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Design of an Aluminum Foundry with Ceramic Fiber Insulation

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Abstract

Aluminum is one of the most versatile engineering metals, finding its use in a variety of fields including construction, architecture, aerospace, automotive, consumer products, and many more. The high demand for aluminum production is driven by its advantageous physical, chemical, and mechanical properties, such as a high strength to weight ratio and good corrosion resistance. Additionally, aluminum can be recycled using processes that require only a fraction of the energy required for primary production. Aluminum recycling is primarily accomplished by melting in foundries. In some aluminum foundries, a large amount of energy is lost due to poor insulation and an inaccurate knowledge of the crucible temperature. This project focused on designing a safe, efficient electric aluminum foundry. Using theoretical calculations, an electric foundry was designed to melt 3.0 kg of aluminum cans using ~9 MJ of energy. A prototype was successfully fabricated and tested with attention to the structural, thermal, and electrical design aspects. Experiments showed that the foundry was capable of melting 3.0 kg of aluminum cans using ~11 MJ of energy, which was close to the theoretical calculations. The normalized energy usage of the foundry was ~6.9 MJ per kg of pure aluminum produced, which compares well with benchmarked aluminum recycling foundries.

1. Introduction

Non-ferrous metals, specifically aluminum, have applications in many manufactured products, including construction, automotive, aerospace, industrial equipment, and consumer electronics. The key advantages of aluminum include its high strength to weight ratio, good ductility and toughness, excellent corrosion resistance in most environments, good conductivity, and excellent machinability and formability [1].

Aluminum is the most abundant metal on earth, but due to its high reactivity and tendency to rapidly oxidize, aluminum is usually bound up in silicides or oxides and is rarely found as a metal in nature [2]. Chemists made many efforts in the 1700s and 1800s to produce metallic aluminum, but the first successes came when Frederick Wohler produced aluminum powder by reacting anhydrous aluminum chloride with pure potassium in 1827, and then H. St. Claire Deville produced aluminum by passing aluminum proto-chloride ($AlCl_2$) over potassium metal in 1854 [2]. However, aluminum was too costly for most engineering purposes until Hall and Heroult independently developed a process" for smelting aluminum by dissolving aluminum oxide (alumina) in molten cryolite ($Na_3 AlF_6$) and applying an electric current to the molten salt bath to dissociate the alumina. The oxygen collects at a carbon electrode (anode), leading to combustion, and the aluminum collects at the cathode [3]. Thus, aluminum is a relatively recent addition to the list of engineering materials due to the large amount of energy necessary to reduce the metal. The energy required for modern aluminum production is estimated to be ~17,000 kWh/tonne (61 MJ/kg) [4].

Fortunately, aluminum is 100% recyclable [5], and recycling aluminum only requires about 750 kWh/ton (2.7 MJ/kg) [6,7]. Aluminum cans are composed of two different alloys, identified as 3004 aluminum for the can body, and 5182 aluminum for the can lid, with a combined melting temperature range of 850-910 K [8]. One common and effective way to recycle aluminum is by melting in a foundry. Typical energy sources for heating a foundry include coal, natural gas, liquefied petroleum gas (also known as LPG) propane or butane, and electricity. For reasons of safety and reliability, components for aluminum foundries are fabricated from materials with high working temperatures, depending on the proximity of each component to combustion or hot products. Ozer et al. researched the optimal parameters for pre-heating temperature and flux composition for aluminum recycling in an induction furnace. The present work will use electric heating coils, which are easy to obtain and simple to assemble [8].

In many foundries for aluminum recycling, a large amount of heat is lost due to two factors: firstly, poor insulation, and secondly, the inability to measure the crucible temperature. The main aim of the present project was to design a simple, safe, and efficient aluminum foundry. Various options for materials of construction were reviewed and analyzed to optimize the safety, efficacy, and ease of use. Heat transfer analysis was performed to compare and evaluate energy loss for several combinations of materials and dimensions. The dimensions and the shape of the foundry were selected for manufacturability and efficiency. In addition, a temperature measurement system was incorporated for data collection, energy usage calculation, and process control.

2. Theoretical Energy Requirement Calculations

2.1. Thermal Design

Considerations for the thermal design and the heat source design of the aluminum foundry included the amount of heat input required to the system, the amount of heat loss, the amount of aluminum, and the number of electric coils. It was important to analyze the thermal properties of the system because they are crucial in determining the effectiveness and efficiency of the system. Note that heat is a specific form of energy, therefore the terms, heat and energy, are sometimes used interchangeably herein. The total heat input needed to melt the aluminum is an important aspect of the design. The heat input requirements were estimated to be the sum of the following:

- Energy required to raise the temperature of the aluminum and the crucible, $H_{\Delta T}$
- Energy required to melt the aluminum, $H_{Melt,Al}$
- Heat lost due to conduction, $H_{Loss,Cond.}$
- Heat lost due to convection, $H_{loss,Conv.}$, and
- Heat lost due to radiation, $H_{Loss,Rad.}$.

2.1.1. Energy required to raise the temperature of the aluminum and crucible

The heat capacity of aluminum and steel were assumed to be constant over the entire temperature range to simplify the calculation for estimation purposes. Additionally, although the melting point of aluminum is less than 750 K, the target temperature was higher to ensure adequate superheat for subsequent pouring. The energy required to heat the aluminum and the crucible, $H_{\Delta T}$, was estimated to be ~3.1 MJ based on the following expression and assumptions:

$$\boldsymbol{H_{\Delta T} = (m_{Al} * C_{P,Al} + m_{Fe} * C_{P,Fe}) * \Delta T} \qquad (1)$$

Where, m_{Al}: Mass of the aluminum (3.0 kg), $C_{P,Al}$: Heat capacity of aluminum (890 J/kg/K) [9], m_{Fe}: Mass of the steel crucible (3.0 kg), $C_{P,Fe}$: Heat capacity of the steel crucible (470 J/kg/K) [9], and ΔT: Temperature change (assumed to be 750 K).

2.1.2. Energy required to melt the aluminum

The energy required to melt the 3.0 kg of aluminum, $H_{Melt,Al}$, was estimated to be 1.2 MJ based on the following formula and assumption:

$$\boldsymbol{H_{Melt,Al} = m_{Al} * L_t} \qquad (2)$$

Where: L_t is the latent heat of fusion of the aluminum (396 kJ/kg) [10].

2.1.3. Heat lost due to conduction

The process was enclosed in insulating material to retain heat and minimize heat lost to the environment. For conservatism, steady state heat transfer was assumed [11]. One type of heat loss was conductive heat loss, which depends on the thermal conductivity of the insulating material. Heat loss due to conduction through the wall, $H_{Loss,Cond.}$, was calculated using the following formula:

$$\boldsymbol{H_{Loss,Cond.} = \frac{kA}{\Delta X} * \Delta T * t} \qquad (3)$$

Where: k: Thermal conductivity of the insulation material, W/(m.K), i.e., J/(s.m.K), A: Surface area (m^2), ΔX: Wall thickness (m), ΔT: Temperature difference (K), and *t*: Time required for melting (assumed to be 30 min.; i.e. 1800 s).

Four types of materials were selected for foundry structure and heat conservation. The outer wall was fabricated from steel for structural purposes, and the steel was assumed to be infinitely conductive (relative to the insulating materials). Inside of the steel there was a layer of insulating firebrick with a thickness of ~0.05 m, a nominal estimated surface area of ~1.0 m^2, and a thermal conductivity (k) of ~1.1 W/m/K. Inside of the firebrick layer was a layer of aluminum foil with an assumed infinite thermal conductivity. Inside of the aluminum foil layer was a layer of ceramic fiber insulation with a thickness of ~0.025 m, a nominal estimated surface area of ~0.60 m^2, and a thermal conductivity (k) of ~0.105 W/m/K at temperatures above 400 °C. Note that the thermal conductivity of the ceramic is ~0.015 W/m/K at room temperature, however, the higher value was used for conservatism and also because the inside temperature of the foundry was usually >400 °C. The maximum desired time to melt 3 kg of aluminum was 30 minutes. The internal temperature was assumed to be 750 °C. The outer wall temperature was assumed to be 60 °C, which resulted in a ΔT of 690 K.

For a foundry with a multi-layer wall, $\frac{\Delta X}{kA}$ represents the thermal resistance and $\frac{H_{Loss,Cond.}}{t}$ represents the rate of heat loss, i.e. thermal current. Therefore, in the case of the foundry lined with both ceramic fiber and firebrick the heat loss was calculated as follows:

$$\boldsymbol{H_{Loss,Cond.} = \frac{\Delta T * t}{\left(\frac{\Delta X_{ceramic}}{k_{ceramic} A_{ceramic}} + \frac{\Delta X_{firebrick}}{k_{firebrick} A_{firebrick}}\right)}} \qquad (4)$$

Where: ΔT: Temperature difference (assumed to be 690 K), *t*: Time required for melting (assumed to be 30 min, i.e. 1800 s), $\Delta X_{ceramic}$: Thickness of the ceramic fiber layer (calculated based on the design dimensions such as, wide, length, height, and wall thickness of the foundry to be 0.025 m), $k_{ceramic}$: Thermal conductivity of the ceramic fiber (0.105 W/(m.K)) [12], $A_{ceramic}$: Surface area of the ceramic fiber (calculated to be 0.6 m^2), $\Delta X_{firebrick}$: Thickness of the firebrick (calculated to be 0.05 m), $k_{firebrick}$: Thermal conductivity of the firebrick (1.1 W/(m.K)) [13], and $A_{firebrick}$: Surface area of the firebrick (calculated to be 1.0 m^2).

Thus, the estimated heat lost to conduction was ~2.6 MJ. Note that the temperature at the interface between the ceramic fiber and firebrick was calculated to be ~170 °C, therefore the ceramic fiber was a critical material for heat conservation.

2.1.4. Heat lost due to convection

Consideration of the amount of heat lost due to convection is also important. One of the main parameters that determines convective heat loss is the convective heat transfer coefficient, h. A large amount of the heat could be transferred to the air and lost by means of air flow through the lid of the foundry. It is recommended that the foundry be fully covered to minimize convective heat loss due to the air. With the lid closed, the convective heat transfer was thought to be minimal. When the foundry was fully isolated, the convective heat transfer coefficient, and thus the convective heat loss, would approach zero. The following equation was used to estimate convective heat loss, $H_{Loss,Conv.}$ [14]:

$$\boldsymbol{H_{Loss,Conv.} = h * A_{exposed} * (T_{in} - T_{\propto}) * t_{exposed}} \qquad (5)$$

Where: h: Convective heat transfer coefficient (25 W/(m^2.K)) [15], T_{in}: Inside temperature (750 °C), T_{∞}: Outside air temperature (assumed to be 20 °C), $A_{exposed}$: Area exposed to convective heat transfer (lid area, calculated to be 0.09 m^2), and $t_{exposed}$: time exposed to convective heat (open time, assumed to be 300 s).

The aluminum recycling process required opening the foundry multiple times to observe and remove the crucible. The lid was estimated to be removed for 5 min. (300 s) for loading and observation. During these times a large amount of heat could be released to the environment. The convective heat loss was calculated for the amount of time that the lid was removed. The lid area was approximately 0.3 m by 0.3 m, which resulted in an area of 0.09 m^2. Thus, the estimated heat lost by convection was ~0.5 MJ.

2.1.5. Heat lost due to radiative transfer

Thermal radiation could be large for an aluminum foundry because it is an elevated temperature process. However, radiation heat losses are mostly limited to exposed surfaces. Surfaces with higher emissivity transfer more thermal radiation, but surfaces with smaller emissivity do not allow the transfer. The formula below shows the parameters that affect radiation heat loss, $H_{Loss,Rad.}$: [16, 17]

$$\boldsymbol{H_{loss,rad.} = e * \sigma * A * T^4 * t_{exposed}} \qquad (6)$$

Where: $H_{Loss,Rad.}$: Energy Loss due to radiation (J), e: Surface emissivity (unitless), σ: Stefan-Boltzmann constant, 5.67x10^{-8} W/(m^2/K^4), and T: Temperature (K).

A layer of aluminum foil was inserted between the ceramic foam and the firebrick to reduce radiative heat loss internal to the foundry. The emissivity of aluminum foil is ~0.04 [18], thus the aluminum foil served to reflect the heat back into the process and thus reduce radiative heat lost to the environment. With no aluminum foil layer, the heat lost due to radiation could have been quite high because the emissivity of the firebricks was ~0.75.

Nonetheless, similar to convective heat loss, radiative heat loss could have been high during the times that the lid was opened. The emissivity of the environment was assumed to be 1.0. Radiative heat loss was calculated for the amount of time that the lid was removed for the same duration and lid area previously mentioned for convection. Thus the estimated heat lost to radiation was ~1.7 MJ.

The total heat input required, $H_{Total},$ was estimated using the following equation [19]:

$$\boldsymbol{H_{Total} = H_{\Delta T} + H_{Melt,Al} + H_{Loss,Cond.} + H_{Loss,Conv.} + H_{Loss,Rad.}} \qquad (7)$$

Thus, for one melting cycle of 3 kg of aluminum, H_{Total} was estimated to be 9.0 MJ. For comparison with data from the literature, the energy was divided by the mass of aluminum melted, m_{Al}. Normalizing the energy requirement by the mass of aluminum assumed to be melted (3.0 kg), one can obtain a normalized energy requirement of 3.0 MJ/kg.

2.2. Electrical Design and Heat Source

After evaluating several heat sources commonly used in aluminum foundries, such as coal, LPG gas, magnetic conduction, and electric heating coils, electric coils were selected due their efficiency, safety, environmental sustainability, and ease of use and application. The amount of heat the foundry is capable of producing should exceed the calculated minimum requirement to make up for unexpected heat loss during the process and to ensure sufficient superheat. Power, P, is calculated as:

$$\boldsymbol{P = I * V} \qquad (\mathbf{8})$$

Where: I: Current as a function of time (A), and V: Voltage as function of time (V).

The heating coils drew ~2.0 A of single-phase alternating current at a voltage of ~220 V, thus consuming ~440 J/s. They were assumed to generate heat with ~95% efficiency [20]. Thus, assuming stable current and voltage, each heating coil could produce ~0.8 MJ in the 30 min. (1800 s) maximum desired heating time. Since the minimum energy requirement was 9.0 MJ, a minimum of 11 heating coils were required.

3. Materials and Methods

3.1. Prototype Fabrication

The materials selection and fabrication process for the prototype electric aluminum foundry is described in this section.

3.1.1. Outer Shell and Firebrick

Steel was selected for fabrication of the outer shell due to its strength, durability, weldability, and low cost. Five steel plates were welded together to create the square for the foundry as shown in Figure (1a). The corners were reinforced with angle iron. Four wheels were welded to the cart for mobility. Bricks identified as “firebrick” were used to line the walls and bottom of the foundry as shown in Figure (1b). Mortar with an optimized ratio of cement, sand, and water (2:1:1.2) was mixed and used to position the firebricks. Three ports (holes) were drilled through the outer shell and firebrick in order to feed through the power wires and the thermocouple.

a) b)

Figure (1). The outer shell for the foundry, a) as-welded, and b) as lined with firebrick.

3.1.2. Aluminum Foil, Ceramic Fiber Insulation, Heating Elements, and Wiring

To reduce radiative heat losses, aluminum foil was lined inside the firebrick as shown in Figure (2a). After inserting the foil, the ceramic fiber was cut in size to fit into the foundry. The heating elements made of Nickel based material, needed a structure to be fixed inside the foundry. Two steel support structures were fabricated, one for each side of the foundry. Eight heating coils were affixed to each support structure and positioned in the foundry as shown in Figure 2b. Terminals were used in order to connect the coils to the wires and create the two circuits. Inside the foundry, the wires were insulated using temperature resistant asbestos sheaths. Outside the foundry, the wires were attached to terminal in order to be connected using 16 A plugs.

3.1.3. Cover, Lid, Crucible and Tongs

A steel cover was fabricated for the foundry and the underside was lined with the ceramic fiber insulation. A 0.3 m by 0.3 m opening was left in the cover for observation and removal of the crucible. The lid was also made of steel and lined on the process-facing side with ceramic fiber insulation. Bolts were welded on the underside of the lid to position steel wires that fixed the ceramic fiber in place. The cover and lid are shown on the completed foundry in Figure (3a). A crucible was fabricated by parting off the top of a fire extinguisher, and a set of tongs was custom made to grip and carry the crucible with the help of a blacksmith. The crucible and tongs are shown in Figure (3b).

3.1.4. Temperature Sensing Using Thermocouple and Arduino

The ability to monitor the temperature inside the foundry was considered essential to ensure safe and efficient operation. Uncontrolled temperature could lead to excessive heat loss and self-destruction of the foundry components. A type K thermocouple was inserted into the hot section of the foundry and connected on the outside to MAX6675 cold junction, which can measure temperatures up to 1000 °C. The cold junction was connected to the Arduino as shown in Figure (4). The VCC of the cold junction was connected to the 5V pin of the Arduino (red wire), the ground of the sensor to the ground of the Arduino (black wire), and SO (yellow wire), CS (orange wire), and SCK (purple wires) were connected to pins 8, 9, and 10, respectively. In the future, a closed loop control system is recommended to both display the temperature of the system and maintain it at the desired set point [21, 22].

a) b)

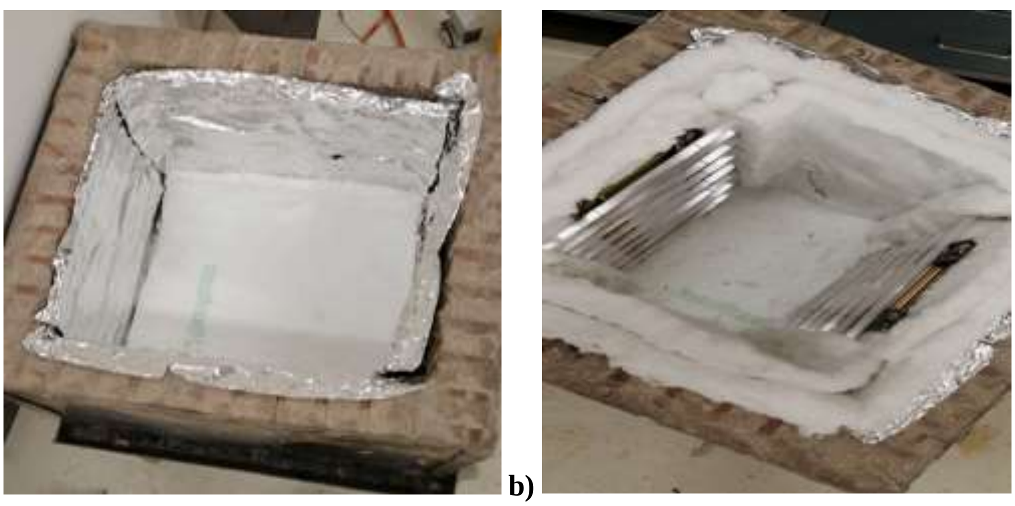
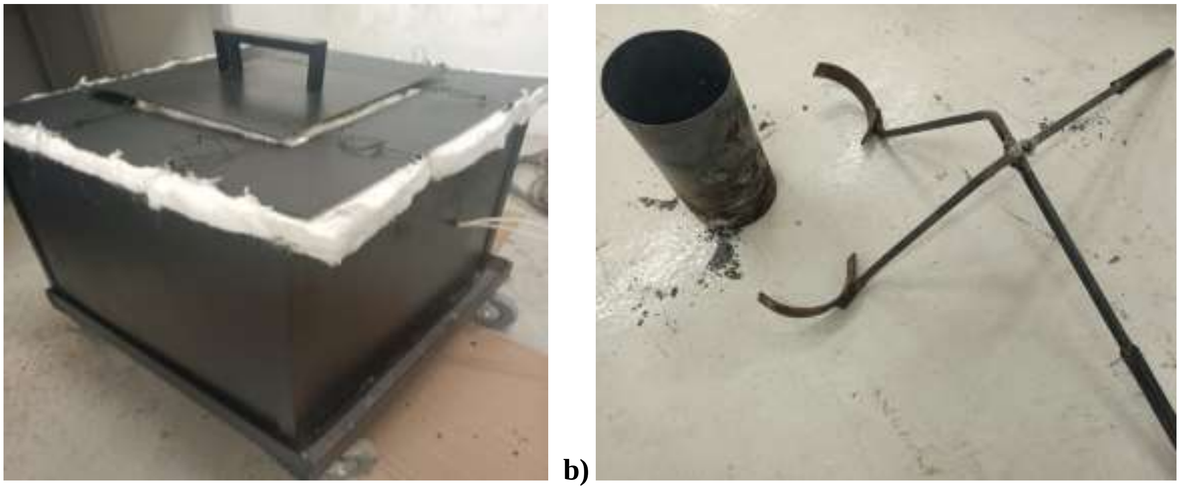


Figure (2). (a) Aluminum foil lining, and (b) ceramic fiber insulation and heating coil insertion.



a) b)

Figure (3). (a) The completed foundry, and (b) the crucible and the tongs.

3.1.5. Prototype Testing

Aluminum cans were collected, cleaned, and crushed. The foundry and crucible were heated up to 750 °C. Then, the crucible was removed and quickly loaded with the given mass of crushed aluminum cans for each run. Upon replacing the loaded crucible, the foundry temperature typically dropped to a little above 400 °C. The initial and final temperatures were kept similar for all runs. The temperature, voltage, and current were frequently recorded to estimate energy usage. Samples of 0.2 kg, 0.3 kg, and 0.4 kg of aluminum cans were tested. For these small samples, the amount of aluminum obtained was insufficient for pouring and there was excess oxidation. Another sample with 0.45 kg of aluminum cans plus 0.1 kg of NaCl was tested under the same conditions. The NaCl was added as an attempt to use a molten salt to improve fluxing of the aluminum oxide layer, to enhance heat transfer within the crucible, and to cover the melt to prevent oxidation.

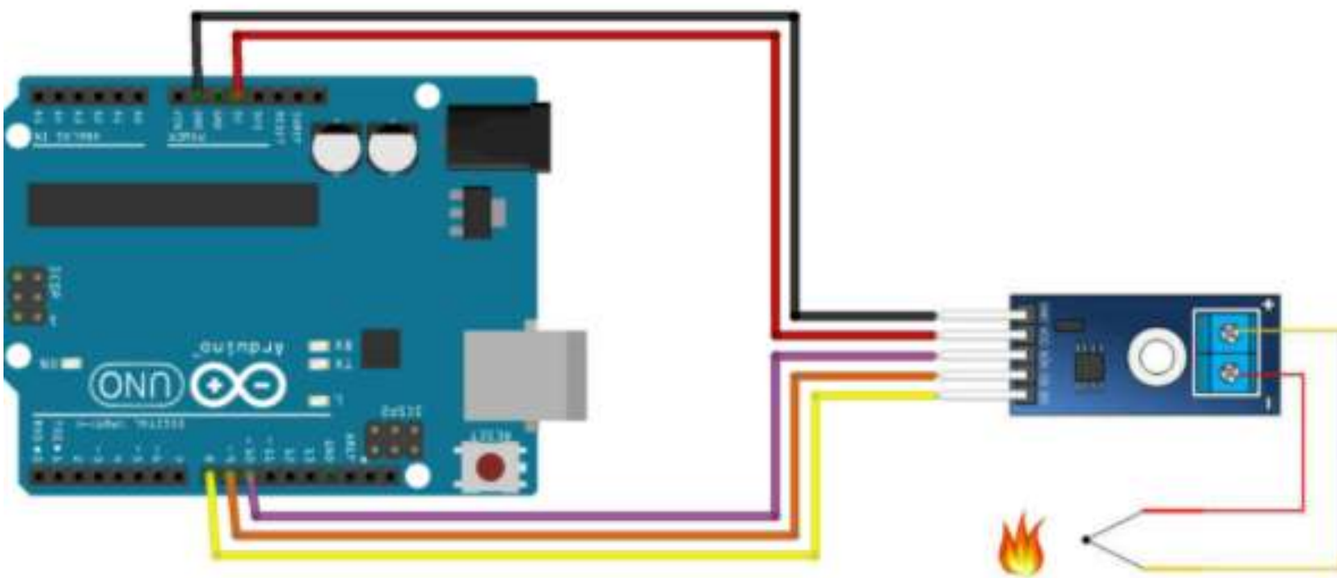


Figure (4). Arduino, MAX6675, and thermocouples circuit [23].

4. Results and Discussion

The recorded time, temperature, voltage, and current from the sample runs are shown in Table 1. To improve efficiency, the temperature was not allowed to drop below about 400 °C among runs. The voltage and current for each of the two sets of eight heating elements are shown. Each heating element was initially assumed based on their specifications and literature to ~2 A of current, which could have resulted in 16 A of current being drawing by each of the two sets of eight heating elements. However, the measured current turned out to be much lower, ~4 A for one set of heating elements and ~8 A for the other set. The lower current drawn could have been due to damaged, disconnected, or substandard heating elements. Nonetheless, the heating elements were able to heat the aluminum and crucible to a temperature higher than the melting temperature of aluminum in a short amount of time (~10 minutes). Note that there were several brief power outages that could have slightly extended the heating time.

For these small samples, the amount of aluminum obtained was insufficient for pouring, and there was excess oxidation. The aluminum cans appeared to form an oxide that prevented melting and consolidation. This lack of consolidation could also have been due to the small quantities of cans that were melted and the oxidized and did not allow the molten pure aluminum to separate as a liquid. Other researchers have also encountered losses of ~50% of the mass of the recycled cans due to oxidation [24]. In one run, 0.45 kg sample of NaCl was added as an attempt to use a molten salt to improve fluxing of the aluminum oxide layer, to enhance heat transfer within the crucible, and to cover the melt to prevent oxidation. However, the temperature achieved was insufficient to melt the NaCl, and the NaCl did not prevent oxidation. The NaCl did not exhibit a major effect on the melting process. Per equation (1), with a specific heat capacity of 0.88 kJ/kg, and a temperature change of 300 K, the 0.1 kg of salt would have added an insignificant amount, <0.03 MJ to the energy requirements. Therefore, the addition of the small amount of NaCl likely had little impact on the energy requirements or heating time.

The data were plotted in two different ways to evaluate the efficiency of the aluminum foundry. The experimental energy input (MJ) was computed by multiplying the average current (A) by the average voltage (V) as shown in equation (8) and then multiplying by time (s). The amount of energy used in each run is shown in Figure (5). As expected, energy usage increases with mass of aluminum melted. The y-intercept, 0.77 MJ, is noteworthy because this value indicates the amount of energy that would be required to heat the foundry even if no aluminum were present, ~0.77 MJ. Additionally, the slope from the linear fit, 3.44 MJ/kg, indicates how much energy would be needed to scale up the operation. For example, if 3 kg of aluminum were to be melted then ~11 MJ of energy would be needed to melt the aluminum, which is only 2 MJ more than the design calculations of 9 MJ required to melt 3 kg of aluminum derived in the Thermal Design section of this paper.

Table (1). Summary of the Experimental Data.

Mass of material (kg)	Time (min)	Temp. (°C)	V_1 (V)	V_2 (V)	I_1 (A)	I_2 (A)
0.2 kg Al	0	431	219	219	4.0	7.9
	1	458	219	220	4.0	8.0
	2	494	220	220	4.1	8.0
	7	676	221	219	4.1	8.1
	9	700	222	219	4.2	8.0
0.3 kg Al	0	420	223	219	4.1	7.8
	3	533	223	219	4.0	7.8
	10	813	223	219	4.0	7.8
0.4 kg Al	0	424	220	218	4.0	7.8
	8	609	223	220	4.1	7.9

	11	830	223	219	4.1	7.9
0.45 kg Al; 0.1 kg NaCl	0	550	221	212	4.2	9.2
	3	716	222	213	4.2	9.2
	5	740	222	213	4.2	9.3
	8	841	220	220	4.2	9.3
	14	850	220	220	4.2	9.3

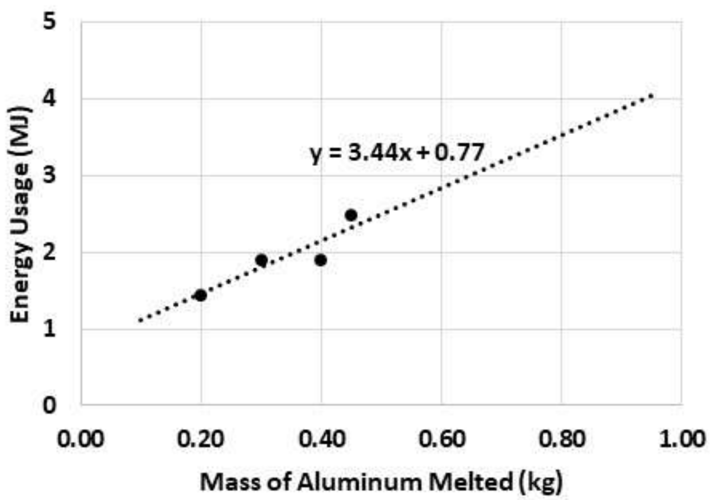


Figure (5). Experimental energy usage (MJ) vs mass of aluminum melted (kg).

The energy used for each run (MJ) was divided by the mass of aluminum melted in that run. As shown in Figure 6, the foundry became more efficient in terms of using less energy per mass of aluminum melted as the mass increased. For example, for masses of 0.2 kg or less, more than 7 MJ of energy was required, but for 1 kg or more aluminum, approximately 4.1 MJ/kg of energy would be required including the energy to heat up the foundry. There is a limit to how much energy efficiency can improve by increasing the mass melted because the line asymptotically approaches 3.44 MJ/kg. This experimental value corresponds well with the design estimate of 3.0 MJ/kg needed to melt aluminum derived in the Thermal Design section of this paper, showing that the assumptions and the calculations were accurately used for the design. Assuming 50% (by weight) of the aluminum could oxidize [24] during melting, the energy to produce pure aluminum metal could be ~6.9 MJ/kg, which agrees well with the 6-10 MJ/kg of aluminum melted theoretical estimate by other researchers [25]. Contrast this energy efficiency with the primary production of aluminum, 50 MJ/kg [25]. Thus, aluminum recycling is far more energy efficient than primary aluminum production.

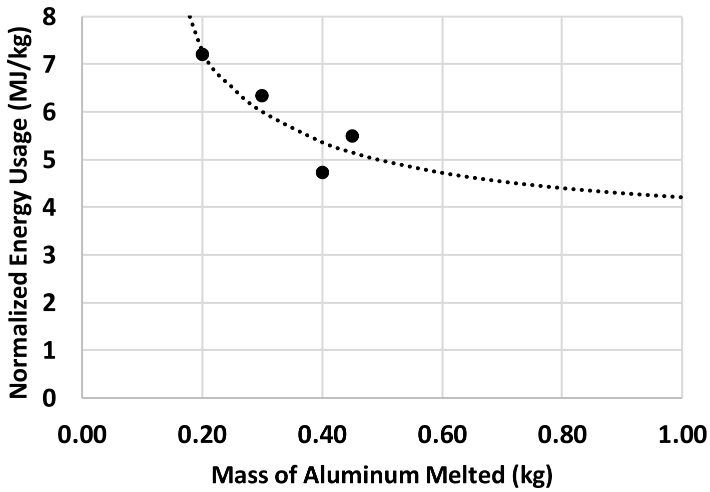


Figure (6). Experimental normalized energy usage (MJ/kg) vs mass of aluminum melted (kg).

4. Future Work

The temperature control for the foundry could be improved. Currently the temperature is manually controlled, which is undesirable. In the future, a proportional–integral (PI) or proportional–integral–derivative (PID) controller could be installed to improve energy efficiency and accuracy in achieving the target temperature. Design optimization algorithms, such as particle swarm optimization (PSO) could be utilized to improve the response, minimize steady-state error, and maximize controller stability. This controller would decrease the risk of overheating the components. The process could also be improved by reducing the oxidation of the aluminum cans which seemed to preclude the separation of the molten aluminum as a liquid. To do so, a flux could be used to enhance heat transfer within the crucible, consolidate the slag, and prevent oxidation. Mixed salts, such as binary or ternary mixtures of NaCl, KCl, and MgCl could be used since they are readily available in small quantities, and they have lower melting points than pure molten salts.

5. Conclusions

The main purpose of this project was to design and fabricate a safe and efficient electric aluminum foundry. The theoretical energy requirement calculations resulted in an estimate of 9.0 MJ required to melt 3.0 kg of aluminum in the foundry by considering the following:

- Energy required to raise the temperature of the aluminum and the crucible (3.1 MJ),
- Energy required to melt the aluminum (1.2 MJ),
- Heat lost due to conduction (2.6 MJ),
- Heat lost due to convection (0.5 MJ), and
- Heat lost due to radiation (1.7 MJ).

The prototype foundry was fabricated, with components including the outer shell, firebricks, aluminum foil liner, ceramic fiber, electrical heating elements, cover, lid, wiring assembly, and thermocouple. Experimental results using the prototype foundry were in good agreement with the theoretical calculations, showing only slightly lower efficiency of an extrapolated ~11 MJ required to melt 3.0 kg of aluminum.

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