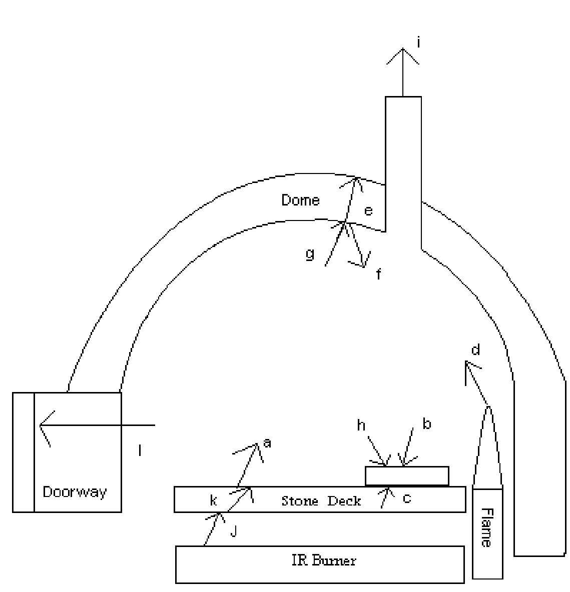

Figure 2 - Heating Diagram

Key to Figure 2 – Heating Diagram

a.) Radiation from stone to air
b.) Conduction through stone to pizza
c.) Convection from air to pizza
d.) Convection from flame to air
e.) Conduction through walls to outside
f.) Radiation from dome to air
g.) Convection from air to dome
h.) Radiation from dome to pizza
i.) Flue gas losses to outside
j.) Radiation from IR burner to stone
k.) Conduction through stone
l.) Losses through door (Open/Closed states)

After we decided on the method for cooking the pizza, we needed to calculate the heat transfer required to cook the pizza. One of the challenges we faced during the course of the project was finding a thermal conductivity value (k) for pizza. After much research, it was decided that it would be best to experimentally determine what the value is. Using a homemade pizza, we measured the initial and final masses, initial and final temperatures, the time difference, and the area and thickness of the pizza. Using equation (1), we calculated the value of k to be 3.43 $^{W}/_{mK}$.

$$\frac{dQ}{dt} = kA\frac{\Delta T}{\Delta x} \quad (1)$$

Once we had a value for thermal conductivity, we were able to calculate the contribution of conduction to our system. Using equation (2), we were able to determine the rate of conduction (Q) to the pizza, which is 11264.9 $^{J}/_{S}$. Conduction provides the vast majority of the heat transfer to the pizza, at 92.9% of the total heat transfer to the pizza.

$$Q = \frac{\lambda}{w} \cdot A \cdot (T_1 - T_2) \quad (2)$$

The rate of radiation (q) to the pizza was the next variable that needed to be determined. We used equation (3) to calculate the radiation to the pizza at 710.7 $^{J}/_{S}$. Radiation contributes a medium amount of heat transfer to the pizza, at 5.9% of the total heat transfer.

$$q = \varepsilon \cdot \sigma \cdot (T_1^4 - T_2^4) \quad (3)$$

The rate of convection (Q) was the last unknown that needed to be solved. Using equation (4), the rate of convection was found to be 144.8 $^{J}/_{S}$. Convection provides the least amount of heat transfer to the system out of the three methods, at 1.2% of the total.

$$Q = \alpha \cdot A \cdot (T - T_w) \quad (4)$$

After the values for the heat transfer rates were determined, the heat required to cook the pizza needed to be determined. We did another experiment to find out this value. After three trials and by using equation (5), the heat required for cooking the pizza was estimated at 1808 kJ. The value for the heat required will vary slightly based on the thickness, weight, and composition of the pizza, but it will be relatively close to 1808 kJ.

$$Q = (m_{init} - m_{final}) * LatentHeat \quad (5)$$

Estimating a total cooking time was next, which was found by dividing the heat required to cook the pizza by the heat rate of the oven. We calculated the cooking time for each pizza to be roughly 2 ½ minutes.

The next major step was to calculate the losses of the oven. The losses through the walls of the oven and the door when it is closed can be calculated by using equation (6), and the losses through the open door and flue are found by using equation (3). After filling in the variables with known constants, the heat loss through the wall by conduction is 176.32 $^{J}/_{S}$, heat loss through conduction through the closed door is 26.81 $^{J}/_{S}$, heat loss by radiation for the open door is 942.5 $^{J}/_{S}$, and the heat loss by radiation for the flue is 44.42 $^{J}/_{S}$. The heat loss to the pizza depends on how many pizzas are loaded into the system, but for an average of 100 pizzas per hour, the heat loss is 50,222 $^{J}/_{S}$.

$$q = \frac{T_{\infty,1} - T_{\infty,x}}{\frac{1}{h_1 A} + \frac{\Delta x_1}{k_1 A} + \frac{\Delta x_2}{k_2 A} + \frac{\Delta x_3}{k_3 A} + \frac{1}{h_2 A}} \quad (6)$$

The final step involved calculating the mass flow rate of propane required to keep the system in steady state conditions. The heat required to keep the oven at steady state is equal to the heat lost through the oven plus the heat lost to the pizzas. Using equation (7) and Moran's [1] HHV of 50,350 $^{kJ}/_{kg}$, the mass rate of propane based on 100 pizzas per hour was calculated at 3.067 $^{kg}/_{hr}$ for the closed door case and 3.672 $^{kg}/_{hr}$ for the open door case. The preheat mass of propane required can be calculated using equation (8) (kg). The mass required for our system is 2.33 kg of propane. Using Excel's curve fit function, two equations were found for the mass flow rate required depending on the pizza load and position of the door. For an open door, we can use equation (9) to find the mass rate required, and equation (10) to be used to find the mass rate for the closed door location (kg/hr). Finally, the air required for the mixture is based on Stoichiometric combustion. One volume of propane requires 24 volumes of air to combust [2]. Therefore, the volume rate of air required to combust one volume of propane is calculated using equation (11). This equation was found using a series of conversions and the 24/1 air/propane mixture ratio (m^3).

$$m_{propanerate} = \frac{Q_{Loss}}{HHV} \quad (7)$$

$$Q = \frac{mc_p \Delta T}{HHV} \quad (8)$$

$$m_{propanerate} = 236.94(load)^{-0.9868} \quad (9)$$

$$m_{propanerate} = 190.08(load)^{-09419} \quad (10)$$

$$m_{airrate} = 15.5 m_{propanerate} \quad (11)$$

MECHANICAL SYSTEM

In attacking the mechanical aspects of the oven prototype, we wanted a stable, safe, affordable and well operating system. In order to achieve the desired heating effects as described above, a heat refractory concrete was deemed the best material to make an insulating dome. The refractory concrete dome could be produced with the appropriate thickness to hold heat in the system and radiate heat back to the cooking pizza. The refractory concrete has the ability to be shaped appropriately, withstand high temperatures, and has a high rate of heat emission. In order to insulate the system so a high temperature can be reached and the exterior of the oven can be safely touched, additional insulation would be needed around the concrete dome. A heat resistant ceramic fiber was chosen with high temperature insulating properties. The calculated thickness to properly insulate the structure is seven inches. In choosing an oven exterior, 22 gage sheet metal will encompass the system and provide an aesthetically pleasing and secure appearance.

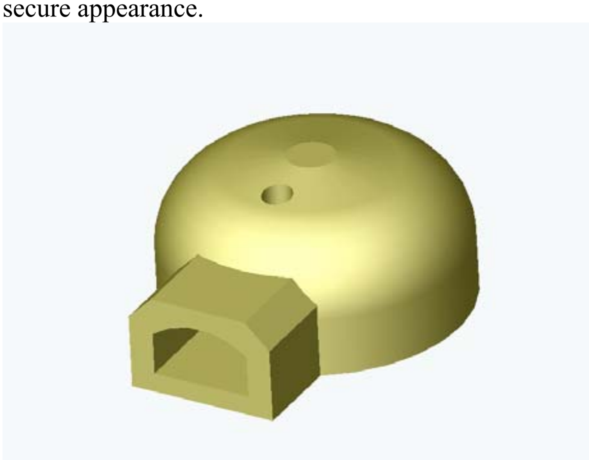

Figure 3 - Refractory Concrete Dome

In order to support the 500 pound dome along with its surrounding insulation, 3x3x3/8" thick angle iron was selected to form our base. After designing a stable, wide-stance base, COSMOS finite element analysis was used to calculate the Von Mises stress, strain, and base displacements. During the base construction, we used arch welding to securely connect the angle iron and sled legs were equipped on the bottom of the base to ensure a stable setup.

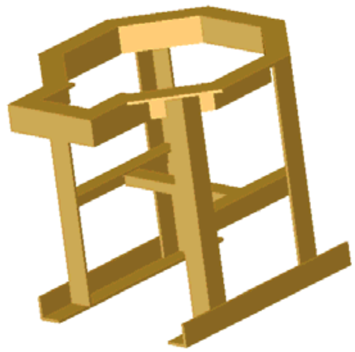

Figure 4 - Angle Iron Base

To incorporate a rotating deck into the prototype oven and remain within the appropriated budget, we devised a geared hand-crank setup. A shaft extends down from the pizza deck and rests on a thrust bearing. Halfway up the shaft, a stabilizing collar surrounds the cantilevered shaft. At the bottom of the shaft, a miter gear is welded and a second miter gear connects at a 90 degree angle. The crank shaft extends out from the second miter gear and provides a simple and inexpensive means to rotate the stone deck.

ELECTRICAL SYSTEM

The temperature measurements in the HTPO will be done using a microcontroller based thermocouple circuit. The temperature will be poled every second and displayed on an LCD. The temperature data will also be sent to the PC via RS232.

This thermocouple based temperature measurement requires two initial calculations. 1. Cold junction compensation. 2. Calculation of the temperature. Cold junction compensation in this design was done in hardware using special IC's (LT1025 from Linear Technology) and can be better visualized in Fig. 5 [3], which shows a typical application of LT1025.

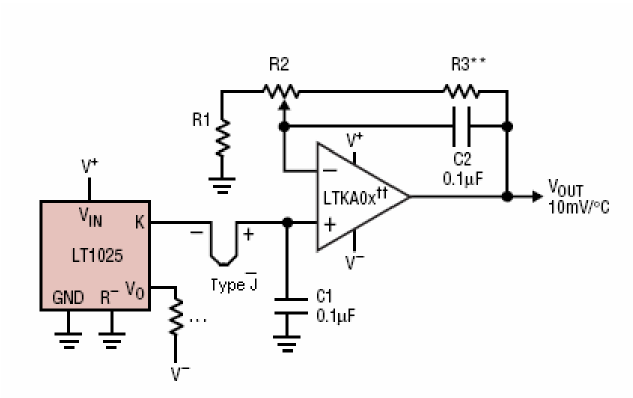

Figure 5 - Typical application of LT1025

An operational amplifier in Fig 5 is used to increase the thermocouple signal value so that it can be digitized by the A/D converter. Both the digitized thermocouple voltage and the digitized reference voltages are fed to a microcontroller. The microcontroller calculates the measured temperature by applying cold junction compensation and the power series polynomial (or the linearized equation), as described in linear approximation section. The microcontroller drives a LCD display to show the measured temperature. The block diagram of the thermocouple measurement system is shown in Fig. 6.

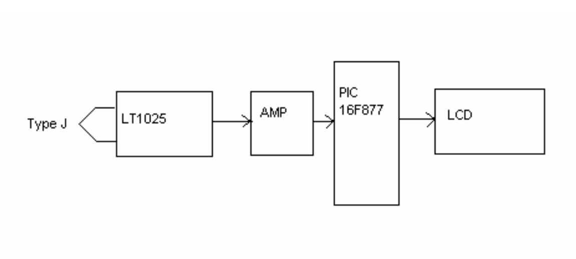

Figure 6 - Block Diagram of Thermocouple Measurment System

The IC chip LT1025 has pins to connect type E, J, K, R, S and T thermocouples and operates with a supply voltage form 4 V to 36 V. In this design we chose to use the operating voltage of 5 V. Typical supply current is 80 uA, resulting in less than 0.1 C internal temperature rise for supply voltage of 5 V. The output of the chip (pin J) is amplified such that the output voltage is 10mV/C. A linearized equation was used in computing the required gain which came out to be 194. Two fixed resistors and a variable resistor are used to adjust the gain appropriately as seen in Fig 5. The output of the amplifier is connected to one of the analogue inputs (AN0) of the PIC16F877 microcontroller. The A/D has a 10-bit resolution and since we are using a 5 V reference supply, one LSB of the converter is equivalent to 5000/1024=4.88 mV. Thus the measurement accuracy will be about 0.5 °C.

The method that was chosen in this design of representing the thermocouple temperature voltage relationship was to use linear approximations over limited temperature ranges. The linear approximation equation is:

$$V = sT + b \qquad (12)$$

V is the thermocouple voltage, s is the slope, T is the temperature, and b is an offset voltage that can be used to represent most thermocouples over limited temperature ranges. All thermocouples have an offset voltages equal to zero. The slope can be determined from the required operating range. Thus the linearized equation (equation 12) becomes:

$$V = sT \qquad (13)$$

V is the thermocouple voltage (uV), s is the Seeback coefficient (uV/°C), and T is the thermocouple junction temperature (°C). The following table (Table 1.) gives the averaged Seeback coefficients for the popular thermocouple types over the operating range of 0 C to 50 C.

Type	$\frac{\mu V}{{}^0C}$
K	40.46
J	51.71
T	40.69
E	60.93
B	0.05
S	6.02
R	5.93

Table 1 – Average Seeback Coefficients

Electrical Summary:

Temperature sensor: Type J thermocouple
Temperature range: 0 °C to 750 °C
Accuracy: 1 °C
Compensation: Hardware
Controller: Microcontroller (PIC16F877A)
Display: LCD
Display format: 6 characters, i.e. "nn.m C"
Update interval: 1 second

CONCLUSION

During the twenty weeks that the Senior Design set of courses encompassed, the HTPO design team has focused on designing and building a working prototype of their oven. The prototype shall demonstrate the theories and engineering principles described in the preceding sections. Testing of the prototype will commence in the days following the composition of this conference paper. The specifications we provide will undoubtedly assist Abraham Fansey and the VP office of Finance and Administration in choosing the option best suited for them when considering further research and design.

ACKNOWLEDGMENTS

We would like to take this opportunity to thank those people who helped us throughout the design process. Abraham Fansey provided us with his vision that generated this project. He also provided assistance whenever required during the design process. James Watters provided the support and financing to make the prototype possible.

Our team mentor, Dr. Satish Kandlikar guided us through intense calculations and the entire design development with his vast knowledge. He has had encouraged and supported us through every aspect of the project and made a great impact on the entire team. We thank him for his extensive help.

Dave Hathaway, Steven Kiosciol, and Rob Kraynik have been invaluable in the construction of the oven. Rob was an exceptional help during the extensive welding process.

Additional thanks go to our team coordinator, Dr. Hensel, and our Senior Design facilitator, Professor Stiebitz for their technical expertise and guidance.

Finally, we thank Donna Mellenthien and Don Kathke for providing the supplies necessary to conduct the vital early heat transfer experiments.

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[2] Bennett, R., 1999, "How Much Air is Excess?," http://www.process-heating.com/CDA/ArticleInformation/Energy_Notes_Item/0,3271,19371,00.html

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