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Increasing Energy Efficiency through Improvements in Ladle Materials and Practices

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Increasing Energy Efficiency through Improvements in Ladle Materials and Practices

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Abstract

Steel foundry ladle practices play an important role in total energy efficiency of melting as well as influence casting quality. Extensive heat losses in the ladle could be associated with excessive superheating of the melt before tap which increases energy consumption, promotes oxidation of the melt and increases refractory consumption. A high cooling rate of the liquid metal in the ladle could also cause casting quality instability.

The overall ladle heat balance and components of heat losses were analyzed using FLUENT and FACTSAGE software and validated with experimental data from both the UMR foundry and industrial foundries. The purpose of this paper is to study foundry steel ladles with a focus on increasing energy efficiency through the use of novel lining materials and special techniques of decreasing thermal losses. Special low thermal conductivity materials have been proven to decrease the heat losses significantly resulting in an increase in the holding times and allowing tap temperatures to be decreased by up to 200^{o}F, depending on ladle practices. The laboratory experimental data were incorporated into a computer model that predicts conditions in industrial foundry ladles.

1. Introduction - components of heat losses in steel foundry ladles

In spite of the simple geometry of a steel foundry ladle, the precise evaluation of the heat losses while holding liquid metal requires the complex analysis of the different heat transfer processes. The large thermal gradients and unsteady thermal conditions that take place during tap into the ladle result in significant heat flow changes during the relatively short periods of pouring time. The main heat losses in the ladle are:

1) internal heat sources in the liquid metal from exothermic or endothermic reactions
2) heat accumulation by lining walls
3) heat conduction from the liquid metal through the lining walls to the atmosphere
4) heat convection and radiation from the liquid slag surface to the atmosphere

A multitude of factors including ladle geometry (shape and size), lining materials, initial lining temperature conditions before tap, slag type and thickness, ladle covers, ladle additions, argon stirring, and oxidizing reactions influence the intensity and direction of the heat flow. To manage the complexity, experimental results were combined with computational software. FLUENT, a computation fluid dynamics (CFD) commercial software was used to analyze heat transfer considering the internal sources/sinks of energy, the different boundary conditions which exist between the liquid steel and the surrounding atmosphere and the thermal state of the lining. Heat transfer was analyzed under the influence of mass transfer caused by steel flow from both natural convection and argon stir. The evaluation of the internal source/sink values was done with FACTSAGE software using thermodynamic data. The factors affecting transfer considered in this study are illustrated in Figure 1.

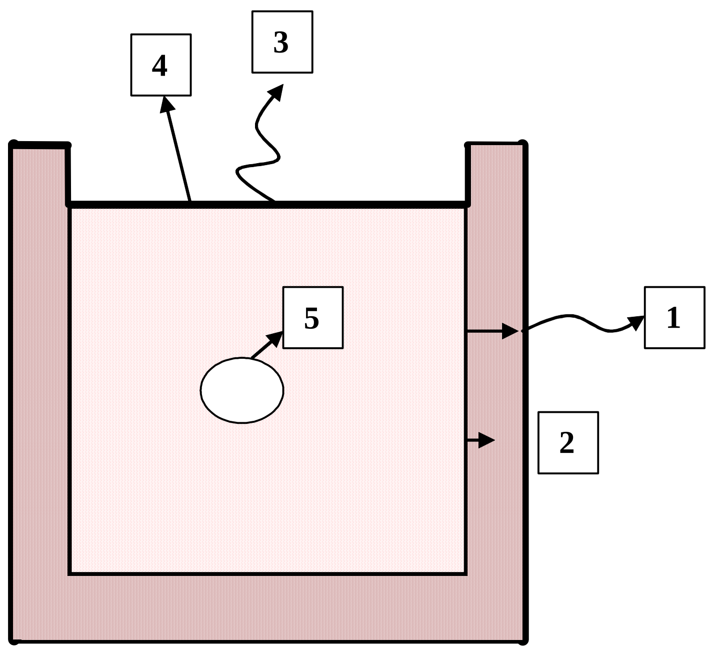


Figure 1. Schematic illustration of steel ladle model with different directions of heat flow:
1) conduction from the melt to atmosphere through the lining walls
2) accumulation by lining walls
3) heat convection from top melt surface to the atmosphere
4) radiation from open top slag surface to the atmosphere
5) internal heat sources/sink.

2. Internal heat sources in the liquid metal

The internal heat sources in the liquid metal could be caused by additives in the ladle and as a result of internal chemical reactions. Chemistry adjustment can be done in the furnace or in the ladle. In mini-mills, the standard practice is to adjust the steel chemistry in the ladle as a way of increasing the EAF productivity. Steel foundry melting practices are significant different. In foundry melt shops equipped with induction furnaces, the final chemistry is typically achieved in the furnace before tap. EAF's in foundries typically make the major chemistry adjustments in the furnace with minor adjustments in the ladle during tap.

The dissolution of room temperature ferroalloys into the liquid steel results in intensive heat and mass transfer. The total heat associated with ferroalloy dissolution into liquid steel includes the change of enthalpy in heating the solid ferroalloy $(c_s^a \nabla T_s)$, in heating the liquid ferroalloy once it melts $(c_l^a \nabla T_l)$, the latent heat of melting (Q^a), plus any chemical enthalpy associated with dissolution ($H_{dissolution}$) and chemical reactions ($H_{reaction}$) with steel components. The enthalpy associated with heating the ferroalloy (solid and liquid) and melting is always endothermic and decreases the melt temperature. The chemical components (dissolution and reactions) could be endothermic or exothermic. The total change in the steel temperature (ΔT) in the ladle for adiabatic conditions (no heat exchange with surrounding) when 1 weight % of room temperature additives, mass (m_a) were added into the steel melt with mass (m_s), was calculated according Eq. 1 using FACTSAGE software and are summarized in Table 1.

$$\nabla T = \frac{\sum m^a (c_s^a \nabla T_s + c_l^a \nabla T_l + Q^a + H^a_{dissolution} + H_{reaction})}{C_l^s (m_s + m_a)} \quad (1)$$

Table 1. Melt temperature change during ladle additions in adiabatic conditions (to 3000^{o}F)

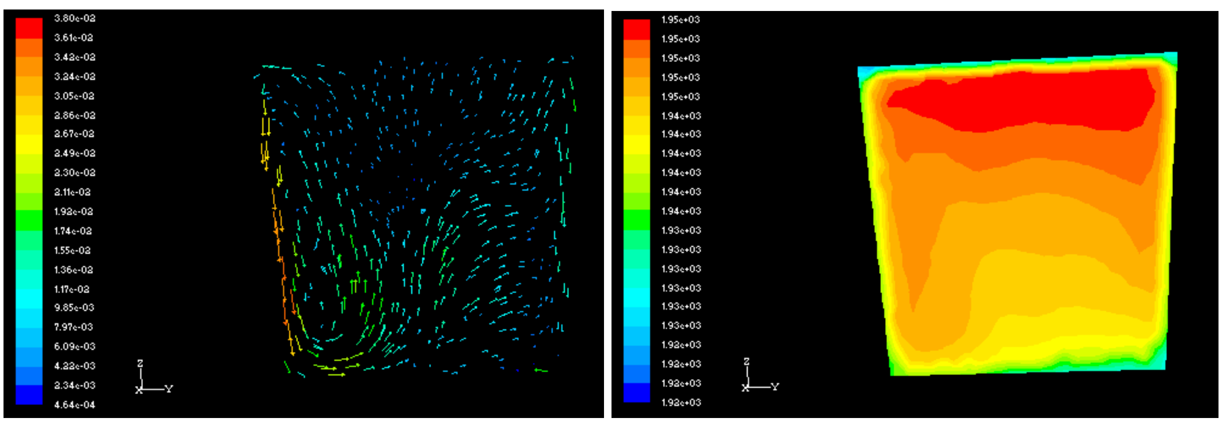
Group description	Additive	Melt temperature change (F)
1. Additives (1 weight %) with endothermic heating/melting and endothermic chemical effects	C	-99
	FeMn (78%Mn 6%C)	-48
	Cu	-38
	Low C FeMn (78%Mn)	-31
	Mn	-31
	Fe	-30
2. Additives (1 weight %) with endothermic heating/melting and exothermic chemical effects	Cr	-18
	Mo	-9
	Nb	-7.2
	Ti	-7.2
	FeSi (50%Si)	-7
	Al	0
	FeSi (75%Si)	+7
	Si	+28
3. Inert gas blowing through the melt (0.1 weight %)	Ar	-3
4. Chemically active gases (O_2) oxidizing 0.1 weight of elements in the melt	Mn	+12
	C (to CO)	+23
	Si	+59

All the additives could be divided into four main groups. The additives from the first group (C, Cu, and Mn) decrease the melt temperature as a result of heating from room temperature to the liquid temperature (including phase changes) and the endothermic chemical heat of dissolution. The heating of iron from room temperature to 3000^{o}F decreases the temperature approximately 30^{o}F for each 1 weight % added in the ladle. Dissolution of the second group of elements in the steel produce exothermic effects which offset some of the energy required to heat and melt the elements. For example, both pure silicon and ferrosilicon (75%) increase the melt temperature. Aluminum and lower grades of ferrosilicon produce a near zero net effect on the temperature when added.

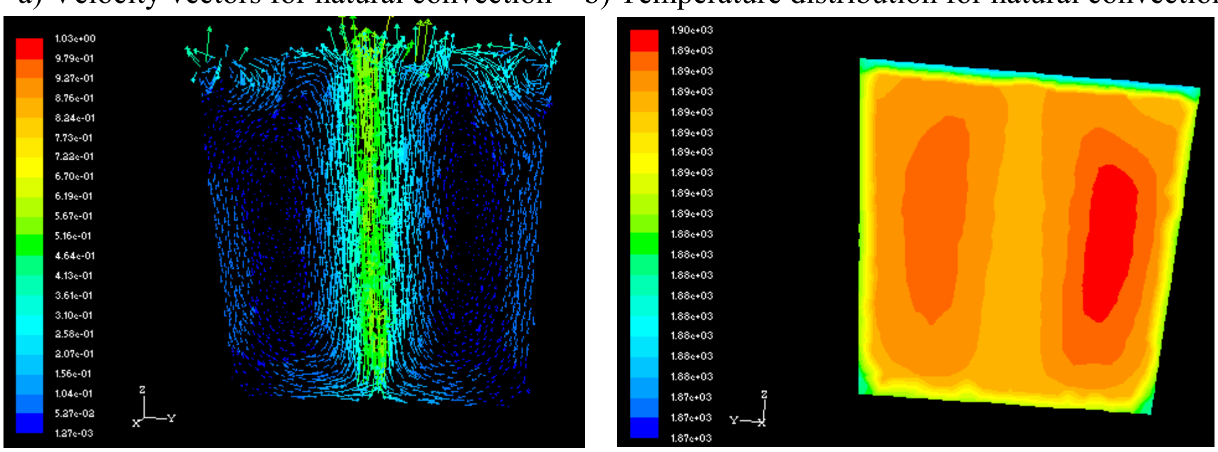
The third group of species includes inert gases which are used for stirring. During stirring by gas injection the direct melt heat losses is negligible since a very low ratio of gas/melt enthalpies is used while the real thermal effect could be more significant as a result of intensification of heat transfer between melt and surrounding environment. Finally, the fourth group contains the chemically active species, for example, oxygen, which could chemically react with alloying elements in the steel and generate heat in-situ. Table 1 contains data predicting the increase in steel temperature when 0.1% C, Si or Mn are oxidized by reaction with room temperature oxygen injected in the melt.

3. Heat and mass transfer inside ladle

Heat and mass transfer conditions within the liquid steel in the ladle play an important role in the steel temperature and chemical composition stability. The forces moving liquid steel in the ladle could be energy of melt stream during tap, natural convection as a result of temperature gradients in the ladle, and external forces such as Ar stirring or electromagnetic forces. FLUENT software was applied for coupled analysis flow, heat transfer, and additive distribution inside the liquid steel. Two commonly used processes were compared for the same size 100 lb lab scale ladle, natural convection and Ar injection through a porous plug in the bottom of the ladle. A comparison of the two cases is shown in terms of velocity vectors and temperature distribution in Figure 2. The average velocity under natural convection was 0.03 m/sec while during Ar injection the average velocity increased an order of magnitude to 0.5 m/sec. The type of metal flow strongly influences the temperature distribution in the ladle. The maximum variation of the metal temperature was 15-20^{o}F in the ladle under natural convection and only 4-6^{o}F with Ar stirring.



a) Velocity vectors for natural convection b) Temperature distribution for natural convection



c) Velocity vectors for Ar stir d) Temperature distribution for Ar stir

Figure 2. Comparison of velocity and temperature distribution in a 100 lb ladle

Ladle chemistry variations after adding FeMn in the ladle both under natural convections and argon stir was studied in the UMR foundry. Very weak natural convection does not homogenize the steel even during relatively long times (up to 3-4 minutes). Intensive argon stirring accelerates the homogenization and stable steel compositions were reached after 20-30 seconds.

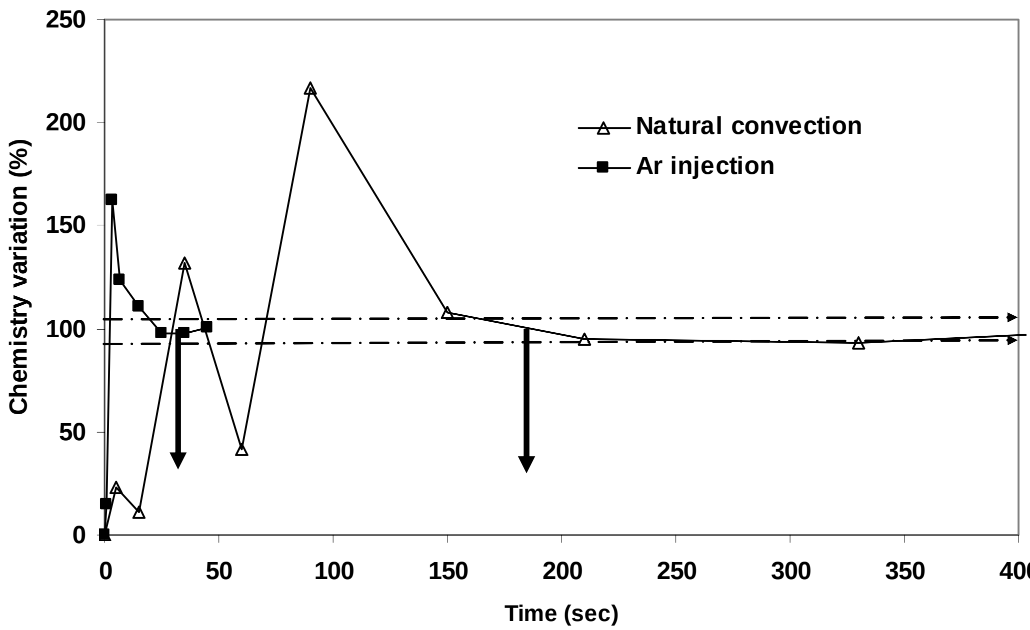


Figure 3. Changing in Mn chemistry during holding in ladle with and without Ar stir

4. Liquid metal - ladle lining heat transfer

Typically, steel foundry ladles are used in unsteady thermal conditions and therefore the heat flowing from the metal to the lining consists of two parts, 1) the heat flowing through the lining (or slag) to the ambient atmosphere and 2) the heat accumulated by the lining. The metal temperature decrease as a result of this heat exchange depends on the ladle size and lining thermal properties. Also, the melt flow as a result of natural convection or Ar stirring could have some influence on heat transfer intensity. The role of all these factors was evaluated experimentally and using FLUENT software.

The ladle size has a crucially important influence on the liquid metal cooling rate. The increase of ladle volume significantly reduces the specific surface value which is a ratio of melt weight in the ladle to lining surface and simultaneously raises the mass melt/lining ratio (see Figure 4a). Industrial statistics showed that the cooling rate in small ladles is 3-10 times greater than larger ladles (see Figure 4b). As a result, companies using small ladles typically need higher (up to 200F) superheat in the furnace prior to tap (Figure 4c).

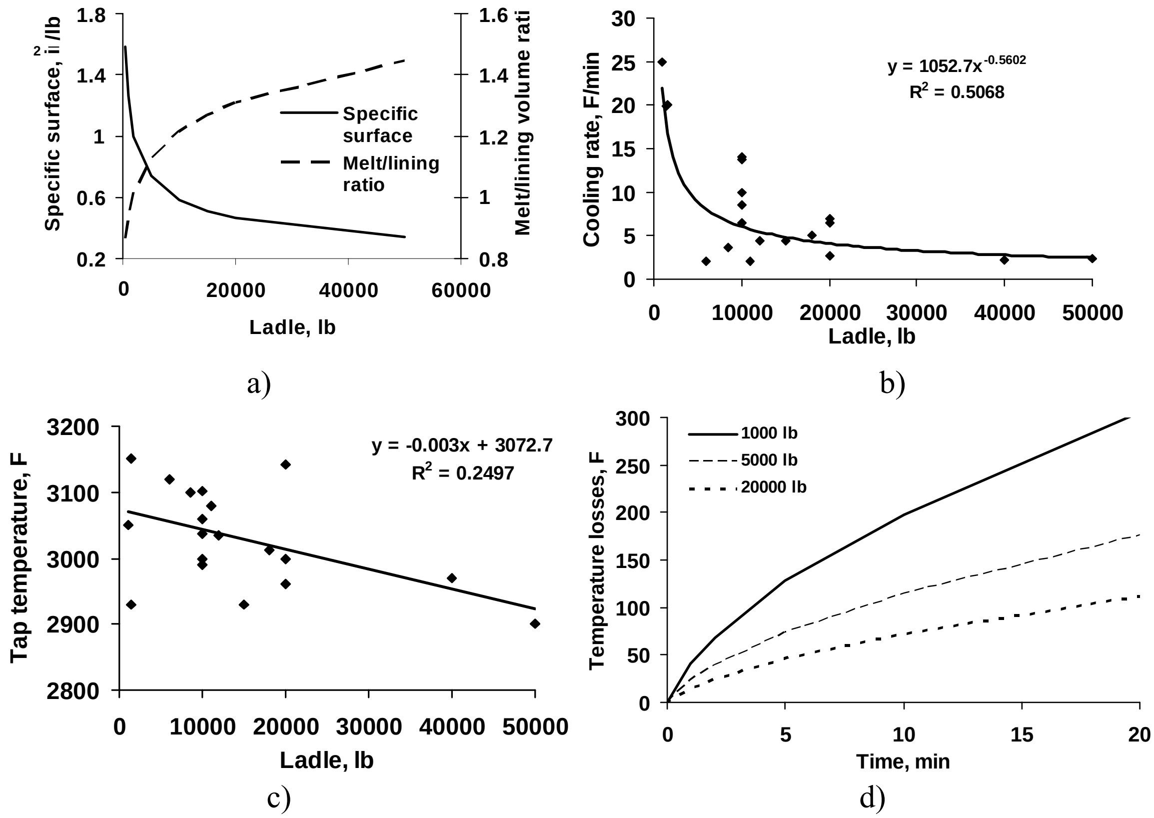


Fig. 4. Influence of ladle size on a) melt/lining ratio, b) metal cooling rate, c) required tap temperature, and d) calculated temperature loss during holding

Large variations in the liquid metal cooling rate are observed in different steel foundries which use similar ladle capacities. This reflects the high sensitivity of the temperature losses to applied lining materials and ladle practices. These variables were computationally analyzed using FLUENT software. The scheme of unsteady heat balance in the lining is shown in Figure 5. The specific metal/lining/air boundary conditions which were used is described below.

Heat input from steel	−	Heat output from lining	+	Heat generated in lining	=	Heat accumulated by lining

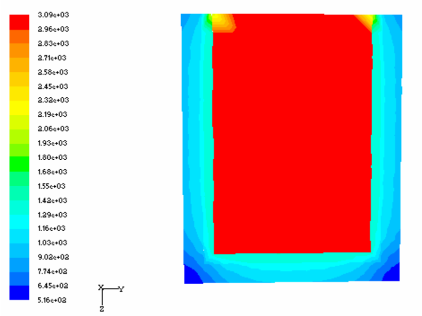
Figure 5. Scheme of computed unsteady heat balance in the lining

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 heat flow to the lining dramatically increases when the temperature of the metal rises from aluminum and copper alloys to irons and steel (Table 2).

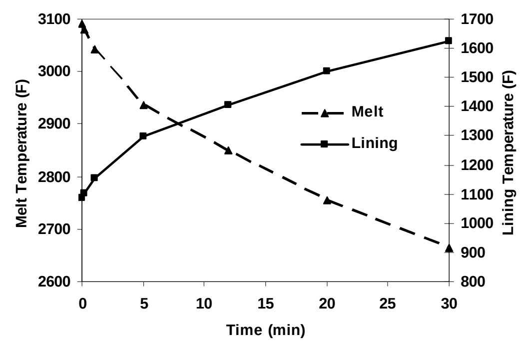
Table 2. Calculated average heat flow (KW/m^2) from different liquid alloys to ladle lining

Aluminum	Copper	Iron	Steel
39	73	113	137

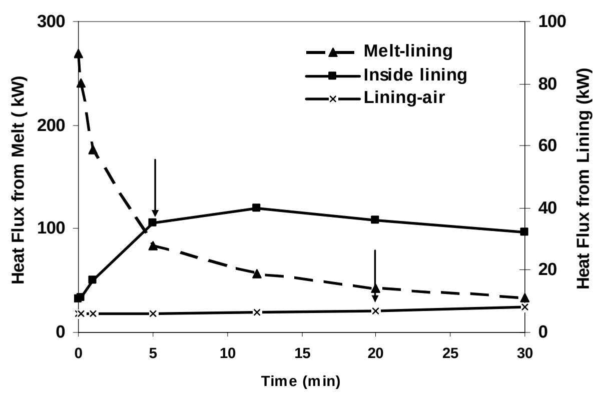
High temperature liquid steel has other important distinctions when compared to holding lower melting temperature alloys in the ladle. The main heat flow from the liquid steel is accumulated by the lining during the relatively short pouring time and only after 10-20 minutes does the heat wave reach the outside steel shell/air boundary. Predictions (FLUENT) of the changing temperatures in the liquid steel and lining for a 1000 lb alumina castable ladle are shown in Figure 6b. A very intensive heat flux from the liquid steel to the lining is generated during the first 20 minutes, which is a maximum possible holding time for this size of ladle. Heat flux on the centre line of lining (approximately 1"-1.5" from the melt) was stabilized after 5 minutes and heat wave get outside steel shell only after 20 minutes (shown by arrows on Fig. 6c). So, in this case, the main part of heat was transferred from the melt to the lining.



a) Temperature distribution after tap



b) Average metal and lining temperature



c) Average heat flux in ladle (arrows denote transition points)

Figure 6. FLUENT predicted temperatures and heat fluxes in a 1000 lb capacity alumina castable ladle preheated to 1500°F prior to tap

The heat flux between the liquid metal and the lining as well as the steel cooling rate depend on the thermal properties of the linings. Three types of ladle linings were tested in the UMR foundry laboratory and the experimental results were compared to calculated data. The experimental procedure and applied materials were described in an earlier paper[1]. The three linings studied (see Table 3) were a commercially available 70% alumina castable, a low density magnesia ladle insert, and a newly developed low density porous high alumina castable. All materials were tested as a 1” thick prefabricated ladle insert of approximately 100 lbs steel capacity (Fig. 7). The metal (cast iron) was superheated to 3000°F in an induction furnace and tapped into the ladle. The ladle was held and temperature measured until the steel was below 2420°F.

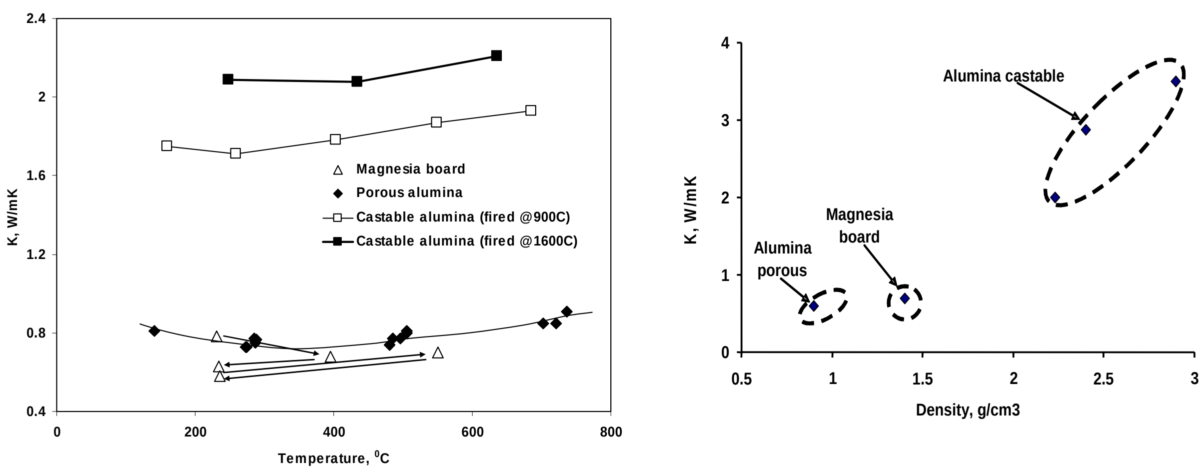
Table 3. Three types of lining materials studied

Ceramics	Density, kg/m^3
70% alumina castable	2300
Low density magnesia crucible	1400
Porous high alumina castable	900-950

a) b) c)

Figure 7. Lining inserts: a) 70% alumina castable, b) low density magnesia, and c) porous alumina castable

The thermal conductivity of each of the materials was measured at different temperatures[1] (Figure 8a). The values of the coefficient of thermal conductivity for the two types of castable linings were stable (although significantly different) at each temperature regardless of the number of temperature cycles. However, measurements of the low density magnesia board material showed unstable data as a result of the material eroding during the tests. The comparison of the thermal conductivity of the different linings shows that the porous alumina material has a thermal conductivity that is 2.2 to 2.8 times lower than 70% alumina castable with much more stable properties than low density magnesia boards. Typically, low density materials are able to produce lower thermal conductivity but suffer from poor mechanical properties of the ceramics. The thermal conductivity of the various linings versus density is given in Figure 8b.



a) Temperature b) Density

Figure 8. Effect of temperature and density on thermal conductivity of different types of ladle linings[1].

The porous alumina castable lining has low density but possesses much higher strength and thermal stability than magnesia boards.

Calculations from the FLUENT model were compared to experimental results using various lining types and conditions in Table 4. The model calculations consider two extreme conditions, a fully isolated top surface (no radiation losses) and open liquid surface where radiation and convection combine to reduce the metal temperature during holding. The differences in the physical properties of the linings had a significant influence on the liquid metal temperature losses while holding in the 100 lb ladle (Figure 9).

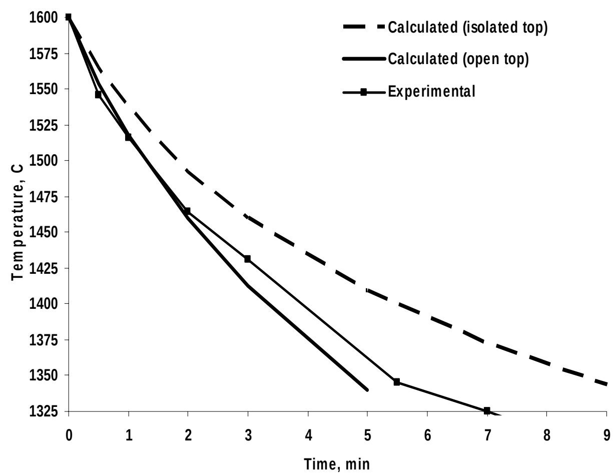
Table 4. Ladle holding time for melt temperature to drop from 3000F to 2420F

Lining	Preheat (F)	Measured time Experimental (min)	Calculated time using FLUENT model (min)	
			Open top	Isolated top
Alumina castable	1290	7	5	10
Low density magnesia board	No preheat	9	7	13
Alumina porous castable	1290	18	12	30

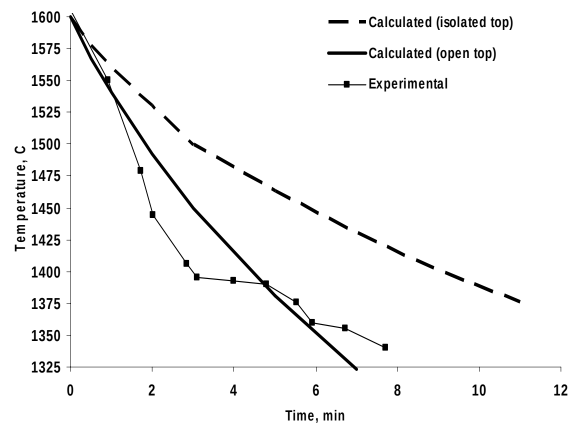
FLUENT modeling helped quantify the energy savings of using a lower thermal conductivity backup material for the bottom and sides of lining inserts. The idea of this ladle design is illustrated in Figure 10a. During the time steel is held in the ladle, there are two distinguishable periods divided by a “transition point.” During the first period, heat is accumulated in the ladle working lining and in the second period, heat actively flows into the backup layer. These calculations were done for a 100 lb lab scale ladle containing porous castable alumina with 1” wall thickness surrounded by a 1” backup lining. The position of transition point depends on the lining type and conditions. Changing the back up material does not have an effect on heat losses until the second period of heat transfer in the ladle. Preheating of the lining increases the positive effect of low thermal conductivity back up lining application (Figure 10b). Experimental trials were completed using a back up layer manufactured from calcium silicate insulating boards 1” in thickness in place of silica sand used in previous experiments. The properties of calcium silicate insulating boards are given in Table 5.

Table 5. Properties of calcium silicate insulating boards

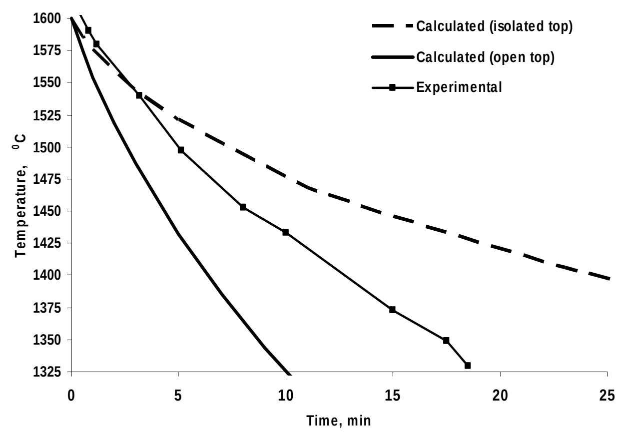
Properties	Value
Maximum service temperature	1100 ^{0}C
Balk density	235 kg/m^3
Porosity	90%
Compression strength	2.7 MPa
Thermal conductivity	0.07 W/mK
Composition	47% SiO_2, 45% CaO



a) Preheated (1500F) 70% alumina castable

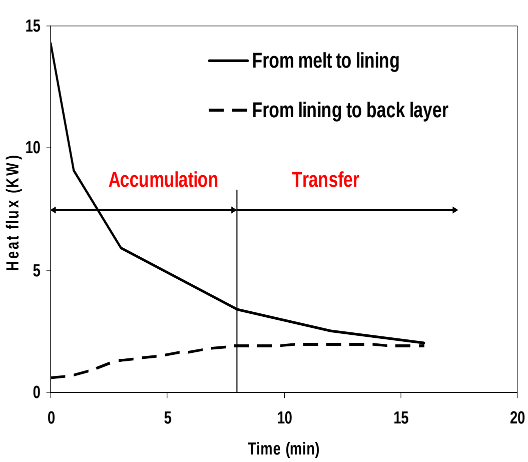


b) Room temperature magnesia board

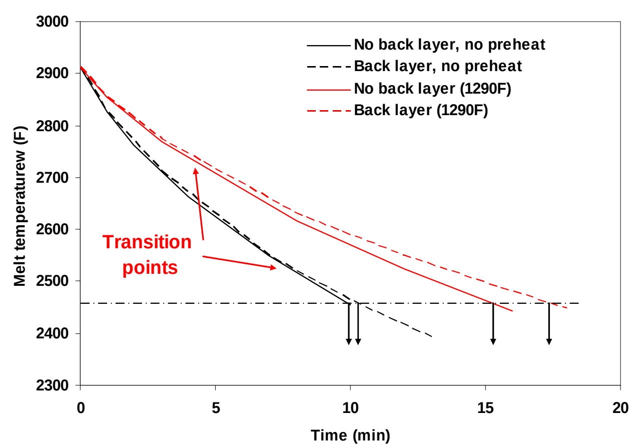


c) Preheated (1290F) porous alumina castable

Figure 9. Comparison of FLUENT model and experimental measurements in 100 lb ladle



a) Heat flux metal to lining to backup



b) Effect of preheat on steel temperature

Figure 10. FLUENT model of heat flux and temperatures during holding in 100 lb ladle

Experimental results are shown in Figure 11. The data presents two tests completed using porous castable alumina inserts. In one test, silica sand was used for the backup layer and in the second test, 1" thick calcium silicate insulating boards were used. In both cases, the linings were preheated to 1290F. There is an easily recognizable transition point (predicted by FLUENT modeling). After passing the transition point, the cooling rate significantly decreased for the calcium silicate back up lining and the total holding time was 26 minutes, significantly longer than any other case tested.

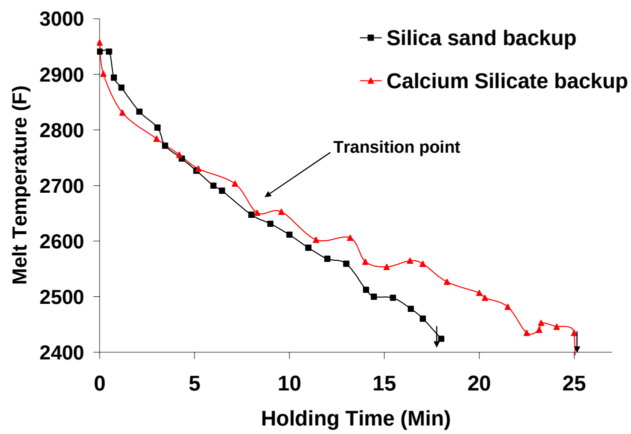


Figure 11. Comparison of metal temperatures in 100 lb ladle lined with a porous castable alumina working lining and two different backup linings (silica sand and calcium silicate).

5. Radiation heat losses from top surface

The effect of radiation heat losses from the top melt surface was evaluated using FLUENT modeling for different surface conditions. Figure 12 illustrates the differences in the liquid steel temperature during holding based on changing the ladle cover conditions in a 1000 lb ladle with 70% alumina castable lining. Full isolation of top surface would have a significant effect on decreasing the metal cooling rate. A simple slag layer 0.5-1" thick halves the radiation losses typical of an open ladle. Industrial examples of radiation protection of different types of ladles are shown in Figure 13. Temporary Kaowool covers (Figure 13a and 13b) decreased the temperature of the radiation surface from 2900-3000F to 400-500F. Ladle lids were even more effective at reducing radiation losses (Figure 13c).

6. Scale up modeling for industrial ladles

Experimental results and FLUENT modeling data provide the possibility of modeling industrial ladles under different refractory lining and metal handling conditions to predict performance. For example, Figure 14 illustrates the temperature profiles using the FLUENT model for 1000 lb ladles with an open melt surface covered by a thin layer of slag.

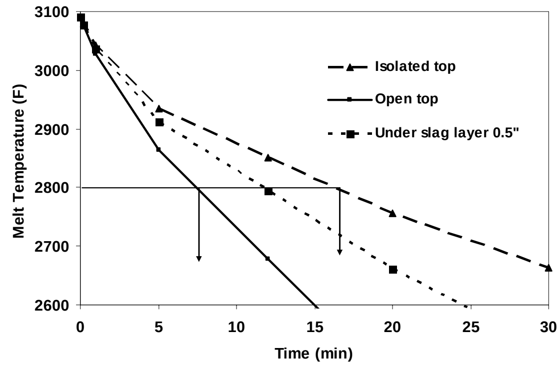
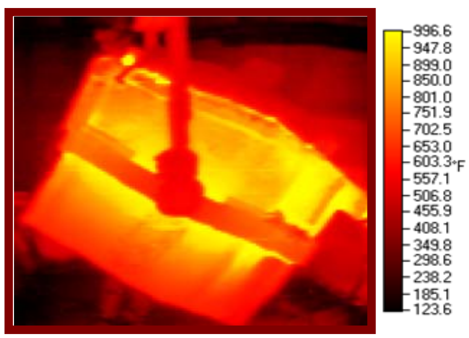
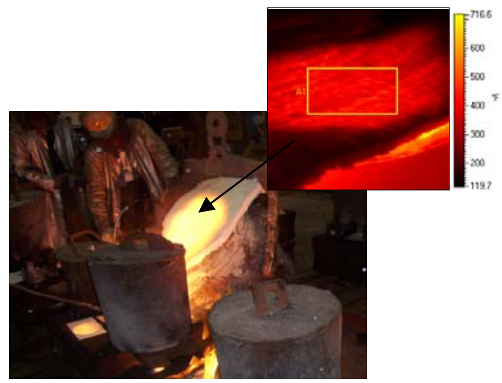


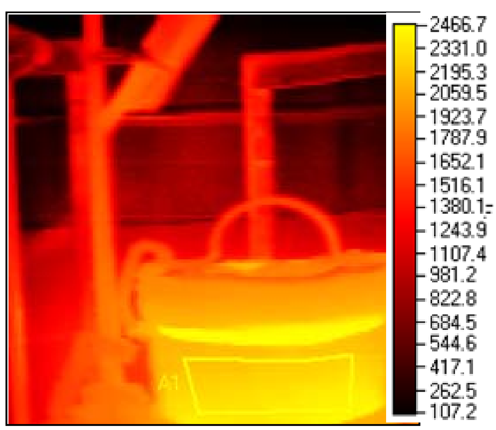
Figure 12. The effects of radiation protection of top melt surface on metal temperature in 1000 lb ladle (1500F preheated castable alumina lining)



a) Kaowool lid on 5 ton ladle



b) Kaowool lid on 400 lb ladle



c) Refractory lined steel shell lid for 200 lb ladle

Figure 13. Radiation protection of top melt surface in ladles

In this case, four lining conditions were compared to calculate the required tap temperature to pour after 12 minutes of handling time at a final pouring temperature of 2840°F. The highest tap temperature (3275°F) was required for a traditional castable alumina lining preheated to at least 1500°F to compensate for the heat losses in the ladle. Low density magnesia boards require a lower tap temperature (3200°F) with less variation in the pour temperature based on differing ladle conditions. The tap temperature could be reduced to 3080°F for similarly constructed castable porous refractory, a significant decrease in temperature due to the reduced energy losses using this new material. The tap temperature could be reduced even further to 3040°F if the porous castable alumina lining is backed up by a lower conductivity (calcium silicate) backup material. This change is a total reduction in the tap temperature of 240°F from traditional alumina castable linings and could increase the holding time at the same tap temperature by at least 30%.

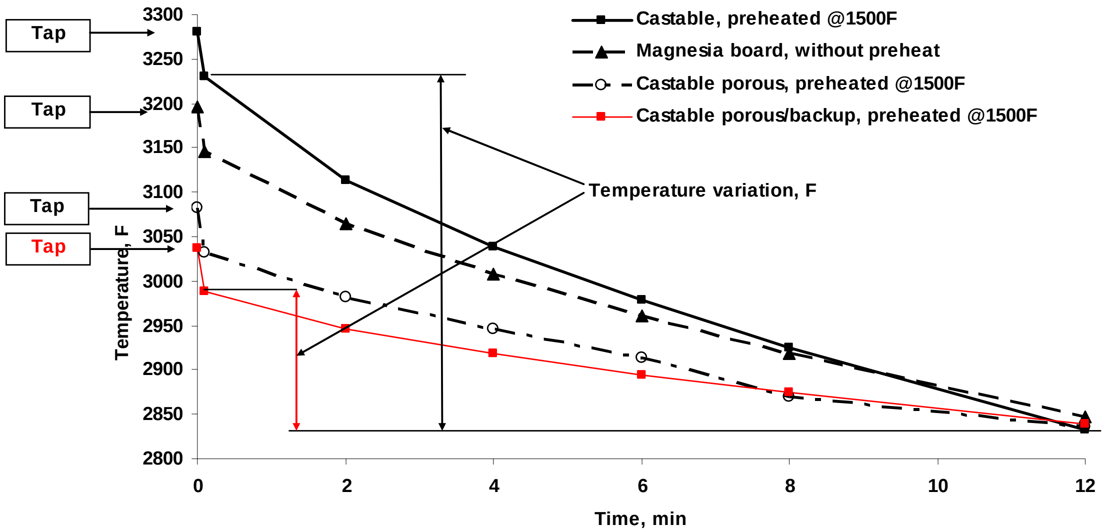


Figure 14. Comparison of required tap temperatures for aim pour temperature of 2840F at 12 minutes after tap in 1000 lb ladles lined with different refractories (FLUENT model).

7. Conclusions

This paper summarizes a research study focusing on increasing the energy efficiency through the use of new ladle linings and improved melt handling processing for the steel foundry industry. The research was completed using a 100 lb lab scale experimental ladle, FLUENT and FACTSAGE computer modeling, industrial measurements and statistics. A new ladle lining system developed at UMR (porous alumina castable working lining combined with a low-density calcium silicate backup lining) has proven to significantly decrease the heat losses of steel in the ladle resulting in an increase of up to 30% in the holding times and allowing tap temperatures to be decreased by as much as 240°F from traditional preheated high alumina castable ladle linings (actual savings depend on present ladle practices). The laboratory experimental data were incorporated into a computer model that predicts conditions in industrial foundry ladles.

8. Acknowledgements

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9. References

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