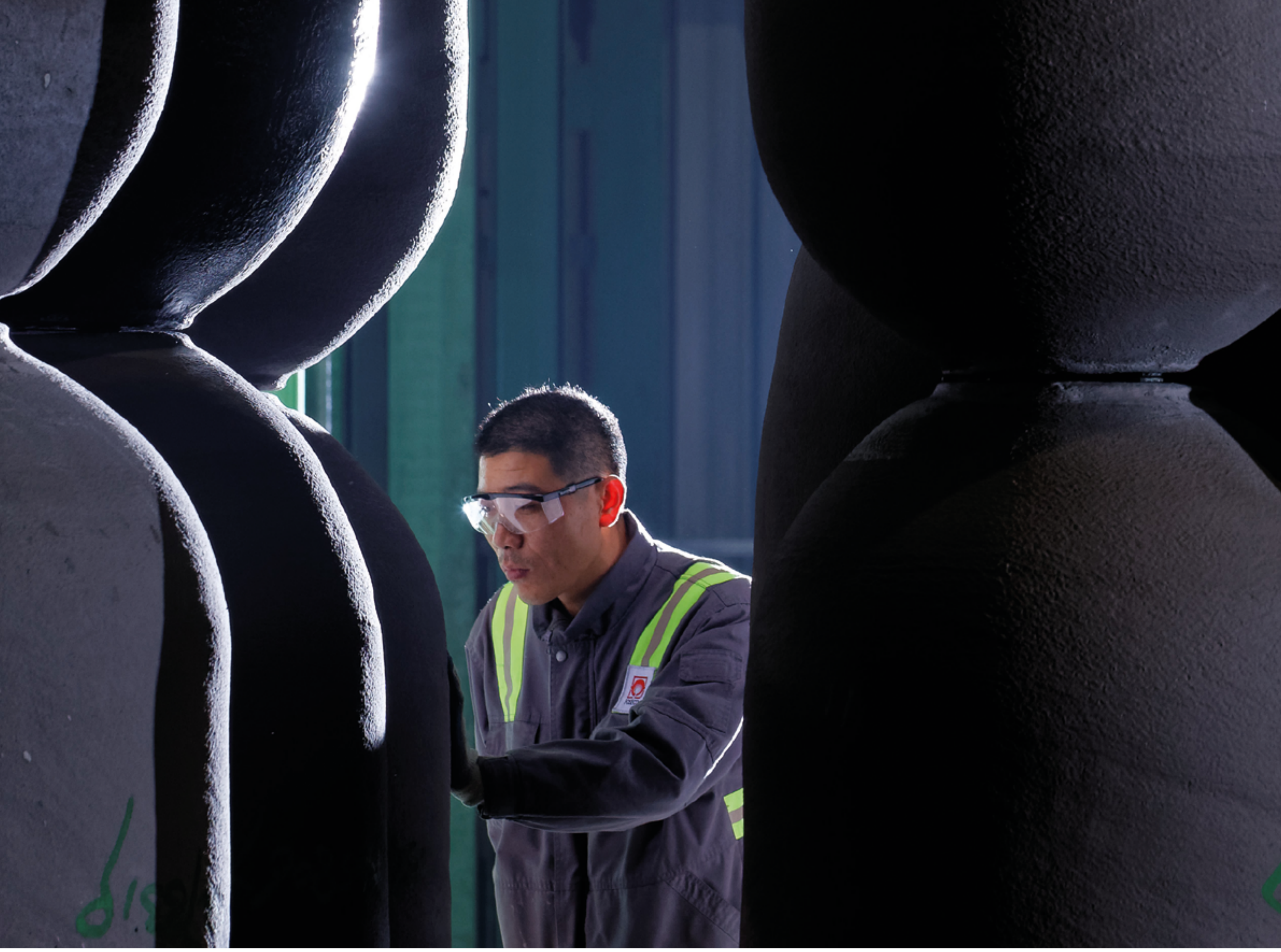

THERMALLY-EFFICIENT CRUCIBLE TECHNOLOGY: FUNDAMENTALS, MODELLING, AND APPLICATIONS FOR ENERGY SAVINGS

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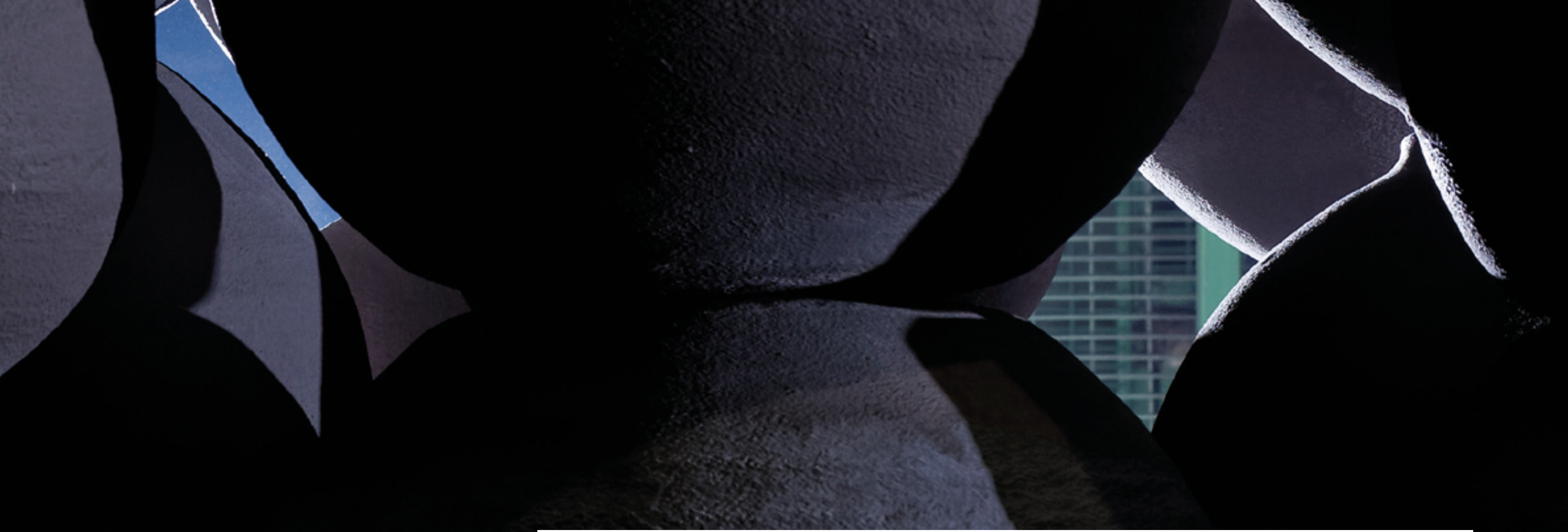
Multivariate mathematical models were created to simulate crucibles being used in aluminum foundry applications with detailed materials characterization data as inputs. The aim was to investigate the effects of crucible geometry and materials properties changes on the overall energy efficiency of the furnace toward melting and holding metal. Effects of key thermal properties were also studied to understand their influence on energy efficiency and thermal stresses, another key factor in understanding crucible behavior. Problems with evaluating these changes practically in foundries stems from the inability to separate out extrinsic factors that also affect furnace efficiency, such as unique configurations, furnace condition and, in some cases, poor operating practices. Since melting and holding metal in crucibles accounts for a large portion of energy demand in the foundry industry, recent advancements in crucible technologies resulting from these studies could significantly impact cost-efficiency and carbon footprint across the industry. In case studies of applications such as aluminum melting and holding, considerable improvements in field performance have been reported.



INTRODUCTION

The energy used for melting and holding metal accounts for nearly 40% of the total energy costs in a typical foundry [1]. Metal casting industries are known for high energy demands, low energy efficiency and high CO_2 emissions [2-4]. On average, the energy consumed by a foundry shop far exceeds that which it is predicted to use based on theoretical calculations [5-7]. This is due to inefficiencies associated with the activities of metal melting and casting; some are inherent to the process, while others are dependent on the types of equipment used as well as specific practices. There are opportunities to improve energy efficiency of a foundry operation, significantly reducing environmental impact while maintaining the sector's competitiveness in the process [8-10]. One of the most common methods used to melt metals is with an electric-resistance or fuel-fired furnace [11,12]. These furnaces contain molten metal at high temperatures within large refractory crucibles. To melt, energy from resistive elements or fuel combustion generated inside the furnace chamber against the outer crucible wall is directed to the metal charge inside and subsequently melts it [11,12]. Literature studies reveal that recommended energy-saving measures are to optimize the furnace configuration and/or improve its melting rate [13-16] with little or no focus on crucibles. If metal is molten, a well-insulated furnace expends only nominal energy to keep it at a set temperature, compensating for heat losses to the environment. However, to get to this point requires a tremendous amount of heat energy, not only to bring the metal to its liquidus temperature and melt it, but also to transmit that heat through a thick, high emissivity ceramic material having high specific heat capacity, all the while opposing the thermodynamic forces that favor carrying heat away to the atmosphere. The crucible is a physical barrier between the heat source and the molten metal, so it plays a pivotal role in determining metal melting efficiency. Thermal conductivity, specific heat capacity and geometry are the main factors, fixed quantities that govern heat transfer through a crucible.

This appears to provide convenient solutions for improving furnace energy efficiency. However, if one considers the many aspects of crucible and furnace use across the industry, the solution becomes more complex. For melting, fast heat conduction through a crucible is very desirable, whereas for holding, slow heat conduction is best. When a crucible is used for both melting and holding applications within the same furnace the challenge of creating a universally efficient crucible becomes more apparent. To add to this complexity, customer practices across the industry are so variable that even correlating a furnace's efficiency to its own crucible becomes extremely difficult. For example, if a furnace has poor insulation, then the effect of changing to a high-thermal-efficiency crucible will be completely clouded by the gross inefficiency of the furnace itself. This has been observed in many field tests. Although laws of thermodynamics predict improved performance, it does not play out this way in practice, making it very difficult to demonstrate an energy-saving crucible to a customer. Therefore, a better way to study and, to an extent, prove the effects of a crucible on thermal efficiency is to completely normalize the environment. In practice this is not possible; however, using theoretical modeling based on finite element analysis methods it can be done. This paper explores how heat flow behavior and energy efficiency can be studied based solely on changes made to the crucible material properties and design in 2D and 3D computer models, keeping the rest of the system constant. In doing so, the benefits of advanced crucible technologies start to become clear.

EXPERIMENTAL

Finite element analysis (FEA) was performed using ABAQUS 6.11 package with its heat transfer and temperature-displacement modules. A two-dimensional heat flow model was created based on the model for a typical bowl-shaped crucible (i.e. BU500) filled with 400 kg of molten aluminum. A three-dimensional model was based on a 100-kW electric-resistance crucible furnace, from which temperature and energy consumption data were derived. For simulation in the computer models, multiple crucible types were considered, including both carbon- and ceramic (clay)-bonded varieties. As with any computer simulation, to develop the most realistic model, reliable "real-world" data are needed to describe the materials being tested. From specimens of finished crucible refractory, many properties were measured, to include: bulk density, porosity, specific gravity, modulus of rupture (MOR), elastic (Young's) modulus, thermal conductivity, and specific heat capacity (Table I). Energy data collected from customer trials was done so using a custom energy monitoring device (FCTM-2, Foseco) capable of simultaneously monitoring energy usage and molten metal throughput on the furnace.

Property	Units	Temperature (°C)	Ref. ASTM standard
Bulk Density	g/cm^3	25	C830-00
Apparent Porosity	%	25	C830-00
Apparent Specific Gravity	-	25	C830-00
Modulus of Rupture	MPa	25; 800; 1200	C78-02
Elastic Modulus	GPa	25 - 1600	E1875-13
Thermal Conductivity	W/m·K	200 - 1000	E1461-13
Specific Heat Capacity	J/kg·K	200 - 1000	E1461-13

Table I. List of material property inputs for thermomechanical modeling of crucibles.

RESULTS AND DISCUSSION

A two-dimensional axisymmetric model was constructed for the express purpose of studying the effects changes to crucibles (i.e. geometry; refractory properties) have on heat flow and aluminum melting efficiency. The model assumes a continuous, uniform heat flux is applied to the outside of a crucible (Figure 1). The model also assumes the crucible is partially filled with aluminum, allowing the inclusion of radiative heat transfer from a molten bath surface and the inside upper wall of the crucible. Figure 1B shows the nodal temperature contours at 3970 s and 5470 s of the simulation, which demonstrate the temperature gradients within the aluminum and the crucible. Without metal against the crucible upper wall region to absorb the heat, it can end up superheated; heat can only be dissipated by radiation or downward conduction through the wall. This situation could lead to thermal shock cracks. Fortunately, the model is somewhat simplistic by assuming uniform heat flux; in an actual furnace the heating elements are typically shorter than the crucible is tall, which results in reduced heating of the upper wall.

While this does alleviate superheating problems, it tends to create the opposite situation – localized underheating, which leads to poor glaze protection, oxidation, and eventual thermal shock cracks anyway. The best practice is to use the furnace in a way that achieves a balance in these two phenomena; fill levels should be as high as safely possible to avoid steep temperature gradients along the crucible wall. On the underside of the crucible at the center (Figure 1B) is its lowest relative temperature because it heats up the slowest. Within the aluminum, the lowest temperature position is in the top center (Figure 1B) due to its distance from the elements combined with surface radiation heat loss. However, since aluminum thermal conductivity is much higher that refractory, the temperature gradient in the metal is much smaller than within the crucible walls.

Figure 2 shows results of a heating simulation focusing on the location identified as the lowest aluminum temperature position ('x' in Figure 1B) plotted versus time. As shown in Figure 2A, each curve has three distinct regions; temperatures rise very quickly in the first region (I) due to rapid heat conduction through solid aluminum. On reaching the solidus temperature (557°C) the slope decreases significantly due to the latent heat absorbed for fusion ($\triangle H_f$ = 398 kJ/kg), defining the second region (II). On exceeding the liquidus (613°C), the temperature starts to rise quickly again (III). Figure 2A also shows seven different plots, each of which represents the same simulation but with a difference in crucible material (A – F) with pure graphite (G) as a reference. This allows for the prediction of time required to fully melt a specific aluminum quantity as a function of crucible composition (Figure 2B). The process time ranged from 193 min to 234 min for refractory compositions (best to worst) and 154 min for pure graphite. The use of pure graphite in the model is solely as a theoretical upper limit for the graphite-containing refractory compositions (A-F). The reason for differences in the melt times for the refractory is related to several key properties, which, through proper development can be tailored to produce a more thermally efficient material. The two most influential properties in this case are thermal conductivity (k) and specific heat capacity (c). A high thermal conductivity means that heat transfer through a material is faster than through a material with a low thermal conductivity. Conversely, a material with high specific heat capacity requires more absorbed energy to increase its temperature than one with a low specific heat capacity. Table II lists the thermal conductivity and specific heat capacities for different crucible compositions.

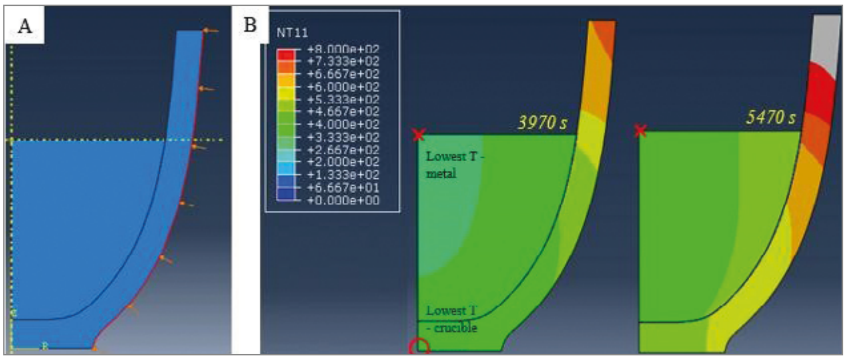


Figure 1. (A) Two-dimensional crucible model showing heat flux applied on the outside surface. (B) Temperature profiles of crucible and molten metal in different time intervals with energy-efficient mix (3970 s and 5470 s).

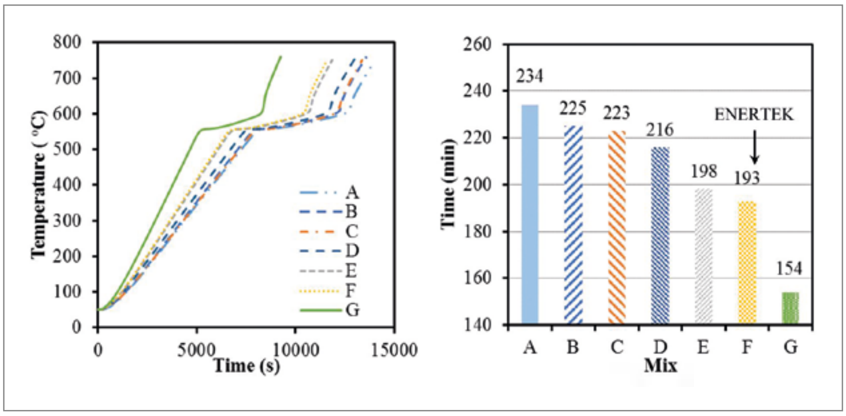


Figure 2. (A) Temperature profiles of the coldest point inside (highlighted in Figure 1) crucible with different compositions. Latent heat was set as 389 kJ/kg. Solidus temperature is 557ºC and the liquidus temperature is 613ºC. (B) Estimated time for the molten metal to be heated at 750ºC.

For Material A, thermal conductivity is low and specific heat capacity is high, resulting in the longest time required to melt the aluminum, and consequently the highest energy cost. Material B has the highest overall thermal conductivity but it also has a very high specific heat capacity; therefore, the melt time was only nine minutes less than Material A. Through R&D efforts to optimize these properties and maximize efficiency, melt times were reduced via Materials C, D and E. Eventually, Material F was developed, with high thermal conductivity paired with low specific heat capacity (branded as ENERTEK*). These properties, when entered in the thermal model predicted a 19.2% improvement in heating efficiency, melt time reduction of 41 minutes and energy cost savings of $8.02 per metric ton.

In addition to material properties, geometric features of a crucible, particularly shape and size, can be highly influential over its energy efficiency. Table III compares simulations of two different crucible configurations. One is a relatively small crucible with 181 kg capacity; the other is a much larger, crucible that can hold 816 kg of aluminum. By altering the crucible geometry and re-running 2D melting time simulations, it becomes evident that increasing the crucible size has a significant effect. As shown earlier, a change to a more efficient crucible material (from Material E to ENERTEK) alone results in a net energy cost reduction.

When applied to the small 181 kg crucible, the improvement is a modest 2.4% per MT. However, by making the material substitution and also increasing the crucible size to 4x capacity, the energy cost per MT of aluminum melted drops significantly from $8.02 to $3.23, a 61% reduction. This is because the mass ratio of crucible to aluminum changes significantly such that more total energy is used melting the aluminum than heating up the crucible. The absolute masses of refractory and metal are higher in the larger crucible; therefore, the total time to melt increases to 351 minutes, but the overall melt rate is increased from 0.91 kg/min to 2.32 kg/min, an increase of 154%. To melt the equivalent mass in the smaller crucible would take at least 2.5 times as long to achieve, not including recharging and melt transfer time. It is true a smaller crucible can melt a lesser amount of aluminum faster, so depending on the throughput of a foundry a smaller crucible may be beneficial to prevent wasted energy (keeping a large crucible molten until the excess metal is completely consumed). For melting large quantities of aluminum, a large crucible is more energy efficient on a cost-per-kg basis, but it does take longer; time has associated costs as well.

As with most efforts to improve properties, there are limitations and trade-offs. Since crucibles are subjected to a wide range of temperatures and the rate of change ($\triangle T$) can vary greatly, thermal stresses are inevitably generated within the material during use. Cracking failure and/or reduced longevity are both effects of thermal stresses, since refractory materials possess limited ductility. While seeking improved thermal efficiency through material changes, the intensity of the residual stresses could be unknowingly increased such that the crucible simply cannot survive the application. Fortunately, another useful feature of the modeling software permits simulation of thermal stresses as a function of material properties, crucible geometry, and temperature. Along with measured mechanical and physical properties data already entered into the model, temperature profiles from actual heating cycles of various crucibles were also collected with a datalogger.

Material	Thermal Conductivity (W/m·K)		Specific Heat Capacity (J/kg·K)		Time to Melt (min)	Total Energy Use (kWh)	Cost ($/MT)
	at 200°C	at 600°C	at 200°C	at 600°C			
A	7.42	6.69	1200	1892	234	103.5	9.72
B	57.03	42.05	1169	1553	225	99.5	9.34
C	29.33	22.45	1330	1790	223	98.6	9.27
D	31.73	20.86	840	1384	216	95.5	8.97
E	27.92	23.41	891	1316	198	87.5	8.22
F (ENERTEK)	43.06	35.82	825	1133	193	85.3	8.02
Graphite	175	171	710	710	154	68.1	6.39

Table II. Physical properties of different crucible compositions with model-predicted total melting times, energy consumption, and associated costs.

Material		Thermal Conductivity (W/m·K)		Time to Melt (min)	Melting Rate (kg/min)	Cost ($/MT)
		at 200°C	at 600°C			
E	181	27.9	23.4	198	0.91	8.22
F (ENERTEK)	181	43.1	35.8	193	0.94	8.02
F (ENERTEK)	816	43.1	35.8	351	2.32	3.23

Table III. Comparison of melting time and energy cost for crucibles with different capacities.

Using this added information, thermal stress states could be predicted using the temperature-displacement model in ABAQUS.

Figure 3 shows an example of the information gained through the computer model. A crucible made from a traditional refractory (Material E) experiences a maximum thermal stress of 15 MPa during heating.

By changing the crucible to a thermally efficient composition (ENERTEK), the maximum thermal stress is reduced significantly, to 8.8MPa. In this situation, efforts to improve thermal efficiency also lowered the thermal stress, but this is not always the case. To illustrate this point, consider the earlier assertion that using a larger crucible is better because thermal efficiency is much higher. This is true but with an increase in crucible diameter size, so does the distance between the lowest temperature location in the crucible bottom (Figure 1B) and the heating elements. This longer conduction path through the crucible results in a larger temperature gradient in the crucible wall, which generates higher thermal stresses.
Shown in Figure 4, a 1055-mm-OD crucible has a much higher thermal stress (15.8 MPa) compared to one with a 655-mm-OD (8.9 MPa). The high stress approaches the strength of the crucible refractory itself. For this situation, to achieve high thermal efficiency of large crucibles without exceeding the material design stresses, it is necessary to utilize thermally efficient compositions where high thermal conductivity helps to reduce temperature gradients and, in so doing, thermal stress.

Two-dimensional modeling allows the rapid calculation of energy efficiency and the study of different compositional effects; however, it is an oversimplification of a vastly more complicated system, neglecting

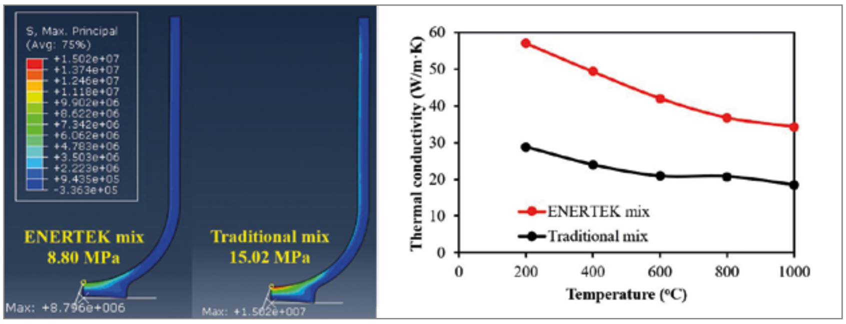


Figure 3. (A) Comparisons of thermal stress for large crucibles with traditional and thermally efficient mix compositions. (B) Comparison of thermal conductivities for two different crucible materials.

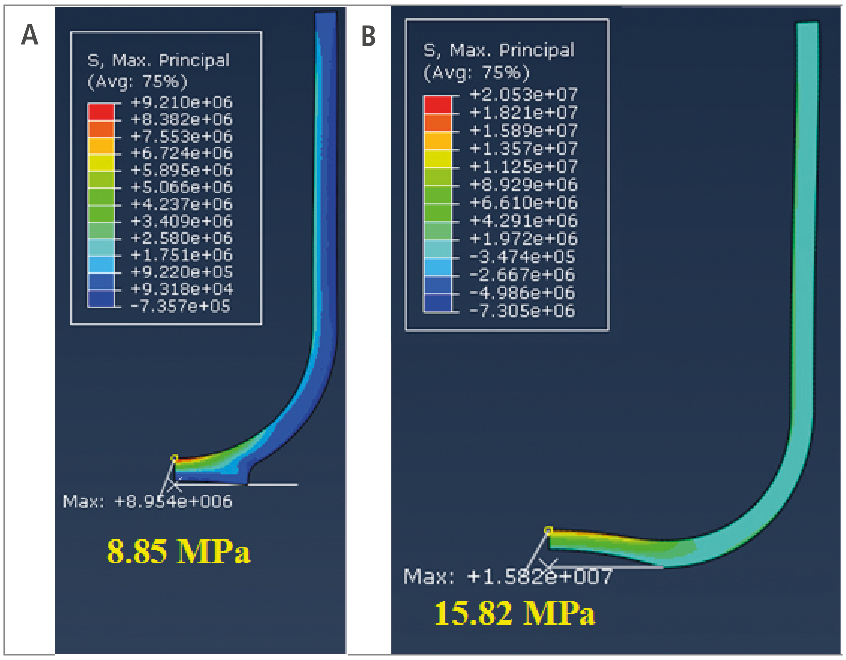


Figure 4. Predicted maximum thermal stress in crucibles with different dimensions. (A) 615 mm OD and 900 mm height, and (B) 1055 mm OD and 1100 mm height. Deformation scale is 100.

several important features and behaviors of an actual crucible furnace. The configuration and position of the electric furnace heating elements is not well-defined in the 2D model- a constant surface heat flux is not very realistic. This type of accuracy is very difficult to achieve since most crucible furnaces operate around a temperature set point not unlike a thermostat. Thus, the heat flux experienced by the crucible exterior is more cyclic in nature, with high and low temperatures bracketing the set point (Figure 5). Furthermore, the heat source isn't a continuum around the crucible, but rather discrete element blocks with a finite size and location in the furnace. To better simulate this, an improved three-dimensional model based on a typical electric resistance furnace was constructed.

Figure 6A shows twelve (12) heating panels distributed around a crucible. Figure 6B shows the meshes used for 3D modeling. Since symmetry still exists within the furnace, one 30-degree segment was modeled using dimensions scaled to an actual furnace, taking into consideration the crucible, aluminum, heating elements, and insulation. As mentioned earlier, the heat flux from the elements is not constant. Figure 6C (black line) shows the actual power consumed by the furnace measured with a data logger. By considering the power factor, the input to the model was calculated (red line) to closely simulate the actual case.

The energy was input as body heat flux into 11 rows of tubular elements. Six different heat transfer scenarios were considered for the model:

1. Body heat flux input to heating elements that converts to radiation.
2. Radiation heat from heating elements projecting onto the crucible exterior.
3. Conduction heat transfer between heating elements and the block insulation.
4. Conduction heat transfer between the crucible and the aluminum.
5. Radiation heat transfer between insulation and the outside of the crucible.
6. Radiation heat losses from the melt surface and top of the crucible.

Figures 7A and 7B show visualizations of the model with colors representing component temperatures (red >> blue) at 1 hr and 2 hrs, respectively. In this time, the heating elements reach very high temperatures, especially toward the bottom and at the element edges.

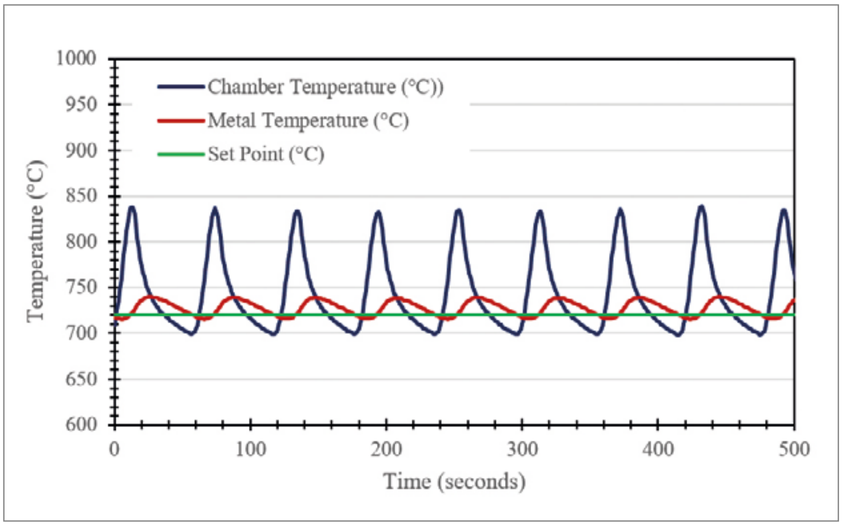


Figure 5. Plots of temperature versus time on a 100-kW electric-resistance crucible furnace, showing the cyclic nature of the heating and cooling (metal and chamber versus fixed set point = 720°C).

This is because their distance to the crucible is larger in these areas, which reduces radiative heat transfer rates.

Like the two-dimensional model, a temperature relative minimum is at the bottom-center of the crucible, where the differential can be as high as 300°C. Figures 7C, 7D, and 7E show similar temperature contours when the aluminum (coldest location) is at 500°C, 600°C, and 700°C. Rather than repeating the studies performed using the 2D model, it was decided to use the 3D model to study other aspects of crucible geometry with respect to melt time. Crucibles were modeled after designs comprised of high-efficiency refractory material (ENERTEK). Then, based on the geometric design changes, their energy consumption and theoretical efficiency were calculated and compared. The first was a standard crucible design but the subsequent models were that of a similar shape but with increasingly thinner wall cross-sections (larger ID). Figure 8 shows a plot of the lowest temperature location in the melt (circle in Figure 7) for both crucibles as a function of time. Figure 8B lists predicted characteristics of both crucibles; 'efficiency' is the ratio of energy used for heating and melting the metal to the total energy expended (x 100%).

This exercise reveals that changing the crucible dimensions has an increasingly significant effect of reducing the mass of the crucible while the volume of aluminum (capacity) has increased. Although there is little change to the melting time, the overall energy use is reduced per kg of aluminum. For this system the maximum melt rate is increased 15% from 1.25 to 1.44 kg/min. For the same amount of energy expenditure by the furnace, more of it is directed to the metal due to the lower refractory mass to absorb it. This increases the efficiency from 65.8% to 72.4%. Over the long-term this can add up to a significant amount of savings. It should be noted that to perform the same simulation using data from a typical crucible material, a similar trend would be observed, albeit to a lesser extent in the absence of the higher efficiency crucible material.

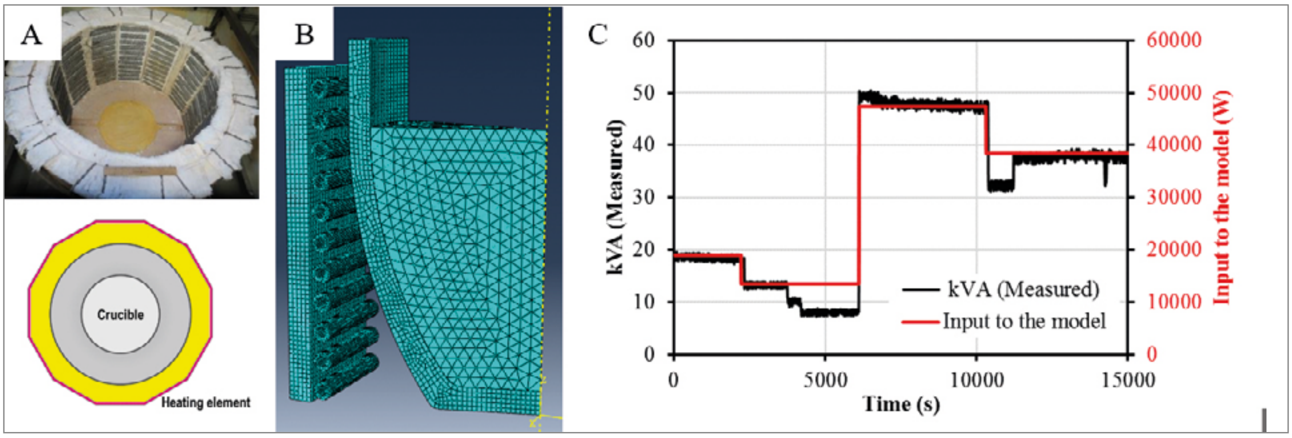


Figure 6. (A) Photo showing the distribution of 12 elements (dodecagon). (B) Meshes showing the insulation panel, heating elements, crucible, and aluminum melt (30o model with 39723 nodes and 35122 elements). (C) Energy consumption measured using an energy meter (kVA) for a typical melting cycle and estimated input to the finite element model.

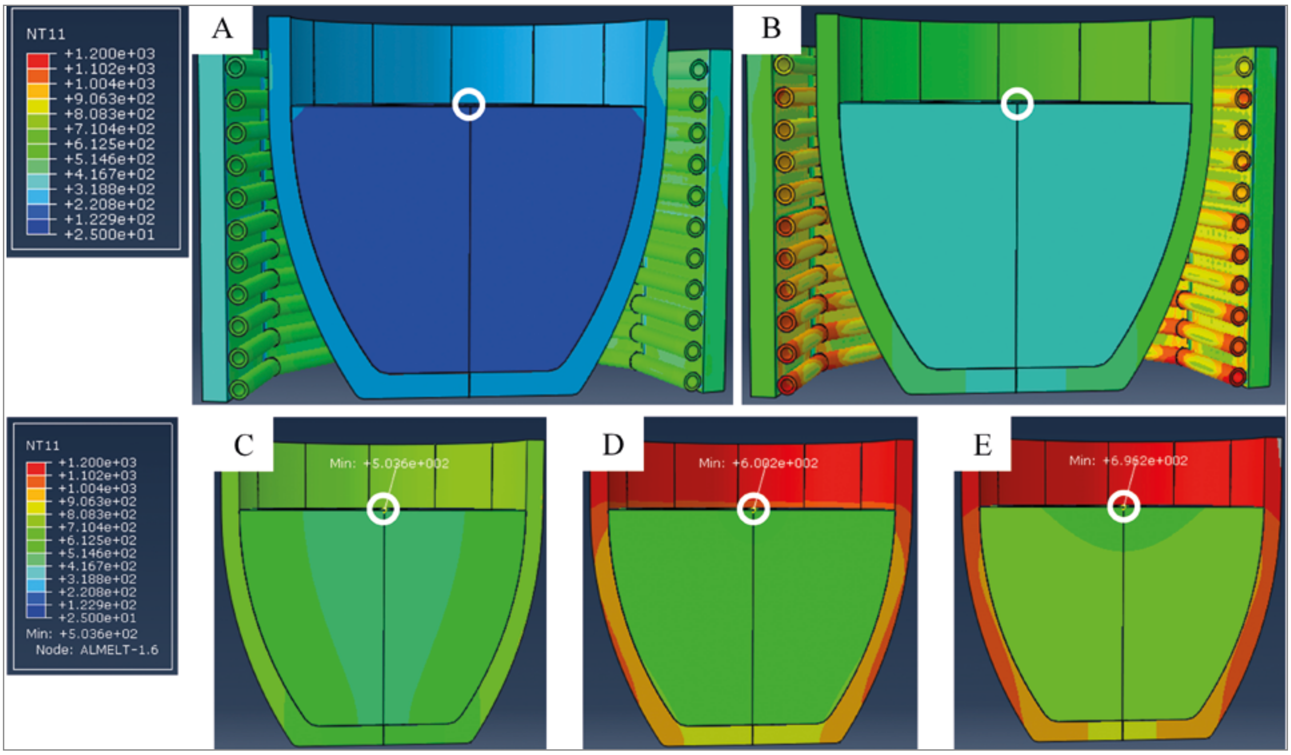


Figure 7. Simulated temperature profiles inside an electrical resistance furnace after (A) 1 h and (B) 2 h. Temperature of isolated crucible and aluminum when nodal temperature (circle) is (C) 500°C, (D) 600°C, and (E) 700°C.

From these simulations it is clear that by utilizing a thermally efficient crucible material coupled with a lower mass/larger capacity design, the melting of aluminum can be done in a more energy-conscious manner. The next logical step was to validate results produced by the simulations. An ENERTEK crucible with reduced mass and increased capacity was manufactured for a special trial at a US foundry. The application was manual sand casting from two near-identical electric resistance furnaces. Furnace use was such that both were filled but only one was used at a time; therefore, one furnace was always holding while the other was being used to cast. What made this a particularly good trial site was that both furnaces were being used for the same operation by the same operators, providing the best chance at minimizing uncontrolled variables while still in an industrial setting. Additionally, both furnaces were only used one shift (8 hrs/day) and then idled for the remainder of the time. This presented an opportunity to collect energy consumption during many different modes of furnace operation.

Throughput of the furnace was accurately measured using a custom crucible energy/throughput monitor capable of constantly measuring energy use and able to keep track of the amount of metal cast per day. This allowed for normalization of energy results to the quantity of aluminum cast. Based on an experiment spanning a six-month period where a standard competitor crucible was compared to an energy-efficient ENERTEK crucible (Figure 9), energy savings during casting was on the order of 20% in favor of the energy-efficient crucible (764 kWh/MT vs. 605 kWh/MT).

While holding the total energy use was also reduced, by 14% (30.4 MWh to 26.0 MWh). Extrapolating from this study, it is estimated that for a single furnace in constant operation, the annual potential energy savings could be as high as 26 MWh, or $2500 in electricity savings per year (est. $0.08/kWh). This also translates to a reduction of 16,573 kg of CO_2 emissions per furnace per year. In a foundry that utilizes many furnaces, the total savings could be quite substantial.

SUMMARY AND CONCLUSIONS

Using traditional evaluation methods, uncontrolled field trials, or simple energy comparisons, it has proven very difficult to justify changing to an energy-efficient crucible. Almost always the benefits are obscured in the presence of other foundry practice-related variables that detract from equipment efficiency. Were the foundry to eliminate or minimize these issues; often it is something simple like replacing deteriorated insulation, keeping the furnace lid closed more- the benefits of an energy-saving crucible would become more obvious. With theoretical modeling it is possible to eliminate these variables from the equation- to estimate differences in energy efficiency directly influenced by changes made to crucible geometry and composition, as well as gain insight as to the limits to which these features can be changed to support energy-saving initiatives. It is critically important not to neglect considering how changes to composition and/or geometry will affect the stress state of the crucible, particularly as a function of temperature. Fortunately, with a nominal amount of additional information, these conditions can be simulated in a computer model as well. With the ability to understand the characteristics and thermal behavior of crucibles to a degree that is relatively unexplored, new materials were developed that not only showed high promise in the theoretical realm, but also showed definite improvements when applied to an actual crucible in a real foundry operation under close surveillance where actual data collected was able to validate the computer models. Extrapolating this achievement across an entire foundry's operation could have large implications with respect to increased energy savings, minimizing carbon footprint and reducing overall costs of operation.

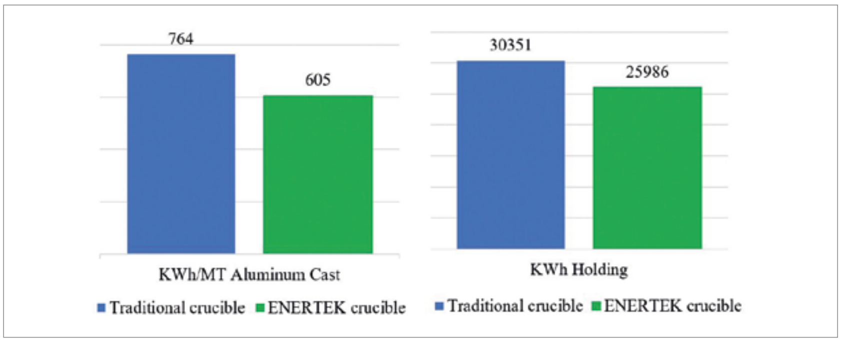
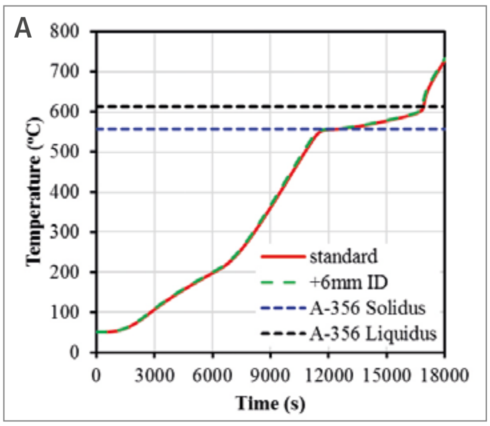


Figure 9. Energy consumption for two different type of crucibles, traditional and thermal efficient mix with reduced ID used for (A) Casting furnace and (B) Holding furnace for a 6-month testing period.



B	ENERTEK mix			
Wall Thickness	**(43 mm)**	**(37 mm)**	**(31 mm)**	**(25 mm)**
Crucible Mass (kg)	173	157	132	111
Al Mass (kg)	353	366	379	403
Melt Time (min)	282	280	279	279
Melt Rate (kg/min)	1.25	1.30	1.36	1.44
Energy Use (kJ/kg)	1461	1400	1341	1264
Efficiency (%)	65.8	68.7	71.6	72.4

Figure. 8 (A) Temperate profiles for the standard crucible and crucible with increased ID. (B) Comparison of weight of crucible, weight of Aluminum, and melt time, energy consumption, and theoretical efficiency as a function of refractory wall thickness.

These concepts are constantly being considered by foundry owners and managers; with the help of these and other evaluation tools they can begin to understand that something as unassuming as a crucible can have a significant impact on their bottom line.

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