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Riser Sleeve Properties for Steel Castings and the Effect of Sleeve Type on Casting Yield

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Abstract

Thermophysical properties of insulating and exothermic riser sleeves are needed to accurately predict their application and performance in casting simulation software. Unfortunately there is little such property data available in the open literature. There are a few sleeve manufacturers who provide the necessary properties, but as a "black box", where the property data and boundary conditions are hidden from the simulation software user. In this paper preliminary results of a study to determine sleeve thermophysical properties are presented. Numerous simulations were performed to determine temperature dependent sleeve properties through achieving agreement between measured and predicted temperatures throughout the cooling history of the casting process. Measured and predicted temperatures for castings with insulating and exothermic sleeves are compared to a control experiment with no sleeve. The thermophysical properties for the insulating and exothermic sleeves are used in solidification and casting yield studies to compare the performance of the sleeves in castings having cube and plate shapes. Based on the exothermic and insulating properties determined, there is little difference between the casting yields resulting from using either type of sleeve. A solidification study using a 7 inch diameter riser showed that the exothermic sleeve increased the time to solidus by 44%, and the insulating sleeve by 55%, over the un-sleeved riser case.

I. INTRODUCTION

Riser sleeves are a well established tool in the steel foundry industry for minimizing riser size, and hence minimizing the volume of metal melted and poured. It is estimated that about 80% of all steel castings are produced using riser sleeves, and the U.S. steel casting industry alone spends about $38 million per year on riser sleeves. Both purely insulating and exothermic riser sleeves are used in steel casting, but a recent survey of steel foundries found that there are widespread practices and opinions about their proper use. Every sleeve supplier uses different materials of generally unknown composition and properties. Therefore, the use of sleeves by foundries is largely based on guesswork and trial-and-error methods. There is no rational means available to foundries for deciding which sleeve from which supplier is most effective for a given casting. Most foundries use computer casting simulation to determine riser sizes. However, the sleeve thermophysical properties, which are needed as input data for such simulations, are not available. It is estimated by the SFSA that if the thermophysical properties of riser sleeves were known accurately, riser sizes could be optimized such that the casting yield could be increased by at least 10% (from 50% currently to 55%). The resulting energy savings would be about 1.5 trillion BTU per year for U.S. steel foundries. Significant additional benefits would arise from improved quality, reduced costs, and increased capacity.

Literature on riser sleeve property measurements is scarce or incomplete. Older literature presents data about the performance of sleeves and their effects on cooling history and solidification time, effective increase in riser modulus, and their effect on riser piping and reduction in required riser volume [1-3]. More recently general temperature dependent curves for density, specific heat and thermal conductivity have been published [4], but these curves show no numerical values and only give the reader a rough sense of the properties' dependency on temperature. Because of the lack of property data for accurate simulation, SFSA members have developed their own practices for using riser sleeves, such as deciding when to use an insulating or exothermic sleeve [5]. Sleeve manufacturers ASK Chemicals and Foseco have provided sleeve properties to users of the casting simulation software *MAGMAsoft* through its property database, but these are proprietary data, hidden from the user. In order to apply riser sleeves through casting simulation accurately, a project is underway to develop property data by matching experimental temperature data recorded during casting trials to simulation results. These experiments are being performed using the most popular riser sleeves used by SFSA members. Resources permitting, the project goal is to conduct experimental trials and develop properties for most of the sleeve products ranked by popularity of use in Figure 1, which was produced from results of a recent survey of SFSA members. The project is ongoing, and at its completion will provide SFSA members not only with the necessary sleeve property data, but comparisons between measured and predicted temperatures from the casting experiments to demonstrate their accuracy.

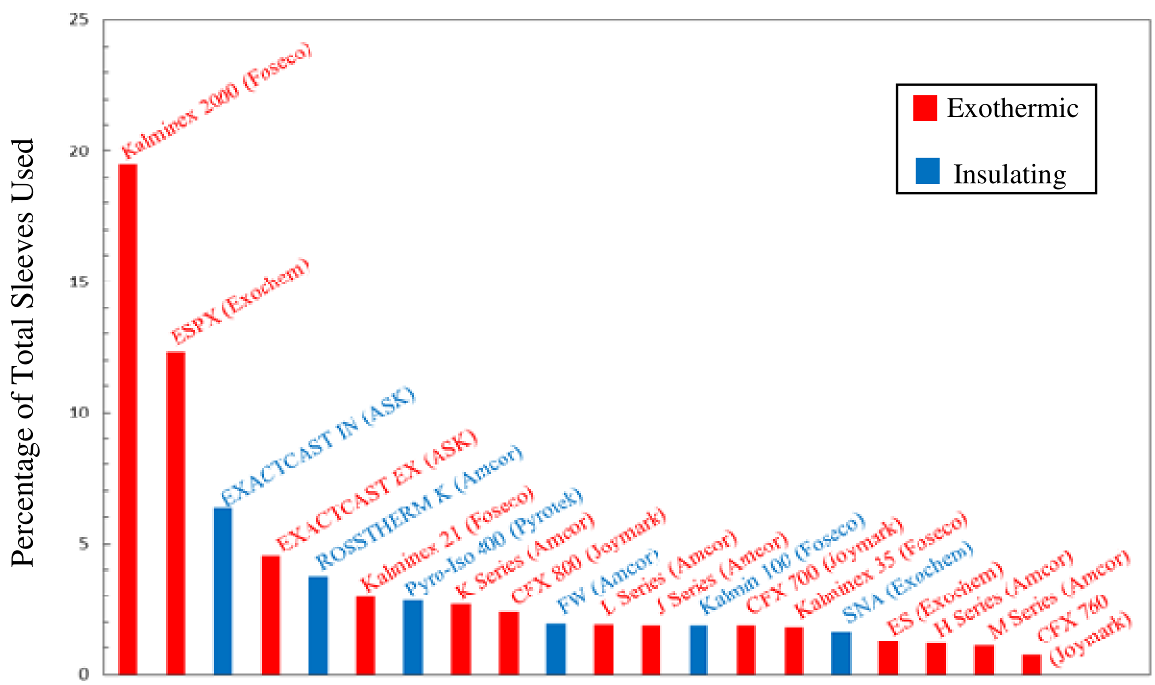


Figure 1. Riser sleeves products and manufacturers ranked by popularity of use by SFSA members.

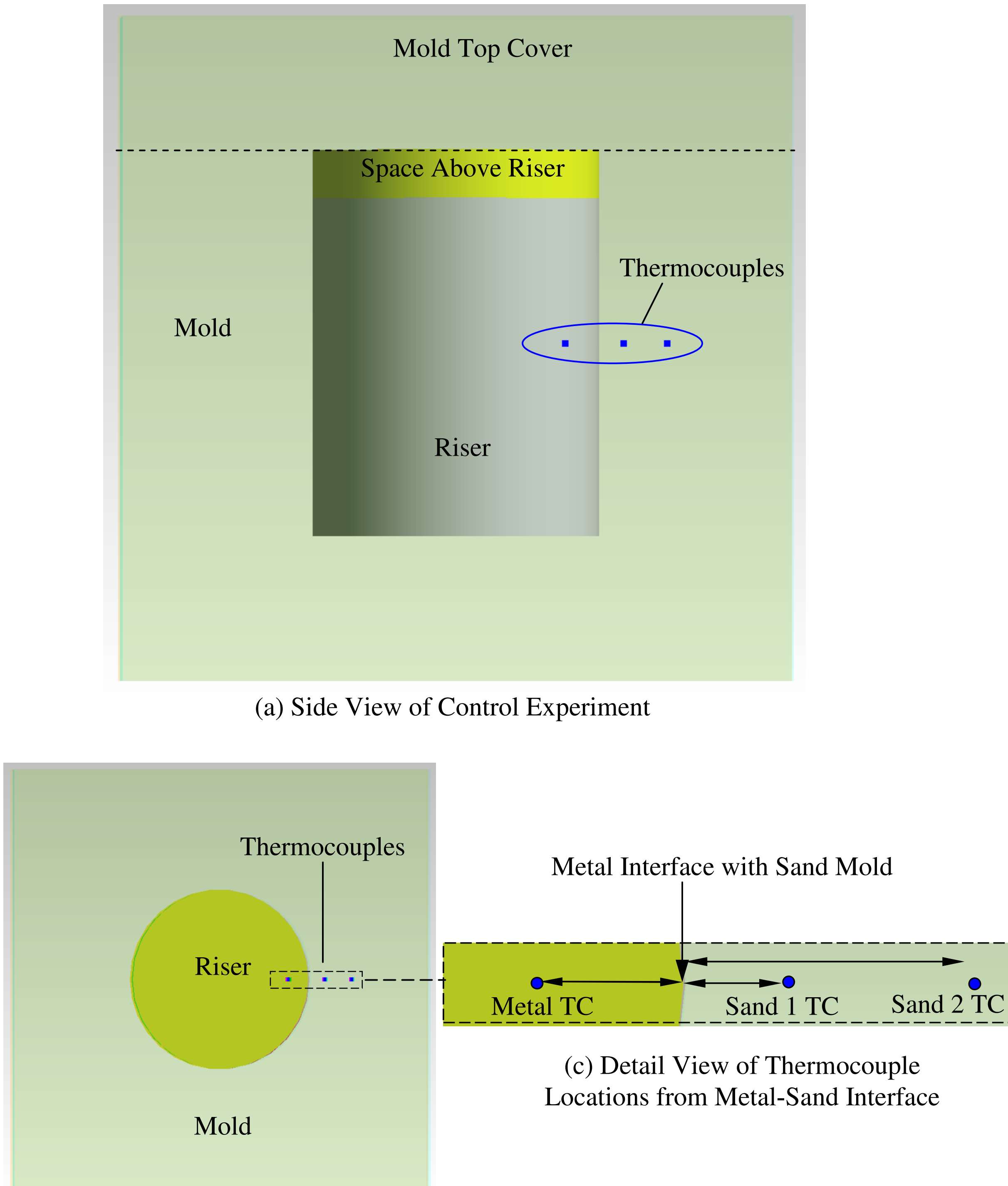
II. CASTING EXPERIMENTS

Since the project work is ongoing, the experiments described here and preliminary results are presented to give the reader an overview the methods used to acquire and determine the sleeve property data. The set of experiments described in this paper were conducted at the University of Northern Iowa (UNI) Metal Casting Center using Foseco Kalmin 70 insulating and Kalminex 2000 exothemic sleeves. In addition to performing casting experimental measurements with sleeves, a control casting experiment without a sleeve is also performed. Side and top views of the control experiment and detailed views of the thermocouple (TC) locations for the control experiment are shown in Figure 2. The control and sleeve experiments are cylindrical castings, essentially just a riser as seen in Figure 2. The molds used in all experiments are 14 inches square as viewed from the top in Figure 2(b). A mold top cover 2.75 inches thick was placed on the top of each casting experiment after filling the mold cavity seen in Figure 2(a). The control experiment was instrumented with three thermocouples as shown in Figure 2, and the positions of the thermocouples were at the riser mid-height with one located in the steel and two located in the sand. The positions of the TCs in the control experiment are given in Table 1 under casting experiment #1 with no sleeve, and the positions of the TCs in units of mm are given with positioning reference to the steel-sand interface (as diagramed in Figure 2(c)). The three thermocouples used in the control experiment are termed “Metal”, “Sand 1” and “Sand 2” shown in Figure 2(c). In all experiments B-Type TCs encased by a quartz tube were used to measure the steel temperatures and K-Type thermocouples were used to measure the mold sand temperatures. Note that the riser and sleeve dimensions for all experiments are also given in Table 1, and that the control experiment and sleeved casting experiment #4 have the same riser size.

One of the casting experiments with a sleeve is shown in Figure 3. It is experiment casting #4 from Table 1. In Figures 3(a) and (b) side and top views of this experiment are shown. Note there are four thermocouple measurements made in the sleeve experiments; one is in the steel and three in the sand mold. In Figure 3(c) the four thermocouples used in the control experiment are termed “Metal”, “Sand 1”, “Sand 2” and “Sand 3”. The positions of the TCs are given with reference to the metal-sleeve interface in Table 1 as shown in Figure 3(c). The sleeve thickness is provided in Table 1 as well so the TC position into the sand from the sand-sleeve interface can also be determined. In the sleeved casting experiments, one size of Kalmin 70 was used and two sizes of Kalminex 2000 were used.

In these experiments silica sand molds were made using a 1.25% Pepset binder based on total sand weight. The steel chemistry poured in these experiments is given in Table 2. The liquidus and solidus temperatures of this steel were found from the steel temperature measurements to be 1466°C (2671°F) and 1340°C (2444°F), respectively.

Since the property data developed for this paper is preliminary, the authors are not including it in this paper. However, comparisons between measured and predicted temperature using the property data in *MAGMAsoft* will be presented. Temperature data from the control experiment is used to determine property data and boundary conditions for the metal and mold used in the casting simulations by matching the control measurements with simulations. Properties and conditions for the metal and mold are not changed from those established by the control experiment when simulating the experiments with sleeves.

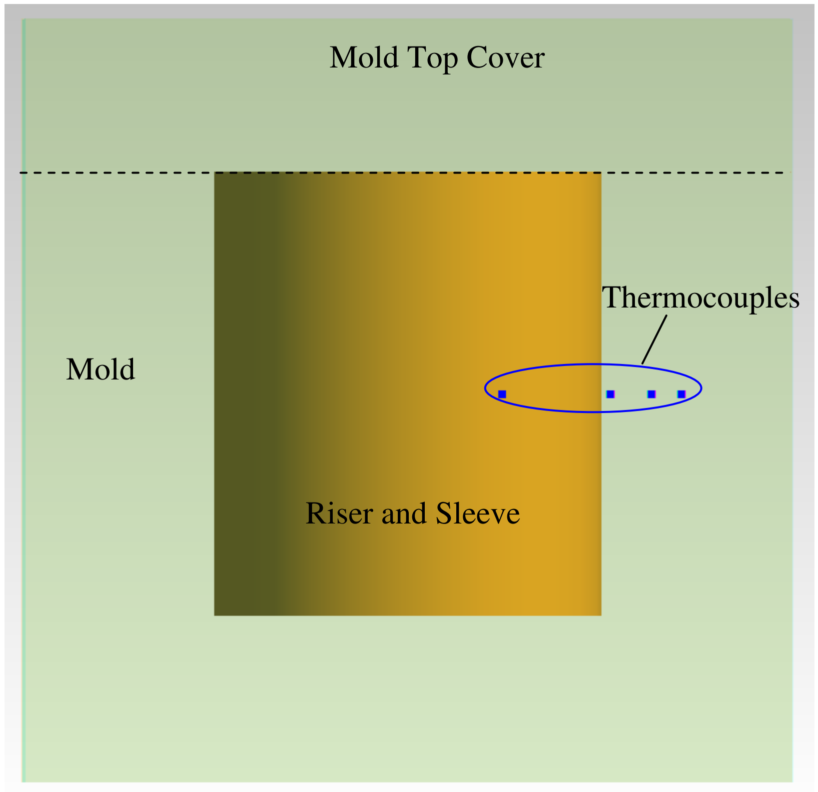


(a) Side View of Control Experiment

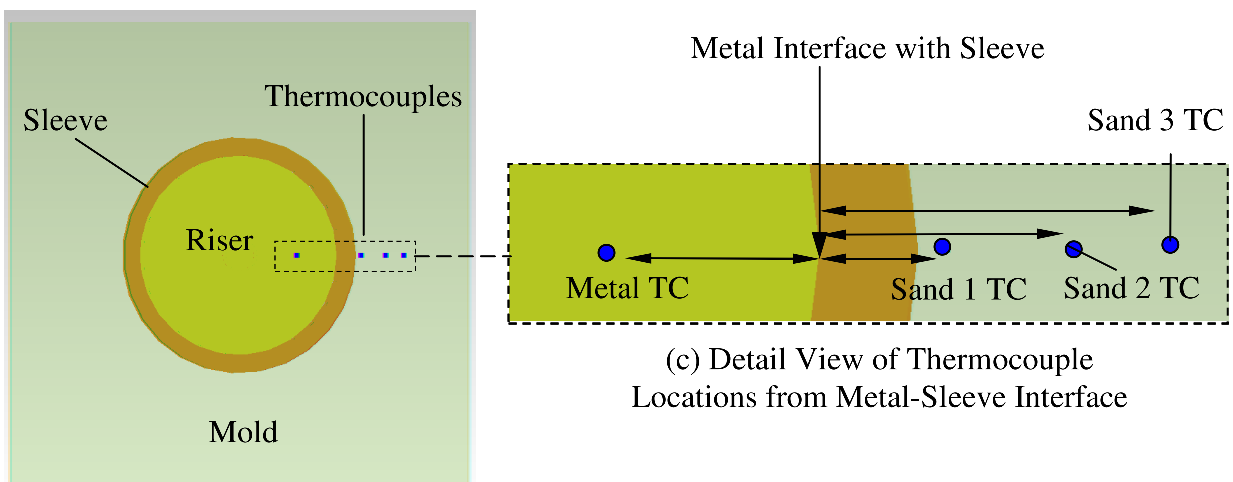
(b) Top View of Control Experiment

(c) Detail View of Thermocouple Locations from Metal-Sand Interface

Figure 2. (a) Side view and (b) top view of control experiment. (c) Detail view of the three thermocouples used in the control experiment and their positions as reported in Table 1 relative to the metal-sand interface.



(a) Side View of Sleeve Experiment



(c) Detail View of Thermocouple Locations from Metal-Sleeve Interface

(b) Top View of Sleeve Experiment

Figure 3. (a) Side view and (b) top view of a sleeve experiment. (c) Detail view of the four thermocouples used in the sleeve experiment and their positions as reported in Table 1 relative to the metal-sleeve interface.

Table 1. Sleeve types, riser dimensions and thermocouple positions relative to the steel-sand or steel-sleeve interfaces from the casting experiments.

					Thermocouple Distance from Metal Interface (mm)			
Experiment Casting #	Sleeve Type	Riser Diameter (in)	Sleeve Height (in)	Sleeve Thickness Measured (mm)	Steel TC	Sand 1 TC	Sand 2 TC	Sand 3 TC
1	No Sleeve	6	8		18	13	36	
2	Kalmin 70	2.5	6	10	20	16	33	46
3	Kalminex 2000	3.5	6	14	24	18	35	51
4	Kalminex 2000	6	8	15	26	18	36	51

Table 2. Chemistry of steel cast in sleeve and control experiments.

Chemical Composition (wt%)											
C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Al	V	Fe
0.43	1.0	1.91	0.02	0.012	1.48	0.05	0.35	0.12	0.06	0.02	94.55 (bal)

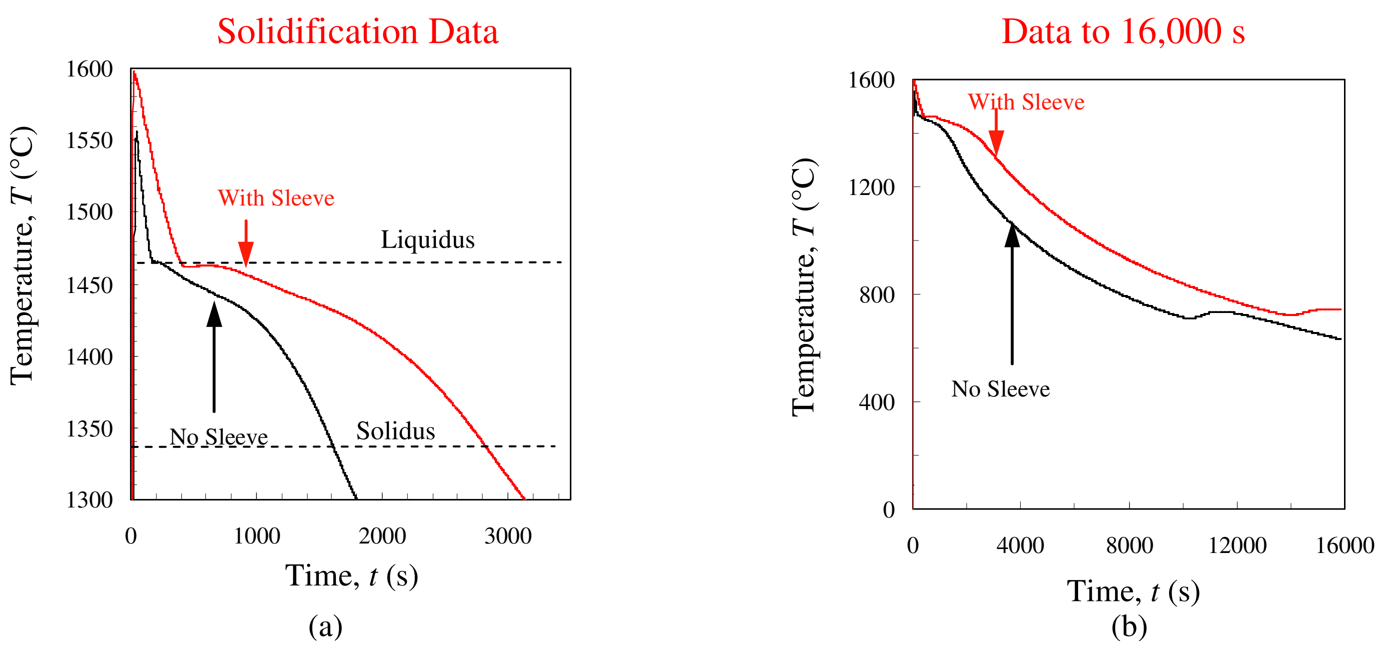


Figure 4. (a) Measured steel temperatures in solidification temperature range for control experiment without sleeve and Casting Experiment #4 with Kalminex 2000 exothermic sleeve, and (b) same temperature data over 16,000 seconds of the experiments.

III. RESULTS OF EXPERIMENTS AND SIMULATIONS

Note from Table 1 that the control experiment (without sleeve) and the larger Kalminex 2000 sleeve are the same size, 6 inch diameter and 8 inch height. These two cases provide a direct comparison of the effect a sleeve has on solidification time for the riser casting. This comparison is shown in Figure 4(a) for the solidification range and to 16,000 s in Figure 4(b). In Figure 4(a) the time to solidus without the sleeve is 1,596 seconds whereas with the sleeve it is 2,801 seconds. This demonstrates the impact a sleeve can have on increasing the effective thermal modulus of a riser. Note too in Figure 4(a) that the time to liquidus is also increased with the sleeve; it is 438 seconds with the sleeve and 173 seconds without.

The measured and simulated temperatures in the steel and sand mold for the control experiment are given in Figures 5 and 6, respectively. Here red curves give the measured data and black curves are the simulated temperatures. The overall agreement in the solidification temperature range is excellent. It was achieved by painstaking trial and error simulations, requiring over 100 simulations, adjusting steel and mold properties and boundary conditions within reasonable ranges. Baseline property data for the steel was determined by software prior to the trial and error simulations. Similarly, baseline data for the mold was taken from the *MAGMAsoft* database. A heat transfer coefficient versus temperature relationship was determined for the steel-sand interface, which accounts for a drop resulting from gap formation between the steel and sand due to thermal contraction. After the steel and mold thermophysical properties and the heat transfer coefficient at the steel interface were determined for the control experiment, they were not altered in the simulations of the sleeved riser experiments. The steel-sand heat transfer

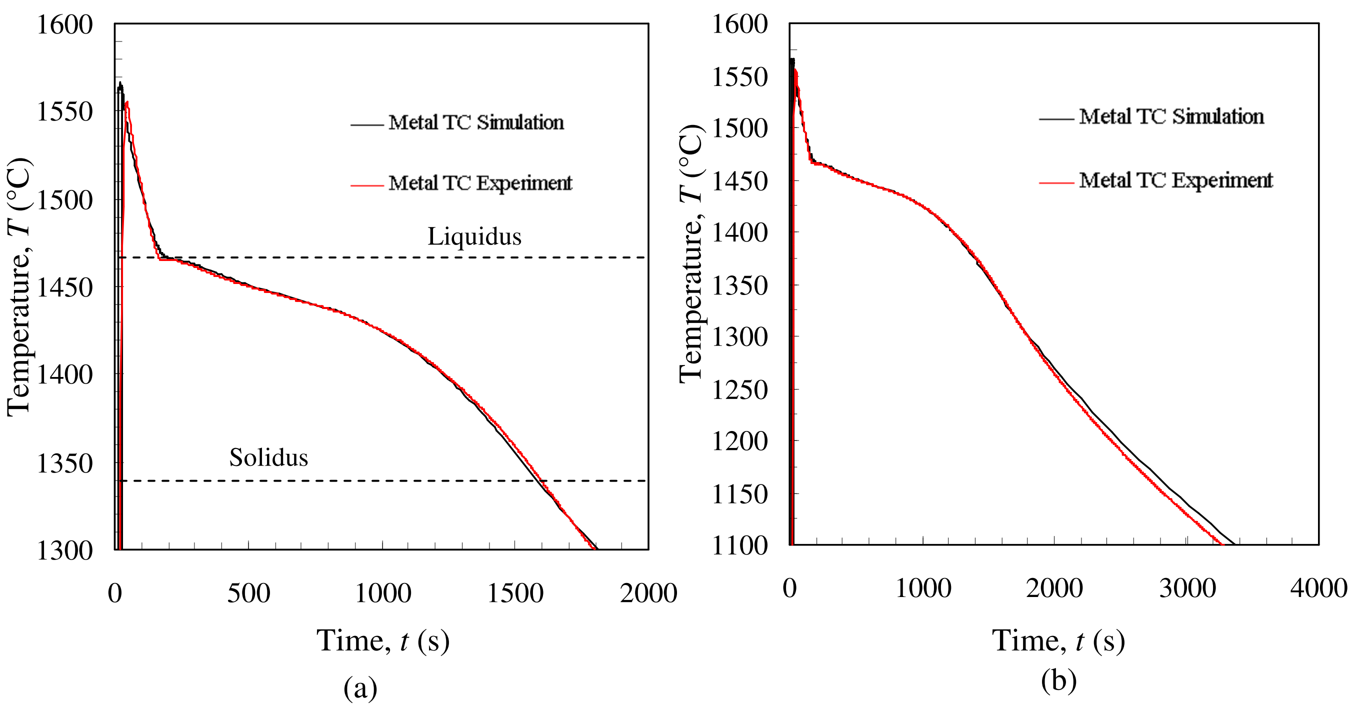


Figure 5. Measured and simulated temperatures in the steel for the control case using the properties and boundary conditions determined to give the best agreement for the steel and mold in the control case. (a) shows the solidification range temperatures, and (b) to 1100°C.

coefficient from the control experimented was used for the steel-sleeve heat transfer coefficient in the simulations with sleeves. The sleeve-sand heat transfer coefficient was set to 1000 W/m^2°C.

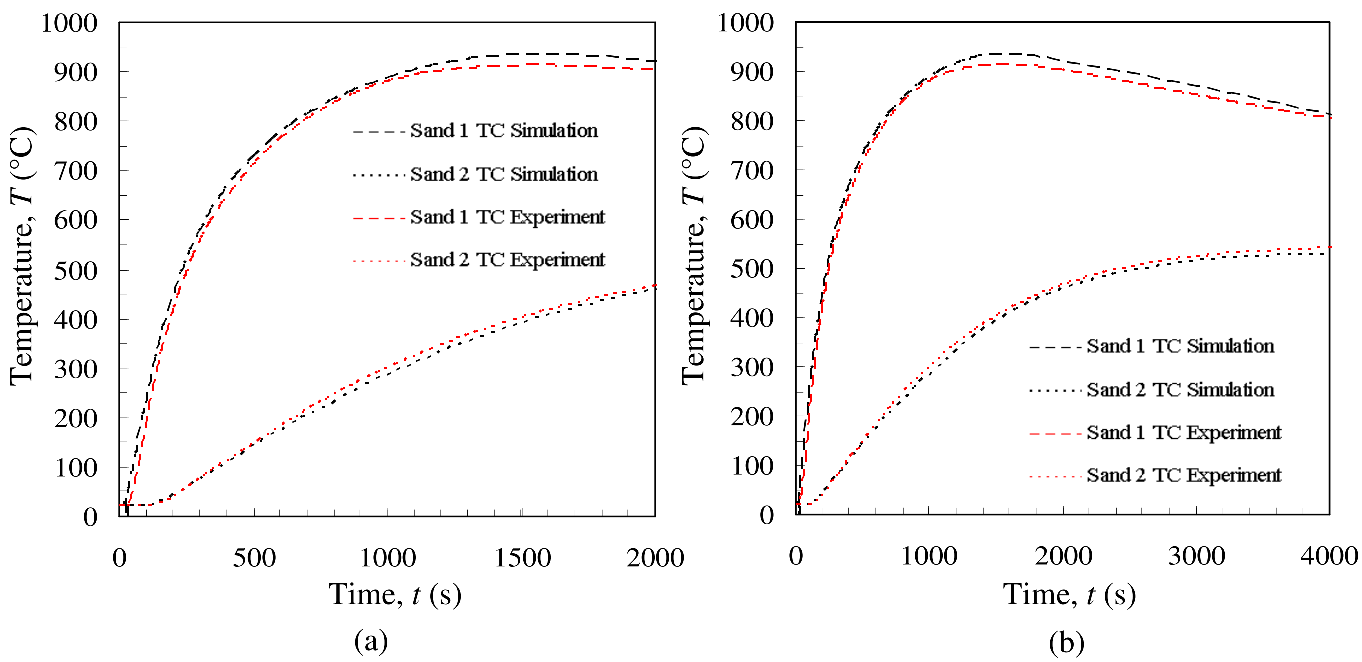
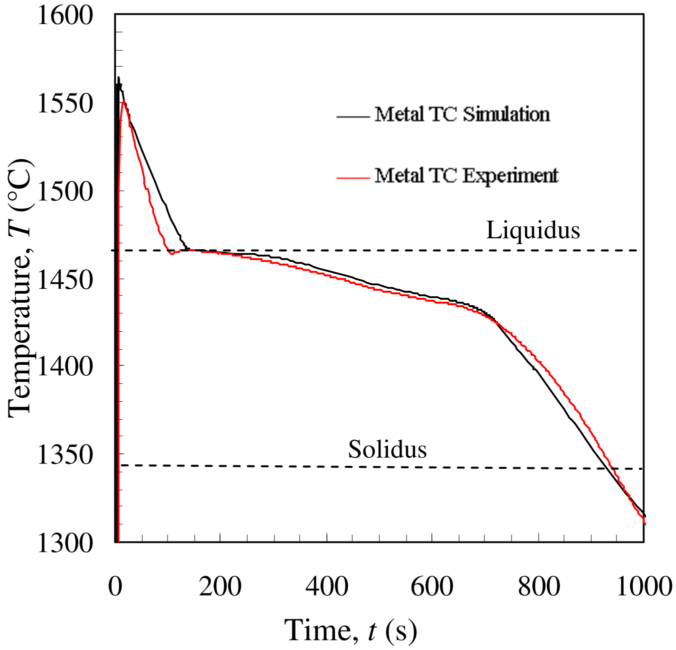


Figure 6. Measured and simulated temperatures in the sand mold for the control case using the properties and boundary conditions determined to give the best agreement for the steel and mold in the control case. (a) time scale to 2000 seconds, and (b) time scale to 4000 seconds.

Measured and simulated temperatures for the Kalmin 70 sleeve experiment in the steel and sand are given in Figures 7 and 8, respectively. These simulation results use the overall best property data determined for this sleeve at this point in the research program. One drawback observed in these results appears to be a slower cooling curve at longer times in Figure 7(b) than measured, and a slightly longer time to liquidus in the simulation in Figure 7(a). However, the overall the agreement is good, especially in the solidification range where accurate sleeve property data is most important. The sand temperatures shown in Figure 8 indicate that the simulations slightly under predict the measured temperatures.

Results for the Kalminex 2000 sleeve are interesting since the same sleeve properties must be used to simulate Experimental Castings #3 and #4 from Table 1, a smaller and larger sleeve, respectively. The exothermic properties used in the *MAGMAsoft* property database must also be determined for this sleeve. These exothermic properties are the burn time, ignition temperature and the heat of the exothermic burn (typically on the order of 1000 kJ/kg). At the time of writing this paper, the best determined Kalminex 2000 sleeve properties were used to simulate the results given in Figures 9 through 12. For the steel temperatures, the comparison shows a slight over prediction of the time to solidus in Figure 9, and a slight under prediction in Figure 11 for the larger sleeve. Again, considering the same properties are used in the predictions, the agreement with the measurements is good. Comparing prediction to measurement in the sand, Figures 10 and 12 show that there is an under prediction of temperature in the sand. The property data in the solidification range is excellent. These properties for the Kalmin 70 and Kalminex 2000 sleeves will be used in the casting yield study that follows investigating the role of sleeve type on casting yield for chunky and rangy shaped steel castings.



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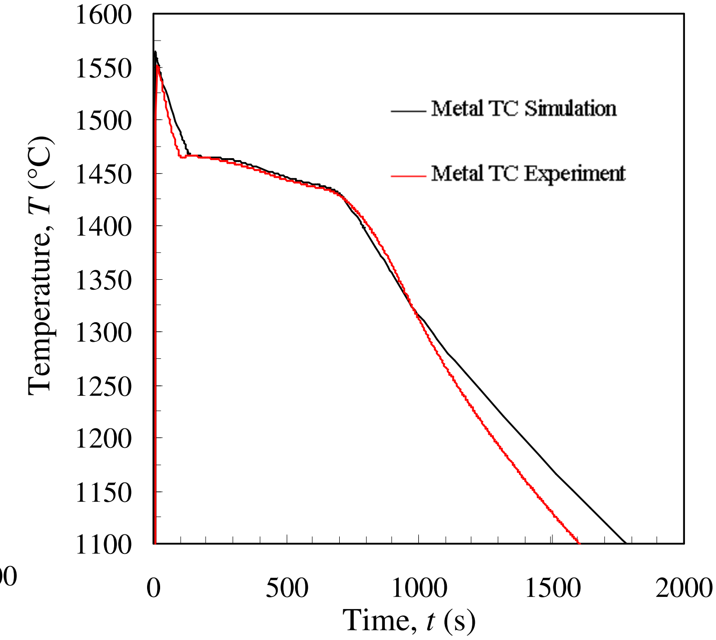


(b)

Figure 7. Measured and simulated temperatures in the steel for the Kalmin 70 sleeve case (experimental casting #2) using the sleeve properties determined to give the best agreement between them. (a) shows the solidification range temperatures, and (b) to 1100°C .

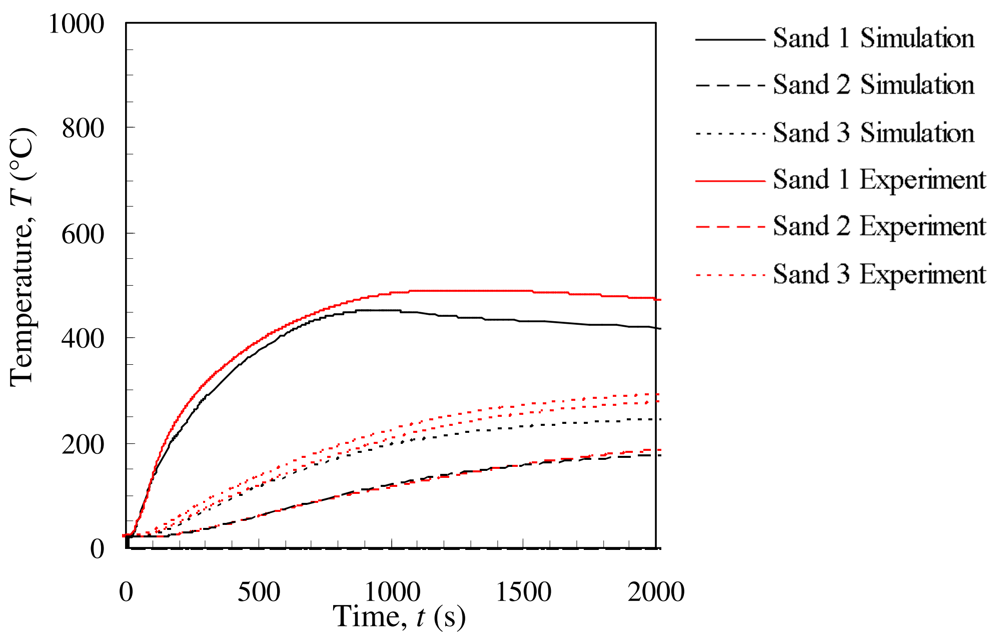
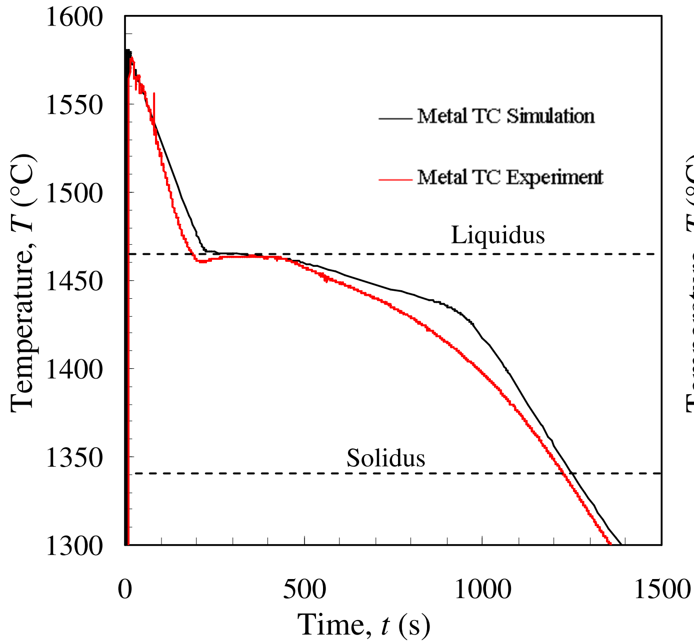
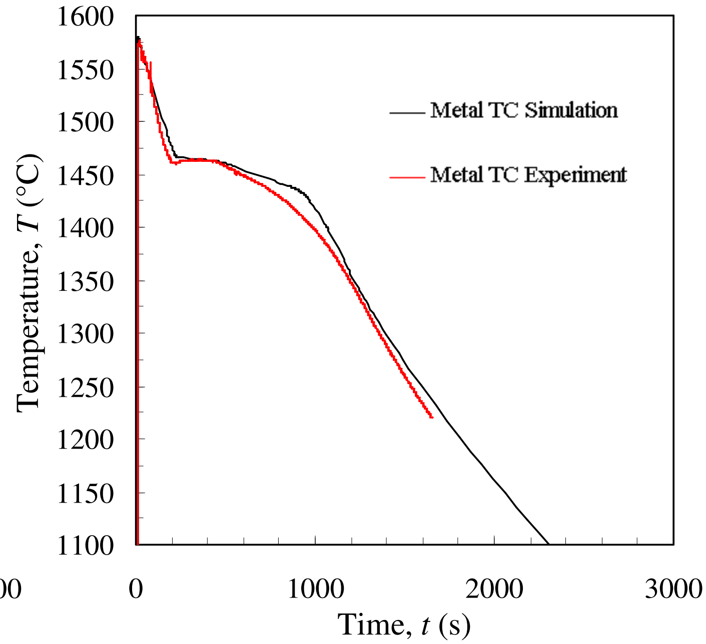


Figure 8. Measured and simulated mold temperatures for the Kalmin 70 sleeve case (experimental casting #2) using the best sleeve properties determined so far in the project.



(a)



(b)

Figure 9. Measured and simulated temperatures in the steel for the small Kalminex 2000 sleeve case (experimental casting #3) using the sleeve properties determined to give the best agreement between them. (a) shows the solidification range temperatures, and (b) to 1100°C .

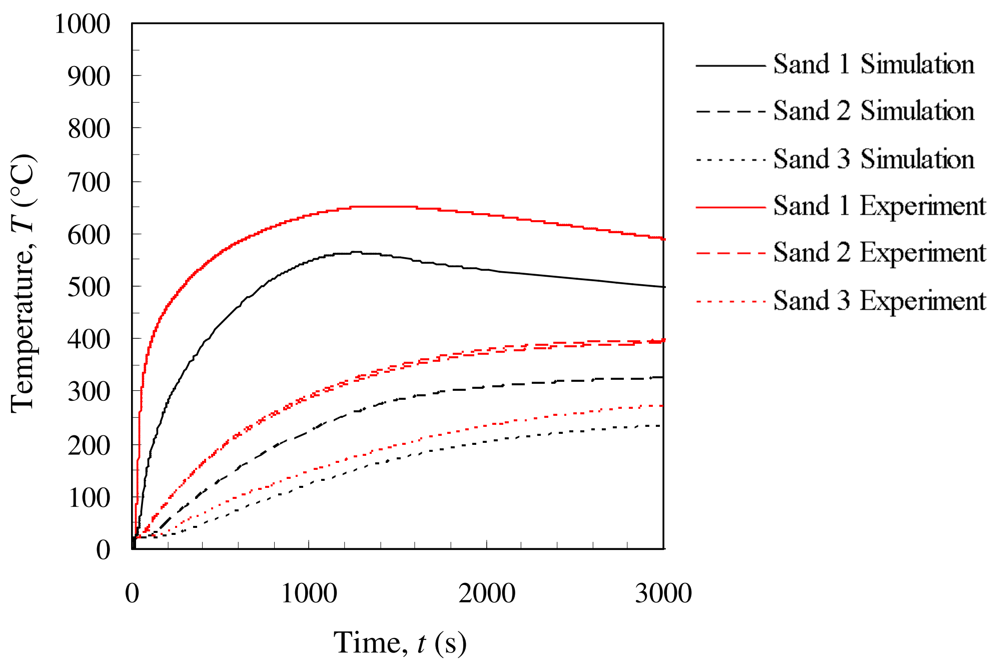


Figure 10. Measured and simulated temperatures in the sand mold for the small Kalminex 2000 sleeve case (experimental casting #3) using the best properties determined so far in the project for this sleeve.

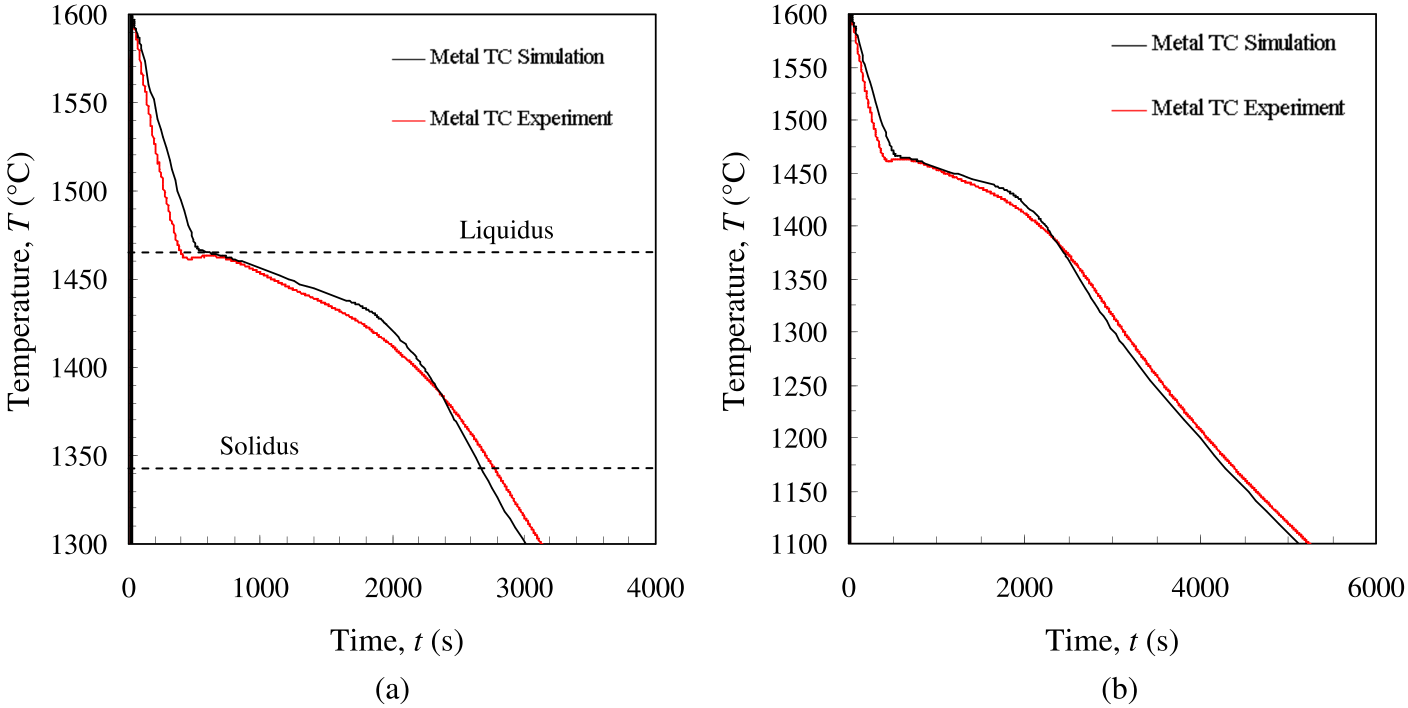


Figure 11. Measured and simulated temperatures in the steel for the large Kalminex 2000 sleeve case (experimental casting #4) using the sleeve properties determined for this sleeve, which were also used in Figures 9 and 10. (a) shows the solidification range temperatures, and (b) to 1100°C.

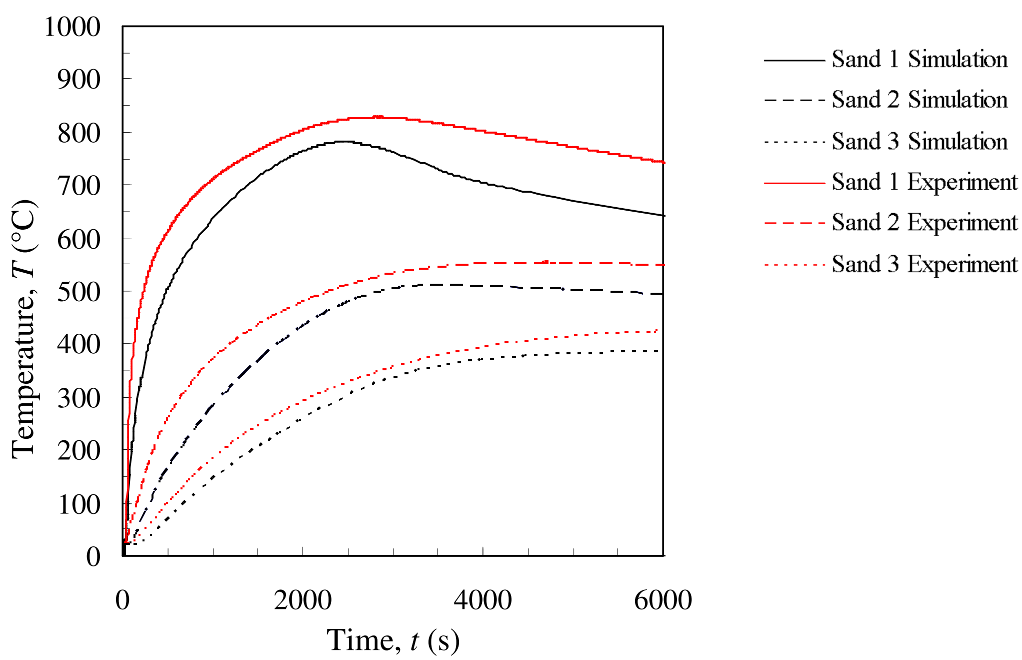
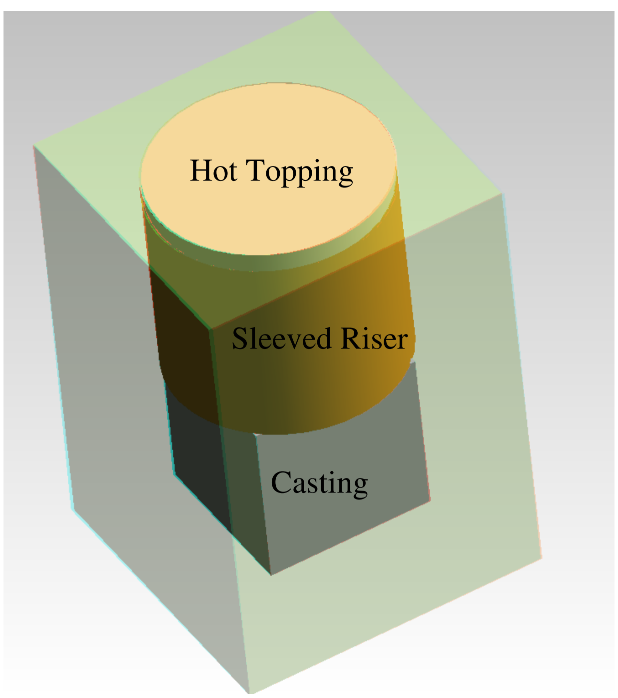


Figure 12. Measured and simulated temperatures in the sand mold for the large Kalminex 2000 sleeve case (experimental casting #4) using the best sleeve properties determined so far in the project. These were also used in Figures 9 and 10.

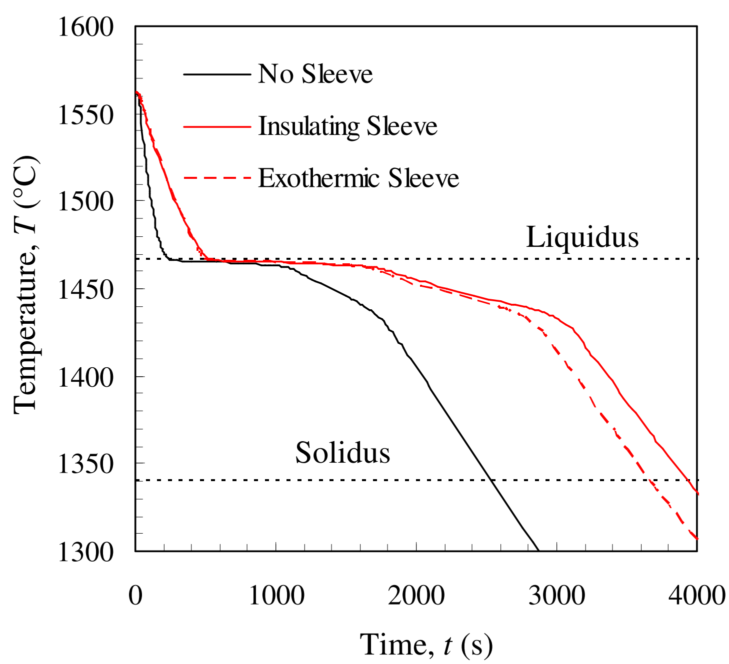
IV. EFFECT OF SLEEVE TYPE ON SOLIDIFICATION AND CASTING YIELD

Using the property data developed for Kalmin 70 and Kalminex 2000 as being representative of insulating and exothermic sleeves, respectively, a study was conducted on the effect of sleeve type on solidification time and casting yield. The solidification behavior for a 6 inch cube casting having a 7 inch diameter by 7 inch high riser was simulated without a sleeve, with an insulating sleeve, and with an exothermic sleeve. This case study casting, and riser with sleeve is shown in Figure 13(a), and is representative of a "chunky" casting. As shown in this figure, hot topping was used in the three simulations cases. The solidification curves for the three cases are shown in Figure 13(b), where the insulating sleeve has the longest time to solidus. The location of the thermocouples for these solidification curves is the riser center at mid-height. The times to solidus in Figure 13(b) for the three cases are 2538 seconds, 3664 seconds and 3938 seconds for the no sleeve, exothermic sleeve and insulating sleeve cases, respectively. The riser piping and safety margins for these three cases are shown in Figure 14. Here the insulating sleeve also appears to perform the best in terms of safety margin, since it is slightly larger than the exothermic sleeve case. In general, the shrinkage piping of the two sleeved cases looks very similar.

A more detailed study was undertaken to study the effect of sleeve type on casting yield. As discussed by Blair in [5] the steel foundry industry has wide ranging opinion on when to use insulating riser sleeves and exothermic sleeves. To help foundries make an informed decision, a study needed to be performed to address the following questions: 1) Is one sleeve type better for given shape or ranginess of casting? 2) Is one type better as riser volume increases? 3) How much yield improvement results from using sleeves? From the perspective of this study, higher casting yield will be used to define which sleeve is better than the other.



(a)



(b)

Figure 13. (a) Cube casting having 6 inch sides and riser with sleeve and hot topping used in solidification behavior case study, and (b) solidification curves for the case study without and with sleeves.

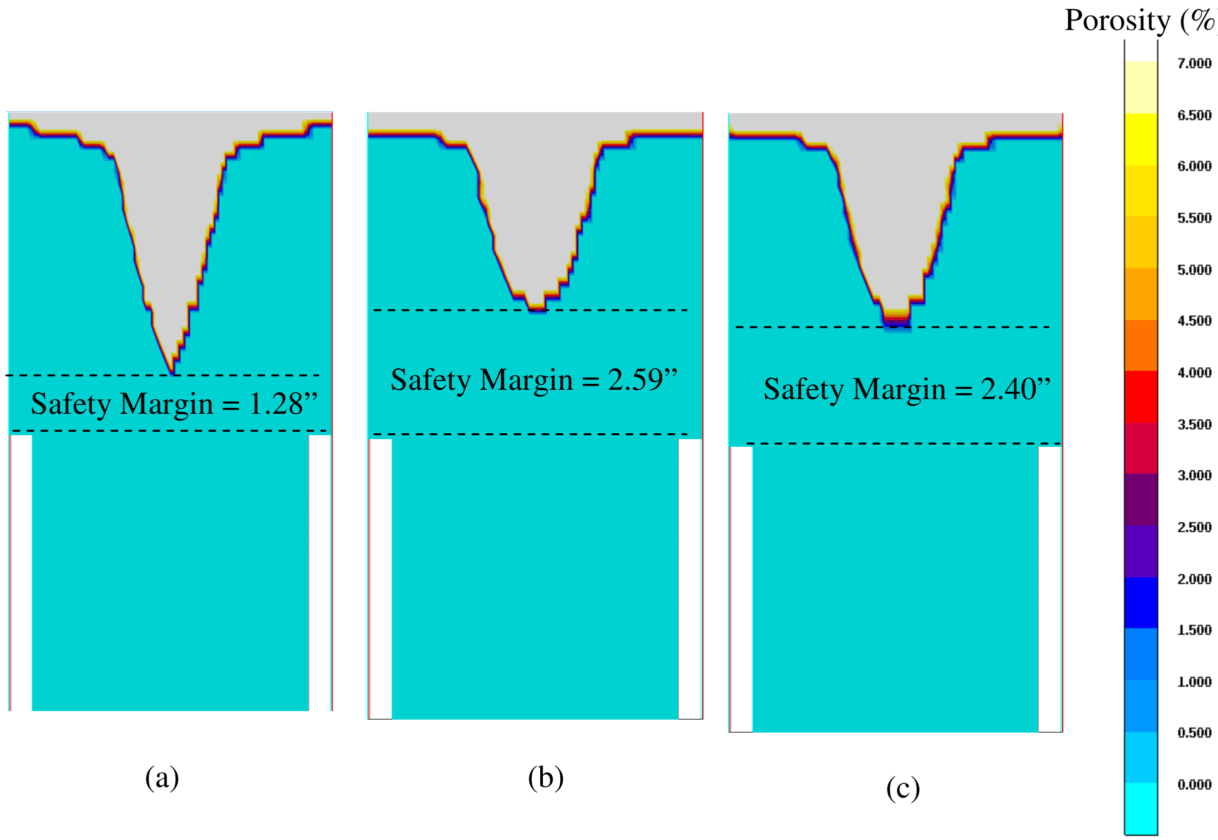


Figure 14. Riser safety margins and shrinkage porosity piping at center of casting and riser for case study castings with (a) no sleeve, (b) insulating sleeve and (c) exothermic sleeve.

In this casting yield study, for given casting shape or ranginess, and size, simulations were run to find the smallest cylindrical riser feeding the casting soundly given a number of constraints. The casting yield for the smallest riser meeting the constraints was then calculated for varying casting volumes and ranginess without and with the riser sleeves. One constraint on the riser geometry was that it have a 1:1 height to diameter ratio. Another constraint was that the riser should have a safety margin of 10% of the riser height. *MAGMAsoft* simulations were performed using a feeding effectivity value of 70% for the riser piping predictions.

Casting ranginess was used to define the casting shape effect in the sleeve yield study. The casting ranginess R is defined as the side length s to thickness t ratio as shown in Figure 15 for the two shapes examined in the casting yield study. In Figure 15(a) the cube shape and its ranginess $R = 1$ is defined, and in Figure 15(b) the square plate having a ranginess of $R = 15$ used in the study is defined. The size of the casting in the casting yield study is defined by the cube root of the casting volume. This is equivalent to comparing the volumes of the castings, but since the resulting value is a length dimension it is more intuitive for our casting "size" measure. Using the two types of casting shapes/ranginess shown in Figure 15, eight cases of varying sized castings were chosen for the yield study as given in Table 3. Note in Table 3 that the same casting volume range is covered by both the shapes.

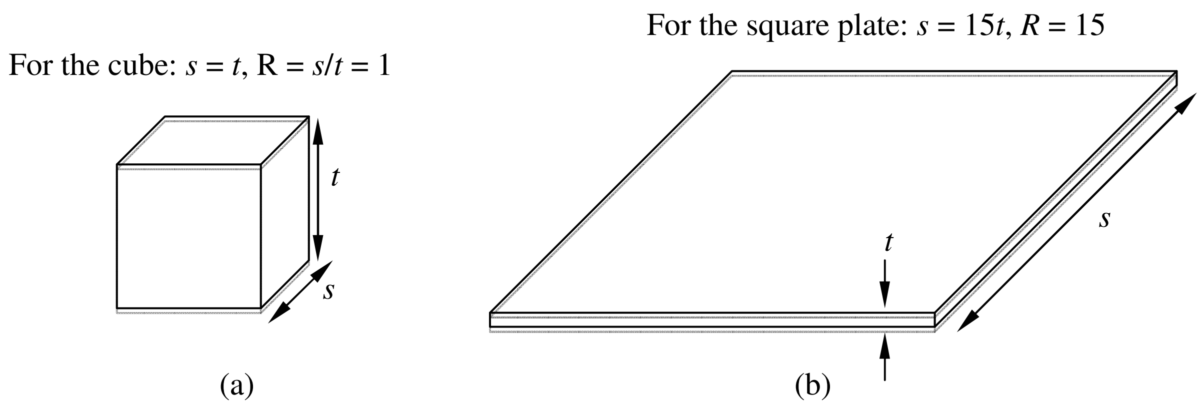


Figure 15. Ranginess defined for the two casting shapes used in the casting yield study (a) the cube and (b) the square plate.

Table 3. Simulated casting cases and dimensions used in the sleeve casting yield study

Simulation Cases										
Ranginess	Shape	Dimensions	Lengths (in)							
1	Cube	s	3	6	9	12	15	18	21	24
15	Square Plate	s	7.5	15	22.5	30	37.5	45	52.5	60
		t	0.5	1	1.5	2	2.5	3	3.5	4

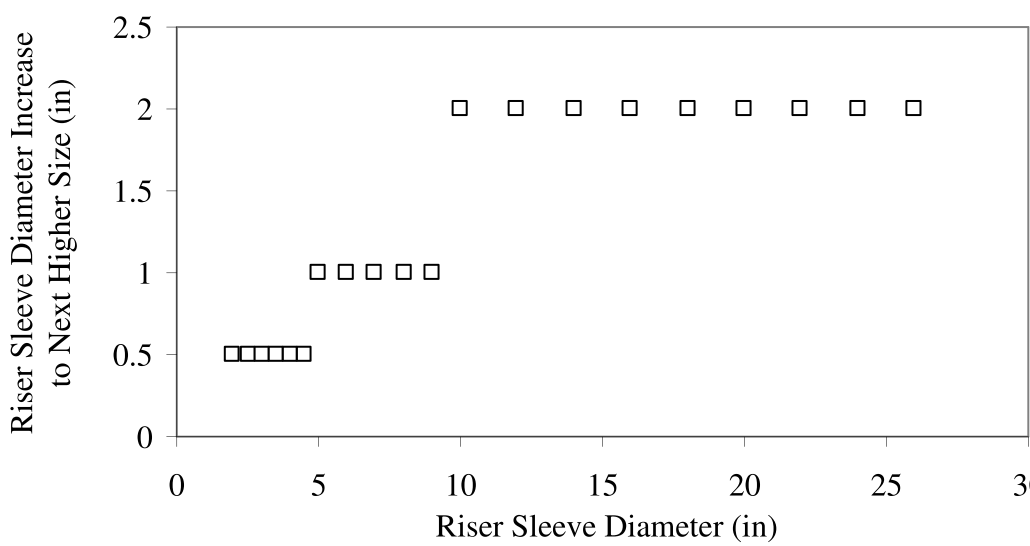


Figure 16. Riser diameters and riser diameter incremental size difference to next higher size used in the sleeve yield study according to available sleeve diameters taken and extrapolated from *MAGMAsoft* Foseco Pro sleeve database .

Incremental riser sizes were used in the sleeve casting yield study. This reflects the reality that risers sleeve sizes are discrete. These sizes were determined according to available sleeve diameters taken and extrapolated from Foseco Pro database in *MAGMAsoft* as shown in Figure 16. Note in Figure 16 that for risers sleeves up to 5 inch diameter the increment between sizes is 0.5 inches, between 5 and 10 inch diameter the size increment is 1 inch, and over 10 inches the increment is 2 inches. These riser size increments will result in fluctuations in the casting yield results to be presented later caused by the shifting to the next higher or lower riser size.

The riser sleeve thickness and thickness of hot topping used in the sleeve yield study were also predetermined as functions of the riser size. The relationship for sleeve thickness versus riser sleeve diameter used in the yield study was established by first examining the sleeve size data from the Foseco database shown by the thick black line in Figure 17. Based on this a linear approximation to this riser sleeve thickness versus diameter data was used in the study as is shown in Figure 17(a). The relationship for riser sleeve thickness is: $t_{Sleeve} = 0.063D + 0.202$ where D is the riser diameter and t_{Sleeve} is the sleeve thickness in inches. Hot topping was used in all simulations and the thickness of the hot topping layer thickness versus riser diameter relation used in the study is shown in Figure 17(b).

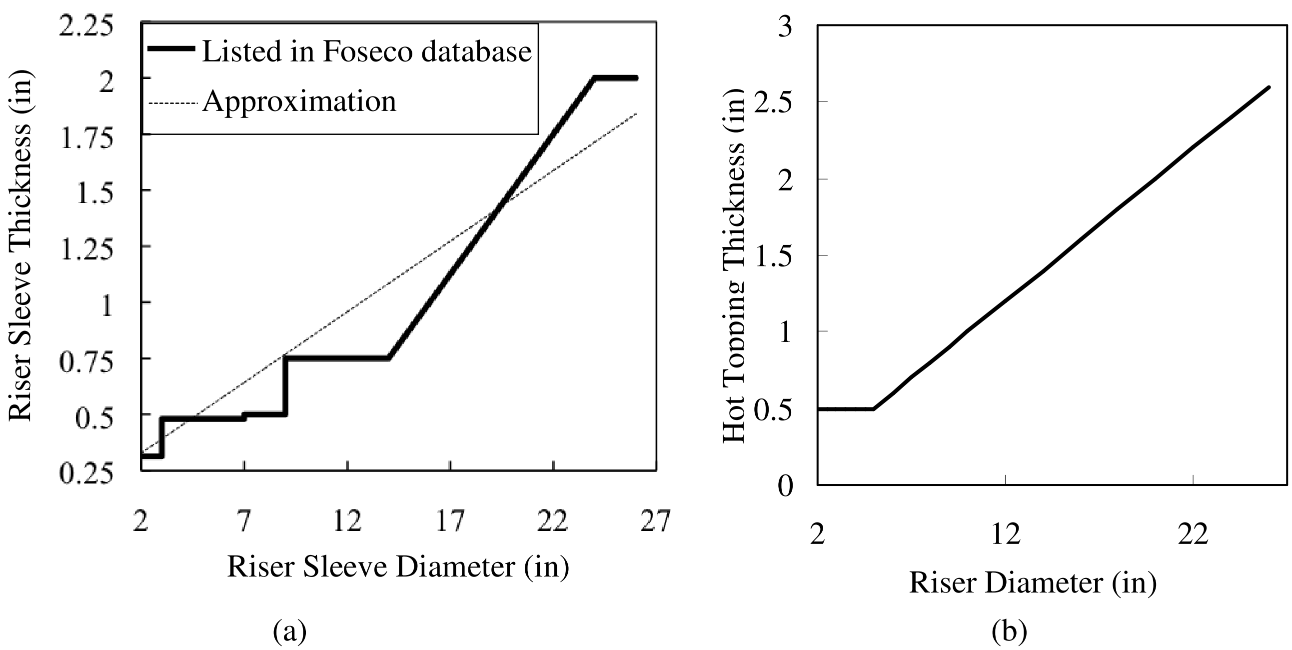
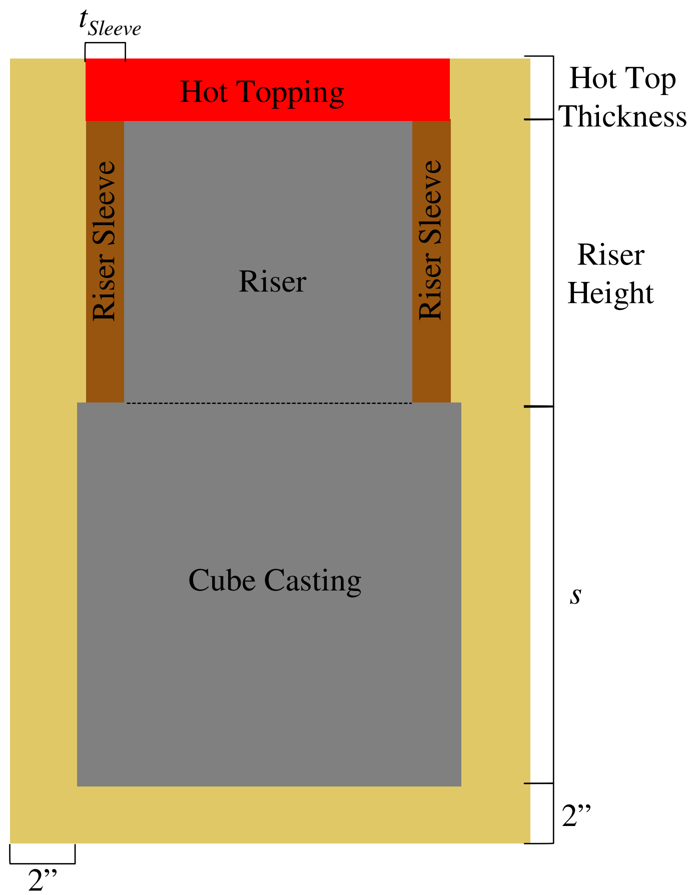


Figure 17. (a) Data and linear approximation for thickness of riser sleeve versus riser diameter used in the yield study, and (b) hot topping layer thickness versus riser diameter relation used in the study.

As mentioned earlier, the casting yield is determined for a given casting in Table 3 with and without riser sleeves such that the riser safety margin (indicated in Figure 14) is 10% of the riser height. Due to the increments in riser diameters this safety margin was not always achievable so in some cases a riser size that gave the closest safety margin to 10% while being greater than 10% was used. The riser pipe and safety margin were determined by the porosity level of 0.7% and greater in the riser pipe. The relative sizes of the mold and casting were handled by increasing the mold size as the casting size increased such that the mold dimensions were always 2” thick around the periphery of the casting, as shown in the diagrams of the simulation geometries in Figures 18(a) and (b).



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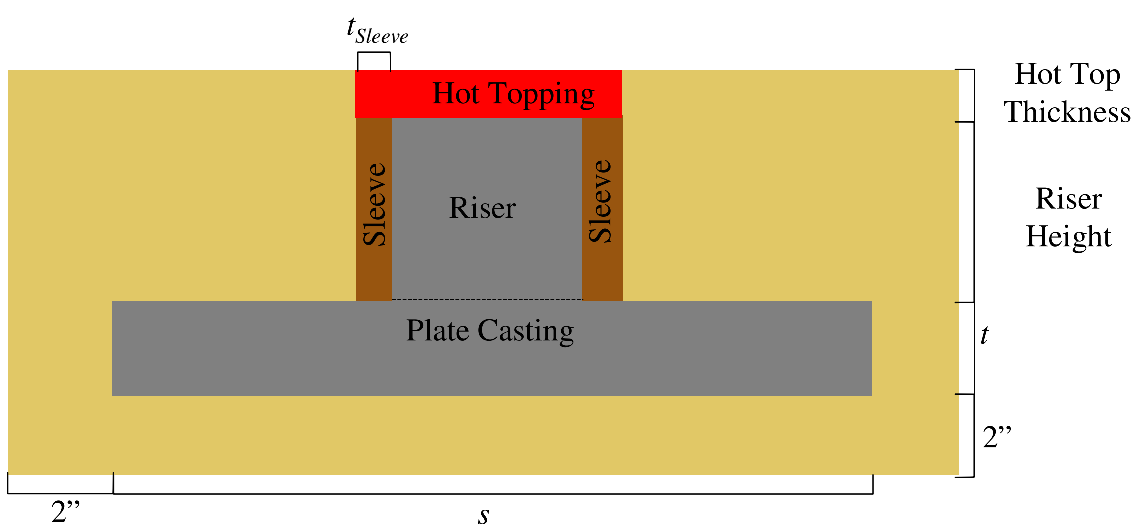

(b)

Figure 18. Diagrams of the simulation geometries for the sleeve casting yield study for (a) the cube shaped casting and (b) the square plate casting.

Results of the sleeve casting yield study are shown in Figure 19 with casting yield plotted against the cube root of the casting volume. For the cases without sleeves (the black curves), the cube casting yield is much lower (around 45%) than the plate casting (around 80%). This is not too surprising due to the much higher modulus for the cube casting, and hence a larger riser required to soundly cast a given volume for the cube shape. For the plate shape with sleeves, there was no difference in yield between the cases with the insulating and exothermic sleeves, and these red and blue dashed curves are seen follow each other in Figure 19. There is also a gradual drop in yield from 90% to 85% for these *R* = 15 sleeve cases as the casting size increases, and the yield is moderately increased over the plate casting without sleeve. For the cube casting with the sleeves, the exothermic and insulating curves track each almost identically. The only difference between them appears where the $\sqrt[3]{Casting\ Volume}$ is about 5 inches, and here the insulating sleeve gives a slightly higher yield. The fluctuations in the yield are due to the risers having discrete sizes. These fluctuation are more pronounced for the cube castings with and without sleeves, but minor fluctuations are also seen in the plate castings with sleeves.

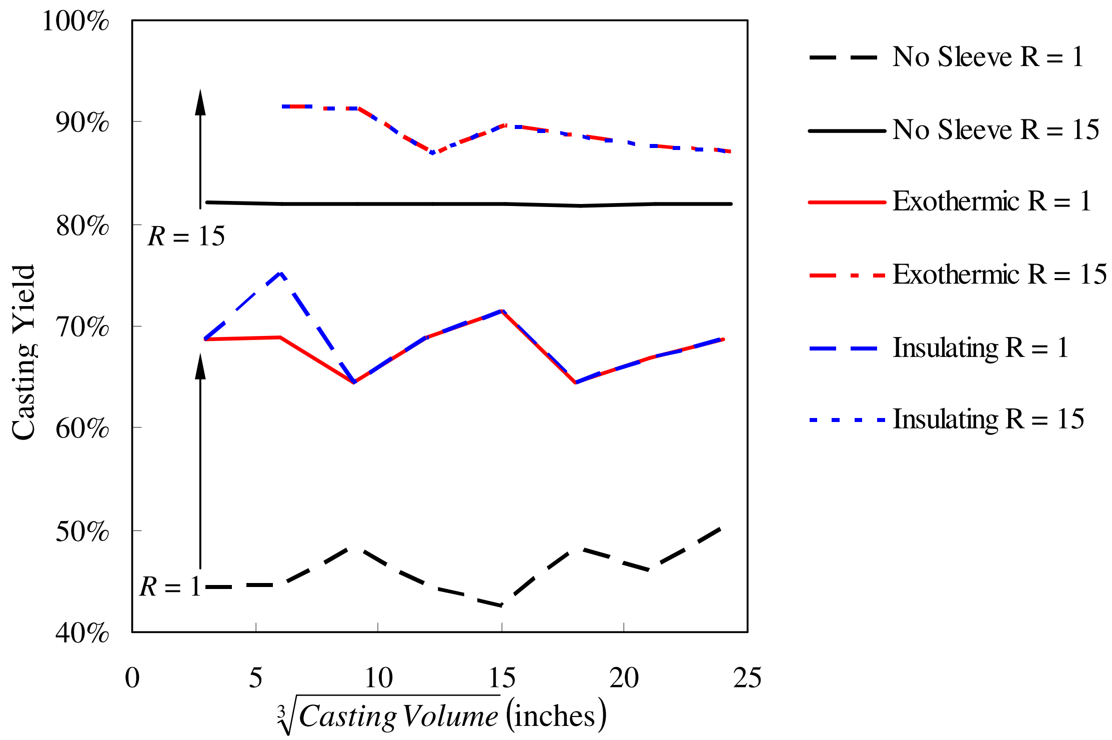

Figure 19. Casting yield versus cube root of casting volume results from the sleeve casting yield study. Cases with and without insulating and exothermic sleeve are given with each case used for a rangy casting (square plate with *R* = 15) and a chunky casting (cube with *R* = 1).

CONCLUSIONS

Thermophysical properties of insulating and exothermic riser sleeves are being developed to accurately predict their performance in casting simulation software. There is little such property data currently available that is open to the software user. Here results of a study to determine sleeve thermophysical properties were presented where good agreement was demonstrated between measured and predicted steel temperatures for castings using Kalmin 70 and Kalminex

2000 sleeves. Development of the temperature dependent sleeve properties required hundreds of simulations. Measured and predicted temperatures for castings with insulating and exothermic sleeves are compared to a control experiment with no sleeve, and demonstrate the effectiveness of the sleeves. Thermophysical properties for the insulating and exothermic sleeves were used in solidification and casting yield studies comparing the performance of the sleeves in castings having cube and plate shapes. Based on the exothermic and insulating properties determined, there was very little difference between the casting yields resulting from using either type of sleeve. A solidification study was performed using a 7 inch diameter riser that showed that the exothermic sleeve increased the time to solidus by 44%, and the insulating sleeve by 55%, over the un-sleeved riser case. While the research conducted in this project is still preliminary, and ongoing, the results are encouraging and demonstrate that greater confidence in the solidification modeling of steel castings using sleeves is possible through development of sleeve properties. In addition, the developed sleeve properties can be used in simulations to determine better guidelines for when to use riser sleeves, and which sleeve type is best for a given application.

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