COLORADO SCHOOL OF MINES

1874

Design Challenge: Easy Bake Oven - Final Report

MEGN 300 Sec: A - 21

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Introduction

In this MEGN 300 design challenge, our team set out to build a functional “easy-bake” style oven from cardboard that can reach and maintain an internal temperature of 350 °F while staying within the 55 W rating of a 12 V halogen lightbulb. Using basic heat transfer analysis, we modeled the oven walls as a multi-layer thermal resistance (aluminum foil–cardboard–air gap–cardboard) and estimated a steady-state heat loss of 44.5 W at 350 °F. This result sets the required average power input and leads directly to a target 81% duty cycle for the 55 W bulb so that the oven holds temperature instead of continually heating up.

To implement this in hardware, the oven uses a nested cardboard box design with a 0.5 in air gap, an aluminum-foil-lined inner cavity, and a thermocouple placed near the baking location to measure air temperature. (Appendix I) A 5 V control signal from our measurement system drives a MOSFET switching device, which in turn switches the 12 V supply to the halogen bulb on and off according to the desired duty cycle. (Appendix E & F) The temperature is regulated using a Proportional-Integral-Derivative (PID) control algorithm implemented in LabVIEW, which adjusts the bulb’s on-time based on the thermocouple feedback to maintain the setpoint of 350 °F.

Please be aware that in the *Design and Thermal Modeling* section, equations i - v are the derivation and steps taken to acquire numbers for the final key heat loss equation:

$$vi.\ Qloss = \Delta T \div Rbox \approx 44.5\,W$$

Methodology

Design and Thermal Modeling

We began by setting quantitative design targets: an internal air temperature of 350 °F and a maximum steady-state heat loss below the 55 W rating of our 12 V halogen bulb. To minimize heat loss while still leaving room for a cookie and stand, we selected a nested-box geometry: a 4 in × 4 in × 4 in inner cavity centered inside a 5 in × 5 in × 5 in outer box using x-notched cardboard spacers that create a uniform 0.5 in air gap on all sides. The inner box is lined with aluminum foil to reflect radiation back toward the cookie, and an aluminum heat-sink block is used as the cookie stand.

To estimate heat loss, we modeled each wall as a one-dimensional, steady-state thermal resistance network consisting of inner cardboard, an air gap, and outer cardboard. For a flat layer of material, the conduction resistance is

$$i.\ R1 = L \div K \cdot A \approx 3.94\,K/W$$

where L is the layer thickness [0.0013 m], K is the thermal conductivity [0.0064 W/(m·K)], and A is the wall area [0.0103226 m²]. For convective heat transfer across the air gap, the equation is

$$ii.\ R2 = 1 \div h \cdot A \approx 17\ K/W$$

where h is the convection coefficient [W/(m²·K)]. The value of h for a 0.5 in (12.7 mm) air gap was taken from the provided design chart (Appendix B), resulting with h ≈ 5.7 W/(m²·K).

The total thermal resistance of a single wall is

$$iii.\ Rwall = 2 \cdot R1 + R2 \approx 20.977$$

where R1 is the conduction resistance of one cardboard layer and R2 is the convective resistance of the air gap. Since all six faces of the box were approximated as having the same area and construction, the overall box resistance Rbox was found by treating the six walls as parallel resistances:

$$iv.\ 1 \div Rbox = 6 \cdot (1 \div Rwall) \quad \rightarrow \quad Rbox \approx 3.496$$

With the inside at Tin = 350 °F (450 Kelvin) and ambient air at Tout = 70 (294.261 Kelvin) °F , the temperature difference (all numbers converted to Kelvin) is

$$v.\ \Delta T = Tin - Tout \approx 155.739\, K$$

and the estimated steady-state heat loss is

$$vi.\ Qloss = \Delta T \div Rbox \approx 44.5\, W$$

Carrying out these calculations for the selected dimensions and material properties gives a total heat loss of Qloss ≈ 44.5 W. This value was then used to size the duty cycle for the bulb.

The required duty cycle D is defined as the fraction of time the bulb is on within each switching period, and is defined by the heat loss over the total power supplied by the light bulb, P (55W):

$$vii.\ D = Qloss \div P \approx 81\,\%$$

Thus, the bulb must be on approximately 81% of the time to balance heat input and heat loss at 350 °F.

Switching Device Selection and Circuit Implementation

Because the control hardware can only supply a 0–5 V logic-level output, while the halogen bulb requires 12 V at up to 55 W, we used an N-channel MOSFET as a low-side switching device. The MOSFET gate is driven by the 5 V digital output from LabVIEW, and the MOSFET switches the 12 V supply to the bulb on and off according to the duty cycle commanded by the PID controller.

The bulb current at full power is

$$I = P \div V \approx 4.6\, A$$

where V is the 12 V supply voltage. We selected a MOSFET with an AWG gauge rated for at least 2x the current we need ($4.6 \cdot 2 \approx 9.2$). From the device datasheet in Appendix A, the AWG gauge for approximately 9 A is 21. However, since the next lowest gauge available to us is 14 gauge, we will use this gauge and have a factor of safety of about 8, which in no way affects the objective of this project. This max is well above our operating values, so the MOSFET safely handles the required voltage and current with ample margin. Along this line, the MOSFET was chosen due to its ability to switch faster than other alternatives, such as a Relay. [1]

The final switching circuit (Figure 3 & 4) is implemented as follows:

- The 12 V supply is connected to one side of the halogen bulb. (Appendix G)
- The other side of the bulb is connected to the MOSFET drain.
- The MOSFET source is tied to ground.
- The MOSFET gate is driven by a 0–5 V digital output line through a small series resistor (to limit gate charging current), with a pull-down resistor to keep the device off when the control signal is low. (Appendix F)
- The thermocouple signal is routed to the data-acquisition hardware and into LabVIEW, where a Proportional-Integral-Derivative (PID) algorithm computes the required duty cycle to maintain the 350 °F setpoint. LabVIEW then outputs a corresponding PWM (pulse-width-modulated) signal to the MOSFET gate, turning the bulb on for 81% of each period at steady state. (Appendix E & H)

This configuration allows a low-power 5 V control signal to modulate a higher-power 12 V load while keeping all electrical stresses within the MOSFET's datasheet limits.

Documentation of Prototype

For this final iteration, our group uses two cardboard boxes, one 4 in × 4 in and another 5 in × 5 in. The smaller 4 in × 4 in box sits inside the 5 in × 5 in box, evenly spaced with a 0.5 in air gap using x-notched cardboard pieces (Figure 1). Aluminum foil covers the inside of the 4 in × 4 in box, which houses the cookie, the tin stand (a heat sink from the MEGN 300 room), the thermocouple, and the lightbulb. The thermocouple passes through a small hole on one side of the box and is positioned approximately halfway between the cookie and the lightbulb to avoid extremely cold or hot spots. On the opposite side of the box, the lightbulb sits with its base oriented sideways between the walls of the two boxes. (Figure 2)

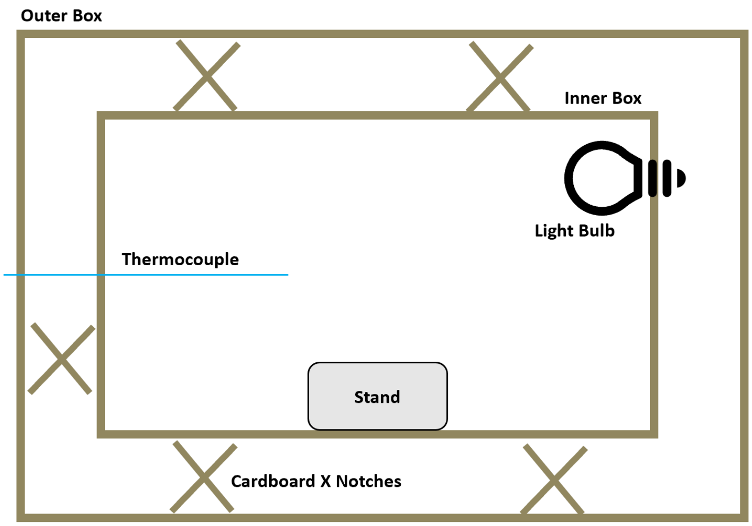


Figure 1: First Design Iteration

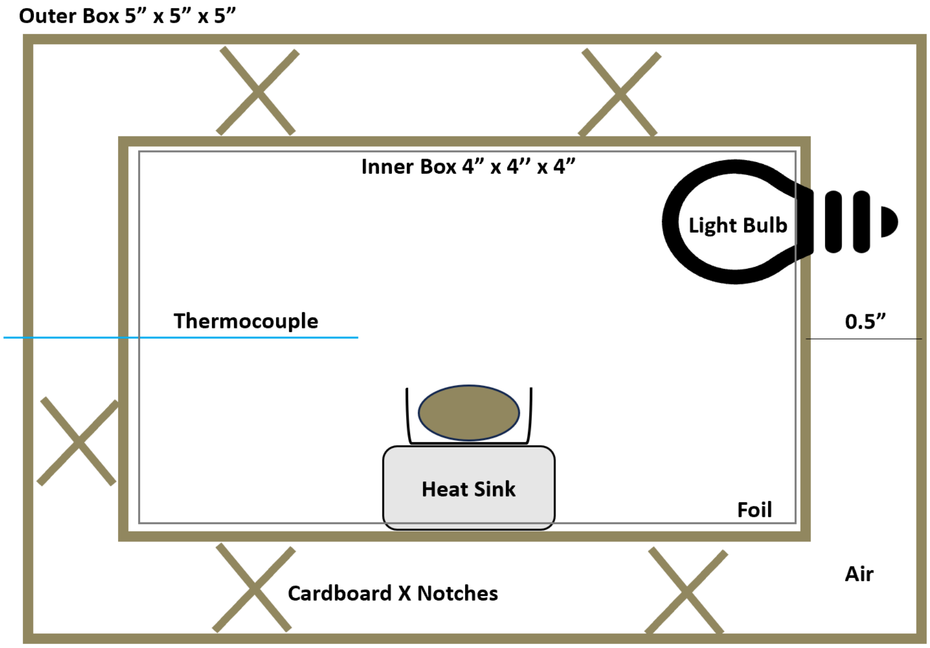


Figure 2: Final Design Iteration

Bill of Materials

To minimize material usage, we built the oven from a small number of inexpensive or reused components. The main items are:

Table 1: Bill of Materials

Item #	Component	Quantity	Specifications	Cost
1	4 in × 4 in × 4 in cardboard box	1	inner oven cavity	\$0
2	5 in × 5 in × 5 in cardboard box	1	outer shell	\$0
3	X-notched cardboard spacers	4	to center inner box and create 0.5 in air gap between inner cavity and outer shell	\$0
4	Aluminum Foil	~2 ft^2	lining for inner cavity walls, floor, and ceiling	\$0
5	Tape	~2 ft		\$0
6	Aluminum heat-sink block	1	cookie stand, reused from lab stock	\$0
7	Cookie pan	1		\$0
8	Cookie Dough	As needed		\$0
9	Halogen Light Bulb	1	12V, 55W	\$0
10	Bulb Socket	1	compatible with the halogen lamp	\$0
11	K-type thermocouple	1		\$0
12	NI PCIe-6321 DAQ	1	provides 0-5V PWM signal on A0 out	\$0
13	MOSFET Module	1	N-channel D4184 variant	\$0
14	Power Wires	2	14 AWG, 6" lengths (V in+/-, V out+/-)	\$0
15	Control Wires	1	22-24 AWG gauge (DAQ to MOSFET Trig/PWM and GND)	\$0

Using two small boxes, a single air gap, and a thin foil lining kept the construction simple and material-efficient while still providing enough thermal resistance to limit heat loss to approximately 44.5 W at the target operating temperature.

Flow Diagram

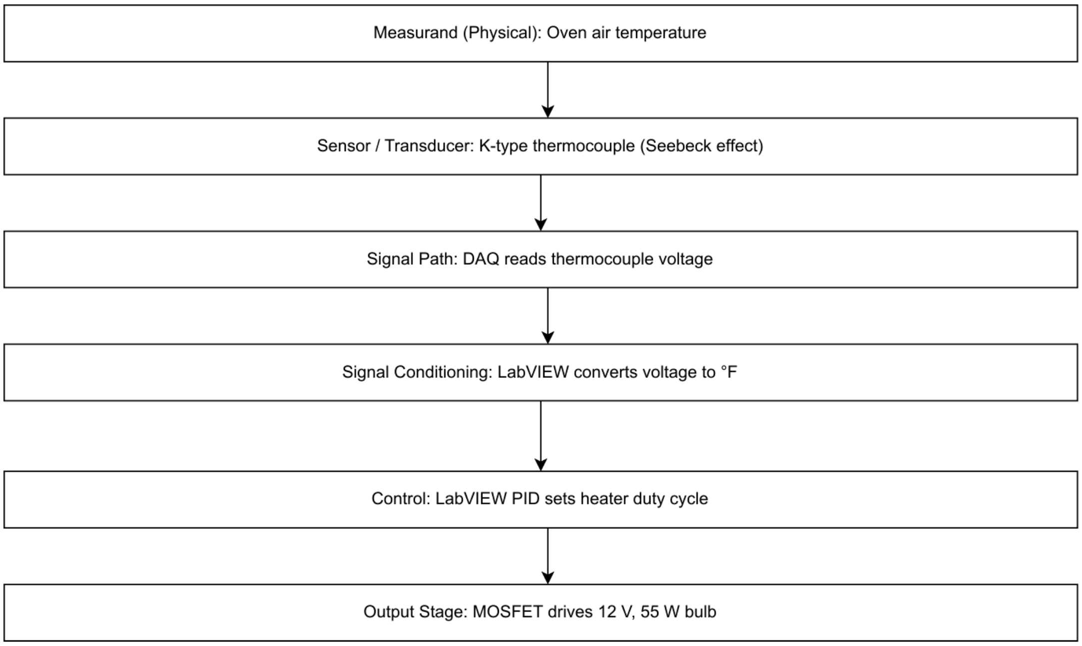


Figure 3: Process Flow Diagram

The flow diagram in Figure 3 summarizes how the measurement and control system for the easy-bake oven operates as a closed loop. At the top level, the measure is the air temperature inside the foil-lined oven cavity, which changes as the 55 W halogen bulb heats the cookie and surrounding air. This temperature is sensed by a K-type thermocouple, our sensor/transducer. Physically, the thermocouple relies on the Seebeck effect: a temperature difference between the hot junction in the oven and the cold junction at the DAQ creates a small voltage. In the signal path, the DAQ reads this thermocouple channel using the built-in thermocouple input mode (THERM TC block), which is configured for a K-type probe and °F units. As a result, the signal conditioning step happens inside that DAQ/thermocouple block, LabVIEW returns a temperature value in degrees Fahrenheit rather than a raw voltage, so the rest of the code can work directly with the measured oven air temperature. This temperature becomes the process variable for the control block: the PID algorithm compares the measured temperature to the 350 °F setpoint, computes the error, and outputs a duty cycle that specifies what fraction of each cycle the heater should be on. Finally, in the output stage, this duty-cycle command is implemented as a 0–5 V PWM signal that drives a MOSFET, which switches the 12 V supply to the halogen bulb. The bulb's average power then determines the oven air temperature, closing the loop back to the thermocouple measurement at the top of the diagram.

Circuit Diagram

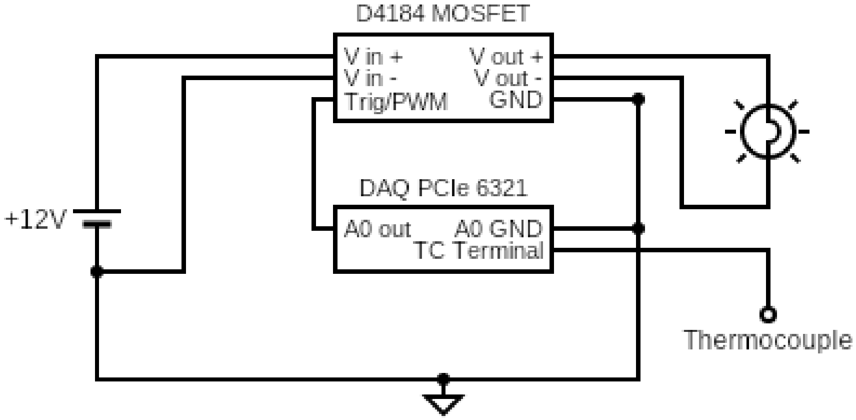


Figure 4: Circuit Diagram

- 12 V supply powers a resistive load (lamp/heater symbol).

- D4184 MOSFET board switches the load on/off with PWM.

- DAQ PCIe-6321 analog-out (A0 out) sends the PWM/trigger signal to the MOSFET input.

- DAQ ground (A0 GND) is tied to the MOSFET ground and the 12 V supply return (common ground).

- A thermocouple is connected to the DAQ TC terminal so the DAQ can measure temperature while controlling the load.

VI Pictures and Explanation

The LabVIEW implementation for the easy-bake oven consists of a main VI (Figure 5 and 6) and a PID controller subVI (Figure 8). The main VI reads the oven temperature from the thermocouple channel on the DAQ, converts the thermocouple voltage to temperature in °F , and displays both the measured temperature and the 350 °F setpoint on a waveform chart. These two signals are passed to the PID Gains subVI along with the user-defined proportional, integral, and derivative gains (KP, KI, KD). The PID subVI computes the control error e(t) = Tset−T forms the proportional, integral, and derivative terms, and sums them to generate a controller output between 0 and 100 that represents the desired duty cycle of the lightbulb.

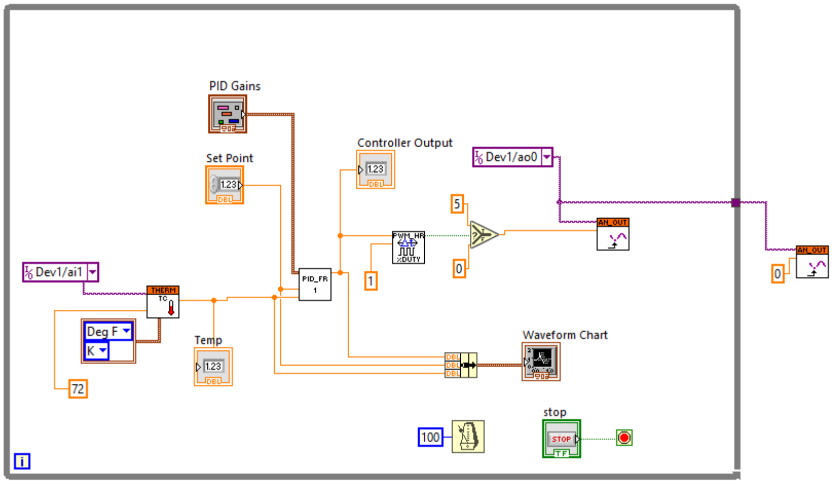
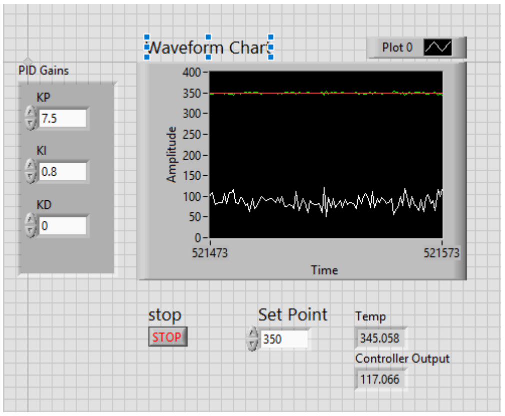


Figure 5: Main Block Diagram

Inside the PID subVI, uninitialized shift registers store the previous error, the integrated error, and the previous time stamp so that the code can calculate both the accumulated error (integral term) and the rate of change of error (derivative term) each time the VI executes. The integral term is limited to a fixed range to prevent integrator wind-up, and the derivative term uses the change in error divided by the elapsed time between cycles. The resulting controller output is sent back to the main VI, where it is used to set the PWM duty cycle on the digital output that drives the MOSFET gate. By tuning KP, KI, and KD, we adjusted how quickly the oven heats up, how tightly it tracks the 350 °F setpoint, and how much overshoot and oscillation occur in the temperature response.

By tuning KP, KI, and KD, we adjusted how quickly the oven heats up, how tightly it tracks the 350 °F setpoint, and how much overshoot and oscillation occur in the temperature response. Through trial-and-error tuning while watching the waveform chart, we increased KPK_PKP until the temperature rose quickly but began to show noticeable overshoot, then backed off slightly and added a small KIK_IKI to remove steady-state error; the final values KP=7.5 and KI=0.8 give a fast rise time with oscillations confined to a narrow band around the setpoint. We left KD=0 because the temperature signal is relatively noisy, and the derivative term mainly amplified this noise without providing a clear improvement in overshoot or settling time for our oven.



PID Gains
KP 7.5
KI 0.8
KD 0
Set Point 350
Temp 345.058
Controller Output 117.066

Figure 6: Main Control Panel

The waveform chart lets us see the full time history of the response so we can visually check if the oven reaches the setpoint, how much it overshoots, and how tightly it holds 350 °F once it settles. We also include numeric indicators for the current temperature and controller output so that we can read off steady-state values (for example, ~350 °F and ~79–81% duty cycle) and compare them directly to our analytical prediction

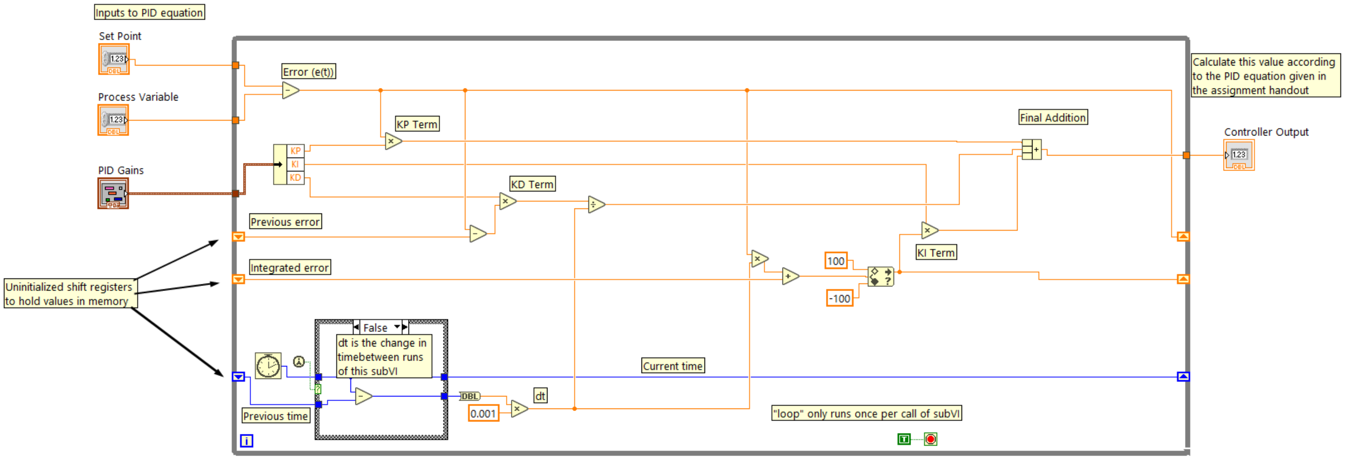


Figure 8: PID SubVI

Results & Discussion

Cookie and Oven Pictures

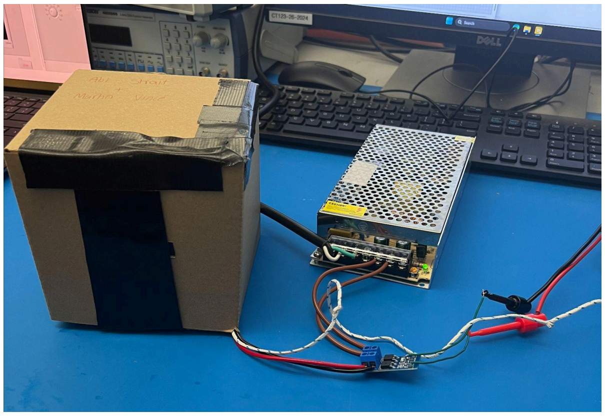


Figure 7: Sealed Oven (While Baking)

Figure 7 shows the oven in its fully sealed configuration during a baking run, with the front flap taped closed to minimize heat loss while the PID controller maintains the 350 °F setpoint. In Figure 9, the oven is opened immediately after the bake, revealing the foil-lined inner cavity, the aluminum heat-sink stand, the thermocouple placement, and the small pan holding the baked cookie, which illustrates how the internal components are arranged around the heat source. Figure 10 provides a close-up view of the cookie after removal from the oven, highlighting the browned, slightly cracked surface and even rise, which visually confirms that the oven maintained a sufficiently high and uniform temperature to fully bake the dough.

Figure 9: Detailed Oven (Before Baking)

Figure 10: Detailed Cookie (After Baking)

Results Discussion

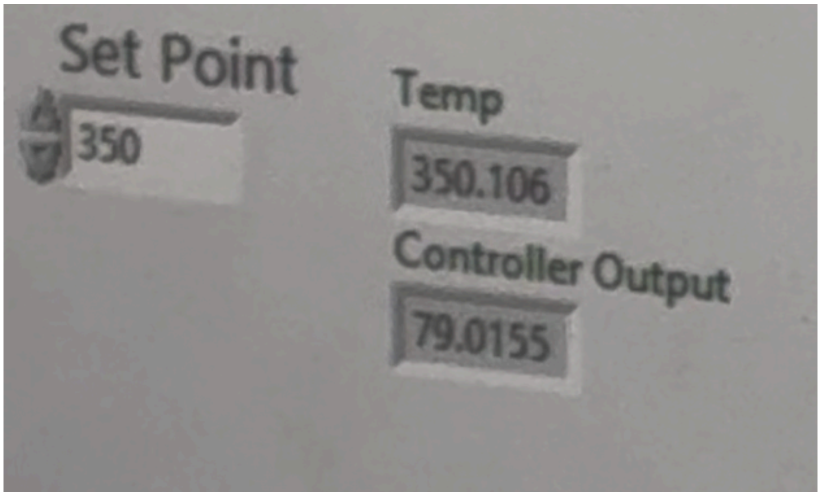

Set Point
350
Temp
350.106
Controller Output
79.0155

Figure 11: Actual Duty Cycle at 350 °F

Figure 11 shows the evolution of the cookie from raw dough to a fully baked cookie inside the completed cardboard oven. Before baking, the dough sits in a small aluminum pan on top of the heat-sink stand in the foil-lined inner box. After running the LabVIEW control program, the cookie rises, the surface turns uniformly golden brown with darker spots at the peaks, and the interior texture appears set rather than doughy. The cookie is firm enough to hold its shape when removed from the pan but still soft in the center, which indicates that the oven maintains a sustained, baking-appropriate temperature rather than just briefly spiking hot. Additionally, the cookie's top surface was a little crisp while the underside was a perfect consistency. This is chalked up to the position up the heat source. It tasted great except for the darkened top.

The LabVIEW front panel confirms that the control system is able to hold the cavity temperature close to the 350 °F setpoint. In the steady-state portion of the run, the temperature trace oscillates in a narrow band around 350 °F, and the numeric readout in the screenshot shows a temperature of 350.106 °F at the moment captured. At that same instant, the controller output is approximately 79%, meaning the PID loop has increased the bulb duty cycle to about 79% to balance the actual heat loss of the oven. This corresponds to an average input power of

$$Pavg = 0.79 \cdot 55\,W \approx 43\,W$$

which is still comfortably below the 55 W design limit.

Comparing this to our design calculations, we originally estimated a heat loss of 44.5 W at 350 °F and therefore predicted a required duty cycle of 81%. The experimental steady-state duty cycle of ~79% is lower, suggesting that the real oven loses less heat than our simplified model captured. The percent error (3.37%) is consistent with uncertainties in material properties, imperfect sealing around the door flap, and the fact that the thermocouple measures temperature at a single point rather than the exact average temperature of the air and cookie.

Overall, the system behavior matches the expectations laid out in the methodology. The nested-box construction and air gap keep the required power well under the bulb rating, the MOSFET-driven PWM successfully modulates the 12 V bulb using a 5 V control signal, and the PID tuning yields a response that reaches the setpoint without large overshoot and then maintains a nearly constant baking temperature. (Appendix E and D) The visible outcome, a fully baked cookie and the measured outcome, a temperature trace centered on 350 °F with a stable controller output. Both indicate that the design achieves the practical goal of functioning as an easy-bake oven.

Conclusion

The goal of this project was to design and build a cardboard easy-bake oven that could reach and maintain 350 °F using a 55 W halogen bulb and to use heat-transfer analysis and closed-loop control to justify and achieve that performance. Our revised thermal model of a cardboard–air–cardboard wall predicts a total heat loss of approximately 44.5 W at 350 °F and a corresponding theoretical duty cycle of about 81% for the bulb. This analysis guided the choice of a nested-box geometry with a 0.5 in air gap and foil-lined inner cavity to keep heat loss below the bulb's power limit.

Experimentally, the PID-controlled oven reached the 350 °F setpoint and maintained it within a narrow band, with the controller output settling around a 79% duty cycle. This measured value is close to the predicted 81% duty cycle and corresponds to an average input power of roughly 43 W, which satisfies the design constraint of staying under 55 W. Most importantly, the oven successfully baked a cookie from raw dough to a browned, fully cooked state, demonstrating that the thermal and control design are sufficient for the intended task.

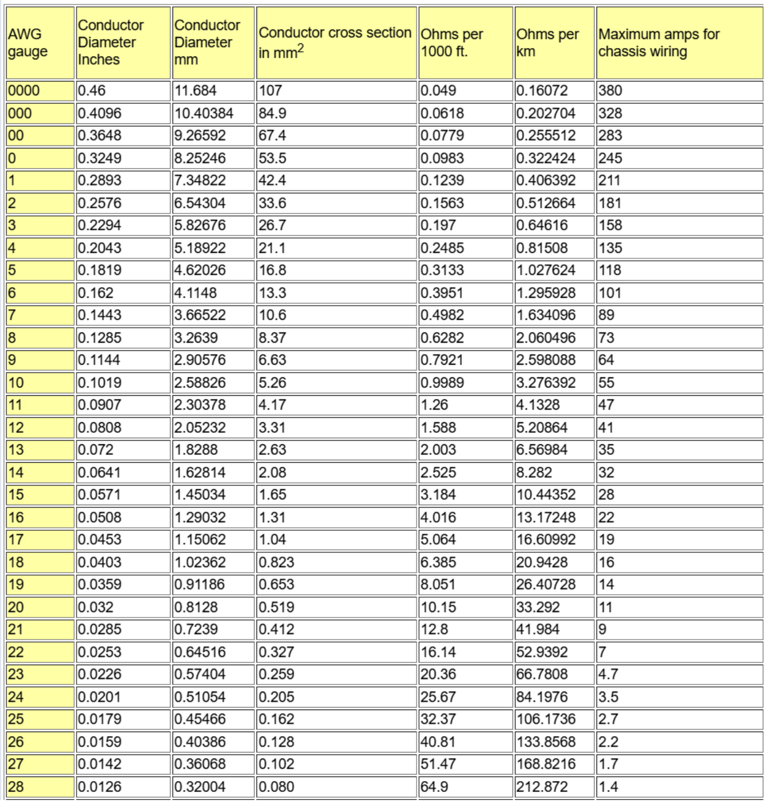
In summary, the project meets the objectives laid out in the introduction: we designed a thermally insulated cardboard oven, quantified its heat loss, implemented a MOSFET-based switching circuit and LabVIEW PID controller, and validated the design by both quantitative measurements (temperature and duty cycle) and qualitative performance (a baked cookie). The small gap between predicted and measured duty cycle highlights typical real-world deviations from ideal models, but it does not prevent the system from operating as a functional, low-power easy-bake oven.

Works Cited

[1] E. As, E. Ar, and T. Stg, “AOD4184A 40V N-Channel MOSFET General Description Product Summary.” Available: https://www.aosmd.com/res/datasheets/AOD4184A.pdf

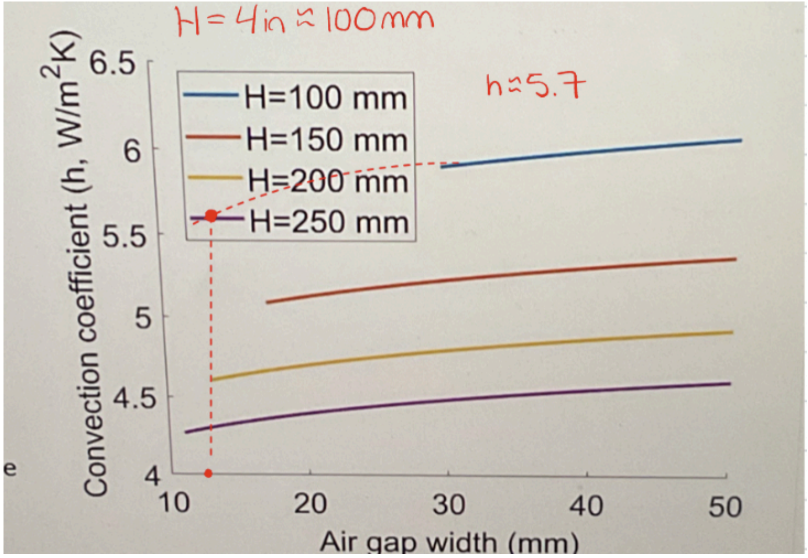
Appendices

Appendix A: Power Stream Wiring Guidelines



AWG gauge	Conductor Diameter Inches	Conductor Diameter mm	Conductor cross section in mm^2	Ohms per 1000 ft.	Ohms per km	Maximum amps for chassis wiring
0000	0.46	11.684	107	0.049	0.16072	380
000	0.4096	10.40384	84.9	0.0618	0.202704	328
00	0.3648	9.26592	67.4	0.0779	0.255512	283
0	0.3249	8.25246	53.5	0.0983	0.322424	245
1	0.2893	7.34822	42.4	0.1239	0.406392	211
2	0.2576	6.54304	33.6	0.1563	0.512664	181
3	0.2294	5.82676	26.7	0.197	0.64616	158
4	0.2043	5.18922	21.1	0.2485	0.81508	135
5	0.1819	4.62026	16.8	0.3133	1.027624	118
6	0.162	4.1148	13.3	0.3951	1.295928	101
7	0.1443	3.66522	10.6	0.4982	1.634096	89
8	0.1285	3.2639	8.37	0.6282	2.060496	73
9	0.1144	2.90576	6.63	0.7921	2.598088	64
10	0.1019	2.58826	5.26	0.9989	3.276392	55
11	0.0907	2.30378	4.17	1.26	4.1328	47
12	0.0808	2.05232	3.31	1.588	5.20864	41
13	0.072	1.8288	2.63	2.003	6.56984	35
14	0.0641	1.62814	2.08	2.525	8.282	32
15	0.0571	1.45034	1.65	3.184	10.44352	28
16	0.0508	1.29032	1.31	4.016	13.17248	22
17	0.0453	1.15062	1.04	5.064	16.60992	19
18	0.0403	1.02362	0.823	6.385	20.9428	16
19	0.0359	0.91186	0.653	8.051	26.40728	14
20	0.032	0.8128	0.519	10.15	33.292	11
21	0.0285	0.7239	0.412	12.8	41.984	9
22	0.0253	0.64516	0.327	16.14	52.9392	7
23	0.0226	0.57404	0.259	20.36	66.7808	4.7
24	0.0201	0.51054	0.205	25.67	84.1976	3.5
25	0.0179	0.45466	0.162	32.37	106.1736	2.7
26	0.0159	0.40386	0.128	40.81	133.8568	2.2
27	0.0142	0.36068	0.102	51.47	168.8216	1.7
28	0.0126	0.32004	0.080	64.9	212.872	1.4

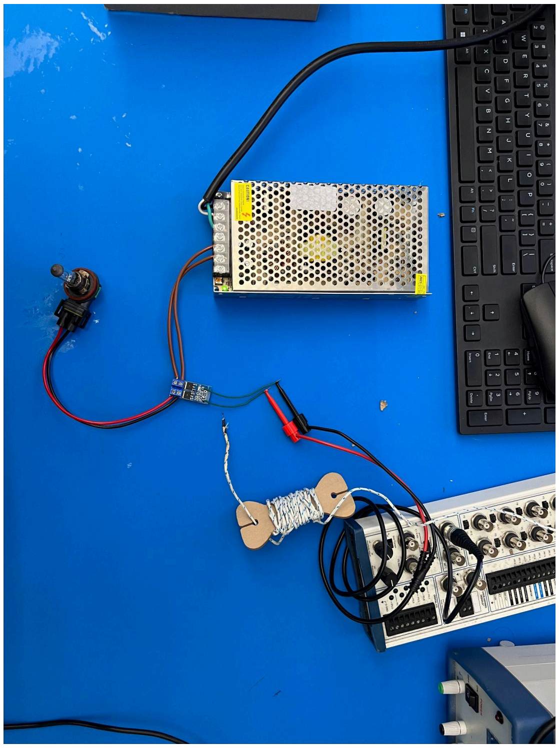
Appendix B: h Coefficient Approximation



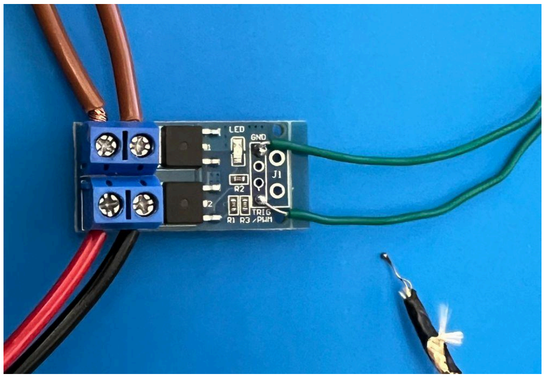
Appendix C: Oven Setup

Appendix D: Inner Cavity Setup

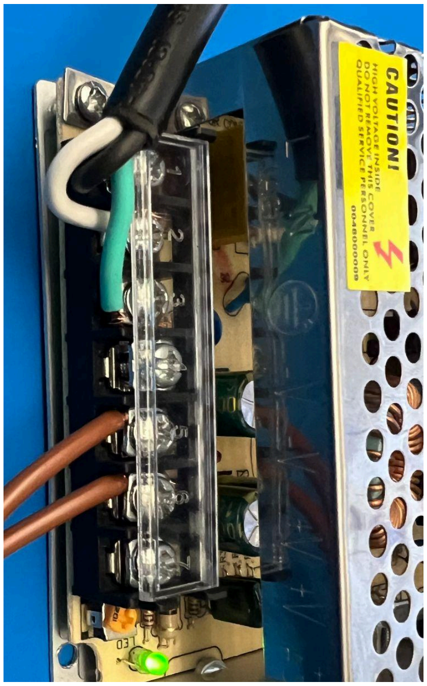
Appendix E: Wiring Setup



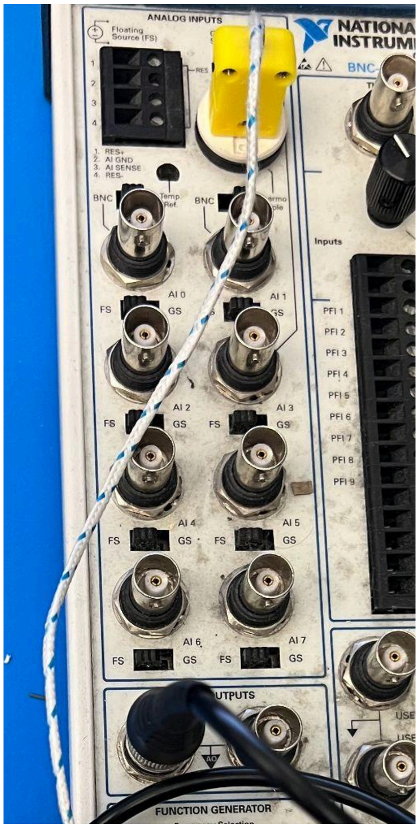
Appendix F: Detailed MOSFET



Appendix G: Detailed Power Supply



Appendix H: Detailed NI PCIe-6321 DAQ



Appendix I: Detailed Oven Setup