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Efficiency in Steel Melting: Ladle Development

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Abstract

Effective ladle design and use is important for steel casting production. In foundry operations, the ladle temperature of the liquid steel is typically 150 to 250°F above the steel's melting point to compensate for the heat losses in small ladles and the associated high cooling rates from the large surface area to volume ratios. Higher superheat is also necessary to provide sufficient steel fluidity to properly fill the mold cavity. In spite of the relatively short time that the steel is in contact with the ladle lining, the huge thermal gradients in the lining drive high values of heat flow through the refractory surface.

Heat transfer between the melt and the ladle lining as well as the associated heat losses in foundry linings are analyzed in this paper. Initial information was taken from a survey of steel foundries and from industrial measurements at seven foundries. Temperature measurements were done with thermocouples and infrared cameras. Fluent software was used for modeling unsteady heat transfer in ladles. The influence of the thermal properties of different ceramic materials typically used for steel ladle linings on heat losses during use was analyzed.

A novel class of ladle linings being developed at UMR based on porous ceramics has the potential of significantly decreasing the heat losses during use in addition to saving considerable ladle preheat energy. This paper reviews progress in developing and testing these linings.

Introduction

Foundry ladle operations require special ceramic lining materials. These materials need to meet the following requirements:

- chemically inert to melt and slag for prevention of lining erosion and alloy contamination
- thermal properties that minimize the heat losses from the steel melt
- mechanical properties for prevention of failure from impact of the tapping stream and thermal cracks
- easy to install lining in a way that results in consistent properties

The temperature of the liquid steel at tap typically varies between 2950°F to 3200°F. These temperatures are close to the softening temperature of the complex *Al*, *Ca*, *Si*, and *Mg* oxide compounds which are often used for ceramic linings. Also, the high rate of chemical reactions between the lining and components of the liquid steel and slag takes place at these temperatures. As a rule, foundry ladles are used in unsteady thermal conditions and are far from steady state heat transfer. Even in cases where the lining is preheated prior to tap, a significant part of the heat energy in the liquid steel accumulates inside the lining during the first 5-30 minutes after tap. Unsteady heat transfer typically takes place during the entire time that liquid metal is in the ladle for all types of foundry alloys, but the rate of soaking by the lining dramatically increases when the temperature of the melt rises from aluminum and copper alloys to irons and steel (Table 1).

Table 1. Comparison of calculated rate of heat flow (KW/m^2)
from liquid alloys to the ladle lining after tap

Aluminum	Copper	Iron	Steel
39	73	113	137

As a result of the high rate of heat soaked into the ladle lining, the total temperature losses during tapping and pouring of steel are typically 250-300°F. High tap temperatures are required to compensate for the large temperature losses. Unfortunately, the energy efficiency during the period of superheating the liquid metal for tap is significantly lower than the earlier periods of heating and melting solid charge materials. For example, the typical operational energy efficiency of a 2000 lb. capacity induction furnace during heating and melting of solid charge materials is 70-80%. However, the efficiency drops to 30-40% during the final period of superheating the liquid steel to the tap temperature. As a result, the extra superheat required to compensate for temperature losses in ladle increases energy consumption in geometrical proportions.

This paper describes a foundry based study of thermal losses during liquid steel transfer and handling and summarizes measurements and computations of energy losses in foundry ladles with different ceramic linings. The work is based on data collected from 19 different foundries, eight industrial trials and several experiments performed in the research laboratories at the University of Missouri-Rolla.

Methodology

Experimental measurements, statistical data, and calculations of heat transfer between the melt, lining, and air were used for evaluation of heat losses during steel tapping, holding, re-ladling, and pouring at steel foundries which used both induction (IF) and electric arc (EAF) furnaces.

Experimental measurements in steel foundries. During industrial observations, detailed thermal data was generated and collected from three to five typical heats at each plant. Frequent temperature measurements were done with immersion thermocouples and an infrared camera (Snap Spot, Infrared Solutions Inc.) capable of measuring surface temperatures up to 2400°F. The data collected included:

- the ladle's preheat procedure
- temperatures on the outside steel shell and inside refractory of ladles before tap
- melt temperature history from tap to pouring

Survey data. In addition to the detailed data collected during the foundry trials, information was collected from the surveys of 19 steel foundries. This data included:

- type of lining materials
- ladle sizes
- temperature profiles

Ceramic materials. Thermal properties of three commonly used castable alumina lining materials (ceramics 1 through 3) are given in Table 2. Equations for the thermal conductivity coefficients were derived by fitting curves through experimental data provided by refractory suppliers. All three of these linings were greater than 80% Al_2O_3 but had different densities and therefore different values of heat conductivity coefficients. Typically, these types of ladles are used in the preheated condition with inside surface temperatures up to 2000°F. A fourth type of ladle lining investigated was a low density ceramic based on magnesia (ceramic 4). This type of low density ceramic is typically manufactured as pre-formed crucibles for ladles with a capacity less than 1000 lbs or as boards for fabricating the lining of larger capacity ladles. These materials are typically disposable single use (or limited to a small number of heats) working linings and are surrounded by a 1-3" layer of dry sand as the backup refractory. These are typically used "cold" (without preheating). The value of the thermal conductivity coefficient for this type of lining was determined through measurements made with thermocouples imbedded at the lining-sand interface during experiments at UMR using a 100 lb ladle of steel. A new extra low density porous ceramic is being developed at UMR (ceramic 5) and will be described in more detail later in the paper. Table 2 contains estimated properties of this ceramic for comparison to existing materials already in use in steel foundry ladles.

Table 2. Thermal properties of lining materials

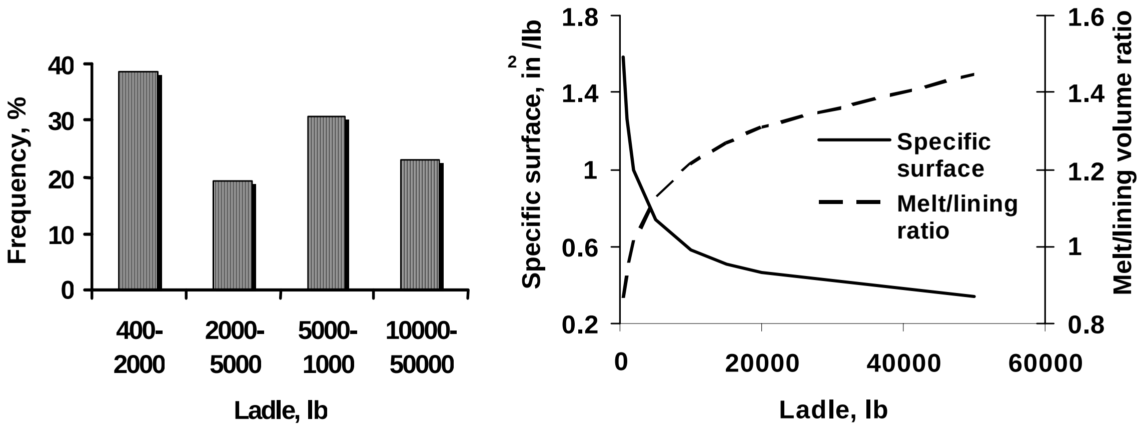
Ceramics	Type	Heat conductivity coefficient, W/mK		Density, kg/m^3
		Equation	Average	
1	Alumina (castable)	$4.1929-0.0033K+(1E-6)K^2$	2.0	2510
2	Alumina (castable)	$4.0186-0.0028K+(1E-6)K^2$	2.4	2880
3	Alumina (castable)	$4.9825-0.002K+(5E-7)K^2$	3.5	2900
4	Magnesia (boards)	$1.164-0.0004K+(2E-7)K^2$	1.0	1400
5	Alumina (porous)	$1.5915-0.0013K+(4E-7)K^2$	0.8	700-800

Heat transfer calculations. Heat transfer calculations were performed using commercial computation fluid dynamic software (FLUENT). Unsteady state heat transfer in the ladle was calculated using the following boundary conditions: coupled boundary between melt and lining, air convection from the steel shell, and radiation from the top melt surface while taking into account the thermal conductivity of the slag layer on the top surface. In addition, temperature losses during the tap of the melt from furnace to ladle were evaluated while taking into account the radiation from the stream surface and the intensive soaking of the lining during tapping (from 1 to 3 minutes depend on ladle size).

Experimental data

Foundry survey

Figure 1a illustrates the variation in capacity of steel foundry ladles currently in use. Capacity ranges from 400 to 50,000 lbs. The smaller the ladle, the higher the lining surface area per lb of melt (in^2/lb). This is important because heat transfer is directly proportional to the surface area. For example, small ladles (<1000 lbs) have 5 times the surface area per ton as large ladles (>20,000 lbs) and therefore would experience 5 times the rate of temperature loss under similar ladle conditions (tap temperature, preheat, refractory materials, etc.).



a) Distribution of ladle size b) Influence of ladle size on lining surface area

Figure 1. Distribution of steel foundry ladle size and influence on lining surface/melt weight

Total pouring time in steel foundries varies between 5 minutes and 30 minutes and generally increases with ladle size (Figure 2). Typically, foundries using re-ladling result in longer pour times. In these cases, the heat is tapped from the furnace into larger transfer ladles and then tapped into smaller 500 – 2000 lb pouring ladles.

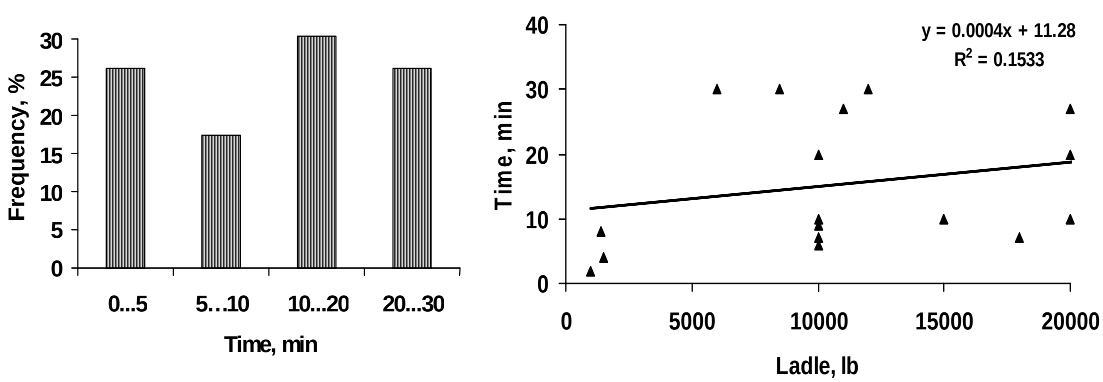
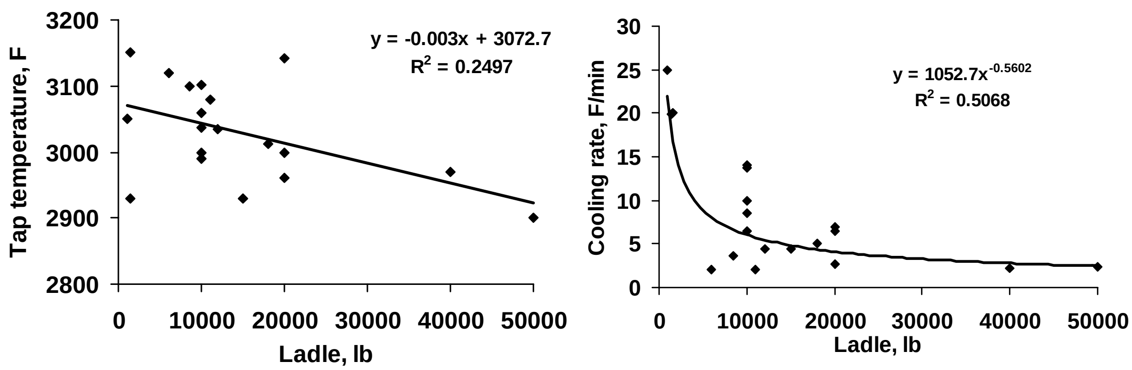


Figure 2. Statistics of pouring time in steel foundries

There are different types of ladles used in foundry practices. Typically, small ladles, also called shank ladles, are top poured and have a simple cylindrical shape that require the slag to be removed before pouring. Usually, medium size ladles (5,000 lbs to 20,000 lbs) are of the teapot shape. This type allows for the clean metal to be poured from the lower portion of ladle, while the melt surface can be partially covered by slag or a special lid. Teapot ladles are also often used as transport ladles. Large bottom poured ladles are used for direct pouring of heavy castings. There are two possible types of bottom poured ladles that are used in steel foundries. The first one uses a stopper rod which is placed inside the ladle, while the second one uses a slide gate which is attached to the ladle bottom. It is important to note, that when ladle with a stopper rod is used, the stopper rod is installed after preheating. The temperature of the internal lining surface typically drops from 1800-1900°F to 1200-1400°F during the stopper rod installation. Alumina is often used for the lining of steel ladles (thermal properties in Table 2). Acid silica linings and fired bricks are seldom used today and therefore, were not analyzed in this paper.

Statistical data of the tap temperatures and the cooling rates in the ladles are presented in Figure 3. In spite of the different steel foundry practices, ladle capacity was the main factor that influenced the heat losses. However, there was a large variation in the the cooling rates of similar size ladles. For example, the cooling rates of 5 tons ladles varied from 3^{o}F/min to 15^{o}F/min depending on the holding time, type of lining, and the preheating practice.



a) b)

Figure 3. Effect of ladle capacity on a) tap temperature and b) rate of temperature loss

Examples of industrial practices.

Case 1. The foundry melts medium carbon and low alloy steels in a 5 ton capacity EAF. Typically, the tap temperature is 3100°F. The melt is tapped from the EAF to an 11,000 lb. alumina lined teapot ladle which was preheated to 1955°F. Then the melt is re-ladled into a 1000 lb. shank ladle with a lining consisting of low thermal conductivity magnesia boards surrounded by dry sand (ceramic 4 in Table 2). This ladle was used for pouring medium and small size castings. The example of the temperature losses during the tap in the teapot ladle and the re-ladling are given in Figure 4. During the 30 minute pouring time, the total temperature loss was 280°F to 300°F. The infrared images of the teapot and shank ladles with liquid steel are also given in Figure 4.

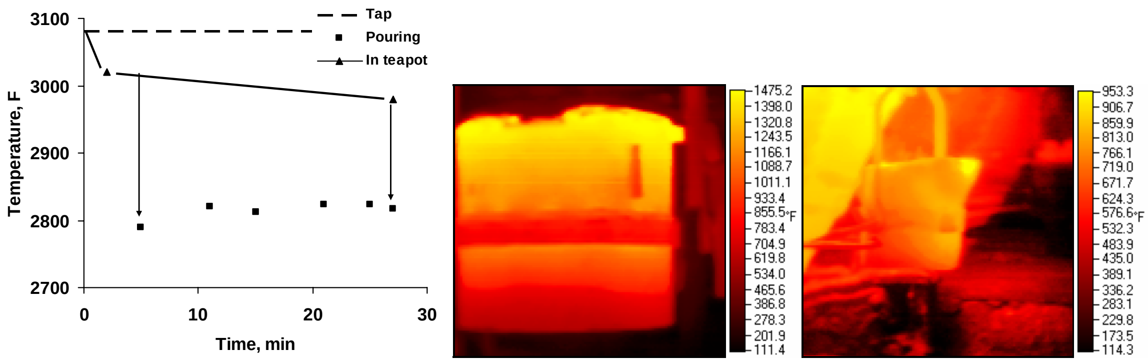


Figure 4. Temperature losses of steel tapped into alumina lined 11,000 lb capacity teapot ladle preheated to 1955°F and re-ladled into cold 1000 lb capacity shank ladle made from low density magnesia lining

Case 2. The foundry melts medium carbon steel in a 5 ton capacity EAF and taps into teapot ladles lined with alumina castable and preheated to 1900°F. In order for the foundry to produce small size castings, the steel is re-ladled simultaneously into two small 400 lb. ladles. In contrast to Case 1, the small ladles used an intensely preheated silica lining. Also, special lids were used to cover these ladles (Figure 5c). The total temperature losses are just under 200°F (Figure 5a). A short pouring time of 2-3 minute per ladle and heat saving lids significantly decreased the melt temperature losses in comparison to Case 1.

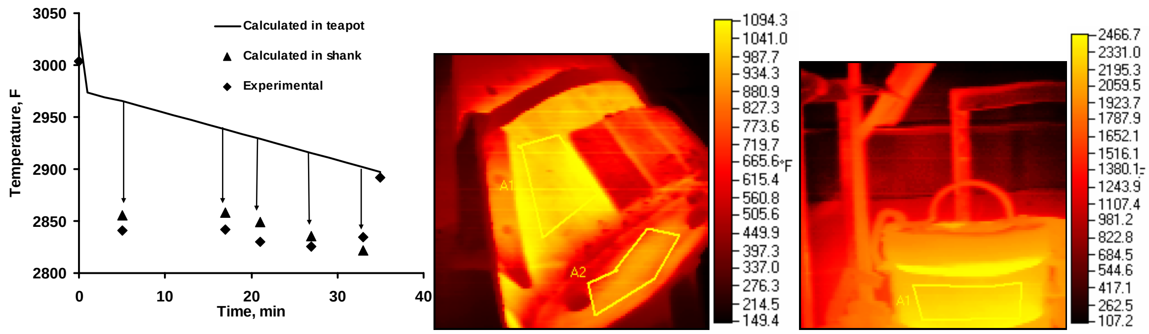


Figure 5. Temperature losses during tap in a 12000 lb. teapot ladle and re-ladling into a 400 lb shank ladle with lid

Case 3. Heavy castings are poured in this foundry using 20,000 lb bottom poured ladles. These ladles have a 5” castable alumina lining and an additional 1” outside layer made from firebrick. The ladles are intensely preheated to 2100°F for 4-6 hours before being used. The melt is stirred by argon for 5-15 minutes during holding and pouring. Temperature measurements during three heats are shown in Figure 6. The temperature loss during holding (without tap losses) depended on the pouring time and varied from 50°F for 5 minutes to 150°F for 15 minutes.

Case 4. The foundry uses a low density magnesia lining (ceramic 4, Table 2) for their 10,000 lb capacity teapot ladle. Each lining is used twice. The first time, the steel is tapped from the furnace into a ladle with a cold lining. After 1½ to 2 hours, steel is tapped a second time into the same ladle with a warm lining (inside surface temperature is 470°F-515°F, Figure 7). The aim pouring temperature is 2875°F to 2900°F. The warm lining allows the tap temperature to be decreased from the normal cold lining tap temperature of 3100°F to 3035°F, a temperature savings of 65°F. The warm lining also decreased the severity of the cooling rate immediately after the tap.

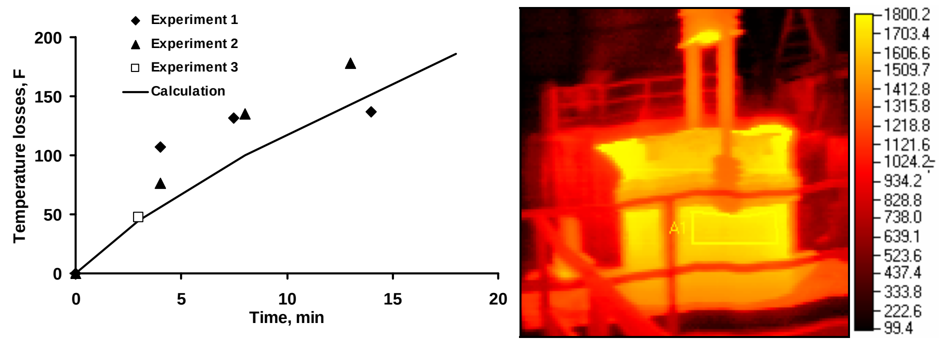


Figure 6. Temperature losses of liquid steel in a 20,000 lb. capacity ladle

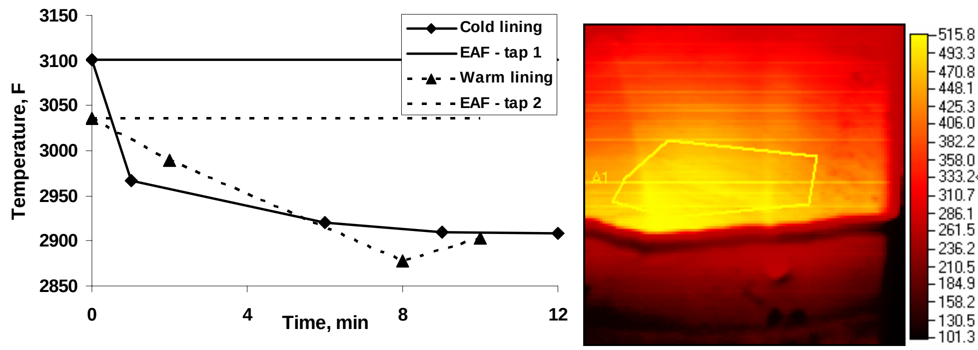


Figure 7. Influence of thermal conditions of low density lining before the tap on temperature losses during holding steel in 10,000 lb. capacity ladle

Case 5. The influence of the preheating temperature of a 12,000 lb ladle with an alumina lining (ceramic 1, Table 2) on the melt cooling rate was studied in a foundry equipped with an IF (Figure 8). In this case, the teapot ladle was covered by a lid. When the ladle was preheated to 2100°F, the temperature losses during the 20 minutes after the tap was less than 110°F, while at the same time in a non-preheated ladle, the temperature loss was 250°F.

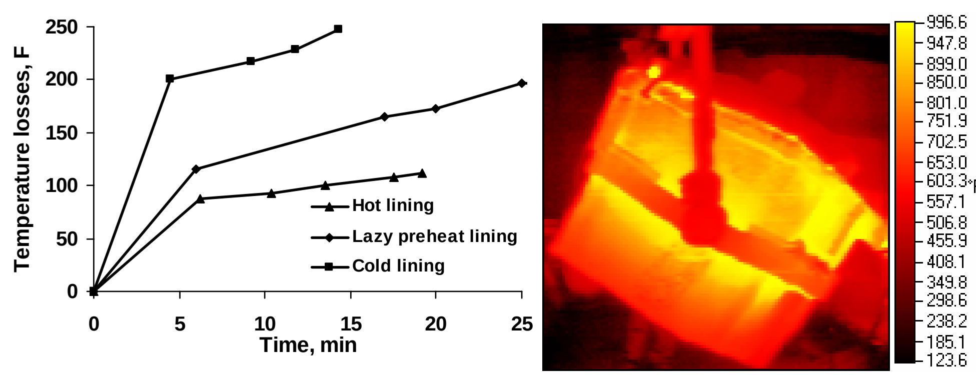
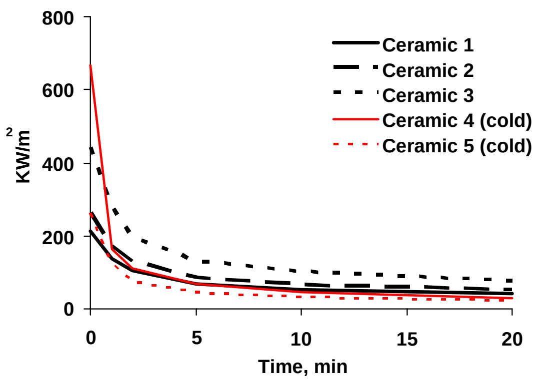


Figure 8. Influence of intensity of lining preheat on temperature losses of steel in 10,000 lb ladle covered by a lid

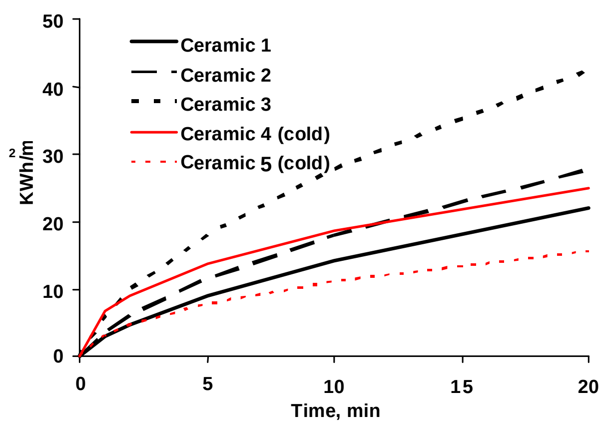
Analysis of heat losses using CFD modeling

A commercial computational fluid dynamic (CFD) modeling software, FLUENT, was used to simulate the heat transfer occurring in foundry ladles. This analysis provides valuable information on the influence that the thermal properties of refractory linings have on the heat losses from liquid steel during transfer, holding and pouring. After the geometry and specific materials for a ladle were established, calculations were done in two steps. The first step was to simulate the temperature distribution in the ladle lining just prior to tap. For example, in a typical preheated ladle, the temperature distribution varies from the inside surface temperature of the refractory at 1850°F to the outside steel shell temperature of 660°F. In another case, a ladle lined with 1” thickness of low density magnesia board (ceramic 4, Table 2) surrounded by a 1” thick dry sand layer was modeled at room temperature. The second step was the calculation of unsteady state heat transfer between a preheated or cold lining and liquid steel poured in the ladle at 2950°F. The simulation results were compared to the industrial experimental measurements in the different steel foundries described above to validate the model.

The computed rate of heat flow from the melt into the lining is illustrated in Figure 9a for different types of linings. There is an initial period (first 30 seconds) in which there is high intensity heat transfer from the melt into the lining. This initial rate varied from 200 KW/m^2 to 600 KW/m^2 for the different types of lining. The integrated values of heat (KWH/m^2) which was accumulated by the linings from the melt are given in Figure 9b. The cold lining board (low density magnesia ceramic) provided a high rate of heat flow initially, but then during the holding of the liquid steel, the integrated value of heat (KWH/m^2) was close to that of preheated high quality alumina castable linings (ceramic 1, Table 2).



a)



b)

Figure 9. Heat intensity (a) and total heat (b) soaked from liquid steel by a lining with 3” thickness

It is clear, that there is a relatively large difference between the lining temperature and the steel temperature even when the lining is preheated resulting in unsteady state heat transfer conditions during use. As a result, a large portion of heat which flows through the lining-melt surface is accumulated by the lining. This was validated by industrial measurements. For example, in industrial Case 3, the outside steel shell temperature did not change from the time of tap through completion of pouring, typically 10 to 25 minutes. Also, calculations showed that the lining thickness has a small influence on the total heat losses from the melt during the first few minutes of initial holding time (Figure 10a). During this initial period, the heat wave generated by the first metal contacting the refractory moves through the lining to the outside ladle surface. Therefore, the lining thickness of a particular lining does not have a significant effect on the initial temperature drop during tap, but is more important for long holding times in the ladle, after the initial heat wave has moved through the refractory. Values of the critical safe lining thickness were calculated (Figure 10b). This is the minimum refractory thickness required to prevent the steel shell temperature from exceeding 1350°F during the holding time. This thickness is dependent on the type of refractory and the maximum holding time required. All of the foundries studied completed pouring in a shorter time (within critical thickness limits) than the maximum time calculated.

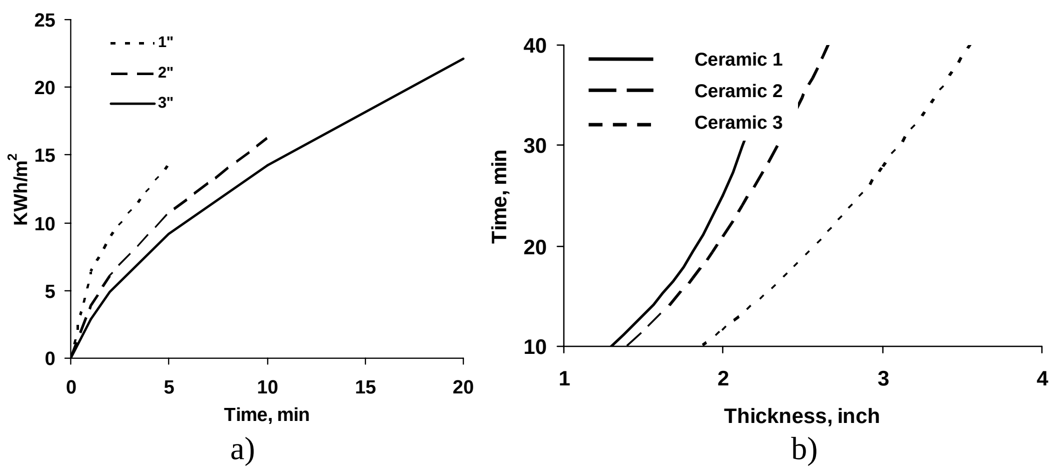


Figure 10. Influence of lining thickness (ceramic 1, Table 2) on the a) total heat soaked from steel melt by lining and b) the holding for steel shell to reach 1350F

Increases in ladle capacity decrease the lining surface to melt volume ratio (Figure 1b). The temperature losses during the holding of the steel melt in different capacity ladles were calculated on the basis of the surface heat losses described above and the lining surface area/melt volume ratios (Figure 11a). For the same lining material and thickness, the decrease in ladle capacity from 20,000 lbs to 1,000 lbs increased the steel temperature losses from 70°F to 200°F during 10 minutes of holding time. This result explains the correlation between the cooling rate and the ladle capacity regardless of the types of linings (Figure 3). Of course, the thermal properties of ceramic linings also play a significant role in the intensity of heat losses from the melt. For example, low thermal conductivity ceramics have the possibility of decreasing the temperature loss during steel holding time by 50% for the same sized ladle (Figure 11b).

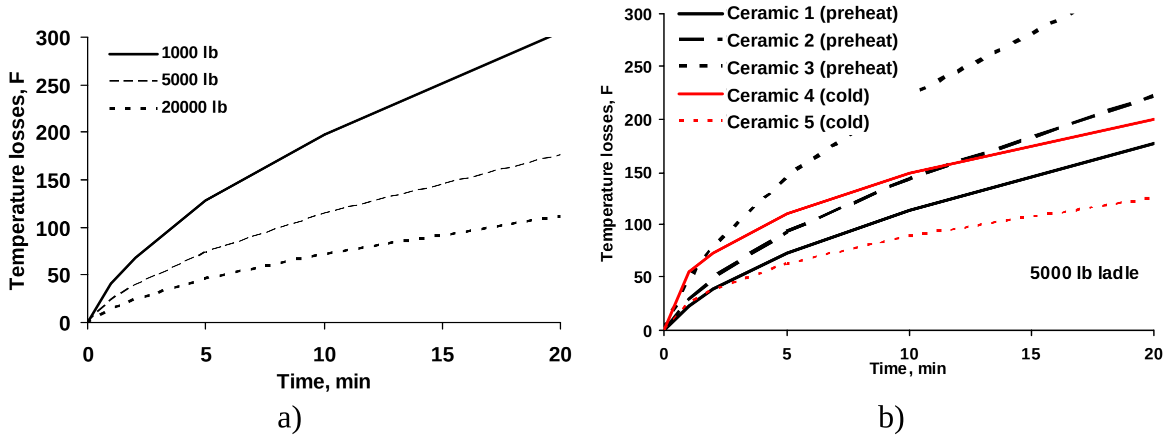


Figure 11. a) Influence of ladle capacity (ceramic 1) on temperature loss and b) types of linings (for a 5000 lb ladle) on temperature loss during holding

Of course, heat transfer from the melt to the lining is not the only source of heat losses from the melt. Large amounts of heat can be lost due to radiation from the top surface of the steel melt. Surfaces vary from open (no or little slag) to slag covered and in some cases covered with a ladle cover. To illustrate the effects of these practices, possible temperature losses by heat transfer through lining and by radiation from the top surface are compared with and without slag in Figure 12 for a 5000 lb ladle (ceramic 1). Heat soaked by the lining is the main cause of the steel melt temperature loss, while the top radiation, especially from a clean surface, could also play a significant role in the total temperature losses.

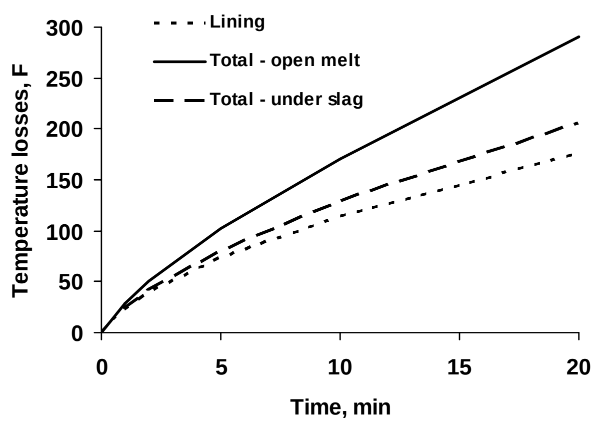


Figure 12. Comparison of temperature losses by heat transfer through lining and by radiation from top surface for 5000 lb ladle with Type 1 lining

The calculated temperature losses using the FLUENT model were validated by comparing with the measured losses in several foundries. The calculated and actual results were found to correlate well. For example, Figure 6 shows the experimental temperature losses for three heats and the calculated values.

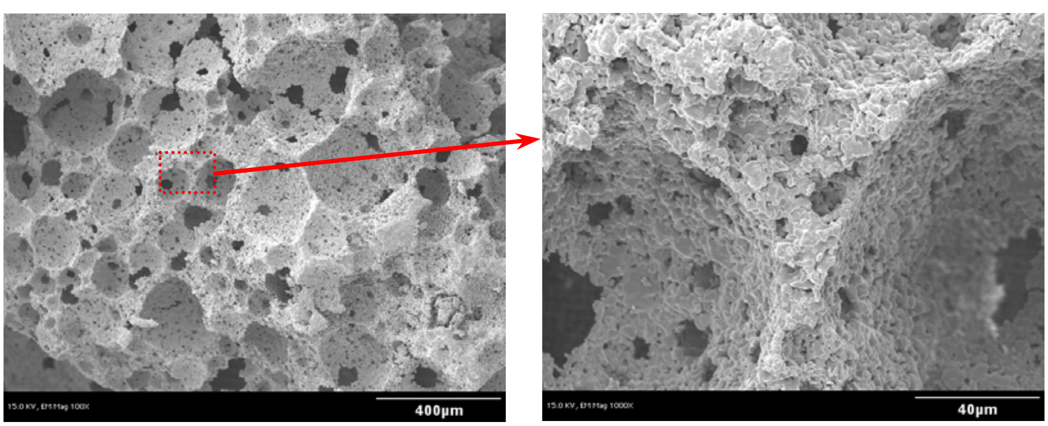
New approach in steel ladle linings

An insulating ladle lining based upon a foamed monolithic refractory castable is being investigated with the objectives of improving thermal performance as well as service lifetime relative to current approaches. Although the most recent developments involve relatively high alumina contents (>95wt.%), the approach can be extended to other material systems.

A standard insulating alumina-based castable containing alumina hollow spheres and calcium aluminate cement binder provides the cornerstone for the method. Conventional alumina aggregates range in density from 3.5 to 3.7 g/cm^3 while hollow alumina aggregate ranges from 0.5 to 0.8 g/cm^3 and provides pores anywhere from 500 to 1500μm in size. It is this aggregate substitution that imparts the first level of porosity to this insulating castable.

In order to render the castable foamable, additional matrix powders are required. In this case ultrafine hydrateable alumina, calcined alumina, and calcium aluminate cement are added to lower the particle size distribution modulus and to provide the requisite fines as well as additional binder for the system. After charging the base-castable and additional fines into a paddle type mixer, it is tempered with enough water to allow the system to be characterized as an excellent vibratable or boarderline self-flow castable. At this moment three surface active agents are introduced and the paddle blade is switched to a whisk attachment in order to facilitate air incorporation and the foaming process. Also added at this time is an engineered fugitive of organic microspheres with an average particle size of 20μm. This very low mass organic material volatilizes upon the initial heating of the castable leaving fine spherical porosity. The specific volume of the castable is increased dramatically during the mixing/foaming process.

The prepared insulating castable material may then be placed directly into the ladle or pre-cast into an appropriate ladle insert shape for later installation. Since the binder for this system is hydratable, the castable is treated from here as any castable material in terms of maintaining a warm and humid environment for setting and curing.



(a) (b)

Figure 13. Scanning electron microscope images of a foamed insulating castable fracture surface

This material is in development and only a limited material property and behavior data set has been established. Laboratory-scale trials are being conducted using 50kg foundry ladles in order to assess the thermal efficiency and overall viability of this and other approaches in direct comparison to current practice. To date, a bulk density of less than 1 g/cm^3 and porosity levels in excess of 75 vol. % has been achieved. Figure 13 is a scanning electron microscope image of a typical fracture surface of the foamed castable. The largest pores in the system are due to the hollow alumina sphere aggregate and are not shown in this particular image set. The second level of porosity is due to air incorporated during the foaming process. These pores range in size from 50 to 500μm and account for the vast majority of the porosity in the system and Figure 13. The third level of porosity results from the engineered organic fugitive material and has an average pore size of about 20μm. Examples of these are seen at the lower right and left of Figure 13(b).

It is proposed that a material of this type may improve foundry ladle practices in terms of thermal efficiency, mechanical integrity, and cycle lifetime of ladle linings. The data cited in Table 2 for this material was estimated based upon the porosity and chemistry of this porous castable. This data was later used as input for the thermal models illustrated in Figures 9 and 11 and serves as an estimate of the potential thermal benefits. The material development and investigations currently underway will verify any utility this approach may offer.

Summary

Ladle practices play an important role in total energy efficiency of steel melting as well as in the quality of castings because high variations in pouring temperature are possible causes of defect formation. The intensity of heat losses significantly decrease with increasing ladle volume. Re-ladling provides more flexibility to allow a high volume melting furnace to pour large numbers of small and medium size castings. Unfortunately, re-ladling also results in additional heat losses through the use of two or more ladles for one heat.

At the same time, lining properties also play an important role in steel melt temperature losses. Typically, foundry ladles experience unsteady state heat transfer conditions with most of heat losses from the steel being attributed to heat accumulating in the lining.

Different methods of decreasing the steel melt heat losses including intensive preheat, radiation protection by slag and covers as well as the use of low density magnesia crucibles and board lining were evaluated in this paper. A low thermal conductivity ladle lining material has the potential of providing an excellent method of reducing heat losses but requires further development by the researchers at UMR.

Acknowledgments

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