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THERMOPHYSICAL PROPERTIES AND PERFORMANCE OF RISER SLEEVES FOR STEEL CASTINGS

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Abstract

Riser sleeves are a popular feeding aid used in the metal casting industry. Reliable simulation of the performance of riser sleeves requires accurate temperature-dependent thermophysical properties. Unfortunately, there are little or no property data available in the open literature. A procedure for developing thermophysical properties of riser sleeves for steel castings is presented here along with its results. Analyses are performed using these sleeve properties to investigate optimal sleeve use. The modulus extension factor (MEF), which quantifies sleeve performance, is calculated for sleeve materials. Regardless of casting size studied here, the MEF determines casting yield improvement when using riser sleeves, and exothermic reactions do not necessarily increase yield unless they increase the MEF. Analyzing the effect of sleeve thickness on casting yield, it is found that the thicknesses of most commercially available riser sleeves are too small to maximize casting yield, particularly for risers of 8 in. diameter and larger.

Keywords: *steel casting, riser sleeves, thermophysical properties, sand casting, casting modulus, casting yield*

Introduction

The riser sleeve is a reliable tool for increasing casting yield, and its use is ubiquitous throughout the metal sand casting industry. It is estimated that about 80 % of all steel castings are produced using riser sleeves.[1] Riser sleeves used in steel casting are generally formulated as purely insulating or exothermically insulating, where a thermite reaction is typically used for heat generation. In short, they are referred to as *insulating* or *exothermic* sleeves. Despite the extent of sleeve use, a survey of foundries found that there is a lack of consensus on the use of riser sleeves.[1] Sleeve suppliers use different raw materials of unknown and proprietary compositions and properties in their manufacturing processes. The suppliers provide mostly unsubstantiated guidance on sleeve use. As a result, application of riser sleeves in foundries is largely based on trusting suppliers, guesswork, and trial-and-error testing.

There are little quantitative data provided to foundries for deciding which sleeve, from which supplier, is most effective for a given casting application. Most foundries use computer casting simulation to determine riser sizes. However, the sleeve material thermophysical properties required as input data for simulations are either not available or are provided by a limited number of suppliers for their products as "black box" databases. These "black box" property databases also include supplier recommended temperature-dependent heat transfer coefficients between various casting system materials (i.e., the casting–sleeve and sleeve–mold interfaces); these are also hidden from the user. The accuracy of these properties and coefficients is unknown. The foundry trusts that the suppliers' databases are accurate. Since the "black box" property data are hidden from the software user, thorough calibration using measured temperatures to validate the data for a given foundry's casting practice is not possible. Finally, since the details of the thermophysical properties are unknown, the physical basis for one sleeve to be superior to another for a given application is unknown.

The authors estimate that if the thermophysical properties of riser sleeve materials were known accurately, selection of riser sizes could be optimized such that the steel foundry industry's casting yield could be increased by up to 10 %. The resulting energy savings would be about 1.5 trillion BTU per year for the US steel foundry industry. Significant additional benefits would arise from improved quality, reduced costs, and increased production capacity.

Literature on riser sleeve material properties and their measurements is scarce or incomplete if available. Older literature presents some data on sleeve performance and the effect of sleeves on cooling history and solidification time, riser modulus, and riser piping.[2–5] More recently, temperature-dependent curves for density, specific heat, and thermal conductivity of several sleeves have been published,[6] but these curves are incomplete. The plots of data in this work give no numerical values and only provide the reader trends of the properties' dependency on temperature. Because of the lack of property data for accurate simulation, foundries have developed their own practices for using riser sleeve products, such as deciding when to use an insulating or exothermic sleeve.[1] Some sleeve manufacturers have provided sleeve material properties to users of certain casting simulation software. However, these are proprietary data and hidden from the user.

Casting modeling software[7] is used in this study with measurements to determine datasets of temperature-dependent sleeve material properties. The property datasets are developed by minimizing the difference between experimental temperature data recorded during casting trials and simulation temperature results through iteratively modifying the sleeve material properties used in the simulations; until sufficient agreement is achieved. Such a property estimation technique is generally referred to as *inverse analysis*.

Ignaszak et al.[8,9] applied the inverse analysis approach to sleeve and sand mold material property estimation. Rather than develop temperature-dependent data, they determined average exothermic sleeve material property data (single values) for use in simulation. Their experiments were similar to this work, where cylindrical castings were poured. They placed two temperature sensors in the metal of each cylinder: one at the centerline and one 30 mm from the outer diameter. In the experiments, one cylinder was cast without a sleeve, from which properties of the mold and metal were estimated. In this work, experimental castings without sleeves are referred to as *control* castings. The property data determined by Ignaszak et al. are for sleeve materials they describe as "insulating-exothermic" and are labeled in their work as "L2" and "L5." The relevant property data they determined for the sleeve materials are: heat capacity, $\rho c_p = 560$ and 500×10^3 (kJ/m^3 K), thermal conductivity, $k = 1.09$ and 0.98 (W/m K), exothermic heat generation = 2257 and 1857 (kJ/kg), and exothermic ignition temperature 150 (°C), respectively, for the "L2" and "L5" sleeves. Ignaszak et al. acknowledge that this ignition temperature is "relatively low" but mention that it produced the lowest error between measured and simulated temperatures in the inverse modeling.

The primary objective of this work is to determine thermophysical properties for riser sleeve materials for use in casting simulation. Properties are determined here for thirteen sleeve materials from five manufactures, with nine of the sleeves described as exothermic and four sleeves as insulating. The sleeve materials in this study are commonly used, as identified by a survey of sleeve use by SFSA member foundries.[10] They account for approximately two-thirds of the sleeve materials used by the surveyed foundries. The properties are determined via inverse modeling using temperature measurements acquired during solidification of cylinder-shaped steel castings. The sleeve material properties are determined such that the error between measured and simulated temperatures is reduced to the smallest error obtainable. After the sleeve material properties are determined, parametric studies are carried out to investigate how sleeve material properties and characteristics impact sleeve performance and casting yield. A method of quantifying sleeve performance is proposed and described using the modulus extension factor. This yield study investigates how exothermic and insulating sleeve characteristics influence riser size and casting yield. Finally, the effect of sleeve thickness on sleeve performance for increasing casting yield is evaluated, and observations are made on the optimal sleeve thickness for maximizing casting yield. The optimal thickness determined from this study is compared with those from commercially available sleeve sizes.

Casting Experiments

Sleeve thermophysical properties, such as the thermal diffusivity, could theoretically be measured in a laboratory using well-established techniques.[6] However, such bench top sleeve material property measurements do not include and capture all physical phenomena occurring when a sleeve is used in an actual casting process. These physical interactions occur because of the presence of all materials in the casting system and should not be ignored. In a real casting process, physical phenomena such as the gases evolved by the sleeve and sand mold binders influence heat transfer in materials and at the interfaces between materials. Gases evolved will travel through the permeable sleeve and sand mold in effect boosting the thermal conductivity. Also, sleeve properties before and after exothermic reactions are expected to be different since the sleeve material undergoes noticeable changes. It seems reasonable that this would introduce a hysteresis-like effect in the sleeve properties, since properties will be different after reacting than before. The same can be said for properties of insulating sleeves before and after their binder burns off. Other processes, such as riser dilation, will also affect sleeve performance. By using an actual casting experiment, interactions of the materials in the casting system like these are accounted for in the property determination of all materials in the casting system. Through the use of the inverse modeling approach, effective sleeve material properties and boundary conditions for modeling sleeves are determined for an actual casting situation. These properties and boundary conditions allow for realistic simulation of casting solidification and cooling. In addition, the accuracy of the properties developed can be readily evaluated in the process of comparing measured and predicted temperatures as the properties are developed.

In order to apply the inverse modeling, experiments were performed to measure temperatures during solidification of cylinder-shaped steel castings. Thermocouples are used to record temperature data in the steel, riser sleeve, and sand mold as the casting cools. The casting experiments were performed over multiple steel heats of approximately 300 pounds each. For each experimental heat, a control casting with no sleeve was poured. From the control casting experiment, temperature-dependent properties and solidification parameters for the mold and metal were determined for each heat of steel. In addition to the control casting, in each experimental heat between two and five cylindrical castings with sleeves were poured depending on the sizes of the sleeves used. In order to ensure that the temperature measurements were repeatable, two nominally identical castings were poured for each sleeve type, except in a few cases where redundant thermocouples were used instead. Using the steel and mold properties determined from the control experiment, simulations were run for the sleeved cylinders. In these simulations, the thermophysical properties of the riser sleeve materials were adjusted until the error between the measured and simulated temperatures for the sleeve experiments was reduced to the smallest error obtainable.

The control casting in each heat ensures that accurate steel and sand mold properties are used in the simulations. A schematic diagram of the experimental setup for a control casting is shown in Figure 1a. Silica sand molds with a 1.25 % polyurethane no-bake binder were used in all experiments. A cope consisting of 2 in. thick bonded sand was used for all castings to maintain a similar heat loss through the top surface of the castings. The cope was fixed to the drag portion of the mold before pouring. The castings were filled using a pouring cup that was placed on top of the mold and drained to a 1″ sprue that passes vertically through the cope. All castings were poured using an ASTM A216 Grade WCB steel. The liquidus and solidus temperatures, found from steel temperature measurements, ranged from 1470 to 1505 °C (2678–2741 °F) and 1340 to 1410 °C (2444–2570 °F), respectively. These variations stem from slight differences in the composition of the heats. A diagram of a sleeve casting experiment is shown in Figure 1b to be identical to that of the no-sleeve castings, with the addition of a sleeve to line the inner cavity. All sleeves investigated in this work as well as dimensions for the corresponding casting experiments are listed in Table 1. Sleeves in Table 1 are labeled with a sleeve material identifier code designating a manufacturer (letters A through F), sleeve material type (number following the letter) and whether the sleeve is insulating (using—I) or exothermic (using—E).

Thermocouples (TCs) are placed in the steel, sleeve, and sand mold to measure temperature–time data in all materials. The thermocouple placed in the sleeve provides data for the detection and determination of exothermic properties of sleeves. As diagramed in Figure 1a, b, two type-K thermocouples were used in the sand mold, and type-B platinum–rhodium thermocouples encased in a thin quartz tube were used to measure temperatures in the steel and sleeve. An analysis of the effect of the quartz tube, including estimates of the measurement uncertainty and the dynamic response, showed that the temperature measurements are reasonably accurate.[11] All thermocouples were positioned at approximately the riser mid-height. The sand mold thermocouples were positioned approximately 10 and 20 mm from the mold–steel or mold–sleeve interfaces. The thermocouple in the metal was positioned approximately 50 mm from the metal–mold or metal–sleeve interfaces, such that the initial cooling from pouring to liquidus temperature, and the liquidus temperature and start of solidification could be sensed. The thermocouple positions varied slightly experiment-by-experiment due to the limitations of instrumenting the molds in a foundry setting; the average position variation was 2 mm, and the maximum was 5 mm. However, the final TC positions were carefully measured in each experiment before pouring and were recorded for each experiment so that TC locations in the simulations matched the experiments as closely as possible. Whenever possible, TC positions were confirmed after the casting cooled to room temperature as well. Having accurate knowledge of the TC positions reduces the inverse modeling simulation iterations required to achieve the desired agreement between all measured and simulated TCs. This knowledge also reduces uncertainty in the final data judged by the error between the final measured and predicted temperatures.

Development of Riser Sleeve Thermophysical Properties

Control Castings

The control castings were used to ensure that the steel and sand mold properties in the simulations are accurate. Due to space limitations, these properties are not provided here, but they are similar to those available in the simulation software database.[7] It was found that only small changes needed to be made to the mold properties from one experimental control case dataset to the next to achieve agreement between measured and predicted temperatures. For the steel, the solid fraction versus temperature curves

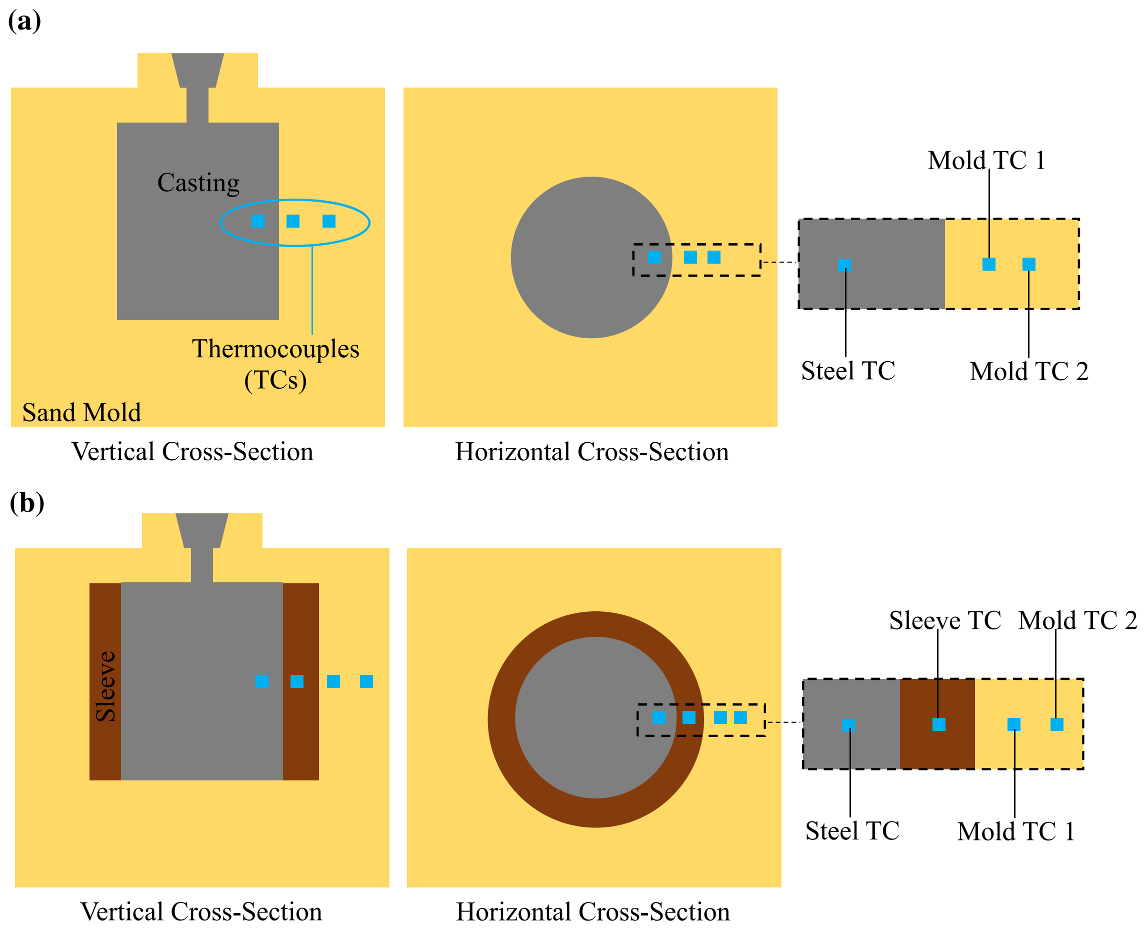

Figure 1. Schematic diagrams of experimental casting setups for (a) castings without a sleeve and (b) castings with a sleeve.

Table 1. Riser Sleeve and Experimental Casting Dimensions

Sleeve designation-insulating/exothermic	Density (kg/m^3)	Sleeve inner diameter (in.)	Casting height (in.)	Sleeve thickness (in.)	Control casting diameter (in.)	Control casting height (in.)
A1-E	422	3.5	6	0.5	4.5	6
A2-E	621	8	8	1	6	6
A3-E	534	3	6	0.625	3	5
A4-I	422	2.5	6	0.375	6	8
B1-E	451	5	5	0.5	5	8
B2-E	451	4.5	6	0.75	4.5	6
B3-E	451	6	6	1	4.5	6
C1-E	676	3	6	1.25	3	5
C2-E	531	3	5	0.5	3	5
C3-I	479	6	6	0.5	6	6
D1-E	529	4.5	6	0.5	4.5	6
D2-I	395	4.25	6	0.375	4.5	6
F1-I	256	4	4	0.5	3	5

were adjusted for each heat in order to match the measured liquidus and solidus temperatures and the temperature variations during solidification. The temperature-dependent interfacial heat transfer coefficient (HTC) at the steel–mold interface was also determined via inverse modeling. It was found that the single HTC curve shown in Figure 2 could be used for all control castings. The steep drop in the HTC results from the gap formation between the steel and mold due to metal contraction, which reduces the heat flow. Details on the procedures used in the inverse modeling of the solid fraction and HTC curves can be found in Reference [11].

An example of agreement between measured and simulated temperatures (the red and black curves, respectively) for a control casting with no sleeve is shown in Figure 3a for the steel TC and in Figure 3b for the sand mold TCs. In Figure 3b, there are two mold TCs at 10 and at 20 mm (the dashed and solid curves, respectively) from the mold–metal interface. The good agreement between measured and predicted temperatures in Figure 3 is similar to that obtained in all control casting cases.

Sensitivity Study

The properties for the sleeve materials were determined after the mold and steel properties were set for a given heat. The temperature-dependent sleeve thermophysical properties required for casting simulation are: density ρ, specific heat c_p, and thermal conductivity k. In modeling heat transfer using the conservation of energy equation, the thermal conductivity appears in the equation independently, whereas density and specific heat always appear as the product ρc_p, the heat capacity. For exothermic sleeves, the casting simulation software uses three additional parameters to describe the exothermic heat release: the ignition temperature, the burn time, and the heat generation per unit mass. Finally, the temperature-dependent heat transfer coefficients between steel and sleeve (h_{ss}) and between sleeve and sand mold (h_{sm}) must also be specified. Using inverse modeling to determine all of these properties and coefficients would be difficult. Therefore, a sensitivity study was performed to identify the one property that has the greatest effect on the simulation results. This property will then be the main focus of the inverse modeling efforts. All other properties and coefficients are set to predetermined values, as described in the next subsection. The three additional parameters needed for exothermic sleeves are determined directly using inverse modeling, so no sensitivity study is needed for those.

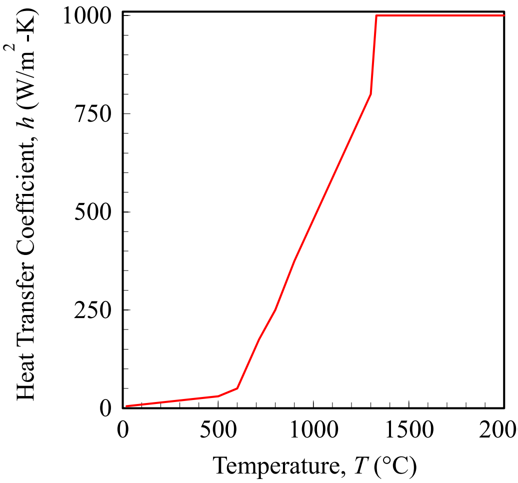

Figure 2. Temperature-dependent interfacial heat transfer coefficient applied at the steel–sand and steel–sleeve interfaces in simulations performed in this study.

The sensitivity of the simulation results to the sleeve properties and coefficients was studied by performing a parametric study where the thermal conductivity, k, the heat capacity, ρc_p, and the heat transfer coefficients between steel and sleeve, h_{ss}, and sleeve and sand mold, h_{sm}, were varied by factors of 0.5 and 2 from their base values. A cylindrical casting with a riser sleeve (see Figure 1) having thermophysical properties k, ρ, and c_p that correspond to sleeve C-3-I was used in the sensitivity study. These base property values are presented later in the text. The heat transfer coefficient between the steel and sleeve, h_{ss}, was taken to be the temperature-dependent coefficient determined from the control experiments without a sleeve (see Figure 2). The base heat transfer coefficient between sleeve and sand, h_{sm}, was taken to be 1000 W/m^2 K. The predicted solidification time of the casting is used to measure the sensitivity of the simulation results to the property changes.

The results of this property sensitivity study are shown in Figure 4. Here, the percentage difference in solidification time predicted relative to the unmodified case using k, ρc_p, h_{ss}, and h_{sm} is presented. The difference percentages are plotted on the left side of the bar chart for all permutations of cases where the sleeve material thermophysical properties k and product ρc_p are multiplied by factors of 0.5 and 2. The cases are grouped according to thermal conductivity used (i.e., multiplier of k) and bars of data corresponding to cases of ρc_p. The first two bars starting on the left side of the plot show that for the baseline values of k the solidification time only changes by +3 and −5 % when the heat capacity is changed by factors of 0.5 and 2, respectively. The next six bars of data show that the predictions are strongly affected by changes in the thermal conductivity of the sleeve. Reducing the thermal conductivity by a factor of 0.5 increases the solidification time by about 40–50 %, depending on the multiplier used for the heat capacity. Similarly, increasing the thermal conductivity by a factor 2 reduces the solidification time by about 30–40 %. The four bars on the right side of the plot show the predicted changes in the solidification time due to modifying the heat transfer coefficients by factors of 0.5 and 2. For the heat transfer coefficient between sleeve and sand mold, h_{sm}, the

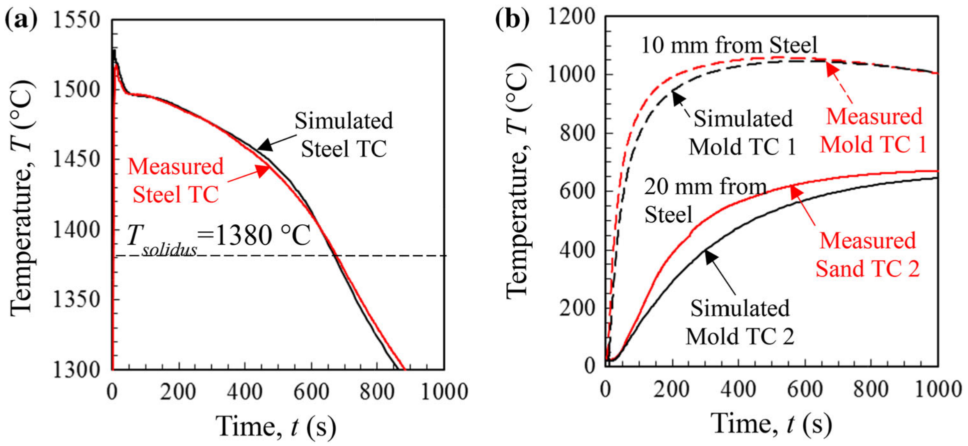

Figure 3. An example of agreement between measured (red curves) and simulated (black curves) temperatures for a casting without sleeve in the (a) steel and (b) sand mold. In (b), the line type denotes position at 10 mm (dashed line) and 20 mm (solid line) from steel–mold interface.

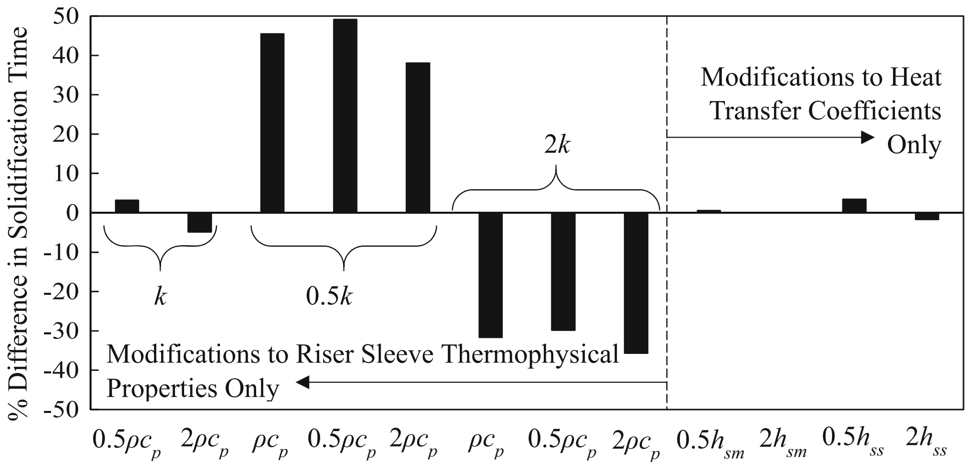

Figure 4. Percentage difference in solidification time for a sleeved cylinder casting predicted by casting simulation for all permutations of cases where the sleeve material thermophysical properties k and product ρc_p are multiplied by factors of 0.5 and 2. Cases are grouped according to multiplier of k, and individual bars correspond to cases of ρc_p. Additionally, there are four cases where the heat transfer coefficients between the sleeve and sand mold (h_{sm}) and between the sleeve and steel (h_{ss}) are modified individually by factors of 0.5 and 2. All differences are relative to the solidification time for a case with unmodified properties and coefficients.

effect on the solidification time is negligibly small (0–1 %), while for the heat transfer coefficient between steel and sleeve, h_{ss}, a 2–5 % effect can be seen. In conclusion, the present sensitivity study shows that the sleeve thermal conductivity is by far the most influential property. Within the ranges studied, all other properties and coefficients have an almost negligible effect on the sleeve performance. These findings are supported by those of Midea et al.[6] who also studied sensitivities of solidification times at the riser neck, and near the casting–riser interface, to changes in k, ρ, c_p, and the heat transfer coefficients. Therefore, the sleeve thermal conductivity was chosen as the focus of the present inverse modeling efforts. Even rough estimates of all of the other sleeve properties and coefficients are sufficient, since they do not affect the simulation results significantly. It is possible that, for example, the gases evolving from a sleeve change the heat transfer coefficients from the no-sleeve case. However, given the results of the present sensitivity study it is difficult to see how this would have a great effect.

Sleeve Thermal Conductivities

Before explaining the procedures used to determine the thermal conductivities for each sleeve, the values assigned to the other sleeve properties and the heat transfer coefficients are summarized. The densities were set to the constant values listed in Table 1. These values represent room temperature measurements. Midea et al.[6] provide a specific heat versus temperature curve with no numbers but the curve shows that specific heat increases with increasing temperature. In this work, the temperature-dependent specific heat was modeled by a common curve for all sleeves having a value of 400 J/kg K at 0 °C (32 °F) that increases to and ranges from 600 to 700 J/kg K between temperatures of 380–2000 °C (716–3632 °F). These values are from the simulation software database,[7] and the shape of the curve used in the current work is the same as in the plot given by Midea et al.[6] The heat transfer coefficient between steel and sleeve was set to the curve provided in Figure 2, and the coefficient between sleeve and sand mold was set to a constant value of 1000 W/m^2 K. All of the above property values and heat transfer coefficients should only be viewed as rough estimates. As shown in the sensitivity study, they have a negligible effect on sleeve performance as long as the actual values are within a factor two.

Development of the thermal conductivity data is accomplished by iteratively adjusting the temperature dependency curve for k used in simulations. Depending on how a modification during an iterative simulation run affects the agreement between simulated and measured temperatures, further modifications are made to progressively improve the agreement. Approximately 100 iterative simulations were performed per sleeve to achieve the best agreement with the measurements. In Figure 5a, an example of a final temperature-dependent thermal conductivity curve for sleeve D2-I is shown in black, labeled "k". Also shown in Figure 5a are curves resulting from multiplying the final thermal conductivities in the curve by factors of 0.5 and 2 corresponding to the blue and green curves, respectively. Note that in the inverse modeling procedure to determine k much smaller adjustments were made to k than factors of 0.5 and 2. Curves for these relatively large factors are shown here to illustrate how changes to the thermal conductivity curve affect the simulated temperatures in the steel, sleeve, and sand. Predicted temperature versus time data at the thermocouple measurement locations are compared to the measurements (red curves) in the steel, sleeve, and sand mold in Figure 5b–d, respectively. These figures include the predictions for the cases where the sleeve thermal conductivity curve was modified by factors of 0.5 and 2. They demonstrate the tradeoffs that are made in determining the final sleeve thermal conductivity curve that gives reasonable agreement at all thermocouple locations in the steel, sleeve, and sand mold. Generally speaking though, achieving agreement between measured and predicted temperatures in the steel is most important since solidification time for the steel is an important sleeve performance measure. The final thermal conductivity curves for all sleeves were determined such that similar agreement between measured and predicted cooling curves was obtained in the steel, sleeve, and mold, as that shown in Figure 5b–d by the red and black curves. Also note that Figure 5b, c contains measured steel and sleeve temperatures (red curves) from two nominally identical experiments. The close agreement between the two red curves in each of these figures demonstrates that the experiments were repeatable. Similar repeatability was achieved in all experiments with sleeves.

Exothermic Sleeve Properties

For exothermic sleeves, the three exothermic properties are also determined by inverse modeling. While there are three exothermic properties which must be determined, simulations performed to investigate their sensitivity to results indicated they affect sleeve performance independently of each other. In the exothermic sleeves studied here, a noticeable temperature peak in the sleeve temperature–time curve was observed provided that the heat generation is greater than about 300–400 kJ/kg. It is found that this peak can be quite high, in the range of 1600–2000 °C, for heat of generation values in the range from 1150 to 1700 kJ/kg. Ignition temperature was found to have an insignificant effect on the simulated temperature results in the range from 400 to 800 °C (752–1472 °F). It was found that setting it to 600 °C (1112 °F) produced reasonable agreement with the heating temperature spike for the exothermic reaction in all exothermic sleeves. The exothermic heat generation influences the height of the spike of the temperature–time curve, while the burn time influences the width (time span) of the exothermic heating spike. Measured (red curves) and predicted (black curves) temperature–time curves in the steel and sleeve are shown in Figure 6 for two exothermic sleeves. In Figure 6a for the steel TC and Figure 6b for the sleeve TC, the predictions use properties determined in this study for the A2-E sleeve material. In Figure 6c for the steel TC and Figure 6d for two sleeve TCs, the predictions use properties determined for the B2-E sleeve material. The two measured sleeve TCs, red curves, shown in Figure 6d give a sense of experimental reproducibility for the sleeve TC measurements, since every effort was made to position them at the same thickness position. The exothermic sleeve TC measurements can be very sensitive to position, which might be one source of the observed difference. However, the difference in the two repeated experimental measurements might indicate sleeve-to-sleeve performance variability as

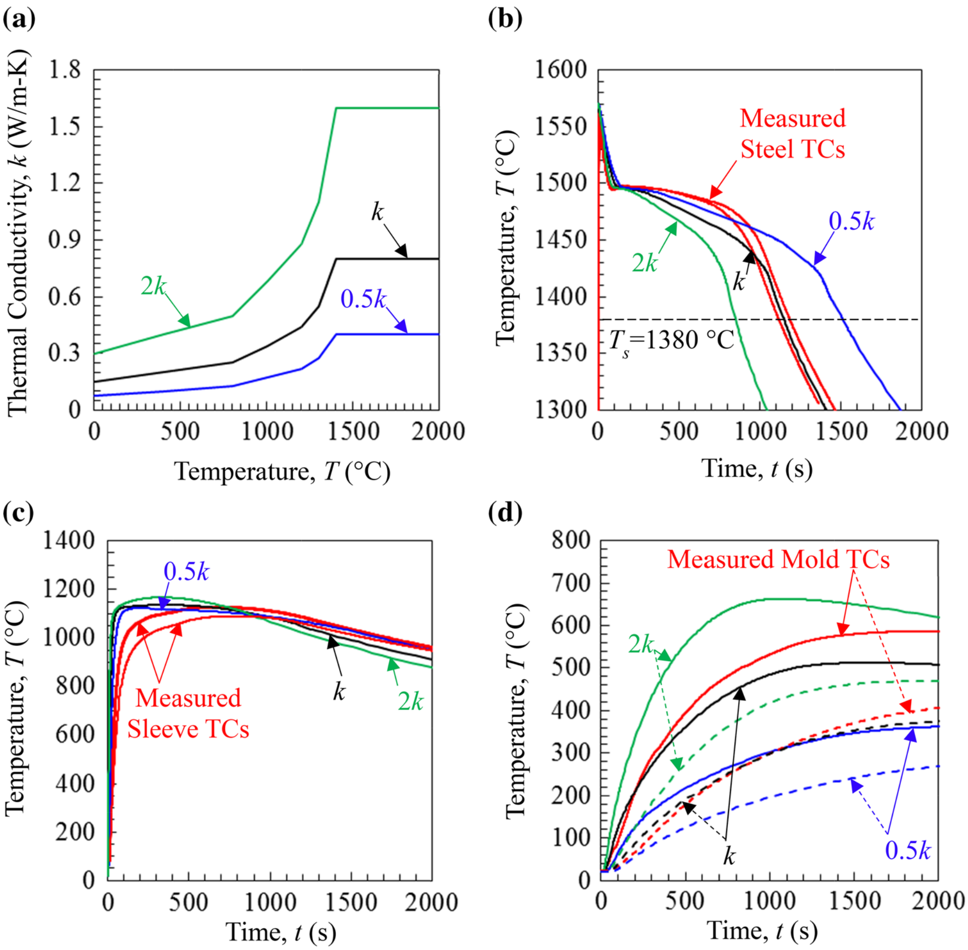

Figure 5. (a) Temperature-dependent riser sleeve thermal conductivity curve determined for the D2-I insulating sleeve material properties with base curve and curves multiplied by factors of 0.5 and 2. Measured cooling curves (red curves) are compared to predicted curves in the (b) steel, (c) sleeve, and (d) sand mold. Effect of multiplying the sleeve thermal conductivity by factors of 0.5 and 2 is shown by the blue and green curves, respectively. Note in (d) there are two measured mold TCs in the plot at 10 and 20 mm from the sleeve–metal interface corresponding to the solid and dashed curves, respectively.

well; this is an interesting issue but outside the scope of the current work.

Next the effects of modifying the exothermic parameters (the heat generation and burn time) on agreement between measured and simulated temperatures are shown in Figures 7 and 8 for the A2-E sleeve in the steel and sleeve, respectively. Similarly, effects of modifying the exothermic parameters on the agreement of the predicted and measured temperatures in both the steel and sleeve are shown in Figure 9 for the B2-E sleeve. The modifications made to the exothermic properties in Figures 7, 8 and 9 are to multiply the value determined in the study (corresponding to the black curves) by factors of 0.5 (the blue curves) and 2 (the green curves). The effect of changing heat generation on the temperature in the steel for the A2-E sleeve is most noticeable when it is doubled, especially as shown in Figure 7b in the initial cooling down to liquidus. Changes in the burn time have no effect on the temperature predictions in the steel for the A2-E sleeve as shown in Figure 7c, d. Looking at the sleeve temperature predictions in Figure 8, changes in both heat generation and burn time have no effect on the temperature predictions over the long time scale as shown in Figure 8a, c. Note for Figure 8a, c that the temperature scales are different and that doubling the heat generation increases the maximum temperature in the sleeve to about 1700 °C in Figure 8a, b. From Figure 8b, d, it is clear that the predictions lead the measurement in time, and additional inverse modeling iterations or changing other properties that were fixed (like ignition temperature, specific heat and density) might eliminate this discrepancy in time. Still, on the casting

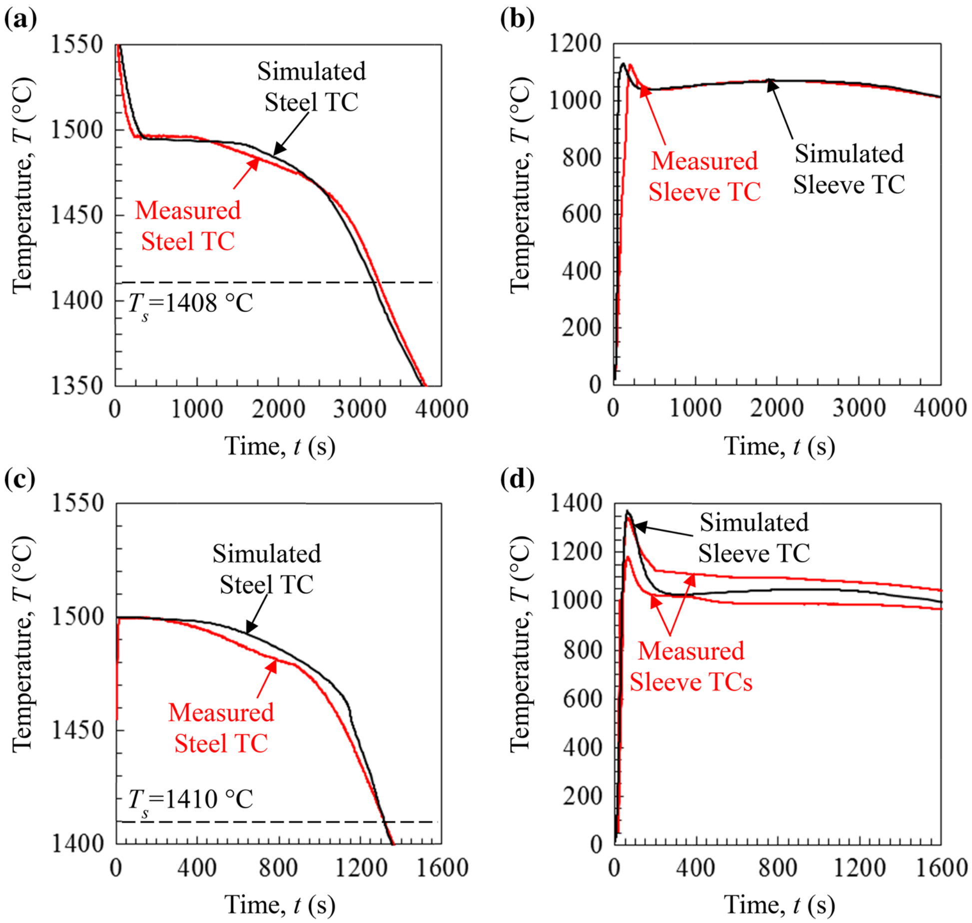

Figure 6. Measured (red curves) and predicted (black curves) temperature versus time curves in the steel and sleeve for two exothermic sleeves. Predictions use properties from this study for the A2-E sleeve casting in the (a) steel and (b) sleeve, and for the B2-E sleeve casting in the (c) steel and (d) sleeve.

solidification time scale, and in the steel, the predictions and measurements agree quite well. For the B2-E sleeve shown in Figure 9, the conclusions of the exothermic property modification study are similar. Modifying the heat generation in Figure 9a–c again shows that the most noticeable effect in the metal is observed when it is doubled. Doubling it also produces a very high temperature, which was not measured in the experimental data. If the temperature were very high, as high as 2000 °C in Figure 9b, the type-B thermocouple sensor would probably have failed. Modifying the burn time shown in Figure 9d–f, no effect on predictions is seen in the steel, and in the sleeve the predictions are only seen to be different in the first 400 s.

The exothermic properties determined for all sleeve materials are listed in Table 2, where the sleeves are listed in order of highest heat generation to lowest. Assuming the heat generated from the exothermic sleeve is produced solely by a thermite reaction ($2Al + Fe_2O_3 \Rightarrow Al_2O_3 + 2Fe + 852$ kJ/mol),[12] for a stoichiometric mixture of reactants having a mass of 214 g/mol, the heat released on a reactant mass basis is 3981 kJ/kg. By equating the total heat produced by thermite with the total heat produced by the sleeve, one may find a simple proportional relationship between mass percent of thermite and heat released by the sleeve per unit mass. Based on this, the estimate of the heat released for an exothermic sleeve using thermite is about 400–800 kJ/kg for a sleeve composed of 10–20 % thermite content by mass. Unfortunately, the exothermic contents of the sleeves studied are not provided by the manufacturer. However, this 10–20 % thermite content range seems reasonable and agrees with the range of heat generation found in this study in Table 2. The maximum heat generation for a sleeve material found in this study was 850 kJ/kg, which corresponds to a 21 % thermite exothermic content based on the reaction estimate. Seven of the nine sleeves studied here were found to have

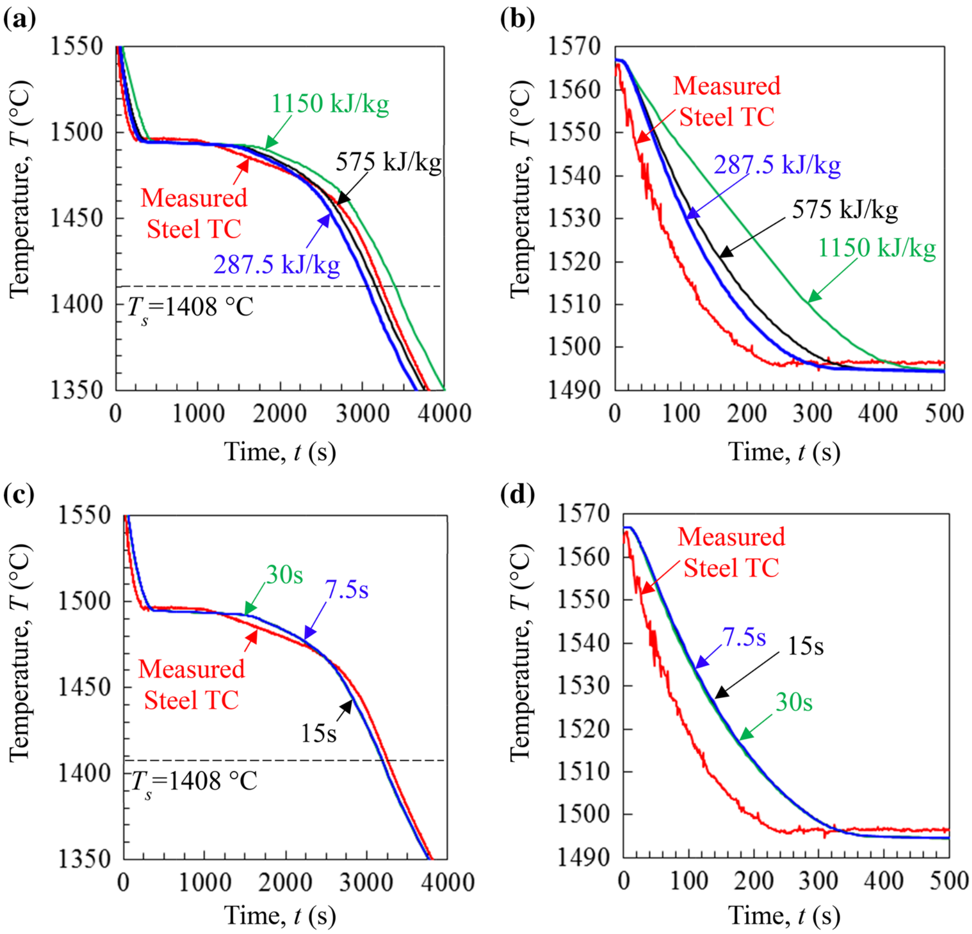

Figure 7. Temperature versus time results in the steel for the A2-E sleeve showing in (a) and (b) the effect of modifying the heat generation on agreement between measured and predicted temperatures on long and short time scales, respectively. (c), (d) The effect of modifying the burn time on agreement between measured and predicted temperatures.

heat generation values in the 10–21 % thermite exothermic content range. The two lowest heat generation values in Table 2 correspond to 6 % thermite exothermic content.

In the inverse modeling of a few sleeves, it was found that the thermal conductivity required slight modification after the exothermic properties were determined to arrive at the final thermal conductivity curves shown in Figure 10. The temperature-dependent thermal conductivity curves determined for all sleeve materials in this study are shown in Figure 10a–d, plotted according to manufacturer. Thermal conductivity data for manufacturers A, B, and C are shown in Figure 10a–c, respectively. Data for manufacturers D and F are shown in Figure 10d. For all sleeves, the lowest values of sleeve thermal conductivity were found at room temperature, ranging from 0.1 to about 0.25 W/m K. Note also for all sleeves that the thermal conductivity was found to remain constant, or increase moderately, up to temperatures from around 900–1200 °C. Above this temperature range, all sleeves, except B2-E, were found to have a steeper increase in thermal conductivity with increasing temperature up to maximum thermal conductivities ranging from about 0.6–1.4 W/m K. The data plateau at the maximum values at the highest temperatures in the solidification range and above. This trend for increasing thermal conductivity to maximum values at the highest temperatures is believed to be caused by heat transport due to flow of sleeve binder, filler, additives and reaction product gases. Therefore, the thermal conductivities presented in Figure 10 are effective thermal conductivity data and are suitable for use in casting simulation to predict riser solidification times.

Modulus Extension Factor

The thermophysical properties of riser sleeve materials developed in the first part of this study were used to

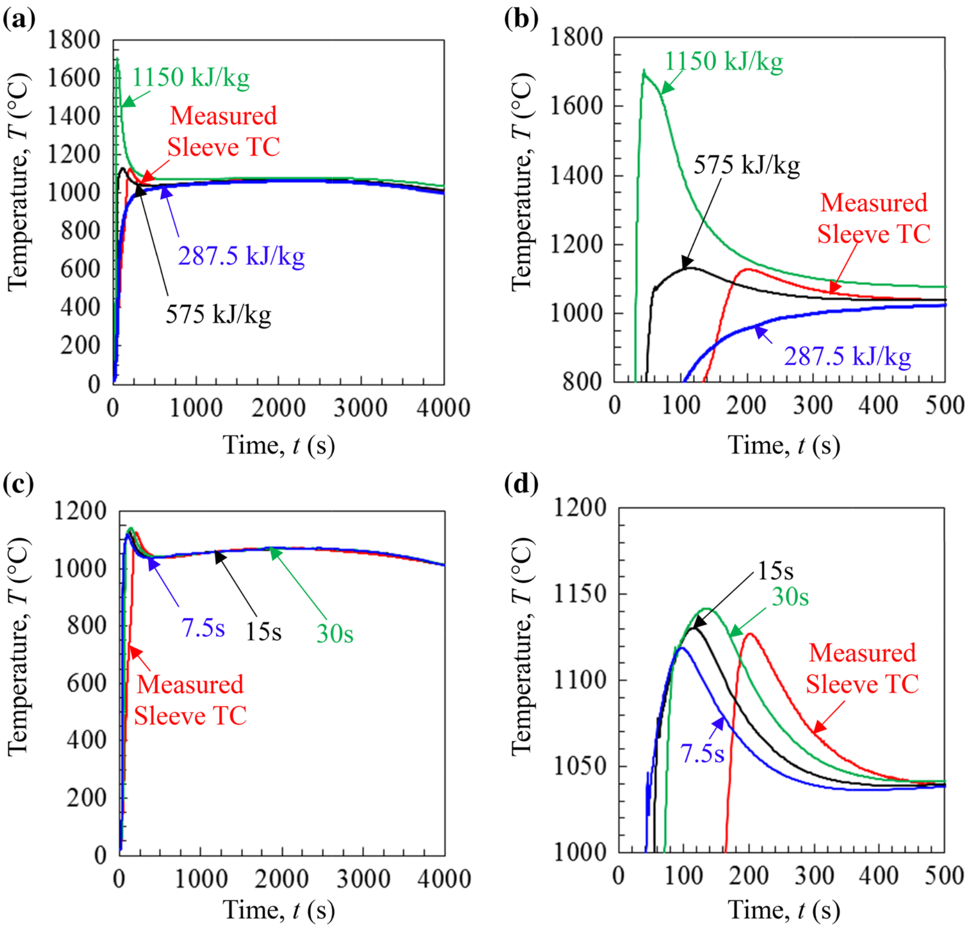

Figure 8. Temperature curves in the sleeve for the A2-E sleeve showing in (a) and (b) the effect of modifying the heat generation on agreement between measured and predicted temperatures on long and short time scales, respectively. (c), (d) The effect of modifying the burn time on agreement between measured and predicted temperatures.

investigate the performance of these materials through casting simulation. Most previous studies investigating riser sleeve performance have used the solidification time of a top riser on a casting, or the riser piping depth and safety margin to casting surface as the measures of performance. While such studies may be useful for a particular sleeve or casting, the results cannot be generalized as a standard measure of performance. Ideally, a sleeve's performance should be characterized by a unique measure of performance that is entirely general. A general method for defining sleeve performance is presented below.

An often used and traditional approach to estimating the required riser size to feed a casting section is the modulus method. The geometric modulus of a riser, or casting, is defined as the quotient V/A, where V is the volume of the riser or casting section, and A is the heat loss surface area of the section. In simple terms, the riser size as defined by geometric modulus is adequate if its solidification time exceeds the casting section solidification time that it feeds with feeding time given by Chvorinov's rule:[13]

$$t_s = K\left(\frac{V}{A}\right)^2 \qquad \text{Eqn. 1}$$

where t_s is the time to solidification of a casting section, and K is a constant combining properties of the steel and sand mold and their interfacial temperature difference. Typically, as a margin of safety, the riser solidification time t_s should exceed the casting t_s by about 20 % when using the modulus method. Equation 1 is derived from the one-dimensional transient energy equation for casting solidification.[13] The resulting solution in Eqn. 1 states that the time to solidification of a casting section is proportional to the square of the modulus of the casting section. This equation can be directly applied to risers without sleeves. When a riser sleeve is used however, the solidification time increases despite the geometric modulus

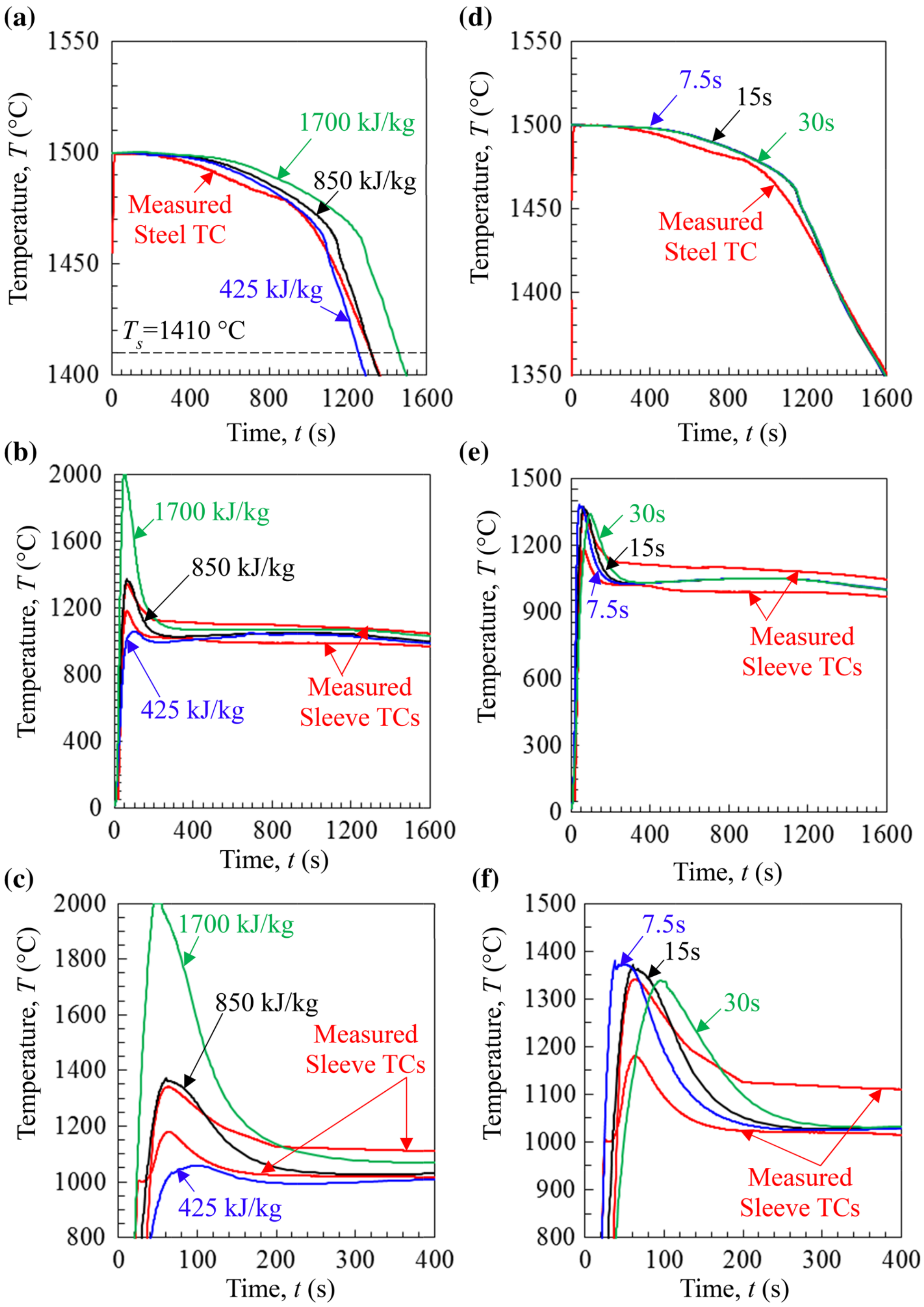

Figure 9. Temperature curves in the steel and sleeve for the B2-E sleeve showing in (a), (b) and (c) the effect of modifying the heat generation on agreement between measured and predicted temperatures on long times scales in (a) and (b) and a short time scale for the sleeve in (c). Analogous temperature curves showing effect of modifying the burn time on agreement between measured and predicted temperatures are shown in (d) for the steel and (e) and (f) for the sleeve.

remaining constant. To explain the increased solidification time, the riser is said to have an *apparent* modulus which is larger than its geometric modulus. The two moduli are related by the equation:

$$M_A = f M_G \qquad \text{Eqn. 2}$$

where M_A is the apparent modulus of a sleeved riser, M_G is the geometric modulus of a sleeved riser, and f is the

Table 2. Riser Sleeve Exothermic Properties Used for Simulation

Sleeve	Heat generation (kJ/kg)	Burn time (s)	Ignition temperature (°C)
B2-E	850	15	600
B1-E	750	15	
A2-E	575	15	
C2-E	520	60	
C1-E	500	45	
D1-E	425	30	
B3-E	425	18	
A1-E	250	40	
A3-E	250	20	

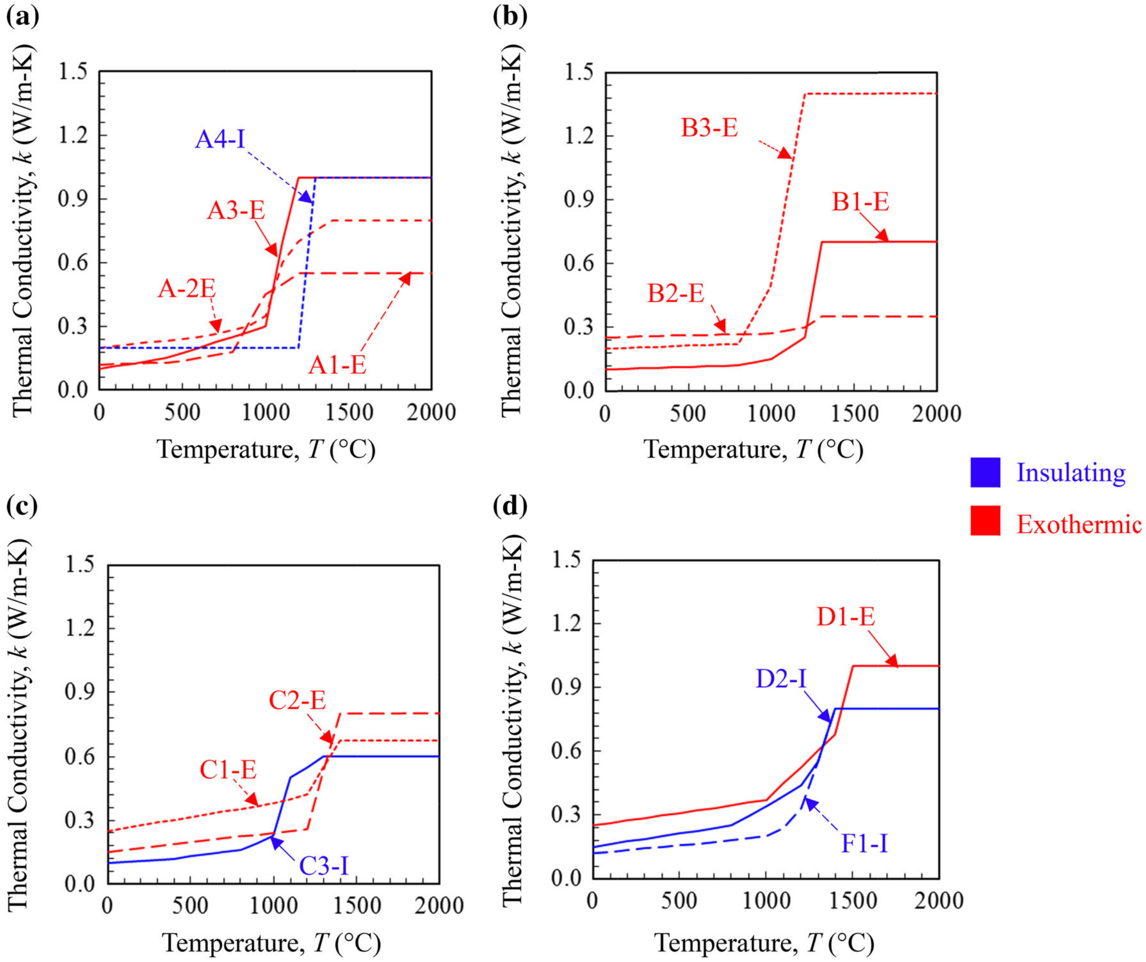

Figure 10. Riser sleeve temperature-dependent thermal conductivity curves for sleeve materials sorted by sleeve manufacturer. Manufacturers are (a) A (b) B (c) C (d) D and F.

modulus extension factor (MEF). Since the riser modulus will change with riser size, it is a poor choice of parameter to use in a sleeve performance study. However, as is verified below, MEF is independent of riser size for a given sleeve thickness. Therefore, the MEF can be determined for a given sleeve material defining its performance by a unique value for any riser size. Because the MEF varies only with sleeve material properties and sleeve thickness, it is the preferred parameter over modulus for investigating sleeve performance. The MEF can be calculated as the ratio of the apparent to geometric modulus of a riser with a sleeve. Since the apparent modulus is not a readily available quantity, it must first be determined either experimentally or by simulation, as described below.

Methods for experimentally determining the apparent modulus have been published.[4] In order to determine the apparent modulus the solidification time of a sleeved riser is measured. Then the modulus for an un-sleeved riser having the same solidification time is determined by iterative experimentation as described below to determine *f*. Since it is hard to pinpoint the exact location of final solidification, a thermocouple is placed at the center of the junction between a riser with a sleeve and a casting underneath it. This location results in representative values of the solidification time required to feed a casting section. The thermocouple is then used to measure the time to solidus temperature at that location for the riser with a sleeve. The same is done for a larger sand riser without a sleeve and feeding an identical casting section. Iterating with additional experiments as needed, the time to solidus is measured for increasingly larger sand risers until one is found to match the time to solidus for the smaller riser with sleeve. The geometric modulus of this larger riser without a sleeve is then adopted as the apparent modulus of the smaller sleeved riser. With the apparent modulus determined, the MEF can readily be calculated.

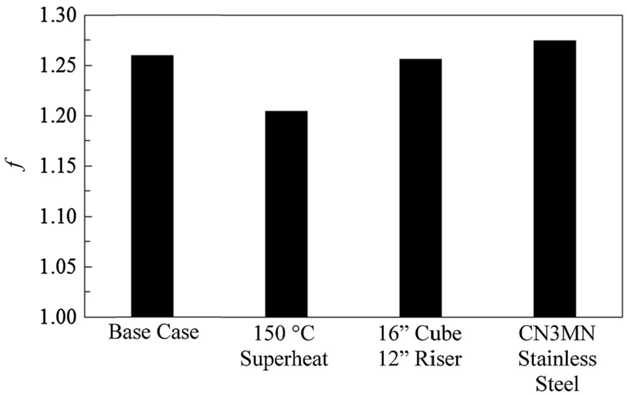

Figure 12. Sensitivity of the modulus extension factor f to three casting parameters: superheat, casting size, and alloy. Base case is an 8″ cube casting with 6″ riser, 0.5″ sleeve, and WCB alloy steel with 30 °C superheat.

Here a method of determining MEF using simulation is proposed. The casting is an 8-in. cube fed by a 6-in.-high cylindrical top riser with 6 in. diameter and a 0.5-in.-thick riser sleeve as shown in Figure 11. A 4-in.-thick layer of silica sand is set around the casting, and the top of the riser is open to the atmosphere. Simulations were performed to test this proposed procedure. In these simulations, an open riser (feeder) was used in conjunction with the software's default boundary condition for an open riser. WCB steel properties were used with a superheat of 30 °C (54 °F). A virtual thermocouple is placed at the junction between the riser and casting, where the solidification time for the riser is determined. A schematic of this configuration is shown in Figure 11. The configuration for the casting without sleeve is the same as that with the sleeve, except for the exclusion of the sleeve and a larger riser size. For consistency, the aspect ratio (diameter/height ratio) of the riser is constant and equal to 1 when changing the size of the riser. The sand riser size is increased in 0.25-in.-diameter

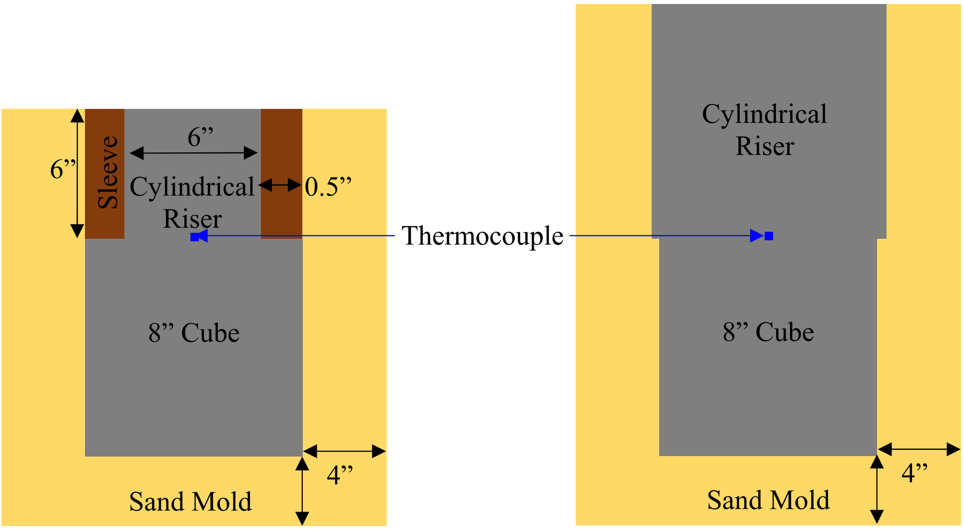

Figure 11. Simulation geometry used to determine the apparent modulus and modulus extension factor for a given riser sleeve. The riser without sleeve has a variable diameter. Riser aspect ratio is always 1.

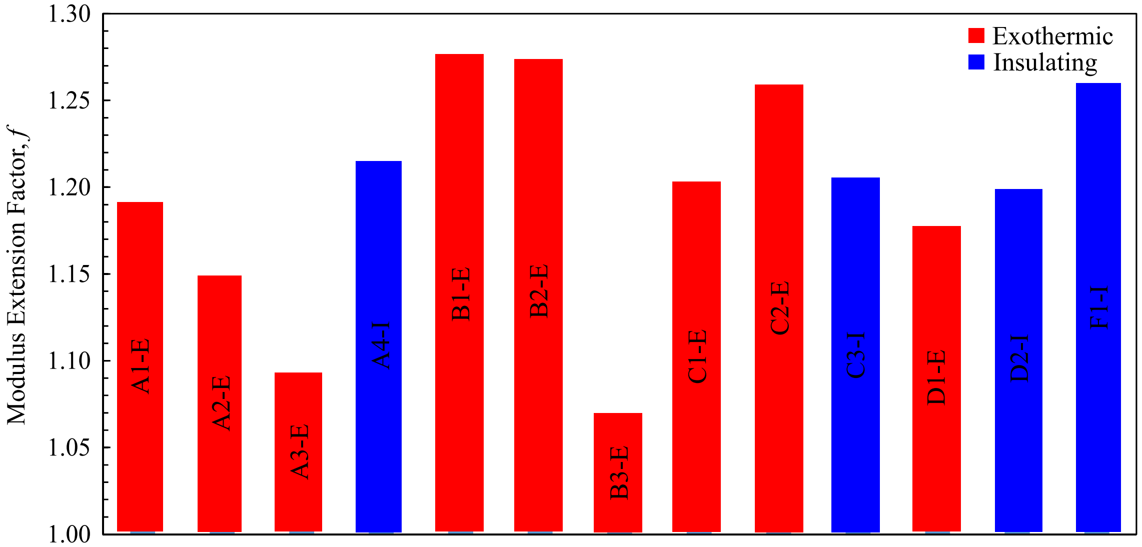

Figure 13. Modulus extension factors for the 13 sleeve materials investigated. Factors were determined via simulation for identical 0.5″ thick sleeves insulating a 6″ diameter × 6″ tall cylindrical top riser on an 8″ cube casting.

increments until consecutive increments have a smaller and larger time to reach solidus temperature than the sleeved riser. For example, an 8.25-in.-diameter sand riser with a smaller time to solidus than the sleeved riser and an 8.5-in. riser with a larger time to reach solidus are the two sand riser sizes used to determine the apparent modulus. Using these sizes and their solidification times, the riser diameter used in calculating the apparent modulus is interpolated at the sleeved riser solidification time. This diameter is then used to calculate the apparent modulus and then the MEF.

The method outlined above is a reliable way to determine a MEF using simulation. However, be aware that there are several casting parameters that affect the value of f and that these should be controlled for consistent results. Figure 12 shows the calculated value of f for one insulating sleeve from this study (F1-I) depending on the modification of several parameters. As shown in Figure 12, casting size and steel alloy have a relatively small effect on f, while superheat has a larger effect. It is important to note that f is representative of the increase in solidification time that is attributable to the use of a sleeve. While it is true that increasing superheat will increase the solidification time of a casting, the increase that is solely attributable to the inclusion of a sleeve is lessened and hence the decrease in f. The MEF provides a common performance measure for sleeve materials despite the variability due to superheat. MEFs, calculated via the method in the preceding paragraph, are shown in Figure 13 for the sleeve materials investigated in this study. The f values calculated in Figure 13 correspond to a constant sleeve thickness of 0.5 in. This allows for a fair comparison of their material performance. The actual thicknesses used in sleeve products are highly variable as will be discussed below. Therefore, performance of actual products will differ from Figure 13, based for example on a product's actual thickness and geometry. To be clear, the MEFs shown in Figure 13 were determined to provide a true comparison of sleeve material performance.

The f values in Figure 13 range from 1.07 to 1.28 with an average value of 1.20. The variability in f can be expressed by the standard deviation of the data in Figure 13 which is 0.07. Based on 95 % confidence, the true mean f value for the sleeves studied here and its confidence interval is 1.20 ± 0.04. Of the sleeve materials with the four highest f values, ranging from 1.26 to 1.28, three are exothermic and one is insulating. Note that some exothermic materials have lower f values than the insulating ones. The two materials with the lowest f values are exothermic sleeve materials, having f values from 1.07 to 1.09. Clearly, whether a sleeve material is insulating or exothermic does not necessarily mean it will perform better. A discussion follows below on the relationship between f values and casting yield increase. Also presented below are results of a study investigating whether the exothermic effect has a greater benefit for smaller or larger castings, since there is a range of opinion among steel foundries on the issue.[1]

Riser Sleeve Effects on Casting Yield

Increased casting yield is among the most prominent reasons for using a riser sleeve. If a given riser sleeve does not result in the use of a smaller riser, using that sleeve is unnecessary and a waste of resources. It is therefore

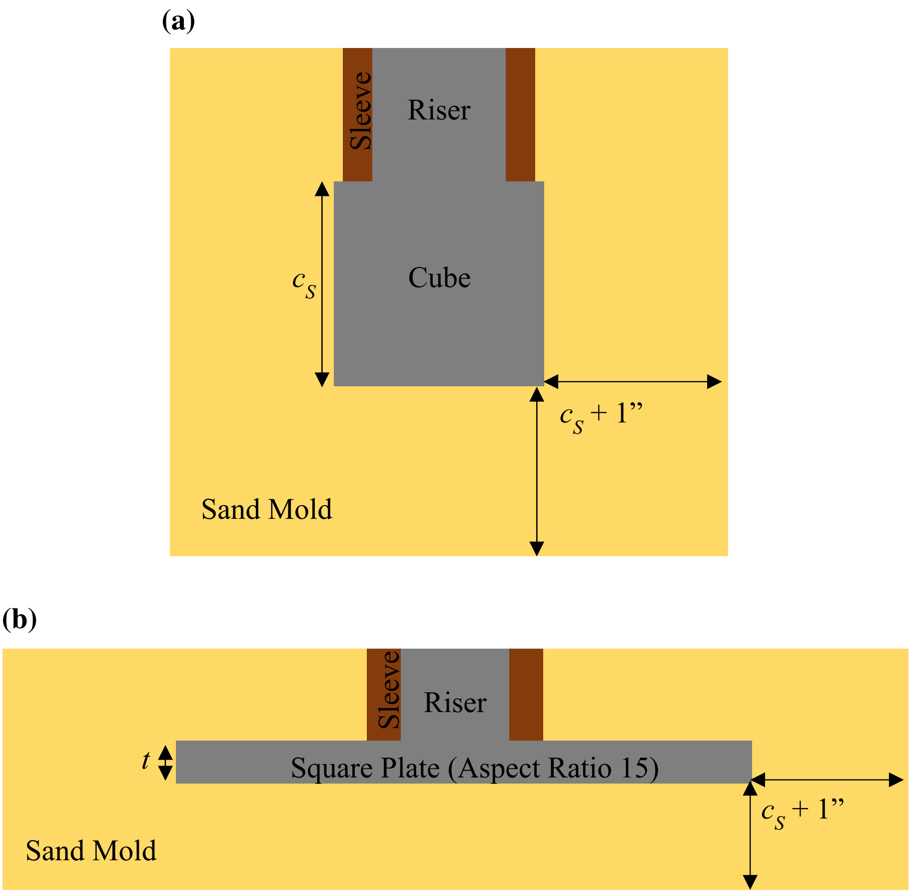

Figure 14. General schematics of the simulation geometries used to study achievable casting yield. (a) Schematic geometry for a cube of side length c_S. Side lengths of 3, 6, 9, 12, 18, and 24 in. were used. (b) Schematic geometry for a square plate of thickness t and aspect ratio 15. The six plate castings studied have volumes equivalent to the six cube volumes.

important to clarify what improvements in casting yield are achievable by using riser sleeves. By analyzing the effect of sleeves on improving casting yield across a range of casting sizes and shapes, it is possible to answer long-standing questions, such as whether exothermic sleeves are more beneficial for smaller or larger riser diameters. All studies in this section were accomplished via simulation.

In order to investigate the effect of sleeves on casting yield, two types of casting geometries were designed for study via simulation. These geometries are shown in Figure 14. The first geometry is a cube, which is a simple approximation of a *chunky* casting. This casting has a high feeding demand on the riser. Cubes of side lengths (c_S) 3, 6, 9, 12, 18, and 24 in. were simulated in this study. The second geometry is a square plate with thickness t and aspect ratio 15. This casting geometry is *rangy* and is a casting with a low feeding demand. Plate volumes used in this study are equivalent to the volumes of the six simulated cube sizes. The goal of this casting geometry study was to determine the smallest size of top riser required to feed the casting's solidification shrinkage. This means that the riser size is highly variable. The riser diameter variability introduces the need for a consistent approach for determining the sleeve thickness used for a given riser size. To address this need, a linear approximation of commercially available sleeve thickness based on riser diameter was created. The approximation can be seen in Figure 15 where sleeve thickness t versus riser diameter D values from manufacturer's product data is plotted. Both insulating and exothermic sleeves are used in this chart; no significant difference was observed between how the thickness varies with diameter for the two types of sleeves. The linear fit, $t = 0.08D + 0.126$, indicates that the riser sleeve thickness increases with the riser sleeve inner diameter with the slope indicating the sleeve thickness is about 8 % of the riser diameter. With the sleeve thickness now determinable for any riser size, the size of the risers for these chunky and rangy castings can be minimized.

The minimum riser size will be determined based on a 10 % minimum margin of safety (based on the riser height) between the casting surface and the closest region of porosity predicted in the riser's shrinkage pipe. Because the investigation will be performed using simulation software, it is necessary to define the edge of the riser's shrinkage porosity region, and here it is defined at the 0.7 % porosity level. For simplicity, risers with an aspect ratio of 1 are used. For consistency, simulation properties for the WCB alloy will be used with a superheat of 30 °C (54 °F) and a feeding effectivity of 70 %. Feeding effectivity is the main simulation parameter used in the simulation software's algorithm for riser shrinkage pipe prediction. The 70 % value used here is somewhat higher than the 30–40 % typically usually used in industry for steel. Using this higher value results in a less conservative riser pipe prediction (i.e., the riser pipe is slightly shallower), but the differences are relatively small. The simulated riser pipe sizes may not always be in exact agreement with those in real castings for a number of reasons, including approximations made in the software's algorithm for shrinkage porosity prediction. In addition, phenomena such as dilation of the riser sleeve during solidification and the resulting increase in the riser diameter are not taken into account in the simulation. Hence, when discussing the predicted trends and relative changes in casting yield below, these caveats need to be kept in mind. Minimization of the riser size is illustrated in Figure 16 for cases with a riser pipe safety margin that is 7 % (left side image) and 12 % (right side image), where the smallest allowable riser size increment is 0.1 in. In this example, the 12 % safety margin case is taken as the minimum riser size, since it represents the case having the maximum achievable casting yield with an acceptable margin of safety.

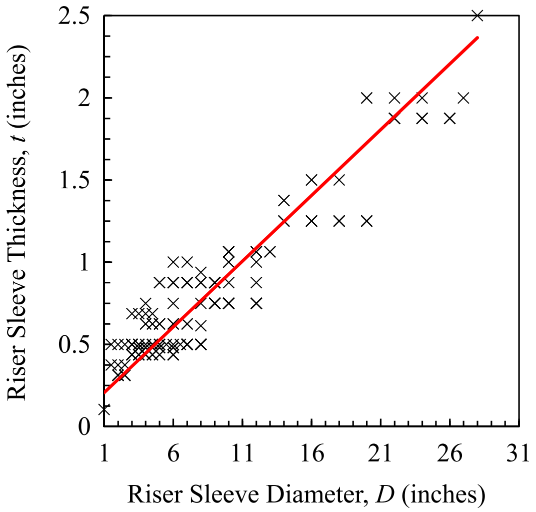

Figure 15. Plot of riser sleeve dimensions as listed in manufacturer's product data. The red line is a linear approximation of the data. The fit indicates that the riser sleeve thickness in inches, t, increases with the riser sleeve inner diameter in inches, D, according to the equation t = 0.08D + 0.126.

Riser sleeve material properties for the B2-E, A1-E and A4-I sleeves were used in the casting yield study. The A1-E and A4-I material data were used since they correspond to the average value of $f = 1.2$. This f value is representative of both insulating and exothermic sleeve materials

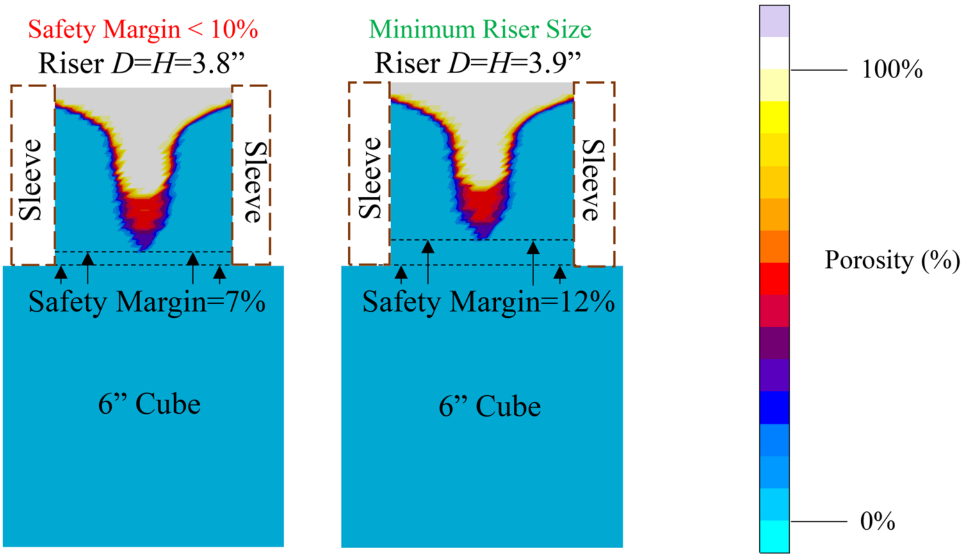

Figure 16. Examples of simulated shrinkage porosity used to determine maximum achievable casting yield. A 0.7 % porosity threshold was used to determine the extent of the riser pipe. The minimum margin of safety goal was 10 % of the riser height.

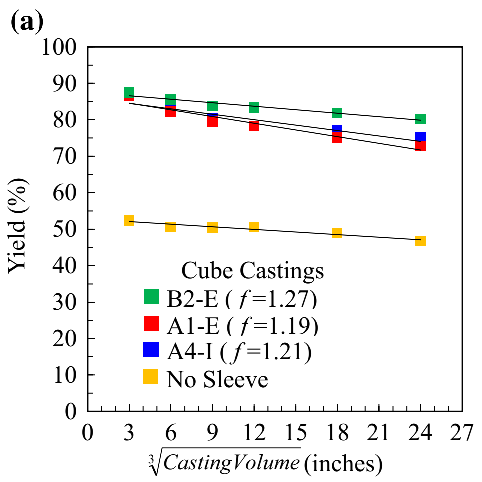

Figure 17. Maximum achievable casting yield for (a) cube castings and (b) square plate castings without sleeve, castings with insulating riser sleeves, and castings with exothermic sleeves. Insulating and exothermic sleeves behave similarly at all sizes. f values are those from Figure 13.

studied. If the exothermic effect has an increased yield benefit for smaller or larger castings, that should be apparent when the yield results for these two sleeves are compared, since their f values are the same. Any difference would be due to the exothermic effect. However, if there is no additional benefit to the exothermic effect for smaller or larger casting, the yield results for these two sleeves should be the same. Sleeve material B2-E was also chosen since it has one of the largest MEF values ($f = 1.27$). This sleeve also has the highest exothermic heat generation determined in this work.

The results of the casting yield investigation are shown for the chunky and rangy castings in Figure 17a, b, respectively. Immediately noticeable is that the rangy plate castings on the right side plot have much higher casting yields than cube castings of the same volume. As a result, the impact of using a sleeve to increase casting yield is much greater for chunky casting sections than the rangy ones. For the chunky castings, casting yield increases from around 50 % without sleeves to about 80 % with sleeves, whereas for rangy castings, yield increases from around 87 % without sleeves to about 93 % with sleeves. Clearly, the use of sleeves only makes an appreciable casting yield improvement for chunky casting sections. Also noticeable is that the maximum achievable casting yields for the insulating (A4-I) and exothermic (A1-E) sleeve materials with $f = 1.2$ overlap each other entirely. Because these sleeves have a similar f value, any difference in casting yield between these insulating and exothermic sleeve materials would be expected if the exothermic effect made a difference at a given casting size. However, there is no difference in casting yield caused by the exothermic effect for the entire range of casting sizes in the study. Furthermore, for the chunky castings and the B2-E sleeve material with $f = 1.27$, there is a noticeable increase in casting yield for all casting volumes over the $f = 1.2$ sleeve materials. For this sleeve material applied to rangy castings, though not plotted in Figure 17b, there is only a 0.5 % increase in the casting yield over the $f = 1.2$ sleeve materials at the largest casting volume. Therefore, even for the best sleeve materials there is no additional payback in yield over poor materials for rangy castings. Concluding, if the exothermic effect increases the f value, then it is beneficial. Whether a sleeve is exothermic or insulating is not alone relevant to performance. Rather, the performance of a sleeve material,

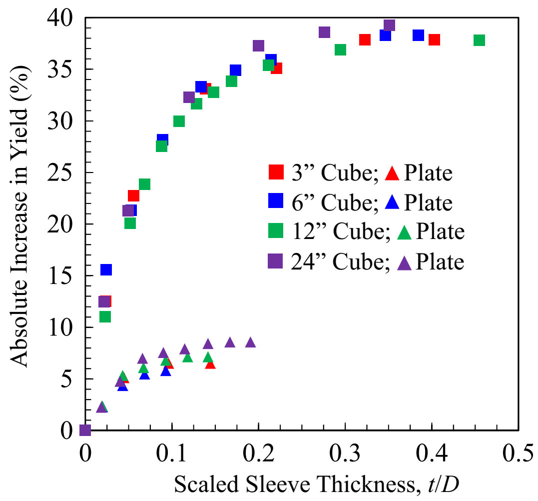

Figure 18. Absolute increase in maximum achievable casting yield for the exothermic riser sleeved casting over the casting with no-sleeve case versus the scaled sleeve thickness (t/D) used. Results are shown for cube castings (squares) and square plate castings (triangles) with an aspect ratio 15 having volumes equal to those of the cube castings.

characterized by its f value, determines its capability to improve casting yield. Additionally, the thickness of a sleeve plays an important role in the performance of the end product, as discussed below.

In order to investigate the impact of sleeve thickness on casting yield, the same procedure using the cube and square plates of varying sizes as in the casting yield study is employed. Only now, rather than using a continuously varying sleeve thickness with riser size, the riser size will be minimized for a given sleeve thickness. Simulations were performed for cube castings of side length 3, 6, 12, and 24 in. and square plate castings of equivalent volumes. In this study of sleeve thickness and casting yield, riser sleeve material properties for a typical exothermic riser sleeve material are used in the simulations; so sleeve material A1-E is used with $f \approx 1.20$, as was also used in the yield study described above.

The results of the study of the effect of sleeve thickness on casting yield are shown in Figure 18. The results are presented as the absolute increase in yield versus varying sleeve thickness for the exothermic sleeve casting over the same-sized casting with no sleeve. In the plot, the sleeve thickness is presented as scaled with the riser diameter (t/D). This scaling is used since increasing riser size, or specifically diameter, requires that the sleeve thickness also increases to maintain a given performance level. This concept is validated given that results shown in Figure 18 for all casting sizes collapse to well-defined curves for cube and plate castings when the sleeve thickness is scaled by the riser diameter. Note in Figure 18 that the maximum increase in yield for a cube casting is 39 % and for a rangy casting is 9 %, regardless of casting size. These results indicate that sleeves are not as effective in increasing yield for rangy casting sections. It is acknowledged that there are reasons other than casting yield for sleeve use in rangy castings, such as product quality improvement. The optimum sleeve thickness can be defined as that where most of the possible yield increase is first achieved, and any further increase in thickness has little benefit. Using 90 % of the possible yield increase as this optimum level, the optimum scaled sleeve thickness for a rangy casting is about 0.1 for the sleeve material considered in the study; thickness above this gives little additional benefit. For chunky castings such as cubes however, the optimum sleeve thickness is about 0.2 times the riser diameter, since the resulting 35 % casting yield increase corresponds to 90 % of the maximum possible yield increase.

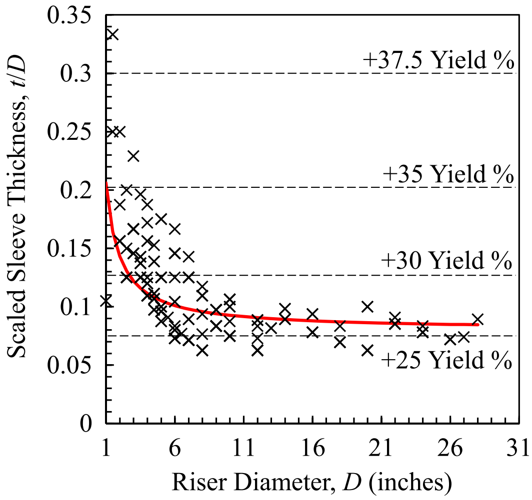

Figure 19. Scaled sleeve thickness of commercially available riser sleeves as determined from manufacturer product information and approximate predicted increases in casting yield for high moduli castings. Horizontal lines give predicted absolute increase in yield over chunky castings with no sleeve. The red curve is the approximation of commercially available sleeve thicknesses derived from Figure 15.

Note that the data in Figure 18 and the optimum sleeve thickness will be different for a sleeve material having a different f value. It is logical that for higher sleeve material f values, the maximum possible casting yields in Figure 18 will be larger and that the increasing yield with increasing sleeve thickness curves will be steeper.

Using the information in Figure 18 for chunky castings and the plot in Figure 15, showing the commercially available sleeve thicknesses (t vs. D), the commercially available sleeve thicknesses can be transformed into a plot of t/D versus D along with the expected yield increase possible at t/D values. Accordingly, the plot shown in Figure 19 is generated for commercially available sleeves (t/D) along with their impact on yield improvement for chunky castings versus riser diameters from 1 in. to about 30 in. Therefore, the horizontal casting yield percent lines in Figure 19 correspond to the absolute yield increase possible for the cube castings from Figure 18. The linear curve fit for the data in Figure 15 (the red line) for commercially available sleeve thicknesses versus riser diameter is transformed in Figure 19 to the red nonlinear curve. This red curve demonstrates there is a trend of decreasing scaled sleeve thickness with increasing riser diameter. This is contrary to the findings in this work, which showed the optimum scaled sleeve thickness to be independent of riser diameter and is constant depending primarily on the casting section geometry. The data plotted in Figure 19 give insight into the feeding aids available for a range of riser diameters and their expected performance from a casting yield perspective. The results plotted in Figure 19 demonstrate that opportunities exist for substantial yield increases for larger casting sections with higher geometric moduli (i.e., cubes) through using thicker sleeves than those in the commercially available dataset.

The transformed plot in Figure 19 shows that most commercially available riser sleeves result in a casting yield increase of at least 25 %. For the smaller diameter sleeves in Figure 19, these are generally thicker and thick enough to achieve the maximum yield increase. A few are perhaps too thick, since they have a scaled thickness >0.2. For risers around 6 in. diameter, from 4 in. to about 8 in., there is a large range of scaled thicknesses in the commercially available sleeve thickness data. In this riser size range, many sleeves are too thin and are below 0.1 scaled thickness. Also in this riser diameter range, all scaled thicknesses are below the optimum for chunky castings, 0.2. As the riser size increases further, >10 in. diameter, all sleeves appear to have scaled thicknesses less than or equal to 0.1. Therefore, all sleeves >10 in. diameter have less than optimum thicknesses.

For the chunkier castings, results from the casting yield and sleeve thickness study shown in Figure 18 indicate that if the scaled sleeve thickness is less than about 0.1 there will be a dramatic drop off in the maximum possible casting yield. It is apparent from Figure 19 that there are a considerable number of sleeve products supplied at or below this scaled sleeve thickness, and many of those are for larger riser diameters, which presumably will be used on larger chunkier castings. This study shows that doubling the riser sleeve thickness at larger diameters could result in an absolute increase in casting yield by 10 % as demonstrated by the horizontal lines. The payback in reduced energy usage and other benefits, such as increased capacity, are much greater for these larger risers as well. Surely these are results that should be of great interest to both the steel foundry industry and sleeve producers. The authors admit there are cost-related issues for manufacturers when producing thicker sleeves. It remains to be seen whether foundries will bear the *assumed* additional cost for improved/thicker sleeves.

Conclusions

In this study, thermophysical properties for thirteen commonly used riser sleeve materials have been determined by inverse modeling. These properties are now available for use in casting simulation. Of these properties, the thermal conductivity was found to have the largest impact on the solidification time of a riser. The modulus extension factor (MEF) was identified as the parameter that best characterizes sleeve material performance, and it is demonstrated to be independent of riser size. For the sleeve materials, in this study the MEF was found to range from 1.07 to 1.28 for a prescribed sleeve geometry that was 0.5 in. thick, 6 in. diameter and 6 in. high.

Analyses were performed to investigate optimal sleeve use for casting yield improvement. Regardless of casting size studied here, the MEF determines casting yield improvement when using sleeves. Whether a sleeve is made from insulating or exothermic materials, the method of achieving a high MEF for a sleeve does not appear to matter. Exothermic sleeve materials were not found to have an advantage over insulating ones regardless of riser size. It was found that up to a 40 % absolute increase in casting yield was possible when using top risers with sleeves on chunky cube-shaped castings for both insulating and exothermic sleeves having MEF $\approx$ 1.2. For rangy castings, having a square plate-shaped geometry with aspect ratio of 15, it was found that only a maximum absolute increase in casting yield of 8 % is possible. In general, sleeves were found to provide a relatively small payback in casting yield improvement for rangy castings when compared to chunky castings. It was demonstrated here that using sleeves for rangy casting applications to increase casting yield might be unnecessary. However, there are reasons other than yield for using sleeves, such as increasing casting soundness, quality improvement, and addressing difficulties in feeding a particular casting.

The maximum achievable casting yield was found to be highly dependent on sleeve thickness. Thickness versus diameter data for commercially available riser sleeves was collected and presented. It was found that the best-fit curve $t = 0.08D + 0.126$ describes the overall relationship between thickness and diameter. When the scaled thickness t/D for this data is compared to the results of the casting yield study, it was found that many riser sleeve products have less than the optimum thickness for maximizing casting yield. In particular, this is true for larger risers, in the range of 10–30 in. diameter. The optimum scaled thicknesses for maximizing the casting yield of rangy and chunky castings was found to be approximately 0.1 and 0.2, respectively.

Acknowledgments

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